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Final Report: 11th International Workshop on Finite Elements for Microwave Engineering -- FEM2012 Student Support Grants

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W911NF-12-1-0144

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

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6. AUTHORS
Branislav M. Notaros

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Colorado State University - Ft. Collins
Sponsored Programs
2002 Campus Delivery
Fort Collins, CO 80523 -2002

8. PERFORMING ORGANIZATION REPORT NUMBER

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U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
61946-EL-CF.1

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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Re: Contract No. W911NF-12-1-0144 – award to Colorado State University (proposal 61946-EL-CF) to fund $7,000.00 for Conference Support Grant for FEM2012 International Workshop (Dr. Dev Palmer, Program Manager)
The conference support grant in the amount of $7000 by ARO was used to support the conference student paper program that was established for this conference for the first time. The ten students – winners of the FEM2012 Student Paper Competition received $700 student travel support grants. The student awardees were recognized at

15. SUBJECT TERMS
FEM2012 International Workshop, Conference Support Grant, Student Paper Competition, student travel support grants

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Branislav Notaros
					19b. TELEPHONE NUMBER
					970-491-3537

Report Title

Final Report: 11th International Workshop on Finite Elements for Microwave Engineering -- FEM2012 Student Support Grants

ABSTRACT

Re: Contract No. W911NF-12-1-0144 – award to Colorado State University (proposal 61946-EL-CF) to fund $7,000.00 for Conference Support Grant for FEM2012 International Workshop (Dr. Dev Palmer, Program Manager)
The conference support grant in the amount of $7000 by ARO was used to support the conference student paper program that was established for this conference for the first time. The ten students – winners of the FEM2012 Student Paper Competition received $700 student travel support grants. The student awardees were recognized at the conference banquet (each of the students received a plaque at the banquet), and presented their winning papers at the workshop.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Dr. Branislav M. Notaros, Professor
Department of Electrical and Computer Engineering
Colorado State University
1373 Campus Delivery
Fort Collins, CO 80523-1373
Phone: (970) 491-3537
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E-mail: notaros@colostate.edu
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September 14, 2012

U.S. Army Research Office
ATTN: RDRL-ROE-L
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Re: **Contract No. W911NF-12-1-0144** – award to Colorado State University (proposal 61946-EL-CF) to fund $7,000.00 for Conference Support Grant for FEM2012 International Workshop (Dr. Dev Palmer, Program Manager)

Dear Colleagues:

Please find enclosed three copes of the Conference Proceedings of FEM2012.

Please also note that the signed Final Certification statement is being sent to ARO as well, at the address indicated in the contract.

The conference support grant in the amount of $7000 by ARO was used to support the conference student paper program that was established for this conference for the first time. The ten students – winners of the FEM2012 Student Paper Competition received $700 student travel support grants. The student awardees were recognized at the conference banquet (each of the students received a plaque at the banquet), and presented their winning papers at the workshop.

I hope that upon the receipt of the copies of the Conference Proceedings and the signed Final Certification statement, the ARO will be able to release the final payment of $700 of the grant (as stipulated in the contract).

Thank you very much for the ARO's support of our conference and student program.

Sincerely,

Branislav Notaros

General Chair of the 11th International Workshop on Finite Elements for Microwave Engineering – FEM2012, held from June 4-6, 2012, in Estes Park, Colorado

Enclosures

Dr. Branislav M. Notaros, Professor
Department of Electrical and Computer Engineering
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E-mail: notaros@colostate.edu
Web: www.engr.colostate.edu/~notaros

September 17, 2012

U.S. Army Contracting Command – Aberdeen Proving Ground
Research Triangle Park Division
ATTN: CCAP-SCR (CLOSEOUTS)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Re: **Contract No. W911NF-12-1-0144** – award to Colorado State University (proposal 61946-EL-CF) to fund $7,000.00 for Conference Support Grant for FEM2012 International Workshop (Dr. Dev Palmer, Program Manager)

Dear Colleagues:

This is the signed Final Certification statement for the above ARO Grant for FEM2012 Conference.

Please also note that the three copes of the Conference Proceedings of FEM2012 were sent to ARO as well, at the address indicated in the contract.

The conference support grant in the amount of $7000 by ARO was used to support the conference student paper program that was established for this conference for the first time. The ten students – winners of the FEM2012 Student Paper Competition received $700 student travel support grants. The student awardees were recognized at the conference banquet (each of the students received a plaque at the banquet), and presented their winning papers at the workshop.

I hope that upon the receipt of the copies of the Conference Proceedings and the signed Final Certification statement, the ARO will be able to release the final payment of $700 of the grant (as stipulated in the contract).

Thank you very much for the ARO's support of our conference and student program.

Final Certification statement:

I certify that the funds provided by the Army Research Office under Grant W911NF-12-1-0144 were expended in accordance with the provisions of the grant and that required conference proceedings have been delivered to the Army Research Office.

Branislav Notaros

General Chair of the 11th International Workshop on Finite Elements for Microwave Engineering – FEM2012, held from June 4-6, 2012, in Estes Park, Colorado

Dr. Branislav M. Notaros, Professor
Department of Electrical and Computer Engineering
Colorado State University
1373 Campus Delivery
Fort Collins, CO 80523-1373
Phone: (970) 491-3537
Fax: (970) 491-2249
E-mail: notaros@colostate.edu
Web: www.engr.colostate.edu/~notaros

For three copes of the Conference Proceedings of FEM2012

United States Postal Service

U.S. Army Research Office
ATTN: RDRL-ROE-L
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Physical Address

U.S. Army Research Office
ATTN: RDRL-ROE-L
4300 South Miami Boulevard
Durham, NC 27703-9142

Main Phone Number: (919) 549-0641

For the signed Final Certification statement

U.S. Army Contracting Command – Aberdeen Proving Ground
Research Triangle Park Division
ATTN: CCAP-SCR (CLOSEOUTS)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

FEM2012

Student Paper Award and US Army Research Office Travel Support Grant

is presented to

Thomas Bauernfeind

for a paper at

The 11th International Workshop on Finite Elements for Microwave Engineering

June 4-6, 2012, Estes Park, Colorado, USA

11th International Workshop on Finite Elements for Microwave Engineering – FEM2012

June 4-6, 2012, Estes Park, Colorado, USA

http://www.engr.colostate.edu/FEM2012

BOOK OF ABSTRACTS

Technical and Social Program at a Glance

Sunday, June 3, 2012
Welcome Reception 19:00-21:00 (Music Room)

Monday, June 4, 2012
Breakfast 7:00-8:00 (MacGregor Room)
Technical Sessions 8:00-11:50 (coffee break 9:40-10:10)
Lunch 11:50-13:10 (MacGregor Room)
Technical Sessions 13:10-17:20 (coffee break 15:10-15:40)
Stanley Hotel Ghost & History Tour – Monday Tour 17:30-19:00
Conference Banquet 19:30-22:30 (MacGregor Room)

Tuesday, June 5, 2012
Breakfast 7:00-8:00 (MacGregor Room)
Technical Sessions 8:00-11:50 (coffee break 9:40-10:10)
Lunch 11:50-13:10 (MacGregor Room)
Technical Sessions 13:10-17:00 (coffee break 15:10-15:40)
Stanley Hotel Ghost & History Tour – Tuesday Tour 17:30-19:00

Wednesday, June 6, 2012
Breakfast 7:00-8:00 (MacGregor Room)
Trip to Rocky Mountain National Park 8:00-14:00 (picnic lunch)
Open Forum Discussions 15:00-18:00 (coffee break 16:30-16:50)
Closing Reception 18:00-21:00 (The Elkhorn Lodge & Ranch)

The FEM International Workshop is a highly focused biannual event providing an ideal meeting place for researchers who are active in either the theoretical and numerical development of finite element and hybrid methods or their application to a broad range of electromagnetic problems.

The FEM2012 Technical Program combines 82 excellent papers organized in 12 special sessions. It also features three open forum discussions, moderated by leading FEM researchers and practitioners from academia, industry, and government.

The FEM2012 Social Program includes welcome reception, conference banquet, closing reception, trip to Rocky Mountain National Park, and Stanley Hotel Ghost & History Tour.

FEM2012 Committees

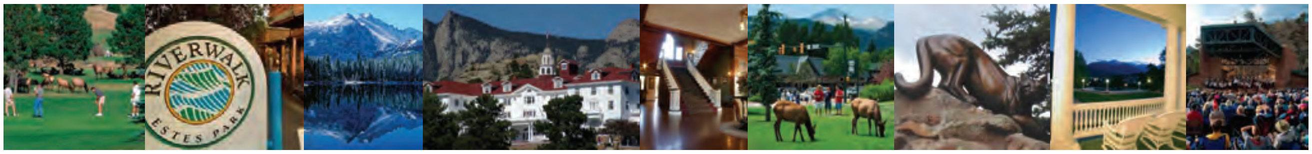
General Chairs:
Branislav M. Notaros, Colorado State University
notaros@colostate.edu

Jian-Ming Jin, University of Illinois
j-jin1@ad.uiuc.edu

Technical Program Committee Chair:
Milan M. Ilic, University of Belgrade and Colorado State University
milanilic@etf.rs

Local Organizing Committee Chair:
Olivera Notaros, Colorado State University
olivera@colostate.edu

Scientific Committee:
A. C. Cangellaris, University of Illinois Urbana-Champaign, USA
Z. J. Cendes, Ansoft LLC., USA
D. B. Davidson, University of Stellenbosch, South Africa
R. Dyczij-Edlinger, Universität des Saarlandes, Germany
R. L. Ferrari, Trinity College, UK
J. Jin, University of Illinois, Urbana-Champaign, USA
L. Kempel, Michigan State University, USA
J.-F. Lee, Ohio State University, USA
R. Lee, Ohio State University, USA
G. Pelosi, University of Florence, Italy
T. Rylander, Chalmers University of Technology, Sweden
M. Salazar-Palma, Universidad Carlos III de Madrid, Spain
J. L. Volakis, Ohio State University, USA
M. N. Vouvakis, University of Massachusetts, USA
J. P. Webb, McGill University, Canada
T. Weiland, Technische Universitaet Darmstadt, Germany



FEM2012 Financial Sponsors

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CST - Computer Simulation Technology

EM Software & Systems-S.A. (Pty) Ltd., FEKO

FEM2012 Student Paper Competition and Travel Grants Sponsor

US Army Research Office (ARO)

The views, opinions, and/or findings contained in this publication are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

FEM2012 Technical Sponsors

IEEE (Institute of Electrical and Electronics Engineers)

IEEE Antennas and Propagation Society

IEEE Microwave Theory and Techniques Society

University of Illinois

URSI (International Union of Radio Science)

FEM2012 Student Paper Competition Awardees

These ten students are winners of the FEM2012 Student Paper Competition and will receive $700 student travel support grants sponsored by the US Army Research Office (ARO). The student awardees will be recognized at the conference banquet, and must present their winning paper at the workshop.

Student name	Affiliation	Paper number and title
Thomas Bauernfeind	Institute for Fundamentals and Theory in Electrical Engineering, Graz University of Technology, Inffeldgasse 18, 8010 Graz, Austria	1.6. Investigation of the Scattering Behavior of Transponder Antennas in Case of Nonlinear Termination
Stylianos Dosopoulos	Electroscience Laboratory, Ohio State University, 1320 Kinnear rd., Columbus OH 43212, USA	2.3. Non-Conformal and Parallel Interior Penalty Discontinuous Galerkin Method for the Time-Domain Maxwell's Equations
Grzegorz Fotyga	Gdansk University of Technology Department of Microwave and Antenna Engineering 11/12 Narutowicza Street, 80-233 Gdansk, Poland	5.2. Efficient Model Order Reduction for FEM Analysis of Waveguide Structures and Resonators
Qing He	School of Electrical and Computer Engineering, Purdue University, 465 Northwestern Avenue, West Lafayette, IN 47907, USA	3.5. An Explicit and Unconditionally Stable Time-Domain Finite-Element Method of Linear Complexity
Gergely Koczka	Institute for Fundamentals and Theory in Electrical Engineering, Graz University of Technology, Inffeldgasse 18, 8010 Graz, Austria	6.8. An Iterative Domain Decomposition Method for Solving Wave Propagation Problems
Ana Manic	Colorado State University, Electrical & Computer Engineering Department, 1373 Campus Delivery, Fort Collins, CO 80523-1373, USA	9.7. Symmetric and Nonsymmetric FEM-MoM Techniques Using Higher Order Hierarchical Vector Basis Functions and Curved Parametric Elements
Safa Salman	Electroscience Laboratory, Ohio State University, 1320 Kinnear rd., Columbus OH 43212, USA	1.1.Highly Coupled Bowtie Array Design with Passive Elements
Nada Sekeljic	Colorado State University, Electrical & Computer Engineering Department, 1373 Campus Delivery, Fort Collins, CO 80523-1373, USA	8.3. Rules for Adoption of Expansion and Integration Orders in FEM Analysis Using Higher Order Hierarchical Bases on Generalized Hexahedral Elements
Ming-Feng Xue	Electromagnetics Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA	6.7. Preliminary Research on the Discontinuous Enrichment Method Based Domain Decomposition Scheme for Solving the Three-Dimensional Vector Curl-Curl Equation
Wang Yao	University of Illinois at Urbana-Champaign, Electrical and Computer Engineering, 1406 West Green Street, Urbana, IL 61801, USA	11.5. Application of Tree-Cotree Splitting to the Dual-Primal Finite Element Tearing and Interconnecting Method for Solving Low-Frequency Breakdown Problems

Overall Technical Program

The Historic Stanley Hotel		Monday June 4	Monday June 4	Tuesday June 5	Tuesday June 5	Wednesday June 6
Time	Slots	Billiard Room	Music Room	Billiard Room	Music Room	Music Room
8:00	Slot 1	Paper 1.1	Paper 2.1	Paper 7.1	Paper 8.1	
8:20	Slot 2	Paper 1.2	Paper 2.2	Paper 7.2	Paper 8.2	
8:40	Slot 3	Paper 1.3	Paper 2.3	Paper 7.3	Paper 8.3	
9:00	Slot 4	Paper 1.4	Paper 2.4	Paper 7.4	Paper 8.4	
9:20	Slot 5	Paper 1.5	Paper 2.5	Paper 7.5	Paper 8.5	
9:40	Coffee break					
10:10	Slot 6	Paper 1.6	Paper 2.6	Paper 9.2	Paper 8.6	
10:30	Slot 7	Paper 1.7	Paper 4.1	Paper 9.3	Paper 8.8	
10:50	Slot 8	Paper 3.1	Paper 4.2	Paper 9.4	Paper 10.1	
11:10	Slot 9	Paper 3.2	Paper 4.3	Paper 9.5	Paper 10.2	
11:30	Slot 10	Paper 3.3	Paper 4.4	Paper 9.6	Paper 10.3	
11:50	Lunch break					
13:10	Slot 11	Paper 3.4	Paper 4.5	Paper 9.7	Paper 10.4	
13:30	Slot 12	Paper 3.5	Paper 4.6	Paper 11.1	Paper 12.1	15:00-15:45
13:50	Slot 13	Paper 3.6	Paper 6.1	Paper 11.2	Paper 12.2	Open forum
14:10	Slot 14	Paper 5.1	Paper 6.2	Paper 11.3	Paper 12.3	discussion 1
14:30	Slot 15	Paper 5.2	Paper 6.3	Paper 11.4	Paper 12.4	15:45-16:30
14:50	Slot 16	Paper 5.3	Paper 6.4	Paper 11.5	Paper 12.5	Open forum
15:10	Coffee break					discussion 2
15:40	Slot 17	Paper 5.4	Paper 6.5	Paper 11.6	Paper 12.6	16:30-16:50
16:00	Slot 18	Paper 5.5	Paper 6.6	Paper 11.7	Paper 12.7	Coffee break
16:20	Slot 19	Paper 5.6	Paper 6.7	Paper 11.8	Paper 12.8	16:50-18:00
16:40	Slot 20	Paper 5.7	Paper 6.8	Paper 11.9	Paper 12.9	Open forum
17:00	Slot 21	Paper 5.8	Paper 6.9	Committee Meeting		discussion 3
17:20	Technical program ends for the day					

S1 Modeling and Design of Antennas and Arrays Using FEM (R. Kindt, D. Filipovic, E. Topsakal)

S2 Discontinuous Galerkin Methods (Q. H. Liu, W. Cai)

S3 Time-Domain FEM and Applications (D. White, O. Biro, T. Rylander)

S4 FEM and CEM Applications in Optics and Nanophotonics (E. Simsek)

S5 Model Order Reduction Techniques (R. Dyczij-Edlinger, V. de la Rubia)

S6 Advances in Vector Bases for CEM (R. Graglia, A. Peterson, D. Wilton)

S7 FETD Modeling of Complex Media and Structures (R. Lee, F. Teixeira)

S8 Adaptive FEM, Higher Order Bases, and Advanced FEM Formulations (J. Webb, M. Gavrilovic, M. Salazar Palma, L. Garcia-Castillo)

S9 Advances in Hybrid Methods and Multiphysics Problems (B. Shanker, L. Kempel)

S10 FEM Modeling and Applications of Metamaterials and Periodic Media (K. Sertel, J. Volakis)

S11 Domain-Decomposition Methods (J.-F. Lee, Z. Peng)

S12 Advanced FEM/MoM Modeling, Design, and Optimization (C.J. Reddy, U. Jakobus, J. Zapata, J. Gil, D. Jiao, A. Cangellaris)

Open forum discussion 1: Open Forum Discussion on FEM and CEM Bases, Elements, and Formulations
(A. Peterson, D. Wilton, J. Webb, K. Sertel)

Open forum discussion 2: Open Forum Discussion on DDM, MOR, and Efficient FEM and Hybrid Solutions
(J.-F. Lee, Zhen Peng, R. Dyczij-Edlinger, V. de la Rubia)

Open forum discussion 3: Open Forum Discussion on FEM-Based Modeling, Design, and Applications
(L. Kempel, B. Shanker, R. Kindt, C.J. Reddy, K. Zhao, T. Euler)

Presentation Information

Language

The working language of the workshop is English, which includes all presentations, printed materials, and discussions.

Presentation Length and Format

All presentations are oral and are allotted 20-minute time slots, which includes 15 minutes for the presentation and 5 minutes for questions and discussion.

All presenters should contact the session chairs no later than 15 minutes before the start of the session to confirm their presence and upload their presentation files to the session computer. If the session starts immediately after the end of the previous session, presenters should arrive to the session room and contact the session chairs during the coffee break or lunch break preceding the start of the session.

Technical Equipment

Each session room is equipped with a laptop computer connected to a video projector. Video resolution is 1280×800 pixels. Session room computers run under Windows 7 Pro and have Microsoft Office 2010 installed.

File Formats

The only file formats supported by the workshop computers are Microsoft PowerPoint (*.ppt, *.pptx) and Adobe PDF (*.pdf).

File Upload

Speakers are asked to upload their presentation files to the session room computer no later than 15 minutes before the session start. If the session starts immediately after the end of the previous session, speakers should upload their files during any breakfast, coffee, or lunch break preceding the session (or even the day/evening before).

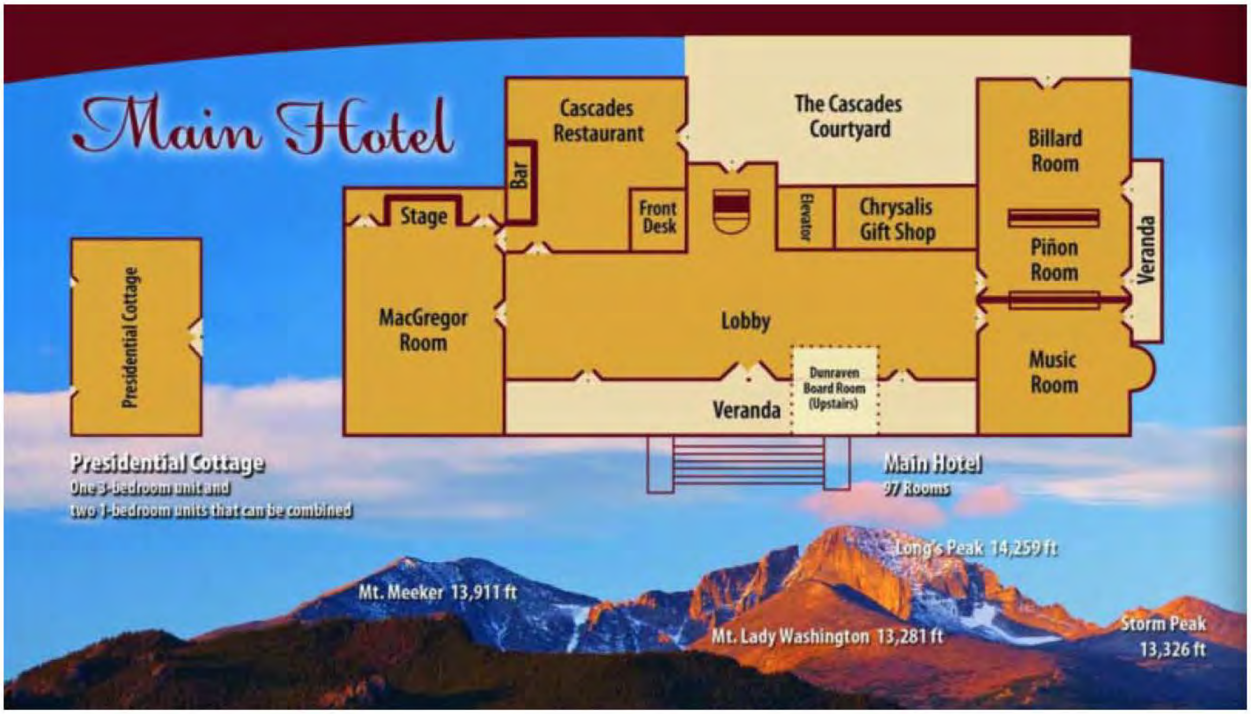
Session room computers are equipped with USB ports and DVD drives. Staff personnel will be available to assist with the upload procedure.

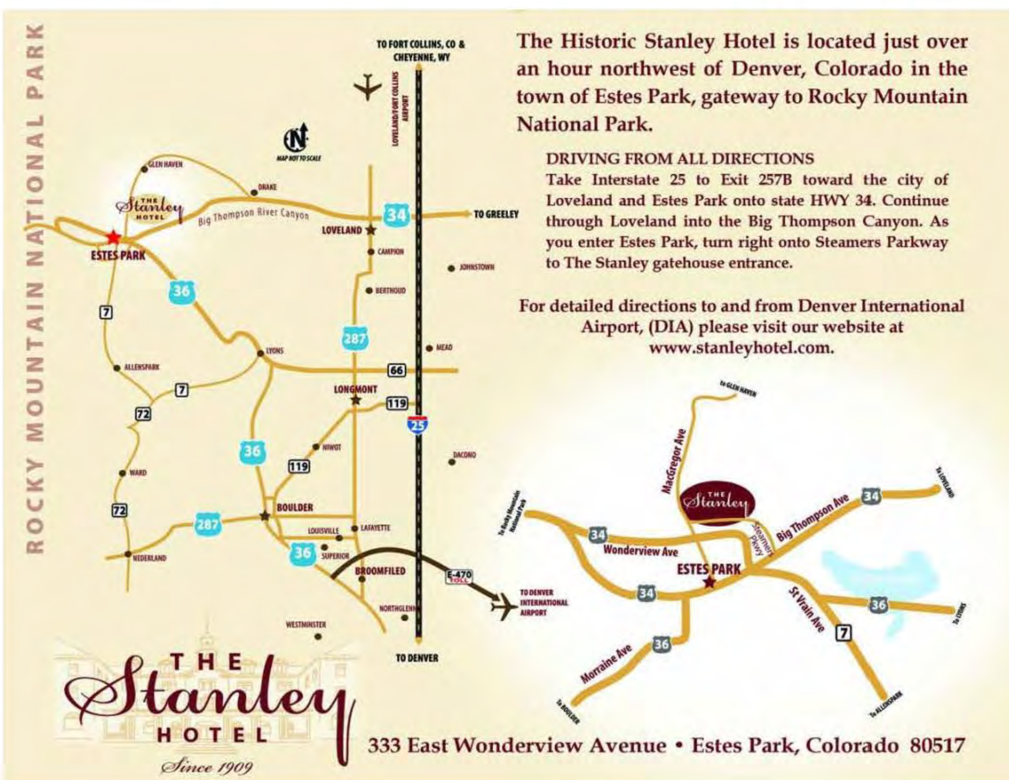
Session Chairs

Special session organizers will serve as session chairs. Session chairs must arrive to the session room no later than 15 minutes before the session start. If the session starts immediately after the end of the previous session, session chairs should come to the room and check if everything is ready during the coffee break or lunch break preceding the start of the session.

Conference Floor Plan and Hotel Directions

Sessions are held in Billiard Room and Music Room, registration and coffee breaks are in Pinion Room, breakfasts, lunches, and conference banquet are in MacGregor Room.





About the Venue

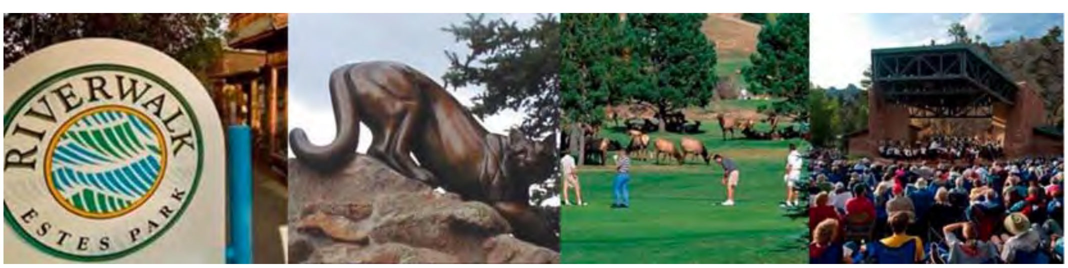
The Historic Stanley Hotel

The Stanley Hotel, http://www.stanleyhotel.com, is a historic landmark hotel in a spectacular mountain-view location, offering old-world charm matched with the latest of modern amenities. Located at an elevation of 7,500 feet (2,286 meters) and within sight of the Rocky Mountain National Park, it was built in 1907-1909 by the inventor of the Stanley Steamer automobile (which is on display in the hotel lobby). It inspired Stephen King to write The Shining, and served as a location site for several movies (including Dumb and Dumber). It hosted many US presidents, royalties, and celebrities. Many believe that the hotel is haunted (the most cases of ghostly activity were reported for the ballroom in which we will have our banquet dinner). The popular Stanley Hotel Ghost & History Tour is included in the workshop package.

Estes Park

Estes Park, http://www.estesparkcvb.com, an hour from Fort Collins or Boulder, and hour and a half from Denver International Airport, is one of the most beautiful resort towns in the US, with numerous galleries, shops, and restaurants, along with majestic nature and abundant wildlife.

The shuttle transportation from Denver International Airport (DIA) to Estes Park (Stanley Hotel) and back to DIA (the shuttle takes about 1h 40 mins) will be provided by Estes Park Shuttle.



Some Details about Social Program

Trip to Rocky Mountain National Park

Wednesday June 6, 2012**,** 8:00–14:00; Picnic lunch included

Rocky Mountain National Park, http://www.nps.gov/romo, established as NP in 1915, is one of the most visited national parks in the US. The bus tour of the park will feature a guided and narrated drive along Trail Ridge Road (the highest continuous motorway in the US), visits to Continental Divide and the start of the mighty Colorado River (which makes the Grand Canyon on its way west), to the "Land Above the Trees" [reaching 12,183 feet (3,713 m) above sea], with a lot of snow (and sun) in June (see http://www.rmnp.com), a visit and longer stay at the Alluvial Fan http://www.rmnp.com/RMNP-Areas-HorseshoePark-AlluvialFan.html, where we will have our picnic lunch, and a drive (and brief stays) through lowland meadows (with herds of elk) and aspen groves.

Stanley Hotel Ghost & History Tour

Monday 17:30-19:00 tour or Tuesday 17:30-19:00 tour

The extremely popular spooky sojourn through time at The Stanley Hotel, http://stanleyhotel.com/tours/, led by the professional and experienced tour guides, includes: 1900's history tour featuring the beginnings of the Hotel, F.O. & Flora Stanley and the Stanley Steamer, Stephen King's The Shining connection to the Hotel – his room #217, where the creation of The Shining began, ghost stories and sightings, the Stanley most haunted rooms and places, tours through the underground tunnel. The Ghost & History Tour lasts approximately 90 minutes.

FEM2012 Closing Reception

Wednesday, June 6, 2012, 18:00–21:00

The Elkhorn Lodge & Ranch, Estes Park – featuring Chuckwagon Dinner and Cowboy Show

Chuckwagon Dinner is a unique Western experience, excellent food in the true Old West setting, including metallic plates etc., plus some cowboy singers and entertainers. The Elkhorn Lodge is the oldest continually occupied structure in Colorado.

About Our Financial Sponsors

ANSYS, Inc.

Today's business environment is rife with competitive challenges, customer requirements and financial pressures. These factors result in the need to find new methods for engineering more innovative products and manufacturing processes — while minimizing costs and time to market. Virtually every industry now recognizes that a key strategy for success is to incorporate computer-based engineering simulation early in the development process, allowing engineers to refine and validate designs at a stage where the cost of making changes is minimal.

The ANSYS simulation software portfolio is ideal for the design of high-performance electronic equipment and electromechanical devices. Companies throughout the world rely on ANSYS electromagnetic, computational fluid dynamics and mechanical analysis solutions when designing mobile communication, internet access, broadband networking components and systems, integrated circuits (ICs) and printed circuit boards (PCBs) as well as electromechanical systems such as automotive components and power electronics systems.

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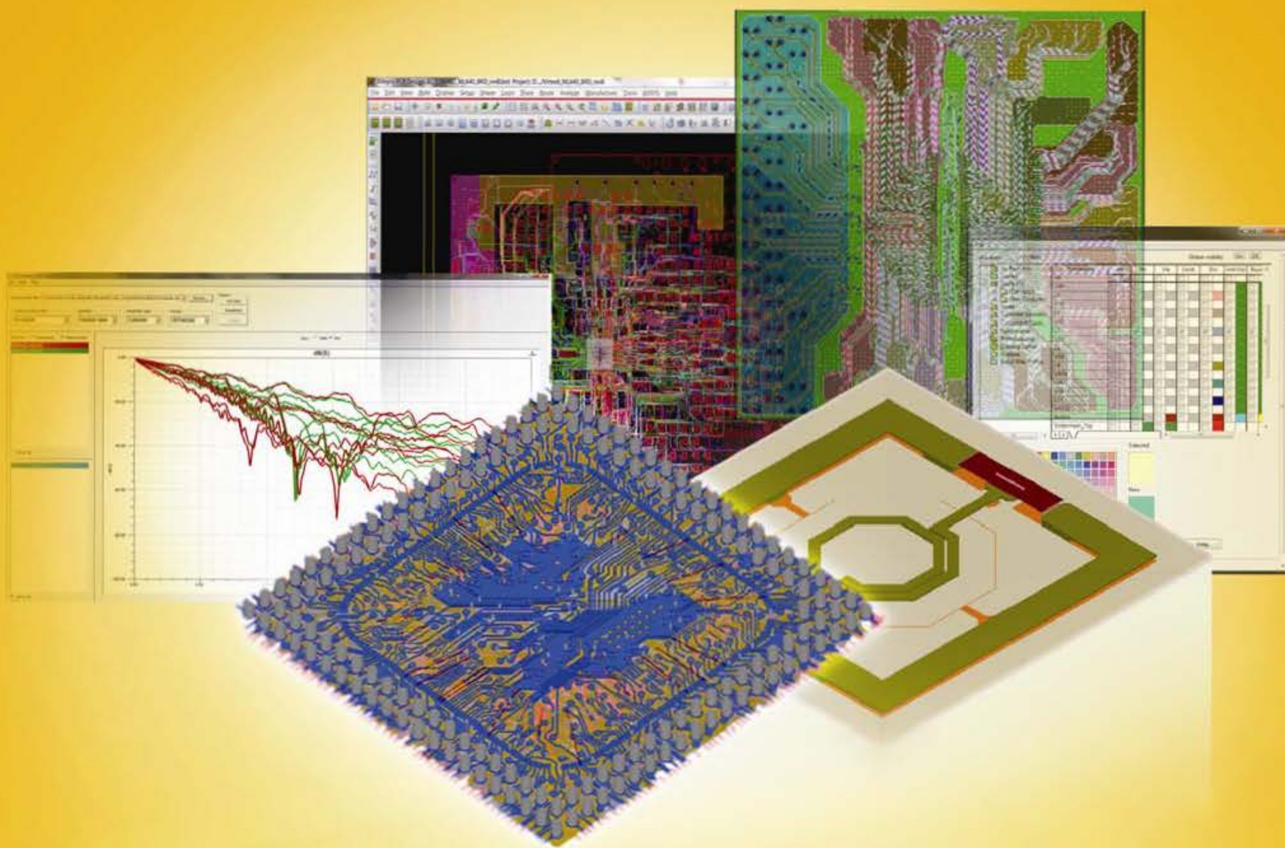

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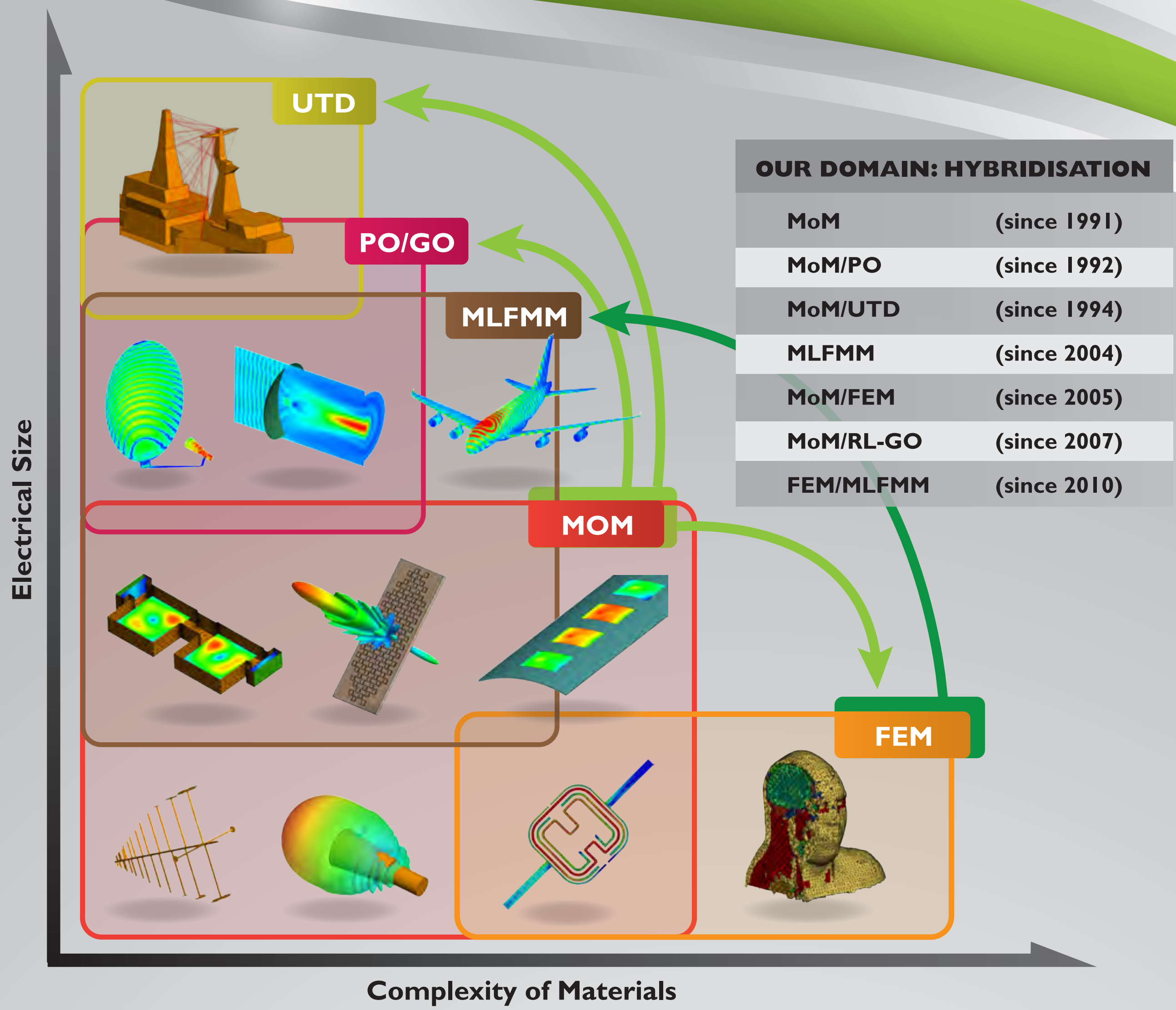

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Detailed Technical and Social Program

Sunday, June 3, 2012	
19:00- 21:00	Welcome reception (Music Room)

Monday, June 4, 2012		
7:00	Breakfast (MacGregor Room)	
	Billiard Room	**Music Room**
8:00	**Session 1: Modeling and Design of Antennas and Arrays Using FEM (R. Kindt, D. Filipovic, E. Topsakal)**	**Session 2: Discontinuous Galerkin Methods (Q. H. Liu, W. Cai)**
	1.1. Highly Coupled Bow-Tie Array Design with Passive Elements *Safa Salman*, Dimitris Psychoudakis, and John L. Volakis*	**2.1.** On the Physics, Accuracy, and Efficiency of the Dual-Field Domain-Decomposition Method for Time-Domain Electromagnetic Simulation *Xiaolei Li and Jian-Ming Jin**
8:20	**1.2.** Fully Overlapping Domain Decomposition in Simulating Irregularly Arranged Arrays in Large Media *Tao Peng*, Kubilay Sertel, and John L. Volakis*	**2.2.** A Full Vectorial Generalized Discontinuous Galerkin Beam Propagation Method for Optical Waveguides *Wei Cai**
8:40	**1.3.** Modeling of Antennas and Arrays Using Domain Decomposition Method *Kezhong Zhao* and Nancy Lambert*	**2.3.** Non-Conformal and Parallel and Interior Penalty Discontinuous Galerkin Method for the Time-Domain Maxwell's Equations *Stylianos Dosopoulos and Jin-Fa Lee*
9:00	**1.4.** Theoretical Analysis of Varactor-loaded Half-width Leaky-wave Antenna Arrays *Leo C. Kempel*, B. Shanker, Edward J. Rothwell, and Prem Chahal*	**2.4.** Discontinuous Galerkin Methods for Ideal MHD Equations *Fengyan Li**
9:20	**1.5.** Non-conformal Domain Decomposition Methods for Modeling Large Finite Antenna Arrays *Zhen Peng, Kheng-Hwee Lim, and Jin-Fa Lee*	**2.5.** New Spectral-Prism-Element for Layered Structures implemented in an efficient implicit DG-FETD method *Luis E. Tobon and Qing H. Liu**
9:40	Coffee break (Pinion room)	
10:10	**1.6.** Investigation of the Scattering Behavior of Transponder Antennas in Case of Nonlinear Termination *Thomas Bauernfeind*, Kurt Preis, Gergely Koczka, and Oszkar Biro*	**2.6.** An Efficient Discontinuous Galerkin Finite-Element Time-Domain Method and its Application to Micro-Resistivity Imager *Jiefu Chen, Carlos Haramboure, Lance Pate, Shawn Wallace, Jay Martin, Medhat Mickael, and Mac Wisler*
10:30	**1.7.** On the Design of Finite Planar Ultrawideband Modular Antenna (PUMA) Arrays using Domain Decomposition Methods *Steve S. Holland, Jack T. Logan, Rick W. Kindt, and Marinos N. Vouvakis**	**Session 4: FEM and CEM Applications in Optics and Nanophotonics (E. Simsek)** **4.1.** Electromagnetic Scattering of Finite Size Periodic Large Scale System: Simulation by Domain Decomposition Spectral Element Method *Ma Luo and Qing Huo Liu**
10:50	**Session 3: Time-Domain FEM and Applications (D. White, O. Biro, T. Rylander)** **3.1.** Numerical Simulation of HPM Devices with ICEPIC *Andrew D. Greenwood**	**4.2.** Efficient alternatives to edge vector finite elements for EM field calculations using Hermite interpolation polynomial basis functions on a nodal grid in 2D *J. D. Albrecht, C. R. Boucher, C. I. Ahheng, and L. R. Ram-Mohan*

Monday, June 4, 2012		
	Billiard Room	**Music Room**
11:10	**3.2.** Time Domain Method for Periodic Nonlinear Eddy Current Problems *Oszkár Bíró, Gergely Koczka, and Kurt Preis*	**4.3.** Parallel Finite Element Electromagnetic Code Suite for Accelerator Modeling and Simulation *Cho Ng, Lixin Ge, Kwok Ko, Kihwan Lee, Zenghai Li, Greg Schussman, and Liling Xiao*
11:30	**3.3.** Hybrid FETD/FDTD Techniques Based on the Discontinuous Galerkin Method *Bao Zhu, Jiefu Chen, Wanxie Zhong, and Qing Huo Liu*	**4.4.** Optical, Electromagnetics, and Thermal Modeling of Interaction of a Focused Beam of Light with Plasmonic Nanoparticles *Eren S. Unlu and Kursat Sendur**
11:50	Lunch break (MacGregor Room)	
13:10	**3.4.** Transient Thermal Analysis using a Non-conformal Domain Decomposition Approach *Yang Shao* , Zhen Peng, and Jin-Fa Lee*	**4.5.** Finite Element Analysis of Wideband Nanostructures for Photovoltaic Applications *Niccolo Breda, Giuseppe Pelosi, Stefano Selleri, and Ruggero Taddei*
13:30	**3.5.** An Explicit and Unconditionally Stable Time-Domain Finite-Element Method of Linear Complexity *Qing He, Duo Chen, and Dan Jiao*	**4.6.** Hybrid Optical Waveguides *Ergun Simsek* and Qing H. Liu*
13:50	**3.6.** Conformal PML Modeling in DGTD using Continuous Material Properties *Jue Wang*, Zhen Peng, and Jin-Fa Lee*	**Session 6: Advances in Vector Bases for CEM (R. Graglia, A. Peterson, D. Wilton)** **6.1.** On the Construction of Well-conditioned Hierarchical Bases for Tetrahedral H(curl)-Conforming Nedelec Element *Wei Cai* and Jianguo Xin*
14:10	**Session 5: Model Order Reduction Techniques (R. Dyczij-Edlinger, V. de la Rubia)** **5.1.** Reduced-order Electromagnetic Modeling in the Presence of Uncertainty *Juan S. Ochoa and Andreas C. Cangellaris**	**6.2.** High Order Finite Elements for Computational Physics: An LLNL Perspective *Robert N. Rieben**
14:30	**5.2.** Efficient Model Order Reduction for FEM Analysis of Waveguide Structures and Resonators *Fotyga G.*, Kulas L., Nyka K., and Mrozowski M.*	**6.3.** FEM-MoM-Diakoptic Analysis of Scatterers with Anisotropic Inhomogeneities Using Hierarchical Vector Bases on Large Curved Elements *Ana B. Manić*, Dragan I. Olćan, Milan M. Ilić, and Branislav M. Notaroš*
14:50	**5.3.** Model Order Reduction for Systems with Geometrical Parameters *Kynthia K. Stavrakakis*, Tilmann Wittig, Wolfgang Ackermann, and Thomas Weiland*	**6.4.** Rapid, High-Order Finite Element Modelling with FEniCS and SUCEM:FEM *A.J. Otto*, E. Lezar, N. Marais, R.G. Marchand, and D.B. Davidson*
15:10	Coffee break (Pinion room)	
15:40	**5.4.** Reduced-Order Models for Geometric Parameters *Stefan Burgard*, Ortwin Farle, and Romanus Dyczij-Edlinger*	**6.5.** Issues Arising in Connection with Singular Vector Bases *Roberto D. Graglia and Andrew F. Peterson**
16:00	**5.5.** Seamless Reduced Basis Element Method for Waveguide Simulation *Yanlai Chen*, Jan S. Hesthaven, and Yvon Maday*	**6.6.** An Orthogonal Prism Vector Bases Based Quadratic Eigenvalue Solver of Linear Complexity for 3-D Electromagnetic Analysis *Jongwon Lee, Duo Chen, and Dan Jiao*
16:20	**5.6.** The Reduced Basis Method for Saddle Point Problems *Karen Veroy* and Anna-Lena Gerner*	**6.7.** Preliminary Research on the Discontinuous Enrichment Method Based Domain Decomposition Scheme for Solving the Three-Dimensional Vector Curl-Curl Equation *Ming-Feng Xue* and Jian-Ming Jin*
16:40	**5.7.** Reliable Fast Frequency Sweep of Microwave Circuits via the Reduced-Basis Method *Valentin de la Rubia*	**6.8.** An Iterative Domain Decomposition Method for Solving Wave Propagation Problems *Gergely Koczka, Kurt Preis*, Thomas Bauernfeind, and Oszkár Bíró*
17:00	**5.8.** Reduced Order Modeling of High Magnetic Field Magnets *C. Daversin, C. Prudhomme, C. Trophime*, and S. Veys*	**6.9.** Evaluating Singular and Near-Singular Integrals on Curvilinear Elements *Donald R. Wilton**
17:30- 19:00	Stanley Hotel Ghost & History Tour	
19:30- 22:30	Conference Banquet (MacGregor Room) (the room opens at 19:00)	

	Tuesday, June 5, 2012	
7:00	Breakfast (MacGregor Room)	
	Billiard Room	**Music Room**
8:00	**Session 7: FETD Modeling of Complex Media and Structures (R. Lee, F. Teixeira)** **7.1.** FETD/FDTD with Automatic Hybrid Mesh Generation *Shumin Wang**	**Session 8 Adaptive FEM, Higher Order Bases, and Advanced FEM Formulations (J. Webb, M. Gavrilovic, M. Salazar Palma, L. G. Castillo)** **8.1.** Hp-adaption for Computing Scattering Parameters on Tetrahedral Meshes *J. P. Webb*
8:20	**7.2.** Study of Numerical Dispersion for Quadrilateral and Triangular Elements Used in the Mixed Finite Element Method *Luis E. Tobon and Qing H. Liu**	**8.2.** Efficient RCS Prediction of Jet Engine Air Intakes Using hp-FEM and Reduced Order Modeling *Adam Zdunek* and Waldemar Rachowicz*
8:40	**7.3.** Probabilistic Finite-Difference Time-Domain Method Through Stochastic Electromagnetic Macro-Models *Ata Zadehgol*, Andreas C. Cangellaris*	**8.3.** Rules for Adoption of Expansion and Integration Orders in FEM Analysis Using Higher Order Hierarchical Bases on Generalized Hexahedral Elements *Nada J. Šekeljić*, Slobodan V. Savić, Milan M. Ilić, and Branislav M. Notaroš*
9:00	**7.4.** Advancing Ultrahigh Field Human MRI using FDTD Method *Tamer S. Ibrahim**	**8.4.** Auxiliary Space Preconditioning for Hierarchical Elements *A. Aghabarati, J. P. Webb*
9:20	**7.5.** The Use of Multiple Time Steps in the FDTD Method *Ruben Ortega and Robert Lee**	**8.5.** Chain Homotopy Operators and Whitney form-based Finite Element Analysis *P. Robert Kotiuga**
9:40	Coffee break (Pinion room)	
10:10	**Session 9: Advances in Hybrid Methods and Multiphysics Problems (B. Shanker, L. Kempel)** **9.2.** Thermal-Aware DC IR-Drop Co-Analysis using a Non-conformal Domain Decomposition Approach *Yang Shao*, Zhen Peng, Jin-Fa Lee*	**8.6.** Comparative Performance of Nodal-Based Versus Edge-Based Finite Element Formulations *Ruben Otin*, Santiago Badia, and Luis E. Garcia-Castillo*
10:30	**9.3.** Development of Time Domain Discontinuous Galerkin-Vector Generalized Finite Element Method *O. Tuncer, B. Shanker*, L. C. Kempel*	**8.8.** A Three-Dimensional Self-Adaptive hp Finite Element Method for the Characterization of Waveguide Discontinuities *Ignacio Gomez-Revuelto, Luis E. Garcia-Castillo, Sergio Llorente-Romano, and David Pardo*
10:50	**9.4.** Multi-solver-based Generalized Impedance Boundary Condition for Complicated EM Simulation *Shiquan He, Jun Hu*, Zaiping Nie, Lijun Jiang, W. C. Chew*	**Session 10: FEM Modeling and Applications of Metamaterials and Periodic Media (K. Sertel, J. Volakis)** **10.1.** Finite Element Modeling of Magnetic Metamaterials and Associated Challenges for Their Experimental Characterization *Nil Apaydin* , Kubilay Sertel, and John L. Volakis*
11:10	**9.5.** Analysis of Electromechanical Devices Using the Dual-Primal Finite Element Tearing and Interconnecting Method Incorporated with the LU Recombination Method *Wang Yao*, Jian-Ming Jin*	**10.2.** A Method for Rapid Evaluation of Space-time Convolutions with the Time Domain Periodic Green's Function *D. Dault and B. Shanker**
11:30	**9.6.** Alternative Formulations for Hybrid Electromagnetic-Circuit Simulators *Vivek Subramanian, Ali E. Yilmaz**	**10.3.** Finite Element Analysis of Photon Density of States for Two-Dimensional Photonic Crystals with Omnidirectional Light Propagation *R. F. Jao and M. C. Lin*
11:50	Lunch break (MacGregor Room)	
13:10	**9.7.** Symmetric and Nonsymmetric FEM-MoM Techniques Using Higher Order Hierarchical Vector Basis Functions and Curved Parametric Elements *Ana Manić*, Milan Ilić, Branislav Notaroš*	**10.4.** A Hybrid Approach for Characterizing Large Anisotropic and Inhomogeneous Metamaterial Structures *Justin G. Pollock and Ashwin K. Iyer**

	Tuesday, June 5, 2012	
	Billiard Room	**Music Room**
13:30	**Session 11: Domain-Decomposition Methods (J.-F. Lee, Z. Peng)** **11.1.** Analysis of Three-Dimensional Array Structures Using Nonconformal and Cement FETI-DP Methods *Ming-Feng Xue* and Jian-Ming Jin*	**Session 12: Advanced FEM/MoM Modeling, Design, and Optimization (C.J. Reddy, U. Jakobus, J. Zapata, J. Gil, D. Jiao, A. Cangellaris)** **12.1.** Overview of the Hybrid Finite Element Method/Method of Moments Capability in FEKO *Marianne Bingle*, Ulrich Jakobus, and Johann J. van Tonder*
13:50	**11.2.** A Domain-Decomposition-Based Preconditioner of FE-BI-MLFMA for Computing EM Scattering by Large Inhomogeneous 3D Targets *Ming-Lin Yang, Xin-Qing Sheng, and Cheng-Dan Huang*	**12.2.** Application of Hybrid FEM/MoM Technique for Handheld Mobile Devices *Rensheng Sun and C. J. Reddy*
14:10	**11.3.** On the Computational Complexity of Domain Wise Multilevel Multifrontal Method *Peng Liu* and Chao-Fu Wang*	**12.3.** Application of Hybrid FEM/MoM Technique for Cavity Backed Apertures *Gopinath Gampala, Rensheng Sun and C. J. Reddy*
14:30	**11.4.** Harmonic Balance Domain Decomposition Finite Element for Nonlinear Passive Microwave Devices Analysis *Laurent Ntibarikure, Giuseppe Pelosi, and Stefano Selleri*	**12.4.** Eigenproblem Approach for Analysis and Optimization of Microwave Filters Using Finite Element Method *Adam Lamecki, Michal Mrozowski*
14:50	**11.5.** Application of Tree-Cotree Splitting to the Dual-Primal Finite Element Tearing and Interconnecting Method for Solving Low-Frequency Breakdown Problems *Wang Yao* and Jian-Ming Jin*	**12.5.** Does Sensitivity Analysis for Fast Frequency Sweeps Converge? *Andreas Köhler, Ortwin Farle, Romanus Dyczij-Edlinger**
15:10	Coffee break (Pinion room)	
15:40	**11.6.** Edge Elements and DPM with PBSV to Accelerate Solving Scattering Problems of Electrically Large Objects *Lianyou Sun*, Lishan Xue, and Wei Hong*	**12.6.** Benchmark of Conformal Finite-Difference Method against Finite Element Method *M. C. Lin*
16:00	**11.7.** Enhancement of Second-harmonic Generation in an Air-bridge Photonic Crystal Slab: Simulation by Spectral Element Method *Ma Luo and Qing Huo Liu**	**12.7.** Layout-Integrated Electromagnetic Interconnect Characterization and Simulation *Dennis Nagle, Jilin Tan, Jian-Ming Jin*
16:20	**11.8.** A Non-overlapping and Non-conformal Domain Decomposition Method with Optimized Second Order Transmission Conditions for Time-Harmonic Maxwell Equations in R^3 *Zhen Peng and Jin-Fa Lee*	**12.8.** An Extraction-Free Circuit Simulator of Linear Complexity Guided by Electromagnetics-Based First Principles *Qing He, Duo Chen, and Dan Jiao*
16:40	**11.9.** The Quest for Robust Domain Decomposition Methods in CEM: Are We There Yet? *Marinos N. Vouvakis* and Georgios N. Paraschos*	**12.9.** A model reduction method for multiple particle electromagnetic scattering in three dimensions *M. Ganesh*, J. Hesthaven, and B. Stamm*
17:00	Technical program ends for the day	
17:00- 18:30	FEM2012 Scientific Committee and Organizing Committee Meeting (Music Room)	
17:30- 19:00	Stanley Hotel Ghost & History Tour	

	Wednesday, June 6, 2012
7:00- 8:00	Breakfast (MacGregor Room)
8:00- 14:00	Trip to Rocky Mountain National Park (picnic lunch)
	Open Forum Discussions (Music Room)
15:00	Open forum discussion 1: Open Forum Discussion on FEM and CEM Bases, Elements, and Formulations (A. Peterson, D. Wilton, J. Webb, K. Sertel)
15:45	Open forum discussion 2: Open Forum Discussion on DDM, MOR, and Efficient FEM and Hybrid Solutions (J.-F. Lee, Zhen Peng, R. Dyczij-Edlinger, V. de la Rubia)
16:30	Coffee break (Pinion Room)
16:50	Open forum discussion 3: Open Forum Discussion on FEM-Based Modeling, Design, and Applications (L. Kempel, B. Shanker, R. Kindt, C.J. Reddy, K. Zhao, T. Euler)
18:00- 21:00	Closing Reception (The Elkhorn Lodge & Ranch - Chuckwagon Dinner and Cowboy Show)

	Monday, June 4, 2012
	Billiard Room
8:00	**Session 1: Modeling and Design of Antennas and Arrays Using FEM (R. Kindt, D. Filipovic, E. Topsakal)**
	1.1. Highly Coupled Bow-Tie Array Design with Passive Elements *Safa Salman*, Dimitris Psychoudakis, and John L. Volakis*
8:20	**1.2.** Fully Overlapping Domain Decomposition in Simulating Irregularly Arranged Arrays in Large Media *Tao Peng*, Kubilay Sertel, and John L. Volakis*
8:40	**1.3.** Modeling of Antennas and Arrays Using Domain Decomposition Method *Kezhong Zhao* and Nancy Lambert*
9:00	**1.4.** Theoretical Analysis of Varactor-loaded Half-width Leaky-wave Antenna Arrays *Leo C. Kempel*, B. Shanker, Edward J. Rothwell, and Prem Chahal*
9:20	**1.5.** Non-conformal Domain Decomposition Methods for Modeling Large Finite Antenna Arrays *Zhen Peng, Kheng-Hwee Lim, and Jin-Fa Lee*
9:40	Coffee break (Pinion room)
10:10	**1.6.** Investigation of the Scattering Behavior of Transponder Antennas in Case of Nonlinear Termination *Thomas Bauernfeind*, Kurt Preis, Gergely Koczka, and Oszkar Biro*
10:30	**1.7.** On the Design of Finite Planar Ultrawideband Modular Antenna (PUMA) Arrays using Domain Decomposition Methods *Steve S. Holland, Jack T. Logan, Rick W. Kindt, and Marinos N. Vouvakis**

Highly Coupled Bow-Tie Array Design with Passive Elements

Safa Salman*, Dimitris Psychoudakis, and John L. Volakis
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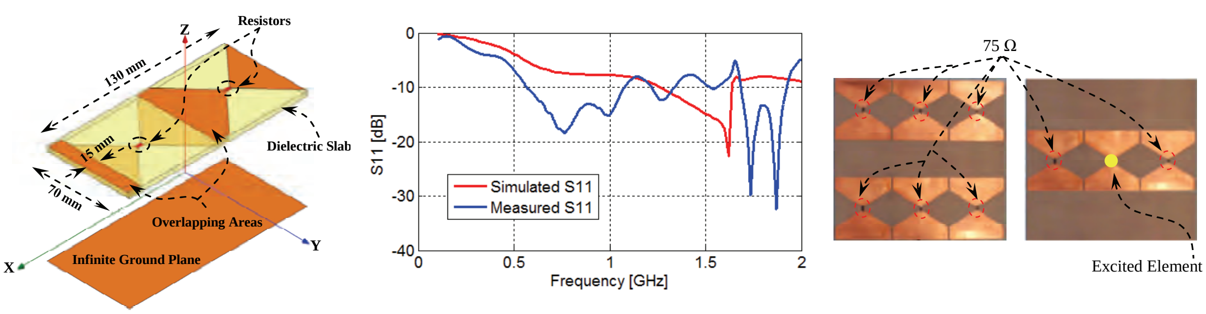
Increasing demand for high speed wireless communication systems implies a need for broadband planar antenna arrays. Broadband conformal antennas become preferable for both transportation and installation on platforms, due to several advantages including their light weight and low-cost production.

In this work, the concept of a current sheet array (CSA) is expanded to design a broadband bowtie-shaped antenna array using HFSS. A bowtie-shaped antenna element was chosen as the element itself has good bandwidth and radiation characteristics. The antenna design parameters were chosen for operating over the VHF and UHF frequency bands. As the overlapping array elements illustrated in the figure suggest, there is a thick substrate layer between the overlapping elements which has a dielectric constant of ε_r=10.2. A key concept of the design was the introduction of strong mutual coupling between the elements, using FEM (via HFSS) to optimize the spacing between the elements. The present approach has the potential to achieve a 7:1 bandwidth over the VHF and UHF frequency bands with wide-angle beam.

A small 3x3 finite array was simulated using HFSS and then fabricated and experimentally tested to verify that the broadband characteristics can still be achieved using a small aperture of overlapped bowtie dipoles. The physical realization of the proposed antenna array is also shown in the figure below. Both top and bottom views are illustrated. The reflection coefficient of the finite array is also shown in the same figure. For testing, only the center element was excited while the others were terminated with 75 **Ω**. This array structure was backed with a finite ground plane of the same dimensions as the dielectric slab and the array both for FEM solutions and measurements. At the lowest frequency the total array thickness was $\lambda_o/4$. As the comparison between simulated and measured data shows, the simulated and measured data follow each other well however more fabrication care needed to insure better agreement.

Future work may involve the use of flat antenna array realizations for more than 7:1 operating bandwidth design target.



Left: Unit cell of the overlapping bowtie antenna array over a dielectric slab with infinite ground plane. **Middle:** Center element reflection coefficient with all other elements terminated at 75 Ω. **Right:** Physical layout of the printed element layer of the array top (left) and bottom (right) views.

Fully Overlapping Domain Decomposition in Simulating Irregularly Arranged Arrays in Large Media

Tao Peng*[1], Kubilay Sertel[1], and John L. Volakis[1]
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A fully overlapping domain decomposition (DDM) algorithm is proposed to simulate small features within large domains. A unique aspect of this approach is that it does not require a common interface between separate subdomains to glue them together. Instead, it employs a coarse background domain with several independently meshed subdomains to model embedded details. Much like other domain decomposition schemes, this approach shares similarities to Multigrid methods, particularly with adaptive refinement Multigrid. However, most Multigrid methods either treat the coarse domain as a preconditioning tool (*V*-cycle Multigrid) or formulate the problem as a local *h* refinement scheme (fast adaptive composite Multigrid). The coarse background meshes in these setups must invariably resolve the small features to obtain correct error updates. In contrast, our approach does not need to resolve the small features within the coarse background domain. Most importantly, the introduced multiple detail domains do not form conforming common interfaces as in traditional non-overlapping DDMs. Instead, communication between the subdomains (modeling the details) and the coarse background mesh is done by treating the subdomain fields as sources to the background domain. These flexibilities enable a modeling ease and much enhanced convenience. In this paper, we employ the proposed non-overlapping DDM to model arrays that may include non-periodic elements.

Modeling highly repetitive structures, as is the case with arrays, is a well studied process. It has been considered in the context of finite element (FEM) and integral methods. In the case of FEM-DDM with sub-structuring, multiple subdomains are used to model the large problem, and the unknowns are typically those at the interface of the smaller subdomains, implying significant reduction in the number of unknowns. To glue all subdomains, bi-directional Robin Transmission Conditions are typically used on the geometrically conformal domain boundaries. Typically, each subdomain must be geometrically connected to all its neighbors. Integral methods, that may also incorporate the multilevel FMM (MLFMM), rely on the same divide-and-conquer philosophy, but can be cumbersome when inhomogeneous media are involved. In contrast to the above, the fully overlapping DDM offers a relatively carefree solution due to its freedom and flexibilities in modeling antenna small features and in configuring irregular arrays. Importantly, trial and error and *in situ* optimizations are frequently indispensable in designing antennas. As the detail subdomains are meshed independently, remeshing of the subdomains during optimizations can be carried out with ease. Therefore, the proposed non-overlapping DDM is very attractive for design optimization. In this paper, the fully overlapping DDM would be applied to multiple irregularly arranged arrays embedded in inhomogeneous media. This is done in the context of the finite element method.

Modeling of Antennas and Arrays Using Domain Decomposition Method

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Computational electromagnetics plays a crucial role in accurate predictions of design performance prior to construction. Accurate simulation of electrically large and geometrically complicated electromagnetic (EM) problems is of vital importance in many areas of electrical engineering, but also is a very challenging task. The scope and application of traditional approaches such as the finite element method (FEM), boundary element method (BEM) and finite difference method (FDM) are limited to moderate electrical size and reduced complexity. These limitations stem from the vast computational resources required by these numerical methods.

The domain decomposition method (DDM) has emerged as a powerful and attractive technique for the analysis of large-scale electromagnetic problems due to its inherent parallelism and its beauty as an efficient and effective preconditioner. DDM is based on a divide-and-conquer philosophy. Instead of tackling a large and complex problem directly as a whole, the original problem is partitioned into smaller, possibly repetitive, and easier to solve sub-domains. In this paper DDM is used as an effective FEM preconditioner where a higher order Robin's transmission condition (TC) is devised to enforce the continuity of electromagnetic fields between adjacent sub-domains and at the same time accelerate the convergence of the iterative process. DDM is also employed to formulate a novel hybridization of FEM with the boundary element method that exact treatment of the radiation condition can be realized. Through this DDM-based hybrid finite element-boundary integral (FE-BI) method, we can allow FEM-domains to be disconnected; the coupling between disjoint domains is naturally taken into account via the Green's function. The advantages of DDM-based FE-BI compared to traditional FE-BI include modularity of FEM and BI domains in terms of mesh and selection of basis functions. This "non-conformal" ability significantly simplifies the integration of existing state-of-art FEM and BEM solvers. The continuity enforcement through Robin's TC naturally renders this FE-BI formulation free of internal resonance issues. Since domains are allowed to be disjoint, if one or more sub-domains are purely metallic or highly conducting, the present DDM can allow integral equation methods to be applied to these sub-domains directly so as to reduce memory consumption. Several real-life antennas and finite antenna arrays will be analyzed to demonstrate the power of this method. In particular we will show that DDM enables scientists and engineers to solve much larger problems via distributed computing.

Theoretical Analysis of Varactor-loaded Half-width Leaky-wave Antenna Arrays

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A subject of investigation over the past few years involves methods to control the radiation properties of half-width leaky-wave (HWLW) antennas using reactive tuning elements. HWLW antennas exhibit dispersion in both the voltage standing-wave ratio (VSWR) and radiation pattern. The impact of the former can be mitigated with an adaptive matching network that incorporates suitable reactive elements. The latter can also be mitigated, over a more limited bandwidth, through the use of reactive loads and in doing so, the requirements for a VSWR matching network are reduced. The effect of pattern dispersion is that the main beam steers from near broadside to near end-fire as the frequency is chirped. Hence, the antenna “looks” at a different portion of the scan space at different frequencies. For some applications, it is desirable that the antenna has a stable pointing direction as the frequency is chirped.

In a recent presentation (L. Kempel, E. Rothwell, B. Shanker, and P. Chahal, “Theoretical analysis of a varactor-loaded half-width leaky-wave antenna,” *XXX URSI General Assembly and Scientific Symposium*, Istanbul, TURKEY, Aug. 2011) results for a single element are presented demonstrating pattern stability over nearly 1 GHz in C-band. Included in the paper is an empirically determined second-order dispersive compensation load equation: $C_{pF}\left(f_{GHz}\right)=0.0032\, f_{GHz}^{2}-0.0668\, f_{GHz}+0.3228$.

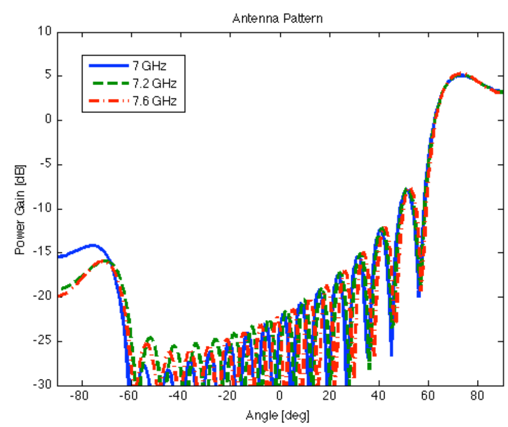

Figure 1. Radiation pattern of the varactor-loaded HWLW antenna at three frequencies.

In this paper, results for such elements placed in arrays will be presented. Of particular interest is whether the load dispersion requirements change due to mutual coupling. The rationale for this line of inquiry lies in the propagation properties of the leaky-wave mode. Since it has both a longitudinal and in-plane orthogonal components, the latter may provide a significant coupling mechanism that could alter the needed reactive compensation.
The analysis will be performed using the finite element-boundary integral (FE-BI) method. It is well suited for this investigation since it permits representation of dielectric as well as metallic materials in addition to reactive lumped (though dispersive) loads. In addition, since simulation at many frequencies is required, the memory and operation count efficiency of the FE-BI method results in fairly small calculation times.

Non-conformal Domain Decomposition Methods for Modeling Large Finite Antenna Arrays

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Large finite antenna arrays are commonly used in wireless communication systems and radars to transmit and receive signals through spaces. These arrays often involve complicated and multi-scale geometrical features and they are usually electrically large. Thus, full wave analysis of such problems by traditional methods demands prohibitive computer resources.

We proposed a non-conformal domain decomposition method (NC-DDM) for solving large antenna arrays mounted on platform, see Fig.1. To further improve the convergence in the DDM iterations, an optimal 2nd order transmission condition is introduced to enforce field continuities across domain interfaces. Moreover, many antenna arrays are also electrically large. Consequently, the use of absorbing boundary condition may not be adequate as an accurate mesh truncation method. Herein, we combine directly the finite element domain decomposition method with a generalized combined field integral equation and form automatically the hybrid finite element and boundary integral (FEBI) method. The use of the boundary integral method, arguably, offers the best accuracy for modeling unbounded electromagnetic radiation and scattering problems, albeit at the increases of memory and CPU times. Furthermore, the finite element tearing and interconnecting (FETI) method is employed to take advantage of the repetitions to drastically reduce the computational resources.

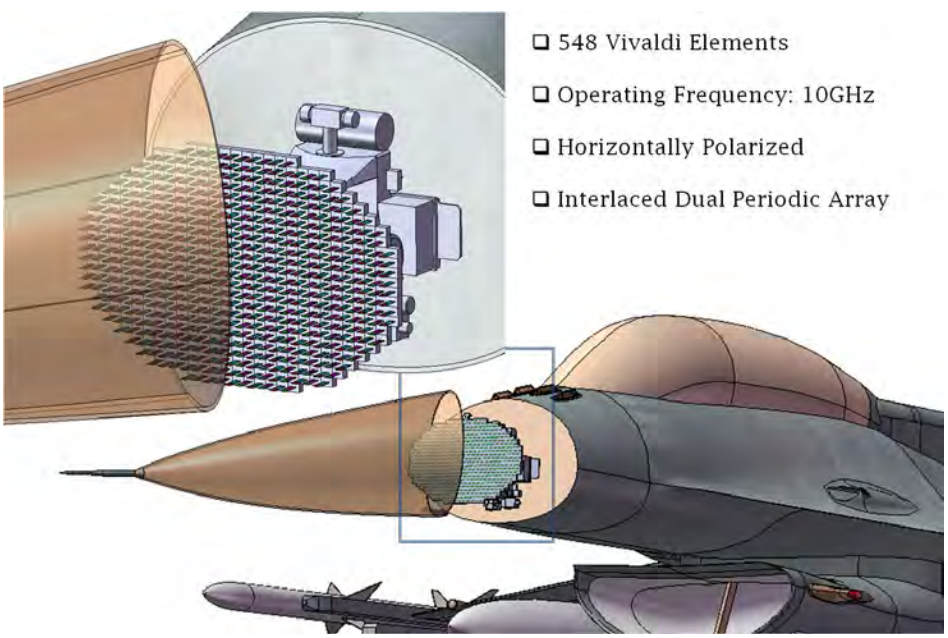

Figure 1: An interlaced dual periodic array mounted on an aircraft

Investigation of the Scattering Behavior of Transponder Antennas in Case of Nonlinear Termination

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Introduction: In passive backscattering applications like UHF-RFID (ultra high frequency-radio frequency identification) the communication between the interrogator unit (reader) and the transponder is established by means of modulating the radar cross section of the transponder. In general, for UHF-RFID applications, this is done by switching the analog input impedance between two states in phase with the data stream to be transmitted. Unfortunately the analog input impedance is not constant, indeed it has a strong nonlinear behavior. This behavior is mainly caused by a voltage limiter at the transponder IC's frontend. Hence, the transponder's input impedance is a function of the induced antenna voltage. In the present work a method based on an analytical approach (R. C. Hansen, "Relationships Between Antennas as Scatterers and as Radiators," Proceedings of the IEEE, Vol. 77, No. 5, 1989, pp. 659-662) is used to investigate the scattered field of the transponder. The analyses are carried out by the method of finite elements.

Scattering investigations: In general the scattered field is investigated by means of a full-wave finite element simulation of the entire communication channel including the antenna of the reader, the air volume between the reader and the transponder and the transponder antenna. Hence, the system of equations can be quite large. To reduce the computational effort the following relationship introduced by Hansen could be used:

$$\frac{\mathbf{E}_{scat}(Z_L)}{I_m^*} = \frac{\mathbf{E}_{scat}(Z_a^*)}{I_m^*} + \frac{\Gamma^* \mathbf{E}_{ant}}{I_a}. \tag{1}$$

In (1) $\mathbf{E}_{scat}(Z_L)$ is the scattered field of the transponder if the transponder antenna is connected to the load impedance Z_L, whereas $\mathbf{E}_{scat}(Z_a^*)$ is the scattered field if the transponder IC is conjugate complex matched to the transponder antenna's input impedance Z_a. $\mathbf{E}_{ant}$ is the field which is radiated by the transponder antenna if the antenna is driven with the current I_a, Γ^* is the reflection coefficient and I_m^* is the current which flows in the antenna in the case of the conjugate complex matching. Hence the influence of the nonlinear transponder can be analyzed by simply scaling the solution of the driven antenna with the reflection coefficient and superimposing the solution of the scattered field in case of the conjugate complex matching. Doing so, the full-wave finite element analyses can be reduced to a minimum set. If the non-linear voltage dependent behavior of the transponder IC is known, e.g. from measurement, one is able to analyze the robustness of the transponder antenna design to changes in the IC impedance.

On the Design of Finite Planar Ultrawideband Modular Antenna (PUMA) Arrays using Domain Decomposition Methods

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The planar ultra-wideband modular array (PUMA) (S. S. Holland et al., IEEE Trans. Antennas Propag., Vol. 60, p. 130, 2012) is a new class of wideband arrays capable of 5:1 bandwidth from a totally-planar, low-profile, modular topology using a feeding technique that permits direct connection to standard unbalanced 50Ω RF interfaces. Extensive studies on infinite array unit cells have resulted into VSWR levels well below 2, but very work little has been done towards understanding the impedance and far-field radiation properties under realistic finite array scenarios (truncation effects).

This work will investigate the radiation properties of finite PUMA arrays using a domain decomposition finite element method (DD-FEM) (G. N. Paraschos et al. IEEE Antennas Prop. Symp 2009, DOI: 10.1109/APS.2009.5171582). The proposed DD-FEM is based on the finite tearing and interconnecting (FETI) method with two Lagrange multiplier sets per interface, effectively enabling the efficient modeling of repetitive structures such as phased arrays, by only storing memory for one array element, and several other building blocks that represent the surrounding array region. Even with this DD-FEM analysis, a full finite array simulation is computationally demanding and not appropriate for design. Alternatively, a faster intermediate modeling step is introduced that involves solving for an finite × infinite array, and is used as the first-pass design. This is achieved by combining the FETI-2λ with periodic boundary conditions (PBCs) (W. Wang et al. IEEE Trans. Antennas Prop. Vol. 59, p. 4142, 2011). Once dominant trends on the array's element design and size are established, the full FETI-2λ DD-FEM method is used to accurately predict the finite PUMA performance.

This talk will begin by introducing the basic topology of the PUMA array highlighting the modeling and design challenges arising from the multi-scale nature of the geometry. The rational and the basic principles behind the DD-FEM will be presented. A baseline test case of a 3:1 bandwidth 16×16 PUMA will be used to present results for the embedded element impedance, radiation pattern, active reflection coefficient and patterns under various exception configurations. The results will be compared with measurements, and trends on the bandwidth versus array size will be given.

	Monday, June 4, 2012
	Music Room
8:00	**Session 2: Discontinuous Galerkin Methods (Q. H. Liu, W. Cai)**
	2.1. On the Physics, Accuracy, and Efficiency of the Dual-Field Domain-Decomposition Method for Time-Domain Electromagnetic Simulation *Xiaolei Li and Jian-Ming Jin**
8:20	**2.2.** A Full Vectorial Generalized Discontinuous Galerkin Beam Propagation Method for Optical Waveguides *Wei Cai**
8:40	**2.3.** Non-Conformal and Parallel and Interior Penalty Discontinuous Galerkin Method for the Time-Domain Maxwell's Equations *Stylianos Dosopoulos and Jin-Fa Lee*
9:00	**2.4.** Discontinuous Galerkin Methods for Ideal MHD Equations *Fengyan Li**
9:20	**2.5.** New Spectral-Prism-Element for Layered Structures implemented in an efficient implicit DG-FETD method *Luis E. Tobon and Qing H. Liu**
9:40	Coffee break (Pinion room)
10:10	**2.6.** An Efficient Discontinuous Galerkin Finite-Element Time-Domain Method and its Application to Micro-Resistivity Imager *Jiefu Chen, Carlos Haramboure, Lance Pate, Shawn Wallace, Jay Martin, Medhat Mickael, and Mac Wisler*

On the Physics, Accuracy, and Efficiency of the Dual-Field Domain-Decomposition Method for Time-Domain Electromagnetic Simulation

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Among various efforts to overcome the major limitation of the finite-element time-domain (FETD) method, which is the need to solve a global matrix equation for each time step, one important progress is the development of the dual-field domain-decomposition (DFDD) method (Z. Lou and J. M. Jin, "A novel dual-field time-domain finite-element domain-decomposition method for computational electromagnetics," *IEEE Trans. Antennas Propag.*, vol. 54, pp. 1850-1862, June 2006). In DFDD, the original problem is broken down into smaller subdomain problems so that only matrix equations at the subdomain level are solved. In contrast to FETD which solves one 2nd-order wave equation, DFDD solves two 2nd-order wave equations:

$$\iiint_V \left[\frac{1}{\mu_r} (\nabla \times \mathbf{T}) \cdot (\nabla \times \mathbf{E}) + \frac{\varepsilon_r}{c_0^2} \mathbf{T} \cdot \frac{\partial^2 \mathbf{E}}{\partial t^2} \right] dV = \mu_0 \iint_S (\hat{n} \times \mathbf{T}) \cdot \left(\hat{n} \times \frac{\partial \mathbf{J}_s}{\partial t} \right) dS \tag{1}$$

$$\iiint_V \left[\frac{1}{\varepsilon_r} (\nabla \times \mathbf{T}) \cdot (\nabla \times \mathbf{H}) + \frac{\mu_r}{c_0^2} \mathbf{T} \cdot \frac{\partial^2 \mathbf{H}}{\partial t^2} \right] dV = \varepsilon_0 \iint_S (\hat{n} \times \mathbf{T}) \cdot \left(\hat{n} \times \frac{\partial \mathbf{M}_s}{\partial t} \right) dS \tag{2}$$

where $\mathbf{J}_s$ and $\mathbf{M}_s$ are the equivalent electric and magnetic currents defined at the subdomain interfaces. Eqs. (1) and (2) are solved at integer and half-integer time steps, respectively, and hence the system is marched in a leapfrog manner. By computing the equivalent currents as $\mathbf{J}_s = \hat{n} \times \mathbf{H}_{\text{neighbor}}$ and $\mathbf{M}_s = -\hat{n} \times \mathbf{E}_{\text{neighbor}}$ where $\hat{n}$ denotes the vector normal to the interface and pointing outward and $\mathbf{E}_{\text{neighbor}}$ and $\mathbf{H}_{\text{neighbor}}$ are the fields from the neighboring subdomain, information is exchanged among subdomains and the tangential field continuities are weakly enforced.

The DFDD method has a clear physical meaning. Eq. (1) represents the application of the surface equivalent principle with a surface electric current radiating in front of a magnetic wall, while Eq. (2) represents the same principle with a surface magnetic current radiating in front of an electric wall. Eqs. (1) and (2) also reflect the well-known Huygens' principle, since the wave front at the subdomain interfaces can be viewed as a secondary source that produces the field inside the local subdomain.

Another important domain-decomposition method is the discontinuous Galerkin time-domain (DGTD) method, which can be categorized into two versions, DGTD-Central and DGTD-Upwind, depending on whether the central or upwind numerical fluxes are used. In terms of the interpolation error, DFDD, DGTD-Central, and DGTD-Upwind have the convergence rates of $O(h^p)$, $O(h^p)$, and $O(h^{p+1})$, respectively, where h is the mesh size and p is the polynomial order of the basis functions. In terms of the energy-conservation property, DFDD and DGTD-Upwind have no numerical dissipation while DGTD-Upwind has slight numerical dissipation which can be reduced by employing higher-order basis functions.

With respect to efficiency, our numerical tests show that the CPU time for DFDD and DGTD-Central are about the same, while DGTD-Upwind consumes more time than the other two methods, when the same mesh and maximum allowable time step are used for all three methods. When the mesh is fixed and the order of basis functions is increased, the three methods consumes about the same amount of time for a specified error level. When the order of basis functions is fixed and the mesh is refined, DGTD-Upwind outperforms the other two methods since it has a higher error convergence rate.

A full vectorial generalized discontinuous Galerkin beam propagation method for optical waveguides

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In this talk, we will present a new full vectorial generalized discontinuous Galerkin beam propagation method (GDG– BPM) to accurately handle the discontinuities in electromagnetic fields associated with wave propagations in inhomogeneous optical waveguides. The numerical method is a combination of the traditional beam propagation method (BPM) with a newly developed generalized discontinuous Galerkin (GDG) method . The GDG method is based on a reformulation, using distributional variables to account for solution jumps across material interfaces, of Schrödinger equations resulting from paraxial approximations of vector Helmholtz equations. Four versions of the GDG–BPM are obtained for either the electric or magnetic field components. Modeling of wave propagations in various optical fibers using the full vectorial GDG–BPM is included. Numerical results validate the high order accuracy and the flexibility of the method for various types of interface jump conditions.

Non-Conformal and Parallel and Interior Penalty Discontinuous Galerkin Method for the Time-Domain Maxwell's Equations

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Complex electromagnetic applications require sophisticated methods to solve the time-dependent Maxwell's equations. Discontinuous Galerkin (DG) finite element methods are highly suitable for time-domain simulations. They support various types and shapes of elements, non-conformal meshes and non-uniform degrees of approximation. Furthermore, they can lead into fully explicit time-marching schemes. Finally, information exchange is required only between neighboring elements, which leads to high parallelization efficiency. In electromagnetism, DG methods were recently applied for the solution of the time dependent Maxwell's equations. In this paper an Interior Penalty Discontinuous Galerkin (IPDG) method will be presented to solve the time domain Maxwell's equations. More specifically, emphasis will be given to the case of non-conformal meshes. The ability to handle non-conformal meshes can be of great practical importance. In many cases the high level of complexity found in practical applications (i.e. IC packaging analysis) makes the task of generating a conformal mesh for the whole structure extremely difficult. Therefore, a divide and conquer approach is needed in such cases. In our approach, the computational domain is initially decomposed into non-overlapping sub-domains. Currently, only planar interfaces are supported between subdomains. Then, each sub-domain is meshed completely independently resulting in non-conformal meshes at subdomain interfaces. This approach provides great flexibility in the meshing process. Moreover, to take advantage of the high parallelization efficiency offered by discontinuous Galerkin methods an MPI parallelization has been implemented. Each sub-domain M_i, is mapped to an MPI process and each MPI process is associated with a cluster node. Within each node, if needed, all CPU cores are used with OpenMP to update the sub-domain. This can be considered as a hybrid MPI+OpenMP approach. Furthermore, due to the multi-scale nature of most application the generated meshes often contain very small or distorted elements. Therefore, the stability condition will result in a very small time step δt. To guarantee stability for all the elements we must choose $\delta t = \delta t_{min} = min(\delta t_i)$, i.e. δt_{min} is the minimum of all the local $min(\delta t_i)$. Consequently, the CPU time will significantly increase. Thus, to mitigate this problem, we combine our parallelization with a local time-stepping strategy to increase efficiency and reduce the computational time.

Discontinuous Galerkin Methods for Ideal MHD Equations

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Ideal magnetohydrodynamics (MHD) equations arise in many areas such as astrophysics, space physics and engineering. They consist of a set of nonlinear hyperbolic conservation laws, with a divergence-free constraint on the magnetic filed. Neglecting this constraint in numerical simulation may lead to instability or non-physical features in solutions. Another numerical issue which can lead to numerical instability is the negative pressue. In this talk, I will present our work in developing numerical divergence treatments and positivity preserving techniques in the discontinuous Galerkin (DG) setting.

In (F. Li and C.-W. Shu, Journal of Scientific Computing, v22-23 (2005), pp.413-442), we introduced a locally divergence-free DG method for the ideal MHD equations. Compared with the standard DG methods, the new component is the use of the locally divergence-free approximations for the magnetic field. Though the idea is simple, the resulting method demonstrates comparable or better accuracy as well as good stability in numerical simulations, with reduced computational complexity. On the other hand, the divergence of the numerical magnetic field is still nonzero due to the jump in its normal component across element interfaces. Motivated by this, we recently proposed a family of exactly divergence-free central DG methods for the ideal MHD system in (F. Li, L. Xu and S. Yakovlev, Journal of Computational Physics, v230 (2011), pp.4828-4847) and (F. Li and L. Xu, Journal of Computational Physics, accepted (2011)). While other conservative quantities are evolved with standard central DG methods, the magnetic field is updated such that its normal component is first approximated along the mesh interfaces based on the magnetic induction equations. A divergence-free reconstruction is then carried out element by element. To achieve higher order accuracy and to ensure the unique solvability of the reconstruction, additional information for the magnetic field is extracted by revisiting the magnetic induction equation. The overall algorithm is local, and it can be of arbitrary order of accuracy. Numerical examples are presented to demonstrate the performance of these methods.

By following the work of (Zhang and Shu, Journal of Computational Physics, v229 (2010), pp.8918-8934), we further develop the positivity preserving DG and central DG methods in MHD simulations. This is based on a simple limiter which can be proved to maintain uniform high order accuracy. This limiter can be easily implemented in multi-dimensions and on general meshes.

New Spectral-Prism-Element for Layered Structures Implemented in an Efficient Implicit DG-FETD Method

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A new kind of prism element with a triangular base is presented for discretization of layered structures. For the triangular base, Mixed-order Curl-Conforming Edge-Based Vector basis functions (CtLn and LtQn) are used (A. F. Peterson, S. L. Ray, and R. Mittra, *Computational methods for electromagnetics*, IEEE press New York, 1998); the prism height adopts spectral basis functions based on Gauss-Lobatto-Legendre polynomials, with an arbitrary order of interpolation (J. Lee, T. Xiao, and Q. H. Liu, "A 3-D Spectral-Element Method Using Mixed-Order Curl-Conforming Vector Basis Functions for Electromagnetic Fields", IEEE Transactions On Microwave Theory And Techniques, Vol. 54, No. 1, Jan 2006). These two families of basis functions allow three major advantages: triangle shapes for a flexible description of the geometry in each layer plane; a high-order accuracy and a low memory cost in the height direction; and, an inherent orthogonality between basis functions in the layer plane (triangle) and height (spectral).

The eigenvalues and eigenvectors are evaluated with this element, and the results are compared with the Finite Elements Method (FEM) based on tetrahedral elements and Spectral Elements Method (SEM) based on hexahedral elements. Excellent accuracy and performance of the new prism element are shown for wave equation and Maxwell's equations. From this analysis, it is verified that, in order to eliminate spurious solutions, one must employ mixed-order of interpolation for electric and magnetic fields (J. Chen, Q. H. Liu, M. Chai, and J. A. Mix, "A Nonspurious 3-D Vector Discontinuous Galerkin Finite-Element Time-Domain Method", IEEE Microwave And Wireless Components Letters, Vol. 20, No. 1, January 2010). Results in time domain for a single domain also show good performance.

An obvious application of this new element is layered structures, with arbitrary geometries and scales for different layers, for instance on-chip interconnects. For this kind of applications, in this work each layer is considered as a subdomain with independent mesh, orders of interpolations, and shared boundaries with neighbor subdomains. To solve the connection between sudbomains the discontinuous Galerkin method with a Riemann solver is applied. Furthermore, subdomains are assumed placed in a sequential order (very common for layered structures) and consequently the coupled system will take the form of a block tri-diagonal system; thus, a block Thomas algorithm is integrated to accelerate and improve the accuracy of the implicit Crank-Nicolson method (J. Chen, L. E. Tobon, M. Chai, J. A. Mix, and Q. H. Liu "Efficient Implicit-Explicit Time Stepping Scheme With Domain Decomposition for Multiscale Modeling of Layered Structures", IEEE Transactions On Components, Packaging And Manufacturing Technology, Vol. 1, No. 9, September 2011). Finally, some applications for integrate circuits are presented, with comparisons with traditional methods and commercial software.

An Efficient Discontinuous Galerkin Finite-Element Time-Domain Method and Its Application to Micro-Resistivity Imager

Jiefu Chen, Carlos Haramboure, Lance Pate, Shawn Wallace,
Jay Martin, Medhat Mickael, and Mac Wisler

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The micro-resistivity imager is a very useful tool for oil drilling and exploration. During rotating / sliding in borehole, it can generate an image containing facture information on the borehole wall. To model the micro-resistivity imager is usually a multiscale problem: the length of an imager tool is several meters, while the details on the imager sensors and the factures on the borehole wall can be as small as millimeters or even micrometers.

In our study we need time domain multiscale simulation of micro-resistivity imagers. This task is very challenging for conventional methods, such as the popular FDTD (finite-element time-domain) technique. On one hand, spatial discretization of a multiscale structure by conventional methods oftentimes leads to a huge number of unknowns; on the other hand, because of fine cells existing in the discretized multiscale system, the stability criterion in time stepping can be extremely strict, and an unaffordable number of time steps is required to finish the simulation of a given time window.

Here we employ an efficient DG-FETD (discontinuous Galerkin finite-element time-domain) method for solving this multiscale problem. An imager structure is divided into several subdomains based on the electrical size of each part. Large and higher order finite elements are used in discretizing electrically coarse structures; small and lower order finite elements are used to capture the geometric characteristics of fine structures. The Riemann solver is employed to stitch the separate subdomains together. After spatial discretization, the implicit-explicit Runge-Kutta (IMEX-RK) scheme is utilized to perform time integration. The explicit RK scheme is used for electrically coarse subdomains discretized with coarse mesh, and the implicit RK scheme is used to overcome the stability criterions of electrically fine subdomains. Numerical examples demonstrate that the DG-FETD method can be several orders more efficient than conventional methods in modeling the micro-resistivity imager.

	Monday, June 4, 2012 Billiard Room
10:50	**Session 3: Time-Domain FEM and Applications (D. White, O. Biro, T. Rylander)** **3.1.** Numerical Simulation of HPM Devices with ICEPIC *Andrew D. Greenwood**
11:10	**3.2.** Time Domain Method for Periodic Nonlinear Eddy Current Problems *Oszkár Bíró, Gergely Koczka, and Kurt Preis*
11:30	**3.3.** Hybrid FETD/FDTD Techniques Based on the Discontinuous Galerkin Method *Bao Zhu, Jiefu Chen, Wanxie Zhong, and Qing Huo Liu*
11:50	Lunch break (MacGregor Room)
13:10	**3.4.** Transient Thermal Analysis using a Non-conformal Domain Decomposition Approach *Yang Shao* , Zhen Peng, and Jin-Fa Lee*
13:30	**3.5.** An Explicit and Unconditionally Stable Time-Domain Finite-Element Method of Linear Complexity *Qing He, Duo Chen, and Dan Jiao*
13:50	**3.6.** Conformal PML Modeling in DGTD using Continuous Material Properties *Jue Wang*, Zhen Peng, and Jin-Fa Lee*

Numerical Simulation of HPM Devices with ICEPIC

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The Improved Concurrent Electromagnetic Particle-In-Cell (ICEPIC) code is used to model high power microwave (HPM) devices. ICEPIC is developed since 1994, and the code is massively parallel with scalability tested to over 16000 CPUs. The relevant physics to model HPM devices, including particle emission, relativistic particle tracking, perfectly matched layer absorbing boundary conditions, and material handling are included in the code. Temporal filtering is used to remove poorly resolved waves that can lead to non-physical, numerical Cerenkov radiation. The code also contains an interface to allow other FEM codes to model antenna structures with additional flexibility. For high density plasmas, the PIC method becomes intractable, and a simplified fluid model is included in the code. The model handles both unmagnetized and magnetized plasmas.

Recently, there is interest in using frequency dispersive and non-linear dielectric materials in HPM devices. The code includes a Lorentz-Drude model in the time domain for inclusion of frequency dispersive dielectrics. Nonlinear material modeling is an area of active research. Two types of materials are considered. The first is nonlinear dielectric materials for which the permittivity is a function of the electric field magnitude. The second is ferrite material. For these materials, the Landau-Lifshitz-Gilbert equation is discretized. Nonlinear materials can suffer from a non-physical instability that is related to the spatial cutoff frequency of the computational mesh. Efforts to suppress the instability by filtering are discussed.

Time Domain Method for Periodic Nonlinear Eddy Current Problems

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The most straightforward method of solving nonlinear electromagnetic field problems in the time domain by the method of finite elements is using time-stepping techniques. This requires the solution of a large nonlinear equation system at each time step and is therefore very time consuming, especially if a three-dimensional problem is being treated. If the excitations are non-periodic or if, in case of periodic excitations, the transient solution is required, one cannot avoid time-stepping. In many cases however, the excitations of the problem are periodic, and it is only the steady-state periodic solution which is needed. Then, it is wasteful to step through several periods to achieve this by the "brute force" method of time stepping.

A time domain technique using the fixed-point method to decouple the time steps has been introduced in (O. Bíró, K. Preis, An efficient time domain method for nonlinear periodic eddy current problems, IEEE Transactions on Magnetics, 42, (2006), 695–698). In later work, the optimal choice of the fixed point reluctivity for such problems has been determined both in the time domain and using harmonic balance principles. The method can be applied to three-dimensional problems both in terms of a magnetic vector potential and an electric scalar potential (A,v-A formulation) and applying a current vector potential and a magnetic scalar potential (T,Φ-Φ formulation).

The aim of this paper is to show the application of the method to industrial problems arising in the design of large power transformers.

Hybrid FETD/FDTD Techniques Based on the Discontinuous Galerkin Method

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Hybrid FETD/FDTD techniques that combine the advantages of both finite-element time-domain (FETD) and finite-difference time-domain (FDTD) methods and avoid their weaknesses have been developed recently. The FETD method is applied to model structures with complex geometries and boundaries, and the FDTD method is efficient to model large homogeneous volumes and more regular structures. In the previous hybrid approaches, to our knowledge, the structured FDTD grid and unstructured FETD mesh are required to be conformal to each other; thus, a transition element is needed to joint the structured FDTD grid with the unstructured FETD mesh, making mesh generation very challenging. To improve flexibility and efficiency of the FETD/FDTD hybridization, a non-conforming mesh between the structured and unstructured grids is desirable for simulating multi-scale structures. We recently proposed the highly parallel discontinuous Galerkin method as an appropriate framework for hybridizing the FETD and FDTD methods, as the discontinuous Galerkin method allows discontinuous basis functions across different subdomains.

In this presentation, we summarize the hybrid FETD/FDTD technique based on the discontinuous Galerkin method developed recently. This technique can use arbitrary non-conformal meshes between the structured FETD mesh and unstructured FDTD grid. Multiple FETD subdomains are allowed in this method, so it is suitable to be applied to multiple zones divided for parallel computation. In the hybrid method, either explicit scheme such as the 4th-order Runge-Kutta method (RK4) or implicit scheme such as Crank-Nicholson method can be used in the FETD regions for time integration. Several examples will be presented to show the validity and efficiency of the proposed hybrid method.

Transient Thermal Analysis using a Non-conformal Domain Decomposition Approach

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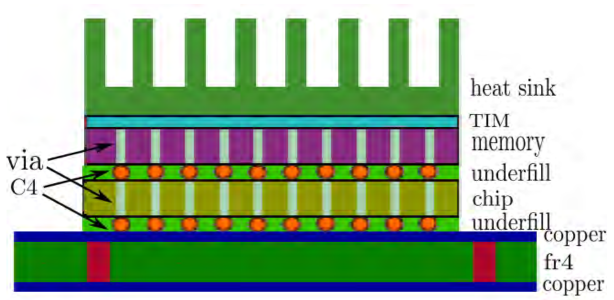
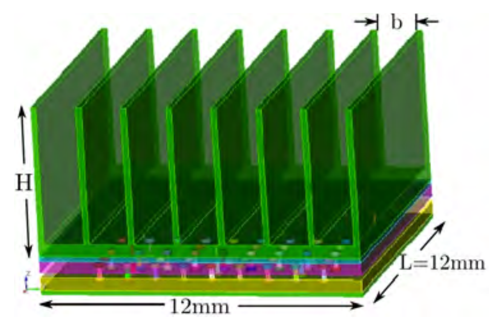
In this paper, we present our efforts in combating the multi-scale thermal problems through the use of non-conformal Domain Decomposition Method (DDM). The non-conformal DDM have received considerable attention because they provide effective, efficient preconditioned iterative solution algorithms for the numerical solution of moderately stiff parabolic partial differential equations (PDEs) in inhomogeneous domains.

The numerical procedure that we introduced herein is based on the non-conformal and non-overlapping DDM for transient thermal analysis. Specifically, we partition the problem geometry into many non-overlapping sub-domains. Within each sub-domain, we strive to maintain similar geometrical feature sizes. Next, each of the sub-domains is meshed independently without considerations of adjacent sub-domains. The required temperature and heat flux continuities across domain interfaces are guaranteed by the Robin transmission condition, which is enforced weakly through the Galerkin method. Consequently, the proposed non-conformal DDM greatly relaxes the burden of mesh generation for complicated multi-scale thermal problems and provides an inherent parallelism and flexibility.

Moreover, the time discrelization employed is based on an unconditional stable, implicit Euler scheme. The unconditionally stable time marching algorithm is beneficial since the time-step size is no longer governed by the spatial discretization of the mesh, but rather by the desired accuracy. Additionally, the numerical investigations of the convergence properties of the proposed non-conformal DDM are included.





Furthermore, we extend the non-conformal DDM formulation for the steady state thermal analysis to study the steady thermal temperature distribution within complex ICs. Finally, numerical results are shown for a chip-package-PCB example with cooling techniques of both natural convection and forced convection cooling through the heat sinks.

An Explicit and Unconditionally Stable Time-Domain Finite-Element Method of Linear Complexity

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Time-domain methods can be categorized into two broad classes. One is the explicit time-domain method; the other is the implicit time-domain method. Explicit methods can avoid solving a matrix, while implicit methods require a matrix solution. Despite its advantage of being matrix free, an explicit method requires the time step to be restricted by the smallest space step for ensuring stability. For problems that have fine features relative to working wavelength like integrated circuits, explicit methods require a large number of time steps to finish one simulation, which is computationally expensive. Existing unconditionally stable methods (methods that permit the use of any large time step without becoming unstable) are all implicit methods such as ADI (alternating direction implicit)-FDTD, the CN (Crank-Nicolson)-FDTD, the Laguerre-FDTD, and the Newmark-Beta based time-domain finite-element method (TDFEM). Although they permit the use of any large time step, they require the solution of a large-scale matrix for large problems. Moreover, late-time instability has been observed from implicit methods. Recently, research has also been done to extend the stability limit of the explicit FDTD method by spatial filtering. As yet, no explicit methods have achieved unconditional stability. The research question considered in this work is: can an explicit method be made unconditionally stable so that its matrix-free strength can be retained and its shortcoming in time step can be eliminated?

The preliminary research of this work was reported in (Q. He and D. Jiao, 2011 IEEE AP-S symposium), where we quantitatively identified the root cause of the instability associated with an explicit time-domain method that uses a time step beyond stability criterion. Based on such a finding, we successfully developed an explicit time-domain finite-element method that is unconditionally stable, i.e., stable for any large time step. The formulations given in (Q. He and D. Jiao, 2011 IEEE AP-S symposium) are for lossless cases in which only ideal dielectrics and conductors are considered. In addition, linear (optimal) computational complexity was not reported. The contribution of this paper is the successful development of a linear-complexity explicit and unconditionally stable time-domain finite-element method for the simulation of arbitrarily shaped 3-D non-ideal conductors embedded in inhomogeneous materials. We also provide a theoretical basis for making an explicit time-domain method unconditionally stable. Numerical experiments have demonstrated that the proposed unconditionally stable explicit method outperforms both the conditionally stable explicit method and the unconditionally stable implicit method in computational efficiency and stability. Although the proposed method is presented in the framework of a time-domain finite-element method, the essential idea can be applied to other time-domain methods.

Conformal PML Modeling in DGTD using Continuous Material Properties

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Discontinuous Galerkin (DG) finite element method is well-suited on unstructured meshes for high order approximation with the freedom of non-matching grids and choosing the order of basis functions in each element locally. Moreover, DG can handle complicated geometries with curved boundary easily. Further, since information exchange in DG only involves neighboring elements which results in block diagonal mass matrices, high efficiency in parallelization can be achieved for time domain method using explicit time marching scheme. As a truncation to the computational domain for finite element method,perfect matched layer (PML) is adopted in this paper. By making the shape of the layer conformal to the target scatterer the size of the domain can be reduced. Conformal PML can be treated as an artificial anisotropic layer where the material properties vary continuously in space. In order to model this spatially changing materials in conformal PML, this paper uses a universal array approach where inside each element the material property tensors change as a function of location. Compared to the conventionally treatment of element-wise constant material property, this method provides a more accurate physical model for problems with continuously varying material properties in an efficient way, in this case the modeling of conformal PML and many other real life applications as well.

The main contribution of this paper is a combination of the universal array method for continuous material property and MPI-based parallel implementation of three dimensional (3D) DGTD method with explicit time marching scheme and local time stepping to solve for the first order Maxwell's equations.

	Monday, June 4, 2012 Music Room
10:30	**Session 4: FEM and CEM Applications in Optics and Nanophotonics (E. Simsek)** **4.1.** Electromagnetic Scattering of Finite Size Periodic Large Scale System: Simulation by Domain Decomposition Spectral Element Method *Ma Luo and Qing Huo Liu**
10:50	**4.2.** Efficient alternatives to edge vector finite elements for EM field calculations using Hermite interpolation polynomial basis functions on a nodal grid in 2D *J. D. Albrecht, C. R. Boucher, C. I. Ahheng, and L. R. Ram-Mohan*
11:10	**4.3.** Parallel Finite Element Electromagnetic Code Suite for Accelerator Modeling and Simulation *Cho Ng, Lixin Ge, Kwok Ko, Kihwan Lee, Zenghai Li, Greg Schussman, and Liling Xiao*
11:30	**4.4.** Optical, Electromagnetics, and Thermal Modeling of Interaction of a Focused Beam of Light with Plasmonic Nanoparticles *Eren S. Unlu and Kursat Sendur**
11:50	Lunch break (MacGregor Room)
13:10	**4.5.** Finite Element Analysis of Wideband Nanostructures for Photovoltaic Applications *Niccolo Breda, Giuseppe Pelosi, Stefano Selleri, and Ruggero Taddei*
13:30	**4.6.** Hybrid Optical Waveguides *Ergun Simsek* and Qing H. Liu*

Electromagnetic scattering of finite size periodic large scale system: simulation by domain decomposition spectral element method

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Hybrid finite element method and method of moments is a powerful tool to simulate electromagnetic scattering of dielectric object. The finite element method can model complicated structure with unstructured mesh. The method of moments exactly describe the propagation of electromagnetic field in the background. However, when the size of the simulated system is much larger than the wavelength, it is more difficult for this solver to find the solution. When the number of unknowns become larger, the solver consume more memory. In addition, the iterative solver might not be able to converge when the size of the system matrix is large.

One of the solution to this bottleneck is to introduce domain decomposition, which split up the whole system into a few smaller system, or sub-domains. The system matrix of each sub-domain is smaller enough to be solved by directed solver. The solution of the whole system is obtained by considering the interfere between the solution of adjacent sub-domains. We use Riemann solver to model the interfere between adjacent sub-domains. The electromagnetic field within each sub-domain is model to spectral element method, which is a kind of high order finite element method base on hexahedral elements. The Riemann solver is inserted into the surface integral of the weak form. For finite periodic system, each period is defined as a sub-domain. Thus, each sub-domain have the same structure, which generates the same system matrix. As a result, we don't need to store the repeating system matrix.

The background is defined as one sub-domain, which is modeled by method of moments. In order to reduce memory cost and CPU time, the spectral integral method is used to store and solve the method of moments matrixes. The combined field integral equation is used in the implementation of the method of moments. Numerical examples show that the convergent speed is fast.

Efficient alternatives to edge vector finite elements for EM field calculations using Hermite interpolation polynomial basis functions on a nodal grid in 2D

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The use of vector finite elements for representing electromagnetic fields is standard procedure for modern simulations and is a staple of academic instruction. Properly constructed edge elements offer clear mathematical advantages such as tangential field component continuity, the suppression of spurious solutions, and the satisfaction of the Nedelec conditions to prevent pathological representations. Two penalties that are tolerated to obtain the advantages of edge elements are their mixed polynomial order (edge vs. normal field descriptions) and the infrastructural overhead associated with a non-nodal mesh bookkeeping. In the first case, the same mathematical advantages that allow vector bases to simultaneously satisfy tangential boundary conditions, maintain consistency with the operator, and retain the physics of the problem result in the tangential and normal field components at the edges to be of mixed polynomial order. While many elegant forms have been published to make edge elements hierarchical to increased polynomial order, none overcome the obstacle that the edge field description is of order $n-1$ compared to polynomial order n interior to the triangle. The second issue of not using a straightforward nodal representation common to scalar field problems is a practical one. For example, even order edge field basis functions (such as published constant or quadratic tangential field elements) require not only spatial coordination between adjacent triangles, but edge directionality to be consistent. This necessitates cumbersome modifications or add-ons to the prevalent technology infrastructure for mesh generation. Custom software requirements are a serious hindrances to advancing the using of more sophisticated basis functions in electromagnetic simulations.

In this work, we propose alternative polynomial basis functions for use in electromagnetic field calculations that can be used with triangular elements on a simple nodal mesh. We employ scalar, fifth-order Hermite interpolation polynomials to solve Maxwell's equations in two dimensions in the finite element method. Each field component is represented by scalar Hermite elements while maintaining field and derivative continuity for treating boundary conditions and avoiding spurious modes. We have analyzed homogeneous conducting waveguides, inhomogeneous interior waveguides, and photonic crystals. The Hermite interpolation functions provide greater accuracy than vector finite elements of equal polynomial order, while bypassing the issue of spurious modes observed when using Lagrange polynomials. Comparisons are made to edge vector element calculations with comparable number of degrees of freedom. In addition to highly accurate eigenvalue computation, the calculated spatial fields representing the eigenmodes do not suffer degradation from mixed polynomial order. The impact is that few elements can be used to resolve the same level of accuracy.

*Approved for Public Release, Distribution Unlimited

Parallel Finite Element Electromagnetic Code Suite for Accelerator Modeling and Simulation

Cho Ng, Lixin Ge, Kwok Ko, Kihwan Lee, Zenghai Li, Greg Schussman, and Liling Xiao
SLAC National Accelerator Laboratory

A parallel scalable electromagnetic code suite, ACE3P, has been developed at SLAC over the past decades for particle accelerator design, optimization and analysis. Based on the high-order finite-element method, ACE3P allows high-fidelity modeling of complex accelerator structures and, running on state-of-the-art supercomputers, enables computationally challenging, large-scale problems to be solved with unprecedented accuracy. ACE3P's comprehensive simulation capabilities include eigensolvers and scattering matrix calculation in the frequency domain, transient and full-wave particle-in-cell simualtions in the time domain, charged particle tracking, as well as integrated multiphysics analysis with electromagnetic, thermal and mechanical effects. Applications of ACE3P to accelerator projects for wakefield computation at the system level, large-scale optimization of accelerator structures, and far-field radiation calculation for photonic bandgap optical fibers will be presented.

Optical, Electromagnetics, and Thermal Modeling of Interaction of a Focused Beam of Light with Plasmonic Nanoparticles

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The interaction of photons with metallic nanoparticles is important to a number of emerging nanotechnology applications due to the large enhancement and tight localization of electromagnetic fields in the vicinity of nanoparticles. This interaction has existing and emerging applications at the nanoscale, including near-field scanning optical microscopy, high-density data storage, and bio-chemical sensing. Although there has been much effort to understand the effects of various parameters on the plasmon resonances of nanoparticles, the interaction of nanoparticles with a focused beam of light has largely been omitted in the context of particle plasmons. In addition, a tightly focused beam of incident light can be used to excite a metallic nano-antenna. Since the incident electric field illuminating the nano-antenna increases, the near-field radiation from the nano-antenna also increases.

In the first part of this study, it is demonstrated that the focused light can be utilized to manipulate the distribution of Mie-plasmons on nanoparticles. This interaction is particularly important for applications such as optical and magneto-optical data storage, where strong optical fields are desired at specific locations. The interaction of light with a nanoparticle is investigated for beams with various angular spectra. To analyze the effect of the angular spectrum on the particle plasmons, a silver nanoparticle is illuminated using a focused beam of light with various half-beam angles. Also in this part, interaction of a focused beam of light with a nano-antenna structure is studied. A metallic antenna is placed in the vicinity of a solid immersion lens, and the effect of various parameters, including the angular spectrum of the beam on the near-field radiation from the nano-antenna is studied.

In the second part of this study, localized radiative energy transfer from a near-field emitter to a magnetic thin film structure is investigated. A magnetic thin film stack is placed in the near-field of the plasmonic nanoantenna to utilize the evanescent mode coupling between the nanoantenna and magnetic thin film stack. A bow-tie nano-optical antenna is excited with a tightly focused beam of light to improve near-field radiative energy transfer from the antenna to the magnetic thin film structure. A tightly focused incident optical beam with a wide angular spectrum is formulated using Richards-Wolf vector field equations. Localized radiative energy transfer between the near-field emitter and the magnetic thin film structure is quantified for a given optical laser power at various distances between the near-field emitter and magnetic thin film.

Finite element analysis of wideband nanostructures for photovoltaic applications

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Nanostructures enhanced solar cells are progressively emerging as a theoretically viable alternative to conventional ones (K. R. Catchpole and A. Polman, ”Plasmonic solar cells”, Optical Express, Vol. 16, 2008, pp. 21793-21800). While first and second generations solar cells exploit traditional photovoltaic effect, the so called third generation of solar energy harvesting techniques is aimed at taking advantage of the plasmonic resonance phenomenon.

Localised surface plasmon (LSP) resonances have been shown to obtain a great electric field enhancement in the vicinity of metallic nanoparticles immersed in a conventional semi-conductive slab (Crozier, K.B et al., ”Field enhancement and resonance in optical antennas”, Quantum Electronics and Laser Science, 2003. QELS. Postconference Digest, 2003). This increase in the electric field magnitude can then be exploited to lead to greater efficiencies with respect to conventional solar cells.

The LSP resonance occurs at a particular frequency in the optical range, where metals cannot be modelled any more as perfect conductors, but rather assume a plasma behavior, expressed through a modified Drude-Lorentz model (B.Ung, Y. Sheng, ”Interference of surface waves in a metallic nanoslit”, Optics Express, Vol. 15, No. 3, 2007, pp. 1182-1190).

To gain more insight on this particular behavior, finite element (FE) simulations are conducted on a periodic arrangement of gold and silver nanoparticles on top of a silicon slab. Particles with various geometries are investigated; their size is shown to affect the onset of the plasmonic resonance phenomenon. Particles with sizes between 20 and 50 nm are shown to lead to the desired field enhancement, which appears as a minimum in the reflection coefficient. The analysis is then deepened by placing an arrangement of metal particles with different sizes on a same substrate.

Hybrid Optical Waveguides

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Recently, metal and carbon nano wires (NWs) have received a serious amount of interest due to their potential in confining light transversally to sub-wavelength dimensions and yet to be used as an optical waveguide or an antenna in the visible (Bharadwaj *et al.*, Adv. Opt. Photon. 1, 2009). Oulton *et al.* has shown that a hybrid optical waveguide (HOW), which consists of a dielectric NW separated from a metal surface by a nano scale dielectric gap, can provide extremely long propagation length (dozens of wavelengths) and strong mode confinement (Nat. Photonics 2, 2008). Experimental and theoretical results reveal a huge potential for realistic nano scale semiconductor-based plasmonics and photonics.

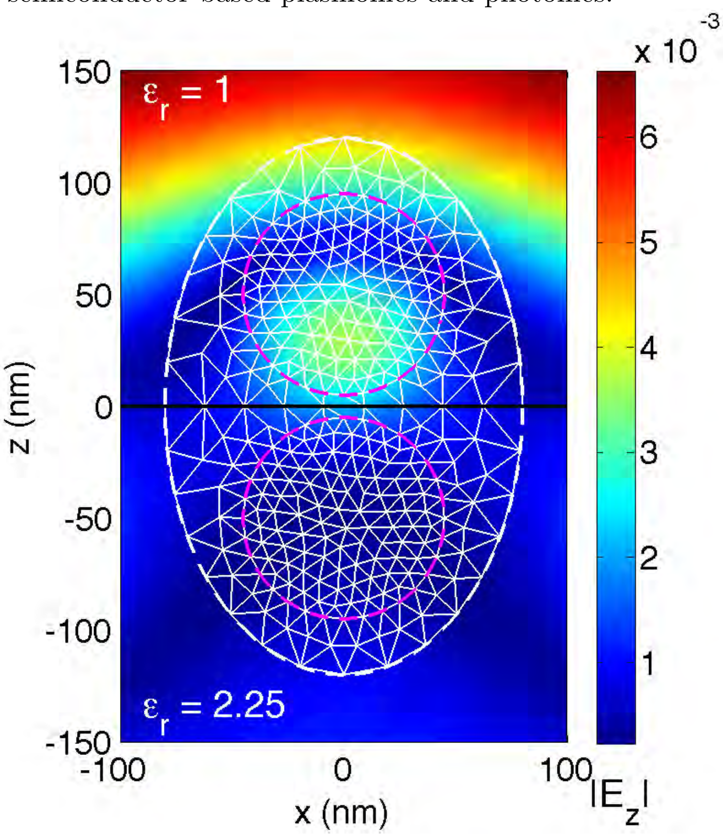

Figure 1: Total electric field (incident + scattered) for 2 NWs (depicted as magenta dashed lines) embedded in a 2-layered medium. Black line represents the air-glass interface. White lines show the FEM mesh. $\epsilon_r^{NW_1} = 16$, $\epsilon_r^{NW_2} = -7.6321 + 0.7306i$.

In this work we propose a novel HOW structure which can provide even longer propagation lengths. The superiority of the design comes from the metallic loss reduction obtained by replacing the metal planar layer with a metal cylinder. Numerical results (obtained with a two dimensional mode solver) show that this reduction in the metal surface area increases the propagation length.

In order to understand electromagnetic field distribution throughout the whole structure, we also calculated the total electric field due to plane wave incidence of different incidence angles. In this direction, we use the spectral integral method (SIM) as an exact radiation boundary condition to truncate the computational domain in the finite element method (FEM) to form a hybrid SIM/FEM which is applicable to arbitrary inhomogeneous objects. Fig. 1 shows the field distribution around 2 NWs, where the silver one is embedded in glass for a normally incident plane wave ($\lambda = 500$ nm).

At the conference, we will discuss the performances of the proposed and traditional HOWs in great detail.

	Monday, June 4, 2012
	Billiard Room
14:10	**Session 5: Model Order Reduction Techniques** **(R. Dyczij-Edlinger, V. de la Rubia)**
	5.1. Reduced-order Electromagnetic Modeling in the Presence of Uncertainty *Juan S. Ochoa and Andreas C. Cangellaris**
14:30	**5.2.** Efficient Model Order Reduction for FEM Analysis of Waveguide Structures and Resonators *Fotyga G.*, Kulas L., Nyka K., and Mrozowski M.*
14:50	**5.3.** Model Order Reduction for Systems with Geometrical Parameters *Kynthia K. Stavrakakis*, Tilmann Wittig, Wolfgang Ackermann, and Thomas Weiland*
15:10	Coffee break (Pinion room)
15:40	**5.4.** Reduced-Order Models for Geometric Parameters *Stefan Burgard*, Ortwin Farle, and Romanus Dyczij-Edlinger*
16:00	**5.5.** Seamless Reduced Basis Element Method for Waveguide Simulation *Yanlai Chen*, Jan S. Hesthaven, and Yvon Maday*
16:20	**5.6.** The Reduced Basis Method for Saddle Point Problems *Karen Veroy* and Anna-Lena Gerner*
16:40	**5.7.** Reliable Fast Frequency Sweep of Microwave Circuits via the Reduced-Basis Method *Valentin de la Rubia*
17:00	**5.8.** Reduced Order Modeling of High Magnetic Field Magnets *C. Daversin, C. Prudhomme, C. Trophime*, and S. Veys*

Reduced-order Electromagnetic Modeling in the Presence of Uncertainty

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This paper is concerned with the development of reduced-order, compact models that account for uncertainty (randomness) in geometric and material properties in the finite element modeling of electromagnetic wave phenomena in complex structures. Of particular interest are structures where such uncertainty is localized, occurring in a finite number of regions inside the structure. For such cases, the Monte Carlo-based numerical electromagnetic analysis of the structure can be expedited by eliminating the repeated mesh generation required for each sampling point in the random space defined by the independent random variables that parameterize the uncertainty in the structure.

Toward this objective, this paper considers the development of stochastic reduced-order macromodels for each one of the regions exhibiting uncertainty, with each macromodel defined over a fixed surface enclosing the associated random region. In this manner, the geometry exterior to the union of the random regions is deterministically defined. Thus, a single finite element mesh needs to be generated for the discretization of the overall structure. The only thing that changes for each sample in the Monte Carlo process is the stochastic macromodel for each one of the random regions.

The stochastic macromodel is defined on the fixed boundary enclosing the random region in terms of a global admittance matrix. More specifically, with the tangential electric and magnetic fields on the boundary interpolated in terms of appropriate sets of deterministic spatial expansion functions, the global admittance matrix relates the coefficients in these expansions. These coefficients are functions of both frequency and the independent random variables involved in the parameterization of the uncertainty inside the region. With each random variable defined in terms of its probability density function, use is made of generalized polynomial chaos expansions for the representation of these coefficients in terms of truncated polynomial expansions in random space. With a finite element model used for the discretization of the interior of the random region, a sparse stochastic collocation method is used to develop reduced-order macromodels of the admittance matrix that are expressed in terms of generalized polynomial chaos expansions over the random space for the region (P. Sumant, et al, “A Sparse Grid Based Collocation Method for Model Order Reduction of Finite Element Approximations of Passive Electromagnetic Devices Under Uncertainty,” 2010 IEEE MTT-S International Microwave Symposium Digest, pp. 1652 - 1655, Anaheim, CA, 2010).

The basic steps involved in the development of reduced-order, stochastic macromodel is presented in the context of specific applications involving electromagnetic wave scattering by clusters of targets exhibiting uncertainty. These applications are used to highlight the attributes of the proposed stochastic finite element macromodels and demonstrate the computational benefits resulting from their utilization.

Efficient Model Order Reduction for FEM Analysis of Waveguide Structures and Resonators

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This contribution addresses the problem of applying a model order reduction technique locally in three-dimensional finite element analysis of waveguide structures and resonators. The basic idea of the presented approach is to identify subregions requiring strong mesh refinement and replace their large subsystems of equations with the much smaller ones, called macro-elements, which are created by means of the model order reduction ENOR algorithm. As a result, the overall size of the problem and the computation time are significantly reduced, without sacrificing the accuracy of simulation. What is more, if the number of macro-elements and the reduction order is large, the dense macro-element matrices can be subject to the second reduction and the diagonalization process.

The efficiency of the reduction process depends on the number of variables inside the macro-element subregion, the order of reduction and the number of elements which couple the external region with the macro-element. Since this number is much bigger in 3D than in 2D domains, the performance of the reduction algorithm is usually significantly affected in 3D problems. In order to overcome this limitation we decrease the size of an individual macro-element interface by projecting the fields of its boundary onto a subspace spanned by a reduced modal base.

The modal projection and the reduction process used in our approach does not introduce any frequency-dependent elements into the resultant system of equations, therefore it can be applied not only to efficiently solve the driven problems with wideband frequency sweeps, but also to compute the resonant frequencies of the cavities, without resorting to nonlinear solvers.

Model Order Reduction for Systems with Geometrical Parameters

Kynthia K. Stavrakakis*[1], Tilmann Wittig[2], Wolfgang Ackermann[1], and Thomas Weiland[1]

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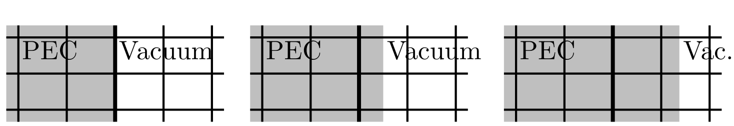
With Model Order Reduction (MOR) methods an original, typically large-scale system $\mathbf{\Sigma}$ is reduced to a smaller system $\hat{\mathbf{\Sigma}}$ which approximates the transfer function of $\mathbf{\Sigma}$. If $\mathbf{\Sigma}$ is parameter-dependent, it is wished to retain the dependence in $\hat{\mathbf{\Sigma}}$. The methods for the latter are known as Parametric Model Order Reduction (PMOR). In both cases, commonly the reduction is accomplished by projection (A.Antoulas, 'Approximation of Large Scale Dynamical Systems', SIAM, 2005).

The models stem from the Maxwell grid equations which are obtained from the continuous Maxwell equations with the help of the Finite Integration Theory (FIT) (T.Weiland, 'Time domain electromagnetic field computation with finite difference methods', Int.J.Num.Mod, 9:295-319,1996). For the PMOR described in the following, the systems are derived from the discrete Helmholtz equation

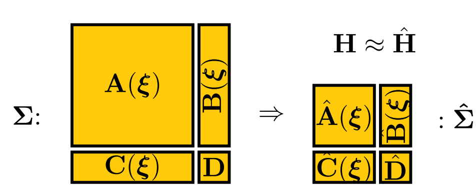
$$\mathbf{\Sigma}: \quad \left(\mathbf{M}_{\varepsilon}(\boldsymbol{\xi})s^2 + \mathbf{C}_{\mathrm{FIT}}^{\mathrm{T}}\mathbf{M}_{\mu}^{-1}(\boldsymbol{\xi})\mathbf{C}_{\mathrm{FIT}}\right)\mathbf{x} = \mathbf{B}\mathbf{i}, \quad \mathbf{u} = \mathbf{C}\mathbf{x}, \tag{1}$$

The diagonal matrices $\mathbf{M}_{\varepsilon}$, $\mathbf{M}_{\mu}$ contain the material and geometry information of $\mathbf{\Sigma}$ and the vector $\boldsymbol{\xi}$ indicates the parameter dependence. The topology-matrix $\mathbf{C}_{\mathrm{FIT}}$ represents the curl operator. The block-vectors $\mathbf{i}$ and $\mathbf{u}$ are the in- and output of $\mathbf{\Sigma}$ and are associated to the matrices $\mathbf{B}$ and $\mathbf{C}$.

The most important challenge in calculating appropriate projection matrices $\mathbf{V}$ are geometrical variations, as the models usually stem from automatically created meshes, that change for geometry variations. Thus, both the model size and the mesh topology change, a fact that most PMOR methods cannot deal with. One method that can cope with geometrical parameters is presented in (K.Stavrakakis, T.Wittig, W.Ackermann, T.Weiland, 'Model Order Reduction Methods for Multivariate Parameterized Dynamical Systems obtained by the Finite Integration Theory', Proceedings URSIGASS, 2011). Projection matrices corresponding to local systems $\mathbf{V}_i$ are used to form $\mathbf{V}_{\mathrm{all}} = [\mathbf{V}_1 \dots \mathbf{V}_n]$. The projection matrix $\mathbf{V}$ is chosen as the leading singular vectors of $\mathbf{V}_{\mathrm{all}}$. This method has been successfully applied to parameterized FIT systems (1), as shown in the above reference. In order to work on a constant mesh basis, the mesh is freezed while the parameter is varied. Unlike for dielectric material, a problem arises for perfectly electric conducting (PEC) material, as with its variation the zero entries in the material matrices change. Typically, the zeros are removed in order to avoid redundancy. Thus, the system size changes, without the mesh being changed. This can be handled by not allowing for a variation greater than the mesh-cell size. Within this limit, the geometry variation is carried out by the Partially Filled Cells feature of the FIT. An interesting case which needs special treatment arises if the variation is considered larger than the mesh-cell size.



(a) Nominal value (left), variation within a cell (center) and greater than the mesh-cell size (right).



(b) PMOR: the transfer function $\hat{\mathbf{H}}$ approximates $\mathbf{H}$.

Reduced-Order Models for Geometric Parameters

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Besides frequency, passive microwave structures may exhibit a number of design variables, such as material properties or geometric parameters. Many practical applications require the solution response of such structures over a broad frequency band and a wide range of design parameters.

As long as the parameter-dependence of the finite-element (FE) model is affine, as is the case for operating frequency and materials, response surfaces are constructed very efficiently by means of projection-based methods of model-order reduction (MOR): robust single-point (SP) and multi-point (MP) algorithms are readily available. The important class of geometric parameters, however, does not lead to affine parameter-dependence and is hence not accessible to such techniques. To cope with this situation, several methods for replacing the original parameterization by some affine interpolation or approximation have been proposed, e.g. in [1]. This is a field of active research, and present parametric model-order reduction algorithms [2], [3] exhibit various limitations, e.g., with respect to the size of the parameter domain, computational complexity or convergence rates.

This contribution proposes a framework for generating parametric models that are of very low dimension and thus fast to evaluate. It is capable of handling geometric design parameters as well as frequency and materials and features convergence-rates that are superior to competing methods. In addition, important system properties, such as passivity or reciprocity, are preserved. The suggested methodology is based on affine parameter-reconstruction combined with a new type of parameter-dependent projection matrices.

In our talk, we will present the underlying theory and give numerical examples that demonstrate the characteristic features of the suggested approach.

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Seamless Reduced Basis Element Method for Waveguide Simulation

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We present a reduced basis element method (RBEM) for the time-harmonic Maxwell's equation after introducing the reduced basis method (RBM) and some of its interesting applications including a Pacman scattering problem. RBM is indispensable in scenarios where a large number of numerical solutions to a parametrized partial di erential equation are desired in a fast/real-time fashion. Thanks to an o ine-online procedure and the recognition that the parameter-induced solution manifolds can be well approximated by finite-dimensional spaces, RBM can improve e ciency by several orders of magnitudes. This is achieved by approximating and storing the solutions of the PDE for a wisely-selected set of parameters, and then finding the reduced basis approximation for a new parameter as a Galerkin projection onto the low-dimensional space spanned by these pre-computed solutions. Its accuracy is maintained through a rigorous a posteriori error estimate.

The RBEM is RBM with a particular parameter, that is, the geometry of the computational domain, coupled with domain decomposition method. The basic idea is to first decompose the computational domain into a series of sub-domains that are deformed from several reference domains; then to associate with each reference domain pre-computed solutions to the same governing partial differential equation, but with di erent choices of deformations; Finally to seek the approximation on the whole domain as a linear combination of the corresponding pre-computed solutions on each subdomain.

We will introduce a new RBEM that simulate electromagnetic wave propagation in a pipe of varying shape. This has potential application in fine-tuning waveguide design. Unlike the traditional methods with domain decomposition, we do not need a mortar type method to glue the various local functions. This gluing is done automatically thanks to the underlying discontinuous Galerkin method we are using. We present the rationale of the method together with numerical results showing exponential convergence.

The Reduced Basis Method for Saddle Point Problems

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We present reduced basis (RB) approximation and associated a posteriori error estimation for rapid and reliable solution of parametrized partial differential equations (PDEs). We focus in particular on saddle point problems which arise in a wide variety of applications in computational science and engineering. Examples of sources of saddle point problems include mixed finite element methods in fluid and solid mechanics, and optimization with PDEs. This particular work was motivated by and applied to problems in incompressible fluid flow through parametrized domains, but the methodology can be applied to saddle point problems in general.

Although RB methods are well-developed for several classes of PDEs, parametrized saddle point problems pose additional difficulties that have not been fully addressed: Parameter-dependent constraints cause complications not only in the choice of stable RB approximation spaces, but also in the construction of rigorous and computationally efficient a posteriori error bounds. Saddle point systems with parameter-dependent constraints occur, for example, when applying the RB method to incompressible fluid flow in parametrized domains. Earlier work on the RB method for the Stokes and incompressible Navier-Stokes equations has established the method for non-parametrized domains (i.e., for the case of parameter-independent constraints). There have also been some efforts at extending the method to the Navier-Stokes equations in parametrized domains; however, in these earlier examples, either the simple geometric variations considered are applicable only to a very limited set of problems, or rigorous error bounds were not treated, or the proposed error bounds require the evaluation of constants which are very difficult to compute.

In this work, we focus on two important aspects. First, we present a posteriori error estimates that, unlike earlier approaches, provide separate upper bounds for the errors in the approximations for the primal variable and the Lagrange multiplier (e.g., the velocity and pressure variables, respectively, in the case of the Stokes equations). The proposed method is a direct application of Brezzi's theory for saddle point problems to the RB context, and exhibits significant advantages over existing a posteriori error estimators based on either Babuškas theory for noncoercive problems or a penalty approach. Second, in view of approximation stability and computational cost, we shall analyze and compare several options for the RB approximation spaces. Through numerical tests, we illustrate the significant savings (compared to earlier strategies) achievable by enriching the RB approximation space for the primal variable appropriately. Finally, both a posteriori error bounds and enrichment strategies are employed in an adaptive sampling procedure for constructing RB approximation spaces that are not only stable but also efficient.

We present numerical results for a problem of steady Stokes flow through a two-dimensional channel with a parametrized rectangular obstacle. The results demonstrate the significant effects of the enrichment of the velocity space on approximation stability, the rapid convergence of (stable) reduced basis approximations, and the performance of the proposed error bounds with respect to sharpness and computational cost.

Reliable Fast Frequency Sweep of Microwave Circuits via the Reduced-Basis Method

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Finite Element Methods (FEM) have proven to be robust in solving the time-harmonic Maxwell's equations for the analysis of microwave devices. Nowadays, microwave engineering relies on full-wave analysis not only to accurately predict the electrical behaviour prior to construction of microwave circuits, but also to actually design their electrical response. In this last framework, reduced-order models may be of help, since many modifications will be carried out on a given circuit either by experienced engineers or global optimization techniques, until some target electrical response is achieved. Indeed, model order reduction techniques will be as valuable as FEM analysis if the reduced-order model is a reliable surrogate of the original problem. Otherwise, we may not trust on these techniques for design automation, although they are computationally more efficient, and may still rely on rather time-consuming, but accurate, FEM analyses. This would set aside reduced-order models for academic purposes but never for industrial use.

In this work, we focus on a rapid and reliable frequency-parameter sweep in microwave circuits based on the reduced-basis method. We pay special attention to come up with a formulation dropping singularities in frequency out of the Maxwell operator. The proposed model order reduction is based upon the following observation: should the field solution of the original system be considered as a function of frequency, the field solution itself does not arbitrarily vary as frequency changes, but it varies smoothly with frequency, i.e., the field solution resides on a very low dimensional subspace induced by the frequency variation. This observation is a direct consequence of the fact that the Maxwell operator as well as the forcing term are smooth functions of frequency. The reduced-basis method focuses on approximating the evolution of the electromagnetic field as a function of frequency, rather than approximating the electromagnetic field itself as the FEM does. We propose a model order reduction approach where field solutions at different frequencies are used as new basis functions to capture the dynamics of the electromagnetic field as frequency changes. Galerkin projection is applied to reduce the original FEM system into a small system detailing the frequency behavior of the original problem. Thus, the frequency response of the structure under analysis can be obtained with ease. Nevertheless, we still need to solve the large original problem at specific frequencies to get the reduced basis functions. In this work, we pay special attention to adaptively select those field solution frequency samples that give rise to a robust reduced basis approximation space. In addition, the accuracy of the reduced-order model is certified by means of the residual error of the reduced field solution throughout the whole frequency band of interest. As a result, a fully automatic and completely reliable model order reduction process is achieved.

Several microwave devices, such as dieletric resonator filters, dual-mode filters and ultrawideband monopole antennas, will illustrate the capabilities of this approach.

Reduced order modeling of high magnetic field magnets

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The Laboratoire National des Champs Magnétiques Intenses (LNCMI) is a French large scale facility enabling researchers to perform experiments in the highest possible magnetic field (up to 35 T static field). High magnetic fields are obtained by using water cooled resistive magnets (cf. fig. 1) connected with a 24 MW power supply (C. Trophime et al., Magnet calculations at the GHMFL, IEEE Trans. Applied Superconductivity 12, 1, 1483-1487, 2002).

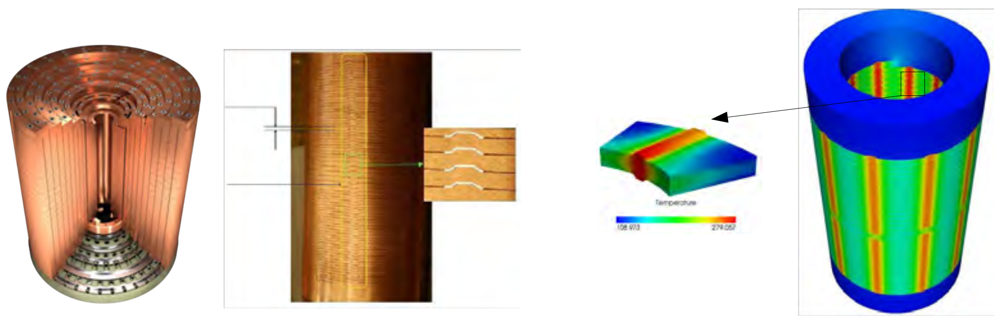

Figure 1: A high field magnet: (left) exploded view; (center) detailled view of the inner part; (right) temperature of the inner part with a zoom on a “turn”.

The design and optimization of these magnets requires from an engineering point of view the prediction of certain “quantities of interest,” or performance metrics, which we shall denote *outputs* — namely magnetic field in the center, maximum stresses, maximum and average temperatures. These outputs are expressed as functionals of field variables associated with a set of coupled parametrized partial differential equations which describe the physical behavior of our magnets. The parameters, which we shall denote *inputs*, represent characterization variables — such as physical properties heat transfer coefficients, water temperature and flowrate, and geometric variables in optimisation studies. To evaluate these implicit *input–output* relationships, solutions of a multi-physics model involving electro-thermal, magnetostatics, electro-thermal-mechanical and thermo-hydraulics are requested. It should be noted that this model is non-linear as the material properties depend on temperature. In practice these evaluations represents a huge of computational time but are mandatory to improve the magnet design as we cannot rely on common physical sense.

To significantly reduce this computational time, we chose to use model order reduction strategies, and specifically to use the reduced basis method which is well adapted to the evaluation of input/output relationships (C. Prud’homme, D. V. Rovas, K. Veroy, L. Machiels, Y. Maday, A. T. Patera, G. Turinici, Reliable real-time solution of parametrized partial differential equations: Reduced-basis output bound methods, Journal of Fluids Engineering, 124 , 2002). We will present the reduced basis method applied to the non-linear electro-thermal coupled problem. To perform this work we rely on reduced basis framework set up by the feel++ library (http://www.feelpp.org/).

	Monday, June 4, 2012 Music Room
13:50	**Session 6: Advances in Vector Bases for CEM (R. Graglia, A. Peterson, D. Wilton)** **6.1.** On the Construction of Well-conditioned Hierarchical Bases for Tetrahedral H(curl)-Conforming Nedelec Element *Wei Cai* and Jianguo Xin*
14:10	**6.2.** High Order Finite Elements for Computational Physics: An LLNL Perspective *Robert N. Rieben**
14:30	**6.3.** FEM-MoM-Diakoptic Analysis of Scatterers with Anisotropic Inhomogeneities Using Hierarchical Vector Bases on Large Curved Elements *Ana B. Manić*, Dragan I. Olćan, Milan M. Ilić, and Branislav M. Notaroš*
14:50	**6.4.** Rapid, High-Order Finite Element Modelling with FEniCS and SUCEM:FEM *A.J. Otto*, E. Lezar, N. Marais, R.G. Marchand, and D.B. Davidson*
15:10	Coffee break (Pinion room)
15:40	**6.5.** Issues Arising in Connection with Singular Vector Bases *Roberto D. Graglia and Andrew F. Peterson**
16:00	**6.6.** An Orthogonal Prism Vector Bases Based Quadratic Eigenvalue Solver of Linear Complexity for 3-D Electromagnetic Analysis *Jongwon Lee, Duo Chen, and Dan Jiao*
16:20	**6.7.** Preliminary Research on the Discontinuous Enrichment Method Based Domain Decomposition Scheme for Solving the Three-Dimensional Vector Curl-Curl Equation *Ming-Feng Xue* and Jian-Ming Jin*
16:40	**6.8.** An Iterative Domain Decomposition Method for Solving Wave Propagation Problems *Gergely Koczka, Kurt Preis*, Thomas Bauernfeind, and Oszkár Bíró*
17:00	**6.9.** Evaluating Singular and Near-Singular Integrals on Curvilinear Elements *Donald R. Wilton**

On the Construction of Well-conditioned Hierarchical Bases for Tetrahedral H(curl)-Conforming Nedelec Element

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wcai@uncc.edu & jxin@uncc.edu

A partially orthonormal high order basis is constructed with better conditioning properties for tetrahedral H(curl)-conforming Nedelec elements. The shape functions are classified into several categories with respect to their topological entities on the reference 3-simplex. The basis functions in each category are constructed to achieve maximum orthogonality. The new basis the composite matrix $\mu M+S$ has better conditioning than existing basis.

High Order Finite Elements for Computational Physics: An LLNL Perspective

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Multi-physics simulation codes are designed to solve systems of partial differential equations (PDEs) for modeling phenomena such as electromagnetic wave propagation, shock-hydrodynamics, elastic-plastic flow and magneto-hydrodynamics (MHD). In this talk we will review some recent work at LLNL focused on the development, software implementation and application of high order finite element methods for computational physics. The common theme across each multi-physics application area is the use of high order finite element basis functions in a common and general finite element discretization approach.

This effort started in the context of the linear hyperbolic Maxwell equations, where it is known that high order methods are capable of yielding far more accurate numerical solutions when compared to corresponding grid refined 2nd order methods, and often at a significant reduction in total computational cost. We will begin with a review of the development of high order H(Curl) and H(Div) finite element basis functions on curvilinear elements combined with high order, energy conserving symplectic time integration algorithms in the massively parallel CEM code, EMSolve. We will review their use in simulating electrically large 3D wave guiding structures and highlight some benefits of this approach. This work is based on the C++ software library FEMSTER that describes an object-oriented implementation of high order, curvilinear finite elements at the element level.

Modifications were made to the EMSolve code to support the modeling of transient magnetic diffusion processes under the so-called MHD approximation of Maxwell’s equations. We will review the use of high order vector finite elements for solving transient magnetic diffusion problems and their verification on benchmark / analytic problems. This work was ultimately incorporated into existing, massively parallel, multi-material arbitrary Lagrangian-Eulerian (ALE) hydrodynamics codes for the purposes of modeling coupled electro-thermal-mechanical (or MHD) applications. We will discuss the use of divergence preserving finite element methods in the context of magnetic advection and diffusion in an ALE setting and demonstrate their use in large-scale 3D MHD simulations.

Finally, we consider the use of high order finite element methods for multi-material Lagrangian hydrodynamics. The numerical approximation of the Euler equations of gas dynamics in a moving Lagrangian frame is at the heart of many multi-physics simulation algorithms. Recently, we have developed a general framework for high-order Lagrangian discretizations of these compressible shock hydrodynamics equations using high order, curvilinear finite elements. This work is based on our current state of the art, open source, parallel C++ library for finite element methods research and development, called MFEM (mfem.googlecode.com). We conclude the talk by presenting an overview of this approach and its implementation in the BLAST Lagrangian hydro research code (www.llnl.gov/casc/blast) and we demonstrate the advantages that high order curvilinear finite element methods can provide in the context of (moving mesh) Lagrangian hydrodynamics.

FEM-MoM-Diakoptic Analysis of Scatterers with Anisotropic Inhomogeneities Using Hierarchical Vector Bases on Large Curved Elements

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The finite element method (FEM) is, by its inherent features, especially suitable for modeling and analysis of structures that contain inhomogeneous, complex electromagnetic materials and geometrical irregularities. The FEM is well established as a method of choice for such applications, with the analysis of open-region scattering structures being performed truncating the FEM domain by a hybridization with the method of moments (MoM) or by some sort of a boundary condition. One possible general strategy aimed at extending the practical applicability of both FEM and MoM methods over their inherent numerical limits and considerably enhancing their efficiency in real-world simulations is the diakoptic approach (Olcan, Ilic, Notaros, Kolundzija, and Djordjevic, “Diakoptic Higher-Order FEM-MoM Approach,” 2010 IEEE Antennas and Propagation Society International Symposium Digest), according to which, the solution of a large and complex electromagnetic system is found as a linear combination of solutions of diakoptic subsystems, using explicit linear relations between coefficients in expansions of equivalent electric and magnetic surface currents on boundary surfaces of subsystems.

This paper presents a new FEM-MoM-diakoptic technique for scattering analysis in the frequency domain that is specifically designed and developed for higher order modeling of material complexities and a full exploitation of computational efficiency of large curved finite elements with *p*-refined high-order field approximations in applications involving arbitrary material anisotropy and inhomogeneity. The technique implements Lagrange-type generalized curved parametric hexahedral finite elements of arbitrary geometrical-mapping orders, filled with anisotropic inhomogeneous materials with continuous spatial variations of complex relative permittivity and permeability tensors described by Lagrange interpolation polynomials of arbitrary material-representation orders. Curl-conforming hierarchical polynomial vector basis functions of arbitrary field-expansion orders are used for the approximation of the electric field vector within the finite elements, while fully compatible divergence-conforming higher order vector bases on generalized curved parametric quadrilaterals are implemented for both MoM and diakoptic surfaces. Being solely based on manipulations with expansion coefficients, the diakoptic approach enables great flexibility in selective *p*- and *hp*-refinements of different parts of a complex structure combined with entire-domain modeling of anisotropic inhomogeneous electromagnetic materials – for the best overall performance of the FEM-MoM-diakoptic solver.

The FEM-MoM-diakoptics is validated, evaluated, and discussed in a variety of examples of scatterers, which demonstrate theoretical features and computational advancements of the diakoptics as a general modeling methodology and in conjunction with particular higher order vector basis functions and curved elements used for diakoptic subsystems. The examples show benefits of using truly higher order geometrical and current/field modeling of both electromagnetic subsystems and diakoptic surfaces, when compared to low-order basis functions and elements. They also show the efficiency of combining the higher order bases with the entire-domain FEM modeling of anisotropic inhomogeneous domains with continuous spatial variations of material parameters (permittivity and permeability tensors). The results demonstrate that the more complex the original system (problem), in terms of material inhomogeneity and anisotropy and geometrical irregularity of diakoptic subsystems, the more advantageous the diakoptic analysis over the standard approaches implementing the same type of higher order numerical discretization.

Rapid, High-Order Finite Element Modelling with FEniCS and SUCEM:FEM

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The FEniCS Project (www.fenicsproject.org) is a collection of open source tools focused on the automated solution of differential equations using the finite element method (FEM). The main user interface is DOLFIN, which is both a library and a problem solving environment that provides a simple and consistent means to interact with the other FEniCS components.

One of the main strengths of FEniCS is that it provides a set of high-level tools with which to describe a finite element problem and ultimately solve the resulting equations. This paper considers the use of FEniCS in the modelling of a number of computational electromagnetic (CEM) examples. This is aided greatly by the included support for higher order basis functions from Nédélec and Lagrange function spaces – both important in the FEM as applied to CEM – that allow for the rapid implementation and testing of a wide range of formulation aspects. This means that more time can be spent doing new research as opposed to concerning oneself over implementation issues.

Although FEniCS provides much the functionality required to solve basic CEM problems such as waveguide cutoff and dispersion analysis (discussed in A. Logg, K.-A. Mardal, G.N. Wells et al. "Automated Solution of Differential Equations by the Finite Element Method," Volume 84 of Lecture Notes in Computational Science and Engineering, Springer, 2011.), as well as resonant cavity problems, there are a number of shortcomings that impede its use for more advanced problems. These limitations are also discussed and addressed as part of a new software package called SUCEM:FEM (available at http://github.com/cemagg/sucem-fem) which is built on FEniCS and also available under an open source license. This new solution framework allows for a much wider class of CEM problems – including radiation and scattering problems – to be addressed.

Issues Arising in Connection with Singular Vector Bases

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It is well known that in the vicinity of conducting or penetrable edges and corners certain field components and the surface charge and current densities can be singular. Although this behavior is localized at the edge or corner, it raises the cost of computation since one needs to use more expensive, very dense meshes in the neighborhood of the singular region. The literature shows that *iterative mesh-refinement* is widely used in the FEM context to treat singularities, which is feasible since matrices are sparse and a relatively small number of matrix coefficients must be recomputed for the refined mesh. However, iterative mesh refinement involves complex procedures and codes, uses additional unknowns and it usually results in an increase of the computational time and/or memory requirements; most of all, any iterative mesh refinement technique requires the full control of the pre-processor code(s) used to discretize the computational domain. The best alternative for the accurate treatment of fields near edges is the introduction of singular basis functions of the additive kind. These are obtained by incrementing the regular polynomial vector bases with additional degrees of freedom to model the singular behavior of fields and currents. Interest in incorporating edge conditions in FEM and MoM applications dates back several decades and a non-exhaustive list of references is available in (Graglia & Lombardi, *IEEE Trans. Antennas Propagat.*, vol. 52, pp. 1672-1685, July 2004 and Graglia & Lombardi, *IEEE Trans. Antennas Propagat.*, vol. 56, pp. 3768–3788, Dec. 2008). This presentation will review the development of singular basis functions for applications ranging from simple scalar problems to general vector problems. Some of the issues that arise include the following:

- The number of degrees of freedom associated with additive basis sets formed by regular and singular basis functions.
- Error reduction due to the use of singular basis functions.
- Weight functions associated with singular basis function subsets and implications for the commonly used Galerkin testing technique.
- Numerical integration techniques used to compute the matrix coefficients arising from singular basis functions.
- Metric to judge the relative linear independence of basis sets formed by regular and singular basis functions.
- Deterioration of the matrix condition number due to the singular basis function subsets.
- Continuity of the curl or divergence-conforming singular vector functions across adjacent cells.
- Treatment of corners and tips, since canonical solutions in those cases are as not well known as the wedge.

An Orthogonal Prism Vector Bases Based Quadratic Eigenvalue Solver of Linear Complexity for 3-D Electromagnetic Analysis

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It is of critical importance to efficiently and accurately predict global resonances of a 3-D electromagnetic structure such as an integrated circuit system that involves arbitrarily shaped lossy conductors and inhomogeneous materials. A quadratic eigenvalue solver of linear complexity and electromagnetic accuracy is developed in this work to fulfill this task. Without sacrificing accuracy, the proposed eigenvalue solver has shown a clear advantage over state-of-the-art eigenvalue solvers in fast CPU time. It successfully solves a quadratic eigenvalue problem of over 2.5 million unknowns associated with a large-scale 3-D on-chip circuit embedded in inhomogeneous materials in 40 minutes on a single 3 GHz 8222SE AMD Opteron processor.

In the proposed solver, a quadratic eigenvalue problem is first formulated for analyzing 3-D integrated circuit structures that involve arbitrarily shaped lossy conductors and nonuniform materials. The quadratic eigenvalue problem is then converted to a generalized eigenvalue problem to facilitate efficient computation. The computational bottleneck of the generalized eigenvalue problem is analyzed and found to be the solution of a large-scale 3-D sparse matrix. A set of orthogonal prism vector bases are then developed to achieve a linear-complexity solution of the large-scale sparse matrix, holding the complexity of the entire eigenvalue solution to linear. Furthermore, the spurious eigenvalues associated with the orthogonal vector basis based discretization of the generalized eigenvalue problem are identified. The origin of the spurious eigenvalues is analyzed, and the approach to removing the spurious eigenvalues is given. In addition, the accuracy of a quadratic eigenvalue solution is investigated. The backward error is introduced to quantitatively measure the accuracy of the proposed eigenvalue solution. An optimal scaling technique is used to transform the original quadratic eigenvalue problem to a scaled quadratic eigenvalue problem, improving the accuracy of the quadratic eigenvalue solution by a few orders of magnitude.

Preliminary Research on the Discontinuous Enrichment Method Based Domain Decomposition Scheme for Solving the Three-Dimensional Vector Curl-Curl Equation

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A variety of physical phenomena such as acoustic and electromagnetic time-harmonic wave propagation can be described as boundary-value problems governed by the Helmholtz equation. It is well known that when the Helmholtz operator is discretized by the standard Galerkin finite element method (FEM), the accuracy of the numerical solution deteriorates rapidly with an increasing wavenumber, and the discretized Helmholtz operator becomes indefinite (D. Wang et al, “Overview of the discontinuous enrichment method, the ultra-weak variational formulation, and the partition of unity method for acoustic scattering in the medium frequency regime and performance comparisons,” *Int. J. Numer. Meth. Engng.*, 2011, in press). Normally, a higher resolution has to be used to retain a certain level of accuracy at the price of a dramatic increase in the cost of the standard finite element analysis. During the past decades, several FEMs with plane wave basis functions have been proposed to alleviate the negative effect of the numerical dispersion to achieve an efficient finite element discretization of the Helmholtz equation. These include the partition of unity method (PUM), the ultra-weak variational formulation (UWVF), and the discontinuous enrichment method (DEM) (C. Farhat, I. Harari, and L. P. Franca, “The discontinuous enrichment method,” *Comput. Methods Appl. Mech. Engrg.*, vol. 190, pp. 6455-4796, 2001). Compared to the other two methods, DEM exhibited higher accuracy and better computational efficiency.

Specifically, the enrichment field of DEM is not continuous across the element interfaces. It is the Lagrange multipliers defined on element boundaries that weakly enforce the continuity. Due to the discontinuity, the enrichment can be eliminated at the element level by static condensation, which simplifies the method and improves matrix conditioning. Furthermore, if combined with a domain decomposition method (DDM), the above condensed algebraic system, which is related to element-level Lagrange multipliers, can be formulated in terms of the subdomain interface Lagrange multipliers only. Similar to the finite element tearing and interconnecting (FETI) method, this system of global subdomain interface Lagrange multipliers can be solved iteratively by a Krylov subspace method (C. Farhat, R. Tezaur, and J. Toivanen, “A domain decomposition method for discontinuous Galerkin discretizations of Helmholtz problems with plane waves and Lagrange multipliers,” *Int. J. Numer. Meth. Engng.*, vol. 78, pp. 1513-1531, 2009). Therefore, DEM is very suitable for solving large-scale problems on parallel computing facilities.

One important research topic related to DEM is the construction of plane wave basis functions. During the past few years, several papers have been published on the choice of basis functions to expand the enrichment field. They could be associated with either quadrilateral/triangular elements for two-dimensional modeling, or hexahedral/tetrahedral elements for three-dimensional cases. However, all previous work is limited to solving the scalar two- or three-dimensional Helmholtz equation. This paper is dedicated to the implementation of DEM for solving the three-dimensional vector curl-curl equation, which is the governing equation for electromagnetic simulations. The potential difficulties include the construction of vector plane wave basis functions, which are the nontrivial solution of the vector curl-curl equation. We will focus on basis functions compatible with triangular and tetrahedral elements since they have better modeling capability for arbitrarily shaped geometry. We will demonstrate the efficiency and scalability of the discontinuous enrichment method in solving three-dimensional vector wave propagation and scattering problems.

An Iterative Domain Decomposition Method for Solving Wave Propagation Problems

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Solving wave propagation problems with FEM results in a large number of unknowns due to the huge air volume to be modeled. These equation systems are very ill-conditioned because of the great material differences, element-size changes and since the equation systems are indefinite. Common iterative methods (CG, GMRES) have bad convergence quality due to these conditions.
Applying direct solver methods to overcome the problem of the ill-conditioned system of equations results in high memory requirements. The aim of this paper is to present a method with smaller memory requirement than the direct methods and converging faster than iterative methods.
A possibility of decreasing the memory requirement of the common LU decomposition is using a Domain Decomposition (DD) based Schur-complement method. Assembling the Schur complement matrix requires a long time. However, solving the reduced equation system doesn't need the full Schur complement matrix. Applying the biconjugate gradient method to solve the Schur complement (DD-BiCG) equation system will result in an efficient iterative solver for solving wave propagation problems.
The efficiency of this method is shown on a dipole. The dipole has a length of 140 mm a width of 1 mm and thickness of 20 µm. There is a 160 µm air gap in the middle. An air volume of 250 mm is modeled around the antenna. The air volume is truncated by a first order absorbing boundary condition (ABC). The voltage is prescribed in the air gap (1 V, 1.5 GHz). Modeling an eighth of the problem, using A,v formulation (A is the magnetic vector potential, v is the modified electric scalar potential), and second order hexahedral finite elements (20 nodes, 36 edges) the resulting problem has 1.986.152 edges and 669.398 nodes.
The efficiency of the DD-BiCG method compared with the incomplete Cholesky preconditioned Biconjugate gradient method (IC-BiCG) is shown in Fig. 1. The iteration will be finished when the global relative residual is smaller than 10^{-7}. The DD-BiCG achieves this criterion after 975 iterations and 15.861 seconds using 41.8 GB RAM. The IC-BiCG was not able to converge after 40.000 iterations and 165.000 seconds, its best relative residuum is $1.198 \cdot 10^{-5}$, its memory requirement is 5.25 GB RAM. With the direct method PARDISO implemented in Intel FORTRAN Math Kernel Library required 81.5 GB RAM and hence was not able to finish the calculation on a 64 GB RAM machine.

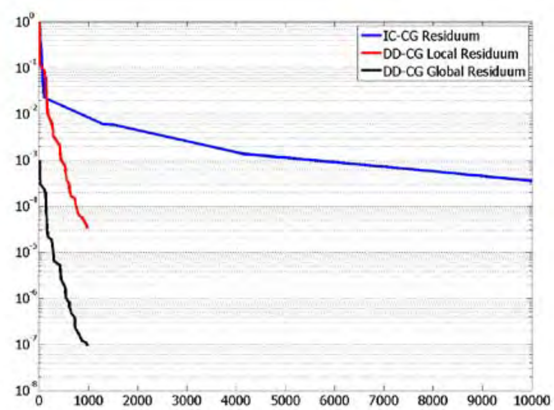

Fig. 1. The best residuum of the methods during the iterations.
Blue line: IC-BiCG; Red line: DD-BiCG residuum on the interface; Black line: DD-BiCG residuum in the whole domain.

Evaluating Singular and Near-Singular Integrals on Curvilinear Elements

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In this presentation we examine in detail the generation of quadrature rules for singular and near-singular integrals associated with integral equations and higher order (curvilinear) elements. Though the approach is geometry-representation independent, we review and illustrate it using the Silvester-Lagrange interpolation representation of curvilinear triangles. For illustrative purposes, interpolatory divergence-conforming bases are also reviewed and assumed (Graglia, R. D., D. R. Wilton, and A. F. Peterson, "Higher Order Interpolatory Vector Bases for Computational Electromagnetics," *IEEE Trans. Antennas and Propagat.*, Vol. 45, Mar. 1997, pp. 329-342).

Given an observation point either on or very near a curvilinear element, one should first construct an appropriate tangent element. The point of tangency (in area coordinates, $\boldsymbol{\xi}_0 = (\xi_{01}, \xi_{02}, \xi_{03})$) is either the observation point on the element, or, for near singularities, the closest point on the surface or its extension. In the latter case, for surfaces convex with respect to the observation point, the closest point is found by solving a coupled pair of non-linear equations via Newton's method. If the surface is concave with respect to the observation point, the solution may not be unique.

Position vector derivatives with respect to the area coordinates determine two tangent vectors, $\boldsymbol{\ell}_1, \boldsymbol{\ell}_2$, that also form two edge vectors of the tangent triangle; the third is merely $\boldsymbol{\ell}_3 = -\boldsymbol{\ell}_1 - \boldsymbol{\ell}_2$. The tangent triangle vertex locations, element Jacobian, and height vectors can then be used to define curvilinear basis functions at the tangent point in terms of like quantities on planar triangles. Also points, tangent vectors, displacement vectors, and Jacobians on the tangent triangle differ from those of the curvilinear triangle only to second order with respect to area coordinates about $\boldsymbol{\xi}_0$. Hence singularity cancellation quadrature schemes developed for handling a given singularity type on the (planar) tangent triangle are valid on the curvilinear triangle—only a few more sample points may be needed to account for the higher order variation due to curvature. Significantly, for divergence-conforming bases, the Jacobians appearing in the bases and differential surface elements cancel, so that all curvature effects are confined to the edge vectors $\boldsymbol{\ell}_i$, $i = 1, 2, 3$, and the displacement term $|\mathbf{r} - \mathbf{r}'|$.

	Tuesday, June 5, 2012
	Billiard Room
8:00	**Session 7: FETD Modeling of Complex Media and Structures (R. Lee, F. Teixeira)**
	7.1. FETD/FDTD with Automatic Hybrid Mesh Generation *Shumin Wang**
8:20	**7.2.** Study of Numerical Dispersion for Quadrilateral and Triangular Elements Used in the Mixed Finite Element Method *Luis E. Tobon and Qing H. Liu**
8:40	**7.3.** Probabilistic Finite-Difference Time-Domain Method Through Stochastic Electromagnetic Macro-Models *Ata Zadehgol*, Andreas C. Cangellaris*
9:20	**7.5.** The Use of Multiple Time Steps in the FDTD Method *Ruben Ortega and Robert Lee**

FETD/FDTD with Automatic Hybrid Mesh Generation

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Over the past decade, there has been growing interest in the FDTD/FETD hybrid method for time-domain electromagnetic simulations. This method models part of the computational domain where extra modeling accuracy is demanded by the FETD method, while applies the FDTD method elsewhere. Typically, the FDTD/FETD hybrid method is suitable for problems with locally fine features, so that the computational expensive FETD method is limited to certain regions, not the entire domain.

To effectively apply the FDTD/FETD hybrid method, one needs to generate a Cartesian/tetrahedral hybrid mesh by embedding the tetrahedral region inside background Cartesian grids. That is to say, the boundary of the tetrahedral region, which is the FDTD/FETD interface, is fixed. Moreover, the tetrahedral region is desired to be conformal to target as much as possible. This not only reduces the number of degrees of freedom (DOF) in the FETD analysis, but also improves the computational efficiency of direct matrix solvers, such as the sparse Cholesky decomposition.

Two methods are common in automatic mesh generation with fixed boundaries, i.e., the constrained Delaunay and the advancing front technique. It was observed that the Delaunay method is faster, but meshes generated by the advancing front technique are often of higher quality and much easier to improve. Since the FETD method is intended to be applied in small and highly confined regions in the hybrid approach, mesh quality is often a more important and critical issue than the speed. The CPU time of mesh generation is typically much less than that of hybrid simulations, while mesh quality in a highly confined region is difficult to achieve. With the above concerns, the advancing front technique is chosen for hybrid mesh generation.

In this presentation, a three-step approach was presented for automatic Cartesian/tetrahedral hybrid mesh generation. With a prescribed triangular surface model, this approach ``grows" a buffer zone from the surface of a target at first and positions it in a background Cartesian mesh. The tightness of the buffer zone can be adjusted to balance the needs of mesh quality and computational costs. Subsequently, a tetrahedral mesh is generated by the advancing front technique with respect to the fixed FDTD/FETD interface. Finally, the quality of the tetrahedral mesh is further improved by a combination of edge splitting/merging, face and edge swapping, smart Laplacian and optimization-based smoothing. As the result, high-quality meshes with good computational efficiency in the subsequent FDTD/FETD hybrid analysis can be generated.

Study of Numerical Dispersion for Quadrilateral and Triangular Elements in the Mixed Finite Element Method

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The finite element discretization of wave equations produces a numerical, or artificial, dispersion of propagating waves. As the Mixed Finite Element Method (MFEM) is based on the discretization of Maxwell's equations, a system of continuous differential operators, it retains an inherent dispersive behavior. The objective of this work is to analyze the numerical dispersion of the mixed FEM for the first-order partial differential equations based on Faraday's and Ampére's laws rather than the more conventional second-order wave equation.

Two different approaches are applied in this work to analyze the numerical dispersion of MFEM. Both approaches assume an harmonic plane wave propagating through an infinite two-dimensional vector finite element mesh. The first approach, known as semi-discrete analysis, is analytical, and it is based on the application of the well-known periodic properties of an harmonic plane wave to a portion of the infinite mesh; thus, it obtains an expression of the numerical wave number as a function of the correct value and direction of the wavenumber. This approach becomes very cumbersome for higher orders basis functions.

A second approach, known as modal analysis, requires the application of periodic boundary condition in a rectangular domain to allow propagation of plane waves. In this case, a plane wave with a particular wavenumber (value and direction) defines an approximate eigenvector for the system, hence Rayleigh quotient is exploited to obtain an approximate numerical wavenumber. This approach is cross-validated with the first approach for low-order basis functions; however, high-order basis functions are also analyzed.

Two different type of elements are analyzed: triangular and quadrilateral. For triangular elements, Mixed-order Curl-Conforming Edge-Based Vector basis functions (CtLn and LtQn) are used (A. F. Peterson, S. L. Ray, and R. Mittra, *Computational methods for electromagnetics*, IEEE press New York, 1998). Quadrilateral elements adopt spectral basis functions based on Gauss-Lobatto-Legendre polynomials, with an arbitrary order of interpolation (J. Lee, T. Xiao, and Q. H. Liu, "A 3-D Spectral-Element Method Using Mixed-Order Curl-Conforming Vector Basis Functions for Electromagnetic Fields", IEEE Transactions On Microwave Theory And Techniques, Vol. 54, No. 1, Jan 2006).

To understand the spurious modes produced by some combinations of basis function, we study the effects of several factors on the numerical dispersion: direction of propagation, order of basis functions, type of element, size of element, and variation in the shape of element. Finally, the consequences of the numerical dispersion on some parameters in frequency and time domains are also analyzed, such as phase and group velocities, phase and group delays, and the presence of spurious solutions (non-monotonic dispersion curves).

PROBABILISTIC FINITE-DIFFERENCE TIME-DOMAIN METHOD THROUGH STOCHASTIC ELECTROMAGNETIC MACRO-MODELS

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To engage in the practical design of electronic components and systems, one must contend with the presence of uncertainty in the design and manufacturing process which leads to material and structural variability in the final production system. To maximize production yields of widely multi-scale structures under conditions of uncertainty in a high volume manufacturing (HVM) environment, the engineer resorts to electrical design automation (EDA) tools in the search for a robust design solution space. In this context, the accuracy and efficiency of the underlying models and methods of EDA are fundamentally critical to the characterization efforts of the component/system and in providing indispensable guidance to the engineer throughout the design process. To enable an efficient stochastic-based design optimization methodology for electrical components and systems, which comprehends random material and geometric variability, we infuse the reduced-order state-space electromagnetic model together with the stochastic collocation method, into one of the methods used extensively for electromagnetic component/system analysis and design, namely, the method of finite-difference time-domain (FDTD). To this end, we develop the *stochastic electromagnetic macro-model* in FDTD by formulating an abstraction layer that encapsulates those regions where, most often, uncertainty is present, namely, the fine-features of the multi-scale structure.

In essence, the electromagnetic macro-model is a reduced-order state-space representation of the discretized Maxwell's equations for the FDTD sub-domain exhibiting uncertainty. From the full-order state-space form, it is possible to obtain an admittance transfer function (ATF) which serves to map the macro-model and the FDTD grid at the union of their common boundary. The input (excitation) to this ATF is the magnetic field at the boundary of the macro-model. The output (response) of the ATF is the electric field at the inner perimeter of the macro-model. To further enhance the computational efficiency of operations pertaining to the system ATF, model order reduction (MOR) techniques may be utilized to reduce the degrees of freedom of the full-order state-space model while maintaining the desired accuracy. Thus, we apply a modified version of the enhanced nodal order reduction (ENOR) technique to the full-order state-space electromagnetic system ATF, and use the resulting stochastic projection matrix to build the passive reduced-order stochastic electromagnetic system. We name this reduced-order stochastic abstraction layer, the stochastic electromagnetic macro-model. At its heart, building the stochastic macro-model relies on highly accurate numerical integration over random space; for this, we utilize the sparse Smoljak grid and the Clenshaw-Curtis quadrature rule in one-dimensional random space, and extend these principles to cubature in multi-dimensional random space.

In the current state of the art EDA, and in absence of the stochastic electromagnetic macro-model, it is necessary to perform repeated discretization of the large deterministic domain for every random variation in the small fine-featured stochastic sub-domains. The development of the stochastic electromagnetic macro-model eliminates the need for repeated discretization of the overall structure, for every such random variation. Indeed, only a **single** FDTD grid needs to be developed for the deterministic portion of the overall structure irrespective of the realization generated by a specific choice of the random parameters in the sub-domains exhibiting statistical variability; thus, the macro-model results in **significant computational savings** by eliminating operations pertaining to repeated discretization of the deterministic domain for each variation in the stochastic sub-domains. To this end, we provide a methodology for the efficient **generation** and **utilization** of the stochastic macro-model for the purpose of time-domain analysis in FDTD, under material/geometric uncertainty conditions.

The Use of Multiple Time Steps in the FDTD Method

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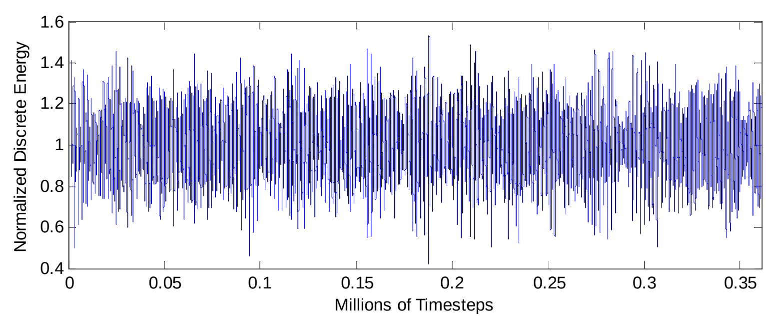
The use of time-domain methods to simulate electromagnetic problems is well rooted in the electromagnetics community due to several reasons, one being the ability to obtain wide band frequency results in a single simulation. The Finite-Difference Time-Domain (FDTD) method in particular is one of the most popular methods utilized for this purpose. However, one of the limiting factors inherent to standard FDTD is the need to conform a grid to a coordinate system, which poses significant problems when attempting to model large objects with fine features or small objects in large domains. One common solution proposed to overcome this difficulty is the use of spatial sub-gridding techniques. This solution itself poses new problems such as instability due to the insertion of coarse/fine grid interface(s). Many of the proposed methods for spatial subgridding, while handling dissimilar grid interfaces effectively, ignore time-discretization all together. This imposes further restrictions since the time-step size allowable in order to maintain numerical stability due to the Courant stability limit is dictated by the most finely gridded region. This dependence on a global time step is sub-optimal for the more coarsely gridded region(s) causing further complications such as numerical dispersion.

The ultimate goal for a subgridding scheme would be for each dissimilarly gridded region to have its own optimal time-step size regardless of the granularity of the remainder of the domain. The method proposed here is the first step in the solution to address this issue which is to have two distinct time-step sizes for a uniformly gridded spatial domain. The method is based on the idea that a regular finite-element time-domain (FETD) hexagonal mesh can be proven equivalent to standard FDTD method through the use of "lumping" of the mass matrices or simply, mass-lumping. The purpose for deriving an FDTD scheme via finite-elements is an effort to maintain proper field continuities and physical field properties. The procedure is then extended to include the time axis and is considered as a separate and discretizable axis similar to the spatial axes and is "time-lumped" accordingly. The lumped FETD elements are then assembled via assembly or joining matrices and FDTD stencils with special updates along the time boundary are derived and introduced into a standard FDTD scheme.

The method described above was applied to a two-dimensional FDTD grid spatially discretized uniformly throughout the domain and divided into two regions. One portion of the grid was time-stepped at one temporal discretization size (coarse-time grid), while the other portion of the grid (fine-time grid) is stepped at a rate double of the coarse-time step size. The domain boundaries were terminated with perfect electric conductor (PEC) material. As a preliminary indicator for stability the domain was excited with a Gaussian pulse which was allowed to propagate for over 300,000 time-steps. At every time step the discrete energy in the electric field throughout the FDTD grid was calculated and recorded. As the figure above shows, for the proper choice of Courant limit, the mean discrete energy did not increase. This suggests that the scheme is conditionally stable and conservative.



	Tuesday, June 5, 2012
	Music Room
8:00	**Session 8 Adaptive FEM, Higher Order Bases, and Advanced FEM Formulations (J. Webb, M. Gavrilovic, M. Salazar Palma, L. G. Castillo)**
	8.1. Hp-adaption for Computing Scattering Parameters on Tetrahedral Meshes *J. P. Webb*
8:20	**8.2.** Efficient RCS Prediction of Jet Engine Air Intakes Using hp-FEM and Reduced Order Modeling *Adam Zdunek* and Waldemar Rachowicz*
8:40	**8.3.** Rules for Adoption of Expansion and Integration Orders in FEM Analysis Using Higher Order Hierarchical Bases on Generalized Hexahedral Elements *Nada J. Šekeljić*, Slobodan V. Savić, Milan M. Ilić, and Branislav M. Notaroš*
9:00	**8.4.** Auxiliary Space Preconditioning for Hierarchical Elements *A. Aghabarati, J. P. Webb*
9:20	**8.5.** Chain Homotopy Operators and Whitney form-based Finite Element Analysis *P. Robert Kotiuga**
9:40	Coffee break (Pinion room)
10:10	**8.6.** Comparative Performance of Nodal-Based Versus Edge-Based Finite Element Formulations *Ruben Otin*, Santiago Badia, and Luis E. Garcia-Castillo*
10:30	**8.8.** A Three-Dimensional Self-Adaptive hp Finite Element Method for the Characterization of Waveguide Discontinuities *Ignacio Gomez-Revuelto, Luis E. Garcia-Castillo, Sergio Llorente-Romano, and David Pardo*

Hp-adaption for computing scattering parameters on tetrahedral meshes

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P-adaption – increasing the polynomial orders of elements automatically based on estimated errors – is in many respects preferable to the alternative of refining the finite element mesh (*h*-adaption). It avoids the complexities of mesh refinement and, when the fields are smooth, provides excellent convergence. By using singular elements, it can even perform well when the field is singular, e.g., at sharp metal edges. However, it is ultimately limited by the maximum available polynomial order. Combined *hp*-adaption offers the possibility of even faster convergence, with no built-in limit. This paper explores the application of *hp*-adaption to the computation of the scattering parameters of microwave devices using hierarchical, tetrahedral finite elements.

In true *hp*-adaption, after every solution the mesh may be refined in some places and the polynomial order increased in other places. This requires that there is some way of tracking the polynomial order everywhere in the mesh through successive mesh refinements. For example, if at some stage the order of an element is 2 and then the mesh in that region is refined, the order 2 has to be carried to some of the new elements created. This presents a problem for many mesh refinement schemes, in which an element created by refinement does not necessarily fit inside the boundaries of an earlier coarse element – what order, then, should be assigned to the new element?

One way around this problem is to use special elements with hanging nodes. These permit a form of *h*-refinement is which each new element “belongs” to a coarser parent, so there is no ambiguity about the order of the refined element. A good example is (L. E. Garcia-Castillo, D. Pardo, L.F. Demkowicz, "Energy-norm-based and goal-oriented automatic *hp* adaptivity for electromagnetics: application to waveguide discontinuities," *IEEE Trans. MTT*, vol.56, no.12, pp.3039-3049, Dec. 2008). An alternative is proposed here. Any set of hierarchical, tetrahedral elements can be used, but a mesh refinement scheme is employed that preserves, to a large extent, the nested character that is needed for *hp*-adaption. The scheme is due to J. Bey ("Tetrahedral grid refinement," *Computing*, vol. 55, pp. 355-378, 1995). The essential refinement operation is the subdivision of a tetrahedron into 8 “sons”. In addition, there are several “irregular” refinements that permit a transition from a coarse region to a more finely subdivided region. The sons produced by irregular refinement are temporary: when one of them needs to be refined, all of them are removed and the parent tetrahedron is refined regularly. In this way, there is no propagation of irregular shapes.

An *hp*-adaptive scheme based on Bey mesh refinement is applied to the computation of scattering parameters in the frequency domain. An error indicator previously used for *p*-adaption, which targets the error in the scattering parameters, is used to guide the adaption (D. Nair, J. P. Webb, "*P*-adaptive computation of the scattering parameters of 3-D microwave devices," *IEEE Trans. Magnetics*, vol. 40, pp. 1428-1431, Mar 2004).

Efficient RCS prediction of jet engine air intakes using *hp*-FEM and reduced order modelling

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Jet engine inlets are often electrically huge semi-open channels. Measurements have revealed that these channels are one of the major contributors to the overall RCS signature of an airplane. Reliable and accurate Radar Cross-Section (RCS) prediction of air intakes remain one of the most challenging problems in computational electromagnetics, (CEM). For low RCS they are often curved and partially coated with radar absorbing materials (RAM) to hide jet engine fan disks at the far end, see Figure 1.

Highly efficient parallelised computational techniques have to be used. Multi-level domain-decomposition (DD) techniques provide an efficient way to divide and conquer the resulting huge computational problem. Different models may be used and mixed along the channel to obtain the requested efficiency, accuracy and reliability of the RCS prediction. We use the so-called *hp*-version of the Finite Element Method (FEM) for modelling sections with material inhomogeneities and for modelling the scattering on the terminating section consisting of disks with irregular jet engine fan blades. We discuss cavity RCS predictions based on a reduced order uncoupled interior problem analysis and the Kirchhoff aperture integration procedure. The efficiency gain and modelling error introduced using this simplified approach is discussed. The DD-technique in terms of Neumann-to-Dirichlet (NtD) operators is outlined. The sub-domain wise contributions are assembled projecting the contributions of coupling neighbours onto an auxiliary complete basis at the common interface. A choice we investigate for a homogeneous channel cross-section is the (TE-,TM-) waveguide modal basis. The use of truncated projections is investigated.

The efficiency of the method is illustrated. The reduced order *hp*-FE sub-domain based scattering matrix methodology is proven suitable for calculating the Radar Cross-Section (RCS) for electrically huge jet engine air intakes. The efficiency gain in degrees of freedom obtained by using *hp*-version FEM instead of classical low order *h*-version FEM is shown to be roughly one order of magnitude. The model reduction achieved by changing from inter-facial FE-d.o.f:s to guided wave participation factors implies another gain in degrees of freedom which becomes very substantial for air intakes with electrically large homogeneous sections. It is shown that the modal reduction can be made without significant loss of accuracy in the cavity-RCS.

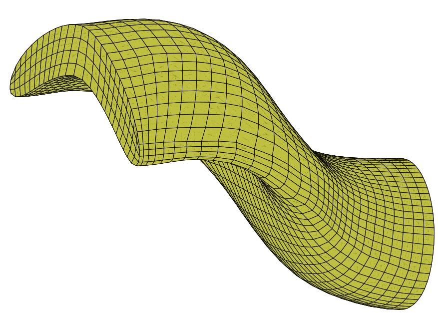

Figure 1: Low RCS S-shaped jet engine air intake.

Rules for Adoption of Expansion and Integration Orders in FEM Analysis Using Higher Order Hierarchical Bases on Generalized Hexahedral Elements

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There has lately been a noticeable interest within the computational electromagnetics (CEM) community for higher order techniques, which rely on basis functions of high orders set on electrically large (whenever possible) elements (B. M. Notaroš, "Higher Order Frequency-Domain Computational Electromagnetics," IEEE Trans. Antennas Propagat., Vol. 56, August 2008). Additionally, higher order techniques allow for efficient utilization of irregular, elongated, and curved elements, defined using Lagrange interpolating polynomials, Bézier curves, or NURBS curves, which can be tremendously beneficial in creating effective meshes and in yielding the final systems of equations with significantly fewer number of unknowns. Most importantly, higher order bases and elements enable efficient *p*- and *hp*-refinements, as well as adaptive CEM schemes.

However, the great modeling flexibility of higher order elements, basis and testing functions, and integration procedures, which is the principal advantage of the higher order CEM, is also its greatest shortcoming. Namely, it poses numerous dilemmas, uncertainties, options, and decisions to be made on how to actually use these elements and functions. In other words, with the additional degrees of freedom in modeling, a user has to handle many more parameters in building a CEM model, which requires a great deal of modeling experience and expertise, and possibly considerably increases the overall simulation (modeling plus computation) time. Examples of questions that need to be addressed are how large the elements can be, what polynomial orders of bases should be used in particular cases, and how accurate the integration has to be depending on the adopted polynomial orders in different directions.

Within efforts to answer these questions, we have recently established and validated general guidelines and instructions, and as precise as possible quantitative rules, for adoptions of optimal higher order parameters for electromagnetic modeling using the method of moments (MoM) in single precision computations. For instance, we have concluded that (in cases with well-behaved fields) the Lagrange-type (curved or flat) quadrilaterals as large as up to two wavelengths on a side, with polynomial orders of the equivalent surface current approximation of $N = 6$ in each direction and the number of points in Gauss-Legendre quadrature integrations of about $N + 2$, are generally optimal.

In our continued study of higher order parameters in CEM, this paper addresses the same problem and defines similar rules for the finite element method (FEM) using *p*- and *hp*-refined higher order hierarchical generalized hexahedral elements and models in double precision computations. To define these rules and draw some general conclusions, we carefully and systematically study a diverse and comprehensive set of higher order FEM simulations of three-dimensional (3-D) cavities, 2-D waveguides, and 3-D scatterers (with the FEM domain closed using the first order absorbing boundary condition or a fixed high-order boundary integral), applying exhaustive sweeps in frequency, polynomial orders of the field approximation, and numbers of points in the Gauss-Legendre integration (integration accuracy). Preliminary results show that, while it can generally be adopted that curved Lagrange-type hexahedral finite elements can be as large as two wavelengths on a side (analogously to the MoM analysis), somewhat larger numbers of integration points can be used in each direction than those reported in the MoM study. However, higher integration accuracy results in possibly substantially longer matrix filling times; hence, in this work, we also discuss a compromise between the two requirements.

Auxiliary Space Preconditioning for Hierarchical Elements

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When high order, hierarchical, tetrahedral finite elements are used to solve large, time-harmonic, electromagnetic wave problems, an efficient way to solve the resulting matrix equation is to use a Krylov iterative method with a multilevel preconditioner, e.g., P. Ingelstrom, V. Hill, R. Dyczij-Edlinger, "Comparison of hierarchical basis functions for efficient multilevel solvers," *IET Science Measurement & Technology*, vol. 1, pp. 48-52, Jan 2007. The preconditioner uses a few steps of Gauss-Seidel relaxation at the second order and higher levels, but requires, at each iteration, the direct solution of a matrix problem corresponding to the lowest order level, i.e., Whitney elements with one degree of freedom per edge of the mesh. For large problems with fine geometric detail, the number of elements may be large enough that direct solution on this level requires too much memory or takes too long. An iterative alternative is desirable. One possibility that has been widely explored is domain decomposition. We consider an alternative method that does not require domain decomposition.

The simplest approach is to replace the direct solution by a single step of Gauss-Seidel relaxation. Actually, to take into account the kernel of the curl operator it is necessary to use what is known as a hybrid smoother, in which a second relaxation is applied in a space corresponding to nodal scalar basis functions. This approach, P1, does work, but the number of iterations is considerably greater than with direct solution.

An alternative (P2) is to apply an auxiliary space preconditioner (R. Hiptmair, J. C. Xu, "Auxiliary space preconditioning for edge elements," *IEEE Transactions on Magnetics*, vol. 44, pp. 938-941, Jun 2008). To date, this has been applied only to quasti-static problems and has not been used with higher order elements. It requires the solution of two auxiliary nodal problems: the first one corresponding to nodal scalar functions, as in P1, and the second corresponding to nodal vector functions. The nodal problems are solved by an algebraic multigrid method. We employ a W-cycle, solving each nodal problem three times per Krylov iteration.

The table below shows the results for a sample problem, an E-plane, corrugated, waveguide filter, with an unstructured mesh of 226,160 tetrahedra. The waveguide cross section is 19.0mm x 9.5mm and the filter length is 91.5mm, which is about 3 wavelengths at the analysis frequency (10 GHz). To solve each nodal problem, three levels of algebraic multigrid are used, followed by a direct solve at the coarsest level (matrix dimension 5,665). The new preconditioner (P2) substantially reduces the number of iterations. Notice that at order 3 the reduction in the number of iterations has more impact because of the extra cost associated with the second and third level parts of the overall preconditioner and this is reflected in the greater speed-up.

Element order	Matrix dimension	Preconditioner	Krylov iterations	CPU time (seconds)	Speed-up
1	352,971	P1	370	106	
1	352,971	P2	54	47	2.3
3	4,415,571	P1	349	2,790	
3	4,415,571	P2	60	531	5.2

Chain Homotopy Operators and Whitney form-based Finite Element Analysis

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This presentation will continue an exploration of limitations and possibilities for discrete differential forms, and in particular, the Whiteny forms which generalize edge and face elements which made their way into the finite element analysis of electromagnetic fields in the 1980s. Starting in the 1950s, Andre Weil, H. Whitney, H. Federer, D. Sullivan, J. Dodzuik, J. Dupont, W. Muller, R. Hiptmair, S. Wilson, E. Getzler and P. Mnev, contributed to the development and application of Whitney forms to various problems in topology and computational electromagnetics and more recently to computational fluid dynamics (the most recent work can be found by searching on http://arXiv.org).

This presentation will build on the author's presentation of the de Rham and Whitney maps (COMPUMAG 2007; IEEE Trans Mag, 2008) in order to characterize the kernel of the Whitney map and explore the implications for computational electromagnetics. Specifically, the contributions of the above authors are considered in order to:

1) Standardize notation between application areas in order to facilitate an exchange of results.
2) Develop a framework for comparing error analyses in various fields. For example, the Sobolev space framework in finite element analysis, the norms of geometric measure theory (GMT) and the IR-UV decompositions of quantum field theory will be contrasted.
3) Develop frameworks for both h-p refinement in the finite element analysis of electromagnetic fields and measures of simplicity of "cuts" for magnetic scalar potentials.

In all these aspects, the Dupont chain homotopy operator plays a central role. How this operator characterizes the kernel of the de Rham map and how it is underappreciated in the computational electromagnetics community will be stressed.

Comparative performance of nodal-based versus edge-based finite element formulations

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The aim of this work is to compare the computational performance of nodal-based finite element formulations versus edge-based finite element formulations. Edge-based formulations are widely adopted in the EM community and known to be stable (M. Salazar-Palma et al., "Iterative and Self-Adaptive Finite-Elements in Electromagnetic Modeling". Artech House Publishers, 1998. J. M. Jin, "The Finite Element Method in Electromagnetics", John Wiley & Sons, 2002). However, straightforward nodal-based finite element formulations suffer from stability problems. Recently, two nodal based formulations overcoming the mentioned stability problems have been proposed by the authors. Details of the two formulations are given below. The comparison is established between each one of the nodal-based formulations and their edge-based counterparts.

The first nodal approximation is the simplification of the weighted regularized Maxwell equation method explained in (R. Otin. "Regularized Maxwell equations and nodal finite elements for electromagnetic field computations." Electromagnetics, vol. 30, pp. 190-204, 2010). This formulation presents several advantages: It provides spurious-free solutions and well-conditioned matrices without the need of Lagrange multipliers, its integral representation is well-suited for hybridization with integral numerical techniques and the nodal solution of the electromagnetic domain is usually easier to couple in multi-physics problems. On the other hand, this regularized formulation presents a serious drawback: if the electromagnetic field has a singularity in the problem domain, a globally wrong solution is obtained. Fortunately, this disadvantage can be corrected, but, in doing this, the well-conditioning of the matrix can be put in jeopardy. Then, the question we try to solve in this work is if the computational advantages of the proposed nodal formulation compensate its drawbacks when compared with the well-establish edge double-curl finite element formulation.

The second nodal formulation we are going to test is based on the algorithm explained in (S. Badia and R. Codina, "A nodal-based finite element approximation of the Maxwell problem suitable for singular solutions," *submitted*) for the Maxwell operator. This formulation will be adapted to the frequency domain and compared with mixed edge element formulations. The main differences between this new nodal formulation and the one based on weighted regularization is the fact that a Lagrange multiplier is needed in order to enforce the divergence-free constraint at the discrete level but there is no need to define the weighting functions. This last point is important, since it does not require to determine *a priori* were the singularities are, making the method easier to apply and implement. On the other hand, it does not exhibit the problem of integrating numerically the weighted terms and no additional (regularized) boundary conditions are needed. Finally, this method has been easily extended to coefficient jumps in (S. Badia and R. Codina, "A combined nodal continuous-discontinuous finite element formulation for the Maxwell problem," Applied Mathematics and Computation, vol. 218, pp. 4276-4294, 2011) using dG-type terms on the material interfaces.

A Three-Dimensional Self-Adaptive *hp* Finite Element Method for the Characterization of Waveguide Discontinuities

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The Finite Element Method (FEM) enables the use of "adapted" meshes, not only to the geometry of the problem domain, but to the solution of the problem itself. One of the most powerful methods to generate these "adapted" meshes is through *hp*-adaptivity (i.e., by simultaneously varying the size h and the polynomial order p of the finite elements of the mesh). *hp*-adaptivity provides exponential rates of solution convergence, even in the presence of singularities, in contrast to h and p schemes, in which algebraic rates of solution convergence are, in general, obtained. Thus, very accurate solutions can be obtained with an hp-adaptive strategy, even in the presence of singularities. Equivalently, approximate solutions within engineering accuracy can be obtained using a minimum number of unknowns.

In the last years, the authors have developed two dimensional (2D) automatic hp-adaptive FE methods for electrodynamic (i.e., full wave) problems. The problems solved include closed domain and open region problems; specifically, waveguiding problems (L. E. Garcia-Castillo et al., IEEE Trans. MTT, 12, 3039-3049, 2008), radiation and RCS computation problems (I. Gomez-Revuelto at al., IEEE Trans. MAG, 43(4), 1337-1340, 2007), and geophysics applications (D. Pardo et al., Comp. Meth. App. Mech. Eng., 197, 3836-3849, 2008).

In this paper, a three-dimensional (3D) fully automatic energy-norm based *hp*-adaptive Finite Element (FE) strategy is described and applied to solve relevant electromagnetic waveguide structures. It is based on the work on hp adaptivity leaded by Prof. Demkowicz of the University of Texas at Austin. As in the 2D case, the three dimensional hp-strategy supports anisotropic refinements on irregular meshes with hanging nodes, and isoparametric as well as exact-geometry elements.

Extensive numerical results demonstrate the suitability of the *hp*-adaptive method for solving different rectangular waveguide discontinuities. These results illustrate the flexibility, reliability, and high-accuracy of the method. Solutions of waveguide problems delivered by the self-adaptive *hp*-FEM are comparable (and in many cases more accurate) than those obtained with semi-analytical techniques such as the Mode Matching method, for problems where the latest methods can be applied.

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	Tuesday, June 5, 2012
	Billiard Room
10:10	**Session 9: Advances in Hybrid Methods and Multiphysics Problems (B. Shanker, L. Kempel)**
	9.2. Thermal-Aware DC IR-Drop Co-Analysis using a Non-conformal Domain Decomposition Approach *Yang Shao*, Zhen Peng, Jin-Fa Lee*
10:30	**9.3.** Development of Time Domain Discontinuous Galerkin-Vector Generalized Finite Element Method *O. Tuncer, B. Shanker*, L. C. Kempel*
10:50	**9.4.** Multi-solver-based Generalized Impedance Boundary Condition for Complicated EM Simulation *Shiquan He, Jun Hu*, Zaiping Nie, Lijun Jiang, W. C. Chew*
11:10	**9.5.** Analysis of Electromechanical Devices Using the Dual-Primal Finite Element Tearing and Interconnecting Method Incorporated with the LU Recombination Method *Wang Yao*, Jian-Ming Jin*
11:30	**9.6.** Alternative Formulations for Hybrid Electromagnetic-Circuit Simulators *Vivek Subramanian, Ali E. Yilmaz**
11:50	Lunch break (MacGregor Room)
13:10	**9.7.** Symmetric and Nonsymmetric FEM-MoM Techniques Using Higher Order Hierarchical Vector Basis Functions and Curved Parametric Elements *Ana Manić*, Milan Ilić, Branislav Notaroš*

Thermal-Aware DC IR-Drop Co-Analysis using a Non-conformal Domain Decomposition Approach

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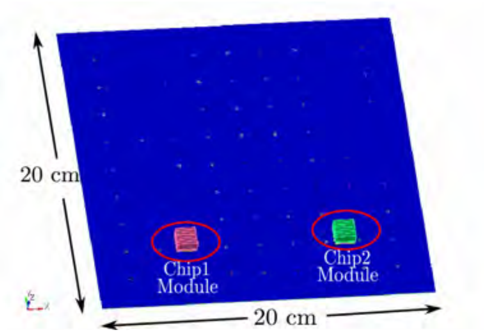
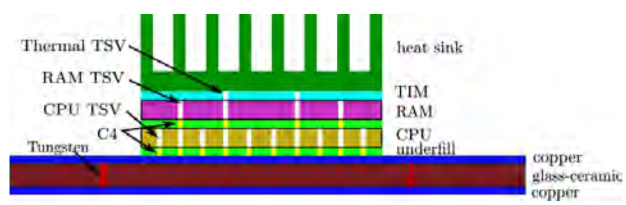
In the past few years, there have been increasing research activities aiming at developing a robust and efficient numerical solution strategy combating multi-scale electromagnetic problems. Such multi-scale electromagnetic problems tax heavily on numerical methods (finite elements, finite difference, integral equation methods etc.) in terms of desired accuracy and stability of mathematical formulations. Besides, almost various physical phenomena are usually interacting and coupling to each other. For instance, the resistivity of most conducting metals increases linearly with the increases of the surrounding temperature resulting from the Joule heating by electric currents flowing through the conductors. Therefore, in order to accurately characterize the performance of high power integrated circuits (ICs), package and printed circuit boards (PCBs), it is essential to account for both electric and thermal effects and the intimate couplings between them.





One of the major power integrity (PI) issues is the IR drop, caused by the finite resistivity of metals and current drawn off from the power/ground planes. When the resistance of power/ground plane increases with the shrinking of complex geometries, the IR drops will in turn increase as well. To further confound the difficult issue, the rise of the thermal temperature due to the current carrying interconnects also has tremendous impact on the IC performance and reliability. Current flow in a VLSI interconnect can cause a power dissipation, which is referred to as Joule heating or self-heating. Therefore, due to the linear temperature dependency of metal resistivity, the non-uniform temperature distribution affects the electrical performance of power delivery network (PDN) and substantially increases the IR drops in the power/ground planes.

In this paper, we present non-conformal, non-overlapping domain decomposition methods (DDMs) for the thermal-aware DC IR drop co-analysis of high-power IC-Package-PCBs. The proposed DDM starts by partitioning the composite device into inhomogeneous sub-regions with temperature dependent material properties. Subsequently, each sub-domain is meshed independently according to its own characteristic features. As a consequence, the troublesome mesh generation task for complex ICs can be greatly subdued. The proposed thermal-aware DC IR drop co-analysis applies the non-conformal DDM for both conduction and steady state heat transfer analyses with two-way couplings between them. Numerical examples, including an IC package and an IC-Package-PCB, demonstrate the flexibility and potentials of the proposed thermal-aware DC IR-drop co-analysis using non-conformal DDMs.

Development of Time Domain Discontinuous Galerkin-Vector Generalized Finite Element Method

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In this paper, we propose developing a hybrid time domain discontinuous Galerkin vector generalized finite element method (TD-DG-VGFEM) and examine its accuracy, efficiency, and stability for transient electromagnetic (EM) problems. Both VGFEM and DG can be cast under the umbrella of partition of unity methods. In VGFEM, the partition of unity function is defined on overlapping domains, whereas in DG, the overlap is zero. As a consequence, while continuity is built into space of functions in VGFEM, it is not in DG. Therefore, additional constraints are necessary in DG to enforce continuity. Both these methods have been used to provide robust solutions to electromagnetic problems (O. Tuncer, B. Shanker and L.C Kempel, IEEE TAP 2010, IEEE APS 2011; J. S. Hesthaven and T. Warburton, J. Comp. Phys., 2002; I. Perugia, D. Schotzau, and P. Monk, Comput. Methods Appl. Mech. Engrg. 2002; S. Dosopoulos and Jin-Fa Lee, IEEE TAP 2010). Both methods are theoretically capable of including polynomials and non-polynomial functions in approximation space. While non-polynomial approximation functions have been used in VGFEM, they have not, to our knowledge, been used within a DG framework.

In this paper, we intend to investigate a hybridization of these two methods to solve Maxwell equations in the time domain. Specifically, we are interested in examining trade-offs that arise out of this hybridization, and stability and convergence of the proposed approach. To this end, we will present the mathematical framework necessary for this integration as well as a number of results that examine these issues. In addition, we present applications to a range of practical problems.

Multi-solver-based Generalized Impedance Boundary Condition for Complicated EM Simulation

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As technological devices become smaller, faster, and more complex, computer simulations of physical phenomena become an increasingly important part of the design process. The multiscale problem caused by a disparate mesh usually leads to a large unknown count and a slow convergence of the iterative solver because low-frequency circuit physics and high-frequency wave physics coexist in one problem. Applying single CEM method for the entire problem will inevitably cost tremendously more computational resources and incapable of treating every part of the problem domain efficiently. For example, it is most efficient to solve the PEC structures with boundary integral equation (BIE) accelerated with powerful fast algorithms. However, the complicated dielectric materials are more efficient to be modeled with finite element method (FEM). For the eclectically large surrounding regions, high frequency approximation is a more preferable choice.

Aimed at efficiently calculating the radiation and scattering from arbitrary composite objects, multiple targets and finite periodic structures, a multi-solver-based generalized impedance boundary condition (MS-GIBC) is proposed and finally a domain decomposing method (DDM) is achieved. According to the Huygens equivalence principle, the scattering from complex structures is equivalent to the radiation of equivalent sources (electric current and magnetic current) resided on their boundaries. A generalized impedance boundary condition (GIBC) is established between the equivalent magnetic current and electric current. Different solvers, such as BIE and FEM, can be adopted in different domain to construct the GIBC. Finally, we only need to solve the boundary integral equations concerning equivalent current at each boundary. Moreover, it is very convenient to use multilevel fast multipole algorithm (MLFMA), multifrontal massively parallel sparse direct solver (MUMPS) and various preconditioners to accelerate the solution process.

Due to the GIBC, only equivalent electric current **J**s at each interface is introduced and a sparse matrix with smaller size for each region is inverted to transfer the original unknowns to the unknowns on the equivalent surface. The dimension of the final impedance matrix becomes much smaller as well. Furthermore, the non-conforming grids are permitted to discretize the inner fields and currents on equivalent surface. Compared with recently proposed multi-solver domain decomposition method (MS-DDM), the tangential continuities of **E** and **H** fields across each interface are imposed directly without extra transmission conditions. Various combinations of BIEs in our method right correspond to different transmission conditions in FEM-DDM.

Analysis of Electromechanical Devices Using the Dual-Primal Finite Element Tearing and Interconnecting Method Incorporated with the LU Recombination Method

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In this paper, the dual-primal finite element tearing and interconnecting (FETI-DP) method, a robust domain decomposition method, is adopted together with the LU recombination method to expand the capability and improve the efficiency of 3-D finite-element analysis of electromechanical problems. The FETI-DP method divides an original large-scale problem into smaller subdomain problems and then deals with the subdomains in parallel using multiple processors to significantly reduce the total computation time. The LU recombination method is adopted to deal with the low-frequency breakdown problem, which often accompanies the finite-element analysis of electromechanical problems.

A general electromechanical device consisting of linear materials can be described by the magnetic diffusion equation

$$\nabla\times(\nu\nabla\times\mathbf{A})+j\omega\sigma\mathbf{A}=\mathbf{J}_i \quad \text{in } \Omega\subset R^3 \tag{1}$$

where $\nu=\mu^{-1}$. With the FETI-DP method, the entire computational domain is first partitioned into N_s subdomains. At each subdomain interface, the tangential continuity of the magnetic field intensity and the normal continuity of the magnetic flux density should be satisfied, which can be written as

$$\begin{cases}\hat{n}_i\times(\hat{n}_i\times\mathbf{A}_i)=\hat{n}_j\times(\hat{n}_j\times\mathbf{A}_j)\\ \hat{n}_i\times(\nu_i\nabla\times\mathbf{A}_i)=-\hat{n}_j\times(\nu_j\nabla\times\mathbf{A}_j)=\mathbf{\Lambda}.\end{cases} \tag{2}$$

The second boundary condition contains an unknown vector $\mathbf{\Lambda}$, often referred to as the "dual" unknown, which has to be solved to recover the field values inside each subdomain. In order to enforce the continuity condition along corner edges, one set of global corner unknowns, A_c, often referred to as the "primal" unknowns, is used within the entire computational domain. Application of the standard finite element method to each subdomain yields the subdomain system which involves the dual, primal, and remaining unknowns. By eliminating the remaining unknowns, we obtain two global systems of equations involving only the primal and dual unknowns. By further eliminating the primal unknowns, we obtain an interface system which involves only the dual unknowns. This interface system, which has a much smaller number of unknowns than that in the original 3-D problem, can be solved by a Krylov subspace method. The introduction of the aforementioned primal unknowns improves the convergence rate of the Krylov subspace method in a similar manner to the multigrid method.

When dealing with electromechanical problems, the finite-element analysis with vector basis functions usually encounters the so-called low-frequency breakdown problem. An effective way to solve this problem is to use the LU recombination algorithm to remove the dependant equations (H. Ke, T. H. Hubing, and F. Maradei, "Using the LU recombination method to extend the application of circuit-oriented finite element methods to arbitrarily low frequencies," *IEEE Trans. Microw. Theory Tech.*, vol. 58, pp. 1189-1195, 2010). With the LU recombination method, the system matrix is first factorized to be a lower- and an upper-triangular matrices. Since a null space exists for the system matrix, some diagonal values of the upper-triangular matrix are several orders smaller than others. These nearly-zero diagonal values actually correspond to the dependant equations of the system matrix, which can be identified easily. By eliminating the dependant equations and the corresponding unknowns, the system matrix is then regularized. Compared to the tree-cotree splitting method, this method deals with the system matrix directly, and therefore can be implemented more easily together with higher-order basis functions.

Alternative Formulations for Hybrid Electromagnetic-Circuit Simulators

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In the last decade, various hybrid electromagnetic-circuit (EM-CKT) simulators that *simultaneously* solve Kirchoff's equations for voltages/currents on lumped-element networks and Maxwell's equations for electromagnetic fields/currents on complex volumes/surfaces have been proposed. On the one hand, such simulators generally use the modified nodal analysis technique to formulate circuit equations and solve them for node voltages and voltage-source currents. On the other hand, they employ a variety of techniques to formulate partial differential or integro-differential electromagnetic equations and solve them for fields or currents, respectively, and can be categorized as differential- or integral-equation based simulators. These hybrid EM-CKT simulators can also be categorized based on their temporal discretization method as frequency-domain, time-domain, and more recently, envelope-tracking solvers (V. Subramanian and A. E. Yılmaz, "An envelope-tracking field-circuit simulator for nonlinearly loaded wire antennas," in Proc. USNC/URSI Radio Science Meeting, July 2011); they represent time variations of signals (fields, currents, voltages) of interest in terms of sinusoidal functions, interpolatory sub-domain basis functions, and Fourier series with slowly time-varying coefficients, respectively.

This article focuses on integral-equation based time-domain and envelope-tracking hybrid EM-CKT simulators and their coupling methods. The principle formulation used in these simulators is as follows (A. E. Yılmaz, J. M. Jin, and E. Michielssen, "A parallel FFT accelerated transient field-circuit simulator," IEEE Trans. Microwave Theory Techniques, vol. 53, 2005, pp. 2851-2865): In the CKT-solver component, first the vector $\mathbf{V}(t)$, which represents node voltages and voltage-source currents, is discretized, then branch constitutive relations at voltage source branches and Kirchoff's current law at each node are enforced, i.e., $\sum_k I_k = 0$, where I_k denotes the current entering to the node from the k^{th} branch connected to it. In the EM-solver component, first the current densities are discretized, then the time-derivative of the tangential boundary conditions are enforced, e.g., $\partial_t \mathbf{E}^{\mathrm{inc}}_{\mathrm{tan}}(\mathbf{r},t) = -\partial_t \mathbf{E}^{\mathrm{sca}}_{\mathrm{tan}}(\mathbf{J},\mathbf{r},t)$ on a perfectly conducting surface S, where $\mathbf{J}$ denotes the surface current density on S and the time-derivative of the sum of components of the incident and scattered fields tangential to S are equated to zero. The two components are interfaced at electrically small (lumped) ports using controlled sources: The EM-solver component enforces the time-derivative of (line integral of) the total electric field at each port p be equal to the time-derivative of the port voltage $V_p(t)$, which is discretized by the CKT-solver component. Similarly, the CKT-solver component enforces the currents entering to the nodes of each port p to be equal to that of the current leaving the port $\iint \mathbf{J}_p ds$, which is discretized by the EM-solver component. While this $\mathbf{J} / \partial_t \mathbf{E} - \mathbf{V} / I$ formulation is suitable for coupling established EM and CKT solvers without major changes to their implementation, it requires that the time-derivative of port voltages be computed numerically, which can cause error propagation and non-convergence especially when the circuits of interest contain strong nonlinearities. In this article, two alternative formulations that avoid the numerical time derivative in the coupling are proposed: The first alternative is the $\mathbf{J} / \partial_t \mathbf{E} - \partial_t \mathbf{V} / I$ formulation, where the EM-solver component remains the same as above but the CKT-solver component is reformulated to discretize the time-derivative of voltages. The second alternative is the $\int \mathbf{J} dt / \mathbf{E} - \mathbf{V} / \int I dt$ formulation, where the EM-solver component is reformulated to discretize integral of the surface current density and to enforce the tangential boundary conditions (and not their time derivatives) and the CKT-solver component is reformulated to enforce the time-integral of the Kirchoff's current law at each node. Various numerical results for linearly and nonlinearly-loaded antennas that demonstrate the merits of these alternative formulations will be presented at the workshop.

Symmetric and Nonsymmetric FEM-MoM Techniques Using Higher Order Hierarchical Vector Basis Functions and Curved Parametric Elements

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Different hybridizations of the finite element method (FEM) and the method of moments (MoM) have been extensively utilized for an exact truncation of the unbounded spatial domain in the FEM analysis for quite some time. As one of the principal approaches to the FEM-MoM hybridization, symmetric coupling between FEM and MoM is, essentially, a combination of the appropriate FEM equations (e.g., a Galerkin-type weak form of the curl-curl electric field vector wave equation) with the magnetic field integral equation (MFIE) and the electric field integral equation (EFIE) that gives rise to a symmetric FEM-MoM matrix system of equations.

This paper presents three different symmetric and nonsymmetric FEM-MoM techniques using higher order basis functions and generalized curved parametric hexahedral finite and quadrilateral boundary elements, with both FEM and MoM leading to considerably smaller numbers of unknowns when compared to similar methods with low-order basis functions and simple elements. Curl- and divergence-conforming hierarchical polynomial vector bases are used for the field and current approximations on FEM hexahedra and MoM quadrilaterals, respectively, enabling different coupling methods and ways of combining appropriate electromagnetic quantities while satisfying their natural interrelations.

A nonsymmetric formulation (M. M. Ilić, M. Djordjević, A. Ž. Ilić, and B. M. Notaroš, IEEE Trans. Antennas Propagat., vol. 57, May 2009) places equivalent currents at the boundary surface around the FEM domain and equates tangential electric and magnetic field components on each side of the boundary, while not enforcing a direct connection between the magnetic current and the electric field at the surface. It uses a FEM field representation in the MFIE and EFIE, and the unknowns are surface currents at the boundary, which are later used to calculate the fields in the FEM domain.

In a higher order FEM-MoM technique developed and implemented according to the first symmetric formulation considered (D. J. Hoppe, L. W. Epp, and J. Lee, IEEE Trans. Antennas Propagat., vol. 42, June 1994), FEM, EFIE, and MFIE equations are used independently and connected in a final system of equations. Again, equivalent surface currents are placed at the FEM boundary, giving three sets of unknown coefficients, for the electric field and the magnetic and electric currents, respectively, with only an implicit connection between the field and the magnetic current.

In another higher order FEM-MoM technique developed and implemented according to the second symmetric formulation (M. N. Vouvakis, S. Lee, K. Zhao, and J. Lee, IEEE Trans. Antennas Propagat., vol. 52, Nov. 2004), the FEM and MFIE are combined into one equation, while the EFIE is independently added. The method explicitly forces a natural relation between the electric field and the magnetic current, and uses the same coefficients in expansions of these unknowns. It thus computes only two sets of unknown coefficients, while directly solving for all three unknown quantities. In support of this option, the method implements dual sets of curl- and divergence-conforming basis functions modeling the field and current, respectively.

The paper evaluates, discusses, and compares theoretical features and computational properties of the three methods, all implemented using truly higher order geometrical and current/field modeling.

	Tuesday, June 5, 2012
	Music Room
10:50	**Session 10: FEM Modeling and Applications of Metamaterials and Periodic Media (K. Sertel, J. Volakis)**
	10.1. Finite Element Modeling of Magnetic Metamaterials and Associated Challenges for Their Experimental Characterization *Nil Apaydin* , Kubilay Sertel, and John L. Volakis*
11:10	**10.2.** A Method for Rapid Evaluation of Space-time Convolutions with the Time Domain Periodic Green's Function *D. Dault and B. Shanker**
11:30	**10.3.** Finite Element Analysis of Photon Density of States for Two-Dimensional Photonic Crystals with Omnidirectional Light Propagation *R. F. Jao and M. C. Lin*
11:50	Lunch break (MacGregor Room)
13:10	**10.4.** A Hybrid Approach for Characterizing Large Anisotropic and Inhomogeneous Metamaterial Structures *Justin G. Pollock and Ashwin K. Iyer**

Finite Element Modeling of Magnetic Metamaterials and Associated Challenges for Their Experimental Characterization

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Metamaterials have attracted a lot of attention from the microwave community due to their unprecedented electromagnetic properties and novel modes (Special Issue on Metamaterials, IEEE Transaction on Antennas and Propagation, Vol. 51, No. 10, 2003, pp. 2546-2750). Many new antennas and microwave devices have been developed, harnessing the new phenomena realized by man-made metamaterials such as negative refraction. The latter was essential in proposing sub-wavelength focusing super lenses and even more controversial “cloaking” applications. We recently demonstrated that material anisotropy provides even greater mode diversity. Moreover, inclusion of ferromagnetic materials leads to more degrees of design freedom, paving way for unforeseen microwave devices and new antenna designs (J.L. Volakis *et al.*, “Narrowband and Wideband Metamaterial Antennas Based on Degenerate Band Edge and Magnetic Photonic Crystals,” Proc. IEEE, Vol. 99, No. 10, 2011, pp. 1732-1745). In particular, biased ferromagnetic layers used in a simple 1-dimensional magnetic photonic crystal (MPC) can support a “frozen mode” with zero group velocity. Design of such a structure using the finite element method is perhaps the most accurate and efficient among other alternatives.

Thanks to the developments in the past decade, the FEM is quite mature in modeling infinite periodic structures as well as antenna arrays. For metamaterial modeling, periodic boundary conditions are typically utilized to truncate the FEM domain and dispersion characteristics can be readily computed. Geometrical and material complexity of the unit cell can be easily handled by the adaptability of the FEM mesh. However, electromagnetic parameters of the constituent materials must be supplied before one can form the FEM eigensystem and its subsequent solution. This creates an issue if the dielectric materials have frequency-dependent permittivity and/or ferromagnetic materials have permeabilities as a function of the local magnetic field intensity. To alleviate this, an iterative approach can be employed to compute the dispersion characteristics of these layouts. Material properties of the substrate and the computed dispersion data need to be iteratively updated until a predefined error measure is satisfied.

More importantly, experimental verification of metamaterial dispersion characteristics is a challenge due to finite sizes of samples. Evanescent/boundary modes usually corrupt measurement data and the dispersion/group-delay needs to be indirectly calculated. For this, one can use two finite metamaterial slabs of different thicknesses to remove the evanescent field corruption (N. Apaydin *et al.*, "Experimental verification of frozen mode phenomenon in printed magnetic photonic crystals," Proc. 5th European Conf. Antennas and Propagation, 2011, pp. 2396 -2398). We should remark that the number of unit-cells in the finite samples should be chosen to be reasonably large, such that the coveted metamaterial properties are prominent. This requirement presents an inevitable computational challenge for modeling large, finite-size metamaterials with very small features compared to the wavelength. We will present computational results to illustrate the benefits of the FEM for the design and validation of this new class of magnetic metamaterials.

A Method for Rapid Evaluation of Space-time Convolutions with the Time Domain Periodic Green's Function

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The evaluation of fields in time domain for large, dense, and/or multiscale periodic structures is a topic of significant interest to many sectors of the electromagnetics community. Characteristics such as rise-time, ringing, dispersive effects, time-varying feeds and many other temporal processes are of crucial importance to accurate designs of numerous devices. Additionally, the inclusion of nonlinearities, which are integral to many electromagnetic systems, is most amenable to time domain analysis. Time Domain Integral Equation (TDIE) solvers are a promising class of tools for solving periodic systems in time due to their implicit satisfaction of free space boundary conditions without requiring domain truncation and absorbing boundary conditions. However, the evaluation of temporal and spatial convolutions required in the TDIE kernel is a computationally intensive task, scaling as $\mathcal{O}(N_s^2 N_t^2)$ per mode when fields are represented in terms of a Floquet expansion. Here, N_s is the number of spatial degrees of freedom and N_t is the number of time steps. Additionally, the Floquet representation of the time domain periodic Green's function consists of an infinite summation over spectral modes that must be truncated in some way to be practical.

In this work we present a method for effecting fast convolutions with the Time Domain Floquet Wave Green's function that is constructed specifically for introduction into a Marching on in Time (MOT) TDIE framework. To accomplish the speedup, we utilize an alternate representation of the Time Domain Floquet Wave Green's Function that explicitly separates space and time, allowing independent spatial and temporal acceleration. We employ the method of Accelerated Cartesian Expansions, an $\mathcal{O}(N_s)$ scheme based on generalized Taylor expansions to accelerate spatial convolutions, and a block-FFT scheme to accelerate temporal convolutions. The resulting algorithm scales as $\mathcal{O}(N_s N_t \log^2 N_t)$ per Floquet mode. In addition to accelerating the convolutions, we also employ a strictly band-limited temporal basis function which, upon convolution with the time domain Floquet Wave Green's function, limits the number of contributing Floquet modes to $\mathcal{O}(1)$ (Chen at el. Radio Science 2005, Vol 40). The form in which the temporal convolutions are cast allows reconstruction to arbitrary precision using the ACE algorithm. Thus, the entire method scales asymptotically as $\mathcal{O}(N_s N_t \log^2 N_t)$ and can represent reconstructed fields to a high degree of accuracy. In this work we provide a detailed explanation of the formulation, bounds on error, and results validating scaling of the method.

Finite Element Analysis of Photon Density of States for Two-Dimensional Photonic Crystals with Omnidirectional light propagation

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Omnidirectional light propagation in two-dimensional (2D) photonic crystals (PCs) is investigated. An efficient approach to identifying a complete photonic band gap (PBG) in 2D PCs has been developed. The in-plane band structure of 2D photonic crystals is calculated by an adaptive finite element method, as implemented in FEMLAB. With adopting the suitable boundary conditions, the eigenvalues can be easily and rapidly calculated no matter how complex the geometric structures are. By symmetry, the omnidirectional photon density of states (PDOS) can be calculated based on the in-plane dispersion relation within the irreducible Brillouin zone. The PDOS corresponding to both the radiation and evanescent waves can be obtained accurately and efficiently. We demonstrate that the "complete band gaps" showed by some previous work due to considering only the radiation modes will be closed by including the contributions of the evanescent modes. Therefore, the complete PBGs do not exist in 2D PCs where evanescent waves can propagate. These results are of general importance and relevant to the spontaneous emission by an atom, or to dipole radiation in two-dimensional periodic structures.

A Hybrid Approach for Characterizing Large Anisotropic and Inhomogeneous Metamaterial Structures

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Metamaterials are engineered periodic structures whose macroscopic electromagnetic response is determined by the subwavelength features of their constituent unit cells. Accurate characterization of this response in a full-wave simulation environment requires dense discretization of the features of each unit cell, and often several hundred or thousand such unit cells are present a single computational domain. Whereas the availability of powerful, low-cost computers has enabled the solution of many previously intractable simulation problems, it has also motivated researchers to explore increasingly complex metamaterial structures. As a result, full-wave simulation of large metamaterial structures is still plagued by lengthy simulation times and excessive memory requirements. Effective-medium models based on simplified analytical descriptions of metamaterial unit cells (e.g. equivalent-circuit models) have been successful in mitigating these issues; however, these models are not always accurate, and this is particularly true for the highly complex unit-cell geometries generated, for example, from fractals, space-filling curves, and genetic algorithms. Alternatively, the effective-medium parameters of an isotropic, homogeneous metamaterial can be extracted by inversion of the simulated scattering parameters of a thin slab [D. R. Smith et al. *Physical Review B,* vol. 65, no. 19, p.195104, 2002.]. This procedure is suited to full-wave simulators like Ansys HFSS, which, in simple rectangular geometries, can apply periodic boundary conditions to limit the size of the computational domain. However, more complex geometrical arrangements of metamaterials, such as cylindrical or spherical arrangements, are not so easily described by such simulators, particularly because these arrangements may result in anisotropic and inhomogeneous properties. The computational domains for these structures cannot easily be reduced.

To address this issue, we present a hybrid numerical/semi-analytical approach to the modeling of generally anisotropic and inhomogeneous metamaterials. Inhomogeneity is modeled in a discrete, multilayer fashion. Anisotropy is addressed by decomposing propagation into orthogonal directions, and an equivalent full-wave rectangular metamaterial geometry is determined for each direction. Each model may then be reduced using periodic boundary conditions and effective-medium parameters corresponding to each direction may then be extracted as for homogeneous, isotropic metamaterial slabs. An analytical formulation utilizes these extracted parameters in an effective medium model to obtain the near- and far-field of the structure. We focus on the case of a cylindrical negative-refractive-index transmission-line (NRI-TL) metamaterial structure [Pollock et al. *Proc. of Metamaterials 2011*, 30-32 (2011)] created by radially arranging several planar NRI-TL metamaterial layers, which exhibits uniaxial anisotropy and radial inhomogeneity. We apply the extracted data to our analytical formulation and demonstrate that the near-fields, radiation patterns, and radiated power produced by a source placed next to the cylindrical NRI-TL metamaterial are in excellent agreement with those acquired from full-wave FEM simulations of the entire structure using Ansys HFSS. The full-wave simulation region consisted of a cylinder of diameter between 0.66 and 0.73 free-space wavelengths over the simulated frequency range, and a height of between 0.055 and 0.062 free-space wavelengths. A sufficiently converged result required a minimum of 990,000 tetrahehdra, over 11GB of memory, and 1.5 hours of simulation time per frequency point on a 3.4GHz quad-core desktop computer. In our analytical method, the solution is based on a cylindrical-wave expansion of the fields, which causes the computation time to depend on both the required spatial resolution and truncation limit on the number of azimuthal modes contributing to the solution. To obtain a commensurate degree of resolution and convergence, the fields can be obtained for a single frequency point in just over 5 minutes. Even when taking into account the time required to extract the anisotropic parameters using full-wave simulations, we observe an order of magnitude reduction in total simulation time.

	Tuesday, June 5, 2012
	Billiard Room
13:30	**Session 11: Domain-Decomposition Methods (J.-F. Lee, Z. Peng)**
	11.1. Analysis of Three-Dimensional Array Structures Using Nonconformal and Cement FETI-DP Methods *Ming-Feng Xue* and Jian-Ming Jin*
13:50	**11.2.** A Domain-Decomposition-Based Preconditioner of FE-BI-MLFMA for Computing EM Scattering by Large Inhomogeneous 3D Targets *Ming-Lin Yang, Xin-Qing Sheng, and Cheng-Dan Huang*
14:10	**11.3.** On the Computational Complexity of Domain Wise Multilevel Multifrontal Method *Peng Liu* and Chao-Fu Wang*
14:30	**11.4.** Harmonic Balance Domain Decomposition Finite Element for Nonlinear Passive Microwave Devices Analysis *Laurent Ntibarikure, Giuseppe Pelosi, and Stefano Selleri*
14:50	**11.5.** Application of Tree-Cotree Splitting to the Dual-Primal Finite Element Tearing and Interconnecting Method for Solving Low-Frequency Breakdown Problems *Wang Yao* and Jian-Ming Jin*
15:10	Coffee break (Pinion room)
15:40	**11.6.** Edge Elements and DPM with PBSV to Accelerate Solving Scattering Problems of Electrically Large Objects *Lianyou Sun*, Lishan Xue, and Wei Hong*
16:00	**11.7.** Enhancement of Second-harmonic Generation in an Air-bridge Photonic Crystal Slab: Simulation by Spectral Element Method *Ma Luo and Qing Huo Liu**
16:20	**11.8.** A Non-overlapping and Non-conformal Domain Decomposition Method with Optimized Second Order Transmission Conditions for Time-Harmonic Maxwell Equations in R^3 *Zhen Peng and Jin-Fa Lee*
16:40	**11.9.** The Quest for Robust Domain Decomposition Methods in CEM: Are We There Yet? *Marinos N. Vouvakis* and Georgios N. Paraschos*

Analysis of Three-Dimensional Array Structures Using Nonconformal and Cement FETI-DP Methods

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The dual-primal finite element tearing and interconnecting (FETI-DP) method is one of the most advanced non-overlapping domain decomposition methods (DDMs). It has been successfully used in large-scale electromagnetic analysis such as phased-array antenna and photonic crystal (PhC) simulations. The earlier two conformal versions of this method in computational electromagnetics community are referred to as FETI-DPEM1 (Y. J. Li and J. M. Jin, "A vector dual-primal finite element tearing and interconnecting method for solving 3-D large-scale electromagnetic problems," *IEEE Trans. Antennas Propagat.*, vol. 54, pp. 3000-3009, 2006) and FETI-DPEM2 (Y. J. Li and J. M. Jin, "A new dual-primal domain decomposition approach for finite element simulation of 3D large-scale electromagnetic problems," *IEEE Trans. Antennas Propagat.*, vol. 55, pp. 2803-2810, 2007), respectively. These two schemes employ the Dirichlet-Newmann transmission condition and the Robin-type transmission condition at the subdomain interfaces, respectively. Eigenspectrum analysis and Numerical simulation show the FETI-DPEM2 outperforms FETI-DPEM1 in terms of convergence rate of the iterative solution of the global interface problem, even without preconditioning. At the same time, a nonconformal counterpart of the conformal FETI-DP method, which is called FETI-like method, was proposed (K. Zhao et al, "A domain decomposition method with nonconformal meshes for finite periodic and semi-periodic structures," *IEEE Trans. Antennas Propagat.*, vol. 55, pp. 2559-2570, 2007). It reformulates the Robin-type transmission condition and has a similar convergence behavior as that of FETI-DPEM2.

In order to further enhance the capability of the FETI-DP method for modeling large-scale and complex antenna structures, two nonconforming FETI-DP methods are proposed in our recent work. They are referred to as the nonconformal FETI-DP method and the cement FETI-DP method, respectively. Both of these two methods implement a Robin-type transmission condition at the subdomain interfaces to preserve the fast convergence when solving the global interface problem at high frequencies iteratively. Similar to the conformal FETI-DP method, a global coarse problem related to the unknowns associated with the subdomain corner edges is designed to propagate the residual error to the whole computational domain at each iteration. The nonconformal FETI-DP method extends the conformal FETI-DP method to deal with nonconformal interface and corner meshes, and the cement FETI-DP method formulates the FETI-like method to combine interface dual unknowns with global primal unknowns defined on corners.

The FETI method is particularly suitable for simulating large finite arrays because the geometrical repetitions of an array structure can be exploited to further enhance the computational performance. In some engineering applications, we may encounter structures with repetitions in all three dimensions. For example, negative refraction by using materials with nonnegative permittivity and permeability is a hot research topic in the optics society. In the past few decades, experiments and simulations have demonstrated negative refraction and negative refraction imaging by two-dimensional (2D) PhC flat lenses. However, these 2D flat lenses have shown lensing ability only along one direction; consequently, the usage of 2D flat lenses is limited in real-life applications. For this reason, "flat spherical" lenses, which work by full 3D negative refraction (F3DNR) and provide super resolution imaging, are especially desired. In a recently published paper, a so-called 3D photonic crystal flat lens was fabricated and the F3DNR phenomenon was experimentally observed. This paper will focus on simulating the F3DNR phenomenon and show the effectiveness and efficiency of the nonconformal and cement FETI-DP methods in modeling 3D photonic crystal array structures.

A Domain-Decomposition-Based Preconditioner of FE-BI-MLFMA for Computing EM Scattering by Large Inhomogeneous 3D Targets

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It is a well established that the hybrid finite element - boundary integral - multilevel fast multipole algorithm (FE-BI-MLFMA) is a general, accurate, and efficient computation technique for open region problems such as scattering / radiation problems. The conventional algorithm of FE-BI-MLFMA is directly to apply the iterative solvers to the final FE-BI matrix equation (X. Q. Sheng et al. “On the formulation of hybrid finite-element and boundary-integral method for 3D scattering,” *IEEE Trans. Antennas Propagat*, Vol. 46, No. 3, 1998, pp. 303-311). This conventional algorithm converges slowly, sometimes even failing to converge due to ill-conditioned nature of the associated FE-BI matrix equation. Many fast algorithms of FE-BI-MLFMA have been developed over the past years to address this shortcoming (J. Liu et al., “A highly effective preconditioner for solving the finite element-boundary integral matrix equation for 3-D scattering,” *IEEE Trans. Antennas Propagat*. Vol. 50, No. 9, 2002, pp. 1212-1221). The key to designing fast algorithms of FE-BI-MLFMA is the efficient construction of a suitable preconditioner for the FE-BI matrix equation. Thereby, the FE-BI matrix is first decomposed into parts taking advantage of inherent favourable properties of FEM and BI. Different methods have been employed to construct preconditioners for the FEM- and BI-parts, respectively. In particular the idea of the finite element tearing and interconnecting method (Y. J. Li et al., “A new dual-primal domain decomposition approach for finite element simulation of 3-D large-scale electromagnetic problems”, *IEEE Trans. Antennas Propag.,* vol. 55, No. 10, 2007, pp. 2803-2810) is employed to construct the preconditioner for the FEM part of the FE-BI matrix equation. The sparse approximation inverse method is directly utilized to construct the preconditioner for the BI part of the FE-BI matrix equation. Afterwards, a solution algorithm of FE-BI-MLFMA based on the above two preconditioners is designed. The numerical performance of the proposed domain-decomposition-based preconditoner of FE-BI-MLFMA is investigated in detail, including the scalability of this algorithm.

On the Computational Complexity of Domain Wise Multilevel Multifrontal Method

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In computational electromagnetics and other application fields, multifrontal method is considered as one of the most efficient direct solvers for large sparse equation system. But like other direct solvers, the multifrontal method requires complete construction of the global stiffness matrix, which may be a significant demerit for large-scale applications. Because in the original frontal method, the global stiffness matrix is never constructed, each stage of assembling and solving stiffness matrix is alternately executed, thus fully assembled unknowns are eliminated immediately from the frontal matrix. This process makes the frontal method based programs particularly memory efficient for large-scale applications.

To overcome aforementioned demerit, the idea of partitioning the whole computational mesh into a number of subdomains and then implementing the frontal scheme separately in each subdomain has been appeared. This method was originally termed as the multiple front method. Fully implemented multilevel domain-wise multifrontal approach is proposed by Kim: (J. H. Kim and S. J. Kim, "A Multifrontal Solver Combined with Graph Partitioners," AIAA Journal, Vol. 38, 1999, pp. 964-970), where a bisection algorithm is first applied to recursively partition the sets of elements into two subdomains, and then two neighboring domains are merged in the reverse order until all elements are assembled on the coarsest mesh. In these approaches, domain partitioning and numbering are performed instead of matrix ordering, the global assembly of the stiffness matrix is not required, and the out-of-core technique can be used easily and seamlessly as the frontal method does.

Although various implementations of the domain-wise multifrontal approach have been studied over the years, the theoretical knowledge of how they perform lags way behind. In this work, the computational complexity of a P-way domain wise multilevel multifrontal algorithm, pertaining to the finite element method, is analyzed on regular 2D and 3D meshes in various aspects and with different parameters, such as the number of fronts, the number of partition levels, the ordering of fronts, and the type of boundary condition.

The operation counts of both local and multilevel global condensation phase are accurately estimated along with the relevant parameters, which make the theory more accurate and more generous than previous estimations, and more over, enable us to illustrate how the number of fronts, the number of partition levels, and the performance of the method are related, and how the multilevel multifrontal scheme reduces the total numerical operations intrinsically.

The operation count and execution time of the method are measured experimentally on a sequence of 2D and 3D examples. The theoretical estimations agree well with experimental results, as well as the optimal number of fronts. The results also show that due to its intrinsical reduction of the operation counts, the domain wise multilevel multifrontal method achieves a huge amount of CPU time saving, and thereby offers, without approximation, an easy way to substantially upgrade the frontal method based programs.

Harmonic Balance Domain Decomposition Finite Element for Nonlinear Passive Microwave Devices Analysis

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When high power densities are involved within passive microwave and millimeter-wave devices, materials may present a significant nonlinear behavior. A frequency domain analysis is sometimes preferable to a time-domain analysis, especially when steady-state fields are aimed at for a finite set of frequencies. Frequency domain finite element (FE) method provides an invaluable analysis tool for linear devices, but it fails when material properties present a dependence on the fields strength. To take into account of harmonic distortion that occurs in such a case, Harmonic Balance (HB) techniques may be used.

The proposed method extends the previous work (G. Guarnieri, G. Pelosi, L. Rossi, and S. Selleri, "A Domain Decomposition Technique for Efficient Iterative Solution of Nonlinear Electromagnetic Problems," IEEE Trans. Antennas Propag., vol. 58, no. 12, pp. 4090–4095, Dec. 2010) to include higher order harmonics. As a result, a global HB-FE system is assembled and solved iteratively, converging to the solution within a prescribed tolerance. Depending on the nonlinearity degree of the model, either Picard or relaxed iterations are used.

One or two fundamental frequency excitations have been investigated, the latter allowing to accurately compute third order intermodulation products. Coupling between harmonics is performed by testing the product of the nonlinear material property with the multiharmonic field amplitude (F. Bachinger, U. Langer, and J. Schöberl, "Numerical analysis of nonlinear multiharmonic eddy current problems," Numer. Math., vol. 100, no. 4, pp. 593-616, Jun. 2005). The material property can actually be expressed in terms of a sum of harmonics, being dependent on the multiharmonic field. The procedure of testing can be performed analytically for the single frequency excitation case, providing algebraic relations between first and higher order harmonics (S. Yamada, K. Bessho, and J. Lu,"Harmonic balance finite element method applied to nonlinear AC magnetic analysis," IEEE Trans. Magn., vol. 25, no. 4, pp. 2971-2973, Jul. 1989). In case of multiple excitation frequencies impinging on the device, an analytic testing can become impractical. Hence, coupling coefficients have been computed by the use of the fast Fourier transform algorithm.

A substructuring Domain Decomposition method has been applied to isolate unknowns contributing to non-linear elements from those remaining linear, in order to limit the nonlinear solving loop to a smaller domain. Numerical simulations have been carried out to validate the technique and perform timings comparisons with the full domain HB-FE analysis.

Application of Tree-Cotree Splitting to the Dual-Primal Finite Element Tearing and Interconnecting Method for Solving Low-Frequency Breakdown Problems

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The dual-primal finite element tearing and interconnecting (FETI-DP) method, a robust domain decomposition method, has been successfully applied to solve large-scale electromagnetic problems (Y. Li and J. M. Jin, "A vector dual-primal finite element tearing and interconnecting method for solving 3-D large-scale electromagnetic problems," *IEEE Trans. Antennas Progag.*, vol. 54, no. 10, pp. 3000-3009, 2006). The FETI-DP method divides an original large-scale problem into smaller subdomain problems and then deals with the subdomains in parallel using multiple processors to significantly reduce the total computation time. However, when the operating frequency is very low, the finite-element analysis with vector basis functions results in an ill-conditioned system matrix, which causes the so-called low-frequency breakdown problem. This problem may also occur when very small elements are used in the finite-element mesh. In this paper, the tree-cotree splitting (TCS) method is adopted to eliminate the low-frequency breakdown problem within the FETI-DP framework.

The proposed algorithm is used to solve the vector Helmholtz equation for the electric field given by

$$\nabla\times(\mu^{-1}\nabla\times\mathbf{E})-\omega^2\varepsilon\mathbf{E}=-j\omega\mathbf{J}_i \quad \text{in } \Omega\subset R^3 \tag{1}$$

where ε and μ are the permittivity and permeability, respectively. The FETI-DP method generally consists of three steps. First, the computational domain is divided into N_s nonoverlapping subdomains, and an incomplete solution of each subdomain is obtained using a direct solver. Next, Dirichlet and Neumann boundary conditions are enforced at the subdomain interfaces using Lagrange multipliers, which results in a global interface and a global corner system. These two global systems are then solved using the Krylov subspace method, whose solution is then used to recover the field values inside each subdomain. The construction of the global corner system improves the convergence rate of the Krylov subspace method in a similar manner to the multigrid method. In all three steps of the FETI-DP method, computations can be accelerated using parallel computing schemes to reduce the computation time.

When the operating frequency is very low, the displacement current term becomes much smaller compared to the curl-curl term in (1). Unfortunately, the finite element discretization of the curl-curl operator with edge elements result in an ill-conditioned matrix, which causes the low-frequency breakdown problem. An effective approach to solving this problem is to use the TCS method to remove the dependent equations (J. B. Manges and Z. J. Cendes, "A generalized tree-cotree gauge for magnetic field computation," *IEEE Trans. Magn.*, vol. 31, pp. 1342-1347, 1995). To apply the TCS method in the FETI-DP framework, three conditions must be satisfied simultaneously: (1) A tree structure is constructed for the global corner system consisting of all the corner edges; (2) A tree structure is constructed for each subdomain consisting of local volume and interface edges; (3) The tree and cotree edges are defined consistently on the subdomain interfaces so that the Dirichlet and Neumann boundary conditions can be enforced. In order to satisfy all three requirements, we apply the TCS algorithm in a nested manner. First, we construct a tree structure for the corner system to connect all the corner nodes, which together with the original reference nodes are considered as the new root. Next, we grow the tree from the new root to include all the nodes on the subdomain interfaces, so that a consistent tree structure can be built on the interfaces. Once all the corner and interface nodes are connected, we continue to construct the tree structure inside each subdomain until a complete tree is formed.

Edge Elements and DPM with PBSV to Accelerate Solving Scattering Problems of Electrically Large Objects

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For solving scattering problems of polygonal prisms, the normal component of the magnetic field may have a discontinuity across a material interface, and its direction changes infinitely rapidly at a sharp edge. The node-based finite element method cannot model these effects properly because its basis functions are continuous in all components from one element to other. Fortunately, edge elements are more flexible. Generally, vector fields which are represented by edge elements have normal discontinuities, and are only tangentially continuous. In addition, the degrees of freedom of edge elements are associated with the edges, not the nodes, so they allow the vector field to change direction abruptly at the sharp edge. Therefore, edge elements are very suitable for solving scattering from polygonal prisms.

When the scattering problem is discretized by edge elements, the problem is transformed into a linear system of algebraic equations. Generally, electrically large objects involve a large number of unknowns, because there must be enough edge elements per wavelength to represent the field variation accurately. The corresponding linear system of algebraic equations is very costly to solve. For such systems, the idea of splitting the domain is attractive. The whole domain is divided into many smaller sub-domains, which are solved individually. The size of each sub-domain can be adjusted according to the computer resources available. The Decomposition Projective Method (DPM) can meet these requirements well and is therefore used here. Not only is the order of the system of equations on each sub-domain very small, but also the convergence rates of DPM is geometric.

With DPM, the equations on sub-domains are solved repeatedly because DPM is an iterative method. When most sub-domains have the same structure, their coefficient matrix of the linear systems of algebraic equations are also the same. If the basic set of solutions of these equations is solved, the solution can be got by combination of the basic set of solutions, which saves much time on computation. Partial basic solution vectors (PBSV) method can complete it.

As a numerical example, edge elements and DPM with PBSV are used to analyze scattering from a square, perfectly-conducting, infinitely-long, cylinder of side 10λ0. Fig. 1 is the surface current density on the surface of the cylinder with an incident TM wave. The mesh nodes are almost the same for edge elements and MoM. There are about 52,600 unknowns in the edge element method. DPM without PBSV takes 181s to compute, and there are 830 iterations. Using DPM with PBSV, it takes 51s and also 830 iterations. Clearly, DPM with PBSV costs less time than DPM alone. Meanwhile, Fig. 1 also shows that the numerical approach of edge elements is better than that of MoM especially along side CD.

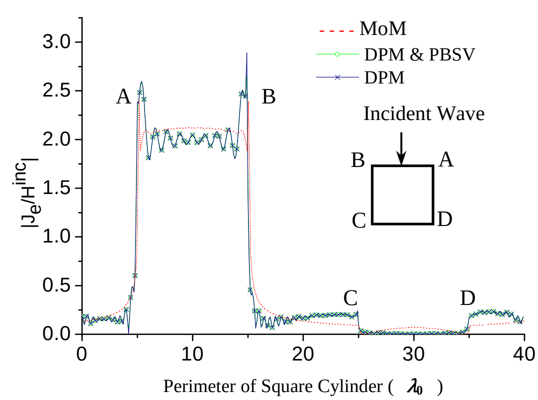

Fig.1. Surface current density on the cylinder.

Enhancement of second-harmonic generation in an air-bridge photonic crystal slab: simulation by spectral element method

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Previously, the spectral element method was implemented to calculate the transmission rate of an infinite periodic photonic crystal slab under plane wave incidence. The electric field in the computational domain is interpolated by the spectral element basis functions. The periodic boundary conditions are used for the vertical boundary, and the method of moments are used as the boundary conditions for the top and bottom horizontal boundary.

In this work, the implementation was extended to calculate the eigenstate of the photonic crystal slab. The method of moments gives integral equation of electromagnetic field base on the Green's function, which is a nonlinear function of the frequency. Because the frequency is the eigenvalue, the weak form of the spectral element method with the method of moments gives a nonlinear eigenvalue problem for the eigenstate of the photonic crystal slab. This nonlinear eigenvalue problem was solved by iterative solver. The band structure of the air bridge photonic crystal can be obtained.

In addition, the second order nonlinear optical effect is also modeled in this numerical method. With the given nonlinear susceptibility of the nonlinear optical material, the second order nonlinear optical effect can be directly simulated by the Maxwell's wave equation of the electromagnetic field. The only approximation in the modeling is the numerical discretization by the spectral element method. The nonlinear polarization field can be calculated from the interpolation of the electric field. This polarization field is tested as the source field in the spectral element method, which gives the second harmonic generation field. The second harmonic generation rate versus the wavelength and incident angle were calculated.

The band structure of the air bridge photonic crystal slab is compare with the second harmonic generation rate. Numerical results show that the resonance between the band structure and the second harmonic frequency could enhance the nonlinear effect. The additional conditions for the enhancement is the matching of the symmetry property between the eigenstate and the generated second harmonic polarization field. Comparing to homogeneous dielectric slab, the air bridge photonic crystal can enhance the second harmonic generation rate for four magnitude at certain wavelength.

A Non-overlapping and Non-conformal Domain Decomposition Method with Optimized Second Order Transmission Conditions for Time-Harmonic Maxwell Equations in $\mathbb{R}^3$.

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Recently, the domain decomposition methods (DDMs) have been demonstrated effective in solving many mission-critical electromagnetic applications. One category of the DDMs is the non-overlapping DDMs. The basic idea is to decompose the original entire problem domain into several non-overlapping sub-domains. The continuities of electromagnetic fields at the interfaces between adjacent sub-domains are enforced through some boundary conditions. Moreover, the non-conformal DDMs which relieve the restriction of mesh conformity have been proposed and shown to be accurate and efficient.

We present a non-overlapping and non-conformal domain decomposition method (DDM) for solving the time-harmonic Maxwell equations in $\mathbb{R}^3$. It has been recognized in the past that the convergence behavior of non-overlapping DDMs depends heavily upon the transmission conditions used to enforce the continuity of tangential fields on the interface between sub-domains. Recently, a true second order transmission condition, which involves two second-order transverse derivatives, is proposed and allows convergence of both propagating and evanescent electromagnetic waves across domain interfaces. Here, we introduce a new optimal second order transmission condition to further improve the convergence in the DDM iterations. Furthermore, through an analysis of the DDM with the SOTC, we show that there still exists a weakly convergent region where the convergence in the DDM can still be unbearably slow for electrically large problems. It is found that the weakly convergent region is centered at the cutoff modes, or electromagnetic waves propagate in parallel to the domain interfaces. Subsequently, a global plane wave deflation technique is utilized to derive an effective global-coarse-grid preconditioner to promote fast convergence of the cutoff or near cutoff modes in the vicinity of domain interfaces.

The Quest for Robust Domain Decomposition Methods in CEM: Are We There Yet?

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Proliferation of CPU cores in modern computing has renewed the interest in computational strategies and algorithms that leverage parallel processing. In the area of scientific computation, such as computational electromagnetics (CEM), the domain decomposition (DD) computational paradigm offers a viable alternative to traditional finite element or boundary element fast solvers, e.g. multigrid or fast multipole. DD methods first divide the discrete computational model into portions (domains) that are individually solved in each core. During the second and most important step, the solution of the overall model is recovered by locally communicating portions from each domain solution across processors, often in an iterative fashion. Although this strategy offers distinct advantages, such as straightforward programing and balanced usage of processing power, when difficult CEM models are encountered, no guarantees on speed or success of the iterative convergence exist. The iterative convergence of most popular DD methods, such as the finite element tearing and interconnecting (FETI) method, depends strongly on discretization size, frequency, field regularity and domain shape, hampering scalability and robustness.

Over the past years a large body of literature has been published in applied mathematics and CEM communities trying to overcome the various robustness and scalability problems using higher order transmission conditions (HOTCs) (Rawat et al. SIAM J. Sci. Comput. Vol. 32, p. 3584, 2010), combination of primal FEMs with FETI (FETI-DP) (Toselli, IMA J. Numer. Anal., Vol. 26, p. 96, 2006), (Y. Li et al., IEEE Trans. Antennas Prop., Vol. 55, p. 2803, 2007), or corner penalty methods (Z. Peng et al. IEEE Trans. Antennas Prop. Vol. 59, p. 1638, 2011). Even-thought, these methods have offer significant improvements, there are still cases that iterative convergence is problematic or simply the computational overhead is too large.

The talk will begin by exploring the landscape of the state-of-the-art DD methods for CEM. In the main part of the talk key insights about the root causes of the robustness and scalability problems of DD methods will be given, leading the way to the development of a new class of preconditioners, the locally exact algebraic preconditioner (LEAP) and the Dual Overlaping Primal FETI (FETI-DOP). The talk will close with results, future outlooks, and extensions to outer disciplines.

	Tuesday, June 5, 2012
	Music Room
13:30	**Session 12: Advanced FEM/MoM Modeling, Design, and Optimization (C. J. Reddy, U. Jakobus, J. Zapata, J. Gil, D. Jiao, A. Cangellaris)**
	12.1. Overview of the Hybrid Finite Element Method/Method of Moments Capability in FEKO *Marianne Bingle*, Ulrich Jakobus, and Johann J. van Tonder*
13:50	**12.2.** Application of Hybrid FEM/MoM Technique for Handheld Mobile Devices *Rensheng Sun and C. J. Reddy*
14:10	**12.3.** Application of Hybrid FEM/MoM Technique for Cavity Backed Apertures *Gopinath Gampala, Rensheng Sun and C. J. Reddy*
14:30	**12.4.** Eigenproblem Approach for Analysis and Optimization of Microwave Filters Using Finite Element Method *Adam Lamecki, Michal Mrozowski*
14:50	**12.5.** Does Sensitivity Analysis for Fast Frequency Sweeps Converge? *Andreas Köhler, Ortwin Farle, Romanus Dyczij-Edlinger**
15:10	Coffee break (Pinion room)
15:40	**12.6.** Benchmark of Conformal Finite-Difference Method against Finite Element Method *M. C. Lin*
16:00	**12.7.** Layout-Integrated Electromagnetic Interconnect Characterization and Simulation *Dennis Nagle, Jilin Tan, Jian-Ming Jin*
16:20	**12.8.** An Extraction-Free Circuit Simulator of Linear Complexity Guided by Electromagnetics-Based First Principles *Qing He, Duo Chen, and Dan Jiao*
16:40	**12.9.** A model reduction method for multiple particle electromagnetic scattering in three dimensions *M. Ganesh*, J. Hesthaven, and B. Stamm*

Overview of the Hybrid Finite Element Method / Method of Moments Capability in FEKO

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FEKO (www.feko.info) has been established as a versatile and comprehensive electromagnetic simulation software tool. The core technology is the method of moments (MoM). Over the past two decades the MoM has been hybridized in FEKO with other methods, including the Finite Element Method (FEM), Physical Optics (PO), Geometrical Optics (GO) and the Uniform Theory of Diffraction (UTD). Hybridization expands the range of application, allowing solution of problems which would be intractable with any individual method. Furthermore, the Multilevel Fast Multipole Method (MLFMM) — a fast integral equation solution technique — is supported in the MoM and hybrid FEM/MoM frameworks.

This presentation will give an overview of the hybrid FEM/MoM capability in FEKO.

The hybrid FEM/MoM takes the full coupling between metallic structures in the MoM region and dielectric bodies in the FEM region into account. The strengths of the two techniques can thus be exploited, viz. the efficiency of the MoM for modeling open boundary radiating structures without discretization of the environment, and the efficiency of the FEM for modeling inhomogeneous dielectric bodies. The MLFMM is an acceleration technique for the MoM. It extends the capability to compute full wave solutions for electrically large structures, and in particular in combination with the FEM for electrically large structures together with complex dielectrics objects.

Computational aspects regarding the FEM/MoM and FEM/MLFMM include the following: Iterative solvers are employed together with sophisticated preconditioners for an efficient computation. A good preconditioner is essential to ensure convergence, with trade-offs between calculation time, memory usage and iterative convergence rate. Parallel processing for distributed memory environments is supported. Parallel processing achieves faster solution times and by employing distributed memory larger problems can be solved on less expensive computing clusters.

Electromagnetic modeling capabilities for the FEM include the following: dielectric and magnetic materials, perfect conductor surfaces, complex surface properties, e.g. metallic surfaces exhibiting the skin effect, modal ports of arbitrary cross section, impressed filament current sources, lumped complex load impedances. The FEM and MoM can be decoupled for a simplified solution, then only coupling from MoM to FEM is taken into account and an absorbing boundary condition is applied to the FEM and symmetry may be employed to enhance solver efficiency.

Typical applications include antenna simulations, radiation hazard investigations where humans interact with RF equipment, the modeling of waveguide filters with dielectric blocks in the filter and the modeling of microstrip patches on finite substrates.

Application of Hybrid FEM/MoM Technique for Handheld Mobile Devices

Rensheng Sun and C. J. Reddy

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The increasing prevalence of handheld mobile devices such as smartphones and tablet computers provides both opportunities and challenges to antenna design engineers nowadays, because the designers not only need to have antennas cover multi-band and/or multi-purpose communications as standalone elements, they are also required to make sure the antennas perform well after the integration into the devices. Very often, full wave analysis needs to be carried out to study the mutual couplings between multiple antennas in addition to their radiation characteristics, considering the effects not only from handset case and LCD, but also from many other components, such as battery, speaker, PCB, etc.

The finite element method (FEM) is intrinsically suitable for such problems since it is very efficient on modeling 3D volumes that have complex geometrical details and material inhomogeneities. However, as FEM formulation doesn't incorporate the Sommerfeld radiation condition, usually the radiation condition in FEM implementations is applied using appropriate absorbing boundary condition (ABC), or perfectly matched layer (PML) technique. This requires the domain of discretization be extended far from the source region. The integral equation method such as Method of Moments (MoM) is an ideal formulation for open boundary radiating/scattering structures. As a result, the domain of discretization can be kept to a minimum. The hybrid FEM/MoM exploits the benefits from both techniques: the efficiency of the MoM for the treatment of open boundary radiating structures because no discretization of three-dimensional (3-D) space is required, and the efficiency of the FEM for the treatment of inhomogeneous dielectric bodies. The approach proves to be especially efficient when both transmitter and receiver need to be included in the same modeling session. It is also a preferred method for bioelectromagnetic problems such as radiation hazard with specific absorption rate (SAR) calculations (F.J.C. Meyer, *etc*. "Human exposure assessment in the near field of GSM base-station antennas using a hybrid finite element/method of moments technique," IEEE Trans. Biomedical Engineering, vol. 50, no. 2, pp. 224-233, Feb. 2003).

In this talk, various examples and extensive results from full wave simulations with hybrid FEM/MoM for handheld mobile devices will be presented. Performance of standalone antennas and possible degradation after the integration will be examined. Computational resources and solution accuracy will be discussed as well, along with the considerations on how problem complexity and material inhomogeneity affect the computation performance.

Application of Hybrid FEM/MoM Technique for Cavity Backed Apertures

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Abstract:

The finite element method (FEM) is widely used in computational electromagnetics since it is very efficient on modeling 3D volumes that have complex geometrical details and material inhomogeneities. For radiation/scattering problems, usually the radiation condition in FEM implementations is applied using appropriate absorbing boundary condition (ABC), or perfectly matched layer (PML) technique. This requires the domain of discretization be extended far from the source region. The integral equation method such as Method of Moments (MoM) is an ideal formulation for open boundary radiating/scattering structures. As a result, the domain of discretization can be kept to a minimum. Hybrid FEM/MoM technique was used in the past to predict characteristics of cavity backed antennas embedded in infinite ground plane. In most antenna-pattern measurements, the infinite ground plane is simulated by a relatively large finite ground plane. Although this simulation does not appreciably affect the input admittance measurements, diffractions from the edges of the ground plane modify the radiation pattern considerably. In the past, the geometrical theory of diffraction (GTD) was successfully applied to predict the changes in the radiation pattern of the aperture antennas caused by a finite ground plane. In ref 1 and 2, various cavity backed apertures (a) open coaxial line[1], (b) coaxial cavity[1] and (c) cavity-backed spiral antenna[2] were analyzed using FEM/MoM/GTD technique. The hybrid FEM/MoM was introduced with the commercial code FEKO. Simulations are carried out to validate implementation hybrid FEM/MoM technique using measured data in ref (2). Some of the validation results were presented at FEM 2006 workshop, Though we have seen excellent agreement between measured data and FEKO simulations for cases (a) and (b), we noticed discrepancy between FEKO simulations and measured data for case (c). In this paper we revisited this problem to investigate and resolved discrepancies observed earlier. In addition, we also applied newly introduced FEM/MLFMM technique in FEKO to the above problems for validation using the experimental data in ref (1 & 2). Numerical results will be presented at the FEM 2012 workshop.

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Eigenproblem Approach For Analysis and Optimization of Microwave Filters Using Finite Element Method

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Design of high power filters and multiplexers for modern communication systems involves full wave optimization based on extensive electromagnetic simulations of complex 3D structures. These simulations are often carried out using finite element method (FEM) due its ability to handle arbitrary shapes. However, the numerical cost associated with FEM analysis is high as one has to evaluate filter's response at several frequencies and optimize the design to fulfil the specifications, while modifying filter geometry.

A classic approach for computation of scattering/impedance parameters for a structure using FEM leads to a linear system $A \cdot x = b$ that has to be solved anew at each frequency point for a collection of excitations at the feeding ports (for the N-port device one gets N right hand sides at each frequency). Since matrix A is usually large, sparse and frequency-dependent, the numeric cost of solution procedure (using either direct or iterative methods) is high, especially if response at tens or hundreds frequency points needs to be computed.

An alterative approach is to replace the repeated solutions of linear problems with a defined set of eigenproblems. The new formulation binds the eigenvalues of the predefined eigenproblems with zeros and poles of the rational representation of impedance parameters $z_{ij(s)} = \frac{P(s)}{Q(s)}$ of the analyzed structure. Additionally, it is shown that the resulting eigenproblems can be efficiently solved using iterative eigensolvers, such as shift-and-invert Lanczos methods. The proposed formulation is particularly well suited for analysis of high frequency filtering devices, since their responses are commonly described by zeros and poles of the transfer function. This is because the extracted zeros and poles can be directly used in optimization of microwave filters using a special cost function involving sets of reference zeros and poles of ideal filter prototype (P. Kozakowski, M. Mrozowski, "Automated CAD of coupled resonator filters," IEEE Microwave and Wireless Components Letters, vol.12, no.12, pp. 470- 472, Dec 2002). The applications of the new methodology based on eigenvalue computations for optimization of microwave filters using FEM will be presented at the workshop.

Does Sensitivity Analysis for Fast Frequency Sweeps Converge?

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Fast frequency sweep (FFS) is a common term for highly efficient solution strategies for the broadband finite-element (FE) analysis of passive microwave structures. However, many applications do not only require the frequency response of certain system outputs but also their sensitivities w.r.t. variations in parameters such as geometry or material properties. In case of the original FE system, sensitivities at a given solution frequency are computed very efficiently by means of adjoint variables techniques: a number of forward-back substitutions suffice. It is therefore very appealing to apply the same method to the reduced-order systems of FFS's [1], [2]. Even though this approach has been used very successfully in the context of FE's [3], its convergence is far from obvious, for the following reasons: First, sensitivities are no longer given by first-order derivatives about expansions points at which the exact solution of the FE system is known. Second, the reduced-order models of FFS's are constructed with only the frequency in mind. Since the trial and testing spaces are of very low order, they may hold little information about derivatives w.r.t. to some other parameter.

The first part of the talk gives a formal convergence analysis in the general context of projection-based MOR, which covers both single- and multi-point methods. It will be proven theoretically and demonstrated numerically that, under the precondition that two-sided projections are used, i.e. that both excitation vectors and output functionals are taken into account, sensitivities of these outputs do converge, at a lower rate though. However, sensitivities of the (generalized) state variables do not converge. The latter deficiency is cumbersome in those cases when outputs are constructed in a post-processing step. Typical applications include the a posteriori definition of field probes, Huygens surfaces, or similar. The second part of the talk introduces an improved FFS approach that guarantees convergence of the sensitivities of the (generalized) system state and hence of any output defined in a post-processing step. We will present a general framework for the construction of trial and testing spaces which also covers recent works in circuit theory [4], and give numerical examples that illustrate our findings.

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Benchmark of Conformal Finite-Difference Method against Finite Element Method

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This work introduces a conformal finite difference method (CFDM) to accurately and efficiently study resonances in electromagnetic or radio frequency (RF) structures. For benchmark, we calculate the resonances of a circular cavity using the CFDM and compare the results with those from the finite element method (FEM). The accuracy of the CFDM is measured by comparing with calculations based on the finite element method. The results show that an accuracy of 99.4% can be achieved by using only 10,000 mesh points with the Dey-Mittra algorithm as implemented in the CFDM. By comparison, a mesh number of 250,000 is needed to preserve 99% accuracy using a staircased FDM. This suggests one can more efficiently and accurately study RF structures using the CFDM than a conventional FDM. For illustration, the dispersion relation of an A6 relativistic magnetron has also been determined and a comparison with finite element method has been done.

Layout-Integrated Electromagnetic Interconnect Characterization and Simulation

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MOTIVATION

With the continuous advancements in semiconductor technology, IC circuit's operating speed, routing density, and routing complexity have increased rapidly while the operating voltage and voltage swing have decreased sharply. Unwanted electromagnetic behaviors, such as signal reflection, cross-talk, signal noise, and electromagnetic interference impact significantly the performance of the circuitry functionalities and lead to the misjudgment of the digital signal's level and timing. The desired and unwanted electromagnetic behavior over interconnects among different subsystems, functional modules on a PCB or in a packaging must be analyzed and characterized accurately and efficiently to ensure a reliable system design.

The ever-increasing speed and the interconnect complexity lead to a wavelength comparable to the interconnect size which necessitates full-wave electromagnetic analysis. However, such a full-wave analysis is in general highly computationally demanding in terms of both memory and computation time. Most of the full-wave analysis algorithms typically require large-scale matrix equation solving which consumes the most memory and CPU usage. It has been one of the most crucial challenges to effectively solve the matrix equations with hundreds of thousands and even millions of unknowns to make the full-wave characterization and simulation practical. One way to reduce the complexity is domain decomposition. In this presentation, we discuss two decomposition mechanism implemented Cadence Allegro product line with finite element method. One is layout-aware decomposition and the other is EM solver specific decomposition.

LAYOUT LEVEL DOMAIN DECOMPOSITION

Typically in a PCB design, an initial layout exists which in parallel requires interactively SI analysis. Figure 1 shows a layout where a signal channel is selected for characterization and SI analysis. Look into the highlighted signal channel, clearly it would be resource misuse to solve the entire channel as one 3D structure when it can be decomposed into sub-domains while on the decomposition interfaces a few propagation modes can be well defined and be easily found. This layout level of decomposition can be applied to complicated SiP or SOP designs in which systems are contained in the other system and are implemented in one or multiple stacked packages.

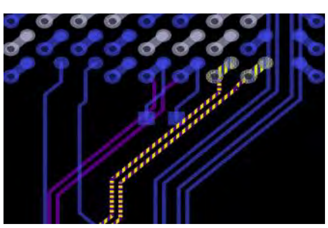
Figure1 Layout in Cadence Allegro editor

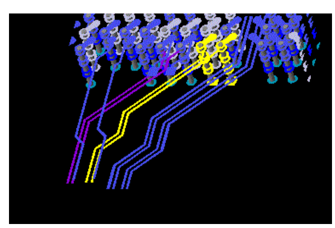
Figure2 Sub-domain for EM Solver to apply

DOMAIN DECOMPOSITION WITHIN EM SOLVER

For each decomposed sub-domains, computational electromagnetic methods will be applied to extract necessary electrical parameters, either in FD or in TD. Since each so divided sub-domain can still be large and complicated, respected to today's computation software and hardware, further domain decomposition needs to be performed in the EM computation level. For this purpose, the finite element method is highly desired and efficient. Cadence and UIUC are jointly working actively on these levels of decomposition. Those sub-domains characterization or simulation is performed parallel on multi-core and even on distributed computation systems.

SUB-DOMAIN INTEGRATION

The decomposition is performed in such a way that each sub-domain is constructed in SPICE sub-circuit format and all the I/Os of those sub-circuit are clearly defined in the layout level structure extraction. The system level simulation can be performed naturally. Cadence and UIUC has developed full-wave spice to address the complicated EM behavior on SiP design which includes EMI and EMC prediction.

An Extraction-Free Circuit Simulator of Linear Complexity Guided by Electromagnetics-Based First Principles

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Circuit simulation is an increasingly indispensable tool for the design of integrated circuits (ICs). The most prominent circuit simulation programs are SPICE (Simulation Program with Integrated Circuit Emphasis) and its derivatives. SPICE is highly capable of simulating active devices. In the early years when interconnects could be modeled simply as lumped capacitors, the linear network is a very small component of an IC. The exponentially increased complexity of ICs, however, has made circuit simulation increasingly challenging.

In the prevailing circuit simulation paradigm, even though the simulation of a circuit is the end goal, the state-of-the-art circuit simulation flow involves first the construction of an RLC-based, T(ransmission)-line-based, or S-parameters-based representation of the linear network; this step is called extraction. The extracted model of the linear network is then stitched with the nonlinear devices for the simulation of the entire circuit. The sheer dominance of the linear network over the nonlinear network in today's and future generation integrated circuits poses challenges to the prevailing simulation paradigm in both extraction and simulation.

In this work, we develop an extraction-free circuit simulator that overcomes the challenges facing existing SPICE-based circuit simulators. It bypasses the step of extraction, while retaining an RLC-based perspective that allows a designer to continue to exercise his or her circuit intuition. The underlying model for simulation is inherently passive and stable. Moreover, it captures the interaction between the nonlinear circuit and the linear network, with the nonlinear-linear coupling rigorously taken into consideration. Perhaps more important, it allows for the simulation of a circuit of O(N) size including both nonlinear devices and the linear network in O(N) complexity, i.e., optimal complexity. As an added bonus, the proposed circuit simulator achieves electromagnetic-physics based accuracy. Application to very large-scale on-chip circuits involving close to 1 million CMOS transistors and interconnects having hundreds of millions of unknowns has demonstrated the superior performance of the proposed extraction-free circuit simulator.

A model reduction method for multiple particle electromagnetic scattering in three dimensions

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We consider a parameterized multiple electromagnetic scattering wave propagation model in three dimensions. The parameters in the model describe the location, orientation, size, shape, and number of scattering particles as well as properties of the input source field such as the frequency, polarization, and incident direction. The need for fast and efficient (online) simulation of the interacting scattered fields under parametric variation of the multiple particle surface scattering configuration is fundamental to several applications for design, detection, or uncertainty quantification.

For such dynamic parameterized multiple scattering models, the standard discretization procedures are prohibitively expensive due to the computational cost associated with solving the full model for each online parameter choice. In this work, we propose an iterative offline/online reduced basis computer model reduction approach for a boundary element method to simulate a parameterized system of surface integral equations reformulation of the multiple particle wave propagation model.

The approach includes (i) a greedy algorithm based computationally intensive offline procedure to create a selection of a set of a snapshot parameters and the construction of an associated reduced boundary element basis for each reference scatterer and (ii) an inexpensive online algorithm to generate the surface current and scattered field of the parameterized multiple wave propagation model for *any* choice of parameters within the parameter domains used in the offline procedure. Comparison of our numerical results with experimentally measured results for some benchmark configuration demonstrate the power of our method to rapidly simulate the interaction of scattered wave fields under parametric variation of the overall multiple particle configuration.

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