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14. ABSTRACT

This document is the first interim research performance report of the Young Investigator Program (YIP) project funded by the Office of Naval Research. The report discusses the tasks performed during the first year of the project and the outcomes achieved.

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Contents

1. Summary of Annual Accomplishments

In this reporting period, we focused on examining the performance of the dual-mode conformal, ultra-broadband miniaturized antenna (CUBMA) in its common and differential modes of operation both theoretically and experimentally. The impact of the frequency-dependent mode-combining feed network on the performance of the antenna was also examined. It was demonstrated that an optimum feed network exists, which can considerably enhance the response of the antenna in its differential mode and offer broadband impedance matching in the differential mode. The effect of using a PEC[1], PMC[2], and a composite PEC/PMC ground plane on shaping the radiation characteristics of the antenna in its differential mode of operation were theoretically examined. We demonstrated that in each of these three cases, the radiation characteristics of the antenna in the differential mode can be tailored to enhance the vertically-polarized radiation from the antenna along the azimuth plane. This is instrumental in making the radiation characteristics of the antenna in the differential mode similar to that of the common mode. Additionally, the effect of antenna-platform coupling was also investigated for each of these three cases and antenna/platform decoupling techniques were developed for the cases where this coupling constituted a significant problem. Finally, two prototypes of a dual-mode CUBMA, which utilizes a PEC ground plane and an appropriate frequency-dependent mode combining network, were fabricated and tested. It was demonstrated that the proposed frequency-dependent mode-combining feed network can successfully be used to feed the dual-

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[1] PEC: Perfect Electric Conductor

[2] PMC: Perfect Magnetic Conductor

mode CUBMA in the appropriate mode of operation based on the frequency of the excitation signal.

2. Major Tasks Conducted in Year 1 and Outcomes

In this project, we pursue four specific aims as listed below:

- Aim 1: Investigation of the “closely-coupled miniaturized radiator” concept.
- Aim 2: Self-interference mitigation and broadband consistent radiation patterns.
- Aim 3: Antenna/platform coupling issues and decoupling techniques.
- Aim 4: Visual signature elimination and radar signature evaluation.

The tasks conducted in this reporting period pertain to Aims 1, 2, and 3. Specifically, four major tasks were conducted as described in Sections 2.1-2.4. In the following sections, we refer to the figures and the results presented at the program review meeting slides (PRMS). A copy of PRMS is provided as Appendix 1.

2.1. Developing Theoretical Framework for the Concept of Closely-Coupled Multi-Mode Radiators

The concept of closely-coupled multi-mode radiators was investigated theoretically by examining the dual-mode radiator shown in Slide 6 of PRMS. Since the behavior of this antenna in its common mode is well understood, our focus was on the antenna’s performance in the differential mode (DM).

Feed Network Effects: The effect of feed network on the impedance matching of the antenna in the differential mode was examined (see Slides 10-12 of PRMS). It was shown that a feed network composed of a power divider and frequency-dependent phase shifter offers a broader impedance bandwidth than a direct differential feed (e.g., using a balanced transmission line). The results are shown on Slides 10-12 of PRMS.

Mode Shaping Using the Ground Plane: To tailor the radiation characteristics of the antenna in the differential mode and make it similar to that of the common mode (CM), we investigated the use of three different ground plane arrangements. These include a PEC ground plane, a PMC one, and a hybrid PEC/PMC ground plane as shown in Slide 9 of the PRMS. It was demonstrated that the type of the ground plane affects the current distribution on the surface of the antenna and hence, the mode of radiation. This was used as a means to shape the radiation characteristics of the antenna in the DM and make that similar to that of the CM. In particular, the emphasis was on enhancing the vertically-polarized radiation from the antenna in the DM along the azimuth plane. It was found out that each of these three different cases offers the possibility of having dominant vertically-polarized radiation along the direction of azimuth plane. In particular, for the PMC and PEC/PMC ground planes, the finite size of the PMC was instrumental in enhancing the vertically polarized radiation from the antenna along the direction of the azimuth plane. The results of this investigation are presented in Slides 12-19 (PEC), Slides 20-25 (PMC), and Slides 26-27 (PEC/PMC) or the PRMS.

2.2. Radiation Pattern Optimization

In this period, we also investigated methods that can be used to enhance the omni-directionality of the antenna in the DM along the azimuth plane. In the DM, the antenna radiates as a two-element monopole array with excitation coefficients of +1 and -1 (see Slide 12 of PRMS). Therefore, the antenna's radiation pattern in this mode has a figure 8 shape in the azimuth plane (for the vertical component of the radiated field). While this may be useful for some applications that require directionality in the azimuth plane, in other applications, an omni-directional coverage is desired. We examined methods that can be used to enhance the omni-directionality of the antenna in the DM mode. Two principal methods can be envisioned to achieve this. These include: 1) Using an asymmetric array to reduce the depth of the null in the azimuth plane; and 2) Using a rotationally symmetric version of this antenna in conjunction with quadrature feeding to achieve omni-directionality. The effect of using an asymmetric structure in enhancing the omni-directionality of the antenna in the azimuth plane is shown in Slides 18-19 (for PEC) and Slide 27 (for PEC/PMC) of the PRMS. It is expected that achieving omni-directionality by using a quadrature feeding technique in conjunction with a rotationally symmetric version of the structure (see Slide 25 of PRMS) will be a more promising approach.

2.3. Antenna/Platform Coupling Investigation

All of the antenna designs described in previous sections have finite dimensions of 20 cm × 20 cm × 3 cm. In this period, we also examined how the response of this antenna changes when it is placed on top of a large metallic platform. It was found out that the response of the antenna in the differential mode is more sensitive to the presence of the platform than its response in the common mode is. In particular, the response of the antenna that uses a full PEC ground plane was found to be extremely sensitive to the presence of a large metallic platform. This scenario is shown in Slide 14 of PRMS where it can be seen that the response of the structure in the DM completely deteriorates when the antenna is mounted on a large metallic platform. We found that this change is due to the flow of electric current from the ground plane of the antenna to the platform. This allows for the establishment of image currents, which completely cancel the horizontal component of the electric currents flowing on the surface of the antenna. This reduces the radiation resistance of the structure and makes it almost impossible to achieve impedance matching in the DM. It was found out that this problem can be solved by electrically insulating the ground plane of the antenna from its supporting platform as shown in Slide 15 of PRMS. As can be seen in Slides 15 and 16 of PRMS, this decoupling technique restores the performance of the antenna in the differential mode.

The effect of antenna/platform coupling for other ground plane arrangements were also investigated (PMC and PEC/PMC). It was found that the response of the antenna utilizing a PMC ground plane is practically insensitive to the platform presence (see Slides 23 and 24 of PRMS). Antenna/platform coupling issues for the antenna utilizing a hybrid PEC/PMC are still under investigation.

2.4. Experimental Verification

To verify the underlying hypotheses, two prototypes of a dual-mode CUBMA were also fabricated. The first prototype is an asymmetric structure which uses a complete PEC ground plane (see Slides 30-31 of PRMS). The frequency-dependent feed network shown in Slide 29-30 of PRMS was used to feed this antenna in the appropriate mode of operation based on the frequency of the excitation signal. Initial measurements of the structure demonstrate that the responses of the two modes can be successfully combined and the bandwidth of the antenna can be extended at the lower frequency range by utilizing the differential mode. In particular, the measurement results shown in Slide 31 of PRMS show that the lowest frequency of operation of the antenna can be reduced by almost a factor of 2 when the DM is effectively utilized.

A second prototype of a dual-mode CUBMA is also fabricated and is currently under test. This prototype uses a rotationally symmetric version of the antenna in conjunction with a quadrature feeding technique. A feed network composed of power dividers, frequency-dependent phase shifters, and 90° phase shifters has been used to feed this prototype. Initial measurements demonstrate that the mode combining works in this structure as well. However, because of the strong interactions of different radiators with each other, the optimum parameters of the feed network are expected to be different from our initial assumption. We are currently in the process of re-optimizing this rotationally symmetric prototype.

3. List of Publications

- Y. Yusuf and N. Behdad, “Miniaturization of a Class of Ultra-Wideband Antennas Using Dual-Mode Radiating Structures,” *submitted to the 2012 IEEE International Conference on Wireless Information Technology and Systems (ICWITS)*, July 29-Aug 3 2012, Honolulu, HI.
- Y. Yusuf and N. Behdad, “Compact, Low-Profile UWB Antennas Exploiting the Concept of Closely-Coupled Dual-Mode Radiators,” *Accepted for Publication, 2012 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting*, July 8-14, 2012, Chicago, IL.
- N. Behdad, M. Li, and M. Al-Joumayly, “Ultra-Low Profile, Compact UWB Antennas Based on the Concept of Closely Coupled, Dual-Mode Radiators,” *2011 Antenna Applications Symposium*, Robert Allerton Park, Monticello IL, September 20-22, 2011.

4. Appendix

4.1. Appendix 1: Electronic version of the slides presented at the program review meeting

A copy of the slides presented at the program review meeting held on February 8. 2012 is attached as Appendix 1.

4.2. Appendix 2: Electronic copies of the publications

Electronic versions of the accepted/published papers that resulted from this work in the first reporting period are attached as Appendix 2.

THE UNIVERSITY of WISCONSIN MADISON

Closely coupled multi-mode radiators: A new concept for improving the performance of electrically small antennas

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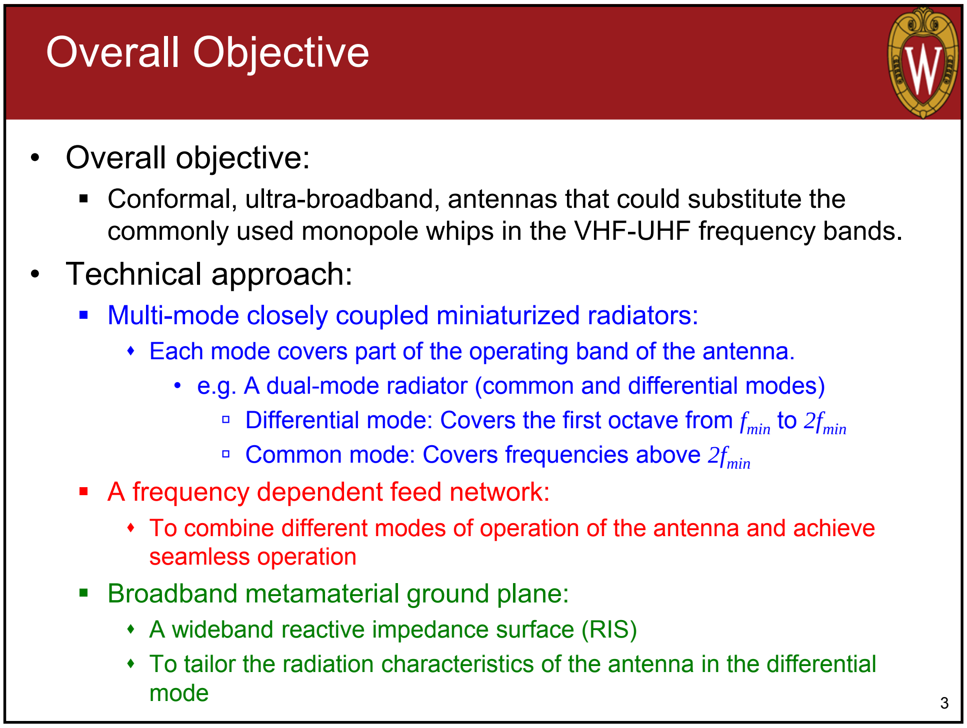
Department of Electrical and Computer Engineering
University of Wisconsin-Madison

ONR YIP Project Program Review Meeting
Wednesday February 8, 2012

This material is based upon work supported by the Office of Naval Research under ONR Award No. N00014-11-1-0618.

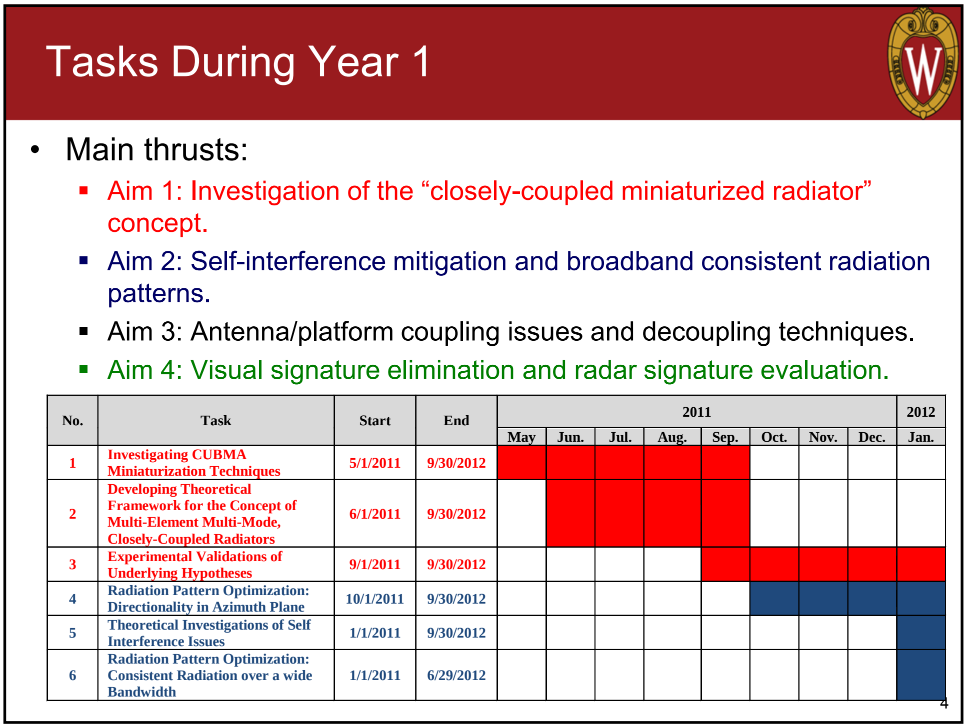
Outline

- Review of overall objectives
- Specific aims
- Tasks during year 1
- Summary of the important results of our current studies so far:
    - Theoretical analysis of the antenna in the differential mode for (PEC, PMC, and PEC/PMC) ground planes
    - Antenna platform coupling
    - Feed network design
    - Experiments
- Timeline
- Future work



Overall Objective

- Overall objective:
  - Conformal, ultra-broadband, antennas that could substitute the commonly used monopole whips in the VHF-UHF frequency bands.
- Technical approach:
  - Multi-mode closely coupled miniaturized radiators:
    - Each mode covers part of the operating band of the antenna.
      - e.g. A dual-mode radiator (common and differential modes)
        - Differential mode: Covers the first octave from f_{min} to $2f_{min}$
        - Common mode: Covers frequencies above $2f_{min}$
  - A frequency dependent feed network:
    - To combine different modes of operation of the antenna and achieve seamless operation
  - Broadband metamaterial ground plane:
    - A wideband reactive impedance surface (RIS)
    - To tailor the radiation characteristics of the antenna in the differential mode

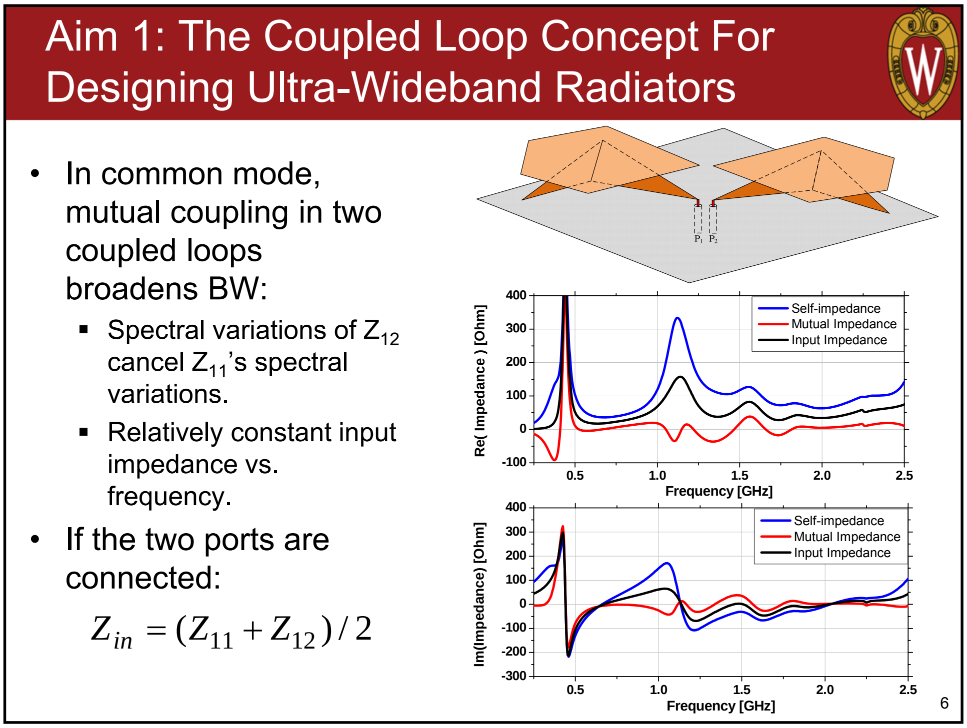


Tasks During Year 1

- Main thrusts:
  - Aim 1: Investigation of the “closely-coupled miniaturized radiator” concept.
  - Aim 2: Self-interference mitigation and broadband consistent radiation patterns.
  - Aim 3: Antenna/platform coupling issues and decoupling techniques.
  - Aim 4: Visual signature elimination and radar signature evaluation.

No.	Task	Start	End	2011								2012
				May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.
1	Investigating CUBMA Miniaturization Techniques	5/1/2011	9/30/2012	🟥	🟥	🟥	🟥	🟥				
2	Developing Theoretical Framework for the Concept of Multi-Element Multi-Mode, Closely-Coupled Radiators	6/1/2011	9/30/2012		🟥	🟥	🟥	🟥				
3	Experimental Validations of Underlying Hypotheses	9/1/2011	9/30/2012					🟥	🟥	🟥	🟥	🟥
4	Radiation Pattern Optimization: Directionality in Azimuth Plane	10/1/2011	9/30/2012						🟦	🟦	🟦	🟦
5	Theoretical Investigations of Self Interference Issues	1/1/2011	9/30/2012									🟦
6	Radiation Pattern Optimization: Consistent Radiation over a wide Bandwidth	1/1/2011	6/29/2012									🟦

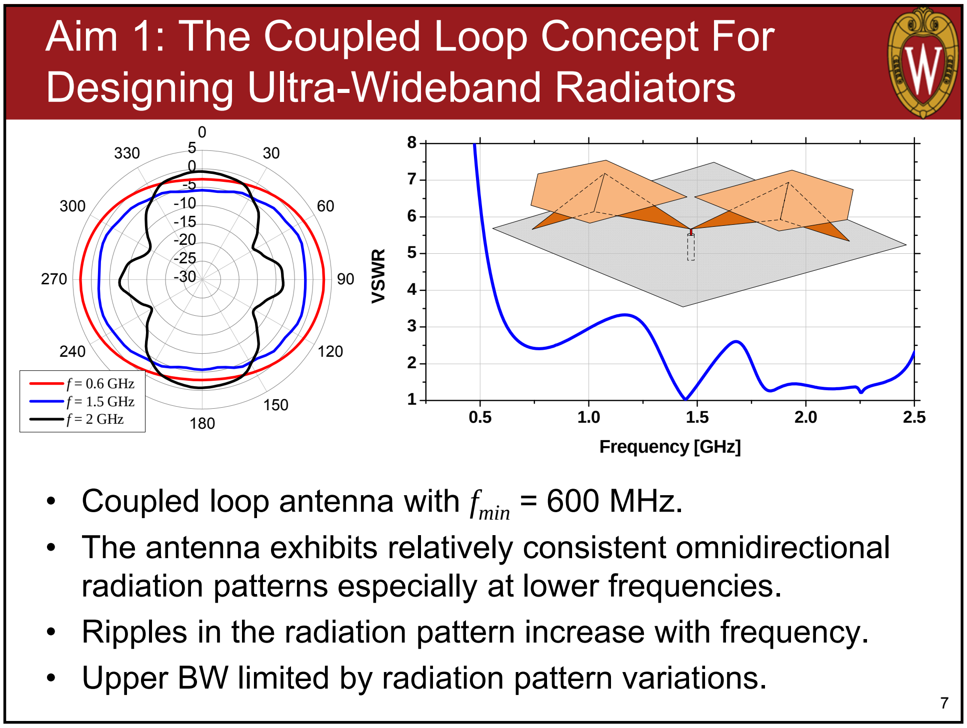
Summary of the Important Results of Our Current Studies



Aim 1: The Coupled Loop Concept For Designing Ultra-Wideband Radiators

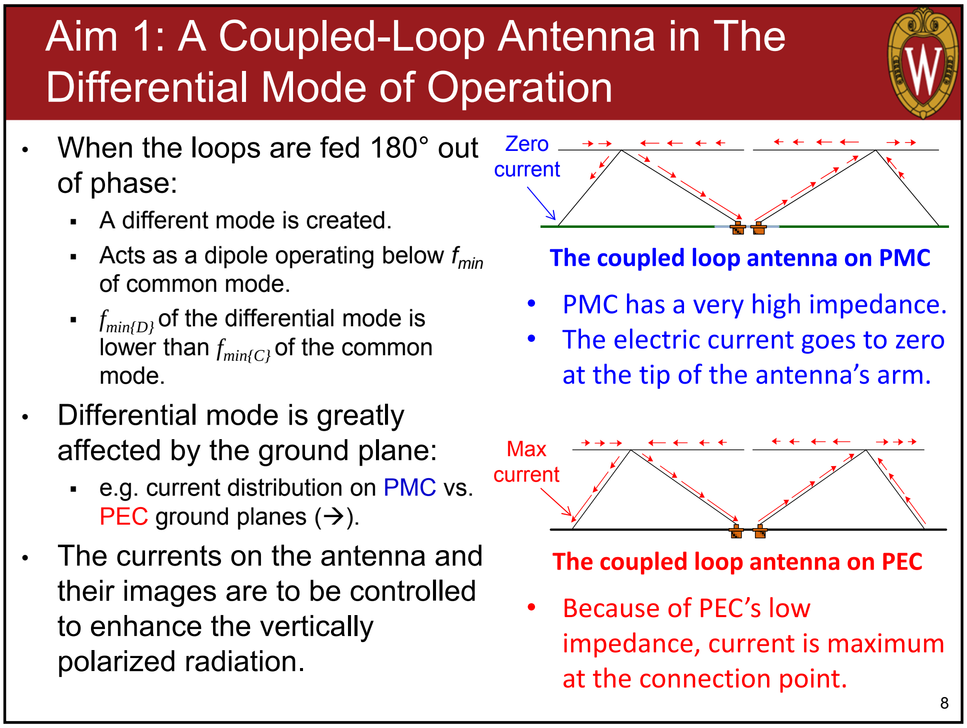
- In common mode, mutual coupling in two coupled loops broadens BW:
  - Spectral variations of Z_{12} cancel Z_{11}'s spectral variations.
  - Relatively constant input impedance vs. frequency.
- If the two ports are connected:

$$Z_{in} = (Z_{11} + Z_{12})/2$$



Aim 1: The Coupled Loop Concept For Designing Ultra-Wideband Radiators

- Coupled loop antenna with f_{min} = 600 MHz.
- The antenna exhibits relatively consistent omnidirectional radiation patterns especially at lower frequencies.
- Ripples in the radiation pattern increase with frequency.
- Upper BW limited by radiation pattern variations.



Aim 1: A Coupled-Loop Antenna in The Differential Mode of Operation

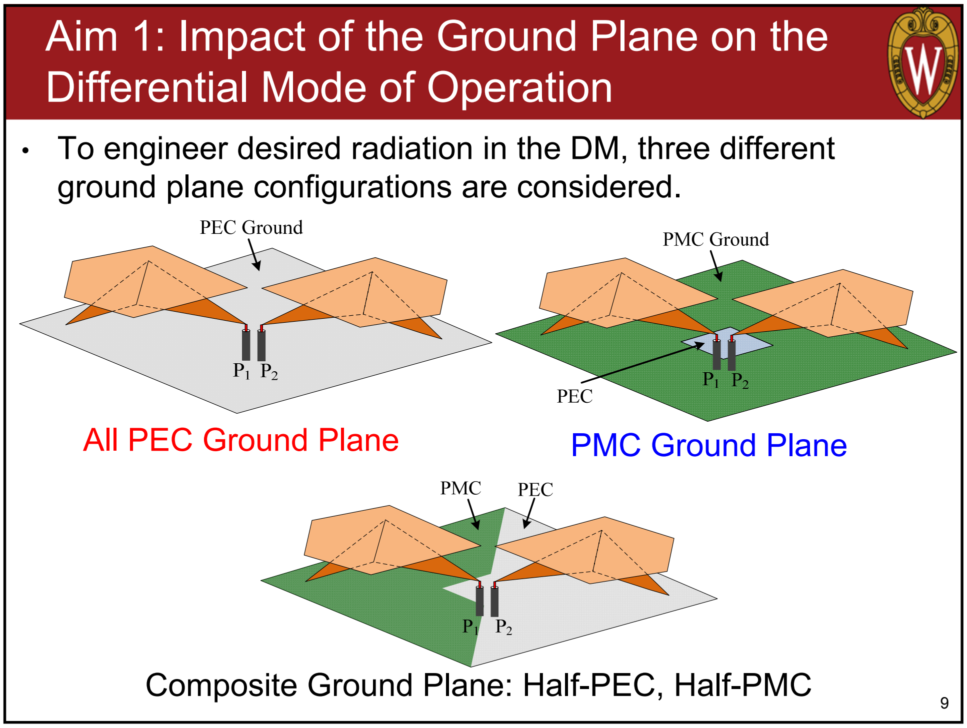
- When the loops are fed 180° out of phase:
  - A different mode is created.
  - Acts as a dipole operating below f_{min} of common mode.
  - $f_{min\{D\}}$ of the differential mode is lower than $f_{min\{C\}}$ of the common mode.
- Differential mode is greatly affected by the ground plane:
  - e.g. current distribution on PMC vs. PEC ground planes (→).
- The currents on the antenna and their images are to be controlled to enhance the vertically polarized radiation.

The coupled loop antenna on PMC

- PMC has a very high impedance.
- The electric current goes to zero at the tip of the antenna’s arm.

The coupled loop antenna on PEC

- Because of PEC’s low impedance, current is maximum at the connection point.



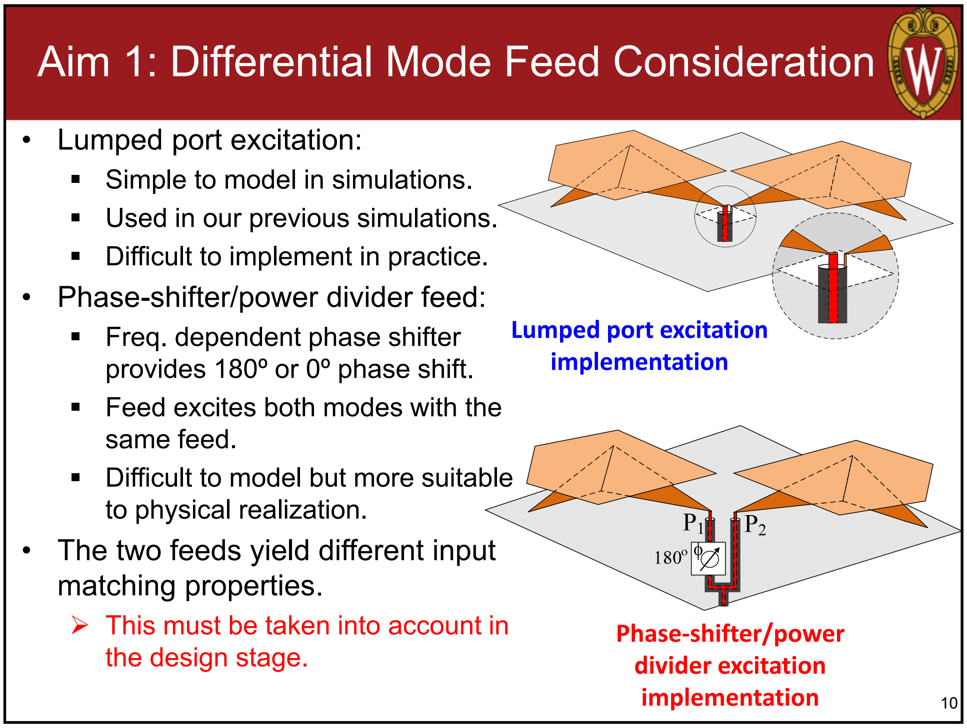
Aim 1: Impact of the Ground Plane on the Differential Mode of Operation

- To engineer desired radiation in the DM, three different ground plane configurations are considered.

All PEC Ground Plane

PMC Ground Plane

Composite Ground Plane: Half-PEC, Half-PMC

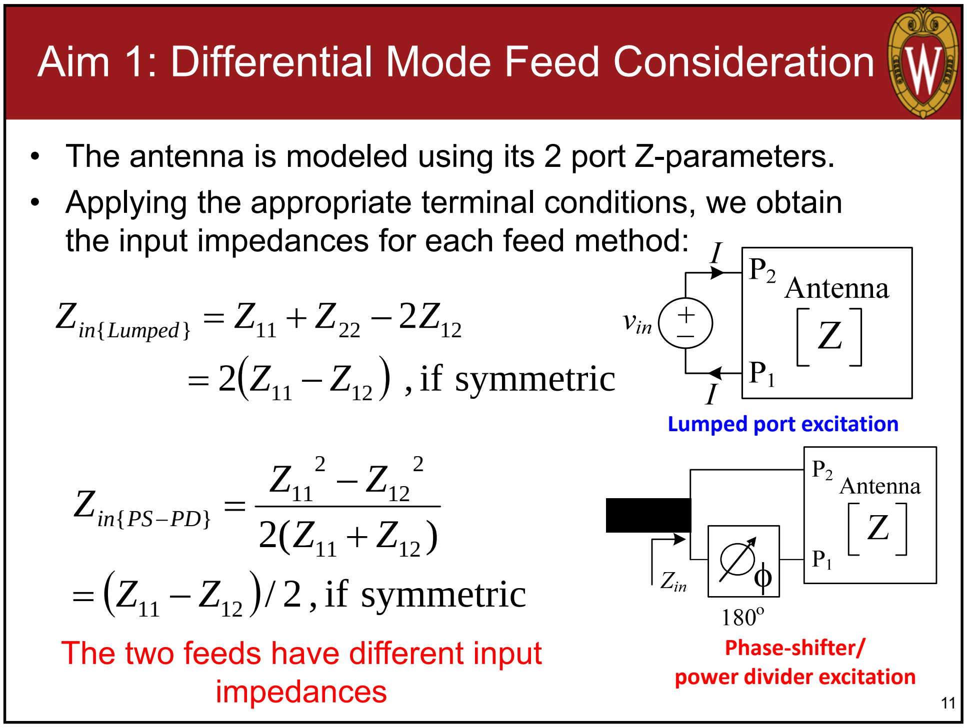


Aim 1: Differential Mode Feed Consideration

- Lumped port excitation:
  - Simple to model in simulations.
  - Used in our previous simulations.
  - Difficult to implement in practice.
- Phase-shifter/power divider feed:
  - Freq. dependent phase shifter provides 180° or 0° phase shift.
  - Feed excites both modes with the same feed.
  - Difficult to model but more suitable to physical realization.
- The two feeds yield different input matching properties.
  - ➢ This must be taken into account in the design stage.

Lumped port excitation implementation

Phase-shifter/power divider excitation implementation



Aim 1: Differential Mode Feed Consideration

- The antenna is modeled using its 2 port Z-parameters.
- Applying the appropriate terminal conditions, we obtain the input impedances for each feed method:

$$Z_{in\{Lumped\}} = Z_{11} + Z_{22} - 2Z_{12}$$

$$= 2\left(Z_{11} - Z_{12}\right) \text{ , if symmetric}$$

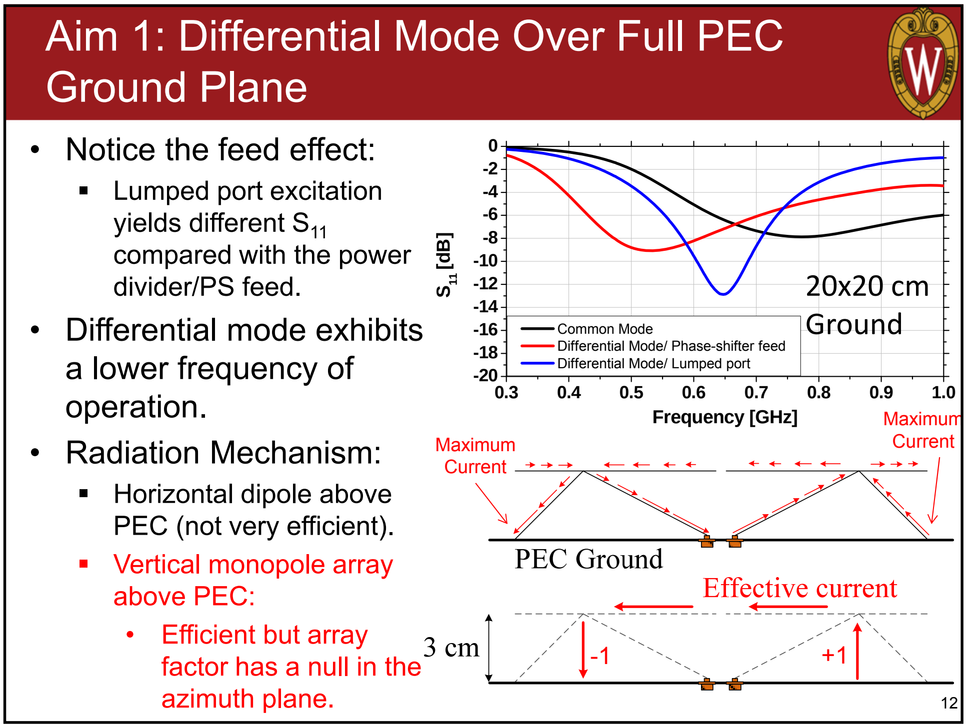
Lumped port excitation

$$Z_{in\{PS-PD\}} = \frac{Z_{11}{}^{2} - Z_{12}{}^{2}}{2(Z_{11} + Z_{12})}$$

$$= \left(Z_{11} - Z_{12}\right)/2 \text{ , if symmetric}$$

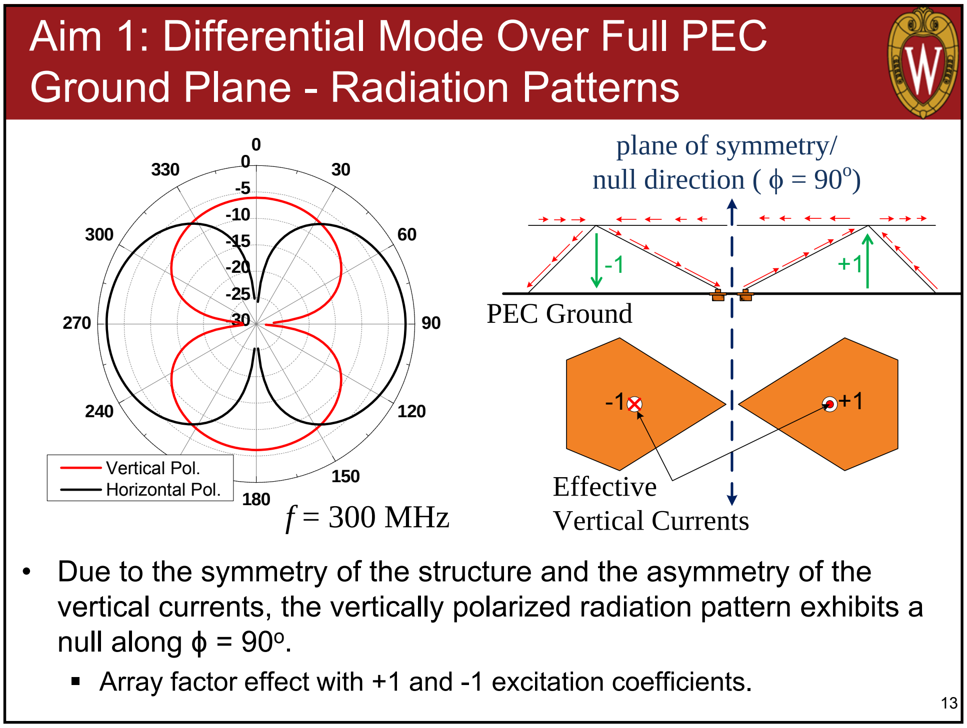
Phase-shifter/ power divider excitation

The two feeds have different input impedances



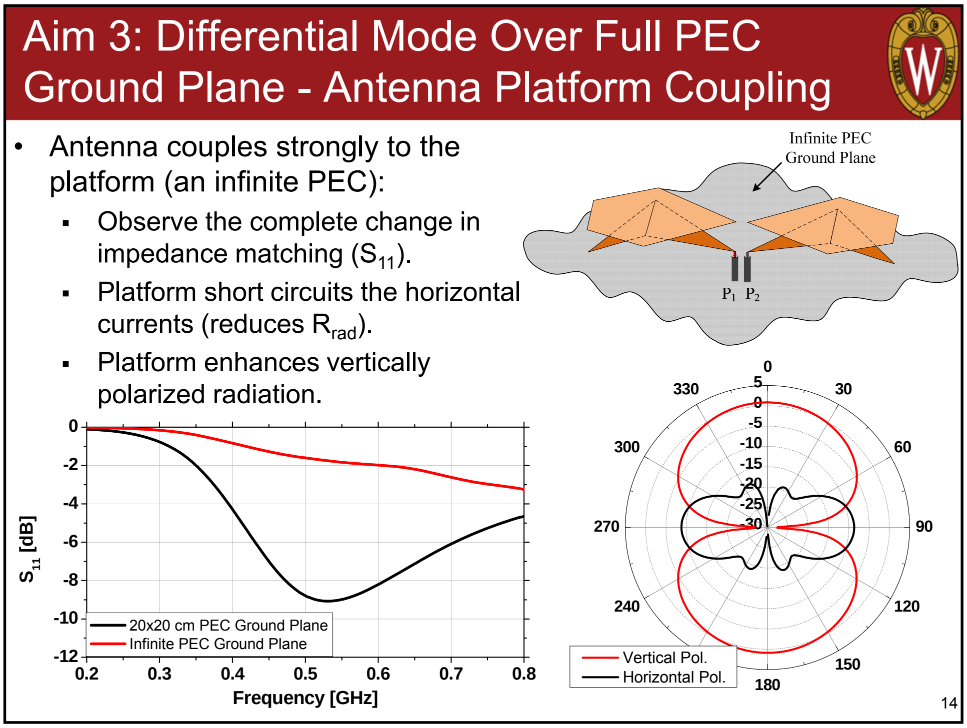
Aim 1: Differential Mode Over Full PEC Ground Plane

- Notice the feed effect:
  - Lumped port excitation yields different S_{11} compared with the power divider/PS feed.
- Differential mode exhibits a lower frequency of operation.
- Radiation Mechanism:
  - Horizontal dipole above PEC (not very efficient).
  - Vertical monopole array above PEC:
    - Efficient but array factor has a null in the azimuth plane.



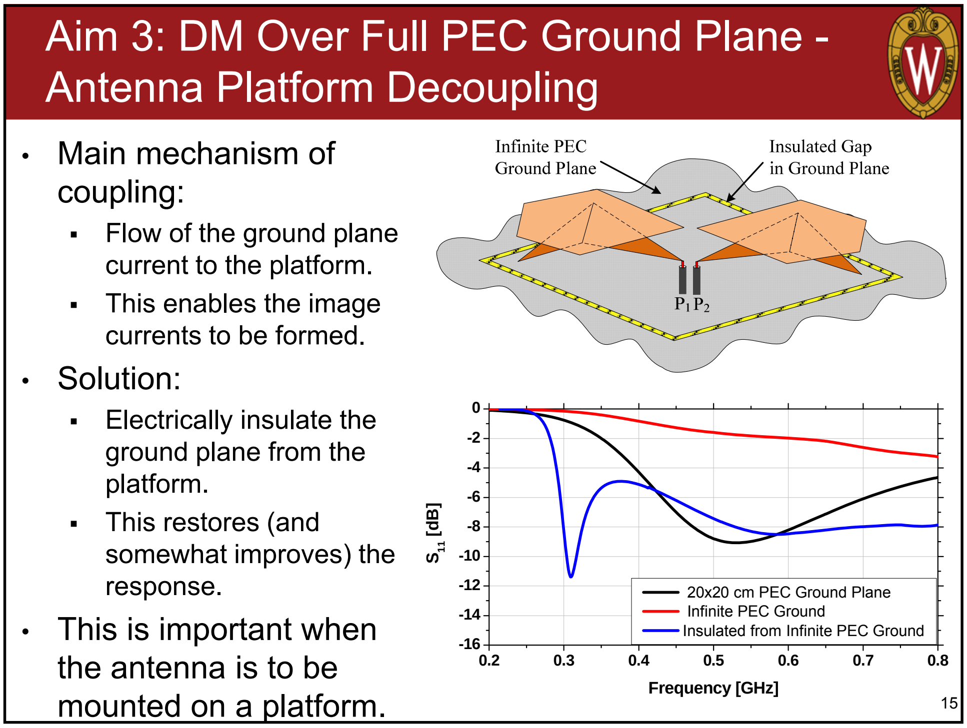
Aim 1: Differential Mode Over Full PEC Ground Plane - Radiation Patterns

- Due to the symmetry of the structure and the asymmetry of the vertical currents, the vertically polarized radiation pattern exhibits a null along ϕ = 90°.
  - Array factor effect with +1 and -1 excitation coefficients.



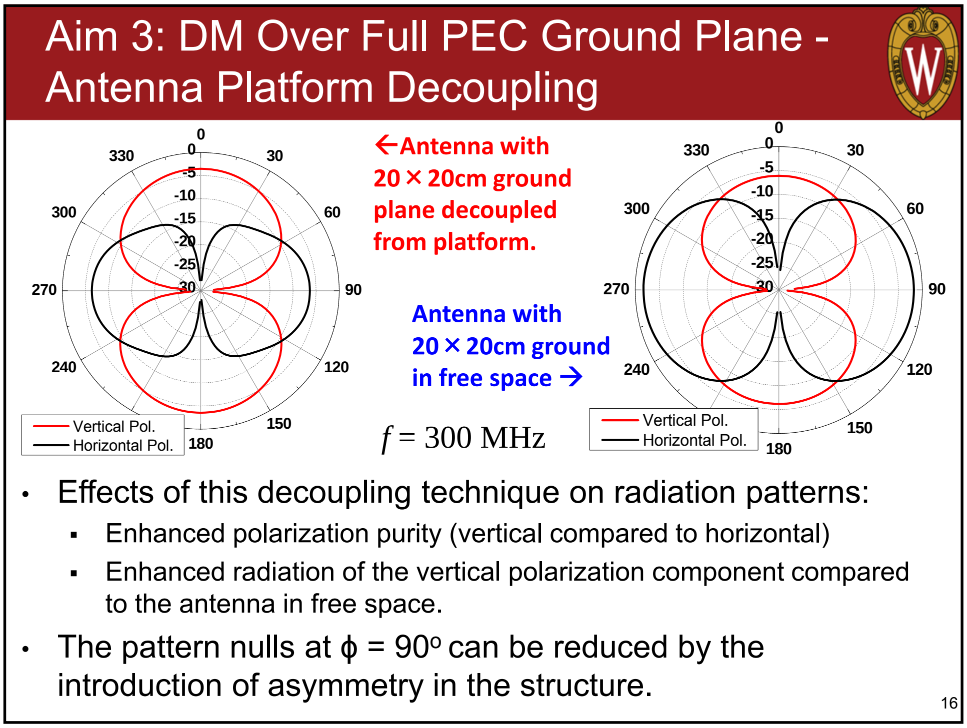
Aim 3: Differential Mode Over Full PEC Ground Plane - Antenna Platform Coupling

- Antenna couples strongly to the platform (an infinite PEC):
  - Observe the complete change in impedance matching (S_{11}).
  - Platform short circuits the horizontal currents (reduces R_{rad}).
  - Platform enhances vertically polarized radiation.



Aim 3: DM Over Full PEC Ground Plane - Antenna Platform Decoupling

- Main mechanism of coupling:
  - Flow of the ground plane current to the platform.
  - This enables the image currents to be formed.
- Solution:
  - Electrically insulate the ground plane from the platform.
  - This restores (and somewhat improves) the response.
- This is important when the antenna is to be mounted on a platform.



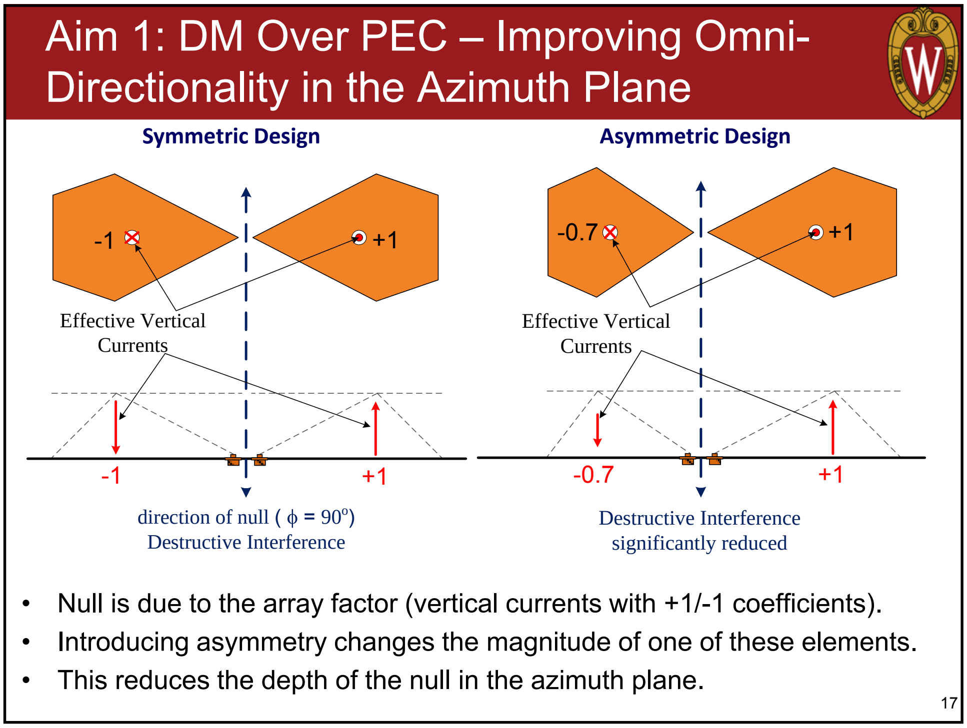
Aim 3: DM Over Full PEC Ground Plane - Antenna Platform Decoupling

←Antenna with 20 × 20cm ground plane decoupled from platform.

Antenna with 20 × 20cm ground in free space →

$f = 300$ MHz

- Effects of this decoupling technique on radiation patterns:
  - Enhanced polarization purity (vertical compared to horizontal)
  - Enhanced radiation of the vertical polarization component compared to the antenna in free space.
- The pattern nulls at ϕ = 90° can be reduced by the introduction of asymmetry in the structure.



Aim 1: DM Over PEC – Improving Omni-Directionality in the Azimuth Plane

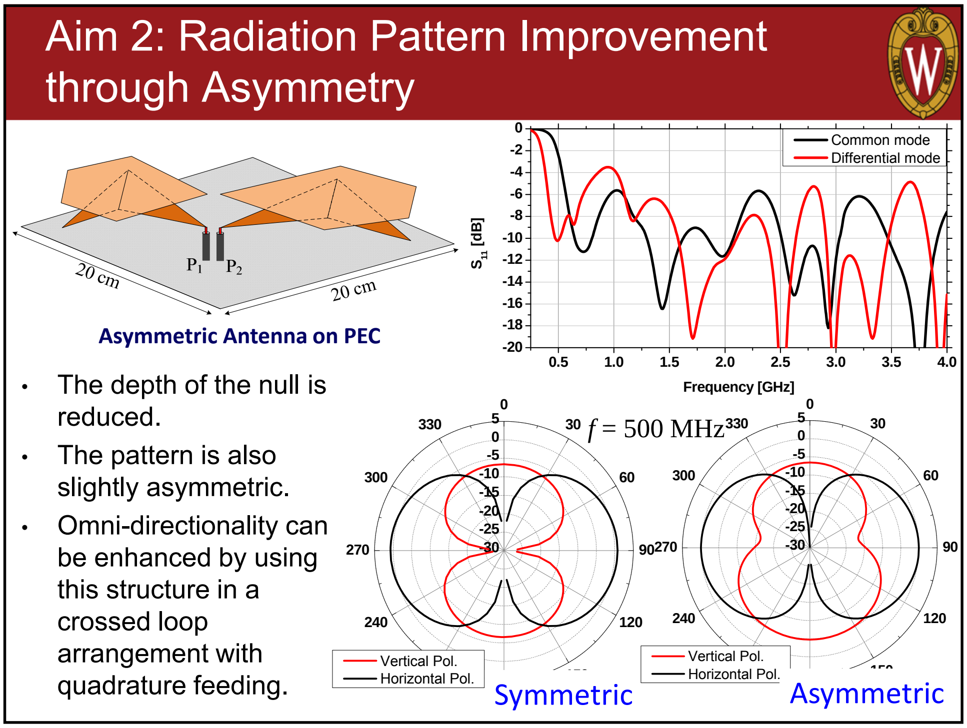
Symmetric Design

Asymmetric Design

direction of null (ϕ = 90^o)
Destructive Interference

Destructive Interference
significantly reduced

- Null is due to the array factor (vertical currents with +1/-1 coefficients).
- Introducing asymmetry changes the magnitude of one of these elements.
- This reduces the depth of the null in the azimuth plane.



Aim 2: Radiation Pattern Improvement through Asymmetry

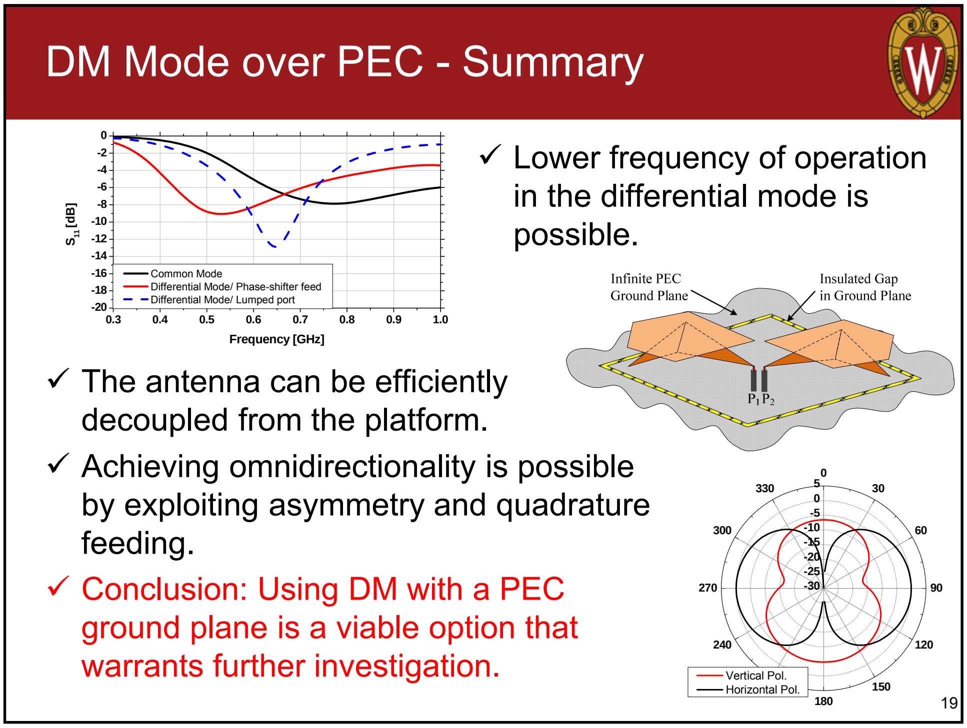
Asymmetric Antenna on PEC

- The depth of the null is reduced.
- The pattern is also slightly asymmetric.
- Omni-directionality can be enhanced by using this structure in a crossed loop arrangement with quadrature feeding.

f = 500 MHz

Symmetric

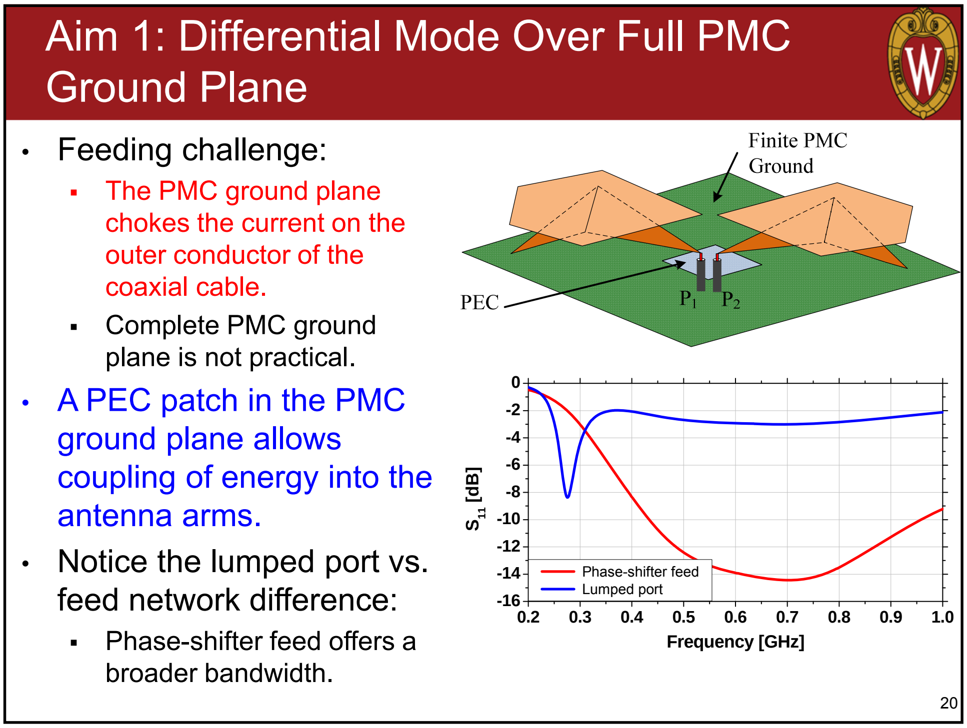
Asymmetric



DM Mode over PEC - Summary

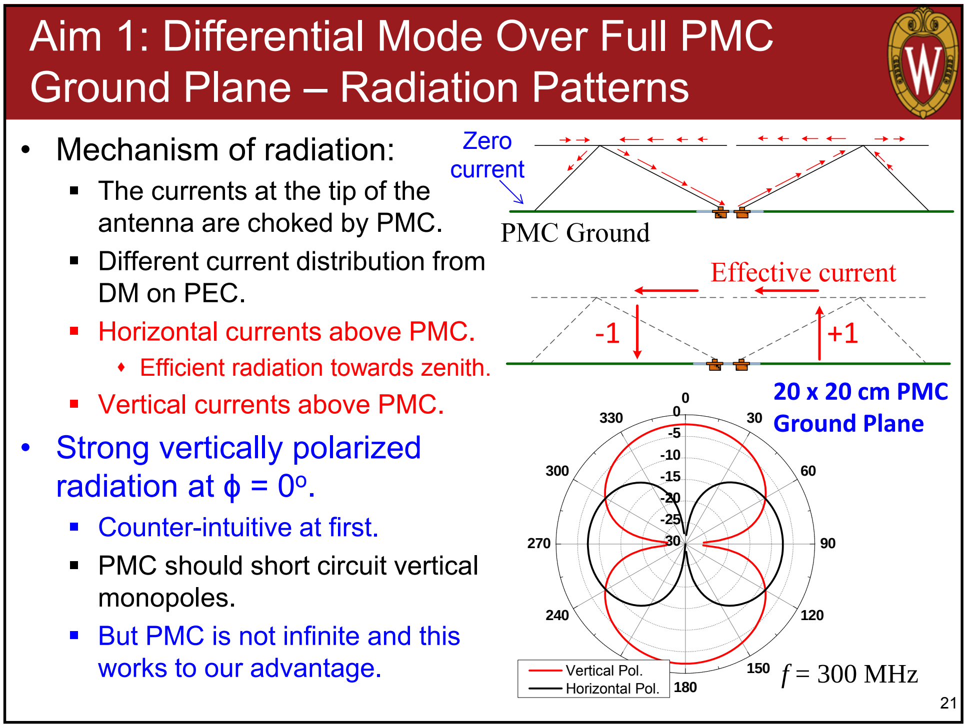
- ✓ Lower frequency of operation in the differential mode is possible.

- ✓ The antenna can be efficiently decoupled from the platform.
- ✓ Achieving omnidirectionality is possible by exploiting asymmetry and quadrature feeding.
- ✓ Conclusion: Using DM with a PEC ground plane is a viable option that warrants further investigation.



Aim 1: Differential Mode Over Full PMC Ground Plane

- Feeding challenge:
  - The PMC ground plane chokes the current on the outer conductor of the coaxial cable.
  - Complete PMC ground plane is not practical.
- A PEC patch in the PMC ground plane allows coupling of energy into the antenna arms.
- Notice the lumped port vs. feed network difference:
  - Phase-shifter feed offers a broader bandwidth.



Aim 1: Differential Mode Over Full PMC Ground Plane – Radiation Patterns

- Mechanism of radiation:
  - The currents at the tip of the antenna are choked by PMC.
  - Different current distribution from DM on PEC.
  - Horizontal currents above PMC.
    - Efficient radiation towards zenith.
  - Vertical currents above PMC.
- Strong vertically polarized radiation at ϕ = 0º.
  - Counter-intuitive at first.
  - PMC should short circuit vertical monopoles.
  - But PMC is not infinite and this works to our advantage.

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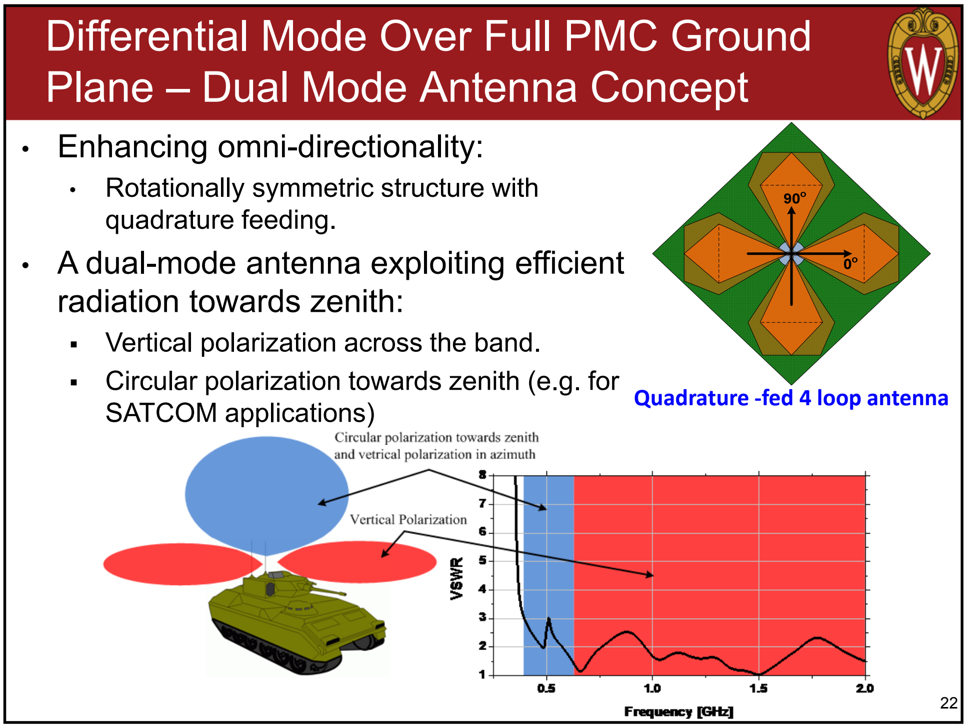

Differential Mode Over Full PMC Ground Plane – Dual Mode Antenna Concept

- Enhancing omni-directionality:
  - Rotationally symmetric structure with quadrature feeding.
- A dual-mode antenna exploiting efficient radiation towards zenith:
  - Vertical polarization across the band.
  - Circular polarization towards zenith (e.g. for SATCOM applications)

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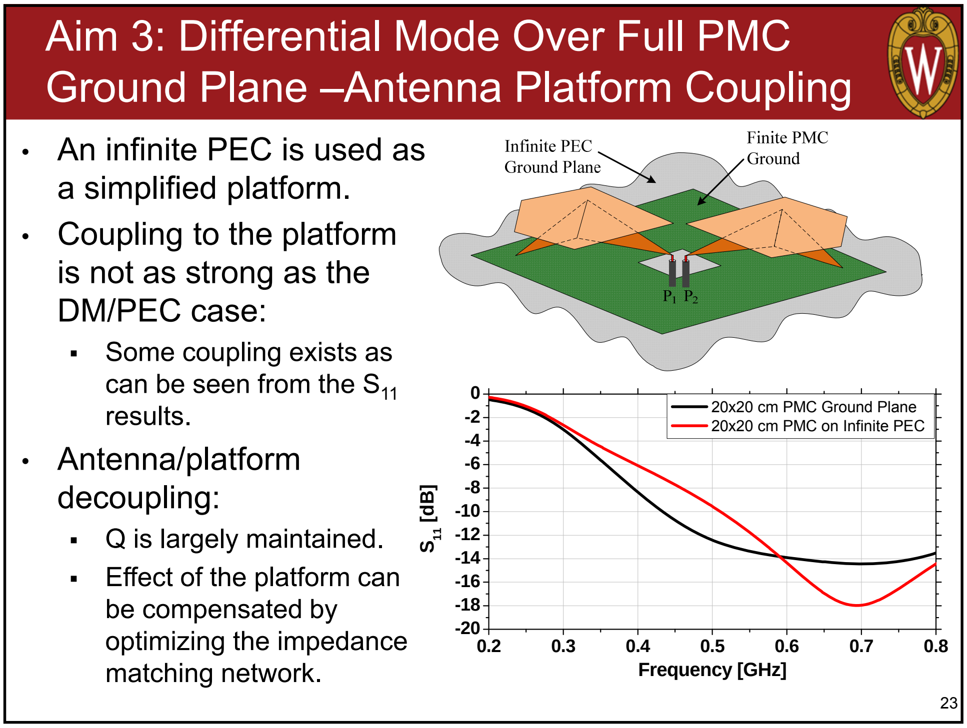
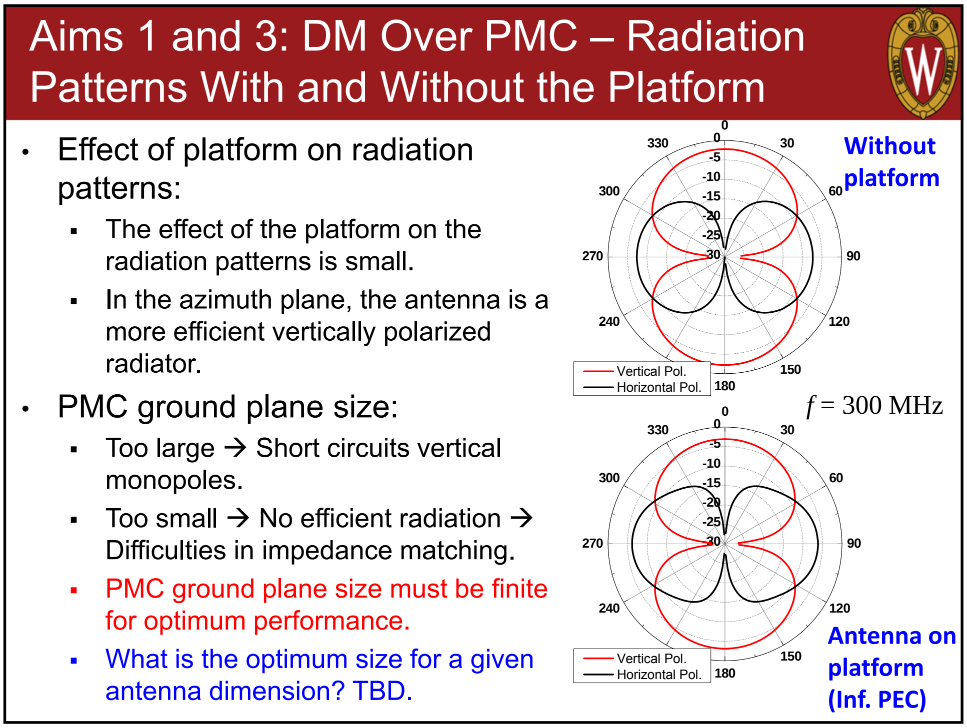


Aim 3: Differential Mode Over Full PMC Ground Plane –Antenna Platform Coupling

- An infinite PEC is used as a simplified platform.
- Coupling to the platform is not as strong as the DM/PEC case:
  - Some coupling exists as can be seen from the S_{11} results.
- Antenna/platform decoupling:
  - Q is largely maintained.
  - Effect of the platform can be compensated by optimizing the impedance matching network.



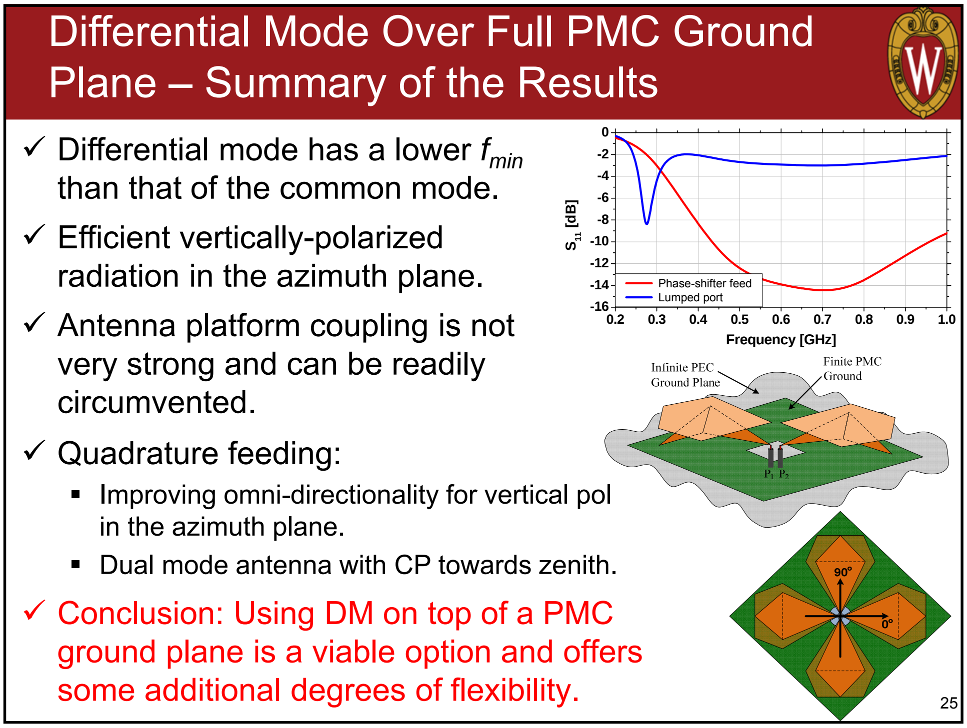
Aims 1 and 3: DM Over PMC – Radiation Patterns With and Without the Platform

- Effect of platform on radiation patterns:
  - The effect of the platform on the radiation patterns is small.
  - In the azimuth plane, the antenna is a more efficient vertically polarized radiator.
- PMC ground plane size:
  - Too large → Short circuits vertical monopoles.
  - Too small → No efficient radiation → Difficulties in impedance matching.
  - PMC ground plane size must be finite for optimum performance.
  - What is the optimum size for a given antenna dimension? TBD.

Without platform

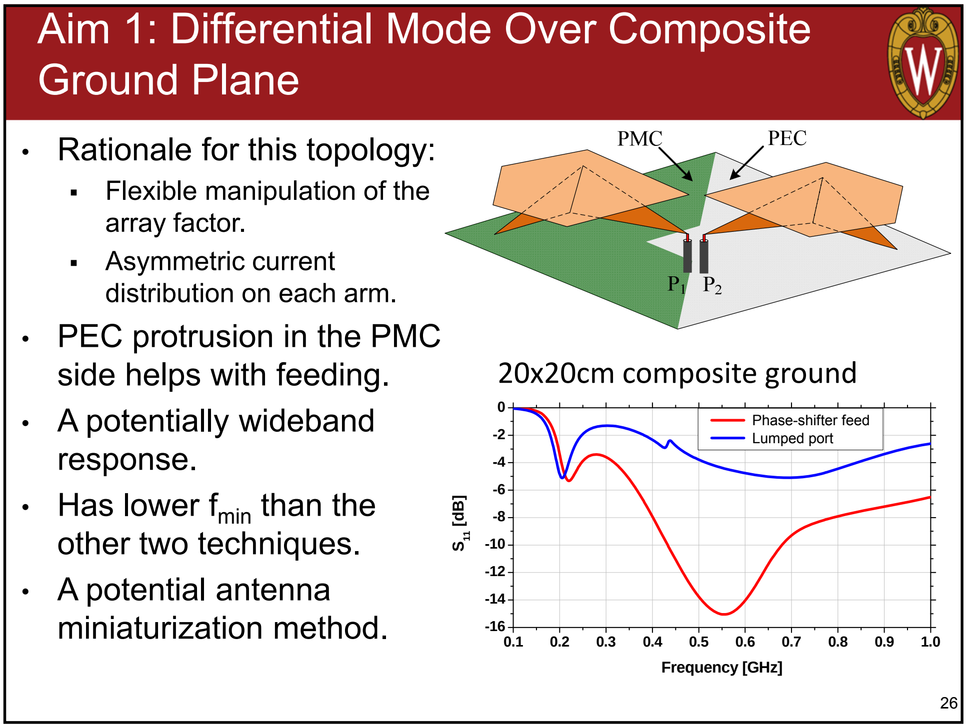
f = 300 MHz

Antenna on platform (Inf. PEC)



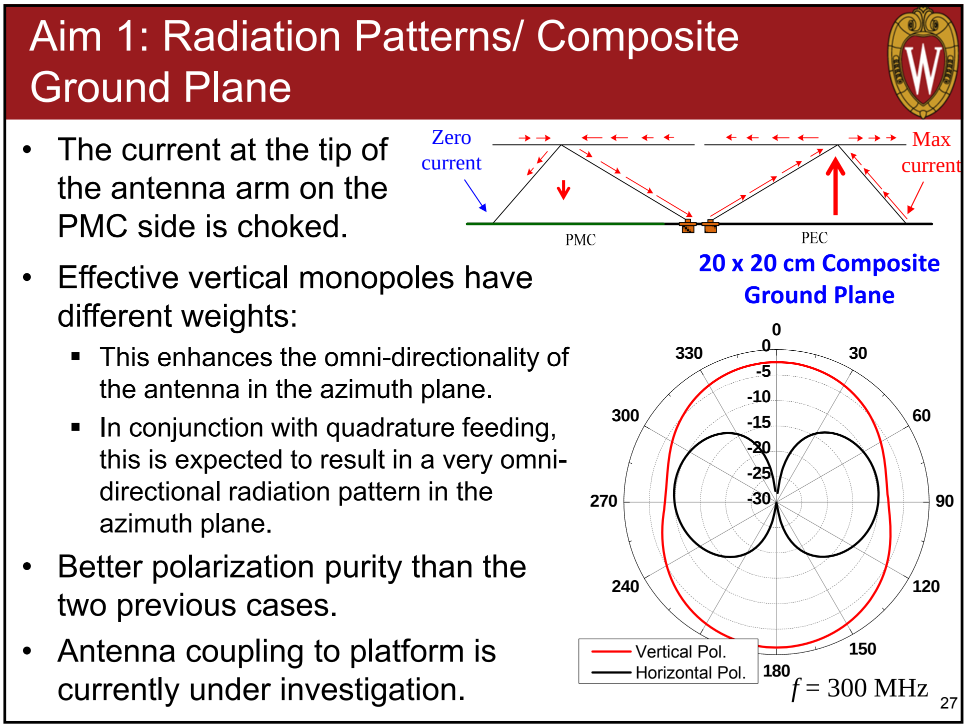
Differential Mode Over Full PMC Ground Plane – Summary of the Results

- ✓ Differential mode has a lower f_{min} than that of the common mode.
- ✓ Efficient vertically-polarized radiation in the azimuth plane.
- ✓ Antenna platform coupling is not very strong and can be readily circumvented.
- ✓ Quadrature feeding:
  - Improving omni-directionality for vertical pol in the azimuth plane.
  - Dual mode antenna with CP towards zenith.
- ✓ Conclusion: Using DM on top of a PMC ground plane is a viable option and offers some additional degrees of flexibility.



Aim 1: Differential Mode Over Composite Ground Plane

- Rationale for this topology:
  - Flexible manipulation of the array factor.
  - Asymmetric current distribution on each arm.
- PEC protrusion in the PMC side helps with feeding.
- A potentially wideband response.
- Has lower f_{min} than the other two techniques.
- A potential antenna miniaturization method.

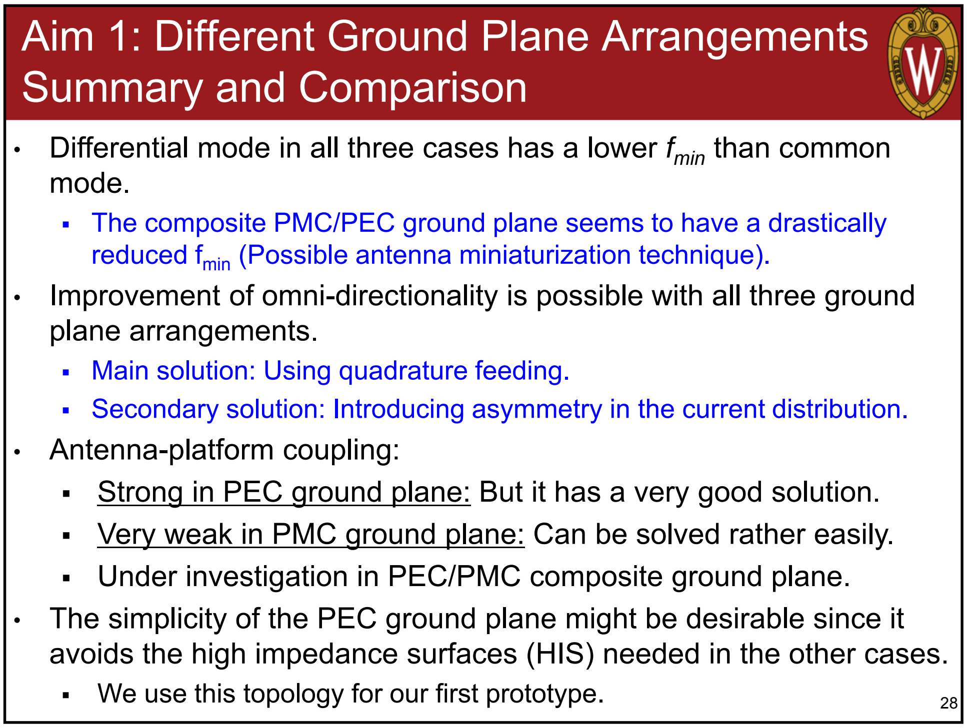


Aim 1: Radiation Patterns/ Composite Ground Plane

- The current at the tip of the antenna arm on the PMC side is choked.
- Effective vertical monopoles have different weights:
  - This enhances the omni-directionality of the antenna in the azimuth plane.
  - In conjunction with quadrature feeding, this is expected to result in a very omni-directional radiation pattern in the azimuth plane.
- Better polarization purity than the two previous cases.
- Antenna coupling to platform is currently under investigation.

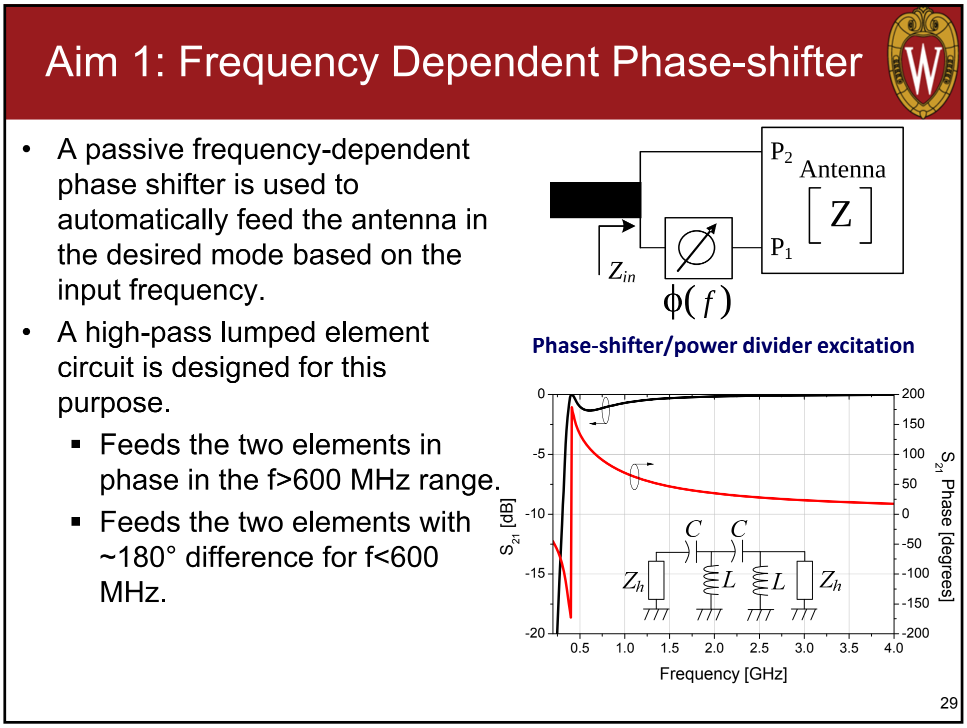
20 x 20 cm Composite Ground Plane

f = 300 MHz



Aim 1: Different Ground Plane Arrangements Summary and Comparison

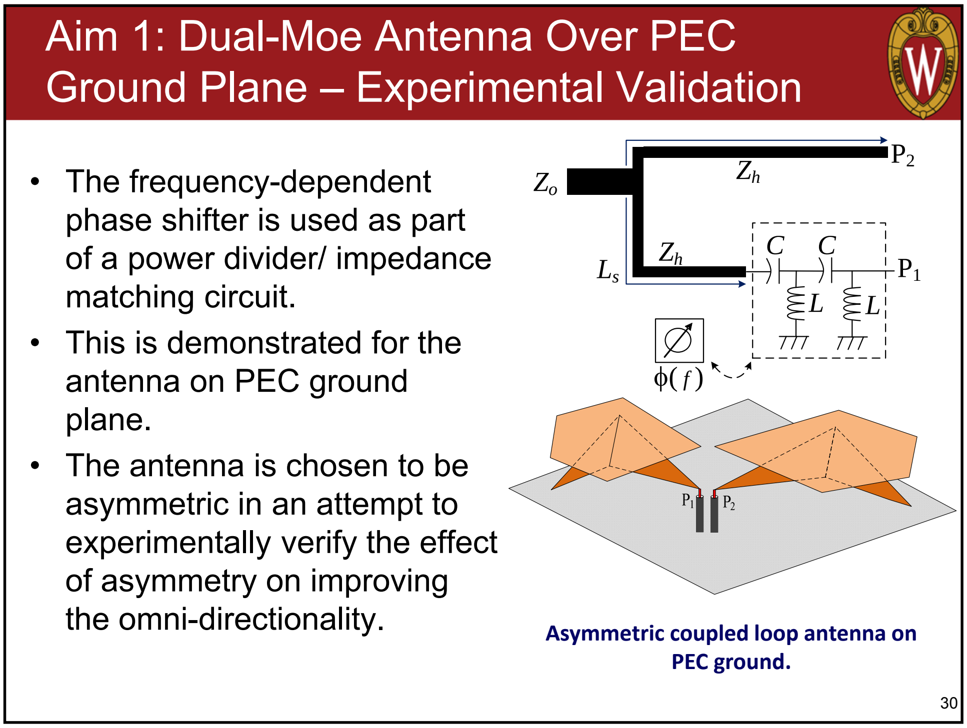
- Differential mode in all three cases has a lower f_{min} than common mode.
  - The composite PMC/PEC ground plane seems to have a drastically reduced f_{min} (Possible antenna miniaturization technique).
- Improvement of omni-directionality is possible with all three ground plane arrangements.
  - Main solution: Using quadrature feeding.
  - Secondary solution: Introducing asymmetry in the current distribution.
- Antenna-platform coupling:
  - <u>Strong in PEC ground plane:</u> But it has a very good solution.
  - <u>Very weak in PMC ground plane:</u> Can be solved rather easily.
  - Under investigation in PEC/PMC composite ground plane.
- The simplicity of the PEC ground plane might be desirable since it avoids the high impedance surfaces (HIS) needed in the other cases.
  - We use this topology for our first prototype.



Aim 1: Frequency Dependent Phase-shifter

- A passive frequency-dependent phase shifter is used to automatically feed the antenna in the desired mode based on the input frequency.
- A high-pass lumped element circuit is designed for this purpose.
  - Feeds the two elements in phase in the f>600 MHz range.
  - Feeds the two elements with ~180° difference for f<600 MHz.

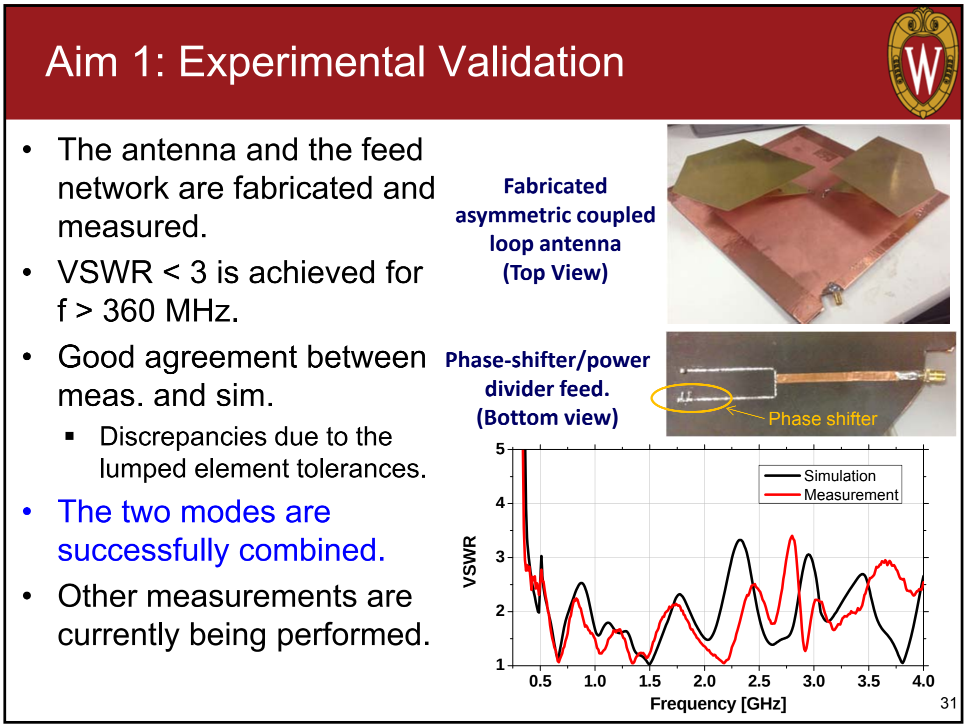
Phase-shifter/power divider excitation



Aim 1: Dual-Moe Antenna Over PEC Ground Plane – Experimental Validation

- The frequency-dependent phase shifter is used as part of a power divider/ impedance matching circuit.
- This is demonstrated for the antenna on PEC ground plane.
- The antenna is chosen to be asymmetric in an attempt to experimentally verify the effect of asymmetry on improving the omni-directionality.

Asymmetric coupled loop antenna on PEC ground.

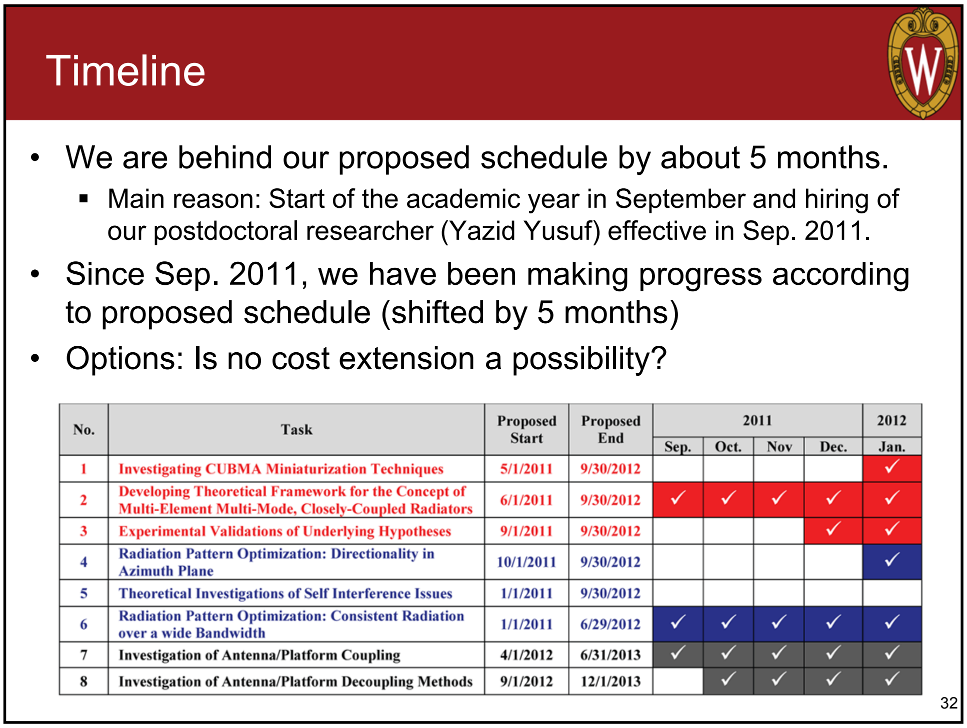


Aim 1: Experimental Validation

- The antenna and the feed network are fabricated and measured.
- VSWR < 3 is achieved for f > 360 MHz.
- Good agreement between meas. and sim.
  - Discrepancies due to the lumped element tolerances.
- The two modes are successfully combined.
- Other measurements are currently being performed.

Fabricated asymmetric coupled loop antenna (Top View)

Phase-shifter/power divider feed. (Bottom view)



Timeline

- We are behind our proposed schedule by about 5 months.
  - Main reason: Start of the academic year in September and hiring of our postdoctoral researcher (Yazid Yusuf) effective in Sep. 2011.
- Since Sep. 2011, we have been making progress according to proposed schedule (shifted by 5 months)
- Options: Is no cost extension a possibility?

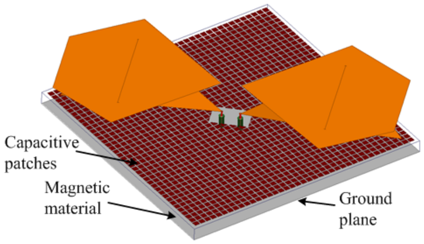
No.	Task	Proposed Start	Proposed End	2011				2012
				Sep.	Oct.	Nov	Dec.	Jan.
1	Investigating CUBMA Miniaturization Techniques	5/1/2011	9/30/2012					✓
2	Developing Theoretical Framework for the Concept of Multi-Element Multi-Mode, Closely-Coupled Radiators	6/1/2011	9/30/2012	✓	✓	✓	✓	✓
3	Experimental Validations of Underlying Hypotheses	9/1/2011	9/30/2012				✓	✓
4	Radiation Pattern Optimization: Directionality in Azimuth Plane	10/1/2011	9/30/2012					✓
5	Theoretical Investigations of Self Interference Issues	1/1/2011	9/30/2012					
6	Radiation Pattern Optimization: Consistent Radiation over a wide Bandwidth	1/1/2011	6/29/2012	✓	✓	✓	✓	✓
7	Investigation of Antenna/Platform Coupling	4/1/2012	6/31/2013	✓	✓	✓	✓	✓
8	Investigation of Antenna/Platform Decoupling Methods	9/1/2012	12/1/2013		✓	✓	✓	✓

Summary of Our Efforts So Far

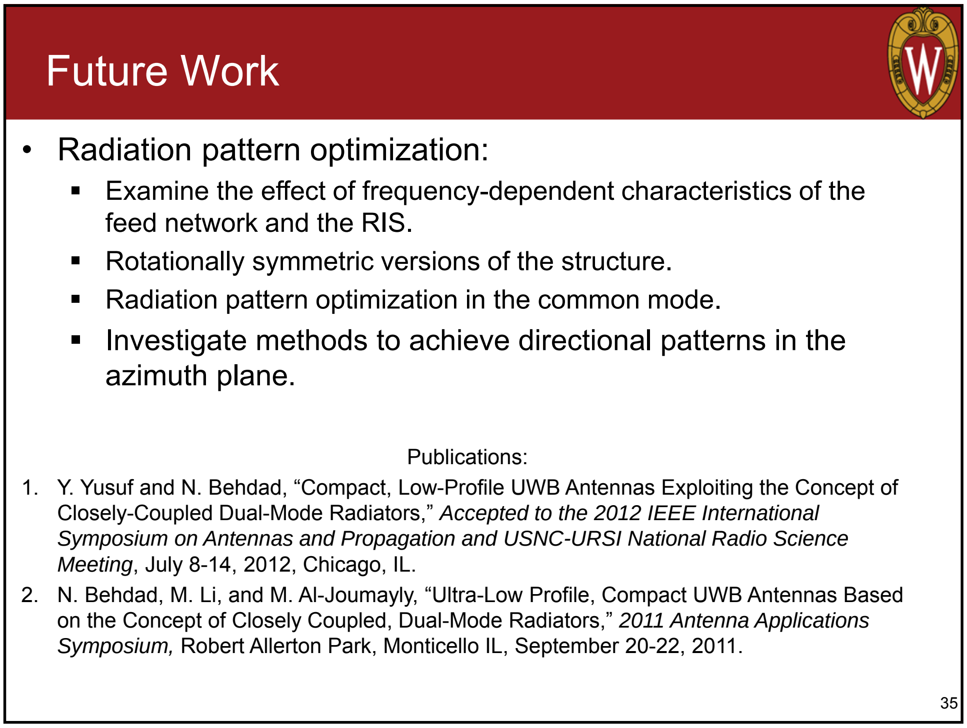
- Theoretical understanding of the antenna’s operation in the differential mode of operation:
  - Effect of ground plane type.
  - Coupling between the antenna/platform and decoupling techniques.
  - Radiation pattern optimization:
    - Enhancing omni-directionality and achieving multi-mode (CP and linear) operation.
- Developed a comprehensive understanding of the feed network operation:
  - Direct differential feeding (lumped port) vs. power divider/phase shifter based feed network.
  - Solved the problem of feeding the antenna when mounted on high impedance surface.
  - Theoretically and experimentally proved our proposed feed concept
    - Mode combining based on the frequency of the excitation signal.

Future Work

- Measure the radiation characteristics of the fabricated antenna on PEC ground.
- Fabricate the prototypes using PMC and the PMC/PEC ground planes using physically realizable metamaterial substrates.



- Antenna miniaturization investigation:
  - Potential use of PEC/PMC composite ground.
  - Capacitive and inductive loading.
  - Magnetic/dielectric loading.
  - Multiple (more than two) coupled radiators.



Future Work

- Radiation pattern optimization:
  - Examine the effect of frequency-dependent characteristics of the feed network and the RIS.
  - Rotationally symmetric versions of the structure.
  - Radiation pattern optimization in the common mode.
  - Investigate methods to achieve directional patterns in the azimuth plane.

Publications:

1. Y. Yusuf and N. Behdad, “Compact, Low-Profile UWB Antennas Exploiting the Concept of Closely-Coupled Dual-Mode Radiators,” *Accepted to the 2012 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting*, July 8-14, 2012, Chicago, IL.
2. N. Behdad, M. Li, and M. Al-Joumayly, “Ultra-Low Profile, Compact UWB Antennas Based on the Concept of Closely Coupled, Dual-Mode Radiators,” *2011 Antenna Applications Symposium,* Robert Allerton Park, Monticello IL, September 20-22, 2011.

Compact, Low-Profile UWB Antennas Exploiting the Concept of Closely-Coupled Dual-Mode Radiators

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***Abstract*—In this paper, the concept of closely-coupled, dual-mode radiators is utilized to design a compact, low-profile, ultra-wideband antenna. An antenna that consists of two closely-coupled loops is shown to exhibit two distinct modes of operation, which have complementary frequency bands of operation. By combining the two modes using a feed network that employs a frequency-dependent phase shifter, the antenna is automatically excited in its appropriate mode of operation depending on the input frequency. With the aid of the feed network, the antenna is demonstrated to achieve a larger overall bandwidth compared with what can be obtained using each mode individually. A prototype of the antenna was fabricated and measured and good agreement between measurements and simulations is observed.**

I. INTRODUCTION

Ultra-wideband technologies find many applications in areas such as radar, and high data rate communication systems [1]. Antennas, in such applications, are required to be impedance matched and have good radiation and polarization characteristics over a large frequency span. Traditional ultra-wideband antennas such as frequency-independent antennas and travelling-wave antennas can be very large in size particularly if they have to operate low frequencies. This prohibits their use in low-frequency (e.g. VHF) applications, where size and weight are of prime importance. In an effort to realize compact ultra-wideband antennas, different antenna miniaturization techniques such as inductive and capacitive loading [2] have been demonstrated.

Recently, the concept of closely-coupled, dual-mode radiators was introduced [3]. The new concept can be potentially used, in conjunction with existing antenna miniaturization approaches, to develop compact, low-profile, ultra-broadband antennas. By making use of two distinct modes of a radiating structure, which have complementary frequency bands of operation, the lowest frequency of operation of an ultra-wideband antenna is significantly extended. In this paper, we further investigate this concept and design a frequency-dependent feed network that automatically feeds the antenna structure in its correct mode of operation. Utilizing such a feed network, an ultra-wideband antenna is demonstrated to achieve a larger overall bandwidth compared to what is obtained using each mode individually. A prototype of the designed antenna is fabricated and measurement results are presented.

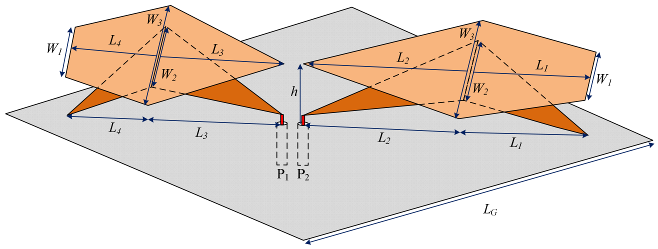

Fig. 1. Schematic of the closely-coupled dual-mode ultra-wideband antenna ($h = 3$, $L_1 = 5.8$, $L_2 = 8.1$, $L_3 = 6.0$, $L_4 = 4.3$, $W_1 = 6.4$, $W_2 = 8.0$, $W_3 = 13$, $L_G = 22$). All dimensions are in centimeters.

II. CONCEPT AND DESIGN

Figure 1 shows an antenna that utilizes the closely-coupled, dual-mode radiator concept[1]. The antenna is composed of two closely-coupled loops, each of which is formed by a bent diamond-shaped conductor and its image with respect to the ground plane. The two loop arms are loaded with pentagon-shaped top hats which provide capacitive loading that reduces the frequency of operation of the loops. The two loop arms are individually fed using two coaxial ports as shown in Fig. 1. Depending on the relative phase of excitation between the two ports, the antenna can be operated in either a common mode or a differential mode. The input voltage standing wave ratio (VSWR) of the antenna in its two different modes of operation which is obtained by feeding the antenna ports using an ideal feed network is shown in Fig. 2. The VSWR of the antenna in the common mode demonstrates its wideband impedance matching characteristics. In addition, the antenna exhibits high radiation efficiencies and relatively consistent radiation characteristics across its wide bandwidth. Within this mode, the antenna's lowest frequency of operation, defined herein as the frequency below which VSWR is less than 3, is found to be 600 MHz.

In the differential mode, in which the two loops are excited with a relative phase difference of 180^o, the antenna's lowest frequency of operation is found to be 410 MHz, which is approximately 1.5 times smaller than the lowest frequency of operation of the common mode. By combining the two modes of operation using an appropriately designed feed, an ultra-

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[1] U.S. and international patents pending.

wideband antenna can be designed that has electrically small dimensions at its lowest frequency of operation.

A feed network that can be used to combine the two modes is shown in Fig. 3(a). The network serves as both a power splitter and a frequency-dependent phase shifter. The frequency-dependent phase shifting is achieved by a lumped element high-pass network composed of capacitors and inductors. The response of the *LC* phase shifter is plotted in Fig. 3(b). The phase shifter provides phase shifts close to 180° and 0° in the differential and common mode frequencies, respectively. The antenna is therefore automatically fed in its desired mode of operation based on the frequency of the input signal. The microstrip lines of the feeding network are designed on a 1.6-mm-thick RT/Duroid® 5880 ($\varepsilon_r = 2.2$, $tan\delta = 0.0009$) substrate. The feed network parameters are optimized using a circuit simulator in order to achieve a VSWR less than 3 over the frequency range from 360 MHz to 4 GHz. The simulation results after optimization are shown in Fig. 3.

III. RESULTS AND DISCUSSION

Prototypes of the antenna and the feed network were fabricated. The feed network is patterned on the bottom side of the antenna ground plane. The reflection coefficient of the antenna combined with the feed network was measured using a vector network analyzer. The measured and simulated VSWRs are compared in Fig. 4. Very good agreement between measured and simulated results is observed, particularly for frequencies below 2 GHz. The slight disagreement at frequencies above 2 GHz is attributed to the variation of the lumped element capacitor and inductor values from their nominal values at those frequencies. Nevertheless, the measurement results demonstrate the broadband performance of the antenna particularly when both modes are employed.

It should be mentioned that even though the antenna operates over a lower frequency band in the differential mode compared with the common mode, its radiation characteristics are somewhat different. Therefore, the radiation characteristics of the antenna in the differential mode must be tailored and made similar to those of the common mode to ensure that the structure maintains consistent characteristics across its entire frequency band of operation. One approach being considered involves the use of reactive impedance surfaces as composite ground planes for the antenna. Preliminary simulation results suggest that appropriately optimized surface impedances of the ground plane can enhance the vertically-polarized component of the radiated fields of the antenna in its differential mode making its radiation characteristics similar to those in the common mode. The use of two loop arms of different dimensions as demonstrated in Fig. 1 was also found beneficial for this purpose. Details of these techniques will be presented and discussed at the symposium.

ACKNOWLEDGEMENT

This work is supported by a Young Investigator Program (YIP) Award from the Office of Naval Research (Award No. N00014-11-1-0618).

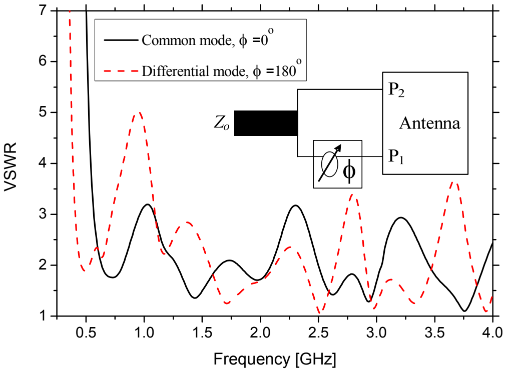

Fig. 2. Simulated VSWR of the antenna in Fig. 1 obtained by feeding its two ports using the ideal feed network shown in the inset.

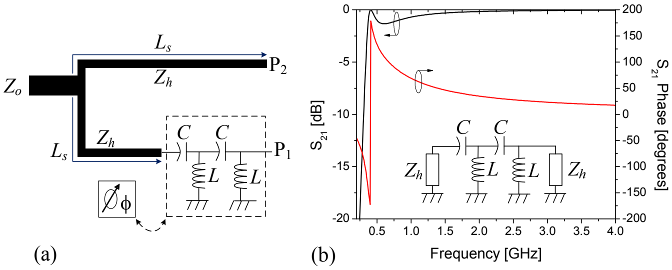

Fig. 3. (a) the feed network used to excite the antenna in Fig. 1. (b) the response of the lumped element frequency-dependent phase shifter in (a).(Here, $Z_o = 50\ \Omega$, $Z_h = 115\ \Omega$, $L_s = 50$ mm, $L = 23$ nH, and $C = 3.3$ pF.)

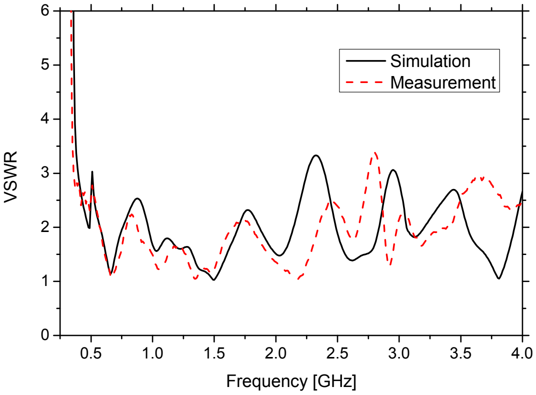

Fig. 4. Simulated and measured VSWR of the antenna combined with the feed network.

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[2] N. Behdad and K. Sarabandi, "Bandwidth enhancement and further size reduction of a class of miniaturized slot antennas", *IEEE Transactions on Antennas and Propagation*, Vol. 52, pp. 1928-1935, Aug 2004.

[3] N. Behdad, M. Li and M.A. Al-Joumayly, “Ultra-low profile, compact UWB antennas based on the concept of closely coupled, dual-mode radiators”, *2011 Antenna Application Symposium*, Robert Allerton Park, Monticello IL, September 20-22, 2011.

ULTRA-LOW PROFILE, COMPACT UWB ANTENNAS BASED ON THE CONCEPT OF CLOSELY-COUPLED, DUAL-MODE RADIATORS

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ABSTRACT: **In this paper, we present a concept for designing ultra-low profile and compact antennas that have the potential of operating over ultra-broad bandwidths. The proposed antenna has two distinct modes of operation: a common mode and a differential mode. In the common mode of operation, the antenna behaves as an ultra-wideband (UWB) coupled loop antenna with compact dimensions. In the differential mode of operation, the antenna operates as a wideband dipole-type antenna. The frequency band of operation of the antenna in the differential mode of operation falls below that of its common mode. Consequently, combining these two modes of operation can be used as a means of reducing the lowest frequency of operation of an ultra-wideband antenna. A frequency dependent feed network can be used to automatically feed the antenna in the correct mode of operation and achieve an overall bandwidth which is greater than the bandwidth of each mode alone.**

1. INTRODUCTION

Antennas are essential parts of any electronic system that uses the electromagnetic wave spectrum. With the current advancements in electronics technology and the trend towards miniaturization and integration of systems and sub-systems on chip-scale devices, the size, weight, and power consumption (SWAP) of wireless systems are reducing with an increasingly rapid pace. However, the antennas used in such systems have not followed suit. This stems from the fact that the basic physics laws mandate certain limitations on the performance of antennas. Nonetheless, the need for small, efficient, and broadband antennas is more than ever felt in both military and commercial systems. This SWAP reduction need is even more critical in military systems as large dimensions and visual signatures of low-frequency antennas used in such systems is not only a logistical burden but also a security treat. Military communication systems operating at frequency bands as low as the HF band routinely use antennas that are as large as 32 feet [1].

The topic of antenna miniaturization is not new and has been the subject of various studies over the past seven decades [2]-[4]. Seminal works studying the fundamental limitations of small antennas have been performed as early as the late 1940s [2]-[3]. There have also been a great number of studies focusing on circumventing the adverse effects of antenna miniaturization. The fundamental limitations that govern the performance of small antennas place certain limitations on the gain-bandwidth product of small antennas. In particular, as the dimensions of an antenna decrease its gain-bandwidth product decreases for a given frequency of operation. Thus, for a given antenna gain and radiation efficiency, the bandwidth of an electrically small antenna is limited. This creates practical problems, especially in systems that use very low frequencies (e.g. HF or VHF bands).

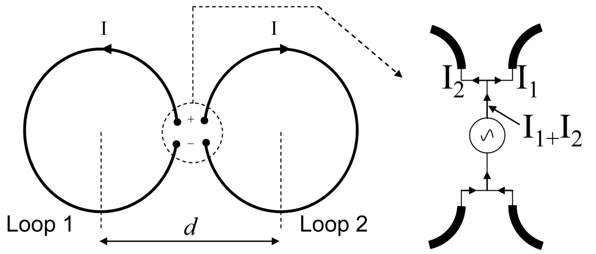

Fig. 1. Topology of two closely coupled loop antennas fed with coherent signals.

In this paper, we report the preliminary results of our studies of a concept that can be used to develop conformal, ultra-broadband miniaturized antennas. An antenna designed using this technique is a dual-mode radiator with two different modes of operation: a common mode (CM) and a differential mode (DM). In the common mode, the structure acts as a coupled loop antenna with compact dimensions. In principle, a system composed of two coupled loop elements can be designed such that the spectral variations of the self impedance (i.e., self impedance vs. frequency) of each radiator are cancelled by the spectral variations of their mutual impedance. If the two radiators are fed with the same coherent source, this system can present a virtually constant input impedance as a function of frequency. Therefore, an antenna designed using this technique acts as a compact, ultra-wideband antenna in their common mode of operation. In the differential mode of operation, the coupled loops that constitute the antenna are fed with a 180° phase difference between them. Consequently, the system acts as a loop with twice the circumference of its constituting loops. Hence, the lowest frequency of operation of the antenna in the differential mode of operation is approximately two times lower than that of the common mode. Consequently, by exciting the two coupled loops with a 180° phase difference, a potentially wideband antenna, operating at a lower frequency band, can be obtained. By combining these two modes of operation using an appropriately designed feed, a UWB antenna can be designed that has electrically small dimensions at its lowest frequency of operation (i.e. the lowest frequency of operation of the differential mode). In what follows, the proposed concept along with preliminary measurement and simulation results will be presented and discussed.

2. BACKGROUND AND THE PROPOSED CONCEPT

Coupled Loop Antennas in the Common Mode of Operation:

Figure 1 shows two loop antennas that are strongly coupled to each other by placing them in the near field of one another. This creates a strong mutual coupling between the two closely coupled loops. If the two antennas are fed with a phase difference less than 90º, the direction of the electric currents flowing in the two loops will be as shown in Fig. 1. This way, the magnetic fields of the two loops strongly link and give rise to a strong

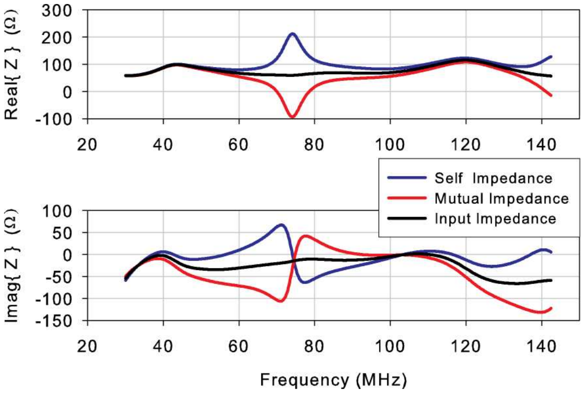

Fig. 2. Self and mutual impedances of the coupled loop antenna arrangement shown in Fig. 1. Real and imaginary parts are shown.

mutual coupling between them. This mutual coupling can be controlled by changing the effective areas of each loop, which changes the flux linkage between them. Since the antennas are fed with the same coherent source, the input impedance of this arrangement, as seen from the two terminals of the source, is:

$$Z_{in} = ½ (Z_{11} + Z_{12})$$

where Z_{11} is the self impedance of each loop in the presence of the other one and Z_{12} is the mutual coupling between the two loops. The self impedance of each loop (Z_{11}) is mainly a function of its geometrical dimensions whereas the mutual coupling (Z_{12}) is mainly a function of the flux linkage between the two loops. This way, it is possible to optimize the topology of this closely coupled system of two radiators such that the variations of the self impedance of each radiator, as a function of frequency, are cancelled by those of their mutual impedance. This will result in a constant input impedance versus frequency for the system. This scenario is shown in Fig. 2 for two closely coupled loop antennas operating at the lower end of the VHF frequency band. Here, the self and mutual impedances of the two closely coupled loop antennas as well as the input impedance of the system are shown.

While this concept can be applied to any type of radiating element, loop antennas are particularly suitable for this application. This is due to the fact that the spectral variations of the input impedances of loop antennas are significantly smoother than those of other types of resonant elements (e.g., dipoles or patches). This way, the abovementioned cancellation of the self and mutual impedances can occur up to very high frequencies. This is shown in Fig. 3, where the input VSWR of a system composed of two closely coupled loops operating at the VHF band is shown. As can be seen the antenna is impedance matched with a typical VSWR of 2:1 and a maximum VSWR of 3:1 over a very wide frequency band. This concept has been successfully applied to closely coupled loop antennas in the past as reported in

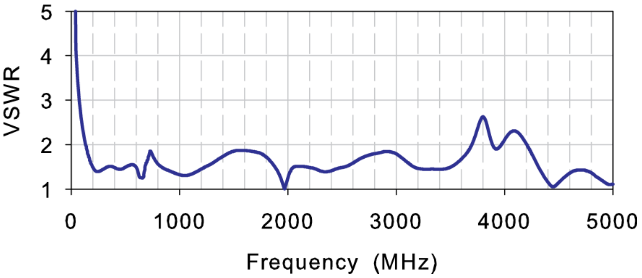

Fig. 3. Input VSWR of a system composed of two closely coupled, compact loop antennas. The system operates from the low-VHF frequency band. The simulation results are obtained using full-wave EM simulations in Ansoft HFSS.

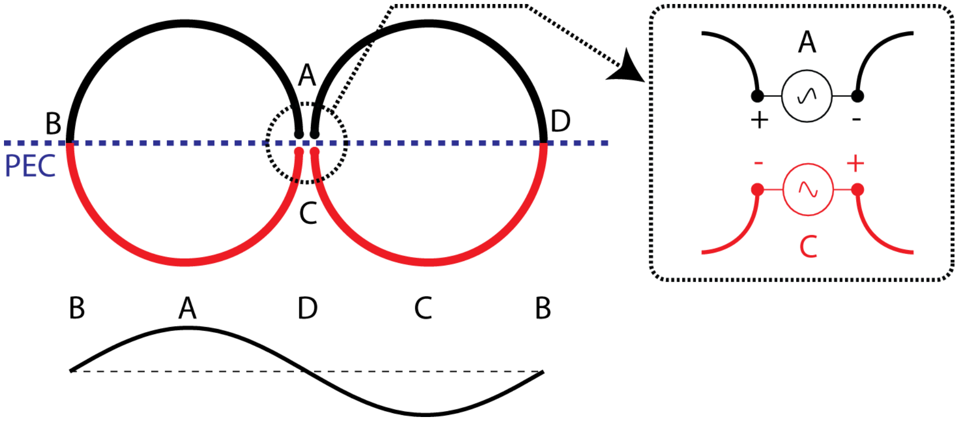

Fig. 4. A coupled loop antenna in its differential mode of operation. When the two loops are fed with a 180° phase difference, the feeds can be rearranged as shown in the inset. This system acts as a simple loop antenna with twice the circumference of each of the loops (or a folded dipole antenna). The current distribution along the loop, in the differential mode, is also shown in the picture.

[5]-[8]. In these references, it is demonstrated that, in addition to achieving low VSWR and good impedance matching, such closely coupled antennas demonstrate very high radiation efficiencies and consistent radiation parameters across their wide bandwidths.

Coupled Loop Antennas in the differential Mode of Operation:

One of the main challenges in the design and miniaturization of a broadband antenna is to reduce its lowest frequency of operation without increasing its occupied volume. For the coupled-loop antennas described previously, this can be done by feeding the two antennas with a 180° phase difference between them. In this case, the antenna's differential feeding can be equivalently represented as the one shown in Fig. 4. As shown in Fig. 4, the two coupled loop antennas act as a loop antenna with twice the circumference. This antenna's lowest frequency of operation is approximately two times lower than that of its individual constituting loops. This is extremely advantageous because a simple feed polarization reversal can be used to considerably reduce the lowest frequency of operation of a broadband antenna without increasing its dimensions. A simple passive feed network can be used to automatically feed the antenna in the appropriate mode of operation, based on the frequency of the excitation signal.

The proposed Concept:

To facilitate the design and optimization process of the proposed dual-mode antenna, rather than using the complete antenna structure shown in Fig. 4, half of this antenna can be used on a composite ground plane as shown in Fig. 5. The particular shapes of the loops shown in Fig. 5 are just used for illustration purposes and signify the fact that the loops are miniaturized to reduce their lowest frequency of operation. In this structure, when the antenna is excited in the differential mode, it operates as a wideband diamond shaped dipole over a frequency band of $f_{min} < f < 2 f_{min}$, where f_{min} is the lowest frequency

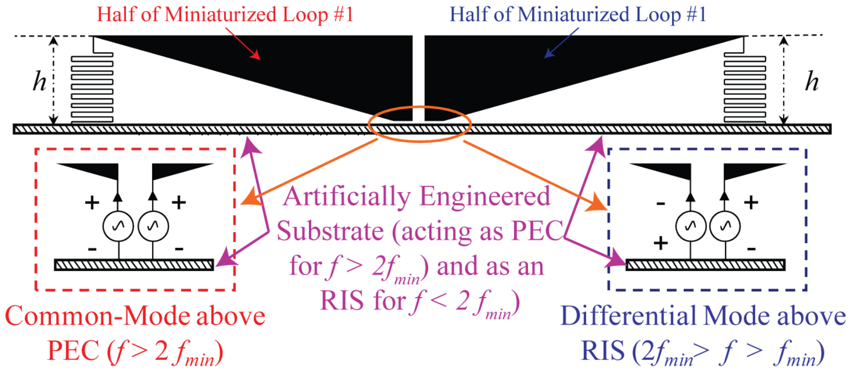

Fig. 5. Practical arrangement for feeding the dual-mode closely coupled structure shown in Fig. 4. A reactive impedance substrate is used as a ground plane to tailor the radiation characteristics of the differential mode and make it similar to that of the first mode.

of operation of the structure. When excited in the common mode, it operates as a UWB coupled loop system with a lowest frequency of operation of $2\,f_{min}$. In this mode, the antenna is impedance matched up to at least $50\,f_{min}$. To ensure that the antenna radiates consistently (with the same polarization, radiation patterns, high radiation efficiency, etc.) across its entire frequency band, irrespective of the operating mode, we anticipate using a composite ground plane similar to the one shown in Fig. 5. This ground plane is an artificially engineered substrate acting as a perfect electric conductor (PEC) in the frequency range of $f > 2\,f_{min}$ and as a reactive impedance surface (RIS) in the range of $f < 2\,f_{min}$. This is done to tailor the radiation properties of the antenna in the differential mode and make them similar to those of the common mode.

3. PRELIMINARY RESULTS

Figure 6 demonstrates the topology of the proposed dual-mode antenna. The structure is composed of two compact loop antennas coupled together. In this antenna topology, only half of each loop antenna is used above the ground plane. Therefore, a complete loop is formed between the actual antenna and its image with respect to the ground plane. Each half-loop is in the form of a bent diamond that is short circuited to the ground plane at the tip. The loop arms are loaded with two pentagon-shaped top hats. This creates a distributed capacitive

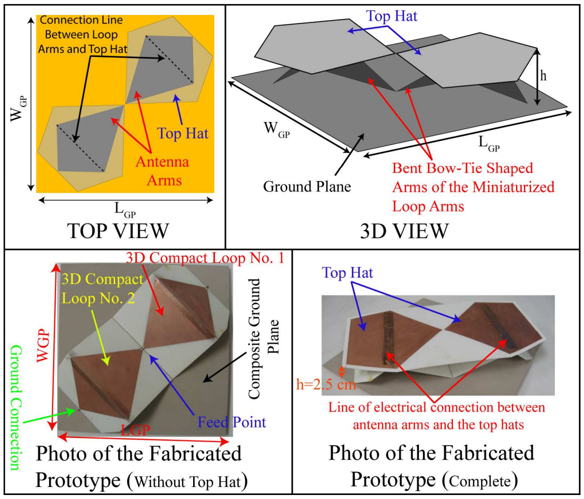

Fig. 6. Photograph and topology of a prototype of a dual-mode radiator optimized for broadband operation in both modes of operation.

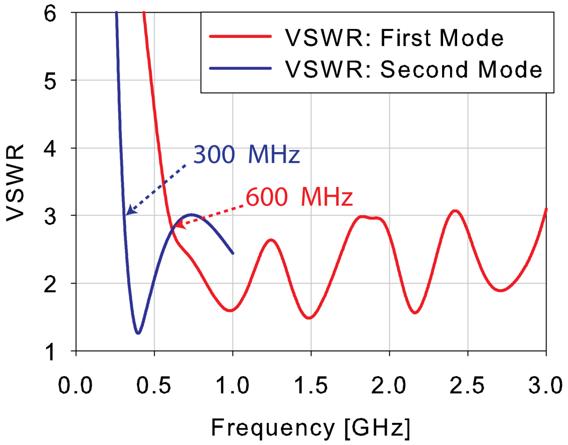

Fig. 7. Simulated VSWR of the optimized antenna in the common mode of operation (first mode) and the differential mode of operation (second mode). In the differential mode, the antenna is assumed to be placed on top of a PMC ground plane.

loading effect that reduces the lowest frequency of operation of a loop by a factor of 2.2 compared to a regular loop. Additionally, when excited in the differential mode, the two half-loops act as a diamond shaped dipole, which behaves as a broadband antenna. This shape is optimized for the dual-mode antenna to ensure that its bandwidth in the differential mode is maximized. Furthermore, the bent nature of the dipoles creates both horizontal and vertical components of the electric field. In the differential mode, the ground plane must act as a reactive impedance surface. The RIS substrate with appropriate phase shift profile is used to enhance the vertical component of the radiating current (in the differential mode) to achieve a radiation characteristics similar to that of the common mode. The entire structure is mounted on a finite, composite ground plane with dimensions of L_{GP}=W_{GP}=20cm and the antenna has an overall height of only 3cm.

The antenna shown in Fig. 6 is simulated in Ansoft HFSS for both the common and the differential modes of operation and the results are presented in Fig. 7. As can be observed, in the common mode, the structure acts as an ultra-wideband antenna with the lowest frequency of operation of approximately 600 MHz. In the differential mode of operation, however, the same structure acts as a broadband antenna covering the frequency range of 300 MHz to 600 MHz.

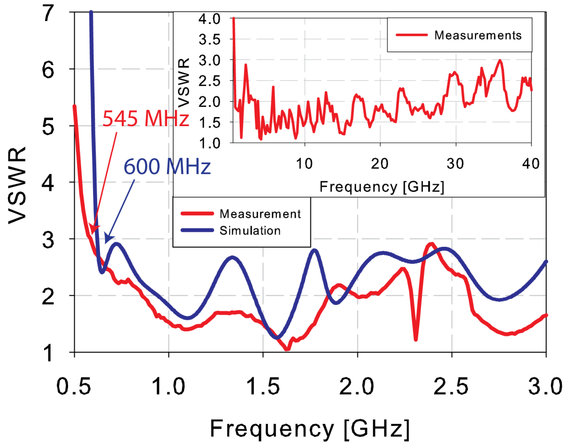

Fig. 8. Measured and simulated VSWR of the optimized antenna prototype shown in Fig. 6 in its common mode of operation. The lowest frequency of operation is lower than expected and the antenna is impedance matched up to at least 40 GHz.

The response of the fabricated prototype shown in Fig. 6 is measured for the common mode of operation and the results are presented in Fig. 8. Figure 8 also shows the simulation results of the antenna obtained using

CST Microwave Studio. Even though there are some discrepancies between the simulation results obtained in HFSS and those obtained from CST, both predict an ultra-wideband response with a VSWR better than 3:1 in the range of 600 MHz to 3.0 GHz. The measurement results of the antenna presented in Fig. 8 also confirm this UWB operation and demonstrate that the antenna has a VSWR better than 2:1 over most of this range and a maximum VSWR of 3:1 as predicted. The input VSWR of the antenna is measured up to 40 GHz and the results are also presented in the inset of Fig. 8. As can be seen the antenna in its common mode of operation is indeed impedance matched up to extremely high frequencies. However, as frequency increases, the radiation characteristics of the antenna start to change and become different.

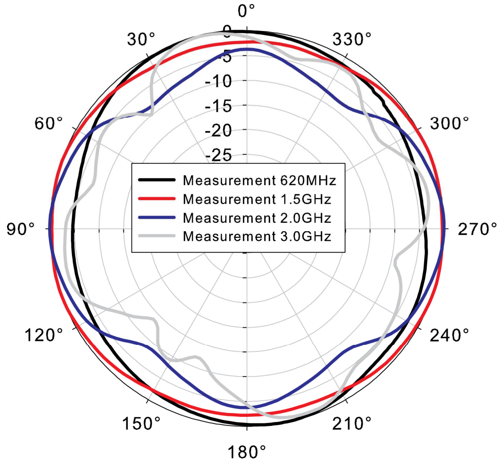

Fig. 9. Measured radiation pattern of the antenna prototype shown in Fig. 6 in the azimuth plane. The antenna radiates a vertically polarized wave along the azimuth plane (similar to a monopole antenna). Its radiation patterns in the elevation plane are also similar to the E-plane of a monopole on top of a finite ground plane.

The radiation patterns of this antenna, in the common mode of operation, are also measured in a far-field anechoic chamber. In the elevation planes, the antenna has radiation patterns similar to a monopole above a finite ground plane. In the azimuth plane, the antenna has an omni-directional radiation pattern and radiates a vertically polarized wave. The radiation patterns of the antenna, in the azimuth plane, are shown in Fig. 9. As can be observed, at low frequencies, the antenna has an almost omni-directional radiation pattern. As frequency increases, the ripples in the radiation patterns of the antenna start to increase and deteriorate the omni-directionality of the radiation pattern. This can be attributed in part to the finite dimensions of the antenna's ground plane. Moreover, as frequency increases, the electrical dimensions of the loop antennas increase and the radiation characteristics of each loop start to become different. Therefore, the bandwidth of this antenna is

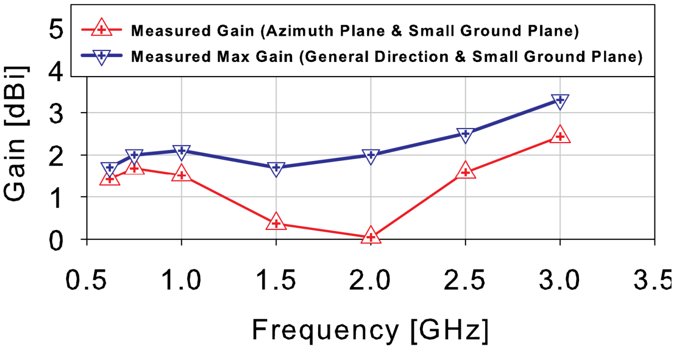

Fig. 10. Measured gain of the antenna prototype shown in Fig. 6 in the common mode. The results for gain along the azimuth plane (θ=90) and the maximum gain values are shown. Both results are obtained for an antenna with very small finite ground plane size.

mainly determined by its radiation characteristics and not by its impedance matching.

The gain of the antenna, in the common mode of operation, is also measured and the results are presented in Fig. 10. The measured gain along the azimuth plane and the maximum measured gain of the antenna are both reported. The results indicate that the maximum radiation of the antenna does not occur along the azimuth plane direction but rather at some other elevation angle. This is behavior is expected and it is also observed in most monopole-type radiators that have finite ground plane dimensions. The antenna prototype shown in Fig. 6 occupies a volume of 20 cm × 20 cm × 3 cm. At 600 MHz, this corresponds to electrical dimensions of $0.4\lambda_0 \times 0.4\lambda_0 \times 0.06\lambda_0$, where λ_0 represents the free-space wavelength.

4. CURRENT STATE OF THE DESIGN AND FUTURE STEPS

The measurement results of the structure, presented in the previous section, demonstrate the UWB performance of the antenna in its common mode of operation. In the differential mode, the antenna acts as a dipole placed on top of a reactive impedance surface ground plane. In this mode, while the antenna operates over a lower frequency band compared to the common mode, its radiation characteristics are considerably different than those of the common mode. Therefore, the radiation characteristics of the antenna in the differential mode must be tailored and made similar to those of the common mode to ensure that the structure maintains consistent characteristics across its entire frequency band of operation. Currently, we are exploring the use of wideband reactive impedance substrates as a means of tailoring the radiation characteristics of the differential mode of the antenna. In particular, a ground plane composed of two RIS sections that provide different surface impedance values is being investigated. Initial simulation results predict that by appropriately optimizing the surface impedances of the ground plane, the vertically-polarized component of the radiated fields of the antenna can be enhanced considerably. Thus, in this mode, the antenna can be forced to radiate similar to a vertically-polarized monopole as well.

Another subject of particular importance in the design of the proposed antenna is the development of an appropriate feed network. We envision that this antenna will work as a single input device which works in the appropriate mode of operation based on the frequency of the excitation signal. This way, the antenna will not need any input from the user and does not need any mode selection or switching mechanism. In general, a simple multi-port feed network can be used to accomplish this task. For example, a three-port network can be designed to act as an equal power divider and provide a 180° phase shift between the two outputs in the frequency range of 300 MHz to 600 MHz and a 0° phase shift for frequencies that are higher than 600 MHz.

The preliminary simulation results of the antenna in the differential mode, the wideband reactive impedance surface, as well as the design of the feed network will be presented and discussed in the symposium.

5. CONCLUSIONS

A new concept for designing compact, ultra-broadband antennas was presented in this paper. The proposed concept takes advantage of two independent modes of a radiating structure, with complementary frequency bands of operation, to significantly extend the lowest frequency of operation of an ultra-wideband antenna. Preliminary results of a dual-mode UWB antenna, having a common and a differential mode of operation, were presented and discussed in the paper. The performance of the antenna in one of these operating modes was characterized experimentally. Challenges that remain to be addressed in this design include mode shaping and feed network design that will be discussed in the symposium.

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