Sensing and Awareness in Microsystems

Dr. Sanjay Raman
Program Manager,
DARPA’s Microsystems Technology Office

The views and opinions presented by the invited speakers are their own and should not be interpreted as representing the official views of DARPA or DoD

Approved For Public Release, Distribution Unlimited
# Report Documentation Page

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

<table>
<thead>
<tr>
<th>1. REPORT DATE</th>
<th>2. REPORT TYPE</th>
<th>3. DATES COVERED</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAR 2009</td>
<td></td>
<td>00-00-2009 to 00-00-2009</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. TITLE AND SUBTITLE</th>
<th>5a. CONTRACT NUMBER</th>
<th>5b. GRANT NUMBER</th>
<th>5c. PROGRAM ELEMENT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTO: Sensing Across the Spectrum</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. AUTHOR(S)</th>
<th>5d. PROJECT NUMBER</th>
<th>5e. TASK NUMBER</th>
<th>5f. WORK UNIT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</th>
<th>8. PERFORMING ORGANIZATION REPORT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defense Advanced Research Projects Agency, Microsystems Technology Office, 3701 North Fairfax Drive, Arlington, VA, 22203</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</th>
<th>10. SPONSOR/MONITOR’S ACRONYM(S)</th>
<th>11. SPONSOR/MONITOR’S REPORT NUMBER(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>12. DISTRIBUTION/AVAILABILITY STATEMENT</th>
<th>13. SUPPLEMENTARY NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approved for public release; distribution unlimited</td>
<td>MTO (DARPA Microsystems Technology Office) Symposium, 2009, Mar 2-5, San Jose, CA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14. ABSTRACT</th>
<th>15. SUBJECT TERMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>16. SECURITY CLASSIFICATION OF:</th>
<th>17. LIMITATION OF ABSTRACT</th>
<th>18. NUMBER OF PAGES</th>
<th>19a. NAME OF RESPONSIBLE PERSON</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. REPORT unclassified</td>
<td>Same as Report (SAR)</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>b. ABSTRACT unclassified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. THIS PAGE unclassified</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
MTO: Sensing Across the Spectrum

Dr. Sanjay Raman
MTO Symposium
San Jose, CA

March 4, 2009
Sensing the Spectrum: Introduction

Radio Frequency

Mechanical Resonance/Vibration

mm-Wave/Sub-mm-Wave/THz

Optical and Beyond

Approved for Public Release, Distribution Unlimited
Sensing the Spectrum: Radio Frequency

Feedback Linearized Amplifier for RF Electronics (FLARE) Raman
Amplifiers for ultra high dynamic-range RF systems

Chip Scale Spectrum Analyzer (CSSA) Polla
High Q (>100,000) resonators at 3 GHz for spectrum analysis

Linear Photonic RF Front-End Technology (PHOR-FRONT) Esman
Photonic 0.5 – 18 GHz RF front-end

Analog Spectral Processors (ASP) Raman
MEMS RF Pre-Select and Sensor Filters from 20 MHz – 6 GHz

Key DoD Applications:
• Cognitive Radio
• Electronic Warfare
• RADAR
• Counter-IED

MTO programs pushing sensitivity, selectivity and dynamic range of RF receivers over wide bandwidths
Recent Accomplishments:
Radio Frequency Sensing

Analog Spectral Processes (ASP)
PM: Sanjay Raman

- **Program Objectives**
  - Low volume, high-Q pre-select filters covering bands over the 20 MHz – 6 GHz range with independently-tunable 25 kHz bandwidths
  - IF filters with tunable BW from 0.1 – 5 MHz
  - Analog sensor with 5 GHz/s scan rate

- **Recent achievements:** parallel banks of tunable 3-6 GHz evanescent cavity filters with <4dB IL, high Q Ag inductors and V-caps enable compact high-Q VHF and IF filters

Feedback Linearized Amplifier for RF Electronics (FLARE)
PM: Sanjay Raman

- **Program Objectives**
  - Radically improve RF amplifiers’ OIP3 for high-dynamic range EW/ELINT receivers
  - Ultra-low noise InP HEMT LNAs, ultra-high linearity HBT LNAs, and all-HBT monolithic ultra-high linearity broadband LNAs

- **Recent achievements:** microwave operational amplifiers with +51.4 dBm OIP3, 5.8 dB Noise Figure, 0.9 W @ 2 GHz & 20 dB gain up to 20GHz bandwidth
On the Horizon: Antennas

Wideband Antenna Dilemma
A wideband cognitive radio front-end can be miniaturized through high-Q MEMS filters and highly integrated RFICs; however, conventional antennas lead to a >10-100x increase in overall volume.

Challenges
- Chu-Harrington limit → electrically small antennas have poor radiation efficiency, narrow bandwidth
- Impossible to cover a wide bandwidth (such as VHF to S-band) in a single, small volume antenna

Opportunities for Research
- Adaptive form-factor antennas
- Small antennas for low-frequency
- Active/non-Fosters antennas
- New materials/metamaterials

Example ASP Architecture

Electrically Small (0.03 λ @ 0.5 GHz) Circular Patch Metamaterial Antenna

Electrically Small (0.03 λ @ 2.45 GHz) Slot Antenna

Multi-layer Chiral Metamaterial Structure
**COGNITIVE RADIO:** “An approach to wireless engineering wherein the radio, radio network, or wireless system is endowed with awareness, reason, and agency to intelligently adapt operational aspects of the radio, radio network, or wireless system.” [SDR Forum 2008]

**Emerging CR Capability: Dynamic Spectrum Access (DSA)**

**Current CR-related DARPA Programs → energy detection and cooperative/ network-based approaches**

**Future CR Capability: Low Power Signal Separation and Recognition**

**Emerging CR Capability: Interference Detection and Avoidance (DAA)**

*TODAY: SOA signal-recognition platforms are large and power hungry. MTO is interested in new, low-power approaches to signal recognition.*
Sensing the Spectrum: mm-Wave/Sub-mm-Wave/THz

MTO is pushing the limits of electronic devices and MMIC technology to >1 THz operation

Key DoD Applications:
- Reduced visibility aircraft landing/navigation systems
- Precision munitions guidance
- High-bandwidth data links
- Standoff contraband detection
- Chem/bio detection

Microantenna Arrays: Technology and Applications (MIATA) Kenny
Microantenna array with sensitivity at 95 GHz

Sub-Millimeter Wave Imaging Focal-Plane Technology (SWIFT) Rosker
Active 340 GHz sub-aperture

Terahertz Imaging Focal-plane Technology (TIFT) Rosker
Multi-element detector receiver focal plane arrays in the THz band

The next step beyond SWIFT and TIFT → Dr. Mark Rosker’s THz Electronics program
Compact, high-performance circuits that operate at center frequencies > 1.0 THz
Recent Accomplishments: mm-Wave/Sub-mm-Wave/THz

Microantenna Arrays: Technology and Applications (MIATA)
PM: Tom Kenny

Sub-millimeter Wave Imaging FPA Technology (SWIFT)
PM: Mark Rosker

**Program Objectives**
- Phase-sensitive imaging opens up heretofore impossible mm-Wave applications
- Phase-sensitive detection via optical upconversion to create conformal imaging arrays
- High resolution with large volume reduction

**Recent achievement:** MMIC-based antenna to detector impedance matching network resulted in world record in sensitivity for mm-Wave detectors

340 GHz sub-MMW Sensor Arrays

- λ/2
- 20 cm (4x128 pixels)

**Program Objectives**
- Demonstrate world’s fastest MMICs for imaging at sub-mm-wave frequencies in a number of all-weather environments and platforms
- Achieve an integrated imaging system consisting of a 1 x 128 pixel active array

**Recent achievements:** LNA with 7.5 dB NF @ 350 GHz with 68 GHz BW (23%); 340 GHz oscillator with PN <-42 dBC/Hz @ 100 Hz

Approved for Public Release, Distribution Unlimited
Sensing the Spectrum: Infrared

MTO has a robust portfolio of sensing and imaging technologies across the IR band → towards hyperspectral imaging

Photon-Trap Structures for Quantum Advanced Detectors (PT-SQUAD) Dhar
Ultra broadband (0.5 to 5μm) highly sensitive focal plane array

Micro Imagers for Sensing (MISI) Horn
SWIR micro-camera-on-a-chip

Adaptive Focal Plane Array (AFPA) Horn
IR Focal Plane Arrays w/o cryogenic cooling

High Operating Temperature Mid-Wave Infrared (HOTMWIR) Horn
IR Focal Plane Arrays w/o cryogenic cooling

Advanced Microsystem Technology Program (AMTP) Kovacs
One goal of this multi-faceted program is 3D integration of new sensor materials for MWIR avalanche photo detector arrays

Key DoD Applications:
• Night Vision systems
• Low ambient light imaging
• Early warning
• Contraband detection
**Recent Accomplishments: Infrared Sensing**

*High Operating Temperature Mid-Wave Infrared (HOT MWIR) PM: Stuart Horn*

- Thermal detectors with wavelength-size features
- Fast scene capture with 12 μm 1024 x 768 FPA with thermal time constant of ~7 ms

**Program Objectives**

- Low thermal mass, short time constant pixel enabled by Diffractive Resonant Cavity (DRC) design & low noise, high TCR a-Si/a-SiGe
- Room temp IR for small platform persistent surveillance & distributed aperture threat warning

**Recent achievements:** 12 μm 1024 x 768 imaging demonstration with NETD ~50 mK → capture of < 3 ms fast events

*Adaptive Focal Plane Array (AFPA) PM: Stuart Horn*

- Adaptive Focal Plane Array (AFPA)
- Dual-Band Detector Array (HgCdTe)
- Dual-Band Readout Integrated Circuit (ROIC) (CMOS)

**Program Objectives**

- Integrate tunable MEMS filters w/ dual-band FPA
- Enable target classification based on LWIR spectral signatures in chip-scale device
- Enable detection of buried mines (IEDs) and camouflaged targets from tactical (UAV) platform

**Recent achievement:** demonstrated narrow band (100 nm) spectral tunable Focal Plane Array from 8 – 11 μm in chip-scale package

Approved for Public Release, Distribution Unlimited
MTO has a strong portfolio in visible and low-light imaging, including exploiting advanced signal processing algorithms for revolutionary imaging capabilities.
Recent Accomplishments: Optical and Beyond

Deep UV Avalanche Photon Detectors (DUVAP)
PM: Henryk Temkin

Hemispherical Array Detector for Imaging (HARDI)
PM: Dev Shenoy

Program Objectives
• Demonstrate arrays of solar-blind Geiger mode avalanche photodetectors.
• Single photon detection of the UV spectrum
• Room temp Geiger mode operation of a SiC APD
• Quantum efficiency of 65% @ 280 nm

Recent achievements: Geiger mode demo with quantum efficiency of 65% @ 280 nm & uniform gain > 10,000

Program Objectives
• Develop hemispherical focal plane arrays for VIS-NIR-SWIR wavelengths for wide field of view (FOV), simple, and robust imagers
• Eliminate the need for multiple detectors or gimbals thus lessening the system complexity

Recent achievements: responsivity of PD material to 1.9 µm & detectivity of >$10^{10}$ cmHz$^{1/2}$/W up to 1400 nm
DoD needs small, high-sensitivity radiation detectors → Fundamentally conflicting requirements

→ Require **new materials** with both good absorption and good quantum efficiency

→ Require **new devices or circuits** to make the most of already existing materials

### Materials and Challenges

**HgI₂, PbI₂, GaSe, CdTe, CdZnTe:** Production of large/uniform single crystals, material cost reduction

**GaAs:** Increasing neutron detection efficiency in a high gamma ray environment

**Boron-based neutron detectors:** Bulk crystal growth and film impurity reduction

### Emerging Device Structures and Circuits

**Pillar Structured, 3D Neutron Detector (Livermore Natl. Lab)**

- Device design takes advantage of high \(^{10}\text{B}\) neutron cross section while overcoming limitations of SOA 2D device geometry
- Prototype device shows 7.3% efficiency → device scaling for high efficiency is feasible

**3D ICs for Particle Detection (Fermilab/MIT LL)**

- First HEP detector using SOI-based 3DIC technology
- Developing sensor integration technologies for stacked sensor/ROIC integration

DARPA MTO is interested in new ideas for compact, high-sensitivity radiation detectors
Sensing the Spectrum: Mechanical Resonance/Vibration

Hybrid Insect MEMS (HI-MEMS) \(Lal\)
Acoustic and ultrasonic sensors mounted to insect platforms

Compact Ultra-Stable Gyro for Absolute Reference (COUGAR) \(Lal\)
Fiber optic resonator gyroscope architecture for ultra-high precision rotation sensing

Micro Inertial Navigation Technology (MINT) \(Lal\)
Combination of microscale inertial and velocity sensors for inertial navigation

Navigation-Grade Integrated Micro Gyroscopes (NGIMG) \(Lal\)
Inertial Sensors with 300 Hz BW

Key DoD Applications:
- Ultra-stable clock references
- Miniaturized inertial grade navigation
- GPS-denied navigation
- Covert sensing with bionic platforms
- Underwater surveillance/SONAR

Sensing of mechanical and atomic vibrations/resonances leads to ultra-precise navigation and timing

Approved for Public Release, Distribution Unlimited
Recent Accomplishments: Mechanical Resonance/Vibration

Navigation-Grade Integrated Micro-Gyroscopes (NGIMG)
PM: Amit Lal

Example: Archangel Spinning Gyro

Recent achievement: devices spinning at 200 rpm (20.9 rad/s) for over 2 hours in a 6 mT vacuum package

Chip-Scale Atomic Clock (CSAC)
PM: Amit Lal

Recent achievement: long-term frequency stability of $-2 \times 10^{-8}$ seconds/day & short term stability of $4 \times 10^{-11} / \sqrt{\text{τ}}$

Program Objectives
- Integrate MEMS, photonic, and electronics technologies to achieve miniature, low-power atomic timing and frequency references with:
  - Allan deviation < 10-11 over 1 hour (1 ms/day)
  - Size < 1 cc & Power Consumption < 30 mW
- Attain tiny gyros and accelerometers with navigation-grade performance and tiny power consumption
- Achieve ultrahigh quality factor resonators ($Q > 10^7$), miniature NMR, and spinning masses

Example of Use: Radio System (SINCGARS)
Clock accuracy of 1s/10,000 yrs $\Rightarrow$ 16-hour re-synch interval or radio silence
Goal: Vol: 1 cm$^3$ Power: 30 mW Stab: 15 in 10k yrs

Physics Package
CSAC Breadboard
Phase II CSAC Prototype

GHz Resonator in Vacuum
VCSEL
Cesium or Rubidium
Detector Substrate

Z
Y
X
On the Horizon: Acoustic Sensing

Opportunities for Research

- Sound localizers and identifiers
- High frequency ultrasound sensors for imaging/ material characterization
- Underwater acoustic sensors/UUV SONAR arrays
- Advanced chemical detection through photo-acoustic sensing

Acoustic sensing has a wide variety of potential applications – recent advancements in materials and MEMS technologies can be brought to bear on problems in this area.
MTO has a growing portfolio in chemical sensing, from fundamental materials and device investigations, to compact MEMS-based analysis platforms.
Recent Achievements:

**Chem/Bio Sensing**

- **Laser Photoacoustic Spectroscopy (L-PAS)**
  - **PM:** Henryk Temkin
  - [Image of L-PAS setup]
  - **Program Objectives**
    - Single mode quantum cascade lasers > 200 mW output power with 400 nm tunability and a PAS system with 1 ppb sensitivity for DMMP
    - Compact, rapid, reliable and highly sensitive chemical warfare agent (CWA) sensors
  - **Recent achievement:** Dimethyl Methylphosphonate (DMMP) detection with a 10.5 μm Quantum Cascade Laser; sensitivity ~ 1 ppb

- **Surface Enhanced Raman Spectroscopy S&T Fundamentals**
  - **PM:** Dennis Polla
  - [Image of SERS setup]
  - **Program Objectives**
    - Enhancement factors of $10^{12}$ for liter-sized nanoparticle samples or 28 in$^2$ nano-array wafers
    - Achieve reproducible performance of nanoparticles and nano-arrays and optimize characterization methods
  - **Recent achievement:** nano-antenna design has achieved reproducible surface Raman spectroscopy enhancement factors of $10^7$
Analog-to-Digital Conversion

An important aspect of sensing is converting the collected information from the analog domain to the digital domain for signal processing.
Potential Approaches:

- **Sub-threshold**: Circuit designs based on transistors operating below $V_{th}$.
- **Charge-Based**: Passes charge packets between stages like a CCD, rather than amplifying with op amps at each stage.
- **Zero-Crossing**: op-amps are replaced with a current source and a zero-crossing detector.
- **Analog Signal Processing**: Performs computationally intensive operations in analog/discrete-time domain.

**Low-Energy, Discrete-Time Analog OFDM Rx**

- FFT moved in front of the ADC, relaxing ADC resolution requirements
- FFT implemented using a single, repeatable butterfly circuit
- Order of magnitude lower power consumption than equivalent ADC/DSP-based approach

**6b 0.2-to-0.9 V Sub-Threshold ADC**

- ADC FOM of 125 fJ/step achieved at 0.4 V sub-threshold supply voltage
- Device variation is a key design challenge at low supply voltages

DARPA MTO is interested in new approaches to achieve high ADC performance at ultra-low energy.
On the Horizon: On-Chip Sensing

A Consequence of Scaling
Severe inter- & intra-die variations in process parameters, voltage and temperature (PVT) in deeply scaled technologies result in performance “left on the table”

On-chip sensors measure impact of variability → in situ control loops drive the circuit back to required specifications

Opportunities for Research
• Novel on-chip variability sensors and actuators for dynamic performance correction
• Robust/stable control algorithms, hardware implementations subject to variability
• Design methodologies/EDA tools for self-healing circuits


DARPA HEALICs program
Kicking off later this March
MTO programs are pushing the limits of sensing from atomic vibrations to optical wavelengths and beyond

DARPA and the DoD need your innovative ideas for “Sensing across the Spectrum”

★ Contact an MTO program manager to discuss your ideas
★ Or consider becoming a PM yourself… …Join Us!