Adaptive Focal Plane Array - A Compact Spectral Imaging Sensor

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Adaptive Focal Plane Array - A Compact Spectral Imaging Sensor

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Motivation for LWIR / MWIR Adaptive FPA

- Conventional hyperspectral imaging systems
  - Large and Heavy
  - Generate large volumes of data
  - Typically scanning systems

- Conventional multispectral imaging systems
  - Fixed detection wavelengths limit capability

AFPA Objective: Develop a compact spectral imaging sensor to enable enhanced target detection / ID in a device that can be deployed on SWAP-constrained platforms and provide real time information

- Wavelength tuned LWIR (8 – 11 µm / Δλ FWHM ~ 100 nm)
- Simultaneous pixel-registered broadband MWIR (3 – 5 µm)
- Spatially resolved, intelligent spectral analysis
AFPA Parameter Objectives

• MEMS tunable filter array integrated with a dual-band focal plane array

• Parameters:
  – Tuning range (individual filters or checkerboard): 8.0 µm $\Rightarrow$ 11.0 µm
  – Filter bandwidth (FWHM): 100 nm ± 20 nm @ 10.0 µm
  – MWIR detection band: ~ 3.5 – 5 µm (nominal)
  – Filter dimension: ~ 400 µm center-to-center spacing
  – Filter optical fill factor: $\geq$ 50%
  – FPA/ROIC: 640x480 20 µm DB-FPA
  – Filter format: Spectral fovea (nominally 8 x 24 filters)
  – Operating temperature: ~ 80K
  – Filter tuning speed: ~ 1 msec
AFPA Phase II MEMS Tunable Filter Array

Si MEMS Substrate
- Lower half of MEMS filter structure
- Includes stationary mirror, actuation traces

MEMS filter array
- Hybridized moveable mirrors
- Spectral Fovea

DB-FPA (MW / LW) Broadband Imaging Area
- 480 x 480 pixels
- "Conventional" DB Imaging

Mechanical Mounting Surface

MW / LW AR Coating

DB-FPA Imager Area
- 640 x 480 pixels

Direct Drive Interconnect Traces

MEMS Actuation IC (MAIC) Chip
- Hybridized to MEMS substrate
- Direct interconnect to each filter

DB-FPA (MW / LW) Broadband Imaging Area

"Conventional" DB Imaging

MAIC Chip
- Hybridized to MEMS substrate
- Direct interconnect to each filter

Direct Drive Interconnect Traces
MEMS Fabry-Perot Filter Design

**MEMS structure**
- Bulk micromachining
- Hybrid assembly using Au-Au thermocompression bond

**Filter characteristics**
- Fabry-Perot filter design
- Tuning band determined by reflection band of dielectric mirrors

**Filter Actuation**
- Filter actuated by applying potential between moveable mirror and substrate mirror
- Displacement driven by electrostatic attraction
- Restoring force provided by Si flexure springs
- Prototype devices - direct drive
Modeled MWIR / LWIR Spectral Performance (Transmission Averaged over F/6.5 Incident cone)

Filter air gap varied between 3.1 – 5.6 µm
MEMS Filter SEM Images

Top View
- AR Coating
- Si Mirror Membrane
- Moveable Mirror w/ Patterned AR Coating
- Flexures
- Supports

Bottom View
- Patterned AR Coating (recessed)
- Thinned Flexure
- Mechanical Support
- Au Bonding Pads
- Si Device Layer

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MEMS Tunable Filter
Measured Optical Performance

IR Microscope Transmission

Scanned Filter Transmission of Tunable CO₂ laser

LWIR Detector Spectral Response with Tunable MEMS Filter

<table>
<thead>
<tr>
<th>CO₂ Laser Wavelength (µm)</th>
<th>Filter Bandwidth (nm FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.23</td>
<td>144</td>
</tr>
<tr>
<td>9.28</td>
<td>138</td>
</tr>
<tr>
<td>9.32</td>
<td>145</td>
</tr>
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<td>9.49</td>
<td>108</td>
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<td>9.52</td>
<td>112</td>
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<td>9.55</td>
<td>145</td>
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<td>9.62</td>
<td>90</td>
</tr>
<tr>
<td>9.66</td>
<td>129</td>
</tr>
</tbody>
</table>
Tunable MEMS Filter Mechanical Response

- Low energy dissipation in Si MEMS structure leads to mechanical “ringing” under vacuum operation
  - 300µs in air, but may be >10’s (or even 1000’s) msec in vacuum
- Exploit gas damping for increased response speed
  - Requires sealed, backfilled package
  - Neon gas provides necessary viscosity for 77K operation

MEMS Filter Response to Voltage Actuation Step

- Vacuum ⇒ Q~35
- ~ 300 µs settling time in 1 atmosphere of air
  Q ~ 1.0
AFPA Phase II Imaging Device Objectives

• **Demonstrate full capability MEMS filter array**
  – Individual, independent filter tunability
  – Extended tuning range: 8.0 – 11.0 µm
  – Narrower bandwidth: 100 nm ± 20 nm @ 10.0 µm
  – Design and implement CMOS MEMS Actuation IC (MAIC) for full array actuation

• **Demonstrate prototype AFPA sensor**
  – Imaging structure with tunable MEMS array coupled with dual-band FPA
  – Demonstrate spectral tunability in an imaging array
  – Spectral Fovea configuration

• **Technical challenges**
  – Overcome tuning limit imposed by MEMS snap-down phenomenon
    • Optimized optical filter design
    • Implement negative capacitance MEMS actuation to overcome parasitic
    • Provide viscous MEMS damping
  – Heterogeneous technology integration in an integrated optimal subsystem
    • Tunable MEMS filter array coupled to DB-FPA in a compact, gas-filled, optical, cryo-enclosure
MEMS Actuation and Snap-down

Theoretical maximum MEMS deflection before snap-down using voltage control (33% of unactuated gap)

- Charge control enables tuning beyond snap-down
- Limited by parasitic capacitance between driver and MEMS device
- Negative capacitance circuit can overcome $C_p$
- Requires low MEMS Q to prevent oscillation past stable point
- Optimize optical coatings to maximize tuning slope / minimize demands on $-C_p$ tuning
Primary Sources of Parasitic Capacitance

- Parasitic Capacitance dominated by coupling capacitance
  - Values depend position inside filter array
  - Largest parasitic cap determines tuning range for entire array
- MAIC will add similar capacitance
- Negative capacitance actuation circuit under development to overcome $C_p$ limited snap-down

<table>
<thead>
<tr>
<th>Capacitor</th>
<th>Specific Capacitance</th>
<th>Length or area</th>
<th>max. total capacitance</th>
<th>min. total capacitance</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^2_{cpM}$</td>
<td>40 [aF/µm]</td>
<td>3200 [µm]</td>
<td>256 [fF]</td>
<td></td>
<td>1 µm spacing</td>
</tr>
<tr>
<td>$C^1_{cpM}$</td>
<td>40 [aF/µm]</td>
<td>200 [µm]</td>
<td>8 [fF]</td>
<td></td>
<td>1 µm spacing</td>
</tr>
<tr>
<td>$C^1_{gndM}$</td>
<td>26 [aF/µm$^2$]</td>
<td>3200 [µm]</td>
<td>83.2 [fF]</td>
<td></td>
<td>1 µm SiO$_2$ thickness</td>
</tr>
<tr>
<td>$C_{gndM}$</td>
<td>26 [aF/µm$^2$]</td>
<td>200 [µm]</td>
<td>5.2 [fF]</td>
<td></td>
<td>1 µm SiO$_2$ thickness</td>
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<tr>
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<td>100 [µm]</td>
<td>2.6 [fF]</td>
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<td>1 µm line width</td>
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<tr>
<td>Total to GND</td>
<td></td>
<td></td>
<td>85.8 [fF]</td>
<td>7.8 [fF]</td>
<td></td>
</tr>
<tr>
<td>Total coupling</td>
<td></td>
<td></td>
<td>256 [fF]</td>
<td>8 [fF]</td>
<td></td>
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<tr>
<td>Total</td>
<td></td>
<td></td>
<td><strong>341.8</strong> [fF]</td>
<td><strong>15.8</strong> [fF]</td>
<td></td>
</tr>
</tbody>
</table>
Integrated AFPA Assembly (Conceptual)

- Gas filled enclosure enables viscous gas damping of MEMS filters
- Resealable cover enables reuse and testing of MEMS filter array component

- MAIC / MEMS array interface key to achieving tuning beyond snap-down

MEMS array / MAIC / DB-FPA
MAIC Connector
Window
Vacuum / gas fill pinch-off tube

Removable cover (Indium crush seal)

MEMS filter array
Dual-band FPA
LCC

In-bump bond interconnect
MAIC wirebonds

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Planned AFPA Prototype Demonstration

Lab bench level testing planned using prototype AFPA sensor

- Demonstration of LWIR spectral response tunability
  - Independent filter actuation

- Demonstration of spectral analysis capability
  - Synthetic input spectra (filtered illumination)
  - Target materials if military interest

- Demonstration of spectral imaging of scene (lab)

- Demonstration of simultaneous LWIR tuning / broadband MWIR imaging

- Future development of field-testable camera with integrated optimal spectral interrogation and analysis algorithms
Summary

• Phase I - LWIR tunable MEMS filter capability demonstrated
  – Tuning range 8.0 – 10.0 µm
  – Filter bandwidth 90 – 150 nm
  – Tuning speed ~ 1 msec
  – Simultaneous broadband MWIR transmission
  – Filters as small as 280 x 280 µm

• Phase II - Integrated dual-band AFPA sensor configuration established
  – Spectral fovea configuration
  – Wide tuning range (8.0 – 11.0 µm) achievable using novel actuation and optimized optical design
  – Independent filter tunability
  – Sensor package combining MEMS array, CMOS MAIC, Dual-band FPA with mechanical MEMS damping
  – Optical configuration requires minimal optical imaging sensor modifications