Millimeter Wave Photonics: Design, Integration and Application

Dennis Prather, Professor
Outline

• Overview of RF imaging
• Optical phase modulators
• Ultra-wideband frequency synthesis
• RF photonic module integration
• Silicon Nanomembranes for 3D RF signal routing
• Summary
RF Imaging
Imaging Across the EM Spectrum

\begin{table}
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{\(0.03\,\text{Å}\)} & \textbf{0.3 \,Å} & \textbf{3 \,Å} & \textbf{3 nm} & \textbf{30 nm} & \textbf{300 nm} & \textbf{3 \,μm} & \textbf{30 \,μm} & \textbf{300 \,μm} & \textbf{3 mm} & \textbf{30 mm} & \textbf{300 mm} & \textbf{3 m} \\
\hline
\textbf{\(10^{20}\)} & \textbf{10^{18}\)} & \textbf{10^{16}\)} & \textbf{10^{14}\)} & \textbf{10^{12}\)} & \textbf{10^{10}\)} & \textbf{10^{8}\)} & \textbf{10^{6}\)} & \textbf{10^{4}\)} & \textbf{10^{2}\)} & \textbf{10^{0}\)} & \textbf{10^{-2}\)} & \textbf{10^{-4}\)} & \textbf{10^{-6}\)} \\
\hline
\textbf{γ-rays} & \textbf{X-rays} & \textbf{EUV} & \textbf{UV} & \textbf{VIS} & \textbf{IR} & \textbf{mm-waves} & \textbf{radio-waves} & \\
\hline
\end{tabular}
\end{table}

- **γ-rays**: Nuclear medicine, Medical Fluoroscopy
- **X-rays**: 13 nm Next generation Lithography, 1.5 μm Telecom
- **EUV**: Security Thermography Industrial monitoring
- **UV**: 77 GHz collision avoidance, 94 GHz Passive imaging
- **VIS**: RADAR
- **IR**:
- **mm-waves**:
- **radio-waves**:
Advantages of Passive mmW Imaging

- Provides *all-weather, day/night imaging* including cloud, fog, smoke, and dust penetration.
- “Cold” sky delivers *high effective contrast* for many man-made targets independent of most camouflage.
- Systems operate using passive detection enabling *covert operation*.
- *Blowing dust/sand has minimal impact* on “passive” mmW for brownout distance scales.
- Imagery is *easily interpreted* by operator as it is similar to FLIR.
Atmospheric Attenuation in the EM Spectrum
Limitations of Real Imagers

- Maximum resolution of ANY imaging system is proportional to the wavelength over maximum aperture diameter.

\[ \theta \sim \frac{\lambda}{D} \]

For “see-through” operation, achievable resolution will be limited by the practical size of aperture that can be found on platform.
Primary Technology Barriers

• Sensitivity:
  – Eight orders of magnitude less power emitted at mmW than in IR wavelengths.
  – Currently requires a large degree of up front gain (LNA’s), cryogenic cooling, or long averaging times. (*high cost per element*)

• Resolution:
  – Physical limitations imposes severe resolution constraints for aperture sizes feasible in most applications.
  – Most imager designs require volumetric scaling to increase resolution and require contiguous space for placement. (*very large SWaP*)

Our design uses optical enabled, distributed aperture to minimize part count and greatly reduce size and weight.
2D vs 3D Scaling
Technology

We use a distributed aperture imaging (DAI) approach over a standard focal plane array (FPA). An FPA requires a lens, larger volume, and an expensive mmW detector for each pixel.

Advantages of DAI:
- increased resolution without a lens and the volumetric scaling of size and weight
- field amplitude and phase is captured at discrete points
- enables a flat or conformal, high resolution imaging system
- lower number of millimeter wave components needed
Optical Upconversion Phase Preservation

The optical field is proportional to the incident complex millimeter-wave field scaled in amplitude and frequency.
mmW Detection: Optical Upconversion

- Mapping mmW signals onto optical carriers using an EO modulator enables optical photodetection.
- Technique has demonstrated sub-picowatt noise-equivalent powers without cooling or low-noise.
- Phase preservation allows for interferometric (or distributed-aperture) imaging.
- Phased array enables electronically controlled focusing and scanning.

Interferometric imaging reduces size and allows for conformal mount.
Optical Upconversion Phased Array

Incoming energy sampled by multiple antennas in a distributed array.

Optical modulators convert energy to optical domain.

Lightweight optical fibers deliver energy to central location.

Distributed aperture enables lightweight and small form-factor realization of high resolution passive mmW imager.

Standard optical camera used to reimage mmW scene.
Optical Upconversion Flow

Array of electro-optic millimeter-wave detectors

Laser source

Fiber optic distribution network

Optical processor with feedback

Optical carrier

Millimeter wave signal in sidebands

Strip off mmW signal with optical filter

Optical processor stabilizes phase of each channel and enables electronic image enhancement techniques such as electronic focus/steering and super-resolution.
Passive mmW Phased Array Imager

We have demonstrated a video rate (15 fps) 35 GHz passive imaging system
Hand Passive Video
Resolution Target Passive Video
Passive W-Band Field Test Images
Scanning Imaging System

- Single-pixel scanning cart based on optical upconversion.
- Operational frequency ~95GHz.
- Noise equivalent temperature resolution of 2K.
- Diffraction-limited spatial resolution.
- Utilized for a variety of phenomenology studies, e.g., desert imaging.

System Schematic

- Antenna
- SPST PIN Switch
- LNA
- Isolator
- EO Modulator
- DFB Laser
- EDFA
- Carrier Pre-Filter
- Optical Source
- Carrier Rejection Filter
- Photodiode
- TIA
- Lock-in Amplifier

Imagery of Yuma, AZ

- 95-GHz mmW Image
- Visible Image
- mmW (95GHz) and visible images
- See through the hull of boats
- Foot prints in the sand and cell phone in pocket
Field Measured Obstacles

Visible

Pickup Truck

mmW (W-band)

AH-1 Helicopter
Field Measured Obstacles

Visible

mmW (W-band)

2’ Diameter Holes

Rock on dirt
Field Measured Obstacles

Visible

mmW (W-band)

6” Brick

Stack of bricks
Field Measured Obstacles

Visible

Person with caulking gun

Concrete Telephone Pole

mmW (W-band)
Field Measured Obstacles

Visible

mmW (W-band)

Wooden Posts with Wire

3/8” and 1” Wire
Field Measured Obstacles

Adobe Hut

Brick building

Visible

mmW (W-band)
Field Measured Obstacles

Visible

mmW (W-band)
Field Measured Obstacles

Visible

mmW (W-band)
Field Measured Obstacles

Visible

mmW (W-band)
Field Measured Obstacles

Range of 100 feet at a declination angle of 27°

Image of three targets on pavement:
• Pair of bricks on end presenting ~7”x6” target (left)
• 6” square aluminum plate (center)
• Cinderblock (right)
Can mmW’s Penetrate Brownout?
H-53 Helicopter at the Yuma Proving Grounds
Dynamic Test Setup

- Data consists of temporal recording of passive detector staring at cold sky reflector during several helicopter passes directly over view path.
- Average height of view path ~1.5 m at a distance of 270’.
- Both V and H polarizations recorded.

Geometry of test provides higher losses than helicopter-mounted sensor will see.
The Problem - Video
IR and Visible Images in Brownout

IR Image in Dust

Visible Image in Dust
Brownout Field Testing Results

- Landing zone obstacles are clearly visible in mmW for all measured obstacles
  - Average contrast on the order of 15°C for H-polarization for ground targets tested
- mmW losses are low under all brownout conditions tested
  - Average maximum values of loss during all flyover tests: 1% for UH-1, 8% for H-60, 20% for H-53 over 150’ path

Flyover testing demonstrates less than 20% contrast reduction for H-53 brownout at target operational range of 150’.

Passive mmW presents sufficient contrast in desert environments and impact of even worst case brownout attenuation is minimal.
How The Technology Works
mmW Detection: Optical Upconversion

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Interferometric imaging reduces size and allows for conformal mount.
Antenna Array Fabrication

- Antenna array fabricated from COTS horn elements embedded in carbon fiber, foam composite.
- Horn element backed by machined flange to mate to upconversion element.
RF Modules

CPW to Modulator

Front Gain Stage

Cascaded Module

W-band antenna integration
Detector module consists of metal housings, patterned alumina substrate, amplifiers, high speed EO modulator and PCB control board.

Fully integrated module with RF absorber filled top housing.
Integrated Detector Module

Wire bond transition and filter

LNA and absorber chain

<1.3dB Probe/WG transition

DC bias control board

Bottom of an integrated detector module

A full module that is under testing

DC biasing network
High Bandwidth Modulators
Design of a Traveling-Wave Modulator

**Electrical Analysis**

Cross section geometry
G, S, B, T, H, R, sw, Δ

Index, losses, and impedance
n_m, a_d, a_c, and Z_m

Interaction length
L

Modulation depth
m(f)

DC half wave voltage
V_π(0)

**Optical Analysis**

To maximize η_mod at high frequency, we need:

1. n_m = n_o = 2.15
2. Z_m = Z_g = 50 Ω
3. a_d, a_c = min
4. V_π(0) = min

Other important parameters include

\[ η_{mod} = \frac{\pi^2 Z_g}{2V_π^2(f)} \]
Modulation Efficiency Calculation

- Voltage on a traveling-wave modulator imposes phase change:

\[
\Delta \phi = \left( \frac{1}{2} \right) n^3 r \bar{E} \left( \frac{2 \pi L}{\lambda} \right) = \left( \frac{\pi n^3 r}{\lambda} \right) \int_0^L \bar{E}(x) \, dx = \left( \frac{\pi n^3 r}{\lambda} \right) \int_0^L \frac{V(x)}{d} \, dx
\]

- \( V_\pi(f) \): voltage for \( \Delta \phi = \pi \)

- Using transmission line theory:

\[
\eta_{\text{mod}}(f) = \left( \frac{\pi^2 Z_m}{2V_\pi^2} \right) = \left( \frac{\pi^2 Z_m}{2 \left( V_{\pi,DC} \cdot m(f) \right)^2} \right) \left( \frac{1}{\text{Watts}} \right)
\]

Depends on \( Z_m, |n_o - n_m|, \alpha_c, \text{ and } \alpha_d \)
Bandwidth Limiting Mechanisms

- Slight index mismatch, \( \Delta_n = |n_o - n_m| \), is primary contributor to the roll-off in frequency response.
- The effective index difference should be less than 0.05 for 95 GHz operation for 2 cm modulator length.
Overview of Fabrication Process

1. LiNbO$_3$ Substrate
2. Ti patterning
3. Ti diffusion
4. Mask patterning
5. ICP etching
6. Buffer layer deposition
7. Seed layer evaporation
8. Electroplating
9. Resist removal
Fabrication process
Formation of Ti strip
Ti in-diffusion
Ridge etching
Oxide layer deposition
Seed layer deposition
Thick resist lithography
Electroplating of gold electrodes
Striping of seed layer
Fabricated High Frequency Modulator

To mitigate the substrate mode, particularly at high frequencies (>50 GHz), the 500um thick LiNbO$_3$ wafer was thinned on the backside of device. A trench with a width of 200um and depth of 450um is formed, thereby leaving a 50um thick device layer.
High Frequency Up-conversion Modulators

- Fully developed simulation tools
- Industrial leading high power ICPs
- Design, simulation, optimization
- Ridge and buffer layer for index matching
- Cross-section of designed modulator structure
- Uniform electro-plating
- Efficient design for low mmW loss
- Eliminate substrate modes via trench

Intensity (dBm)

VNA (0-325GHz)
Microscope
Fiber
Probe

Wavelength (nm)

-100kHz - 125GHz

-75GHz
-80GHz
-85GHz
-90GHz
-95GHz
-100GHz
-105GHz
-110GHz
-115GHz
-120GHz
-125GHz
Wafer level microfabrication includes optical waveguide diffusion, ridge etching, buffer layer deposition and electroplating.

Post-processing and packaging includes dicing, polishing, annealing, index tuning and optical bonding.

Modulator wafer after microfabrication. 61 modulators on each wafer.

Individual modulator chip after dicing, polishing and index tuning.

Modulator is optically integrated to PM fiber through V-groove bonding.
Measurements at 110 GHz

Substrate modes negatively impact the performances of the device in W-band

Conduction loss: $\alpha_m = 0.28 \text{ dB/(cm.GHz}^{1/2})$

Dielectric loss: $\alpha_d = 0.01 \text{ dB/(cm.GHz)}$

Input Impedance: $Z_m = 46.4 \Omega$

Effective index: $n_{\text{eff}} = 2.19$

Optical loss: $L_{\text{opt}} = 3.0 \text{ dB}$
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Substrate Modes Suppression

Substrate modes frequency cut-off [1]:

\[ f_c \text{ (GHz)} = \frac{11.9}{t_s \text{ (mm)}} \]

- 100 GHz: \( t_s = 120 \ \mu\text{m} \)
- 200 GHz: \( t_s = 60 \ \mu\text{m} \)

High Bandwidth Operation
Setup for 220 GHz bandwidth measurements

- Vector Network Analyzer (VNA) - Agilent E8361C
- Optical Spectrum Analyzer (OSA) - Yokogawa AQ6319
- Millimeter Wave VNA Extender - OML V06/V05VNA2-TR
- WR-6/5
- Tunable Laser - Optilab OTWL-CR
- Optical fiber
- Power Meter - Erickson PM4
- Probe - GGB Model 170/220
- Modulator
10-220 GHz Modulation Spectrum

- Sidebands normalized to input power
- Only 3 dB attenuation between 10 GHz and 100 GHz
- Stronger attenuation above 110 GHz
Ultra-Wideband Frequency Synthesis
Why Optical Generation of RF Sources?

• Ultra-wide tuning range
  – Small tuning range in optical domain
    = huge tuning range in RF (200 GHz = 1.6 nm)

• RF distribution for remote LO sources, phased arrays
  – RF over fiber = transmit over km’s with negligible loss/dispersion

• Phase steering in optical domain, UWB
  – Phase is preserved in optical-to-RF conversion = fast, low-power, wide-BW, low-dispersion phase steering in optical domain
Coherent Optical Heterodyning for UWB IF Synthesis & Up/Down-conversion Receivers

- System is designed to clone Laser 2 at an offset frequency using EO modulation & injection seeding.
- By tuning $\Omega$, lasers can be locked to any heterodyne frequency difference desired (up to BW limits of modulator & detector), while preserving statistical correlation.
- Thus, received signal can be optically mixed down to near baseband, easing BW requirements of A/D converters.
Narrow-line Widely Tunable RF Generation System
Narrow-line Widely Tunable RF Generation System
Narrow-line Widely Tunable RF Generation System

\[ \omega_2 \pm n\Omega \]

Sidebands at \( \omega_2 \pm n\Omega \)

DWDM filter spectrum

Diagram showing the system with labeled components and signals.
Narrow-line Widely Tunable RF Generation System

\[ \omega_2 \pm n\Omega \] sidebands at \( \omega_2 \pm n\Omega \)

DWDM filter spectrum

amplified filtered sidebands
Narrow-line Widely Tunable RF Generation System

- Master DFB laser
- Low-frequency reference oscillator (with small tuning range)
- Signal modulation in
- DWDM filters
- Laser 1 thermally tuned, locks to nearest of injected sidebands ($n^{th}$)
- Amplified filtered sidebands
- Sidebands at $\omega_2 \pm n\Omega$
- DWDM filter spectrum
- Photo-detector
- RF Out
Narrow-line Widely Tunable RF Generation System

\[ \omega_2 \]

\[ \Omega \]

sidebands at \( \omega_2 \pm n\Omega \)

DWDM filter spectrum

amplified filtered sidebands

laser 1 thermally tuned, locks to nearest of injected sidebands (\( n^{th} \))

both lasers have identical phase noise

Photodetector

RF Out
Narrow-line Widely Tunable RF Generation System

\[ \omega_2 \pm n\Omega \]

- Amplified filtered sidebands
- DWDM filter spectrum
- Fine tuning range = \( n\delta \)
- Both lasers have identical phase noise

Master DFB laser

Low-frequency reference oscillator (with small tuning range)

Signal modulation in

Laser 1 thermally tuned, locks to nearest of injected sidebands (\( n^{th} \))

Clone DFB laser

RF Out

\[ \omega_1 \]

\[ \omega_2 \]

Photo-detector
Demonstration of Narrow-line, Widely Tunable IF Synthesis

- System is designed to “clone” Laser 2 at an offset frequency using EO modulation & injection seeding, upconvert the received signal with the same modulator, then beat the Master and Clone together on a fast photodetector
  - Lasers’ phases/linewidths cancel out, leaving only spectrally pure RF carrier + received signal!
- Phase modulation generates many harmonics of the reference oscillator, providing ultra-wide tuning range
  - Clone laser can be thermally tuned, will lock to nearest of the injected harmonics
Coherent Optical Heterodyne Receivers: Summary of Accomplishments

- **Linewidth of 1-2 Hz** has been demonstrated over a range from 0.6-49 GHz (upper limit is photodetector bandwidth)
- **Thermally tuned DFB grating in clone laser provides built-in filtering** which allows locking to single sideband when injecting of a comb of harmonics derived from a common reference
- **Lasers can be locked to harmonics of the reference-oscillator frequency**—locking has been demonstrated with 2nd through 10th harmonics, demonstrating wide tunability of RF from a single, low-frequency reference, while preserving the optical phase-noise cancellation from injection locking.
Example Signal: 2-MHz Sine Wave AM Modulated by 1-kHz Square Wave

- Over 20 harmonics of 1-kHz square-wave modulation signal can be recovered with >10 dB SNR, and each with ~1-Hz linewidth!
Integrated DC-40GHz Photodiode Circuit

**Photo-diode Chip Data:**
- Bandwidth: DC-40 GHz
- Max CW Optical Power: 5 mW
- DC Responsivity: 0.55
- Output RF: 50 ohm CPW
Ultra-wideband Integrated Power Amplifier

Characterization setup

~15 dB Gain

S-parameters (dB)

S11  S21  S12  S22

Frequency (GHz)

S21 (deg)

Measured Phase

Frequency (GHz)
• Optical phase shift applied to one laser causes RF interference pattern to shift by the same amount
Optically-fed Phased Array Demonstration

Top view

Coherent 35 GHz sources

Receive horn

Photodetectors

Fibers carrying locked lasers @ 35 GHz offset

Antinode lines

Receive horn

Source spacing 36 mm

Wavelength 8.56 mm
Results: Square-wave Modulation

- Total phase between RF sources is $\phi = \phi_0 + \text{modulation phase}$
- Antenna position kept constant, modulation phase varies between $-\pi/2$ and $+\pi/2$ with modulation frequency of $\sim 400 \text{ Hz}$
Integrated Silicon RF Photonics
Integrated RF-Photonic Module

Gain Chips based on InGaAsP Quantum Wells

High-speed Electro-optic Modulator

Low-phase-noise VCO

Nonlinear Transmission Line Comb Generator

Gratings Form Laser Cavities, Optical Filters (thermally tunable)

Optical Fiber Carrying Phase-locked Laser Signals to Detector/ADCs
Future Integrated Device

Hybrid silicon lasers

Output to modulator
Photo detector
Laser seed
Gain Chip Alignment with Silicon Cavity

Macro view of alignment stage intended to be used to attach the gain chips to the substrate while monitoring output characteristics.

Close up of gain chip aligned to waveguide on substrate.

Integrated Silicon Laser for RF Generation
Process Refining and Calibration
Tuning Distributed Bragg reflector (DBR)

- Tunes at approximately 0.09 nm/°C
Integrated III-V and Silicon Photonic Laser

Grating

Gain Chip

Silicon Waveguide

Gain Chip
Hybrid III-V - Silicon Laser

**Evolution**

**Realization**

- Gain Chip
- Grating

**Characterization**

- 3dB Bandwidth < 866 MHz
Dual Laser Integration
2 Functioning Lasers
Two Lasers on a Chip

Spectrum of Output after MMI

-0.45 nm
~55 GHz
Silicon Nanomembrane 3D Integration for RF Signal Routing
Si-NM Released from SOI Substrate

A 260nm SiNM with 20µm SU-8 substrate

Single crystalline silicon device layers do not need to be associated with bulky rigid substrates
WDM Si-NM Spectral Response

$\lambda = 1550.0 \text{ nm}$

$\lambda = 1558.0 \text{ nm}$
Photonic Crystal Routing Elements
8-Port Router

The switch voltage is 1.2V with 2mA of current

Routing Table

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Switching Table

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Propagation loss

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Switching Power

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<tr>
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</table>
Dosage: $^{14}\text{N}$ and $^{84}\text{Kr}$ ions at 15 MeV with $6 \times 10^6$ ions/cm$^2$ Flux with total doses of 20 krad

Minimal increase in current with set voltage exposed to LET radiation

$\sim 1\%$ decrease in current with set voltage during sample relaxation after ion beam removed
Summary

• Presented an overview of passive RF imaging and the driving needs for advanced systems
• Discussed the realization of ultra high bandwidth optical phase modulators
• Looked at the application of ultra-wideband RF frequency synthesis and linear RF detection
• Discussed nanomembrane integration an RF signal router for multi-functional RF systems
• Thank You!