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





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.



35-GHz image (60 cm aperture)

95-GHz image (60 cm aperture)

Visible image (2 cm aperture)



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*)



[Yujiri et al. IEEE Mic. Mag. , Sep. 2003]



Northrop-Grumman (TRW) MMW imaging camera Weight: 600 lbs, for 0.5 m aperture (~0.5° resolution)

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

Focal Plane Array





Optical Upconversion Phase Preservation



The optical field is proportional to the incident complex millimeterwave 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.

Int.



Interferometric imaging reduces size and allows for conformal mount





Optical Upconversion Phased Array





Optical Upconversion Flow



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

University of Elaware

Passive mmW Phased Array Imager

We have demonstrated a video rate (15 fps) 35 GHz passive imaging system

Visible mmW image

Hand 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











Foot prints in the sand and cell phone in pocket



Imagery of Yuma, AZ





Visible



mmW (W-band)



Pickup Truck





AH-1 Helicopter





2' Diameter Holes

dirt





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ELAWA Π



Person with caulking

Pole





Wooden Posts with Wire



Visible

OASIS LZ

Adobe Hut

























Visible







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?





Imaging Through Obscurants

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. 31

The Problem - Video







IR and Visible Images in Brownout







Visible Image in Dust



Brownout Field Testing Results



mmW and visible images of 2' boulder, 2' diameter holes, and person in Oasis LZ

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

- 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

Passive mmW presents sufficient contrast in desert environments and impact of even worst case brownout attenuation is minimal.

How The Technology Works





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Antenna Array Fabrication



Antenna plate overview

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







Upconversion module mating details

RF Modules









W-band antenna integration



mmW Module 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



A full module that is under testing

High Bandwidth Modulators



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Design of a Traveling-Wave Modulator





Modulation Efficiency Calculation



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

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

- $V_{\pi}(f)$: voltage for $\Delta \phi = \pi$
- Using transmission line theory:

$$\eta_{\text{mod}}(f) = \left(\frac{\pi^2 Z_{\text{m}}}{2V_{\pi,f}^2}\right) = \left(\frac{\pi^2 Z_{\text{m}}}{2\left(V_{\pi,DC} \cdot m(f)\right)^2}\right) \quad \left(\frac{1}{Watts}\right)$$

Dependends on Z_m , $|n_0 - n_{\text{m}}|$, α_c , and α_d



Bandwidth Limiting Mechanisms

- Slight index mismatch, $\Delta_n = |n_0 n_m|$, 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



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





Substrate thinning to eliminate substrate mode



To mitigate the substrate mode, particularly at high frequencies (>50 GHz), the 500um thick LiNbO₃ 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





Modulator Processing and Packaging





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



Measurements at 110 GHz



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



Substrate Modes Suppression



[1] Y. Shi, "Micromachined Wide-Band Lithium-Niobate Electrooptic Modulators," IEEE Trans. Microw. Theory Tech., vol. 54, no. 2, pp 0810-815, Feb. 2006.



High Bandwidth Operation















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





- 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, lowpower, wide-BW, low-dispersion phase steering in optical domain

Coherent Optical Heterodyning for UWB IF Synthesis & Up/Down-conversion Receivers













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RF

Out



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Narrow-line Widely Tunable RF Generation System

EIAWARI



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





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





Experiment Setup





• Optical phase shift applied to one laser causes RF interference pattern to shift by the same amount 79



Optically-fed Phased Array Demonstration





Top view

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 ~400 Hz

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Integrated Silicon RF Photonics





Integrated RF-Photonic Module





Future Integrated Device



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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



Testing Setup





Tuning Distributed Bragg reflector (DBR)



• Tunes at approximately 0.09 nm/°C







Integrated III-V and Silicon Photonic Laser





Hybrid III-V - Silicon Laser



Dual Laser Design







Dual Laser Integration



2 Functioning Lasers





Two Lasers on a Chip





Silicon Nanomembrane 3D Integration for RF Signal Routing



Si-NM Released from SOI Substrate





Single crystalline silicon device layers do not need to be associated with bulky rigid substrates



A 260nm SiNM with 20 μm SU-8 substrate



WDM Si-NM Spectral Response











 $\lambda = 1558.0 \text{ nm}$



Photonic Crystal Routing Elements



8-Port Router



The switch voltage is 1.2V with 2mA of current



Testing at Texas A&M Univ. Cyclotron





- Dosage: ¹⁴N and ⁸⁴Kr ions at15 MeV with 6x10⁶ ions/cm² 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



- 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!