Passive Millimeter-Wave Imaging Toward 1K Resolution

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***Abstract*—Existing millimeter wave imaging systems have not lived up to expectations, neither in performance nor in achieving manageable size, weight, and power (SWAP). As in airports, they remain bulky, time consuming to use and not useful in preventing threats as their promise might have been. We need a small camera-like, low cost, compact, sensitive, and versatile Passive Millimeter-Wave Imaging (PMWI) enable a broader field of imaging applications. The main challenge with existing PMWI is the need for scanning causing bulkiness and time-delays for standoff applications. Similarly, secure communication at long distances is extremely important for all government and commercial applications, but the development of low power and wideband transceivers that operate across large distances is technically a very challenging task;**

Keywords—millimeter wave imaging, eletro-optical modulator

I. Introduction

Typical approaches for mm-wave imaging systems make use of high gain amplifiers that are very noisy, difficult to integrate [1] and expensive. Current state-of-the-art mm-wave imaging systems are "all-electronic," and are primarily used for body scanning as is the case with airports. These systems are expensive, bulky and make use of a slow scanning apparatus for image acquisition. Moreover, they suffer from low sensitivity performance at video rate. Alternatively, Focal Plane Array (FPA) imagining systems make use of mm-wave optics to focus radiation into an array of detectors without a need to use a scanning apparatus. But FPAs, though compact, suffer from low performance, diffraction limits, cost, and large form factor as they require front-end millimeter wave lenses. Further, for reasonable spatial resolution, sensitivity, and field of view, a large number of pixel detectors are needed, driving up the cost and complexity. Because of these issues, millimeter wave imaging systems have yet to reach their potential nor lived up to expectations [1-3]. Therefore, there is still a need for low cost, compact, sensitive, and versatile Passive Millimeter Wave Imaging Systems (PMWI) systems to enable a broader field of imaging applications, especially in homeland security. To realize the potential of PMWI, an alternative approach is to employ sparse interferometric arrays [4]. This will be done by developing a number of key technologies

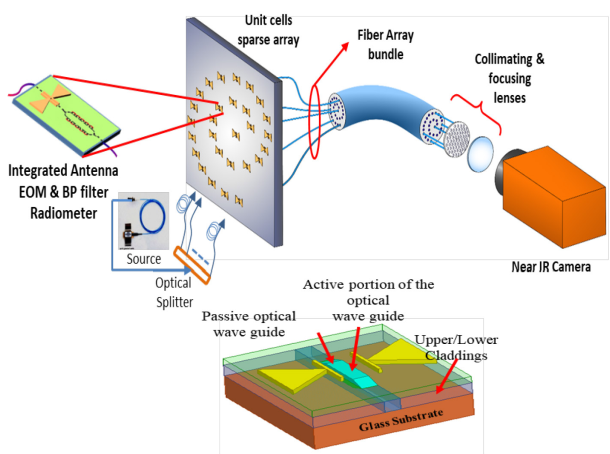

Fig.1. Passive millimeter wave imaging system depiction diagram (top). Antenna Integrated Electro-optic modulator-on- chip unit cell

I.PMWI System overview & Operation

The proposed PMWI system is depicted in Fig. 1. A seen, the imager consists of 1) millimeter-wave sparse antenna array, 2) embedded electro-optical modulator in each antenna element to enable an optical output through a fiber bundle, 3) interferometric lens, illuminated by the optical fiber bundle, to carry out the Fourier Transform for scene imaging, 4) near IR camera for exposing the millimeter-wave image. The operation of the imager is as follows:

- The electro-optically modulated (EOM) antenna receives incident thermal radiation. Generally, it can be assumed that the antenna can receive $0.3x10^{-8}$ Watts when a body is placed at 10m away.
- Incident radiation modulates the optical beam (see Fig. 1)
- Optical beam (carrier) sideband signal is passed through a filter and guided through an optical fiber bundle to illuminate the interferometric lens. By preserving the phase of the collected energy, interferometric sparse array techniques are leveraged herewith to realize a large effective aperture with few individual detectors
- Optical beam passes through the interferometric lens to generates the Fourier Transform of the incoming optical beam, eliminating a need for millimeter wave array scanning.
- Interferometric lens output is received by the near-IR camera to expose image.

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There are a number of key developments in this PMWI that allow its passive operation. Indeed, a prelim analysis of the component sensitivity demonstrated a sub-1 Kelvin sensitivity. Specifically,

- The EOM has an output voltage of V_{π} ~14, a modulation depth of 0.3x10^{-3}
- EOM detector responsivity of ~1 A/W generate a current ~10 nA.
- This current of 10nA is larger than the dark current of ~1 nA for standard pin photodetectors such as InGaAs normally used in the NIR FPA cameras. Therefore, typical near IR camera sensitivity will allow for reliable detection/imaging without active illumination**.**

Notably, our approach eliminates the need for large refractive lenses associated with FPAs and scanning detectors. This also eliminates the need for demanding Low Noise Amplifiers (LNAs), LOs and supporting electronic network, required by current systems. Instead, each detector pixel of the sparse array monolithically integrates only the following components: high-efficiency 94 GHz antenna, a high performance EO phase modulator to perform up-conversion, and fiber pigtails for guiding the optical signals input and output through the antenna feed as depicted in Figure 1. These pixel components are monolithically co-designed and integrated to shape a single channel to form the basis of the front-end prior to processing the signal to the interferometric lens and NIR camera.

For a predefined spatial resolution, an optimum distribution (u-v coverage of the array) mitigates grating lobes that cause blurring. Further, to optically reconstruct the image, we employ a homothetic mapping of the output fiber array with a scaling factor of $(\boldsymbol{\lambda_{opt}/d})\,/\,(\boldsymbol{\lambda_{rf}/D})$. The output from the interferometric lens is collimated onto an off-the shelf near-IR camera, where *d* and *D* are the fiber and antenna spacing, respectively.

II. Millimeter Wave Antenna with Electropitcal Polymer Modulator

The EO phase modulator design uses a large Pockel-effect EO polymer to achieve high efficiency and high speed. To further improve sensitivity, the EO polymer (responsible for modulation) is used only in the active region (where the phase modulation takes place) within the device, while an off-the-shelf product, *polymer* is employed for propagation through the optical link. 250 micron thick fused silica is used a substrate. Fused silica substrates are highly transparent in millimeter wave (mmW) regime. It has a low dielectric constant which contributes to antenna performance. Its refractive index is 1.44. The waveguides are made out of SU-8 polymer that has a refractive index of is 1.55. Since, the refractive index of silica substrate is much lower than the Su-8, therefore the light confinement in the waveguide can be achieved. The fabrication of the antenna integrated EOM photonic chip was done through micro fabrication steps summarized in figure 2. Figure 3 shows sample images of fabricated waveguides and bowtie antennas.

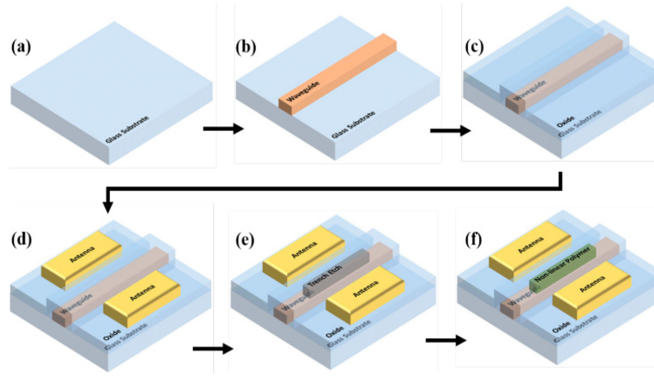

Fig.2. Fabrication flow of the EO-modulator. **(a)** Fused silica substrate. **(b)** SU-8 polymer passive wave guide patterning using lithography**(c)** Silicon dioxide evaporated over the waveguides using e-beam **(d)** Antennas are patterned using contact mask aligner followed by a 1-micron thick Aluminum lift-off. **(e)** The trench is patterned by electron beam lithography, then etched into the silicon dioxide using RIE. **(f)** Non-linear polymer is spun over the wafer to fill the trench.

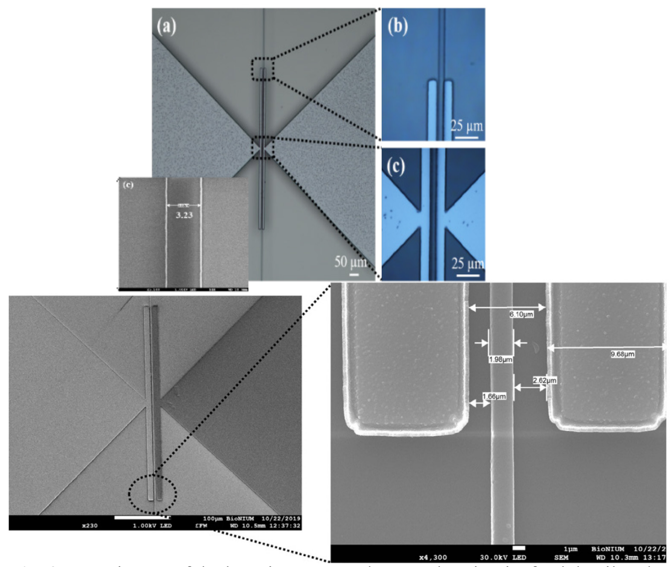

Fig. 3. SEM image of the bowtie antenna element showing its feed detail and location of the polymer insertion

III. Concluding Remarks

At the conference, we will discuss the efficacy of the proposed architecture that promotes maximum sensitivity using polymer material only in the active area of modulation. Importantly, we will present fabrication and measurement details.

References

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