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Tutorial: Optical Arrays and RF-Photonic Devices

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Invited Tutorial

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Abstract – **This tutorial will review recent progress in the development of optical and photonic devices as they apply to RF phased array antennas. It will begin with an overview of RF-photonic device design, fabrication, and integration for both electro-optic modulators (EOMs) and high-power photodetectors (PDs). It will then transition to their application to advanced phased array systems that offer near unlimited beam-bandwidth-product (BBP), with low latency and low power beamspace processing. Using this approach, the entire RF beamspace is "imaged" onto corresponding PDs where every beam is produced and read-out simultaneously. In so doing, the beamspace can be captured by a focal plane array, thereby rendering a real-time video of the RF environment. Alternatively, each beam can be routed to a corresponding PD for signal recovery within that beam, which affords interference mitigation and reduced non-linear intermodulation effects. In addition, by strongly leveraging the microelectronics manufacturing industry, chip-scale optical systems have been implemented, using photonic integrated circuits (PICs), that enable a profound reduction in size, weight, and power (SWaP). Such advances are destined to have a significant impact on the development, application, and commercialization of next generation phased array systems, particularly for phased array transmit (Tx) and receive (Rx) antennas that provide ultra-wideband operation with time-of-flight full beamspace processing.**

Keywords – Radio Frequency Photonics (RF Photonics), Microwave Photonics, Phased Array Antennas, Beamspace Processing

INTRODUCTION

To appreciate the role of RF-photonics in phased array systems, consider that in nearly every phased array the process of up- (Tx) and down-conversion (Rx) take place within the array, which requires non-linear operations that often impose a conversion loss on the signal, not to mention intermodulation distortion and vulnerability to signal interference. Following up/down conversion, analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), for Rx and Tx systems respectively, are used to interface the signal with the backend digital processor, wherein large scale two-dimensional (2D) fast-Fourier-transforms (FFTs) are performed for beamspace processing, i.e., encode or extract spatial directional awareness within the digital data.

While this approach is very successful for lower RF frequencies, e.g., ≤5 GHz, it is not easily scaled to higher frequencies due to the following reasons: (1) higher sampling rate ADCs/DACs suffer from lower effective number of bits (ENOB) thereby reducing the signals dynamic range; (2) their power consumption also increases with increased sampling rate, which often requires external cooling; (3) the amount of digital data grows exponentially across the array as the RF frequency increases thereby making it a challenge to off-load the data; (4) ingesting and processing the data requires significant computational resources and often introduces high levels of latency; (5) the automatic-gain-control (AGC) systems often limit the ADC full-scale to a single signal wherein all others are correspondingly compromised; and (6) the complexity in clock synchronization and concomitant digital component hardware results in expensive implementations. For these reasons, this tutorial will introduce and review an alternative approach for next generation phased arrays based on the use of optical systems and RF-photonic devices.

From an RF-photonics perspective, recent advances in RF-photonic devices are spurring a renewed interest in their application for a host of applications ranging from standard RF-over-Fiber (RFoF) signal remoting to more advanced applications in RF phased array antennas. In this context, RF-photonic devices, namely electro-optic modulators (EOMs) and photodetectors (PDs) are used to perform RF up- and down-conversion, respectively.

As such, the new and enabling features of these devices is the development of EOMs in thin-film lithium niobate [2], which has enabled the realization of ultra-high conversion efficiency where passive conversion gain is possible. Likewise, advances in PDs have resulted in extremely high-power devices that are capable of generating hundreds of milliamps of photocurrent, i.e., multiple Watts of RF power, out of a single device. In addition, strong leverage from the microelectronics manufacturing industry has given rise to the field of photonic integrated circuits (PICs) that enable a profound reduction in size, weight, and power (SWaP). Thus, in combination, these advances have led to significant advances in RF phased array systems that provide ultra-wideband operation with time-of-flight beamspace processing wherein they provide the ability to render a *real-time imaging capability* of the RF environment. In terms of figures-of-merit, these arrays have demonstrated a beam-bandwidth-product of over 10 THz and the ability for simultaneous multi-band, multi-beam, and multi-data processing, which is highly desirable in emerging massive-MIMO applications. An overview of these advances is the topic of this tutorial.

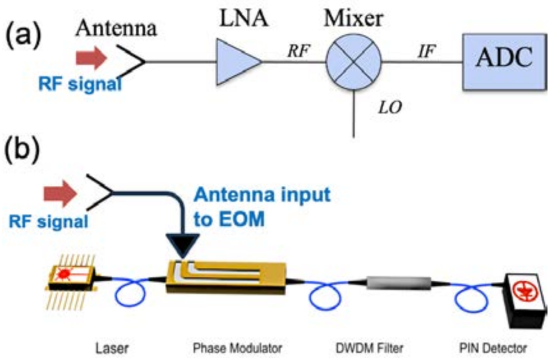

Fig. 1 (a). Generic schematic of an RF mixer and (b) an equivalent mixing implementation using RF-photonics.

TECHNICAL APPROACH

A common operation in many RF systems, particularly phased arrays, is the mixing (or conversion) of RF-to-IF (for Rx) and IF-to-RF (for Tx). A generic mixing operation is shown in Fig. 1(a) for an Rx operation, where the incoming RF signal is mixed down to an intermediate frequency (IF) signal for subsequent digitization and processing. Figure 1(b) shows an RF-photonic implementation of the same operation; however, in this implementation the received RF signal is up-converted to the optical domain by virtue of the EOM, shown in Fig. 2. In this case, the RF signal is routed over an extremely low loss optical fiber, which has the same loss (~0.2 dB/km) independent of RF frequency. At the destination side, i.e., end of the optical fiber link, a PD is used to down-convert the optical signal back to an electronic signal either at RF or IF depending on the implementation, with the latter requiring a coherent down-conversion with a tunable optical local oscillator (TOLO) [1]. Key to the operations of up- and down-conversion is the efficiency with which the RF signal can be encoded (for up) and recovered (for down). Historically, there has been a big price to pay in terms of efficiency, as legacy photonic devices introduced unacceptable amounts of loss. However, recent progress has been made both operations, which has renewed the interest in using RF-photonic devices and components in RF systems.

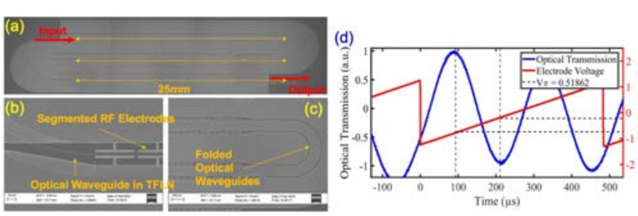

Fig. 2. (a)-(c) SEM pictures of a fabricated folded phase modulator. (a): Top view of folded transitions, (b) zoom-in of the capacitively loaded electrodes that are designed to match the phase velocity of the RF and optical waves, (c) zoom-in of the bend region that has a thicker oxide layer to minimize optical bend loss, and (d) experimentally measured DC $V\pi$ at 2 KHz, where the blue trace is the normalized optical transmission and the red trace is the voltage applied on the device through a DC probe.

The advances in up-conversion efficiency from RF-to-optical conversion are based on the developments in thin-film lithium niobate (TFLN) materials that offer a significant reduction in the optical mode size, which allows for the RF electrodes to be placed closer together thereby improving the efficiency by up to a factor of 10. Figure 2 (a)-(c) show a recently developed folded EOM [2] that has an overall footprint of ~0.25 cm^2. Figure 2 (d) shows the experimentally measured FoM ($V\pi$) of ~0.5 V, which is roughly an order of magnitude smaller than legacy devices. With this device, it is possible to have more energy density in the up-converted RF sideband than the RF signal itself, thus resulting in passive conversion gain, something previously unattainable using RF-photonic devices and something mostly unattainable in passive RF mixers.

While improvements in TFLN based EOM devices have resulted in unprecedented RF-to-optical conversion efficiency, this is only half the story as an efficient optical-to-RF conversion is as equally important at the end of the optical fiber link. To this end, there have also been significant developments in PDs that provide extremely high output photocurrents (PC), or RF power [3]. In fact, the PC can approach 100's of milliamps, which corresponds to Watts of RF power thereby resulting in RF gain on the order of 20-30 dB. Moreover, such PDs have also been engineered for extremely linear operation, resulting in a measured linear dynamic range (LDR) of up to 140dB and third order, or spur free dynamic range (SFDR), approaching 120 dB/Hz$^{2/3}$. For these reasons, there has been considerable effort in using such devices in novel phased array architectures, as discuss in this tutorial.

An additional advantages of up-converting Rx signals to the optical domain is that the entire beamspace can be processed using a passive Fourier transform lens [4], which enables a nearly unlimited BBP, in fact one whose computational order is one, $O(1)$, and is performed in parallel at the speed of light, thereby providing latencies on the order of sub-nanoseconds. While a more detailed discussion of this process is presented in [4], herein we provide a high-level overview.

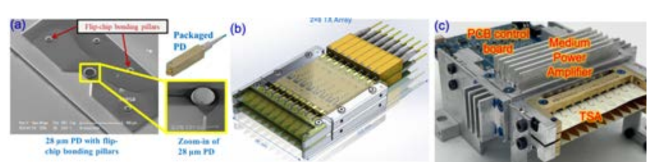

Fig. 3. (a) SEM of fabricated high-power photodetector (PD) [2], (b) packaging and integration of PDs into a 2x8 stacked RF Tx array [3] with an array pitch of 6mm × 8mm and operational BW of 6-50 GHz, and (c) demonstrated array that consists of 2×8 tapered slot antenna arrays, 2×8 medium power amplifiers, and the 2×8 PD array modules.

Figure 3 (b) shows a model of the packaging and integration of the PDs into a streamlined array that enables their direct integration into a 2D Tx phased array, as shown in Fig. 3 (a) and (b) [5].

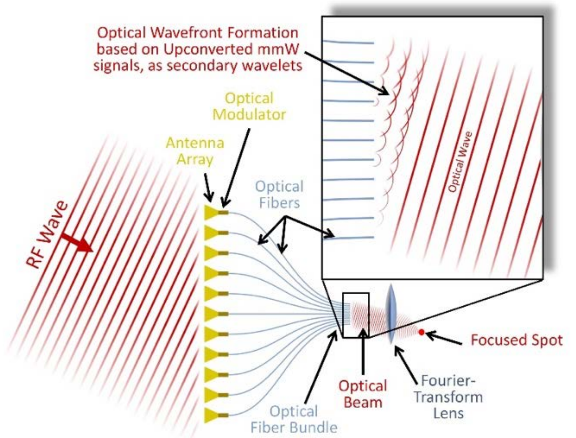

Fig. 4. Illustration of the transformation of the RF beamspace up into the optical domain where a Fourier optics approach can be used to implement instantaneous beamforming over the entire RF beamspace using a single lens and consuming no power.

In addition to Tx phased arrays, Rx phased arrays can also be implemented using a similar approach, where every antenna element is connected to a single EOM, the output of which is the RF signal up-converted onto an optical carrier that resides in an optical fiber. Given that each antenna element has its own fiber output, they can all be gathered into a common bundle where the location of each fiber coincides directly with the place of its corresponding antenna element in the array, as shown in Fig. 4, where RF beamforming can be performed using a Fourier transform lens.

A schematic of the RF-photonic beamformer for an RF phased array is presented in Fig. 4, where the output from each fiber forms a diverging beam that expands and overlaps with all of the expanding beams from the adjacent fibers in the fiber bundle. At this point, the *exact* RF beamspace, i.e., wavefronts, received at the antenna aperture is reformed and incident on a Fourier transform lens, which performs a 2D Fourier transform at the speed of light while consuming no power.

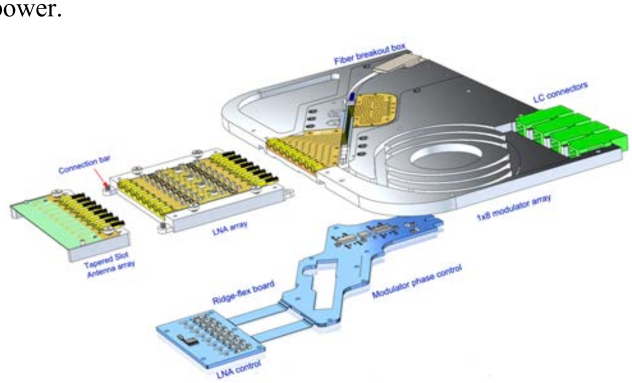

Fig. 5. Modular/interchangeable LNA and antennas arrays allow optimization for any band, Front end consists of antennae, LNAs, and optical modulators for each element of array, built in modular scalable 1×8 units, Broadband modulator array covers any band 1-100 GHz.

Accordingly, the Fourier-transform lens focuses the reformed RF-to-optical plane waves, where each wave corresponds to a unique RF source in the environment, into an array of focused spots, where each spot corresponds to a unique angle-of-arrival (AoA). This process results in an orthogonal beamspace representation, i.e., "imaging," which mitigates/eliminates co- and adjacent-channel interference as well as jamming, unless such interfering signals reside within the same beam as the signal of interest, i.e., they have the same AoA. Lastly, this approach can form all of the incident RF beams simultaneous with unlimited BBP!

To realize Tx and Rx phased array systems, we have developed a modular 1x8, blade-based, integration approach that enables a streamlined manufacturing process [6]. The basic 1x8 Rx blade is shown in Fig. 5, which shows the various components that are connected using SMPM connectors, which are literally plug-and-play. To the left is the antenna array, which consists of a tapered slot antenna (TSA) array made using Rogers 4350 material. The antenna array is connected to a low noise amplifier (LNA) array that consists of integrated commercial LNAs depending on the operational BW that is desired and that which matches the BW of the TSA. Notably, the TSA and LNA elements are the only BW limiting elements in that Rx array, as once the RF signals are up-converted and routed to the optical processor, the entire beamforming process and down-conversion to an output IF is frequency agnostic. This allows for a different RF-frontend to be used, via plug-and-play, connection to completely re define the operational range of the entire Rx phased arrays. In fact, using this process arrays that operate from 6-25 GHz, 20-50 GHz, and 70-110 GHz have all been realized by using the exact same backend optical processor and simply changing out the RF frontends.

The 1x8 modulo integration process also enables the ability to realize larger size arrays by simply stacking them in both the horizontal and vertical directions, as shown in Fig. 6.

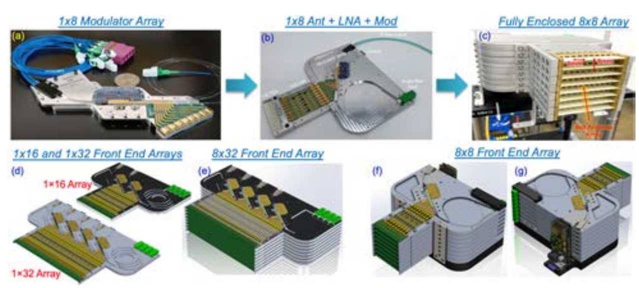

Figure 6. 1x8 module design for antenna array, low-noise amplifier (LNA) array, and modulator array, S-blade is stitchable and stackable to form a 2D array, SMPM connector offers plug and play (PnP) of the different antenna and LNA arrays.

The above reference to the Rx phased arrays being an imaging-based technique begs the question as to if a real-time video rate RF phased array can be built, where one can form a literal spatial rendering, i.e., image of the RF environment. Such a system has been built, shown in Fig. 7, that provides a real time image of the *passive* RF environment, wherein each RF beam entering the aperture arises from a single point of thermal RF emission in the environment, i.e., the kTB emission from whatever the blackbody material properties may be [7]. This system was designed to operate at 86 GHz due to the required spatial resolution needed to render an intuitive image. It should be noted that this system forms ~ 1,600 beams, with each beam having a 4 GHz instantaneous BW (thermal integration spectral range), which corresponds to a BBP of 6 THz. While more details of this system are presented in [7], Fig. 7 (a) presents a computer aided draft (CAD) drawing of the designed system, which is a 2D array containing 1,024 (32x32) elements. The actual built system is shown in Fig. 7 (b), which shows the center array elements replace by boresight aligned visible and infrared cameras, that serve as a reference image to the passive RF imaging gather from the scene. Figures 7 (c) and (d) show the visible and millimeter wave (mmW) image of cars in a parking lot where each are snapshots from real-time video streams. The advantage of having such a real-time mmW image is that it provides an imaging modality that can see through many obscurants such as fog, smoke, dust, clothes, plywood, and many other materials.

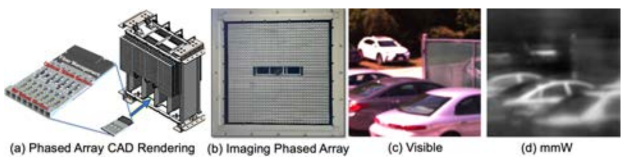

Figure 7. (a) CAD drawing of the 1x8 modulo imaging array, (b) actual built array, (c) visible image taken with the boresight integrated camera, and (d) passive millimeter wave image taken at 85 GHz.

While the developments presented above have led to significant advances in RF phased array systems. Future developments are strongly leveraging the microelectronics manufacturing industry, which has given rise to the field of photonic integrated circuits (PICs) that enable a profound reduction in size, weight, and power (SWaP). Significant leverage with the microelectronics manufacturing infrastructure has accelerated the rapid development and maturation of photonic devices and components into highly integrated systems-on-a-chip [8]. The leverage has produced highly refined process design kits (PDK) and multi-project-wafer runs (MPWs) for several different photonic material platforms [9]. In this case, each PDK/MPW enables the design, fabrication, and integration of advanced PICs with a high manufacturing-readiness-level (MRL). Of particular interest to this work is the realization of high frequency RF systems that contain no high frequency electronic components other than the RF frontend antenna elements and LNAs. In this instance, every RF signal/waveform that enters the array aperture is up-converted, beamspace processed and focused into a pickup fiber that routes the up-converted RF signal to a backend PD where it is mixed with a coherent TOLO. At this point, the RF-to-IF signal conversion is performed, but in the optical domain. This allows for lower sampling rate ADCs to be used, which offers higher ENOBs, or dynamic range, and a significant reduction in both power consumption and cost.

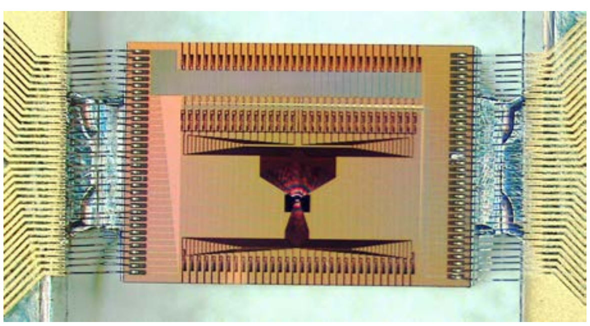

Figure 8. Picture of a photonic integrated circuit that performs time-of-flight RF beamspace processing on optically up-converted RF beams from an imaging Rx array.

The next phase of this work is developing automated integration processes to realize photonic-multi-chip-modules (PMCMs) that enable the realization of increasing advanced RF systems that contain minimal high frequency electronic components, as shown in Fig. 9.

CONCLUSION

Using this the above devices, components, and processes we have discussed their use in advanced RF-photonic phased array systems for Tx and Rx operation. Both array systems are based on Fourier optic implementations that provide unprecedented BBP even to the point where the array can operate as a real-time video camera in the RF spectral region. Future progress will leverage all aspects of circuit-based integration and automation to provide even more advanced systems at much lower cost than today's counterparts.

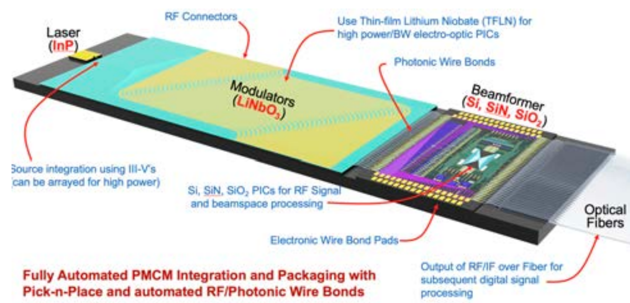

Figure 9. Illustration of a photonic-multi-chip-module (PMCM) that represents a future approach of an automated heterogeneous integration process for RF-photonic systems.

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