Photonics-enabled millimeter-wave phase arrays based on dielectric rod antennas

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Abstract—**Future mobile networks require phase arrays operating in the millimeter-wave and Terahertz range. RF photonics combines the best of both worlds to address the challenges of broadband beam-steerable RF antenna arrays. However, dielectric rod antennas are required for efficient emission from a multi-element semiconductor array.**

***Keywords— Microwave photonics, Antenna-integrated photodiode, Tapered slot antennas, Broadband antennas** (key words)*

I. Introduction

The lower bands (below 20 GHz) of the electromagnetic spectrum, commonly used for wireless communications networks, are rapidly becoming congested and so frequency allocations above 100 GHz are increasing to cater to increasing demand for wireless traffic [1]. Among the technical challenges, the extremely high propagation losses above 100 dB are a concern. High-gain steerable beams can be achieved through the classical beamforming front-end of phased array antennas [2], but this has proven increasingly challenging to implement with broadband antennas operating over the full frequency range.

Microwave photonics (MWP) is a common approach to generate Radiofrequency (RF) signals over a broad-spectrum. Fig.1 shows the building blocks of a Terahertz (THz) transmitter using optical heterodyning technique for signal generation. Based on beating two optical wavelengths (λ_1, λ_2) on a photodiode, allows to easily select the frequency by tuning the wavelength difference of two tunable lasers [3]. In addition, key functionalities can be implemented in the optical domain, such as beamforming, multiplexing and filtering supporting ultra-wideband operation and electromagnetic interference immunity.

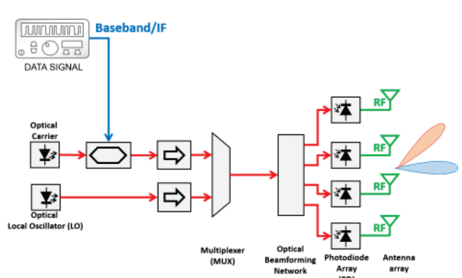

Fig. 1. Block diagram of a photonic-enabled Terahertz transmitter with phase array using optical heterodyne

II. Photonic-enabled THz phase arrays

High speed photodiodes (HSPD) are common devices in photonic THz transmitters to convert signals from the optical to the electrical domain. For continuous-wave terahertz generation, these need planar antennas to emit the RF signal. Two main approaches are used for antenna-integrated photodiode arrays

A. Tapered slot antennas

Tapered slot antennas (TSA) allow developing linear antenna arrays. These can be fabricated on commercial low-loss RF substrates, with peak gain reaching 14.5 dBi for a two-element array, with 3-dB beamwidth for E- and H-plane of 20° and 40° respectively [4]. A monolithically grown tapered-slot transition integrated with an InP-based Modified-Uni-Traveling-Carrier Photodiode has been recently reported [5]. This avoids the RF contact between the photodiode and the antenna. However, the TSA on the semiconductor has two problems: a) suffers from high RF losses of the InP, and b) the semiconductor high permittivity causes most of the generated RF power to remain in the semiconductor substrate. To reduce these effects, the InP is thinned down below 100 µm and a Dielectric Rod Waveguide (DRW) is used to couple out the radiation [6]. A max. available RF output power of –1.6 dBm at 0.12 THz and a relative 10-dB operational bandwidth of 0.2 THz were shown. Another approach to avoid the RF contact between the HSPD on an InP chip and the antennas on an RF substrate is using flip-chip mounting. In this case, as shown in Fig.2, it also becomes critical reducing the substrate thicknesses.

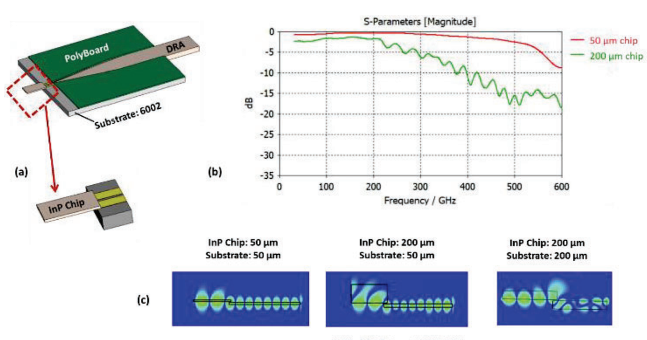

Fig. 2. a) Flip chip assembly of InP HSPD chip on RF substrate, b) Simulated coupling varying InP chip and RF substrate thickness c) The E-field plot in side view of the different thickness of InP chip and substrate

B. *Broadband antennas*

An alternative approach is compact broadband antennas, such as bow-tie, spiral or log-periodic, which are monolithically grown with the photodiode on the semiconductor. The problem is that due to its high permittivity, most of the THz power is radiated into the semiconductor substrate. For efficient radiation into free space, the antenna-integrated photodiode is mounted onto a 10-mm diameter hyper-hemispheric silicon substrate lens, which enable operating at frequencies between 50 GHz and 1 THz, producing 0 dBm output power around 100 GHz [7]. Recent measurements of a silicon lens-integrated PIN-PD emitter reported significant deviations from a Gaussian beam profile and to strongly vary with frequency [8]. We have simulated the integrated antenna on the chip, backside-coupled to an infinite silicon half-space with open/absorptive boundaries. Our results, shown in Fig. 3, indicate that the bow-tie chip produces an irregular, frequency-dependent antenna pattern within the silicon half-space.

Another major concern is that since the dielectric lens is electrically large compared to the carrier wavelength, the required distance between antenna elements in the array cannot be accomplished, leading to the creation of grating lobes. Therefore, using silicon lenses blocks the development of antenna arrays using compact broadband antennas. On the other hand, compact broadband antenna-integrated photodiodes are likely the best way leading to two dimensional arrays as it allows distributing the antennas anywhere in the chip. Therefore, an alternative to the silicon lens for efficient radiation into free space is needed.

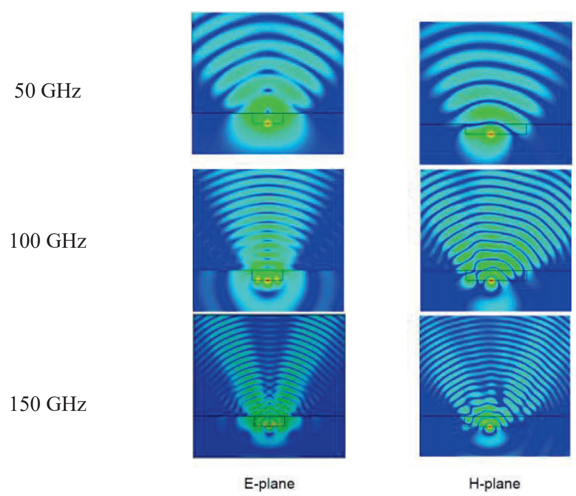

Fig. 3. Dependence with frequency of bow-tie antenna radiation pattern.

III. Dielectric rod waveguide THz arrays

Dielectric rod waveguides (DRW) can be used to efficiently radiate into free space the RF generated by antenna integrated photodiodes [9]. This hands over the problem to the assembly, due to the complexity of placing the DRW on the unpatterned bottom of InP antenna chip, especially as the number of antenna increases when higher gain is desired.

To address this problem, we developed a new approach to reduce the number of individual elements that need assembled, using effective index technology to produce multiple DRW on a single silicon piece as reported in [10]. The DRA were mounted on an InP chip with 4 bow-tie antenna-integrated PIN photodiodes using a flip-chip process and UV-cured epoxy. The individual antenna element radiation patters show that the DRW couples the radiation generated from each individual antenna element out of the chip. When all four elements on the array are driven simultaneously, the beam waist of the emitter radiation narrows down to ±10º.

IV. Conclusion

We review different approaches to realize two-dimensional Terahertz phase arrays, showing that for TSA and broadband antenna approaches, dielectric rod waveguides offer to play the role of single element lens that couples the RF power for each individual antenna-integrated photodiodes, unlocking steering.

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