Photonic-based integrated millimeter-wave/terahertz sources and receivers

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ABSTRACT

Millimeter-wave (MMW) and Terahertz (THz) sources and receivers are essential in a wide range of applications, from high-resolution radar to spectroscopy, as well as high-capacity wireless links. Current efforts are directed towards their integration, benefiting from their small form factor. However, due to the wide bandwidth available at these frequencies, the challenges that need be addressed include increasing the operating bandwidth to use the available spectrum as well as to increase the total radiated power. Two key factors play a role in this, the intrinsic limitation of the components (i.e. limited f_{max}) and the inefficient on-chip radiation. In this work we address how dielectric structures can help improve radiation efficiency.

Keywords: RF photonics, Millimeter-wave range, Wideband antennas, Antenna-integration, Dielectric Rod Waveguide

1. INTRODUCTION

Radiofrequency (RF) photonics is a discipline that combines the best of RF engineering and photonics to push the maximum frequency of RF systems towards the higher end of the spectrum, into the millimeter-wave (MMW, 30 to 300 GHz) and the Terahertz (THz, 300 GHz to 3 THz) achieving unmatched performance, especially regarding bandwidth. Its initial key advantage was the low propagation loss in optical fiber links as well as providing signal generation techniques. While the first allowed to distribute microwave signals without the losses of coaxial cables, the latter spearheaded the access to the MMW and THz such as optical heterodyning, which generate RF signals by beating two optical wavelengths (λ1, λ2) on a photodiode, allows developing widely tunable signal sources [1]. As photonic integration technology advances, an increasing number of RF signal processing can be carried in the optical domain, such as beamforming, multiplexing and filtering supporting ultra-wideband operation and electromagnetic interference immunity[2]. From this simple application, the field emerged enabling RF signals to be generated, distributed, processed, and analyzed using advantages of photonic technologies to provide functions that are very complex or even impossible to carry out directly in the RF domain. The access to the higher bands of the spectrum has promoted their use in an increasing number of applications, from high-resolution radar to spectroscopy [3], as well as high-capacity wireless links [4]. However, applications usually require a reduction in cost, size and power consumption as well as high reliability. Benefiting from their small form factor, photonic integration has become a key technology for RF photonics, enabling placing all the required photonic components onto a single Photonic Integrated Circuit (PIC).

At the end, photonic and electronic approaches to MMW and THz systems have in common that the active components used in these systems are semiconductor based. This means that in both approaches, we must deal with the issue that the RF signals are generated in large dielectric constant materials (i.e. Silicon, ε_{Si}=11.9 or Indium Phosphide, ε_{InP}=12.5), having a large contrast between the substrate and air (ε_{air}=1). Therefore, to be radiated, the waves undergo a strong reflection at the silicon-air interface including a total internal reflection (with an outward angle of about 17°). This turns out to be the main source of the inefficient on-chip radiation. To address this issue, is common to use cm-sized high-resistivity silicon lenses [1], which then impact in the cost and more importantly in the size. The fact that every single antenna element would need such a lens blocks the possibility to develop antenna arrays. This work presents how dielectric rod waveguide technology can address overcome this key issue in MMW and THz transmitter and receivers.

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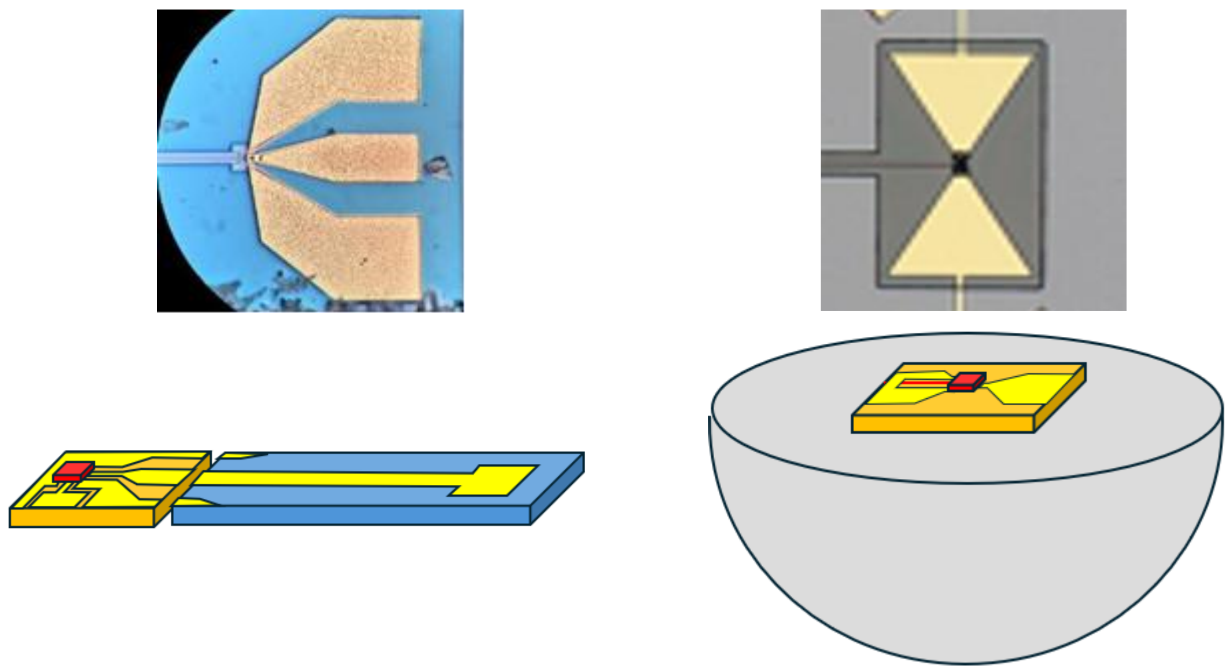
Integrated Optics: Design, Devices, Systems, and Applications VIII, edited by Pavel Cheben,
Jiří Čtyroký, Iñigo Molina-Fernández, Proc. of SPIE Vol. 13530, 135300C
2025 Published by SPIE · 0277-786X · doi: 10.1117/12.3057441

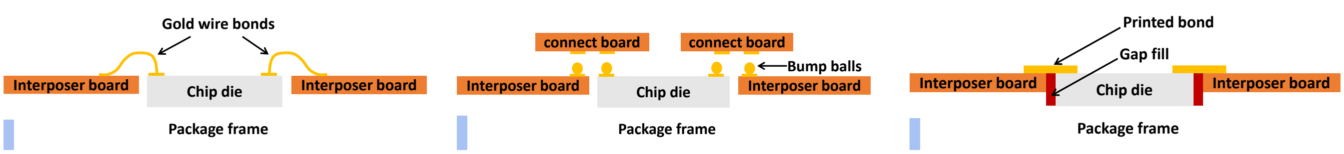
2. ANTENNA INTERFACING

O/E conversion is used in transmitters to generate the RF signal and receivers to translate waveforms from the optical domain to the RF domain, typically as baseband or intermediate frequency (IF) waveform. Here we will focus on the transmitters, which employ different types of photodiodes structures, mainly p-i-n photodiodes (PIN-PD) and Uni-Traveling Carrier Photodiodes (UTC-PD) [5]. Photodiodes may use a Ground-Signal-Gound (GSG) contact pad structure at the edge of the chip, as shown in Figure 1(a), an RF interface usually employed in electronics. This approach avoids the transmission lines in the semiconductor material (which usually is a high loss substrate) and placing the antenna on a large dielectric constant material. On the other hand, this option requires electrical interconnects that operate at high frequencies. Different interconnection techniques are currently used: Wire bonding (shown in Figure 2.a) is commonly used to interconnect a core Integrated Circuit (IC) either to another IC or to an additional substrate. For operating frequencies above 100 GHz, the associated inductances of the wires cause significant reflection, which degrades the performance of the packaged devices [6]. Flip-chip bonding (shown in Figure 2.b) is an attractive alternative technique for interconnecting millimetre and THz signals [7]. However, it requires the formation of bump balls at the contact pads, which detrimental effects on the device behaviour due to off-target excitation [8]. Several research groups have recently published encouraging results in the quest for a wire bond replacement for the MMW range using additive manufacturing technology (shown in Figure 2.c) to circuit interconnects from DC to 80 GHz [9].



(a) (b)

Figure 1. RF interface structures of high-speed photodiodes: (a) Ground-Signal-Gound contact pads, and (b) planar antenna.



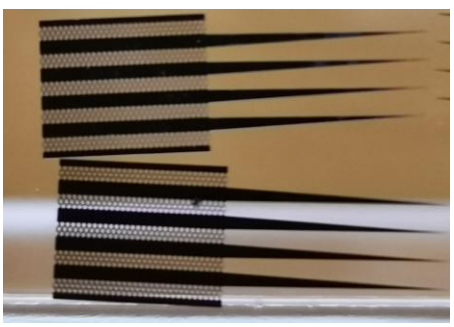
(a) (b) (c)

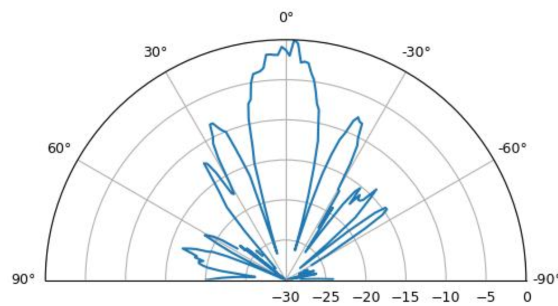
Figure 2. Packaging interconnection technologies for chips with GSG interface: (a) wire bonding, (b) Flip-chip, and (c) 3D printing.

3. DIELECTRIC ROD WAVEGUIDE ANTENNAS

As we have discussed, silicon lenses are a problem to achieve photonic-driven millimeter-wave and Terahertz antenna arrays, as the silicon lens radius determines the pitch between antenna elements. Dielectric rod waveguides (DRW) can be used to replace silicon lenses to efficiently radiate into free space with a smaller footprint towards the antenna integrated photodiode [11]. 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 antennae increases when higher gain is desired.

Dielectric rod waveguides (DRW) have already been demonstrated to interface a single element antenna integrated photoconductive device with free space, generating signals between 100 GHz and 300 GHz t [11]. The footprint of the DRW is 500 µm x 1 mm, which is an order of magnitude smaller than the silicon lens. This enables using DRW to couple the radiation of an array of emitters out of the chip [12]. Within this approach, we hand the complexity to the assembly process, since a DRW must be located to the back of every photodiode in the array in the chip, which has an un-patterned bottom, with no alignment marks available. On top of this, the number of DRWs increases as the number of elements in the array increases for higher gain. To reduce the number of elements that must be assembled, we develop an, using effective index technology to produce multiple DRW on a single silicon piece as shown in Fig. 5. The DRW pieces have two distinct parts. On the left-hand side, four solid dielectric rod waveguides are connected to each other through silicon areas where holes have been created to reduce the effective index of these areas. This allows the THz to be confined to each waveguide while being one silicon piece. On the right-hand side, each DRW is tapered to produce a gradual transition to ensure a good matching with air and achieve efficient THz radiation.





(a) (b)

Figure 3. (a) Picture of a 1x4 DRA array as a single part fabricated on high-resistive silicon using effective index technology, (b) Radiation pattern measured feeding 4 elements simultaneously with a 210 GHz optical heterodyne signal.

The DRA in Fig. 5 were mounted on the InP chips of Fig. 4 with 4 bow-tie antenna-integrated PIN photodiodes using a flip-chip process and UV-cured epoxy. The resulting radiation patterns, determined at 210 GHz, were previously reported in [13].The individual antenna element radiation patterns, obtained by driving one antenna element at a time. The results show that, as expected, the DRW couples the radiation generated from each individual antenna element out of the chip, with a moderate directivity. All four radiation patterns look alike, with a broad beam of about ±30º. This is an important feature, as highly directive individual elements also compromise beam steering. Despite the position of the DRW in the array, the four emitters exhibit similar radiation patterns. When all photodiodes are driven, using phase shifters at each so that there is no phase different between the four elements, the beam waist of the emitter radiation narrows down to ±10º. There is a notable number of side lobes, whose appearance is currently under investigation.

The main advantage of the dielectric rod waveguide antenna approach is its broad bandwidth, which matches that of the photonic components, paving the way for ultrabroadband phase arrays. When properly excited, DRW have been shows to exhibit bandwidth that covers from the microwave (tenths of GHz) to the Terahertz (above 300 GHz) ranges[14]. This makes it suitable for the development of 6G broadband systems, based on analog Radio over Fiber technology.

4. CONCLUSSIONS

We address the complex problem of coupling millimeter and Terahertz wave range signals out of semiconductor based active devices, pointing to dielectric rod waveguides using effective index techniques for paving the way towards 2D phase arrays. The approach is demonstrated for a 1x4 antenna array based on photodiodes. The results show beam forming through the measurement of the radiation pattern when each of the antenna elements was driven individually, as well as when the four elements were driven simultaneously.

ACKNOWLEDGEMENTS

This work was supported by the Smart Networks and Services Joint Undertaking under European Union's (EU) Horizon Europe research and innovation programme TERA6G (G.A. No 101096949), EU through Horizon Europe Framework Programme projects SPRINTER (Grant Agreement 101070581) and POLYNICES (Grant Agreement 101070549). This work was also supported by MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL by the project "6G-Xtreme-II (Ref. TSI-063000-2021-136)" within the Plan de Recuperación, Transformación y Resiliencia. Mecanismo de Recuperación y Resiliencia Perspectiva de género en los materiales de difusión (Unión Europea-NextGenerationEU)

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