Wideband dielectric rod antenna implemented on FR-4 substrate for THz application

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ABSTRACT

We propose a silicon dielectric rod antenna (DRA) for a broadband and cost-effective terahertz (THz) transmitter integrated with an indium phosphide (InP) photoconductive device. To facilitate power transfer from the InP chip to the dielectric rod waveguide (DRW), a tapered-slot antenna (TSA) is employed, providing efficient and broadband coupling. The proposed system, which consists of a DRA and a flip-chip bonded InP active device, is developed on an FR-4 printed circuit board (PCB) with the aim of integrating photonic circuits. We also propose structuring of the InP substrate to improve coupling efficiency from the THz source to the DRW at higher frequencies. In simulation, we confirmed that the proposed interconnection exhibits a 4-dB bandwidth exceeding 200 GHz and stable realized gain of over 5 dBi from 100 GHz to 220 GHz, showing potential for industrial THz applications such as wireless communications and non-destructive spectroscopy.

Keywords: Silicon, Dielectric rod antenna, Broadband, Terahertz, Photonics

1. INTRODUCTION

The terahertz (THz) band holds great potential for useful industrial applications such as spectroscopy and wireless communications owing to its broad bandwidth.[1] To fully exploit the bandwidth, photonics-based THz generation has gained interest, in which the THz signals are generated by the optical heterodyne technique using a high-speed photodiode. This method allows for wide tunability as well as holds potential for developing miniaturized devices with photonic integrated circuits (PICs). Photonics-based systems also enable THz array configurations for power combining and beam steering to overcome fundamental challenges in the THz band.[2] These features are highly beneficial for THz wireless links and imaging applications, paving the way to real-world deployment of THz technologies.

For a broadband operation, THz photodiodes are typically packaged using a silicon lens as a radiator.[3] However, realizing efficient and compact array configurations with these devices is demanding due to packaging complexity and tight alignment tolerances. Any displacement or tilt of the photodiode chip leads to beam pointing deviation. A guided-wave approach would be a preferable alternative for THz array, as it allows for planar integrated systems with a defined guided mode. A substrateless silicon dielectric rod antenna (DRA) is known as a promising THz waveguide-based antenna for its low loss, broad bandwidth and straightforward fabrication using a single etching process.[4–6] The antenna can be easily fabricated by tapering a silicon dielectric rod waveguide (DRW), enabling to develop compact and scalable THz integrated modules. In addition, a silicon waveguide platform is highly suitable for integration with the indium phosphide (InP) substrate of the photodiode due to their matched refractive index, making it possible to achieve high coupling efficiency.

In this work, we propose a silicon DRA integrated with a high-speed photodiode on a printed circuit board (PCB) to develop a photonics-based broadband THz transmitter module (Sec. 2). A tapered slot antenna (TSA)

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is designed on a PCB substrate to achieve broadband and efficient coupling from the InP chip to the DRW.[7,8] We investigate the interconnection from the InP chip to the DRW, PCB materials, and the InP substrate design to maximize coupling efficiency. Finally, we evaluate the radiation patterns as a whole system, showing broadband operation from 100 GHz to 220 GHz and the limitations of the proposed structure (Sec. 3).

2. MODULE DESIGN

The proposed THz module design is presented in Fig.1, consisting of an InP device and a silicon DRA on a PCB, where a TSA is designed followed by RF chokes and bias lines. This section describes the three investigations regarding the interconnection, PCB materials, and InP substrate design, all of which are crucial to develop a broadband and cost-effective module. Although in this work a high-speed PIN photodiode is employed as a photonics-based THz transmitter, the proposed design can also be applicable to THz receivers.

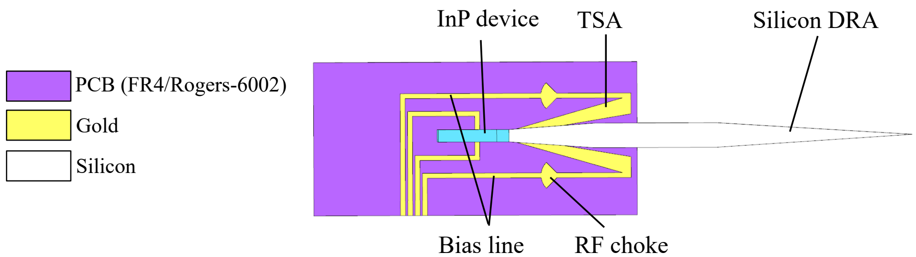

Figure 1. Illustration of the designed module.

2.1 Interconnection

We investigate ground-signal (GS) and ground-signal-ground (GSG) pads for the InP active components to achieve efficient coupling to a DRW as illustrated in Fig. 2(a). The GSG pads are the most common structure for photodiodes, as it is possible to design a 50-Ohm transmission line. However, it requires a coplanar waveguide to coplanar stripline transition (balun) for a TSA, which causes additional insertion loss. The transition from those transmission lines to a DRW is designed based on the method presented[9] and evaluated using full-wave simulation with the commercially available software package CST Studio Suite. We adopt a silicon DRW with a width of 1 mm and the thickness of 0.25 mm for the operation frequency range from 100 GHz to 300 GHz. The results are given in Fig. 2(b), showing that the balun adds $\geq$ 1-dB loss across the frequency range. Furthermore, it is also observed in the E-field distributions that the odd mode-even mode transition introduces distorted field propagation at higher frequencies, as the two modes have different propagation constants. This could lead to the excitation of higher order modes in the DRW, resulting in inconsistent radiation pattern for a DRA. The

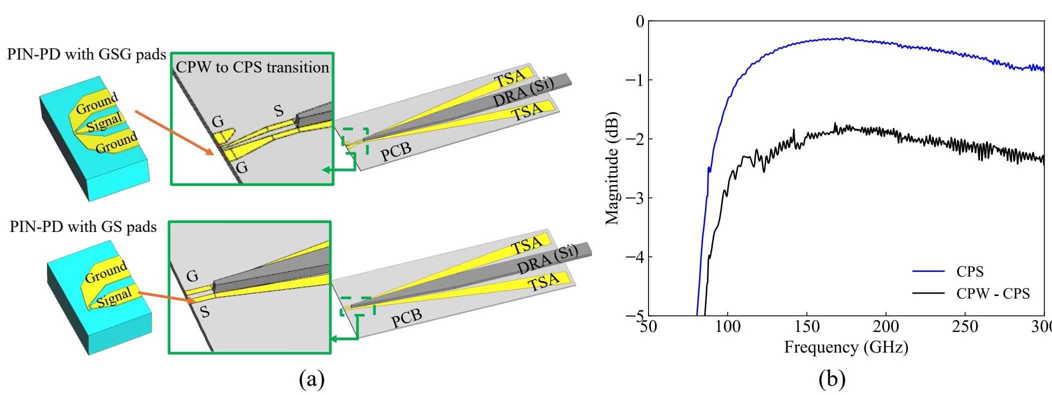

Figure 2. (a) Illustration of the interconnection investigation (b) Simulated S_{21}, showing the difference between the CPS structure and the CPW-CPS structure.

Table 1. A comparison between Rogers 6002 and FR-4 as a PCB substrate.

Substrate	Dielectric constant	Loss tangent	Tensile modulus (kpsi)	Fabrication cost
Rogers 6002	2.94	∼0.0012 @ 10 GHz	828	Expensive
FR-4	4.3	∼0.02 @ 1 GHz	3000	Affordable

effect of this phenomenon can be seen in Fig. 2(b), in which there are ripples in the frequency response of the balun. This is because the waveguide port at the DRW reflects all the modes except for the fundamental mode, leading to the standing waves between the ports. This is a fundamental problem of the baluns and is difficult to avoid for broadband operation. Thus, although the GSG pads offer better impedance matching, the GS pads are selected in this project for better coupling efficiency and antenna performance.

2.2 PCB Material

A PCB plays a key role in the proposed design, as its material loss affects the device performance. A TSA is designed on the PCB substrate with a length of 5 mm followed by bias lines with RF chokes for photonic devices. The InP active device with the width of 0.5 mm and the thickness of 0.25 mm is flip-chip bonded on the PCB. The DRW with the width of 1 mm is tapered by 3 mm and truncated to attach to the InP chip with the same width as shown in Fig 3(a). In this work, Rogers 6002 and FR-4 are compared particularly in terms of material loss, rigidity, and fabrication cost. As shown in Table 1, Rogers 6002 is known to exhibit much lower loss than FR-4, which makes it preferable for high-frequency devices. The high-frequency performance for these two materials is simulated, and the results are shown in Fig. 3(b). The S parameters are renormalized using the conjugate of the simulated characteristic impedance at port 1. We found that although FR-4 shows larger loss from 100 GHz to 150 GHz, the loss above 150 GHz is not significantly different. This can be attributed to the coupling mechanism of this structure, in which high-frequency signals couple from a TSA to a low-loss DRW in the vicinity of the InP chip. Therefore, the material loss of FR-4 does not notably contribute to the overall loss. With respect to rigidity, it is crucial for a PCB to be flat and rigid after the process in order to precisely align the InP chip and the DRW. Misalignment of these two components can lead to inconsistent radiation pattern for the DRA. Compared to Rogers 6002, FR-4 is significantly rigid as well as more economical for the manufacturing process, meeting the mechanical requirement of this structure. For these reasons, FR-4 is selected as a PCB material.

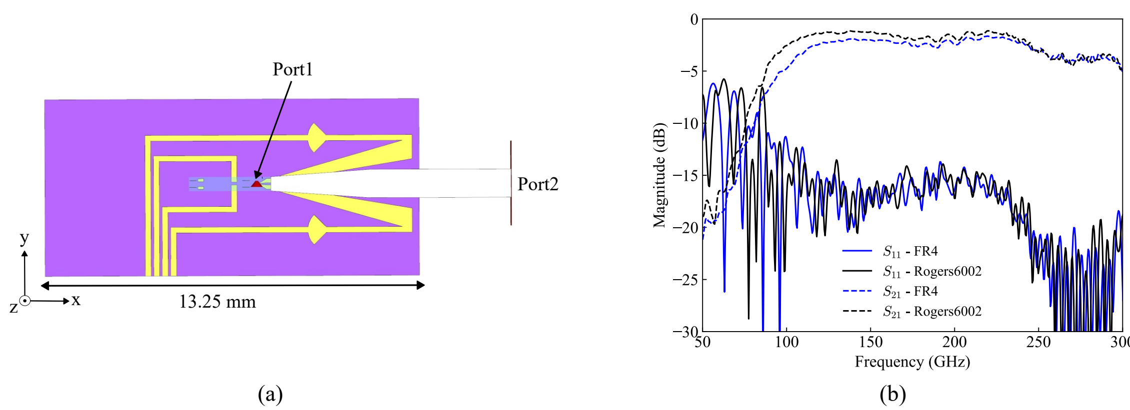

Figure 3. (a) Simulation model. (b) Simulated S parameters, showing the difference between Rogers6002 and FR-4 substrate.

2.3 InP Substrate Design

One of the issues in the integration of high-frequency InP devices in the proposed configuration is undesired substrate modes that arise due to the thick substrate. A thick dielectric allows the electromagnetic field to spread, creating unwanted radiation and interference with the desired signals. However, the fabrication process for a thin InP substrate is complex and challenging, as InP is a mechanically fragile material. To address this issue, we propose to introduce structuring of the InP substrate to reduce the portion of the field that spreads beyond the metal antenna. This structuring is applied along the CPS and the TSA, and its effect is validated through simulation by comparing with a non-structured substrate. The results in Fig. 4 show that the structuring improves coupling efficiency from the THz source to the guided modes of the DRW across the frequency band and supports strong field confinement around the TSA, resulting in a more efficient power transfer to the DRW. The improvement at frequencies above 250 GHz is significant, implying that this structure is highly effective for broadband and high-frequency devices.

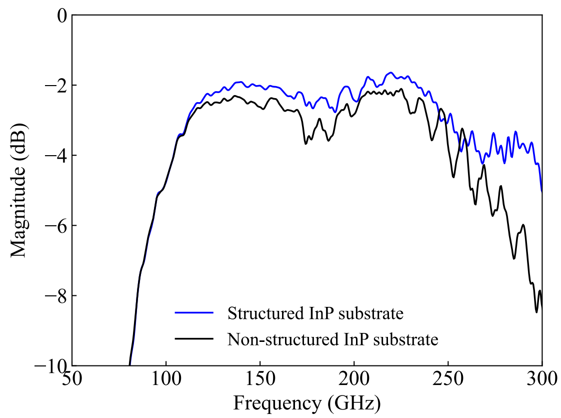

Figure 4. Simulated S_{21}, showing the difference between structured and non-structured InP substrate.

3. DIELECTRIC ROD ANTENNA

The proposed DRA is a substrateless silicon taper with a length of 8 mm, which is monolithically integrated with the DRW. The antenna is simulated with the whole structure including the InP chip and the PCB to evaluate the module performance. Fig. 5 presents the simulated E-plane radiation pattern of the module, where the realized

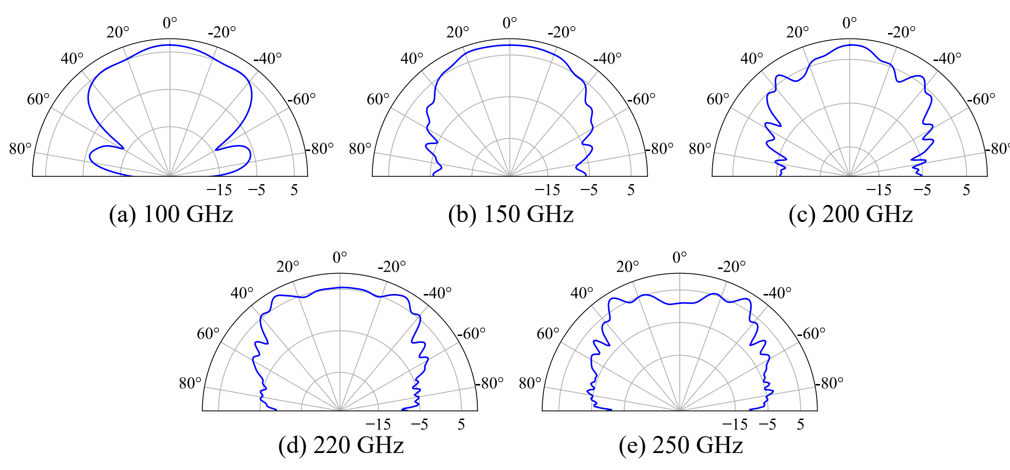

Figure 5. Simulated E-plane Radiation pattern of the dielectric rod antenna integrated with an InP chip on an FR-4 PCB.

gain at 0° is 6.87 dBi at 100 GHz, 7.37 dBi at 150 GHz, 8.28 dBi at 200 GHz, 5.43 dBi at 220 GHz, and 0.95 dBi at 250 GHz. It is clear that the antenna does not provide a desired radiation pattern at 250 GHz. This is attributed to the physical asymmetry of the module in the direction perpendicular to the PCB. Figure 6 shows the simulated E-field distribution at 250 GHz. Although the radiation remains horizontally symmetric in the XY plane, it exhibits a beam tilt in the XZ plane due to the asymmetry introduced by the position of the TSA. As the TSA is not aligned with the DRW in the z direction, the coupling excites distorted field propagation within the DRW at higher frequencies. This results in oblique radiation at the antenna, where the radiation angle is dependent on the frequency. In order to maintain symmetry, the TSA should be placed at the center plane of the DRW. Thus, this is a fundamental problem of this structure that limits the bandwidth of the module.

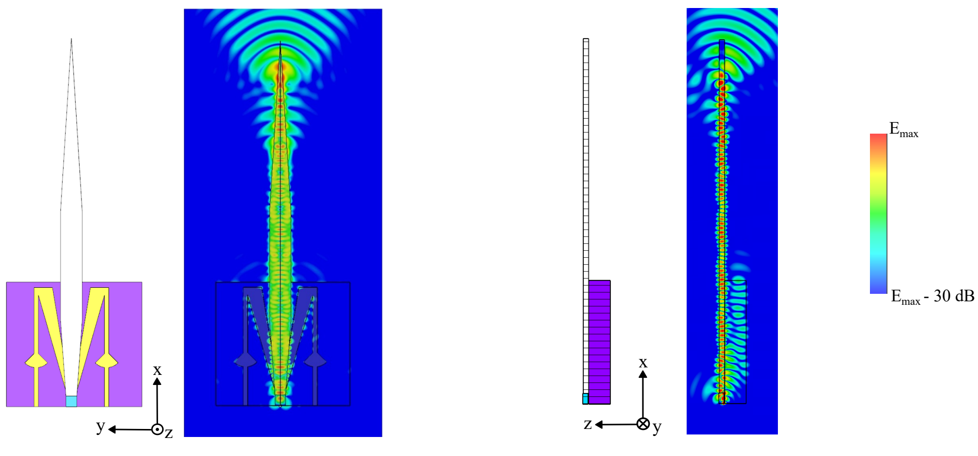

Figure 6. (a) Top view of the simulated E-field distribution and (b) cross-sectional view at 250 GHz.

4. CONCLUSION

We propose a silicon dielectric rod antenna for a broadband THz transmitter, integrated with an InP photoconductive device on a PCB substrate. We found that although GSG pads offer better impedance matching to an InP active device, the GS pads provide symmetric field propagation, making them more suitable for efficient coupling to the DRW-based systems. It is also noted that Rogers 6002 and FR-4 show no significant difference in the insertion loss at higher frequencies owing to the low-loss DRW. This allows us to choose the appropriate PCB material for the designed structure. To further improve coupling efficiency at higher frequencies, the InP substrate can be structured, suppressing undesired substrate modes and making the field confinement stronger for the CPS line. Future iterations include designing and developing THz rod antenna arrays and designing a symmetric coupling structure that prevents distorted field propagation.

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