Sub-terahertz interconnection based on Ge-Si photodetector

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Abstract:
The sub-THz inter-chip interconnections are first demonstrated with terahertz photomixers based on standard-process fabricated germanium-silicon photodetectors and bow-tie antennas, featuring a frequency range over 200 GHz. © 2024 The Author(s)

1. Introduction

The photonic-integrated Terahertz technology has significant applications in terahertz (THz) communication, imaging, and radar owing to its high integration level and wideband tunability [1]. Photo-mixing technology is a crucial way to achieve THz emission and reception [2], which contains high-speed photodetectors and THz antennas. Meanwhile, it has shown high performance in the THz interconnection application [3], making THz interconnection promising in next-generation mobile communications. Due to the large bandwidth and high power, III-V Uni-Traveling-Carrier PDs [3], III-V Positive-Intrinsic-Negative (PIN) PDs [4], and plasmonic PDs [5, 6] are utilized in THz photomixers in recent years. However, these devices suffer from cost or large-scale integration. Fortunately, germanium-silicon (Ge-Si) PDs with CMOS process compatibility have achieved high performance lately [7], which makes it possible to attain high-performance THz signal emission and reception. Yet, THz photomixers based on the Ge-Si PDs with standard fabrication process have not been demonstrated or applied to THz inter-chip interconnection.

In this work, we report the inter-chip interconnection of sub-terahertz wave based on standard-process fabricated Ge-Si PDs and bow-tie antennas. A THz emitter based on PIN PD and a THz receiver based on Metal-Semiconductor-Metal (MSM) PD are fabricated, respectively, both showing good performance in the 0-300 GHz range. Furthermore, the first Ge-Si THz emitter-receiver interconnections are successfully demonstrated with a receiving current of 1 nA near 100 GHz and a maximum frequency range over 200 GHz.

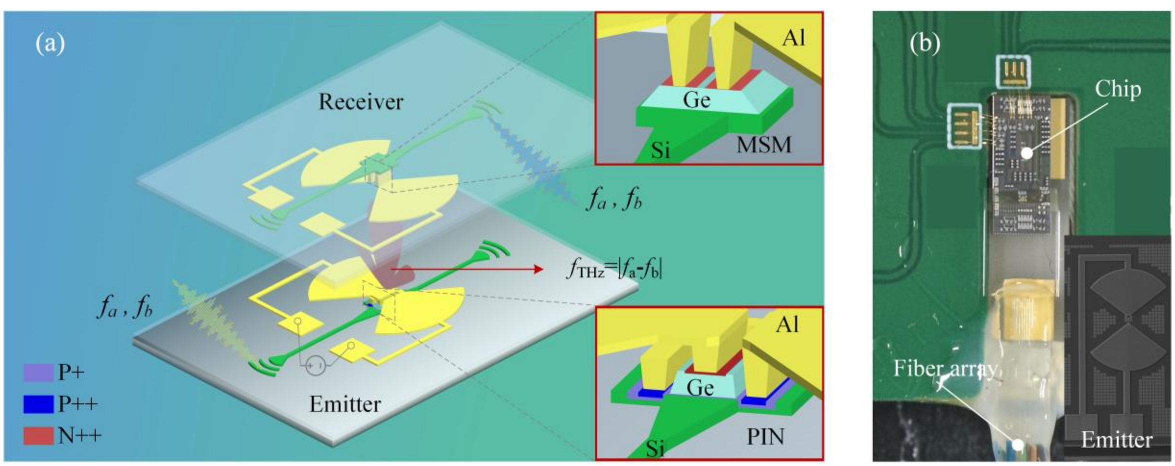

Fig. 1. (a) Schematic diagram of THz emitter-receiver inter-chip interconnection based on Ge-Si PDs. (b) Packaging diagram of THz emitter chip.

2. Device structure and working principle

The inter-chip interconnection schematic of the designed Ge-Si THz emitter and receiver is shown in Fig. 1(a). At the emitting end, the optical signal carries two frequencies f_a and f_b (with a frequency difference $f_{THz}=|f_a-f_b|$) and enters the high-speed PD for photomixing, generating currents carrying terahertz frequencies. It is emitted through the on-chip antenna, realizing the conversion of optical-to-THz-wave (O/T conversion). At the receiving end, two optical carriers enter the receiver to generate a THz local oscillator(LO) and the received THz wave is coherently downconvert to baseband (T/E conversion).

As shown in the insets of Fig. 1(a), the waveguide-coupled vertical Ge-Si PIN PDs are utilized in the THz emitter because of high saturation power and large bandwidth, while the Ge-Si MSM PDs are used in the THz receiver considering the requirement that a bias-sensitive PD is necessary to detect weak terahertz waves. In the PIN PD, the length and width of the Ge region for absorption are 10 and 4.3 μm, respectively. The MSM PD is designed with a length of 8 μm and a width of 9.2 μm. Two metal electrodes are fabricated on two heavily doped ohmic contact layers with a gap of 1.5 μm to form an MSM junction. The thickness of germanium regions in the two PDs are both 0.5 μm. The bow-tie antennas are designed with a same radian of 105 degrees but different radiuses (200 μm and 150 μm) for emitter and receiver to achieve the best interconnect performance. In order to facilitate testing, the THz emitter and receiver are carried on the photoelectric package. As an example, the packaged emitter chip is shown in Fig. 1(b), and the inset illustrate the SEM diagram of an THz emitter.

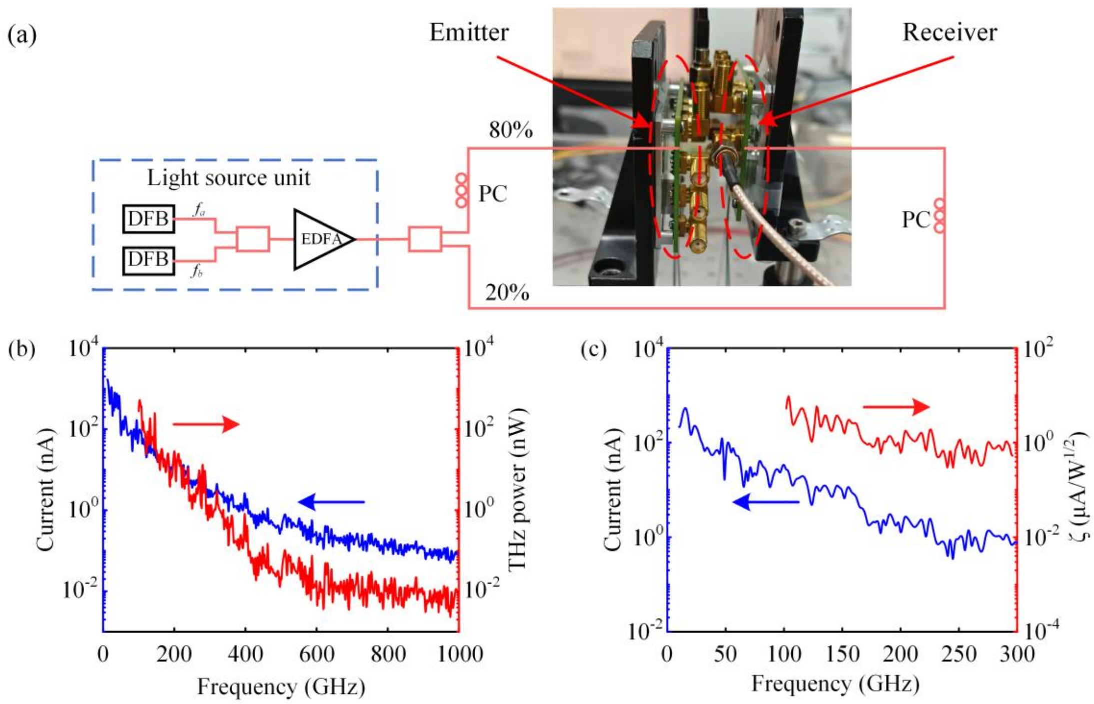

Fig. 2. (a) Experimental setup for the demonstration of sub-terahertz interconnections. (b) Performance of Ge Si PIN-THz emitter. (c) Performance of Ge Si MSM-THz Receiver.

3. Device characteristics and Experimental results

3.1. Demonstration of THz wave emission and reception

An experimental setup based on a commercial THz frequency-domain system (Toptica TeraScan 1550 nm) is used to characterize the proposed devices. As shown in Fig. 2(a), two distributed feedback lasers (DFBs) operating at different frequencies (f_a and f_b) are amplified by an EDFA and enter the THz emitter and receiver, respectively. A variable optical attenuator (VOA) optimizes the optical power to saturate the terahertz current. Electronic chopping and lock-in amplification are employed to improve the sensitivity of THz reception. As a proof-of-concept demonstration, the terahertz transmission is not aided by silicon lenses and other lens sets [3].

First, the emitter and receiver performance are characterized separately. The Ge-Si PIN-THz emitter with an input power of 11.3 dBm (13.5 mW) generates the terahertz wave and it is detected by a commercial receiver (Toptica EK 000 725, Rx) in a distance of 3 mm. The bias voltage applied on the emitter is $-0.5+1.2\sin(\omega t)\mathrm{V}$. The average current ($I_{\mathrm{Rx}}$) (left axis) obtained from Rx measurements and the estimated THz power spectrum (right axis) obtained from the conversion factor $\zeta = I_{Rx} / \sqrt{P_{THz}}$ are presented in Fig. 2(b). The maximum THz emission power is 524 nW (-32.8 dBm) near 100 GHz, while a power of 13.2 nW (-48.8 dBm) is also achieved at 280 GHz, which is much better than the performance of the silicon–plasmonic integrated THz emitter [5]. The ripple on the spectrum originates from the response of the emitting and receiving antennas. On the other hand, the Ge-Si MSM-THz receiver is able to receive the terahertz wave that is emitted from a commercial emitter (Toptica, EK - 000724, Tx).

Fig. 2(c) illustrates the receiver characteristics of the MSM-THz receiver with the conversion factor ζ. A maximum conversion factor of 9.6 μA/W$^{1/2}$ can be obtained near 100 GHz.

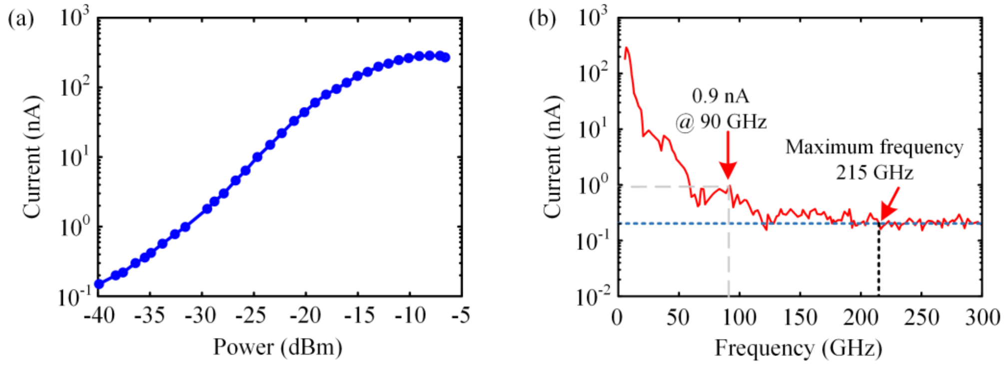

Fig. 3. (a) Influence of LO power on the entire system in the receiver. (b) Spectrum of sub-THz inter-chip interconnect.

3.2. *Demonstration of inter-chip interconnection*

The emitter and receiver characterizations show good performance in the 0-300 GHz range. Then, we replace the commercial emitter/receiver with our PIN-THz emitter and MSM-THz receiver, respectively, conducting the inter-chip interconnection. The inset in Fig. 2(a) shows the picture of the inter-chip interconnection with a spacing of 1 cm. Before performing the interconnection, we characterize the influence of LO power on the entire system in the receiver, as shown in Fig. 3(a). It exhibits a linear relationship at lower powers and the received current approaches saturation near -8 dBm. Based on this result, we can set the incident optical power of the receiver accurately. The transmission results in the 0-300 GHz range are shown in Fig. 3(b), with a noise level of ~0.2 nA indicated by the blue dashed line. According to these preliminary experimental results, up to 215 GHz (the region above the noise level) can be utilized, which belongs to the sub-terahertz region. The appearance of peaks near 90 GHz and near 150 GHz is attributed to the radiation properties of the bow-tie antenna.

4. Summary

We design and fabricate PIN-THz emitter and MSM-THz receiver based on Ge-Si PDs, forming a sub-THz inter-chip interconnection experiments. The emitter achieves a maximum emission power of 524 nW near 100 GHz and a maximum radiation frequency of up to 1 THz, while the receiver achieves receptions in the range of 0-300GHz with a maximum T/E conversion factor of 9.6 μA/W$^{1/2}$ near 100 GHz. Moreover, we preliminarily demonstrate the inter-chip interconnection over 200 GHz. The results suggest that this photomixer based on the standard process fabricated device can be applied in terahertz interconnections. We believe that he THz emitter-receiver chips based on Ge-Si PDs have great potential for low-cost, high-rate THz communications.

5. Acknowledgements

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