Research Towards Terahertz Power Amplifiers in Silicon-Based Process

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Abstract: In view of the existing design challenges for Terahertz (THz) power amplifiers (PAs), the common design methods and the efforts of the State Key Laboratory of Millimeter Wave, Southeast University, China in the development of silicon-based THz PAs, mainly including silicon-based PAs with operating frequencies covering 100–300 GHz, are summarized in this paper. Particularly, we design an LC-balun-based two-stage differential cascode PA with a center frequency of 150 GHz and an output power of 14 dBm. Based on a Marchand balun, we report a 220 GHz three-stage differential cascode PA with a saturated output power of 9.5 dBm. To further increase the output power of THz PA, based on a four-way differential power combining technique, we report a 211–263 GHz dual-LC-tank-based broadband PA with a recorded 14.7 dBm Psat and 16.4 dB peak gain. All the above circuits are designed in a standard 130 nm silicon germanium (SiGe) BiCMOS process.

Keywords: power amplifier; power combining; SiGe; silicon-based; Terahertz

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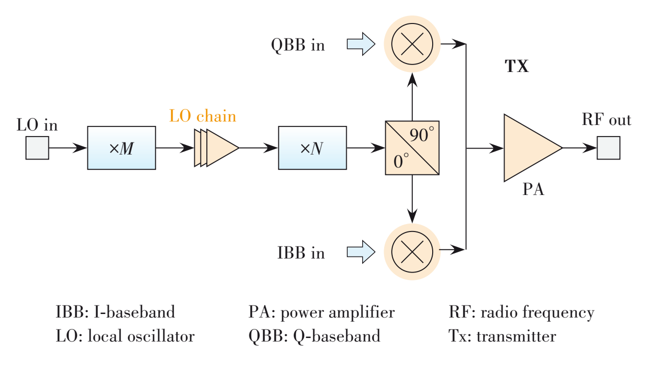
1 Introduction

In recent years, the importance of the Terahertz (THz) spectrum in electronics, radio astronomy and other fields, such as biological imaging, high-speed communication, and high-resolution radar, has gradually emerged mainly due to its spectral resolution safety, perspective and broadband characteristics[1]. However, due to the large loss of free space propagation in the THz frequency band (especially when frequencies are above 100 GHz), combined with the effects of atmospheric attenuation, a transmitter needs to have sufficient effective isotropic radiated power (EIRP) to achieve long-distance wireless transmission. Fig. 1 shows a block diagram of a typical THz transmitter based on a communication application scenario. The power amplifier (PA), as the final active stage of the transmitter, directly drives the post-antenna to transmit the radio frequency (RF) signal into free space. Therefore, its performance indicators, including output power, RF bandwidth, etc., directly determine the performance of the entire transmitter and then restrict the wireless transmission distance of the entire transceiver system.

The III-V compound semiconductor processes are often used in THz PA designs due to their higher cutoff frequency (f_T), higher maximum oscillation frequency (f_{MAX}), higher cutoff voltage, and smaller substrate losses. However, the III-V process is not suitable for integrating large-scale digital and analog circuits, so multiple discrete chips implemented by different processes need to be integrated into the transceiver system. As a result, the channel module size tends to be large, making it difficult to meet the half-wavelength spacing requirements for THz array integration, which limits the performance of THz RF array systems.

With the development of silicon-based integrated circuit



▲**Figure 1. Block diagram of a typical Terahertz (THz) transmitter**

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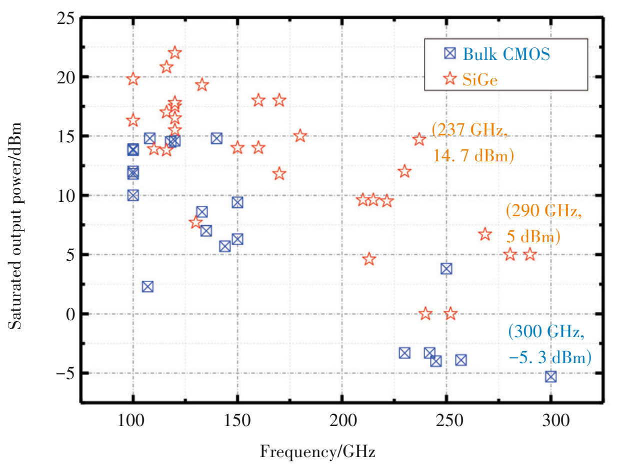
processes, the f_T/f_{MAX} of its transistors has been covered to the 300 GHz band[2], making it possible to design low-cost, highly integrated and small-size THz PAs based on advanced silicon-based processes. However, based on existing advanced silicon-based processes, there are still many challenges in designing high-performance PAs in the frequency band above 100 GHz[3]. First, the shrinking of the characteristic size of the transistor causes the withstand voltage value of the transistor to decrease, so the supply voltage is limited, thereby limiting the output power of the PA. Second, when the operating frequency increases to more than 100 GHz, the loss of the passive structure increases due to the influence of skin effect and radiation effect, which further deteriorates the performance of silicon-based THz PA. Fig. 2 summarizes the output power of currently representative reported PAs, mainly based on bulk complementary metal oxide semiconductor (CMOS) and silicon germanium (SiGe) processes[3]. It can be seen that the output power of silicon-based PAs drops sharply at above 100 GHz, and there is an urgent need to study high-performance silicon-based THz PAs.

To overcome the above difficulties, we have conducted research on THz broadband low-loss single-ended-to-differential signal conversion baluns and gain-boosted PA cores, and developed a variety of 100 – 300 GHz silicon-based differential PAs, including 150 GHz, 220 GHz and 250 GHz PAs[5 – 7]. In addition, aiming at the development of broadband low-loss power combining techniques and high-efficiency miniaturized multi-way power combining structures, we design a 240 GHz three-stage cascode structured PA based on four-way zero-degree transmission line power combining techniques[8].

2 Silicon-Based Differential THz PA

The development of high-performance silicon-based THz PAs is a key link in the practical process of THz communication and radar systems. To ensure that the transmitter has sufficient transmit power, it is critical to study the design of PAs with high output power, high gain, and miniaturization. When the operating frequency rises to the THz frequency band, the influence of circuit parasitic parameters is intensified, coupled with the influence of skin effect and others, the quality factor of passive devices is reduced, the circuit loss increases, and the working bandwidth deteriorates sharply. Conventional single-ended PAs have limited gain, output power, and efficiency in the THz band. Therefore, scholars have conducted extensive research on how to design and produce differential structured silicon-based THz PAs with high performance. According to Ref. [3], PAs based on silicon-based processes currently can operate at frequencies up to 300 GHz. In typical reports like Ref. [9], the PA shows a 3 dB bandwidth of 63 GHz (239 – 302 GHz) in small-signal operation and 94 GHz (223 – 317 GHz) when saturated, and the PA is fabricated in an experimental 130 nm SiGe BiCMOS process with f_T/f_{MAX} of 470/650 GHz.



CMOS: complementary metal oxide semiconductor SiGe: silicon germanium

▲Figure 2. Research status of Terahertz (THz) power amplifiers (PAs) based on bulk CMOS and SiGe process[3]

Differential combining is the commonest power combining method in THz PA designs, and differential power combining structures include LC baluns, transformer baluns, and Marchand baluns. LC baluns consist of lumped component inductors and capacitors, making them easy to design. In the microwave and millimeter wave bands, LC baluns are less used due to the larger inductor size. When operating frequencies are above 100 GHz, the inductor size is greatly reduced as the wavelength decreases, making the LC balun suitable for on-chip differential power combining. Transformer baluns are widely used in the millimeter wave circuit design, by changing the size, spacing, and linewidth of the primary and secondary coils that make up the transformer, and the operating band, coupling coefficient, and bandwidth can be changed to achieve single-ended-to-differential signal conversion. Transformer baluns have the characteristics of small size, high order, wide bandwidth, many adjustable parameters, and strong design flexibility. However, in the THz frequency band, limited by the design rules of the chip processing process, the transformer balun is small in size, and the parasitic parameters and losses are often larger. The coils that make up Marchand baluns are half a wavelength in size and are larger in the lower frequency bands, usually reduced in area by spiral layouts. In the THz band, Marchand baluns, benefiting from a drastically reduced operating wavelength, often have the advantage of a moderate size and excellent RF performance.

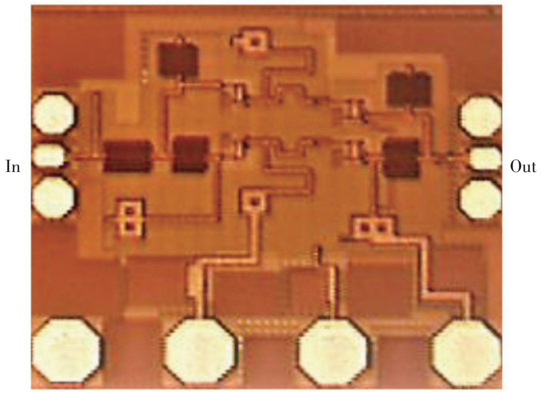
2.1 150 GHz PA Based on LC Balun

The THz band has become a popular candidate for next-generation wireless communications due to its extremely rich spectrum resources. The D-band (110 – 170 GHz) is located in the THz low-frequency band, and there is an atmospheric window in the frequency range of 120 – 160 GHz. The wireless propagation path loss is small, so it is suitable for preliminary verification of THz communication systems. As one of the important components in the communication transceiver, the PA directly restricts the performance of the entire transceiver.

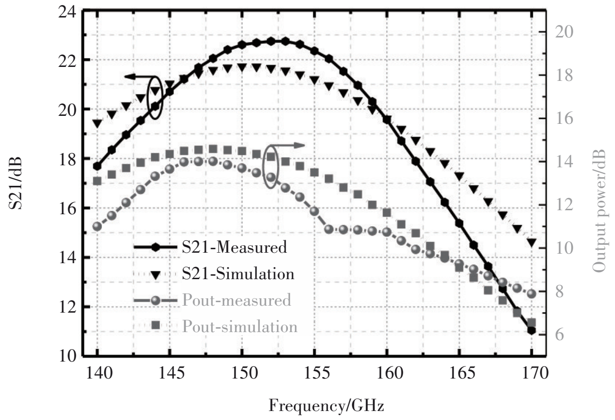
Fig. 3 shows a 150 GHz differential structured PA based on a commercial 130 nm SiGe BiCMOS process[6]. Common-emitter topology amplifiers have high power-added efficiency, but in the 150 GHz band, differential amplifiers based on common-emitter structures have lower single-stage gain due to the large decrease in the intrinsic gain of the transistor, and usually need to cascade four to five stages to obtain a small-signal gain of more than 20 dB. Therefore, the PA usually adopts a cascode structure. In order to further increase the gain of a single-stage cascode amplifier core, inductors L1 and L2 shown in Fig. 3 are introduced to the base of the common-base structure transistor. The base decoupling capacitor of the common-base transistor in a single-ended cascode amplifier will introduce an additional parasitic signal low impedance path to the RF ground, and the introduction of this pole also brings about stability issues, so the PA uses a differential structure. In addition, the size of the transistors in the PA is multiplied in the output direction to increase the power handling capability of the last stage and guarantee the low power performance of the PA.

For easy testing and easy connection to the pre-mixer and post-antenna, the amplifier has single-ended ground-signal-ground (GSG) RF PADs for both input and output. The core of the amplifier is differential, so a low-loss single-ended-to-differential signal conversion structure is required at the input and output ports of the amplifier. As shown in Fig. 3, LC baluns are used for single-ended and differential signal conversion at the input and output ports of the amplifier, where the inductor consists of microstrip lines. When operating at 150 GHz, the differential ports of the on-chip LC balun will have a phase imbalance problem, so the phase compensation lines TL4 and TL11 shown in Fig. 3 are introduced to achieve a good balance performance at the differential ports.

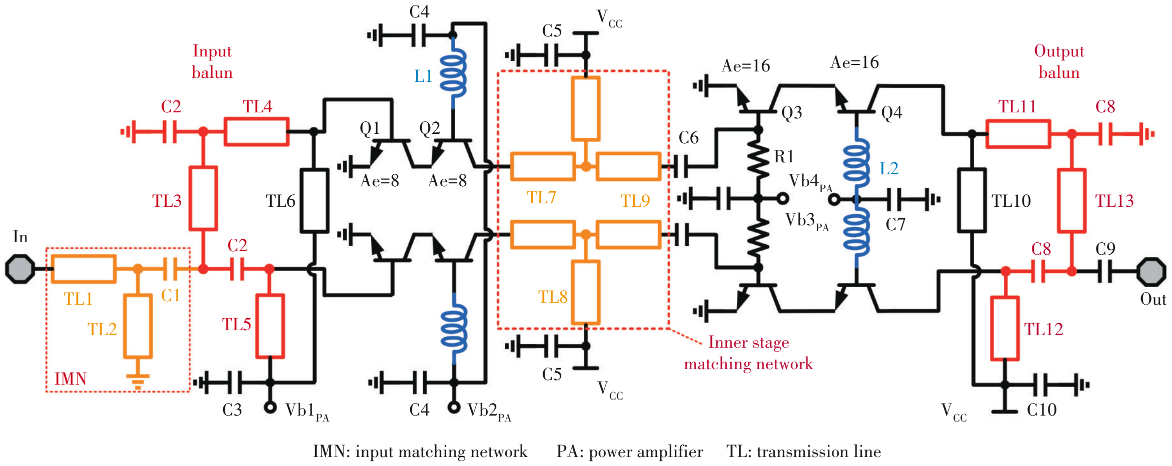
The chip micrograph of the 150 GHz PA is shown in Fig. 4, and the simulation and measured results for the small-signal gain and saturated output power of this PA are shown in Fig. 5.



▲Figure 4. Die photo of the 150 GHz power amplifier (PA)



▲Figure 5. Simulated and measured results of the 150 GHz power amplifier (PA)[6]



▲Figure 3. Schematic of the 150 GHz PA[6]

In the 140 – 160 GHz band, the small-signal gain of the amplifier is measured to be larger than 15 dB, reaching a maximum of 22.7 dB at 152 GHz. Meanwhile, the test shows that the PA obtains a maximum output power at the frequency of 148 GHz, where the power value is 14 dBm, and the 3 dB bandwidth of the output power reaches 16 GHz.

2.2 220 GHz PA Based on Marchand Balun

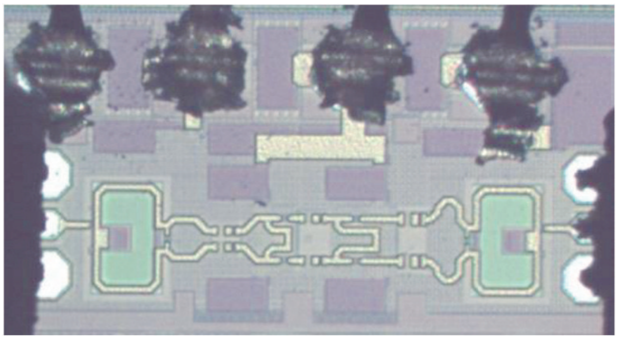
The 220 GHz band is currently a hot spot band, and there are many studies on this frequency band, including ultra-high-speed communications, high-resolution radar, etc. Among them, the PA is one of the key components that restrict the performance of the 220 GHz RF system. Achieving high performance PA in the 220 GHz band faces two major difficulties: one is that the operating frequency is close to the f_T/f_{MAX} of the transistor, resulting in a steep gain drop in the active device, and the other is the low quality factor and large insertion loss of the passive device in the THz band.

As shown in Figs. 6 and 7, the PA is a fully differential three-stage cascode structure[7], and the amplification unit using the cascode structure can reduce the number of stages, thereby reducing the passive loss caused by the inter-stage matching network, and the cascode topology also has better reverse isolation. The input and output networks are based on stacked Marchand baluns for single-ended-to-differential signal conversion. DC feed is performed through the center tap of the Marchand balun's secondary coil. In addition, some series transmission lines and parallel capacitors participate in impedance matching of the input and output networks. In the inner-stage impedance matching network, thanks to the fully differential structure, the intersection of the parallel transmission lines is an RF virtual point that can be used for DC feeding.

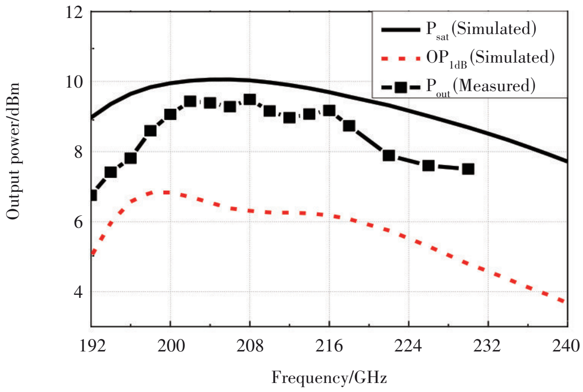
The measured results show the small-signal gain of the amplifier exceeds 20 dB, and the 3 dB bandwidth covers 204 – 239 GHz. Fig. 8 shows the simulated and measured large-signal performance of this PA, with saturated output power exceeding 9 dBm in the 200 – 216 GHz band.

3 Silicon-Based THz PA Based on Multi-way Power Combining Techniques

In silicon-based THz systems, due to the large connection loss of the RF interface (the connection between the RF output port and the antenna), the solution of integrated antenna-on-chip is often used. Limited by the thickness of the silicon process's metal layer, the on-chip antenna has a limited gain of about a few dBi. Therefore, as the device is directly con-

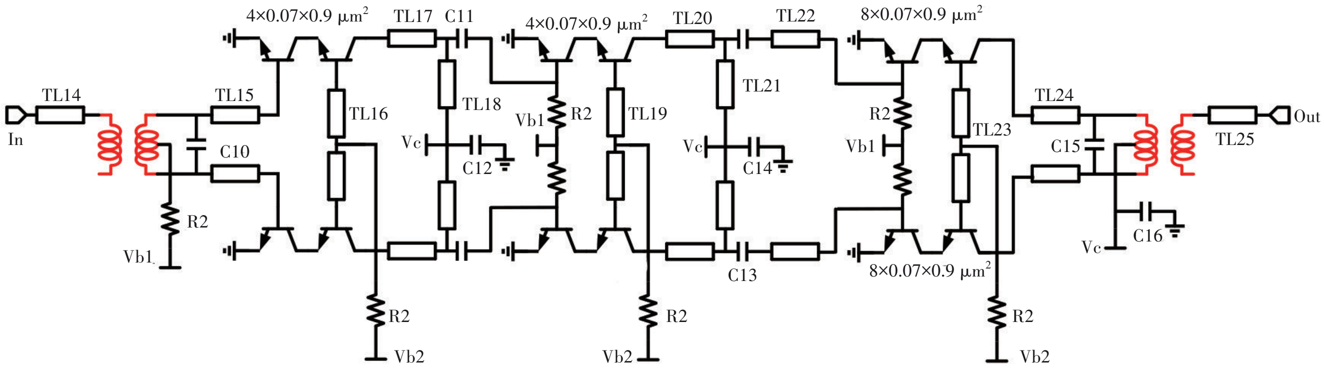


▲Figure 7. Die photo of the 220 GHz power amplifier (PA)[7]



OP: out power

▲Figure 8. Simulated and measured results of the 220 GHz power amplifier (PA)[7]



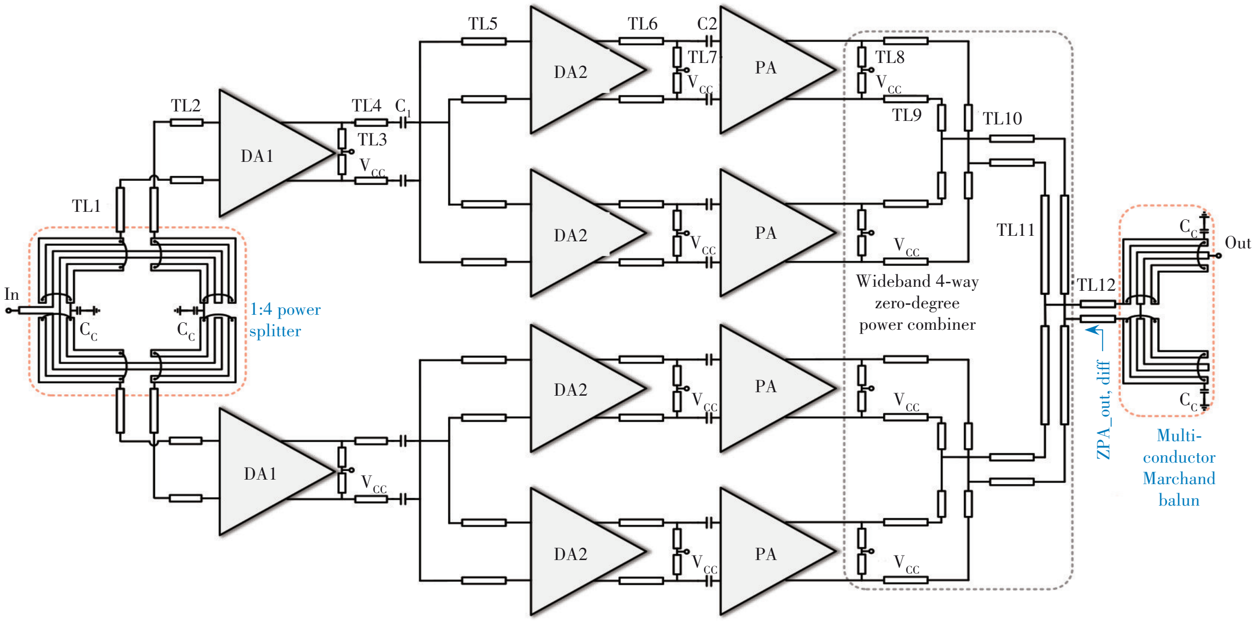
TL: transmission line

▲Figure 6. Schematic of the 220 GHz power amplifier (PA)[7] nected to the on-chip antenna in the RF system, the output power of the PA directly determines the transmission distance of the system[10]. However, the ability of transistors to deliver power in the THz band in silicon-based processes is limited, and power combining techniques must be employed to achieve higher output power.

Power combining techniques in THz bands include free-space power combining and on-chip power combining. Free-space power combining techniques can be co-designed with the on-chip antenna to generate high radiated power in equivalent space through array design[11]. However, on-chip antennas based on silicon-based processes are less efficient, and on-chip antennas tend to be larger in area and higher in cost. On-chip power combining techniques include the direct use of multiple transistors in parallel or multiple transistors stacking, and passive power synthesis techniques based on multi-way PAs. Transistor parallel connection is a current-based power combining method and transistor stacking is a voltage-based power combining method, and a better power combining efficiency can only be achieved when the current and voltage through each transistor are in phase. While the THz frequency is high and the wavelength is short, the connection line of tens of microns will introduce a large phase difference, so the number of transistors connected in parallel or stacked is limited. Passive multi-way power combining is to design a passive power combining network inside the chip and add the output power of the multi-way PAs with high efficiency to improve the final output power.

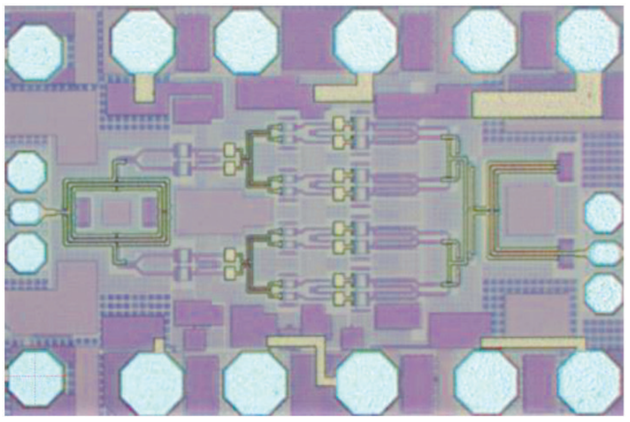
There are three main types of passive on-chip power combining techniques, namely power combining techniques based on a Wilkinson power divider, transformer-based power combining techniques, and zero-degree power combining techniques based on transmission lines. The power combining technique based on Wilkinson power dividers requires a pair of quarter-wavelength transmission lines that occupy a large area and are not suitable for on-chip power combining. At the same time, limited by the quarter-wavelength line, its bandwidth is relatively narrow. When the operating frequency deviates from the design frequency or there is a large parasitic, the isolation and matching between the ports will deteriorate significantly. Power synthesis based on transformers mainly includes voltage combining and current combining. For the transformer, common-mode signals and noise can be transmitted to the output due to parasitic capacitance between coils. When frequencies rise above 200 GHz, capacitance parasitic increases significantly, severely limiting transformers to be used in this frequency band, where Marchand balun's common-mode conversion is much lower than that of transformers, resulting in a smaller insertion loss. Zero-degree power combining techniques directly synthesize the current of multiple PAs to obtain high output power. And in the frequency band above 200 GHz, the T-type zero-degree power combining network has a compact size and low insertion loss.

Combining the characteristics of the above-mentioned on-chip power combining techniques, we have designed a three-stage differential cascode structure PA based on a four-way zero-degree power combining architecture, as depicted in Fig. 9[8]. As illustrated in Fig. 10, the PA's power combining network consists of an improved four-way zero-degree power combining network and a three-conductor Marchand balun, which



DA: driver amplifier PA: power amplifier TL: transmission line

▲**Figure 9. Schematic of the 240 GHz four-way power combining PA[8]**



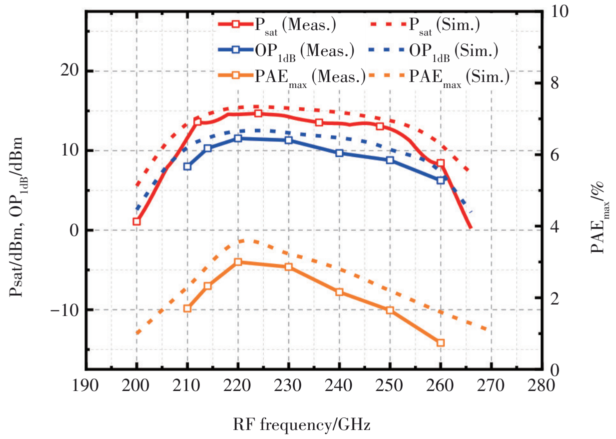
▲**Figure 10. Die photo of the 240 GHz four-way power combining PA**[8]

can achieve wideband impedance matching while completing high-efficiency power synthesis. Traditional zero-degree power combining networks use quarter-wavelength lines and bypass capacitors for DC feeding, which limits the operating bandwidth of the PA.

The zero-degree power combing network used by the PA contains RF virtual points for DC feed, as shown by the microstrip lines TL3 in Fig. 9, which is formed by the central point of the microstrip lines connected in parallel between differential ports. The advantage of such a design is that the broadband matching characteristics of the output network are guaranteed. In addition, to further increase the bandwidth of the output power combining network, we use a wideband Marchand balun based on a three-conductor coupling line as shown by the orange dotted box in Fig. 9 in the output differential-to-single-ended conversion network. When the operating frequency rises to 200 GHz, the lumped components with low figure of merit result in high insertion loss, and a broadband matching network with multi-resonant cavities can only be achieved by distributed networks. The three-conductor Marchand balun in the output impedance matching network achieves wideband matching with dual-LC resonances by absorbing two resonant networks into the coupling structure.

At the input of the PA, unlike the common passive or active power division structure, the PA uses a folded 1-to-4 power distribution network as shown in Fig. 9, where the RF ground of the secondary coil that makes up the balun is achieved by the metal-oxide-metal (MOM) capacitors Cc. The metal-insulator-metal (MIM) capacitors provided in the process have a low quality factor in the frequency band above 200 GHz, so the capacitors used in the PA design are all MOM capacitors. MOM capacitors are made of multilayer metal crossings and stacks for high design flexibility.

The chip micrograph of the designed PA is shown in Fig. 10. Due to the folded input power distribution network and the compact output power combining network, the core area of the PA is only 770×280 μm^2. As shown in Fig. 11, the measured results show that the small-signal gain of the PA exceeds 15 dB and the 3 dB bandwidth is larger than 50 GHz. In the 210 – 250 GHz band, the PA is tested to have saturated output power of more than 13 dBm.



OP: output power PAE: power added efficiency RF: radio frequency

▲**Figure 11. Die photo of the 240 GHz four-way power combining PA**[8]

4 Conclusions

Due to the abundant spectrum resources of the THz frequency band, application scenarios, such as high-speed communication and high-resolution radar with this frequency band, have become research hotspots. The rapid development of silicon-based processes provides new low-cost solutions beyond compound processes for these studies. The above systems have high demands on the performance of PAs such as output power and RF bandwidth. Combined with several PAs designed in our lab in the THz band, this article summarizes the common structure and design methods of PAs in the THz band.

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Biographies

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