An Overview of Semiconductor Technologies and Circuits for Terahertz Communication Applications

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Abstract **– An overview of the current status of the semiconductor device technologies and circuits for terahertz applications, especially for the broadband wireless communication systems, is provided in this work. Comparison between various semiconductor device technologies such as III-V HEMTs and HBTs, SiGe HBTs, and Si MOSFETs is presented and the current record performances of each technology are described. In addition, the best performing amplifiers, oscillators, and mixers as of today for possible terahertz communication system applications are presented and related issues are discussed.**

Index Terms **– broadband communication, semiconductor devices, high-speed integrated circuits**

I. Introduction

The terahertz band, which falls on roughly between the traditional microwave and optical bands, is typically defined as the frequency range of 0.1 – 10 THz. In terms of the wavelength in free space, it corresponds to the range of 3 mm – 0.03 mm. Compared to the neighboring bands, which have been extensively exploited for a myriad of applications, the terahertz spectrum has long remained as a territory only scarcely explored. For this reason, the spectrum has popularly been called the 'terahertz gap'.

A couple of reasons can be mentioned why it has been so hard to fill up the 'gap'. Firstly, it is relatively difficult to develop devices that can reliably generate, detect, or properly process the terahertz signals. In particular, the generation of terahertz signal with sufficient output power is exceptionally challenging. The generation of terahertz pulses is relatively better established, particularly with the femtosecond laser technology. On the other hand, the generation of CW (continuous wave) terahertz signal, which is more useful for the majority of applications, still remains a big challenge. This is clearly seen in Fig. 1, in which the output power of CW terahertz signals generated by various solid-state sources is plotted as a function of the frequency [1]. The output power rapidly drops as the frequency approaches the terahertz from either side of the spectrum, well presenting the terahertz gap. Secondly, the attenuation level of electromagnetic waves in the earth atmosphere is higher for the terahertz band compared to the neighboring bands. Figure 2 illustrates the attenuation as a function of the frequency, which reaches well beyond the 100 dB/km level near 1 THz [2]. This imposes a challenge in exploring terahertz band for applications that need propagation over an extensive distance.

In spite of these challenges, the terahertz band possesses its own unique properties attractive for many practical applications. Various materials such as papers, clothes, plastics, wood panels, and leather are transparent to the terahertz wave unlike to microwave and visible light. On the other hand, the terahertz wave is easily absorbed by water-containing materials such as human body and various biological objects. Also, the terahertz frequency range corresponds to the resonance frequencies of various molecules in the atmosphere and the space. With these distinguishing properties, the terahertz band retains a great potential for applications that range from security and bio imaging, spectroscopy, sensors, to astronomy and atmospheric studies. Another advantage of the terahertz band that attracts increasing interest today is its immense bandwidth available for broadband wireless communication [3]. The channel capacity is proportional to the available bandwidth

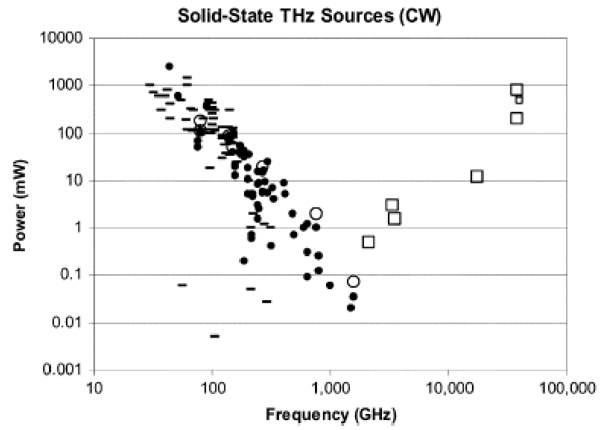

Fig. 1. Output power vs. frequency for various solid-state CW THz sources [1].

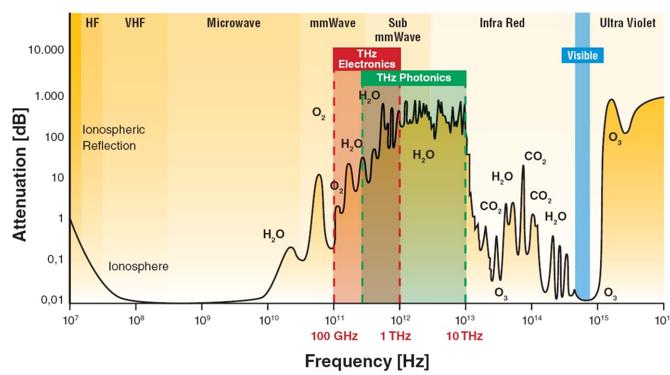

Fig. 2. Attenuation of the electromagnetic wave in the atmosphere (dB/km) [2].

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as indicated by the Shannon's theorem, and the terahertz frequency range is expected to provide data rate of tens of Gbps. Such high data rate would be critical for the efficient data transfer of ever increasing amount of data to be shared between electronic units.

It is noted that there are two approaches for the terahertz band development. One is the 'downward' approach from the traditional optics, for which the reduction of operation frequency is needed. The other one is the 'upward' approach from the traditional electronics, which requires the increase of operation frequency. Current terahertz studies are dominated by the downward approach, which is based on rather bulky optical systems that include femtosecond lasers and optical lenses and mirrors. However, there is a recent growing interest for the upward approach owing to the rapidly improving operation speed of semiconductor device technologies. This would enable the realization of compact terahertz systems with integrated devices and circuits. In this sense, the upward approach based on semiconductor technology is critical for the successful application of the terahertz band for the communication systems.

In this work, an overview of semiconductor technologies and circuits currently available for the possible implementation of the terahertz communication systems is presented, particularly intended for those involved in the communication system-level designs.

II. Semiconductor Technologies for Terahertz

A. Diode vs. Transistor for Terahertz Applications

The key semiconductor electronic devices that can be used for the implementation of terahertz systems are diodes and transistors. Diodes have already been widely employed for various terahertz systems. IMPATT (IMPact Avalanche Transit Time) diodes, Gunn diodes, and RTD (Resonant Tunneling Diode) have been used for generating terahertz signals [4]. Schottky barrier diodes have been a popular choice for the detection of terahertz signals [5]. However, diodes have an inherent limit of being a passive device, which critically limits the range of their applications. On the other hand, the transistors, an active device, provide versatile electronic functions mainly owing to their ability to amplify signals, which leads to critical performance enhancement in electronic systems including the terahertz system.

Such advantage of the transistor-based systems can be easily seen with the heterodyne receiver shown in Fig. 3 as an example. The availability of transistors enables the inclusion of an LNA (low noise amplifier) at the very first stage of the system (Fig. 3(a)). This will not only enhance the overall gain of the system, but, more importantly, can maintain the NF (noise figure) of the system to a sufficiently low level. In addition, the active mixers can be employed after the LNA, which will effectively suppress the noise from the following IF blocks with their own gain larger than unity. On the other hand, for the diode-based system (Fig. 3 (b)), NF of the entire system will be dictated by that of the mixer, which is significantly larger than that of LNA in general. Further, the noise from the IF block will not be suppressed but rather amplified with the loss of the passive diode-based mixer.

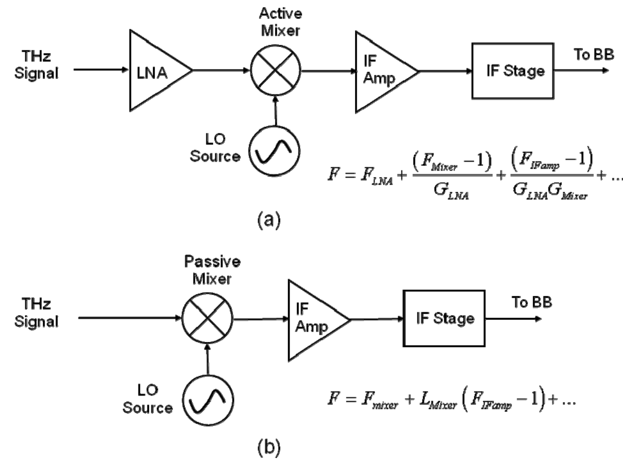


Fig. 3. Receiver block diagram for: (a) transistor-based system; (b) diode-based system

The availability of transistors greatly enhances the performance of the transmitters, too, by enabling the inclusion of a power amplifier at the final stage, which further boosts the output power level from the preceding stage. It can be also noted that the transistor-based circuits can be more easily integrated with other blocks than the diodes. For these reasons, the development of high speed *transistor* technology is the key for the upward approach to the terahertz systems based on electronics.

B. III-V Compound Semiconductor Technologies

Modern semiconductor transistor technologies can be largely categorized into two groups: III-V compound semiconductor technologies and Si technologies. The representative high-speed devices for the former are HBT (Heterojunction Bipolar Transistor) and HEMT (High Electron Mobility Transistor), while those for the latter are SiGe HBT and Si MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor). The speed performance of these devices has been continuously improved over the past decades and now they all have entered the regime of several hundreds of GHz. Figure 4 depicts the trend of the device speed evolution of in terms of the cutoff frequency f_T, which is defined as the frequency where the current gain becomes unity. The trend shows that the III-V devices tend to exhibit superior operation speed than Si devices. This places the III-V HBTs and HEMTs on the front line for the terahertz applications. It is noteworthy to briefly mention that another measure of the device operation speed, the maximum oscillation frequency f_{max}, is a more relevant parameter than f_T for analog and RF circuit designs. However, f_{max} is more sensitive to the details of device layout and its extraction is less reliable than f_T, making f_T more popular for comparisons between technologies.

While both HBT and HEMT are based on III-V semiconductor systems typically represented by GaAs or InP, each device has its own pros and cons in terms of device characteristics. HBTs tend to show higher current driving capability and larger transconductance g_m, which is typical

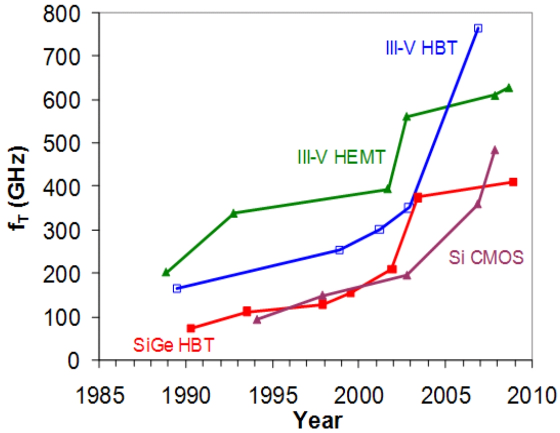


Fig. 4. Trend of the increase of operation frequency for various devices.

characteristics of bipolar transistors, than HEMTs. The epitaxial structure and fabrication steps of HBTs, however, are more complicated as they are basically a vertical device. As of today, the highest reported f_T at room temperature for HBT is 765 GHz, which happens to be the highest for any type of transistors on any semiconductor technology [6]. The device, reported by University of Illinois at Urbana Champaign in 2006, is based on InP technology and its speed can be further pushed up to 845 GHz when the device is cooled down to T = -55 C.

HEMTs are basically a field-effect transistor and the performance tends to be highly dependent on the lateral patterning of the gate electrode, for which E-beam lithography is typically employed. Its epitaxial structure and fabrication steps, on the other hand, are relatively simple. The channel layer is not intentionally doped, leading to the excellent noise performance, especially at low temperatures. HEMTs used to be considered as the fastest device until mid-2000's, when the record HBT performance rapidly increased. The record performance of HEMT as of today is f_T of 628 GHz, achieved with an InP-based device as reported by MIT in 2008 [7].

The excellent speed performance of the III-V devices mainly arises from the superior electron transport characteristics in the III-V semiconductor materials. The low-field electron mobility and the pronounced electron ballistic transport property exceed those of Si, leading to the higher operation frequency of n-type III-V devices. It is noted though that the transport properties of holes for III-V semiconductors is typically worse than those of Si, explaining for the rare adoption of p-type III-V devices for practical applications. In spite of the excellent high frequency performance, the III-V devices suffer from relatively poor reliability compared to the Si counterparts. The typically encountered non-planar structure and high defect density in the active region of the III-V devices tend to cause leakage current due to traps, raising the reliability concerns. Further, the fabrication cost of the III-V technology is on the unfavorable side, mainly due to the expensive and small wafer diameter, costly epitaxial growth steps, and the need for low throughput E-beam lithography process.

C. Si Technologies

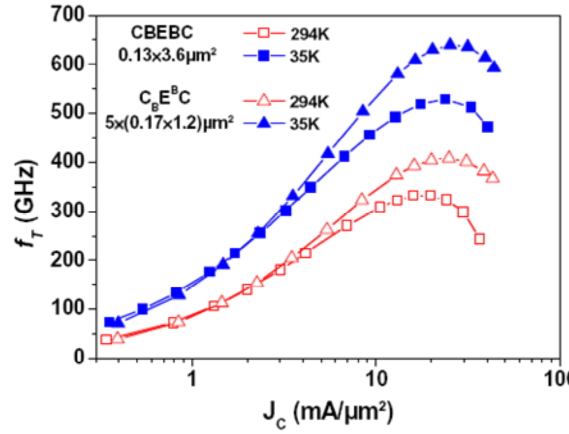


Fig. 5. Cutoff frequency vs. collector current density of a 0.13 μm SiGe HBT for two different layouts options and temperatures [8].

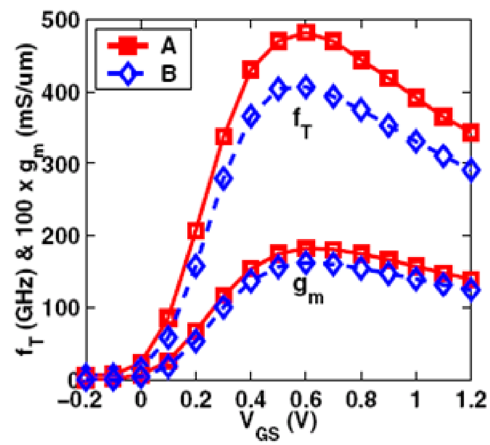


Fig. 6. Cutoff frequency and transconductance vs. V_{GS} of a 45-nm SOI Si n-type MOSFET for two different layout options [9].

Si-based transistors, which are represented by SiGe HBTs and Si MOSFETs, have shown rapid operation speed improvement in recent years, now exhibiting comparable performance as the III-V devices. Moreover, their development is mostly driven by the industry, implying a shorter time to the production line than the III-V devices case. SiGe HBTs are basically a variant of Si bipolar transistors, which contains a small amount of Ge in the base region that helps to significantly improve the device performance. Compared to Si MOSFETs, it provides higher current drivability, larger g_m, superior $1/f$ noise property, and superior device matching. Besides, SiGe HBTs show higher operation frequency than Si MOSFETs for a given lithography node since it is a vertical device whose operation speed is dictated by the vertical rather than lateral dimension. The record performance of SiGe HBTs at this point is f_T of 410 GHz, obtained from the 0.13 μm technology from STM (Fig. 5) [8]. Its speed can be further boosted up to 640 GHz at a cryogenic temperature of 35 K.

Si MOSFETs are by far the dominant device for modern electronics. Until quite recently, however, Si MOSFETs have not been considered as a serious contender for the RF arena. Nonetheless, the continued scaling of Si MOSFETs, driven by

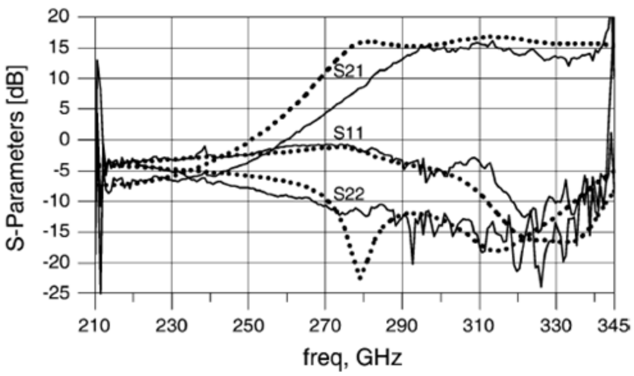
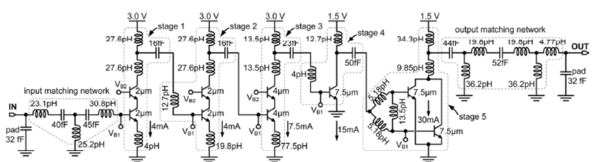


Fig. 7. Characteristics of 3-stage InP HEMT amplifier [10].



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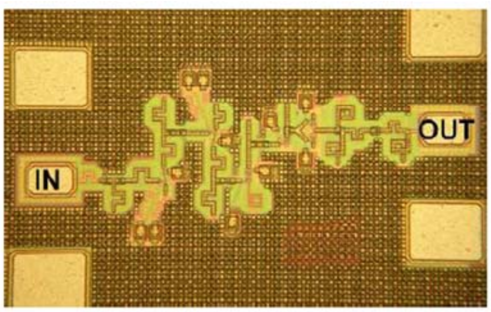

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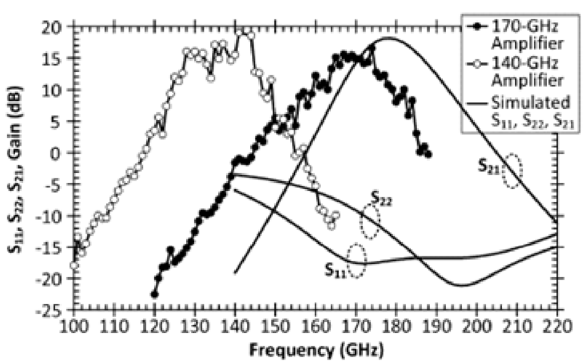


(c)

Fig. 8. 5-stage cascode SiGe HBT: (a) circuit schematic; (b) chip photo; (c) Measured characteristics [13].

the strong need for high-speed digital applications, has consequently advanced the RF properties of the device as well. That has eventually led to the impressive f_T of 485 GHz for an n-type MOSFET from IBM based on 45-nm SOI technology as shown in Fig. 6 [9]. As they benefit from the integratability with other circuit blocks and manufacturing cost, Si MOSFETs will be well posed for the terahertz applications when the operation speed become sufficiently large for the production devices. It is noted that the cost advantage of Si MOSFETs vanishes when the production volume is small, since the cost for the phase shift masks required for the advanced lithography is significant.

One may wonder how the operation speed of Si devices can be comparable to that of the III-V devices despite the less favored material properties of Si. The answer can be found with the state-of-the-art Si process technology that enables the extremely aggressive scaling and extensively optimized device structure. When the excellent reliability of Si devices is considered collectively with the performance, Si devices are expected to find a highly promising opportunity in the terahertz applications in the near future.

III. Semiconductor Circuits for Terahertz

In this section, an overview of three key circuit blocks for terahertz communication systems is provided: amplifiers, oscillators, and mixers.

A. Amplifiers

Among the three types of circuits to be reviewed, amplifiers demand the most stringent requirement for the operation frequency of the transistor, the basic building component of the circuits. To achieve a gain of several dB per stage, which is a typical value, the cutoff frequency of the transistor, or f_{max} for the case of power gain, needs to be at least twice of the amplifier operation frequency assuming the typical gain roll-off of -6 dB/octave. If losses and possible mismatches are taken into account, the required device operation frequency will be even higher.

Such strong dependence of the amplifier operation frequency on the device speed naturally renders the amplifiers based on III-V technologies highly competitive for terahertz applications. Figure 7 shows the performance of a 3-stage amplifier recently reported by JPL [10], which is based on a 35-nm InP HEMT technology. It shows the power gain of around 15 dB for the frequency range of 300 – 345 GHz, which is the highest operation frequency as of today for any amplifier based on semiconductor.

One variant of amplifiers, LNA, is a key component in receivers as mentioned earlier, but reports on LNA operating at multiple hundred GHz range are rare due to the difficulty in the noise measurement. JPL reported an LNA based on a 35-nm InP HEMT technology, for which NF was measured to be 7.5 dB at a single frequency point of 270 GHz [11]. Another LNA reported by Fraunhofer Institute, which is based on a 100 nm GaAs metamorphic GaAs technology, exhibited NF of around 9.4 dB (or 7.4 dB when transition and bond wire loss is subtracted) for frequency range between 180 and 213 GHz [12].

The operation frequency of Si-based amplifiers continues to grow as well. Figure 6 shows the circuit schematic, die photo, and measured performance of 140 and 170 GHz SiGe HBT amplifiers by University of Toronto [13]. The 5-stage cascode amplifiers show the gain around 15 dB based on SiGe HBTs

with f_T and f_{max} of 260 and 340 GHz, respectively. One may notice the compact size of the circuit shown in Fig. 8, which is 200×400 μm^2 without the probing pads. The small size is impressive especially when compared with the complexity of the circuit that includes a plenty of inductors. In fact, this is a good example of the general trend of circuit area reduction with increasing operation frequency, which can be attributed to the shorter wavelength as well as the smaller inductance and capacitance required to achieve a certain value of reactance.

B. Oscillators

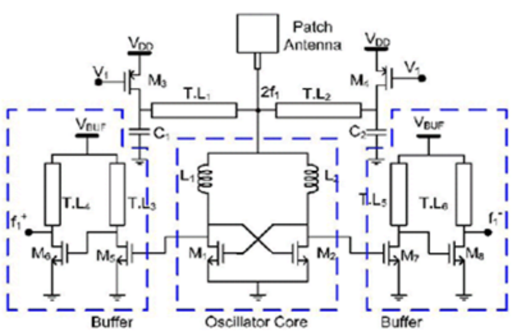
Required device operation frequency for oscillators is not as stringent as for the case of amplifiers. A gain barely enough to compensate for the loss along the feedback loop in oscillators suffices for triggering oscillation. Besides, not only the fundamental but also harmonic oscillation frequencies are available at the output. This makes it possible to obtain oscillation frequencies even larger than the device cutoff frequency when properly designed.

In terms of the fundamental oscillation, 346 GHz is currently the highest frequency reported so far, which is from Northrop Grumman Company [14]. Based on a 35-nm InP HEMT technology, this oscillator is based on the common gate topology with CPW (CoPlanar Waveguide) series feedback, exhibiting the output power of -16 dBm.

Push-push oscillators are widely adopted for high frequency application as it takes the second harmonic at the output while effectively suppressing the fundamental oscillation. For this type of oscillators, a 410 GHz oscillator based on 45-nm Si CMOS technology was reported in 2008 by University of Florida [15]. The circuit schematic and output spectrum are shown in Fig. 9. In fact, this is the highest oscillation frequency in the open literature as of today from any type of oscillator from any semiconductor technology. It is especially surprising that such outstanding performance was achieved with a Si CMOS technology. Although the output power is rather small, -47 dBm, partly due to the fact that it is the second harmonic, the result clearly demonstrates the great possibility of applying Si technology for terahertz systems. One may notice from Fig. 9 that a patch antenna is integrated in the circuit, which was included to radiate the oscillation power to the free space to measure the signal without RF probing but with a bolometer. Such measurement approach was necessary since the highest frequency level for commercial RF probes was 325 GHz at the time of the measurement. One year after the report, 500 GHz RF probes is now commercially available.

C. Mixers

Mixers have been a popular circuit block for the very first stage in the traditional terahertz heterodyne receivers based on diodes to provide the downward frequency conversion to ease the signal detection. However, they were inherently passive



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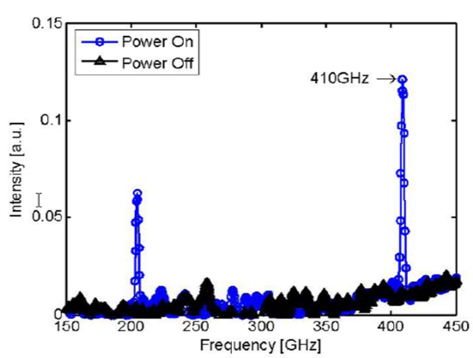
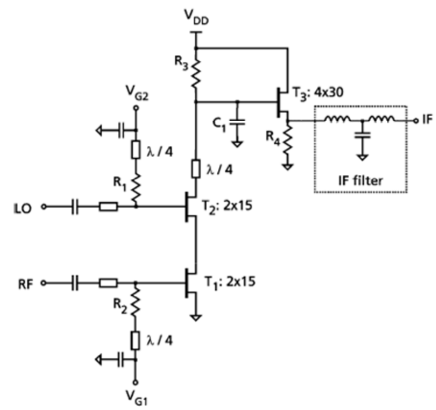


(b)

Fig. 9. 410 GHz push-push Si CMOS oscillator: (a) circuit schematic; (b) Measured output spectrum [15].



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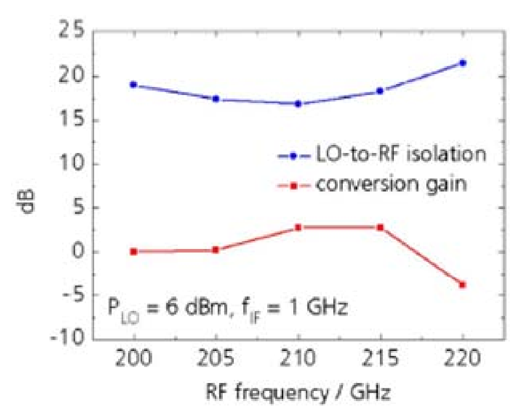

(b)

Fig. 10. 210 GHz 0.1 μm GaAs metamorphic HEMT mixer: (a) circuit schematic; (b) Measured gain and isolation [16].

mixers and the performance was limited as described earlier. Active mixers operating at the multiple hundred GHz frequency range are still rare and only limited number of results have been reported.

A mixer reported by Fraunhofer Institute based on a 0.1 μm GaAs metamorphic HEMT technology shows a positive conversion gain of 2.8 dB at 215 GHz [16]. The mixer, which also exhibits an LO-to-RF isolation of 18.3 dB, is currently the only mixer that shows a positive gain beyond 200 GHz. Figure 10 shows the circuit schematic and the measurement results. Although the record operation frequency of mixers is not as high as those of amplifiers and oscillators, it is expected to grow in the near future with the continuous advance of device technology.

IV. CONCLUSION

In this work, the current status of the semiconductor device technologies and circuits for terahertz applications was reviewed. Wireless communication systems based on the terahertz band is on the horizon for broadband communication applications, and we can expect such systems will be a reality before long when the current performance trend of the semiconductor technologies and circuits is considered. At the same time, it is envisaged that the terahertz communication applications will be a major driving force for the growing 'upward' approach to the development of the terahertz band.

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