Design of THz signal generation circuits using 65nm CMOS technologies

Hyeong Jin Kim and Jin Ho Jeong
Department of Electronics Engineering, Sogang University
E-mail: jjeong@sogang.ac.kr

***Abstract* - In this paper, we present THz signal generation circuits in 65 nm CMOS technologies. All the designed circuits are verified by simulations. A push-push oscillator is designed for a THz signal generation, which has output frequency of 300 GHz and output power of -7.4 dBm. THz on-chip antennas are designed to radiate the signal generated by the oscillators. The simulation results of the designed CMOS loop antenna show the gain of 4.19 dB and radiation efficiency of 70 % at 260 GHz. In order to couple the oscillator to the waveguide, E-plane probe waveguide-to-micro-strip transition is designed to have the simulated insertion loss of 2.1 dB and bandwidth of 118 GHz around 280 GHz.**

***Keywords*–E-plane probe transition, Micro-strip transition, Push-push oscillator, THz signal generation circuits, THz on-chip antenna**

I. INTRODUCTION

Recently, integrated circuits (ICs) operating in terahertz (THz) frequencies such as amplifiers, mixers, oscillators, and detectors have been successfully reported using heterojunction transistors (HBTs) or high-electron mobility transistors (HEMTs) [1]–[5]. The frequencies above 275 GHz have the potential to achieve ultrahigh-speed wireless communication because a wide unallocated frequency band is available. It is challenging to realize a CMOS transmitter or source modules operating above 275 GHz because the maximum operating frequency f_{max} of an NMOSFET of a recent bulk CMOS process is comparable to or below that frequency. However, the rapid progress of CMOS technology by geometry scaling and traditional performance improvements have made circuits operating above 100 GHz feasible. Therefore, sub-harmonically designed circuits can be used in THz systems or modules.

THz antenna is an essential component for composing THz source module. In THz bands, horn antenna or on-chip antenna is widely used. Horn antennas can have broad bandwidth and high gain, but need machining process for fabrication and need waveguide-to-micro-strip transition to connect to ICs. On-chip antennas have advantages that it is easy to fabricate and don't need bondwire and waveguide-to-micro-strip transitions for connecting to THz ICs. However, most of the THz on-chip antennas have problems of low radiation efficiency and narrow bandwidth, which are caused by increased losses from conductors and very thin thickness of substrate between antenna and ground plane. Standard rectangular CMOS on-chip patch antennas have shown fractional bandwidth and radiation efficiency less than 10% [6].

THz ICs are generally fabricated using planar transmission lines such as micro-strip lines or grounded coplanar waveguides (GCPWs). In THz system, waveguide in/output flanges are widely used, because they are easy to fabricate and have low loss. Therefore, transitions from waveguide-to-micro-strip or GCPWs are essential to package THz ICs in the waveguides for module and system applications. Various types of waveguide-to-micro-strip transitions, such as E-plane probe, dipole antenna, fin-line, SIW, are reported [7]–[12]. E-plane probe transition is widely used because of its small circuit size and broad band characteristics. In this paper, we designed new E-plane probe transitions which solve the problems that conventional one has.

In this paper, the designs of THz oscillator, broad-band on-chip antennas, and on-chip waveguide-to-micro-strip transition are presented. In addition, THz source modules are designed by combining these circuits. The proposed circuits are designed using 65-nm CMOS technologies, and verified by simulations.

II. DESIGN OF THz CIRCUITS

A. 300 GHz Push-push oscillator

For designing oscillators have its fundamental oscillation frequency of 300 GHz, proper selection of the topology is required, and because of the oscillation frequency is higher than the f_T/f_{max} of the device. At first, we consider designing a fundamental oscillator, because of its high output power.

a. Corresponding author; jjeong@sogang.ac.kr

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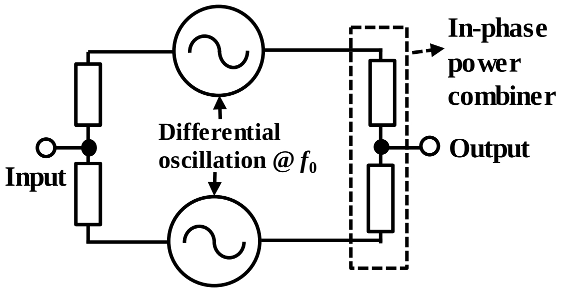


Fig. 1. Designed push-push oscillator using two fundamental oscillators.

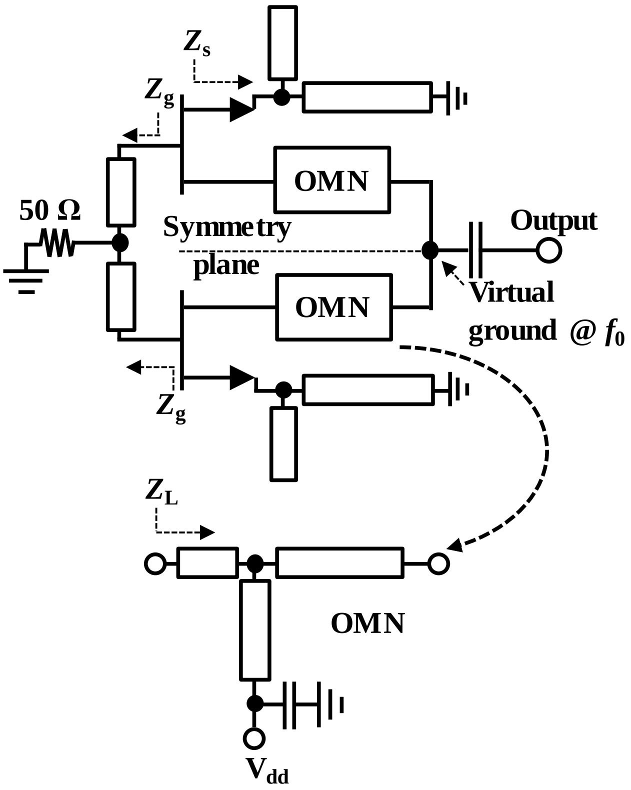


Fig. 2. Schematic of push-push oscillator using 65 nm CMOS process.

However, oscillation condition can be hardly met at 300 GHz among the combinations of the values of gate and source impedances (Z_g and Z_s), and feedback network can be hardly implemented.

To solve this problem, we decide to design push-push oscillator. The push-push oscillator is composed of two fundamental oscillators as shown in Fig. 1. The output ports of the two oscillators are connected and fundamental components(f_0) are canceled out and second harmonic components ($2f_0$), which is used as output frequency, are added constructively. Due to the its operation principles, oscillation condition of push-push oscillator should be met at f_0, and output networks are designed considering fundamental oscillation condition and output power combining. Push-push oscillator has the advantage that it can get output frequency over f_T, but the output power of it is much lower than the fundamental oscillators have same output frequency.

Fig. 2 shows the schematic of the proposed push-push oscillator. Two identical series feed-back oscillators are designed to oscillate at 150 GHz. The gate and source impedances are swept to find its optimum values meeting the oscillation condition at 150 GHz. The values of Z_g and Z_s are chosen to be j65 Ω and –j150 Ω, respectively. To implement these impedances at each ports, gate and source feedback networks were designed. The source feedback network is composed of $\lambda_g/4$-long short stub for biasing and open stub for implementing Z_s, and gate feedback network is designed using simple micro-strip lines. The output matching network is designed to provide load impedance (Z_L) of 35+j15 Ω at 150 GHz for meeting oscillating condition. The push-push oscillator is constructed by connecting two 150 GHz oscillators differentially, as shown in Fig. 2.

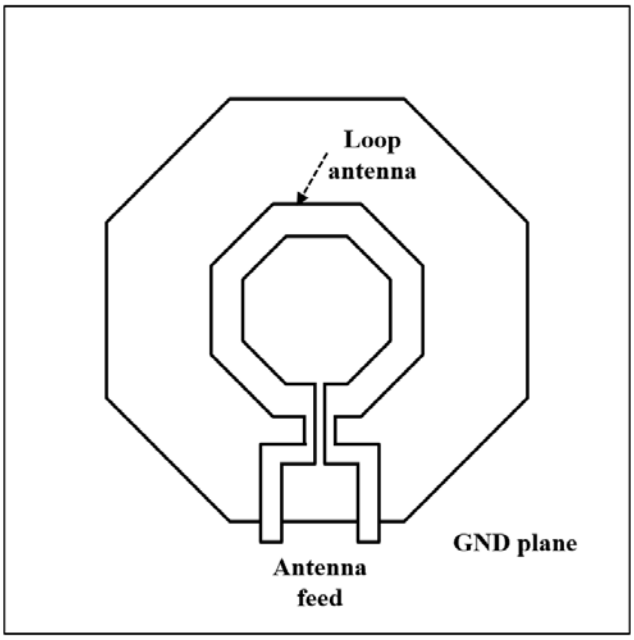


Fig. 3. Structure of the designed CMOS loop antenna.

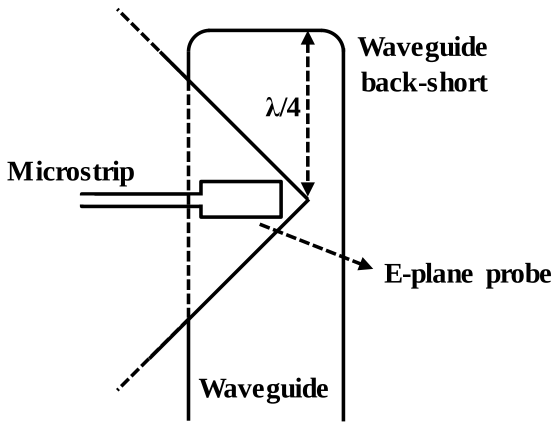
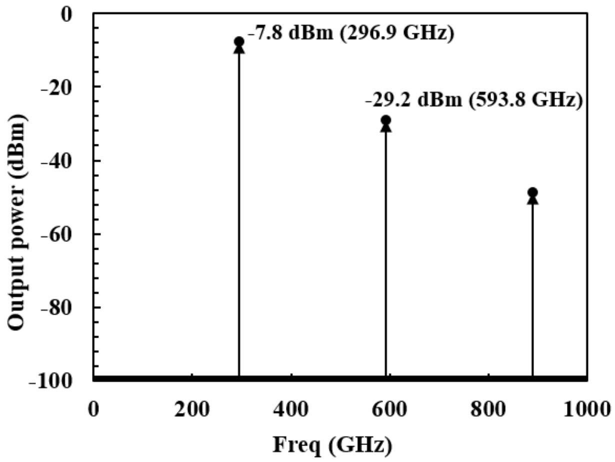


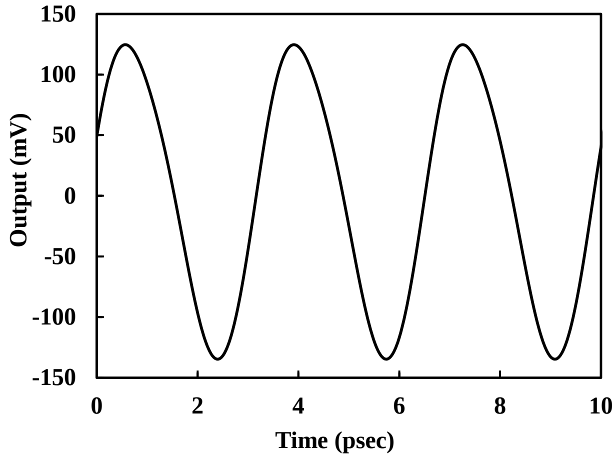
Fig. 4. Structure of designed E-plane transition.

B. THz on-chip antennas

Fig. 3 shows the structure of the designed on-chip loop antenna. The main reasons for the high losses of the THz on-chip patch antennas are metallic loss and thin substrate



(a)



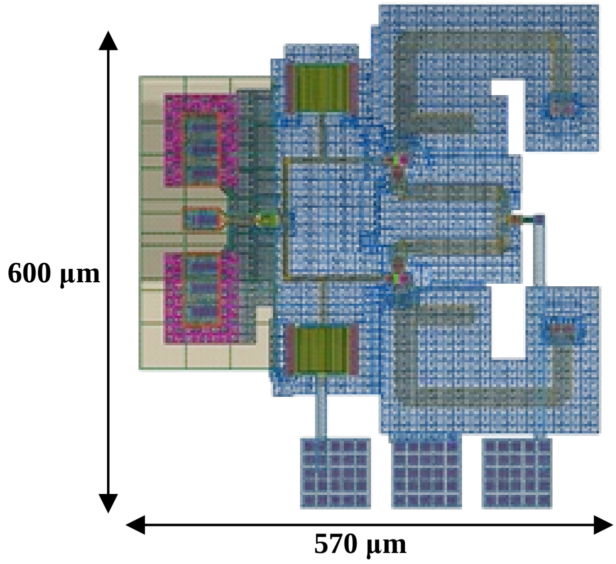
(b)

Fig. 5. Simulation results of the designed push-push oscillator. (a) Output power spectrum. (b) Output voltage waveform.

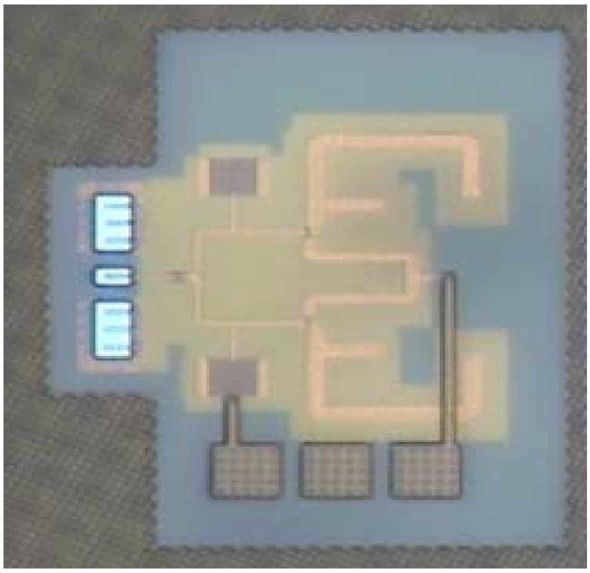
thickness between patch and ground plane. However, loop antenna is known as one of the antenna has high efficiency, because its ground plane is removed and metallic losses and substrate loss can be reduced. It is almost impossible to measure the characteristics of the loop antenna with on-wafer probing because of its no-ground plane structure. To solve this problem, we decided to combine the loop antenna with push-push oscillator.

C. THz on-chip waveguide-to-micro-strip transition

Among many kinds of waveguide-to-micro-strip transition topologies, E-plane probe transition is widely used in THz band, because of its small size and the easy of fabrication. The probe is inserted into the waveguide through the channel which is at the side wall of the waveguide, and placed on the E-plane. The probe is placed at the point apart from approximately $\lambda g/4$ from the waveguide backshort. Because of the direction of the channel is normal to the direction of the waveguide propagation, input and output ports of the waveguide are not aligned and input and output waveguides



(a)



(b)

Fig. 6. Designed THz CMOS push-push oscillator. (a) Layout . (b) Photograph.

are needed to be bended for the port alignment.

The E-plane probe transitions can be fabricated both on-chip and off-chip. By using on-chip transitions, there is no need to use bonding wire for connecting THz ICs to waveguide-to-micro-strip transition. However, on-chip transitions suffer from its limitation of circuit size, because the circuit should be small enough to get into the channel, and the size of channel should be small enough to maintain propagation mode of the waveguide. Because of this, the circuit size can't be bigger than the channel size. To solve this problem, off-chip transition or dry etching process can be used but it accompanies parasitic effects and additional expenses.

To solve these problems, we proposed a new structures of the on-chip E-plane probe transition as shown in Fig. 4. The on-chip probe is placed at the corner of the ICs and the corner

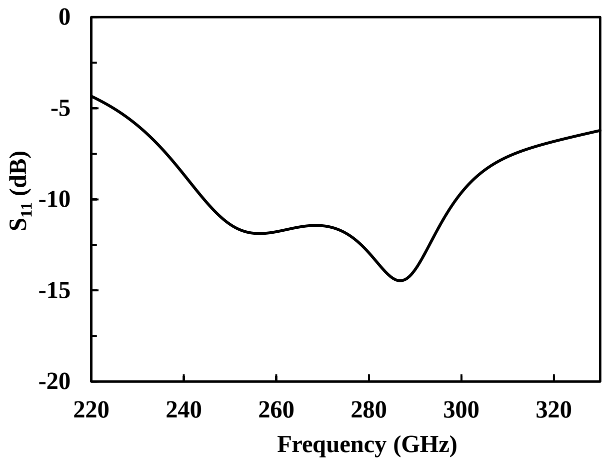


Fig. 7. Simulated reflection coefficient of the designed loop antenna .

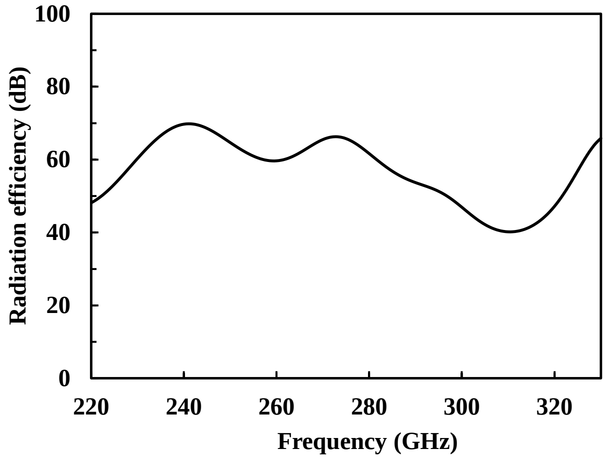


Fig. 8. Simulated radiation efficiency of the designed loop antenna

of the ICs is inserted into the waveguide. By this way, the channel size can be fixed regardless of the IC size.

III. SIMULATION RESULTS AND FABRICATION

A. 300 GHz Push-push oscillator

Fig. 5 shows the simulation results of the designed push-push oscillator. The simulation results show fundamental oscillation frequency of 150 GHz and -7.8 dBm of output power and transient of designed oscillator. Fig. 6 shows the layout of the designed oscillator and photograph of the fabricated circuit. The designed oscillator has size of 600 μm × 570 μm.

B. THz on-chip antennas

Fig. 7 and Fig. 8 show the simulation results of the designed on-chip loop antenna. The simulation results showed radiation efficiency of 70 % (240 GHz) and 10-dB fractional bandwidth of 21.6 %. Fig. 9 show the radiation pattern of designed on-chip loop antenna. It radiates power in –z direction. The peak directivity and gain are 6.59 dBi (260 GHz) and 4.41 dBi (240 GHz). Fig. 10 shows the layout of the designed on-chip loop antenna of the fabricated circuit. The designed loop antenna has size of 1000 μm × 1000 μm.

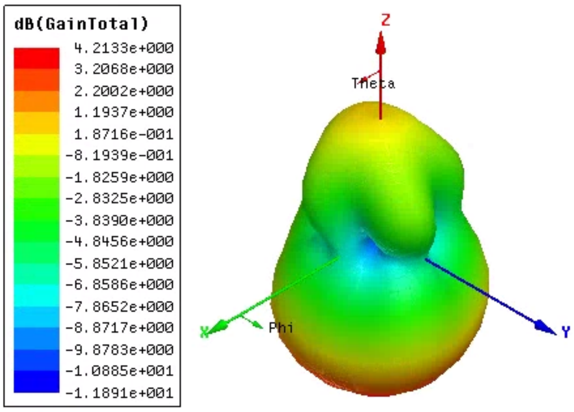


Fig. 9. Radiation pattern of the designed loop antenna at 260 GHz

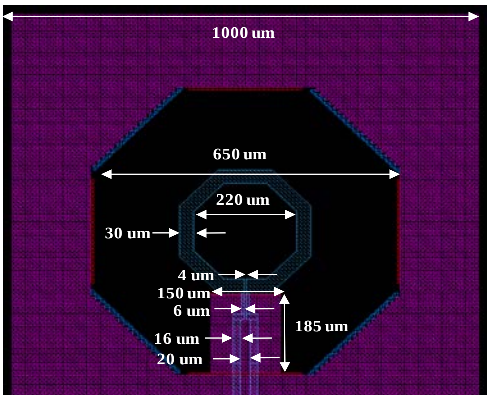


Fig. 10. Layout of the designed loop antenna.

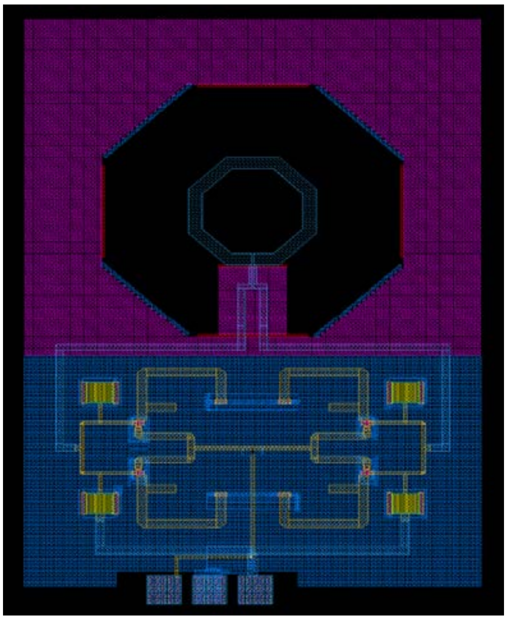


Fig. 11. Layout of the designed THz signal generation circuits with loop antenna and differential oscillator.

Fig. 9 shows the gain pattern of the designed on-chip loop antenna. The loop antenna radiates power in the –Z axis direction.

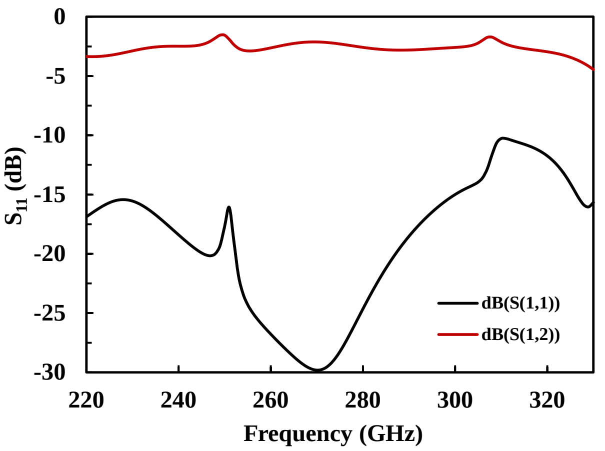


Fig. 12. Simulation results of the designed on-chip E-plane probe transition.

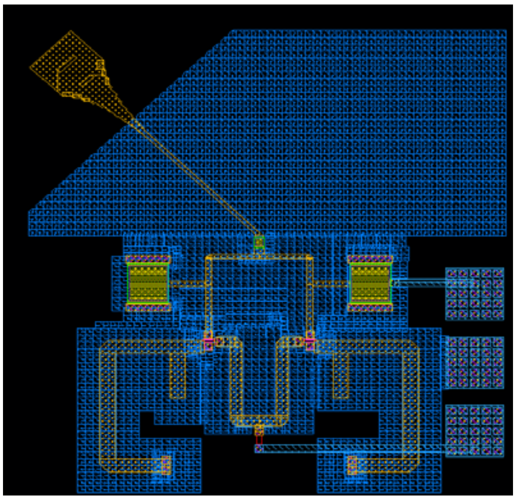


Fig. 13 Layout of the designed THz signal generation circuit with transition and oscillator.

C. On-chip waveguide-to-micro strip transition

Fig. 12 shows the simulation results of the designed on-chip E-plane probe transition. The simulation results was back-to-back insertion loss of 2.56 dB. Fig. 13 shows the layout of the designed on-chip E-plane probe transition of the fabricated circuits. The designed E-plane probe transitions have sizes of 1,000 μm × 600 μm.

IV. DESIGN OF THz SOURCE CIRCUITS

THz source circuits were designed by combining designed THz ICs. Fig. 13 shows the layouts of circuits for THz source. Fig. 13 shows layouts of THz source circuits which is composed of push-push oscillator and on-chip E-plane probe waveguide-to-micro strip transition. The circuit size is 615 μm × 675 μm, and WR-03 horn antenna will be combined with the waveguide source module. Fig. 11 shows another layout of THz source circuit. This circuit is composed of push-push oscillator and on-chip loop antenna.

V. CONCLUSIONS

In this paper, we designed THz circuits using 65-nm CMOS technologies. Push-push oscillators are designed as a THz sources, and its simulation results show output power of dBm and output frequency of 300 GHz. High efficiency THz on-chip antenna was also designed. To improve the bandwidth and radiation efficiency of the on-chip antenna, we designed terahertz on-chip loop antenna. The simulation results show antenna gains of 4.41 dB, and radiation efficiencies of 70 %. To mount THz circuits on waveguide module, THz on-chip waveguide-to-micro-strip transitions were designed. The proposed waveguide-to-micro-strip transitions have advantages that it can be used regardless of the size of the circuits which is connected to the transition. The simulation results show insertion loss of dB and bandwidth of GHz. Finally, we designed CMOS THz source modules by combining each aforementioned THz circuits.

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Hyeong Jin Kim received the B.S. degree in electronics engineering from Sogang University, Seoul, Korea, in 2016. He is working on his M.S. degree in electronics engineering at Sogang University, Seoul.

His research interest include monolithic microwave integrated circuits, THz integrated circuits, and THz antennas.

Jin Ho Jeong (S′00–M′05) received the B.S., M.S.,and Ph.D. degrees in electrical engineering from Seoul National University, Seoul, South Korea, in 997, 1999, and 2004, respectively. From 2004 to 007, he was in the University of California at San Diego, La Jolla, CA, USA, as a Postdoctoral Scholar, where he was involved with the design of highefficiency and high-linearity RF power amplifiers. In 2007, he joined the Department of Electronics and Communications Engineering, Kwangwoon University, Seoul. Since 2010, he has been with the Department of Electronic Engineering, Sogang University, Seoul. His research interests include monolithic microwave integrated circuits, THz integrated circuits, high-efficiency/high-linearity power amplifiers and oscillators, and wireless power transfers.