A 400 GHz Transmitter Integrated with Flip-chipped 3D Printed Horn Antenna with an EIRP of 1.26 dBm

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Abstract—This paper presents a 400 GHz radiating source in 28 nm CMOS technology with a 3D printed horn antenna directly mounted on-top of a on-chip waveguide feed. The CMOS chip is composed of two mutually-coupled triple-push oscillators and a differential microstrip to waveguide transition. A custom horn antenna is mounted on top of this waveguide feed, enabling an efficient and high gain output. The horn antenna is fabricated using a two-photon lithography 3D printing process. The part is metallized with platinum and copper through physical vapor deposition and electroplating. The measured EIRP of the fully integrated system is 1.26 dBm which is 13 dB higher then the EIRP of the standalone transmitter.

Index Terms—CMOS, 3D printed, Horn Antenna, waveguide feed

I. INTRODUCTION

Sub-millimeter wave and THz electronics are getting increasingly more attention in literature with many interesting applications in imaging. Traditionally the active components of THz systems have been made in III-V technologies and these chips are then packaged in split block waveguides [1]. Although these systems show high performance, the cost and bulky sizes, severely limit the transition to cheap consumer products and wide spread use of application with THz waves. This paper proposes a fully packaged 400 GHz THz source which combines a 28 nm CMOS transmitter together with a 3D printed horn antenna (Fig. 1). The CMOS transmitter consists of differential triple push oscillator from which the third harmonic is extracted. This third harmonic signal is then fed to a differential on-chip waveguide feeding structure. The waveguide port of the 3D printed horn antenna is aligned directly on top of the chip providing a low loss transition maximizing the output power of the system.

II. SYSTEM OVERVIEW AND DESIGN

Figure 2 shows the proposed triple-push oscillator [2]. Essentially the oscillator is a three stage ring oscillator where the oscillating frequency is mainly determined by the capacitive parasitics of the transistors and by the drain inductors which are implemented in the form of microstrip lines. At the node where the drains are connected together, there is a virtual ground at the first harmonic due to the fact that the three stages oscillate with a phase difference of 120 deg between them. The currents of the third harmonic however add up in phase at this point making it the ideal extraction point for the

Fig. 1: Overview of the designed and fabricated system: A 400 GHz signal is generated by means of a triple-push oscillator and feed to a 3D printed horn antenna through a coupled microstrip to waveguide transition.

third harmonic. To increase the output power, the oscillator is duplicated and these two oscillators are coupled together to oscillate out of phase. The coupling is established by replacing the gate inductors at one of the stages by a directional coupler. The system is implemented in a 28 nm CMOS technology with 6 thin metal layers and 3 moderately thick metal layers. M1 to M6 are used to form the ground plane. Each of these layers is made into a grid in order to comply with the maximum metal density DRC requirements. The signal

Fig. 2: Circuit overview of the CMOS chip: Two triple push oscillator are coupled together through a directional coupler. At the common drain connection of each oscillator, the third harmonic is extracted. This signal is coupled into a waveguide with a differential patch antenna.

traces were implemented in the top metal layer (M9) and M8 was used as a bridge layer. The transistors were implemented using 40 fingers each with a width of 500 nm. In simulation the oscillator provides -8.38 dBm of output power and has a oscillation frequency of 416 GHz

The differential output from the oscillators is fed to a on-chip microstrip to waveguide transition inspired by [3]. This transition consists of a main patch, a shorted parasitic patch and a ground ring. The signal is fed through a hole in the ground ring to the non radiating side of the main patch. A $20\mu\text{m}$ deep shallow slot is left out in the waveguide port of the 3D printed antenna such to not disturb the differential microstrip feed but not so deep that waves leak out of the waveguide feed (Fig. 1). The main patch has a length of $170\mu\text{m}$ and a width of $210\mu\text{m}$. The center line of the main patch is used as the connection point for the supply of the oscillators. Both patches are implemented in the top aluminum layer and the ground plane is implemented in M1 to M4, to maximize the distance between the patches and ground and thus the bandwidth. The waveguide feed has a width of $500\mu\text{m}$ and a height of $200\mu\text{m}$ which is co-designed with the patches to provide optimal coupling. Ideally the inside dimensions of the ground ring would have the same dimensions as the waveguide feed. Unfortunately, due to DRC requirements, the opening in the passivisation layer of the chip has to be slightly smaller then the aluminum layer forcing the dimensions of the

Fig. 3: Simulated S11 (red dashed line) and S21 (blue line) of the differential microstrip to waveguide coupler

ground ring to be 494 by $183\mu\text{m}$. Figure 3 shows the transition loss of the coupling structure.

The waveguide feed transitions in a pyramidal horn antenna. The horn length is $2630\mu\text{m}$ long and the flare is $2700\mu\text{m}$ wide and $2070\mu\text{m}$ high. The total size of the horn antenna is mainly determined by the printing volume of the manufacturing machine (about $3\times 3\times 3\text{mm}$). In simulation the gain at 416 GHz of horn antenna including the waveguide feed is 14 dB whereas the gain of the system without the horn antenna mounted on top is 1.5 dB. To enable good adhesion of the copper to the 3D printed structure, most sharp edges were rounded over.

III. HORN ANTENNA FABRICATION

The horn antenna is fabricated through a two-photon lithography 3D printing process. Two-photon lithography is similar

(a)

(b)

Fig. 4: Fabricated System: (a) Pcb with horn antenna glued on-top of the chip. (b) chip photograph

TABLE I: COMPARISON WITH PRIOR WORK

Ref.	Freq. (GHz)	P _{out} (dBm)	EIRP (dBm)	P _{DC} (mW)	CMOS node
This work	404	-12.14	1.26*	72	28nm
[6]	340.1	-9.1	-19.6	78.3	40nm
[5]	475-511	-15.3	-4.1*	17.1	40nm
[7]	448	-1.34	-10.6	92.2	65nm

*Use lens or packaged antenna.

to SLA and DLP printing processes as it uses a UV photo-sensitive resin and light to form the structure of the desired part. The main difference is that two-photon lithography makes use of a femtosecond pulsed infrared laser. Only at its focus point the intensity is high enough that two infrared photon get absorbed locally yielding the same effect as a single UV photon and thus locally curing the resin. This allows to realize very highly accurate parts with feature sizes up to 150 nm. The machine used for the 3D printing is the commercially available Photonic Professional GT from Nanoscribe. After 3D printing the part, the remaining uncured photo resin is dissolved in a similar way as with SLA printing. The part is then coated with a 200 nm thin layer of platinum through physical vapor deposition. This conductive seed layer can then be used to electroplate a layer of 7 μm of copper.

The horn antenna is accurately positioned on-top of the chip by means of a Finetech micropositioner and then glued into place with epoxy. The fabrication process is discussed in detail in [4].

IV. RESULTS AND MEASUREMENTS

A picture of the fully fabricated system can be seen in figure 4. The size of the chip is $900\mu\text{m} \times 440\mu\text{m}$ including the bondpads. The EIRP of the system is measured prior and post packaging of the horn antenna. The chip is placed at a distance of 11 cm from a VDI spectrum analyzer extender to ensure that the far field condition is met. The received power is observed on a R&S spectrum analyzer. The EIRP can be easily calculated, after deembedding the conversion losses in the VDI SAX and the free space path loss using the methods described in [5]. Figure 5 shows the EIRP in function of frequency, where the frequency is swept by changing the Vdd voltage from 0.85 to 1 V. The red dashed curve is the EIRP of the chip without the horn antenna mounted on top, whereas the blue curve is the EIRP with horn antenna. An increase of EIRP of about 13 dB is observed with a maximum EIRP of 1.26 dBm. The output power of the oscillator is estimated to be -12.14 dBm when using the simulated antenna gain of 13.46 dB at 404 GHz is used. This gain is including the microstrip to waveguide structure. Fig 6 shows the radiation pattern of the system including horn antenna. Table I summarizes the measured performance and provides comparison with prior works. the measured system has the highest EIRP among single source CMOS transmitters in its frequency band.

Fig. 5: EIRP measurement of the system with (blue curve) and without (red dashed curve) the horn antenna. The frequency is altered by changing the Vdd from 0.85 to 1 V. An increase of 13 dB in the EIRP is observed with the horn antenna. A maximum of 1.26 dBm EIRP is measured.

Fig. 6: Measured radiation pattern of the system including horn antenna

V. CONCLUSION

A 400 GHz source is presented with a EIRP of 1.26 dBm. The source consists of a CMOS transmitter with a on-chip coupled microstrip to waveguide transition. A 3D printed horn antenna is placed on-top of the chip providing an efficient and high gain output.

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