High-Efficiency Horn Antenna Using Solder Balls for Seamless Package with Millimeter-Wave 3D Chips

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***Abstract*—This paper presents a millimeter-wave (mmWave) horn antenna to be inherently integrated with three-dimensional integrated circuits (3D ICs). Compared with conventional in-package antennas which usually require separate chips or substrates, the designed horn efficiently uses the redundant metal solder balls between two chips/substrates. Therefore, this horn antenna neither occupies an alone chip nor increases the footprint of the 3D module. Different from substrate integrated waveguide horns, it also does not have dielectric filling inside, and subsequently features high efficiency (92%), high gain (~10dBi), as well as wide bandwidth (32GHz) at 135GHz. Moreover, this horn antenna uses a simple solder ball as its feeding to interconnect with ICs. This configuration significantly alleviates the high insertion loss between mmWave antenna and ICs, and realizes their packaging in a seamless way.**

***Index Terms*—3D chip, horn antenna, millimeter-wave, system-in-package, through silicon via, solder ball.**

I. INTRODUCTION

Millimeter-wave (mmWave) technology has been attracting world-wide interests from academic, research, and industry communities [1], because it significantly benefits high-speed wireless communication (tens of Gigabit per second or faster), high-resolution imaging, automotive radars, biomedical and military applications, etc.

Recently, many millimeter-wave chips emerge to meet above applications. Nevertheless, some challenging issues exist and slow down the development. One main challenge is that, how to realize a high-performance antenna and efficiently connect it with integrated circuits (ICs) to form a complete mmWave system? A straightforward way is implementing an on-chip antenna to be inherently integrated with circuits on the same chip. This system-on-chip (SoC) approach sounds interesting. Unfortunately, mainly due to the loss silicon substrate with high permittivity (ε_r = 11.9), on-chip antennas typically suffer low radiation efficiency (~10%) and low gain (<0dBi) [2]-[4]. On the other hand, in-package antenna features better performance [1], [5]. But it is challenging to efficiently integrate the antenna with ICs to form a two-demenional system-in-package (2D SiP). For example, if we use bonding wire to connect antenna with ICs, even its length is as short as 60um, this wire will add high loss up to 25dB at 150GHz [6]. Alternatively, three-dimensional (3D) SiP using through-silicon via (TSV) technology [7]-[8] opens a door to solve the above integration issue. As shown in our previous research [7], TSV pair features low transmission loss within 0.4dB up to ~150GHz. Nevertheless, the antenna presented in [8] still has limited efficiency and requires a separate die.

This paper presents a planar horn antenna which has radiation efficiency up to 92% and does not increase chip area or system footprint. In addition, it radiates along the horizontal direction, and therefore greatly facilitates side-by-side communication [9]. Moreover, this antenna with its TSV-based 3D SiP configuration makes it possible to integrate electronics, microelectromechanic system (MEMS), and photonics circuits in a single 3D chip [10].

II. HORN FOR TSV-BASED 3D SIP

Many different antennas have been reported for compact mmWave systems. They are mainly categorized as on-chip antennas and in-package antennas.

A. Reported antennas for SoC and 2D SiP

References [2]-[4] have reviewed on-chip antennas and summarized their advantages and disadvantages. As an example, Fig. 1 (a) shows an antenna inherently integrated with a 60GHz receiver in 90nm CMOS [11]. The whole silicon design has a small chip area of 3.8 mm^2. However, the antenna still suffers gain of around -2dBi and simulated efficiency of 20%, although it performs better than many other typical on-chip antennas [2]-[4]. This antenna therefore seriously limits the communication distance near 5cm only [11].

Meanwhile, in-package antenna performs much better. Fig. 1 (b) presents IBM's 7dBi cavity-backed folded dipole antennas, which is mounted together with a 60GHz transmitter chip onto a printed circuit board (PCB) [1]. The antenna is designed and fabricated separately, and also occupies a footprint larger than that of the transmitter chip.

We have also designed a wide slot antenna as illustrated in Fig. 1 (c) [8]. The in-house fabricated antenna prototype presents a measured gain near 6dBi. Again, this design still requires additional processes to etch a cavity and then fill it

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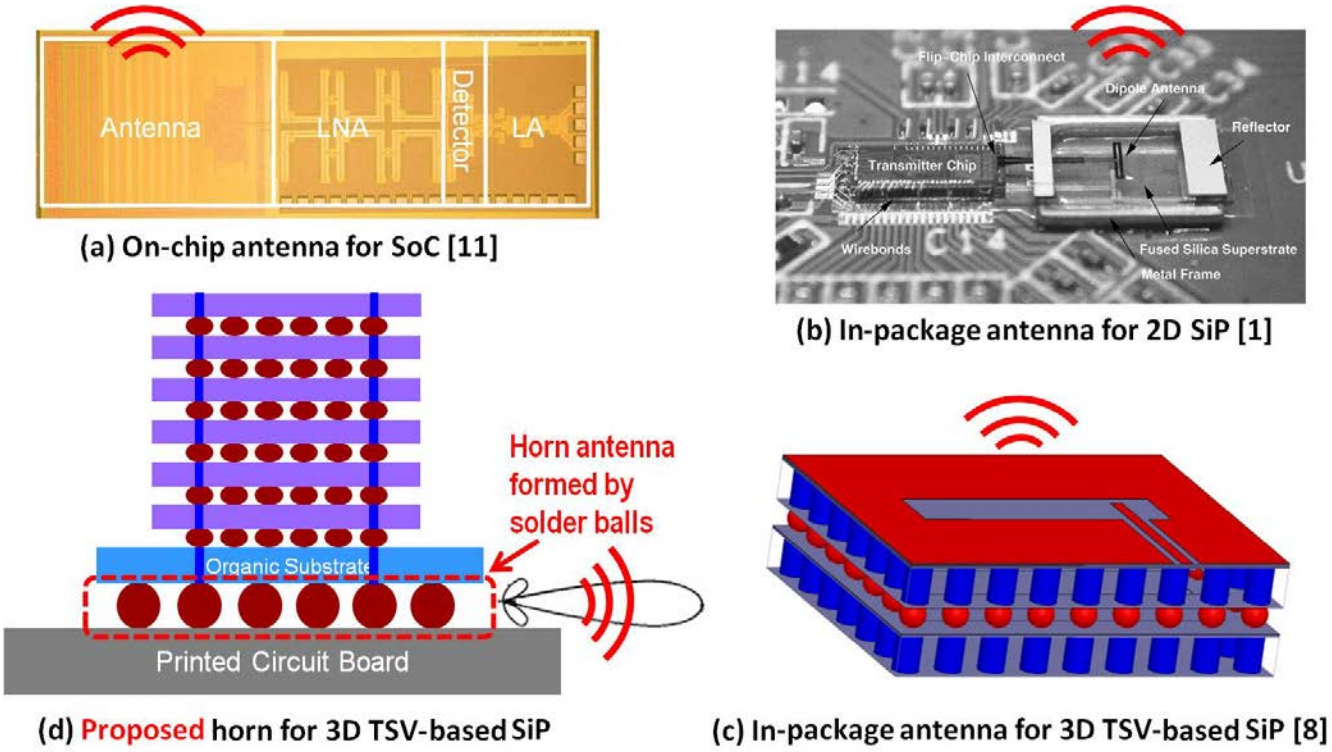


Fig. 1. Different on-chip and in-package antennas for mmWave systems. Figs. 1 (a), (b), and (c) are reproduced from references [11], [1], and [8]. Their copyright belongs to IEEE and John Wiley & Sons, respectively.

using other dielectric material. Moreover, it needs a separate chip and locates the top layer where may be reserved for other devices such as sensors.

B. Proposed horn antenna for 3D SiP

To avoid or alleviate above issues, TSV-based 3D SiP provides a good option. TSV technology shows its great potential for numerous applications which range from 3D memory to millimeter-wave system-in-package [8], because the TSV technology not only empowers chips with high capacity, high speed as well as low power consumption, but also facilitates heterogeneous integration of different functional blocks. For example, in the 3D SiP illustrated in Fig. 1 (d), different functional dies which may include electronics, photonics, and even MEMS devices can be fabricated using different processes, and then stacked together using TSVs and microbumps. These stacked dies are then mounted on the organic substrate which works as a passive interposer to match the different-sized balls/bumps used for PCB/silicon dies.

In this 3D SiP, a horn antenna, which typically features high gain and high radiation efficiency, can be simply realized using some redundant metal solder balls between PCB motherboard and organic substrate. Fig. 2 illustrates the detailed configuration of the proposed horn antenna.

Different from the horns reported in [12] and [13], this antenna is formed by neither etching nor micromachining, but only the ordinary metal solder balls. Therefore, the fabrication

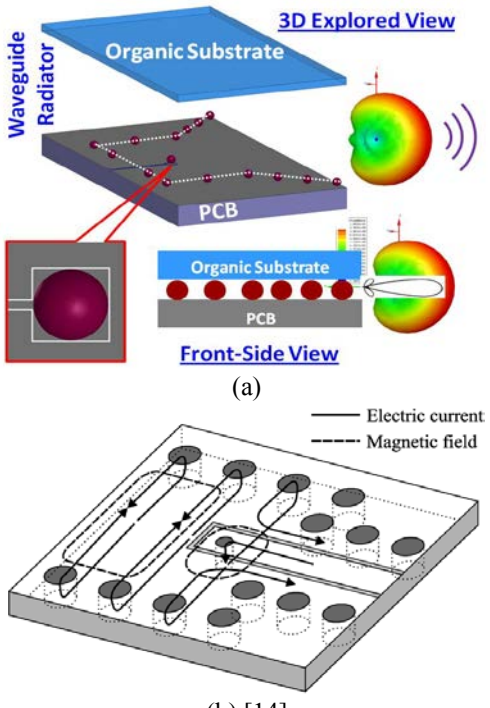


Fig. 2. Detailed configuration of the proposed horn antenna: (a) 3D view and front-side view; and (b) excitation mechanism of the antenna, i.e., using one single ball as a current probe which was studied in [14].

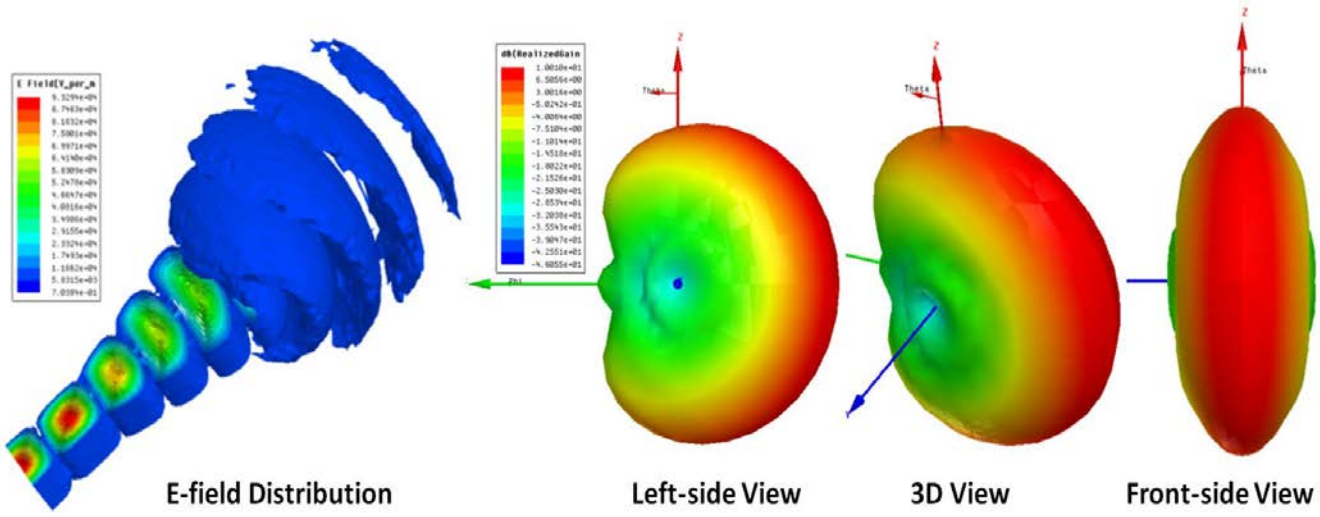
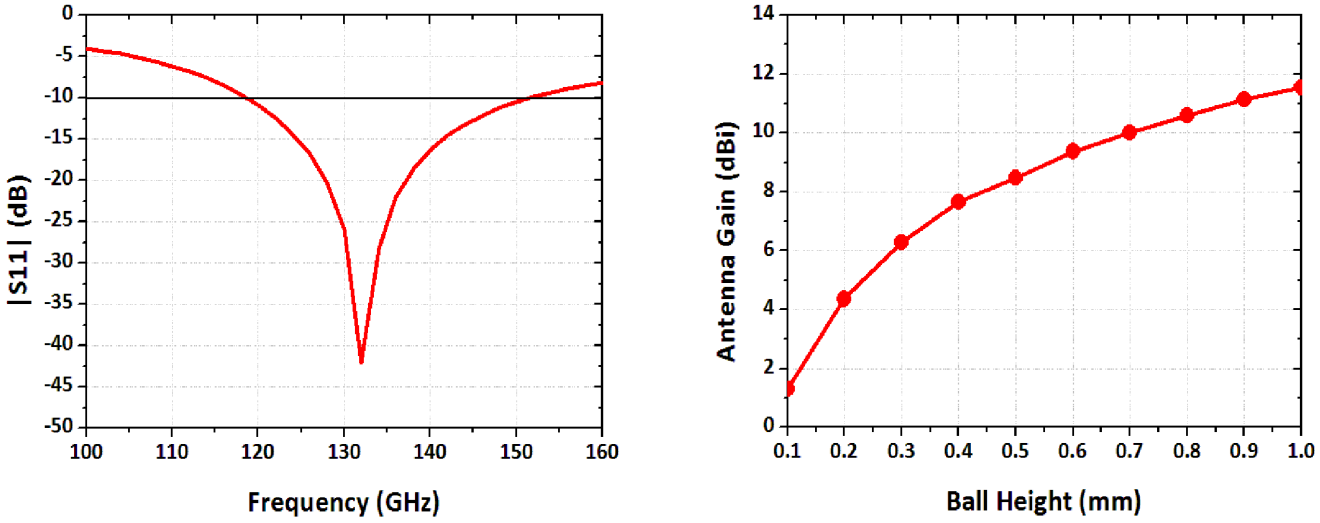


Fig. 3. Simulated E-field distribution and 3D radiation patterns of the horn antenna.



(a) (b)

Fig. 4. Simulated performance of the proposed horn antenna: (a) |S11| curve, and (b) boresight gain versus different ball height.

cost of the proposed antenna is significantly reduced, because it does not require any extra process or procedure. This horn antenna also features low loss and high efficiency, because there is only air but no any loss dielectric material filled inside the horn. In addition, one simple solder ball with same size is used to feed the antenna as a current probe [14] and also interconnect with ICs. Moreover, this horn antenna can be seamlessly packaged with ICs to form a full-functional 3D SiP, and does not occupy additional chip or wafer area.

On the other hand, compared with other on-chip and in-package antennas shown in Fig. 1, the proposed horn radiates along the horizontal plane but not the vertical direction. Therefore, it is very suitable for inter-chip communications or other side-by-side applications.

III. Results and Discussion

A 3D full-wave simulator ANSYS HFSS is used to design and optimize the horn antenna described in the Section II.

Fig. 3 (left) depicts the E-field distribution of the horn antenna. Guided wave with TE_{10} mode is excited in this horn, and then radiated into the free space. Following that, Fig. 3 (right) illustrates the 3D radiation patterns in the far field of this horn antenna. Both these results indicate that, the proposed antenna, which just efficiently uses redundant solder balls between two substrates, performs well and very similarly as a typical H-plane horn.

Fig. 4 (a) presents |S11| curve of the horn antenna. It shows that, the designed horn has a good impedance matching (with

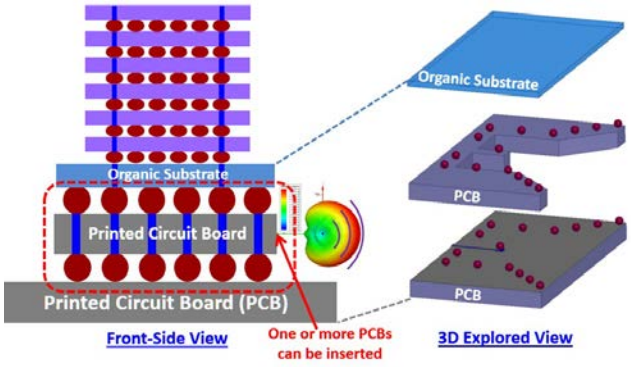


Fig. 5. 3D SiP with higher antenna gain by inserting one or more PCBs to increase horn thickness.

return loss higher than 10dB) from 119 to 151GHz. This wide bandwidth significantly benefits the 3D SiP with ultra-high-speed (tens of Gbps) communication.

Boresight gain of a typical H-plane horn seriously depends on its thickness, i.e., ball height/diameter in this paper. Fig. 4 (b) investigates this variation. When ball height increases from 0.1 to 1mm, boresight gain at 135GHz will vary from 1.3 up to 11.5dBi. For commercial applications, ball height ranging from 0.4 to 0.76mm is affordable by industrial company [15]. To get higher gain or realize a similar antenna at frequencies lower than 135GHz, Fig. 5 presents a new 3D SiP by inserting one more PCB. In this case, the total equivalent ball height, i.e., the thickness of the H-plane horn, will greatly increase.

TABLE I. PERFORMANCE SUMMARY AND COMPARISON OF IN-PACKAGE ANTENNAS

	This Work	MTT 1992 [12]	AP 2009 [13]	MTT 2006 [17]
Antenna Type	Horn	Horn	Horn	Folded dipole
Tech.	Solder balls	16 stacked wafers	Stacked wafers	Flip-chip
Integration with ICs	Seamless	Difficult	Middle	Easy
Added Footprint	NIL	Large	Middle	Small
Antenna Size	8×8×0.7 mm^3	16 wafers	> 20×20×1.4 mm^3	7×11 mm^2
Freq (GHz)	135	12.1	60	60
BW (GHz)	32	N.A.	6.3	6
Gain (dBi)	10.01	18.4	14.4	7
Efficiency	92%	64%	N.A.	~90% (antenna only)

Bumping tolerance is also carefully considered for the horn antenna realization, especially for its feed which is critical and just uses one solder ball. For the ball placement accuracy of around ±15 um which is industrially achievable [16], HFSS simulation results doesn't show significant variation on the antenna performance.

Table I summarizes the performance of the proposed horn antenna and compares it with some prior arts. In addition, different form the horn antennas using substrate integrated waveguide (SIW) technology [14], the proposed horn doesn't contain loss dielectric inside the waveguide. Therefore, it features higher efficiency than a corresponding SIW horn.

IV. CONCLUSION

This paper describes a horn antenna with high gain, high radiation efficiency, and wide bandwidth, operating at mmWave frequency which is beyond 100GHz. Without requiring any additional die, chip area, or process, this horn antenna can be seamlessly packaged with mmWave ICs and other functional blocks to form a hybrid integrated 3D SiP. The idea presented in this paper, i.e., using solder balls to form antennas, is also very promising to realize helix antennas with circular polarization, inductors with high Q factor, and filters with low insertion loss.

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