Micro-machined 3D Cube Antenna for X-Band Communication ICs

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***Abstract*—A 3D cube antenna for CMOS communication ICs is proposed in this paper. The antenna is fabricated on the surface of a cube for the interior CMOS chip placement. The antenna system consists of a meandered line antenna plated gold on three silicon planes of the cube and a balun on one plane. Three planes are then connected and folded by gold, and fixed in a plastic carrier. This antenna is designed for X-band receivers (8-12 GHz) and its measured peak gain is -1.38 dBi with 7% -10 dB reflection coefficient at 10.35 GHz. The antenna cube interior size is 3 mm×3 mm×3 mm, of which the cubic shape allows for CMOS IC packaging inside the cube's hollow interior.**

Keywords—Meandered line antennas, 3D antennas, Dipole antennas, Packaging technology

I. INTRODUCTION

The motivation for this paper is to develop small size antennas for CMOS communication ICs at X band. Planar antennas are widely used because of the low cost and simple fabrication. However, they tend to have large sizes and cross-sectional areas [1]. Therefore, in this paper, a 3D meandered-line antenna is preferred since meandered lines can miniaturize antenna dimensions and 3D antennas have more available interior volume as storage for CMOS IC or other elements (see Fig. 1(a)).

As shown in Fig. 1(b), a prototype antenna is designed with a microstrip feed for coaxial connector to measure antenna performance. A λ/4 parallel plate balun is integrated on the substrate for transition and impedance matching. The Si substrate is etched into three individual faces which are connected by the antenna trace and additional metal straps. Next, these faces can be folded into the cubic structure and inserted into a carrier made by 3D printing. The folded antenna with plastic carrier is connected to a mini SMP connector by silver epoxy (see Fig. 2).

The sections that follow begin with antenna simulations in HFSS. In the antenna fabrication section, a new approach to realize the micro-machined 3D antenna is presented. Then the antenna measurements are shown, including return loss, gain, radiation patterns and efficiency. Finally, a comparison table is presented to analyze this antenna against previously published work.

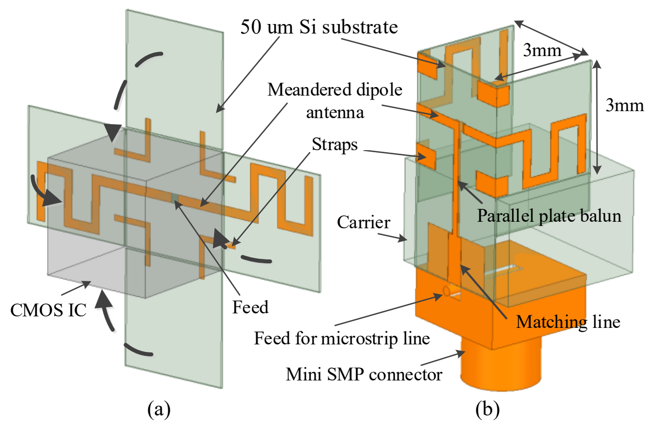

Fig. 1. Geometry of Meandered-line Cube Antenna. (a) Concept Antenna for IC Packaging. (b) Antenna with Coaxial Connector for Measurement.

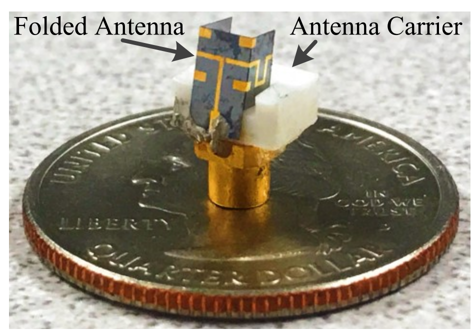

Fig. 2. The Proposed Meandered-line Cube Antenna on a Quarter Coin.

II. CUBE ANTENNA DESIGN

An antenna is considered to be electrically small as a function of *ka*, where *k* is the free space wave number, and *a* is the radius of an imaginary sphere circumscribing the maximum dimensions of the antenna [2]. Consider a straight-wire half wave dipole at 10 GHz in free space, its *ka*=1.59. When the antenna arms are meandered on a cube with 3mm length, and its *ka*=0.44. Thus, compared to the straight-wire dipole, meandered line technology allows designing antennas with features such as small size and 3D packaging. Two symmetric arms of the antenna are meandered in order to reduce the dimension of the antenna. In addition, a λ/4 parallel plate balun is used to provide a high impedance at the antenna side and cancel the unbalanced current from the coaxial feed line [3].

The geometry of a cube antenna with balun is shown in Fig. 1(b). The antenna trace and straps used to strengthen the sides of the cube are 5-um thick gold on a 50-um thick silicon. The plastic carrier is made by 3D printing. To match the input impedance to 50 Ohm, the dimensions of the dipole antenna, parallel plate balun and matching transmission line are optimized by HFSS.

The simulated return loss is better than 10 dB from 9.92 GHz to 10.22 GHz. The antenna has -0.21 dBi peak gain in simulation with 84.7% radiation efficiency. The comparison between simulations and measurements is shown below.

III. MEASUREMENT AND ANALYSIS

A. Antenna Fabrication and Measurement

This paper presents a new fabrication approach based on silicon processing, as shown in Fig. 3. First, a via hole etch is performed (Fig. 3a). Next, lithography is used to gold-plate the via hole and front side (Fig. 3b). Back-side fabrication is similar to front side: Au is plated on the back side after lithography (Fig. 3c). Next the cube faces are formed by Si etch (Fig. 3d). After the fabrication, the silicon faces are folded and inserted into a plastic carrier made by 3D printing (Fig. 4). Then the whole antenna assembly is placed on a mini SMP connector. The antenna is connected to the mini SMP pin by silver epoxy.

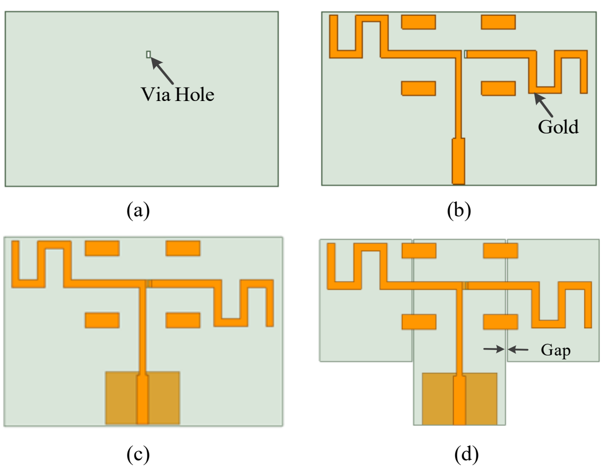

Fig. 3. Cube Antenna Fabrication Process.
(a) Si Etch for Via Hole. (b) Au Plating on the Front Side. (c) Au Plating on the Back Side. (d) Si Etch for Gap.

The antenna assembly is fixed in a plastic rotation holder and placed in a microwave test chamber. Fig. 5 shows the comparison between measured and simulated reflection coefficient of the cube antenna with and without the additional rotation holder. As seen, additional metal and lossy plastic parts could effect antenna efficiency and bandwidth. Although the resonant frequency shifts up by hundreds of megahertz, the measured data fits the simulated data.

Fig 6 shows measured radiation patterns. The peak gain is -3.5 dBi on E-plane and -1.38 dBi on H-plane. Although measured radiation patterns show more loss than simulated, the shape of the pattern is similar. A measure of efficiency is obtained using the Wheeler Cap method [4]. The measured efficiency of the cube antenna with the rotation holder is 55.8% at 10.35 GHz.

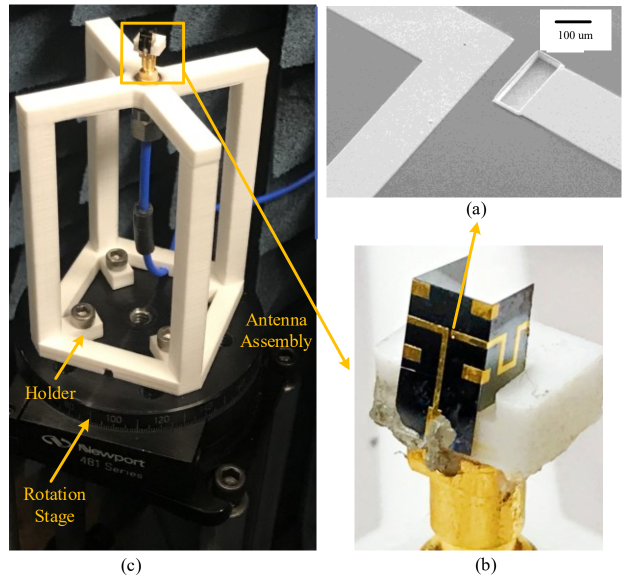

Fig. 4. Antenna Installation and Pictures of Partial Plated Au.
(a) SEM Picture of Partial Plated Au. (b) Antenna Assembly. (c) Antenna with Holder and Stage.

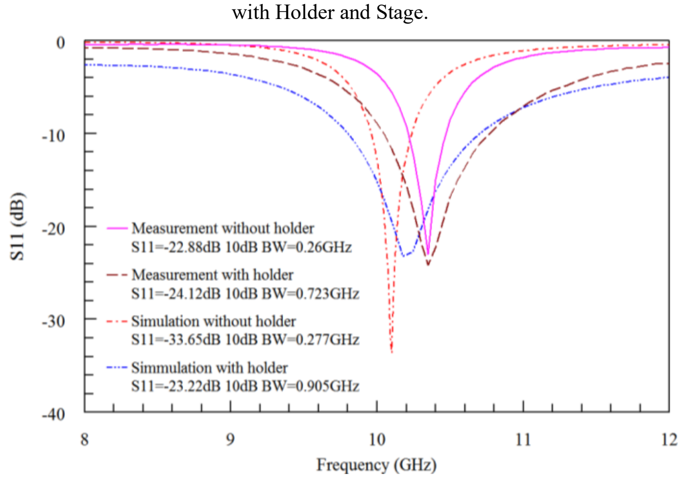

Fig. 5. Simulated and Measured Reflection Coefficient.

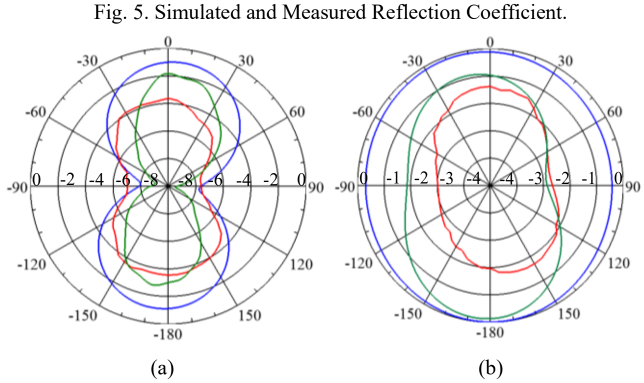

Fig. 6. Measured Radiation Pattern of Cube Antenna (in dB).
(a) E-Plane Radiation Pattern. (b) H-Plane Radiation Pattern.
(blue line: simulation without the holder, green line: simulation with the holder, red line: measured radiation pattern)

Table 2. Comparison of Antenna Performance.

Paper	ka	Antenna type	Fabrication Method	Frequency	Performance
[3]	0.73 0.55	Meandered-line dipole	PCB and stereolithography	2.45 GHz ISM band	Peak gain:2 dBi Efficiency: 78% 10 dB RL BW: 2.7%
[5]	4.9	Patch antenna	3D printing and shape memory polymers Silver nanoparticle (SNP) ink	3.3-3.7 GHz	10 dB RL BW: 4.3% Peak gain: 4.2 dBi
[6]	2.5	Quasi-Yagi antenna	PET flexible substrate silver conductive ink	2.45 GHz ISM band	10 dB RL BW: 10% Peak gain: 5.96 dBi
[7]	NA	Horn antenna	Vertical Multi-Chip Module packaging technology and PCB	Ka band	10 dB RL BW: 6%
[8]	1.75	Dipole antenna	PCB and Pyralux	17.2 GHz	Peak gain: 4.7 dBi
This work	0.44	Meandered-line dipole	Silicon processing	X-band	Peak gain: -1.38 dBi Efficiency: 55.8% 10 dB RL BW: 1.6%

**ka* represents the overall antenna size at a certain frequency where $k = 2\pi / \lambda$, and a is the radius of the smallest sphere enclosing the maximum dimension of the antenna.

B. Comparison and Antenna Applications

Table 2 shows a comparison between the micro-machined 3D meandered-line antenna in this paper and other work on 3D antennas: Paper [3] gives a 3D solution using folded Rogers/RT Duroid 6010, however it cannot be generalized to most commercial substrates, such as FR-4 and silicon. For the 3D printing technology in [3], [5] and [6], the metal choice is limited (silver paste or silver ink) and the currently available substrate materials are lossy relative to the other commercial microwave substrates (e.g. loss tangent=0.045 in [3]). In addition, the 3D printing resolution is about 20 um in [3], thus compared to 3D printing, silicon micro-machining techniques have higher resolution in antenna substrate processing, which can be accurate to a few micrometers. This higher resolution is critical for high frequency antennas.

In paper [7], PCB circuits are stacked layer-by-layer and molded in an epoxy resin with an interconnection system on the cube surface to couple into a compact horn antenna. In paper [8], PCB boards are placed on Pyralux polymers and then folded for packaging. Compared to the substrate and antenna being fabricated by 3D printing, the methods in [7] and [8] are more precise and controllable, but they increase the complexity of both antennas and circuits fabrication.

The motivation of this research is to design antennas working for X-band communication ICs and also provide a packaging solution for the chip. Since this paper adopts meandered line technology, *ka* is small compared to antennas in paper [3]-[8]. The beauty of this design is that the dimensions of the antenna, including antenna arms, balun and matching line, can be redesigned for ICs with different dimensions. Changing the size of balun and matching line will make the input impedance to match to 50 Ohm at different frequencies. Thus, this design is ideal for most IC chip dimensions at microwave frequency range.

IV. CONCLUSION

Designs of 3D cube antennas have been developed in this paper. A new design of a X band cube antenna is presented. The antenna has 7% 10 dB return loss bandwidth and -3.5 dBi gain on E-plane and -1.38 dBi gain on H-plane in measurement. Antenna efficiency is 55.8% at 10.35 GHz. This paper also shows a new fabrication method based on silicon processing. The antenna can be fabricated to match to a range of impedance in the desired frequency band. Besides, the cube can be used as packaging technology, whereby the antenna provides housing for communication ICs.

REFERENCES

[1] G. Whyte, N. Buchanan, and I. Thayne, “An omnidirectional, low cost, low profile 2.45 GHz microstrip fed rectaxial antenna for wireless sensor network applications,” IEEE Conf. Antennas Propag., Loughborough, U.K., 2006.

[2] J.S. McLean, “A re-examination of the fundamental limits on the radiation Q of electrically small antennas,” IEEE Transactions on Antennas and Propagation, Vol 44, No. 5, pp. 672, May 1996.

[3] Ibrahim T. Nassar, Thomas M. Weller, “Development of Novel 3-D Cube Antennas for Compact Wireless Sensor Nodes”, IEEE Transactions on Antennas and Propagation, Vol. 60, No. 2, Feb 2012.

[4] H. A. Wheeler, “The radiansphere around a small antenna,” Proc. IRE, vol. 47, No. 8, pp. 1325–1331, Aug 1959.

[5] John Kimionis, Michael Isakov, Beom S. Koh, Apostolos Georgiadis and Manos M. Tentzeris, “3D-Printed Origami Packaging with Inkjet-Printed Antennas for RF Harvesting Sensors,” IEEE Transactions on Microwave Theory and Techniques, Vol. 63, No. 12, pp. 4521-4531, Dec 2015.

[6] Do Hanh Ngan Bui, Tan-Phu Vuong, Jacques Verdier, Bruno Allard, and Philippe Benech, “Design and Measurement of 3D Flexible Antenna Diversity for Ambient RF Energy Scavenging in Indoor Scenarios,” IEEE Access, Vol 7, pp.17033-17044, Jan 2019.

[7] Barbara Bonnet, Philippe Monfraix, Renaud Chiniard, Jerôme Chaplain, Claude Drevon, Herve Legay, Pascal Couderc, and Jean-Louis Cazaux, “3D Packaging Technology for Integrated Antenna Front-Ends,” 2008 38th European Microwave Conference, Oct 2018.

[8] Amin Enayati ; Steven Brebels ; Walter De Raedt ; Guy A. E. Vandenbosch, “3D-Antenna-in-Package Solution for Microwave Wireless Sensor Network Nodes,” IEEE Transactions on Antennas and Propagation, Vol 59, NO. 10, PP. 3617-3623, Oct 2011.