Design of 26GHz On-Chip Antenna for Microsensors Based on a Standard 0.18μm CMOS Process

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2021 IEEE 3rd International Conference on Circuits and Systems (ICCS) | 978-1-6654-1234-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/ICCS52645.2021.9697176

***Abstract*—With the rapid development of 5G communication network, microsensors become more and more important because they could be the solution of Internet on Everything. To realize microsensors, the miniaturization of antenna is a key issue. The paper demonstrates a 26GHz on-chip antenna for microsensors based on standard 0.18μm CMOS process. Through the introduction of hexagon artificial magnetic conductor structure, the antenna gain is enhanced. The antenna has a peak gain of -7.2dBi and a good front-to-back ratio. The working frequency band of the antenna spans from 21.67GHz to 29.99GHz (32% of center frequency), rendering the antenna capable for 5G communication based on 26GHz frequency band.**

Keywords*—26GHz, Microsensor, Artificial magnetic conductor, On-chip antenna, 5G

I. INTRODUCTION

The rapid development of Internet on Everything (IoE) calls for the development of microsensors. On the other hand, millimeter-wave, an important frequency band for the emerging 5G communication network, is potential for IoE applications. The wavelength of electromagnetic waves in millimeter-wave frequency band is close to or less than one millimeter, thus an antenna with a length of about one millimeter or smaller can have a relative large electric length and be capable for the transmission of electromagnetic waves. Based on this fact, the antenna for 5G millimeter-wave communication microsensors can be miniaturized to the size of a millimeter or smaller, and even possibly integrated into other electronic parts such as integrated circuit (IC) chips.

The mature technique of silicon-based complementary metal–oxide–semiconductor (CMOS) process provides the possibility of the integration of 5G millimeter-wave antennas and electronic chips in recent years. Through the simultaneous fabrication of antenna and chip, signals can be directly transmitted from or to the processing chip, without introducing a dedicated interface between chips and antennas [1]. Thus, the printed circuit board (PCB) size of mobile communication devices can be reduced because antennas no longer take up spaces on PCBs, and these devices, such as microsensors, are subsequently able to be lighter and smaller.

The paper demonstrates the design of an on-chip antenna which is based on a standard 0.18μm CMOS process and works at 26GHz. Because the silicon material in the substrate of the chip has a relatively high dielectric constant compared to atmosphere, much of the energy of the electromagnetic wave emitted by the antenna is dissipated in the substrate, the gain and radiation pattern of an on-chip antenna are degraded. To enhance the performance of on-chip antennas, researchers introduced several special structures such as split ring resonator (SRR) and high impedance surface (HIS). However, few previous papers focused on on-chip antennas working at the frequency of 26GHz, an important band for 5G millimeter-wave communication. The paper introduces the design of the proposed on-chip antenna, including AMC structures and a monopole antenna in Section II, and draws a conclusion in Section III.

II. DESIGN OF THE PROPOSED ANTENNA

A. Design of AMC Unit

The on-chip antenna is based on a standard 0.18μm CMOS process, whose chip structure is illustrated by Fig.1. A chip manufactured by this CMOS process contains a silicon substrate, an inter-layer dielectric (ILD) layer, five inter-metal dielectric (IMD) layers IMD1–IMD5 and a passivation layer. The on-chip antenna die would be further packaged with plastic small-outlined package (PSOP) which attaches the chip die to a thin copper sheet and covers the chip with an FR-4 epoxy shell.

This work is funded by NSFC with project number 62174181 and also supported by GDNRC[2021]32.

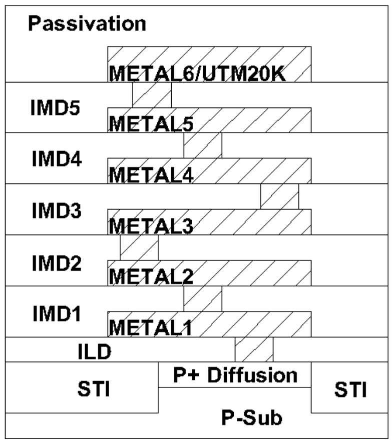

Fig. 1. Chip structure of a standard 0.18μm CMOS process.

Based on the standard CMOS process and packaging process, the simulation model is simplified as below:

- Using a pure silicon cube as the substrate.
- Using solely SiO2 for inter-layer dielectric (ILD) and inter-metal dielectric (IMD*n*) layers.
- Using a layer of SiO_2 and a layer of Si_3N_4 for the passivation layer.
- Directly attaching the copper sheet to the bottom of the substrate.
- Covering the entire chip die with an FR-4 epoxy shell to emulate the actual package.

Fig.2 illustrates the equivalent model of an on-chip antenna without AMC structures. The electromagnetic wave radiated downward by antenna A is reflected by the copper sheet with a phase shift of 180 degrees. Thus, the system can be considered to consist of an on-chip antenna A and a virtual antenna A' with reversed phase. In this case, for far-field conditions ($r \gg h$), the electromagnetic waves emitted by A and A' are almost in reversed phases, making them to cancel out each other. Hence the radiation gain of the antenna is degraded.

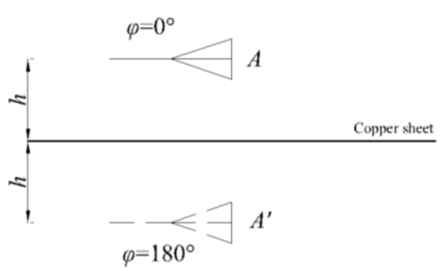

Fig. 2. Equivalent model of on-chip antenna without AMC.

A textured surface with specific pattern called AMC structure can behave like a perfect magnetic conductor in a certain frequency band [2]. This kind of surfaces can fully reflect electromagnetic waves in the frequency band with no phase shift (i.e., in-phase reflection). By introducing an AMC structure under the antenna, the radiated wave and reflected wave are nearly in the same phase. The magnitude of electromagnetic fields excited can thus be increased, and the radiation gain of the antenna can be enhanced. The AMC structure can be thought as an LC resonator, and its equivalent inductance L and capacitance C can be calculated by the equations below [3]:

$$L = \mu_s h \approx \mu_0 h \tag{1}$$

$$C = \frac{w(\varepsilon_1 + \varepsilon_2)}{\pi} \cosh^{-1} \frac{a}{a - w} \tag{2}$$

μ_s is the magnetic conductivity of substrate. Parameters a and w are the length of side of hexagonal unit cell and metal sheet respectively (shown in Fig. 3), and h is the thickness of the silicon substrate. ε_1 and ε_2 are the dielectric coefficient of the materials upon and under the AMC layer, respectively.

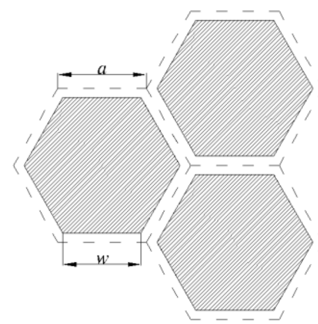

Fig. 3. Structure of artificial magnetic conductor units.

Thus, the working frequency of AMC structure f_0 is:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

From (1) to (3), it is estimated that design parameter w is approximately 443μm while the parameter of a and h are both fixed at 500μm.

Fig. 4 shows the simulation results of insertion loss. After simulation and optimization, the design parameter is $w = 448$μm, which is consistent with theoretical calculations. Fig. 4 indicates that the insertion loss of artificial magnetic conductor unit is less than 0.01dB, which means that the introduction of AMC structure only causes negligible energy loss.

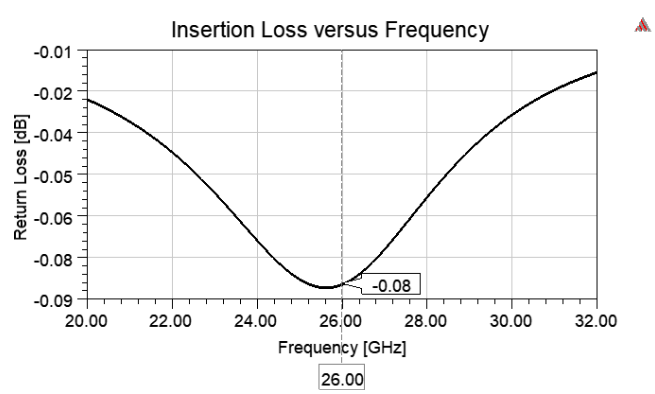

Fig. 4. Insertion loss of artificial magnetic conductor structure.

Fig. 5 illustrates the simulated reflection phase shift. At 26GHz, the reflection phase of artificial magnetic conductor structure is -2.38°, which is very near to the ideal 0°. If we define the working frequency band is between -90° and 90° of the artificial magnetic conductor structure's reflection phase, the proposed artificial magnetic conductor structure attains a working frequency band spanning from 22.70GHz to 29.50GHz, which completely covers n258 frequency band (24.25GHz–27.5GHz).

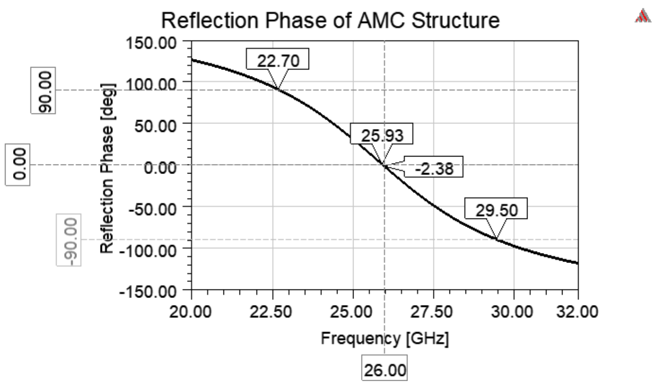

Fig. 5. Reflection phase of AMC structure.

B. Design of On-Chip Antenna with AMC

In this paper, a design of a round monopole antenna with a 50-Ohm co-planar waveguide (CPW) feeder is implemented. The proposed monopole antenna is placed on the uppermost metal layer METAL6/UTM20K, with the artificial magnetic conductor structures laid on the bottom metal layer METAL1. The definition of design parameters of the on-chip antenna is demonstrated in Fig. 6.

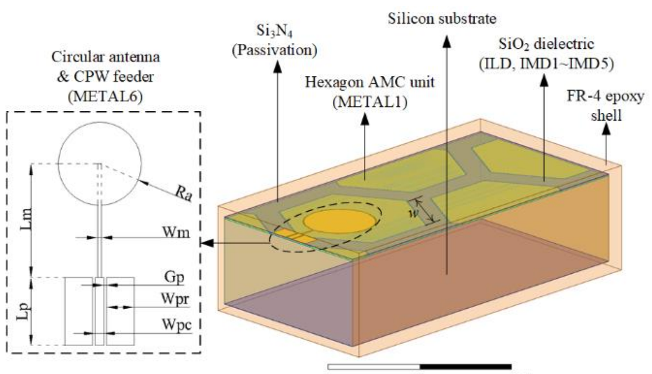

Fig. 6. Monopole antenna with AMC structures.

It should be mentioned that the patterns of metal sheets are created by combining small rectangles, because the lithography masks in standard CMOS progress do not support non-rectangular patterns. The equivalent radiation length and center frequency of circle antenna patch is:

$$l_p = \frac{\mathrm{Ra}^2}{2\pi(\mathrm{Ra}+\mathrm{Lm})} \tag{4}$$

$$L_{\mathrm{eff}} = \mathrm{Ra} + 2\mathrm{Lm} + l_p \tag{5}$$

$$f_0 = \frac{c}{4L_{\mathrm{eff}}\sqrt{\varepsilon_r}} \tag{6}$$

Where c is light speed in vacuum, and ε_r is the dielectric coefficient of substrate.

After simulation and optimization, the electric performance indexes are depicted in Fig. 7 and Fig. 8. Fig. 7 indicates that the return loss of on-chip antenna system is lower than -20dB from 21.67GHz to 29.99GHz, fully covering n258 frequency band. Fig. 8 shows that the input impedance (dashed line for real part and dotted line for imaginary part) of the system at center frequency of 26GHz is 44.48+j0.85Ω, meaning that the system can be fed with a 50-Ohm transmission line with a relatively good matching.

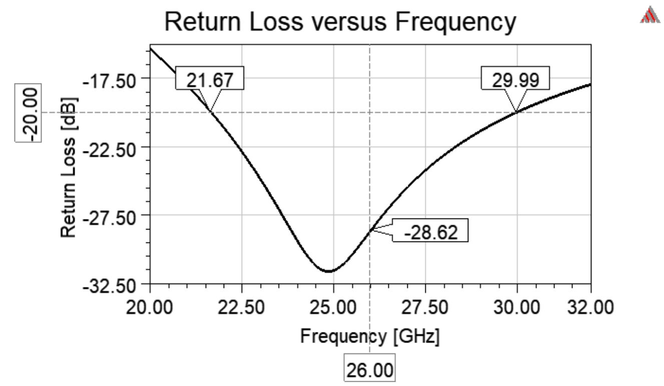

Fig. 7. Return loss of on-chip antenna.

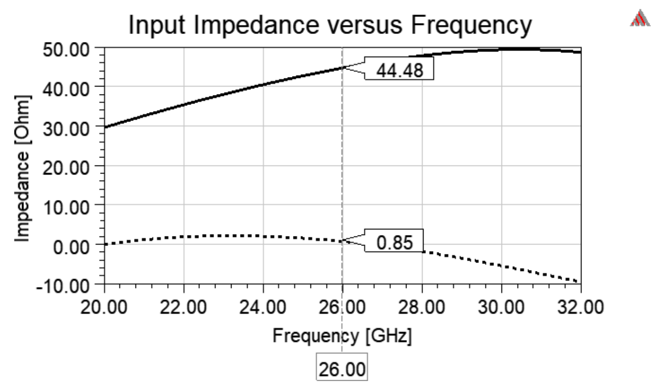

Fig. 8. Input impedance of on-chip antenna.

The radiation characteristics of the on-chip antenna are shown in Fig. 9 and Fig. 10. Fig. 9 shows that the antenna has a relatively small back lobe (less than -12dB), meaning that the antenna has a good front-to-back ratio.

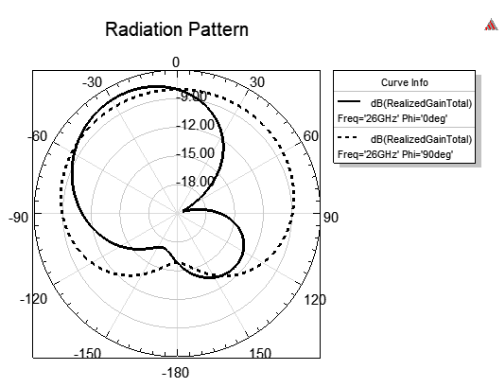

Fig. 9. Radiation pattern of on-chip antenna.

Fig. 10 depicts the full antenna radiation pattern in 3-dimensional view. The radiation pattern of the proposed antenna is in a doughnut shape tilted at 45 degrees with back lobe suppressed. Fig. 10 also suggests that the peak radiation gain of the system is -7.2dBi. Due to the finite conductivity of the dielectric materials, the emitted wave is partially attenuated in dielectric layers, rendering the radiation gain lower than 0dB [4].

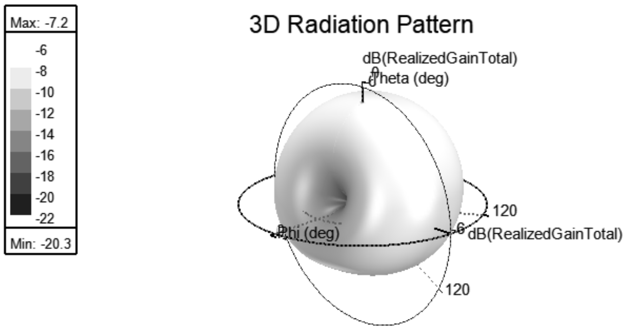

Fig. 10. 3-dimensional radiation pattern of on-chip antenna.

The values of design parameters are shown in Table I. According to (4) to (6), the antenna has a center frequency at approximately 25.88GHz, while the simulation results show that the actual center frequency is about 24.8GHz. The discrepancy is because the antenna and artificial magnetic conductor structures are made by combining small rectangles, which causes the center frequency of antenna to shift, but the results obtained from calculation and simulation generally agree.

TABLE I. VALUES OF DESIGN PARAMETERS

Parameter	Wpr	Wpc	Gp	Lp	Wm
Value (μm)	100	35	10	100	10
Parameter	Lm	Ra	*a*	*w*	*h*
Value (μm)	300	200	500	420	500

Table II shows the comparison of this work with others with regard to performance, size, shape and fabrication process. It should be mentioned that the design in [5] is not compatible with standard CMOS process, since the antenna is directly attached to the top of passivation layer, and is significantly larger than the proposed antenna, making it more difficult to be integrated into small chips. Compared to other designs, the proposed antenna in this paper achieves a wide bandwidth and a good peak gain within a relatively small size, while conserving compatibility with standard CMOS process. Also, compared to other on-chip antennas, the proposed antenna has a simple structure which is easier to manufacture, and the proposed antenna is fully compatible with standard CMOS process, rendering it eligible for mass production. Furthermore, because the emitted signal is completely reflected by artificial magnetic conductor structures, the proposed antenna could be placed above other integrated circuits without causing electromagnetic interference.

TABLE II. COMPARISON OF ANTENNAS

	f_0 (GHz)	**BW/f_0**	**Gain (dBi)**	**Size (mm)**	**Shape**	**Process**
[5]	28	101%	-3.0	3.8× 4.0	Mono-pole	Bulk-Si
[6]	24	24.4%	-8.0	2.5× 2.5	Slot	65nm CMOS
[7]	24	N/A	-7.6	1.5× 2.5	Dipole	CMOS
[8]	24	~2.0%	-20.0	1.5× 1.5	Fractal	TSV
This work	26	32.0%	-7.2	1.0× 2.0	Mono-pole	0.18μm CMOS

III. CONCLUSION

This paper proposes a design of a 26GHz on-chip antenna for 5G network microsensors which can be manufactured via a standard 0.18μm CMOS process. The proposed antenna achieves a bandwidth from 21.47GHz to 29.36GHz (30.4%) and a radiation gain of -7.3dBi. The size and working frequencies of the antenna are obtained through theoretical calculation. The calculation results are in accord with the simulation results.

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