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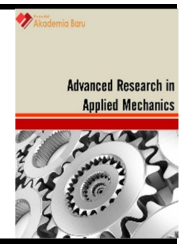

High Gain and Radiation Efficiency Rectangular on-Chip Microstrip Patch Antenna for 60 GHz Applications

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ABSTRACT

This paper introduces the design of the X-shaped unit-cell artificial magnetic conductor for rectangular on-chip microstrip patch antenna. The antenna with 50 Ω CPW for 60 GHz applications is proposed. The radiation characteristics of the antenna are analyzed and simulated using the finite integration technique, FIT. An X-shaped AMC plane is utilized as an electromagnetic shield beneath the on-chip patch antenna for gain and radiation efficiency enhancement. Different configurations of the AMC planes are employed, full plane, 10×10 AMC units removed blank plane, 6×7 AMC units removed blank plane, and 4×5 AMC units removed blank plane. The full AMC plane introduces gain enhancement of 1.15 dBi and radiation efficiency improvement of 10 % compared to that without AMC case. A depletion layer is employed for more enhancements in the performance of the on-chip patch antenna. This procedure boosts the gain and the radiation efficiency to 4.2 dBi and 79 % respectively.

Keywords:
On-chip antenna, artificial magnetic conductor, FIT, depletion layer

1. Introduction

Lately, an interest in millimeter-wave communication is enhanced due to their high data rates. The unlicensed frequency band at 60 GHz has become a potential candidate for short range communication as it is characterized by high attenuation due to atmospheric absorption [1]. Different applications such as uncompressed high definition video streaming, mobile distributed computing, and wireless gaming are prospected. Antenna-on-Chip (AoC) is an emerging technology that guarantees the integration of the antennas, radio frequency circuits and digital circuits on the same chip, allowing the implementation of System-on-Chip (SoC) [2]. The progress of the low-cost Complementary Metal Oxide Semiconductor (CMOS) technology has facilitated the mass production of 60-GHz such circuits [3]. Several CMOS on-chip antennas have been introduced to satisfy the demands of the 60 GHz SoC [4]. Losses due to the high permittivity and low resistivity CMOS substrate lead to performance degradation of the AoC in terms of gain and radiation efficiency. Different techniques are employed to improve the gain and radiation efficiency of AoC, such as proton implantation and micro-machining [5-6]. But these techniques are expensive,

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complex, not compatible with the mainstream CMOS process and reduce the level of the system integration. An efficient technique is employed by inserting EM shielding plane between the antenna and the lossy CMOS substrate using the periodic structure of Artificial Magnetic Conductor (AMC) cells [7].

This technique will minimize the substrate losses and reduce back radiation while maintaining the cost and system level integration. AMC behaves like the perfect magnetic conductor (PMC), where the reflection coefficient is +1 and the reflected wave can constructively enhance the entire electromagnetic field. A wideband patch AoC with two parasitic strips and a snowflake AMC as a shield is introduced in [8]. A triangular patch AoC over Jerusalem-Cross (JC) AMC [9] introduces a gain of 0 dBi and radiation efficiency of 39%, respectively. Different AMC structures used as EM shielding for AoC systems have been introduced to gain and radiation efficiency enhancement [10].

In this paper, the radiation characteristics of on-chip patch antenna have improved by using an X-shape AMC structures. The AoC and AMC are designed using 0.18um CMOS process. For all configurations, both the AMC and the AoC are optimized to cover the 60-GHz wide bandwidth (from 57 to 64 GHz). A depletion layer with high resistivity is inserted into the lossy CMOS substrate below the AMC plane to reduce the substrate losses. The finite integration technique (FIT) [11] is employed to analyze the antenna structure and the results are verified by using finite element method (FEM) [12]. The paper is organized as follows: Section 2.1 introduces the design of the proposed on-chip patch antenna and its radiation characteristics. Section 2.2 presents the proposed X-shape AMC's unit-cell design and reflection coefficient response in addition to introducing the radiation characteristics of the AoC in the presence of different configurations of X-shape AMC plane. Section 2.3 discusses the implementation of a depletion layer into the silicon substrate for more improvements. Finally, the results are concluded in Section 3.

2. Numerical Results

2.1 O-Chip Patch Antenna Design

The geometry of a rectangular on-chip microstrip patch antenna fed by 50 Ω coplanar waveguide (CPW) is presented in Figure 1. The antenna with its CPW feeding structure is placed in the M6 layer and a PEC ground plane is located under the silicon substrate. The dimensions of the proposed patch antenna are optimized to operate at 60 GHz, L_p=0.35 mm, W_p=0.31 mm, L_f=0.266 mm, W_f=0.06 mm, W_t=0.05 mm, L_c=0.05 mm, W_c=0.05 mm, and d=0.12 mm. The variations of the reflection coefficient versus frequency for the proposed antenna are shown in Figure 2a. The antenna introduces broad impedance matching bandwidth of 13.6 GHz (22.3%). Good agreement between the results using the FIT and FEM techniques. The antenna gain and radiation efficiency versus frequency are presented in Figure 2b. The antenna introduces a gain of 0.2 dBi at 60 GHz with a variation from -1.9 to 0.7 dBi over the entire frequency band. The radiation efficiency is varied from 21.5% to 38% from 50 to 70 GHz with a value of 32% at 60 GHz.

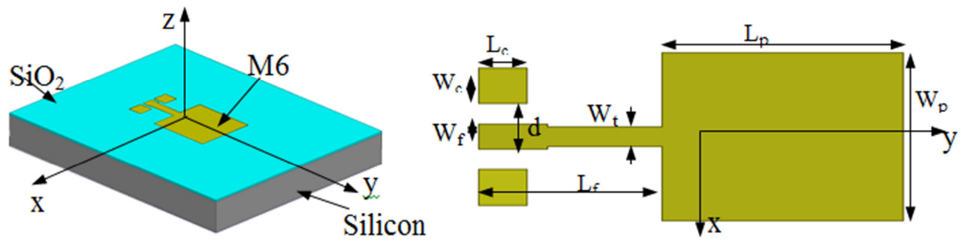
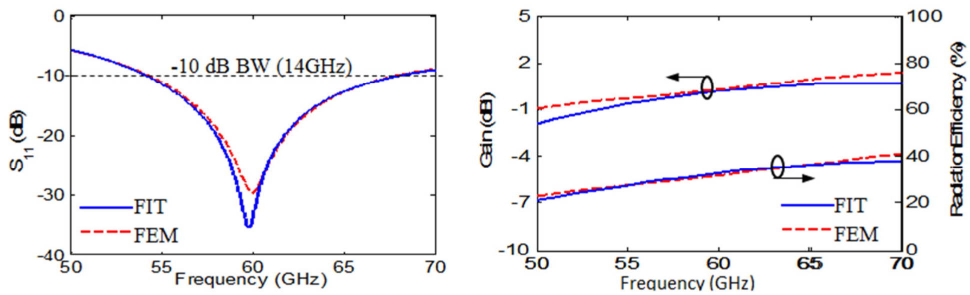
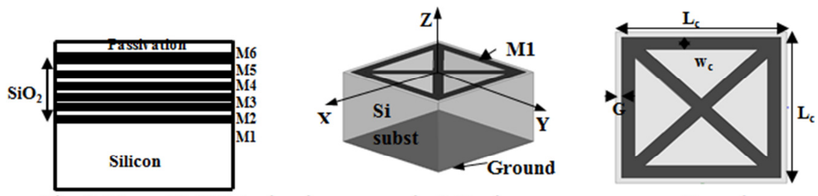


Fig. 1. The structure of the rectangular on-chip microstrip patch patch antenna



(a) (b)

Fig. 2. (a) The reflection coefficient response of the on-chip patch antenna, (b) The responses of gain and radiation efficiency of the on-chip microstrip patch antena



a. The 0.18µm CMOS technology b. 3-D view c Top view

Fig. 3. (a) The Cross-section view of a 0.18um CMOS process with six metal layers over the silicon substrate. b, and c. The geometry of the X-shape AMC unit cell

2.2 On-Chip Antenna Design over AMC Plane

The detailed structure of the on-chip X-shape AMC unit-cell using the 0.18µm CMOS technology is shown in Figure 3a. The 0.18µm CMOS technology consists of six metal layers (M1 to M6) isolated from each other by insulator layers of SiO_2 with thickness 22 µm and relative dielectric constant ε_{ri}=3.9 printed over a silicon substrate with thickness 0.29 mm, relative dielectric constant ε_{rs}=11.9, and conductivity σ=10 S/m. The top metal layer (M6) is assigned for the antenna fabrication and it is thicker than the other layers to guarantee a reduction in the conduction losses, while the bottom metal layer (M1) is utilized for the AMC structure. The configuration of the proposed X-shape on-chip AMC unit-cell is shown in Figures 3b, and 3c. The dimensions of the X-shape AMC unit-cell are L_c= 0.15 mm, Wc= 10 µm, and G=11.5 µm. The dimensions are optimized to operate at 60 GHz. Perfect-E and perfect-H boundary conditions are used to realize the periodic boundary conditions (PBCs) to calculate the reflection response of the AMC unit-cell. The wave port is used as excitation port and is embedded into the surface of the AMC unit-cell as shown in Figure 4a. The variations of the reflection coefficient phase versus frequency of the proposed X-shape AMC unit-cell are presented in Figure 4b. It demonstrates a reflection phase of 0 degree at 60 GHz with ±90º bandwidth of 13.8 GHz (53~66.8 GHz) with a share of 23 %. The proposed AMC unit-cell covers the intended unlicensed band (57~64 GHz). The results are calculated using the FIT and FEM. Good agreement is depicted.

An X-shape AMC surface is realized in M1 layer beneath the antenna as shown in Figure 5. Different configurations of the AMC unit-cell are employed, full plane, 10×10 AMC units removed blank plane, 6×7 AMC units removed blank plane, and 4×5 AMC units removed blank plane are employed. The dimensions of the microstrip patch antenna are optimized in each geometry in order to keep the resonance frequency at 60 GHz. The impedance bandwidth of the full AMC plane case extends from 44 GHz to 93 GHz (81 %). The optimized dimensions of the proposed antennas with different forms of AMC plane are listed in Table 1. The responses of the antenna gain and the radiation efficiency are shown in Figure 6. The full AMC configuration offers the highest gain and radiation efficiency of 1.2 dBi, and 42% respectively. An improvement in antenna gain of 1.15 dBi and 10 % in radiation efficiency compared to the antenna performance without the AMC plane.

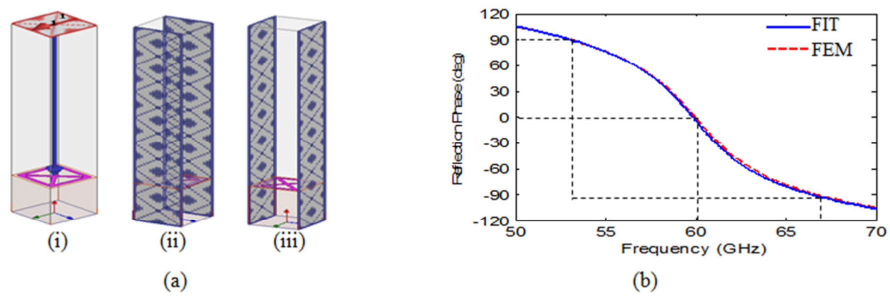


Fig. 4. (a) Simulation model for an AMC cell. (b) The variation of the reflection phase versus frequency of the proposed AMC unit cell

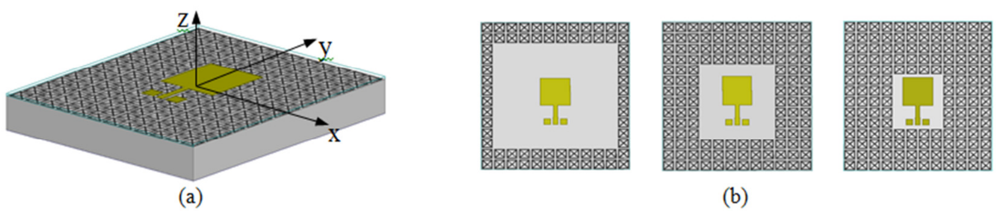


Fig. 5. Simulation models for the on-chip antenna with (a) full AMC plane, and (b) 10x10 AMC units blank, 6×7 AMC units blank and 4×5 AMC units blank

Table 1
The optimized dimensions of the antennas for different AMC planes

Antenna dimensions (mm)	Antenna without AMC	On-chip antenna with AMC 10x10 blank	6x7 blank	4x5 blank	Full AMC
L_p	0.35	0.35	0.38	0.4	0.55
W_p	0.31	0.31	0.335	0.32	0.5
L_f	0.266	0.266	0.266	0.266	0.3
L_c	0.05	0.05	0.05	0.05	0.08
W_c	0.05	0.05	0.05	0.05	0.08
W_t	0.05	0.05	0.05	0.05	0.05
W_f	0.06	0.06	0.06	0.06	0.06
d	0.12	0.12	0.12	0.12	0.12

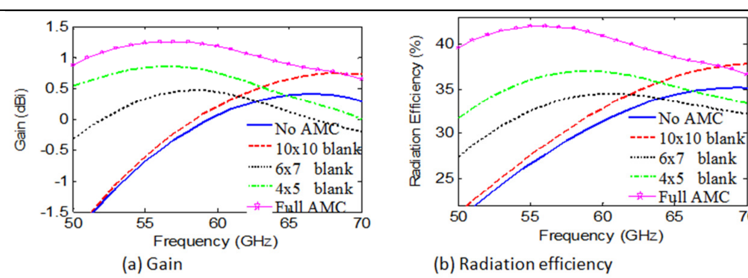


Fig. 6. The variation of the gain and radiation efficiency versus frequency for the proposed on-chip patch antenna with the different structures of the AMC planes

2.3 On-Chip Antenna over Large Depletion Layer

In order to enhance the radiation characteristics of the rectangular on-chip microstrip patch antenna, the properties of the semiconductor (chip) materials are altered in order to reduce its losses. A depletion layer with high resistivity is inserted into the lossy CMOS substrate below the AMC full plane as shown in Figure 7a. The depletion layer in Si substrate has thickness, t_d, relative dielectric constant ε_r = 11.9, and modified conductivity to σ_m = 0.01 S/m. The variations of the reflection coefficient of the AoC versus frequency for t_d=20, 50, 100, 150 and 200 µm are shown in Figure 7b. The implemented depletion layer has less effect on the resonance frequency but the impedance matching bandwidth is reduced by increasing the layer depth. The impedance matching response is maintained from 57GHz to 64 GHz. The responses of antenna gain and radiation efficiency at different values of depletion layer depth are indicated in Figure 8. The existence of depletion layer enhances the gain and the radiation efficiency of the antenna due to the low losses accompanying to this high resistive area. The gain and the radiation efficiency are increased at 60 GHz from 1.2 dB and 42 % at t_d=0 (no depletion layer) to 4.2 dB and 79 % at t_d=200 µm. The antenna has a symmetrical radiation patterns in the two planes and the shape is nearly not changed by varying the value of the depletion layer thickness. It should be noted that the composition of this layer comes at the expense of post-processing cost which increased as the layer thickness increased.

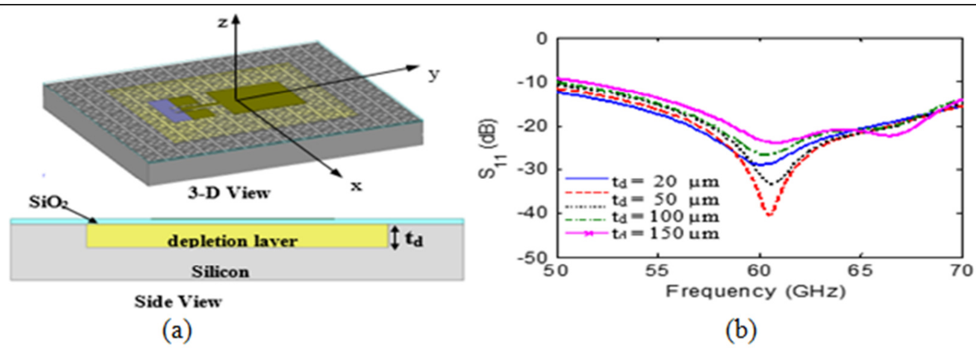


Fig. 7. (a) Simulation model for the on-chip antenna with depletion layer, (b) The reflection coefficient response of the on-chip patch antenna at different values of t_d

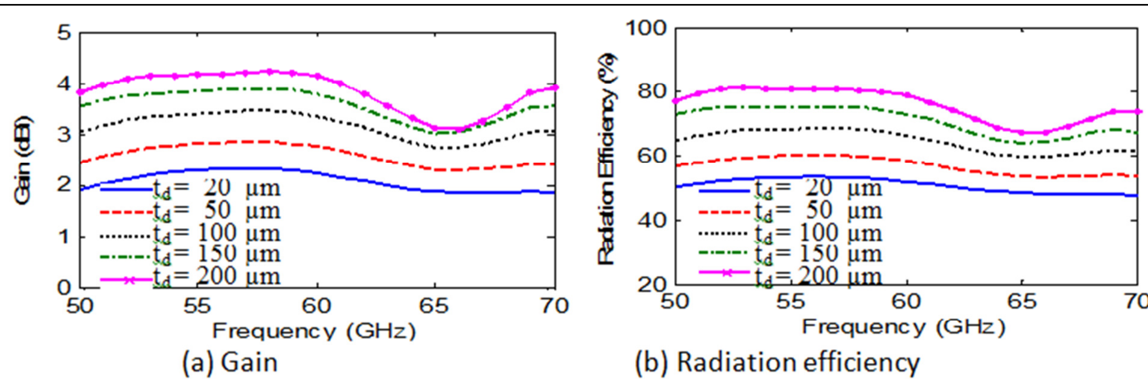


Fig. 8. The variation of the gain and radiation efficiency versus frequency for the on-chip microstrip patch antenna with depletion layer at different values of layer depth (t_d)

3. Conclusion

In this paper, a 60 GHz rectangular on-chip microstrip patch antenna is presented for short range wireless communication applications. This AoC is realized using a standard 0.18µm CMOS process. The performance is improved by two procedures. Firstly, a novel X-shape unit-cell AMC plane is used as an EM shield between the AoC and the lossy silicon substrate. The designed X-shape AMC exhibits a reflection phase of 0º at 60 GHz and with a bandwidth of 23%. The AoC is optimized over several configurations of AMC planes. A maximum gain of 1.2 dB and radiation efficiency of 42 % at 60 GHz is depicted in the case of full AMC plane. An impedance matching bandwidth of 49 GHz (81%) is offered by this antenna. Secondly, a depletion layer is implemented in the substrate beneath the AoC forming a low loss area. The AoC offered a maximum gain of 4.2 dBi and radiation efficiency of 79 % at 60 GHz with a depletion layer thickness of 200 µm. The impedance matching bandwidth covers the band of interest (57-64 GHz).

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