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Compact and Low-Profile On-Chip Antenna Using Underside Electromagnetic Coupling Mechanism for Terahertz Front-End Transceivers

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Abstract: The results presented in this paper show that by employing a combination of metasurface and substrate integrated waveguide (SIW) technologies, we can realize a compact and low-profile antenna that overcomes the drawbacks of narrow-bandwidth and low-radiation properties encountered by terahertz antennas on-chip (AoC). In addition, an effective RF cross-shaped feed structure is used to excite the antenna from its underside by coupling, electromagnetically, RF energy through the multi-layered antenna structure. The feed mechanism facilitates integration with the integrated circuits. The proposed antenna is constructed from five stacked layers, comprising metal–silicon–metal–silicon–metal. The dimensions of the AoC are $1 \times 1 \times 0.265 \text{ mm}^3$. The AoC is shown to have an impedance match, radiation gain and efficiency of $\leq -15 \text{ dB}$, 8.5 dBi and 67.5% , respectively, over a frequency range of $0.20\text{--}0.22 \text{ THz}$. The results show that the proposed AoC design is viable for terahertz front-end applications.

Keywords: antenna on-chip (AoC); metasurface; substrate integrated waveguide (SIW), terahertz (THz); electromagnetic (EM) coupling; feeding mechanism; RF front-end

1. Introduction

The interest in terahertz (THz) bands ($0.1\text{--}10 \text{ THz}$) is steadily growing, as this band enables several important applications, such as biomedical imaging, ultrafast wireless communication, remote non-destructive inspection of packaged goods, security screening, and medical drug applications [1,2]. The current terahertz systems are of low power and low sensitivity. This necessitates the development of terahertz antennas for on-chip applications [3]. Several complementary metal–oxide–semiconductor (CMOS) on-chip antennas have been studied and manufactured to meet the demand of terahertz radio, on-chip, front-end circuit systems [4]. However, most of the terahertz on-chip antennas have problems of low radiation efficiency and narrow bandwidths, which are caused by increased losses from substrate and conductors and the very thin thickness of the substrate between the antenna and ground-plane [5,6]. Standard rectangular CMOS on-chip patch antennas have shown fractional bandwidths and radiation efficiencies of less than 10% [7,8].

In this paper, metasurface and substrate integrated waveguide (SIW) technologies are used to overcome the restrictive bandwidth, radiation gain and efficiency limitations for small antennas [9–11]. A combination of these two technologies is used to design a

compact, low-profile, high-performance terahertz integrated-circuit antenna for on-chip applications. The mechanism used to excite the proposed antenna on-chip uses a cross-shaped feeding structure that is located on the underside of the multi-layered antenna through electromagnetic radio frequency (RF) coupling. The benefits derived from the proposed approach are the reduced substrate loss, suppressed surface-waves, and the enlargement of the antenna's effective aperture. As the results below reveal, the consequence of this is the widening of the impedance bandwidth and the increased radiation performance with no compromise in the total form factor of the antenna.

2. High Performance Antenna On-Chip

The realization of a high-performance antenna in terms of frequency range, radiation gain and efficiency for on-chip implementation is a highly challenging endeavor, due to the small effective aperture area of the chip as well as the adverse effects of the surface waves and substrate loss. To overcome these issues, we employed metasurface and substrate integrated waveguide (SIW) technologies.

The proposed compact on-chip antenna is fabricated on a stack of five layers comprising metal—silicon—metal—silicon—metal. The top silicon layer is sandwiched with two very thin metal layers made of aluminum. The parallel metal layers sandwiching the silicon layer are perforated with a periodic arrangement of circular slot holes, and the two outer edges of the metal layers are connected to each other with metal pins through the silicon layer to create the SIW structure, as shown in Figure 1a,b. The cavity created by the SIW structure only supports the transverse electric (TE) mode because of the gaps between the metallic pins on the side walls of the cavity. The thickness of the silicon substrate is carefully chosen so that the dominant cavity mode is outside the frequency range of interest. The diameter and spacing of the circular slot holes on the extremely thin metal layers are chosen such that the circular slot holes are of subwavelength diameter and the periodicity of the slots is small in comparison to the wavelength of operation [12]. Configuring the metal layers in this fashion causes them to manipulate the electromagnetic (EM) waves that impinge upon them in such a way that is characteristic of metasurfaces, which are a two-dimensional counterpart of metamaterials. This structure has an effect of enhancing the effective aperture area of the antenna [13]. The proposed SIW structure reduces substrate loss, radiation leakage and the adverse effects of surface wave propagation, the consequence of which is enhancement in the radiation gain and efficiency of the antenna. In addition, the slots also improve the impedance match and bandwidth of the antenna.

The mechanism used to excite the antenna is electromagnetically coupling RF energy from a cross-shaped microstrip-line structure that is fabricated on the bottom side of the second silicon layer, as shown in Figure 1. One of the ports is used as the feed port and the other three ports of the cross-shaped feed structure are open-circuited ends. At the junction of the cross is a circular patch whose diameter facilitates the matching of the feedline to the antenna. The antenna is excited through a coplanar waveguide (CPW) feedline, which is realized by being located at the loss proximity to the feedline at the ground-plane. This structure confines the electromagnetic energy within the dielectric and enables the feedline to be implemented on a single plane. Electromagnetic energy from the CPW port excites the feeding structure's three tentacles that couple the RF energy through the two silicon layers and the circular slots. The ground-plane (GND) metal layers have a thickness of 5 μm . The silicon layers of 125 μm thickness have a dielectric constant of 11.9 and loss tangent of $\text{Tan}(\delta)=0.00025$. The dimensions of the structural parameters of the AoC are given in Table 1.

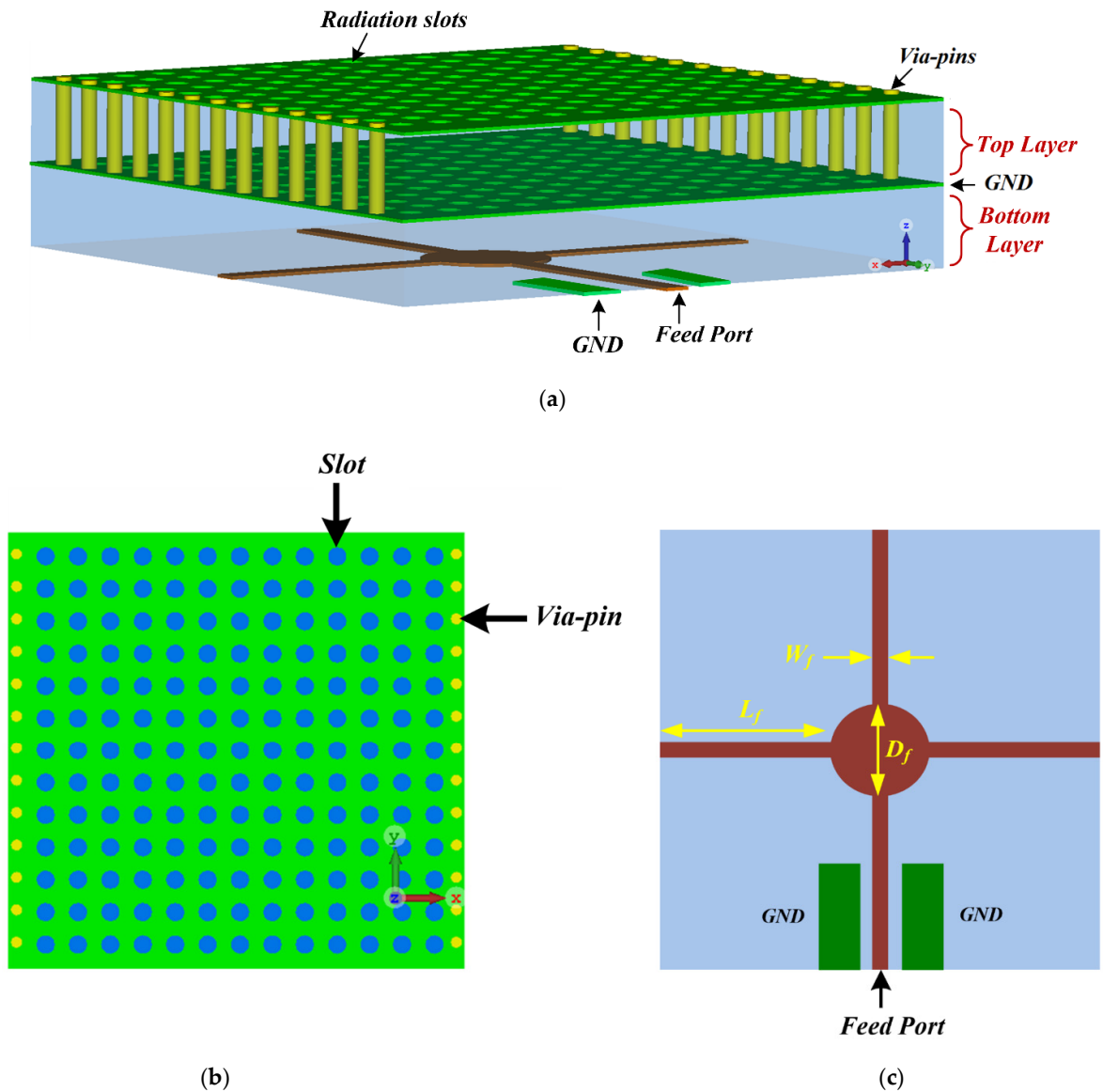
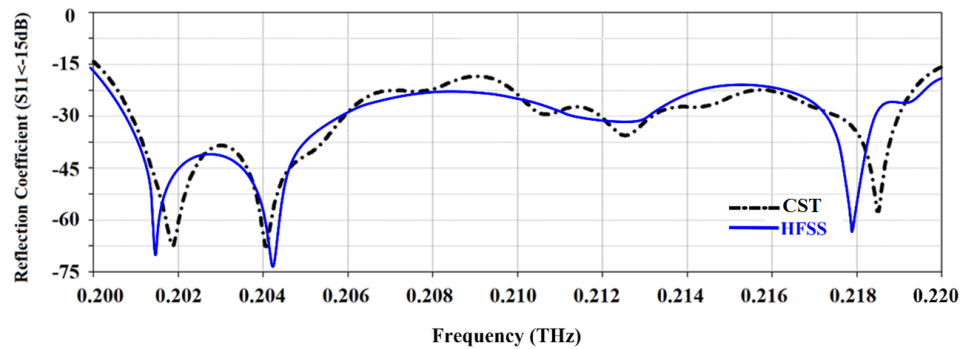


Figure 1. Geometric structure of the proposed AoC, implemented using metasurface and SIW technologies, (a) isometric view, (b) top metallic layer embedded with circular slot holes of sub-wavelength diameter and periodicity of the slots is smaller than the wavelength of operation, and (c) cross-shaped microstrip feedline structure implemented on the bottom-side of the lower silicon layer.

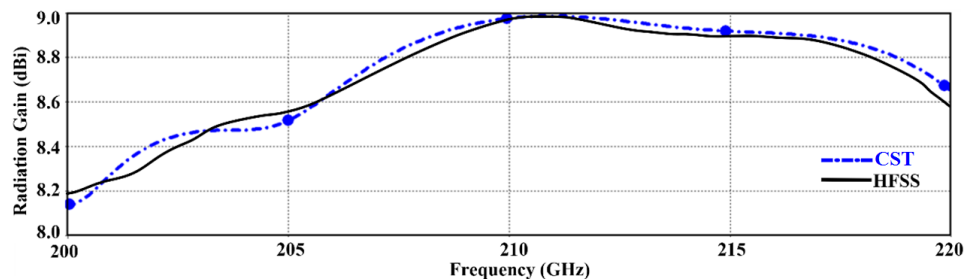
Two different 3D full-wave electromagnetic computational techniques, i.e., CST-Microwave Studio and HFSS Designer, are used to validate the proposed antenna's characteristics, namely, the reflection coefficient (S_{11}), radiation gain and efficiency response. CST is based upon the Finite Integration Technique (FIT) and HFSS is based on the Finite Element Method (FEM). The reflection coefficient, radiation gain and efficiency performance across the antenna's operating frequency range are shown in Figure 2. There is excellent correlation between the two computational techniques. It is evident from Figure 2a that the proposed antenna operates from 0.2 THz to 0.22 THz for S_{11} better than -15 dB. The antenna's radiation gain and efficiency across its operating frequency vary between 8.15 dBi and 9 dBi, and 60% and 72.5%. The average radiation gain and efficiency are 8.7 dBi and 67.50%, respectively. The optimum gain and efficiency are noted at 210 GHz.

Table 1. Geometrical design parameters.

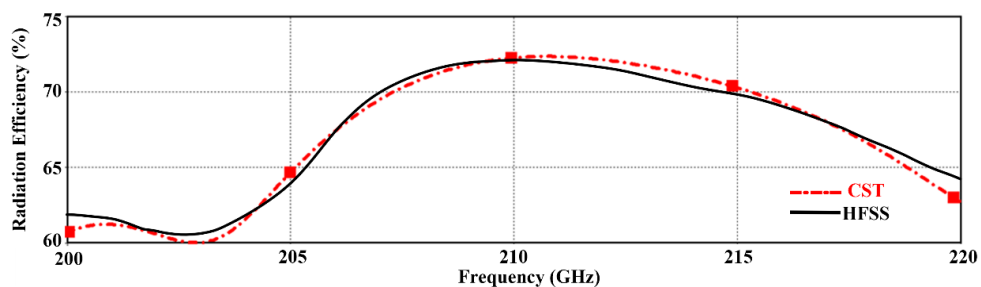
Parameter	Dimensions
Thickness of silicon layers	125 μm
Thickness of metal layers	5 μm
Radius of slots	20 μm
Gap between slots	30 μm
Radius of via-pins	12 μm
Height of via-pins	135 μm
Gap between via-pins	46 μm
L_f (see Figure 1)	400 μm
W_f (see Figure 1)	40 μm
D_f (see Figure 1)	200 μm
Surface area of AoC	1000 \times 1000 μm^2
GND plane	1000 \times 1000 μm^2



(a)



(b)



(c)

Figure 2. Performance of the proposed AoC, (a) reflection-coefficient response, (b) radiation gain, and (c) radiation efficiency.

The three-dimensional radiation pattern of the on-chip antenna at 210 GHz in Figure 3 shows a simulated gain of +9 dBi with boresight pointed toward the z-axis. Co-polarization radiation patterns at the E(xz)-plane and H(yz)-plane at the lower, middle, and top end of its operating frequency are plotted in Figure 4. Stable broadside radiation and almost symmetrical EH-plane patterns are also observed over a wide frequency band. The front-to-back ratio is about 10 dB mainly due to the residual leakage. No side-lobes are observed from the antenna.

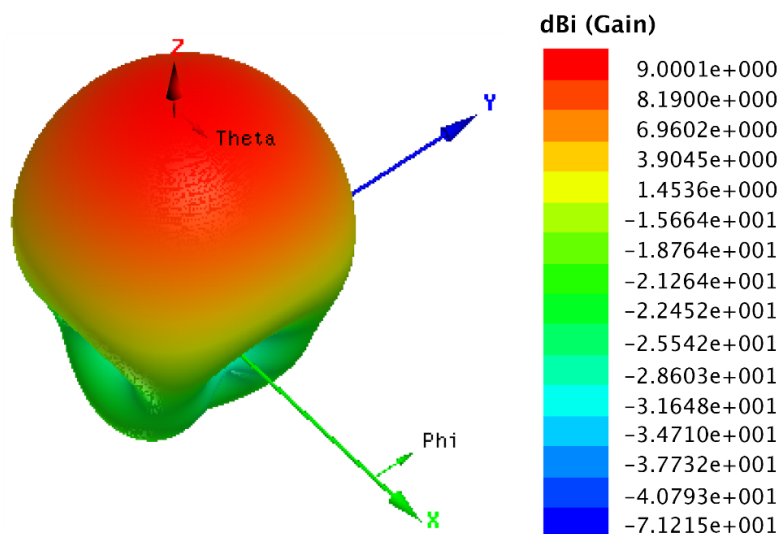
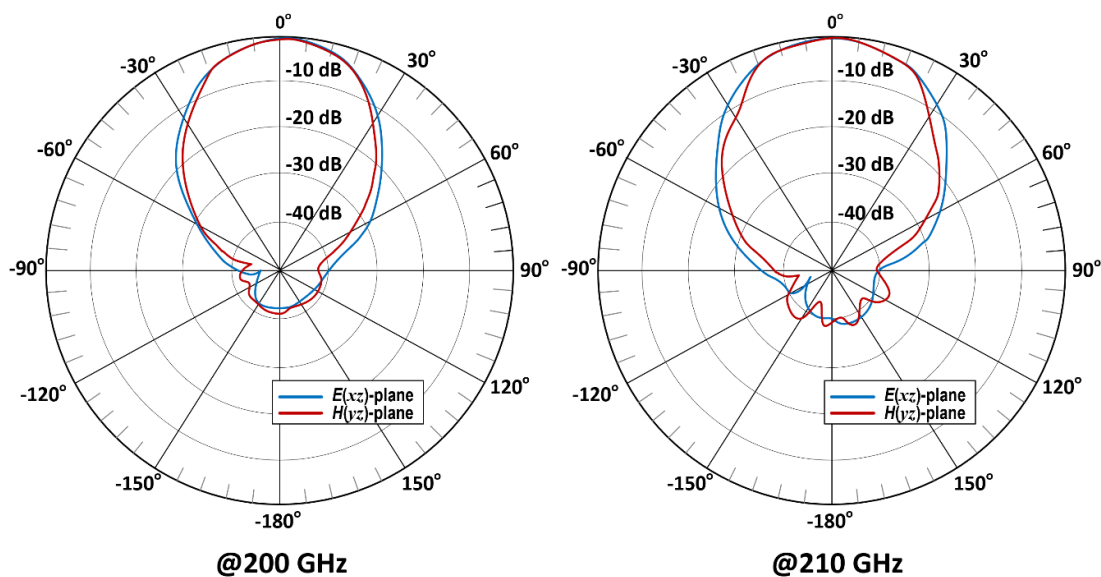


Figure 3. The full three-dimensional radiation pattern of the on-chip antenna at 210 GHz.



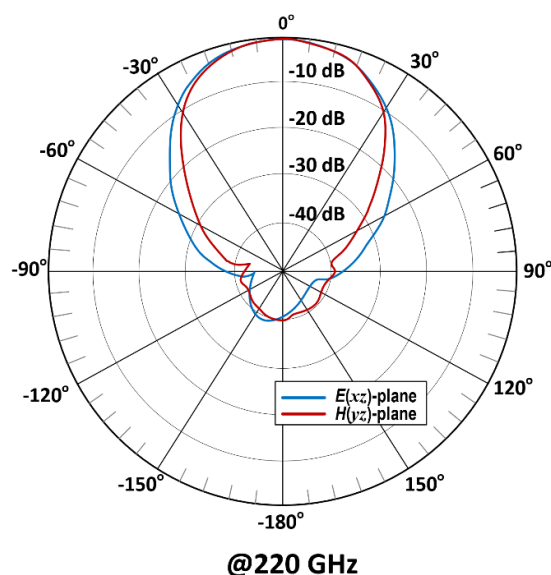


Figure 4. Simulated normalized radiation patterns of the proposed antenna at 200 GHz, 210 GHz, and 220 GHz in the xz- and yz-planes.

The above results confirm that the proposed multilayer antenna structure, implemented with metasurface and SIW technologies, can yield a compact and low-profile antenna for on-chip application that operates across a wide frequency range from 200 GHz to 220 GHz for a reflection coefficient better than -15 dB. Moreover, it is capable of a radiation gain of 9 dBi and an efficiency of 72.5%. The antenna structure is suitable for applications in terahertz, RF, on-chip, front-end wireless systems.

3. Conclusions

The feasibility of a novel antenna on-chip design is presented for wideband, high-gain and high-efficiency for terahertz integrated-circuit applications. The antenna design combines metasurface and substrate integrated waveguide technologies implemented on a multi-layered silicon substrate. The coplanar waveguide port of a cross-shaped microstrip line was used to excite the antenna from the underside of the bottom silicon substrate. The antenna's radiation pattern was stable over its operating frequency range. This was achieved by coupling EM energy through the silicon layers to the circular slots implemented on the metallized silicon layers. The results confirm that the proposed antenna is compatible for fully integrated terahertz transceiver systems.

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