

Research Article

On-Chip Antenna Design Using the Concepts of Metamaterial and SIW Principles Applicable to Terahertz Integrated Circuits Operating over 0.6–0.622 THz

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This research work presents the investigation of realizing an on-chip antenna based on the metamaterial concept, which is working over the terahertz (THz) band for applications in integrated circuits. The proposed on-chip antenna is constructed of five stacked layers of polyimide and aluminum as top and bottom substrates, radiation patches, ground plane, and feed line. The four square-shaped radiation patches are implemented on the $50\ \mu\text{m}$ top-polyimide substrate, and the feed line is realized on the $50\ \mu\text{m}$ bottom-polyimide layer by designing the simple square microstrip lines, which are all connected to each other and then excited by waveguide port. The ground plane including a coupling square slot has sandwiched between the top- and bottom-polyimide layers. The coupling square slot etched on the ground plane is exactly placed under the patch to optimum transfer the electromagnetic signal from the bottom feed line to the top radiation patch. To achieve high performance parameters without increasing the antenna's physical dimensions, the metamaterial and substrate integrated waveguide properties have been applied to the antenna structure by implementing linear tapered slots on the patch top surfaces and metallic via holes throughout the middle ground plane connecting top and bottom substrates to each other. The slots play the role of series left-handed (LH) capacitors (C_L) and the via holes act as shunt LH inductors (L_L). The overall dimension of the proposed metamaterial-based on-chip antenna is $1000 \times 1000 \times 100\ \mu\text{m}^3$. This antenna can cover the frequency band from 0.6 THz to 0.622 THz, which is equal to 20 GHz bandwidth. The radiation gain and efficiency across the operating frequency band varies from 1.1 dBi to 1.8 dBi, and from 58% to 60.5%, respectively. The results confirm that the proposed on-chip antenna with compact dimensions, wide bandwidth over the terahertz domain, low profile, cost effective, simple configuration, and easy to manufacture can be potentially appropriate for terahertz integrated circuits.

1. Introduction

The millimeter-wave (mmW) and terahertz (THz) systems are being utilized for radio astronomy and imaging applications. Enhancing the requests for low-cost circuits and more data transfer at these bands has caused potential commercial applications such as automotive radars and high data rate systems [1–4]. These bands are attractive since with the reducing wavelengths the components physical size can be decreased, so in a specific physical area denser arrays can be constructed.

These applications become practical only if the solutions can be effective and highly integrated and at low cost [5–7].

In addition to the size decrement benefit, moving toward higher bands brings new tasks. Lossy silicon layers are not pleasantly suitable for realizing effective antennas, and for the devices operating over the microwave band, the antenna sizes make them the largest elements of the system that create them infeasible to produce on-chip. Antennas can operate effectively on low-loss printed circuit boards (PCB) that need interconnects between the antenna and the chips.

Although, as the frequency moves higher, the matching networks and interconnects become lossier. Bond-wire interconnects restrict the functionality as they decrease the frequency band because of parasitic reactance. An alternative, flip-chip bonding enhances the cost. Hence, possible low-cost on-chip antenna solutions are of great interest [8, 9].

On-chip antennas enable system-on-chip (SoC) solutions, omitting the demand for conventional 50-ohm interfaces and lossy RF interconnects [10]. Although, on-chip antennas present major difficulties because of physical constraints, low resistivity ($10\ \Omega\cdot\text{cm}$) silicon, that is, the typical layer of commercial integrated circuit processes forbids the effective antenna implementation. As well as, a considerable amount of power is coupled to the surface-wave modes on silicon substrates [11, 12]. Although, typical integrated circuit processes enable an oxide layer thickness of $\sim 10\ \mu\text{m}$ that is still not sufficient in mm-W and THz bands, off-chip radiator and lens based solutions have been introduced in [13–15]. Off-chip radiators need post-manufacture steps on other layers, and lenses are bulky in comparison with the size of the chips. Utilizing high-permittivity superstrates provides a solution without the demand of additional manufacture steps and still achieves high efficiency on-chip antennas [16]. The main drawback of this method is the complexity of the design process and not applicable for mass production in a cost-effective method. Additionally, the on-chip antennas are operating on a narrow bandwidth.

Therefore, in this paper an on-chip antenna has proposed which is implemented on $50\ \mu\text{m}$ polyimide layers. The antenna structure has constructed from five stacked layers of two polyimide substrates and three aluminum layers as radiation patches, middle ground plane, and bottom feed line. The radiating patches have been isolated from the lossy polyimide by a ground plane, which eliminates the polyimide loss effect and causes the antenna to have a very thin substrate degrading the frequency bandwidth, radiation gain, and efficiency, which also makes the antenna unidirectional. The antenna excited by a microstrip feed line was placed on the bottom polyimide layer through coupling the electromagnetic signals to the top radiation patch through the coupling slot etched on the sandwiched ground plane realized between the two top- and bottom-polyimide substrates. The metallic via-hole-inspired substrate integrated waveguides (SIW) are also implemented to connect both polyimide layers to each other to reduce their losses and suppress the surface waves. Additionally, the metamaterial (MTM) property has employed to the radiation patches to extend their effective aperture area to improve the performance parameters. It is shown, after applying both SIW and MTM approaches, the on-chip antenna with simple design structure and compact dimensions exhibits wide bandwidth

over terahertz (THz) territory, high radiation gain, and efficiency over the operating bandwidth. The design process of the proposed on-chip antenna has been presented and investigated in Section 2. The results confirm that the proposed on-chip antenna can be applicable for integration in THz circuits.

2. Design Process of the $50\ \mu\text{m}$ Polyimide Layer-Based On-Chip Antenna Design-Inspired MTM and SIW Properties for THz-Integrated Circuit Applications

The configuration of the proposed on-chip antenna has been shown in Figure 1. The proposed antenna has constructed of five stacked layers of aluminum (radiation patches)-polyimide substrate aluminum (sandwiched ground plane)-polyimide substrate aluminum (microstrip feed line). The thickness, dielectric constant, and tangent loss of the polyimide substrates are $50\ \mu\text{m}$, 3.5, and 0.0027, respectively. As it is obvious from Figure 1(a), on the top polyimide layer, four radiation patches with square shape have modeled, which all have been connected to each other by simple linear microstrip lines, since the antenna is excited only by one waveguide port. Underneath of the top polyimide substrate, the antenna's ground plane (GND) has been implemented, as shown in Figure 1(b). By realizing this GND layer, the antenna structure can be isolated from the lossy polyimide layer, which causes to improve the radiation properties and impedance matching of the antenna. Besides that, a square slot has been etched inside the GND layer as a coupling slot to transfer the electromagnetic (EM) energy to the top radiation patches. This slot is exactly aligned under the radiation patch to couple the optimum EM signal for the radiation process. The GND layer from its bottom side has been connected to the second polyimide layer as the bottom substrate with the same specifications with the top polyimide substrate. As it is displayed in Figure 1(c), underneath the bottom-polyimide substrate, a simple microstrip line is realized as the feeding line that, from its one side, has connected to the waveguide port to excite the structure. The schematic view of the proposed structure is shown in Figure 1(d), which clearly explains that this feeding line is exactly placed underneath the coupling slot etched inside the GND to transfer the maximum EM signal to the coupling slot, and consequently coupling the maximum EM signal from the GND's slot to the radiation patches on the top side of the top polyimide substrate to have optimum signal radiation. To suppress the substrate losses and diminish the surface waves, the SIW concept has been applied by implementing metallic via holes on the edges of the structure throughout the GND layer connecting both top- and bottom-

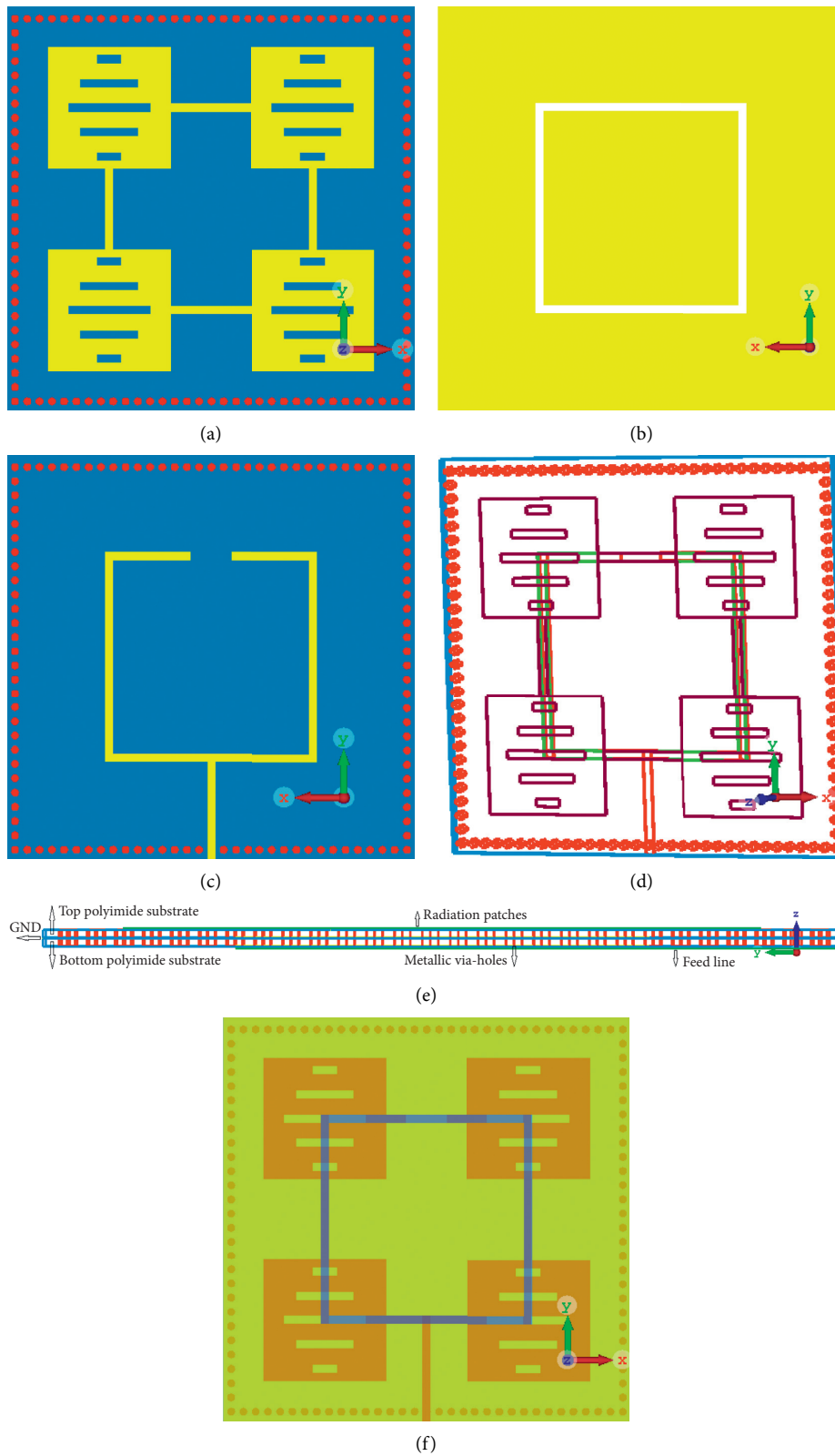


FIGURE 1: SIW- and MTM-based on-chip antenna configuration. (a) Top view, (b) middle GND, (c) back view, (d) schematic view, (e) side view, and (f) overall view to show all components realized on the top, middle, and bottom layers.

polyimide layers to each other, as shown in Figure 1(e). This technique has been applied to the antenna structure with keeping constant physical dimensions. Figure 1(e) exhibits a side view of the five layers stacked on-chip antenna, on which all layers are connected to each other by the metallic via-hole-inspired SIW content. The reductions in the substrate losses and surface waves will cause to improve the performance parameters such as impedance matching, frequency bandwidth, gain, and radiation efficiency. Figure 1(f) displays the GND layer with its coupling slot which is sandwiched between the top- and bottom-polyimide substrates along with an overall view of the antenna structure showing all structural parameters such as radiation patches on the top-polyimide substrate, the microstrip lines connecting the patches to each others, the microstrip feed line on the bottom-polyimide layer, and metallic via-holes throughout the GND layers connecting both polyimide substrates to each other.

As shown in Figure 1, besides the SIW approach, the metamaterial (MTM) concept has been employed to the radiation patches to achieve more improvements on the performance parameters of the on-chip antenna, without extending its physical dimensions. In this method, the tapered slots have been engraved on the top surface of the square patches. Five linear slots have been etched on each patch which has expanded the effective aperture area of the patches without increasing their physical sizes, which will lead to increase in the radiation properties and extend in the frequency band.

The overall dimensions of the proposed on-chip antenna-inspired SIW and MTM properties is $1000 \times 1000 \times 100 \mu\text{m}^3$, so its structural parameters have been listed in Table 1. It is worth to comment that the proposed antenna has been modeled, tooled, and designed by the two 3D full-wave electromagnetic software of CST Microwave Studio and High-Frequency Structure Simulator (HFSS). To validate the antenna design process, the results achieved from both electromagnetic software have been presented and compared in Table 1, which show an excellent coherence with each other.

The reflection coefficient responses ($S_{11} < -15 \text{ dB}$) of the proposed on-chip antenna based on the SIW and MTM approaches are plotted in Figure 2. To validate the results, Figure 2 shows the frequency bandwidths achieved from both CST and HFSS 3D full-wave EM simulators. It is shown that the on-chip antenna can cover the frequency band from 0.600 THz to 0.622 THz, which is corresponding to a wide bandwidth of 22 GHz and a fractional bandwidth of 3.6%. Besides the impedance bandwidth, it is obvious that the proposed antenna applying SIW and MTM concepts shows an average impedance matching better than 25 dB across the

entire frequency band. The S-parameter responses achieved from both EM simulators are listed in Table 2. It is shown that both CST and HFSS results have excellent agreement with each other, which confirm the effectiveness of the proposed approaches.

Besides the frequency bandwidth, the radiation specifications are other important parameters to design antenna structures. Figures 3 and 4 depict the radiation gain and efficiency curves over the operating frequency bandwidth. As it is shown in Figure 3, the radiation gains achieved by CST and HFSS software vary from 1.1 dBi to 1.8 dBi throughout the operating frequency band. The results from both simulators are summarized in Table 3. It is exhibited that there is an excellent coherence between both CST and HFSS curves.

Figure 4 shows the radiation efficiency curves obtained by the CST and HFSS simulators over the frequency band. Both curves exhibit that the radiation efficiency changes from 58% to 60.5%. The results from both simulators are presented in Table 4. There is a good agreement between the CST and HFSS results.

The radiation patterns of the proposed on-antenna in the xy - and xz -planes at 0.60 THz, 0.61 THz, and 0.62 THz are shown in Figure 5. The antenna's radiation energy is mainly focused in the x -direction. The beamwidth is narrower in the xy -plane. The radiation pattern is stable and symmetrical within the operating band of the antenna.

3. Comparison Section

In this section, the proposed on-chip antenna has been compared with other published papers available in the literature in terms of proposed approaches, dimensions, frequency band, gain, and radiation efficiency. The results are listed in Table 5. It is obvious that the proposed on-chip antenna with a compact dimension is operating over a much higher frequency band exhibiting comparable radiation gain and efficiency in comparison with other cited works in Table 5.

Therefore, the results confirm that the proposed on-chip antenna based on the MTM and SIW concepts with compact dimensions of $1 \times 1 \times 0.1 \text{ mm}^3$ operating over 0.600 THz to 0.622 THz with the average gain and radiation efficiency of 1.5 dBi and 60% can be good candidate for integration to utilize in THz circuits. Other advantages of the proposed antenna are its low profile, simple design, easy fabrication process, and low cost, which make it applicable for mass production.

TABLE 1: Structural parameters of the proposed on-chip antenna-inspired SIW and MTM properties.

On-chip antenna dimensions	$1000 \times 1000 \times 100 \mu\text{m}^3$
Ground plane	$1000 \times 1000 \mu\text{m}^2$
Radiation patches dimensions	$300 \times 300 \mu\text{m}^2$
Polyimide substrates thickness	$50 \mu\text{m}$
Length variations of the slots etched on the patches	$60 \mu\text{m} \leq L \leq 200 \mu\text{m}$
Width of the slots etched on the patches	$20 \mu\text{m}$
Length of the lines connecting the patches	$200 \mu\text{m}$
Width of the lines connecting the patches	$20 \mu\text{m}$
Radius of the metallic via-holes	$10 \mu\text{m}$
Distance between the metallic via-holes	$5 \mu\text{m}$
Length of each side of the square slot etched on the ground plane	$520 \mu\text{m}$
Width of the square slot etched on the ground plane	$20 \mu\text{m}$
Width of the feed line	$20 \mu\text{m}$

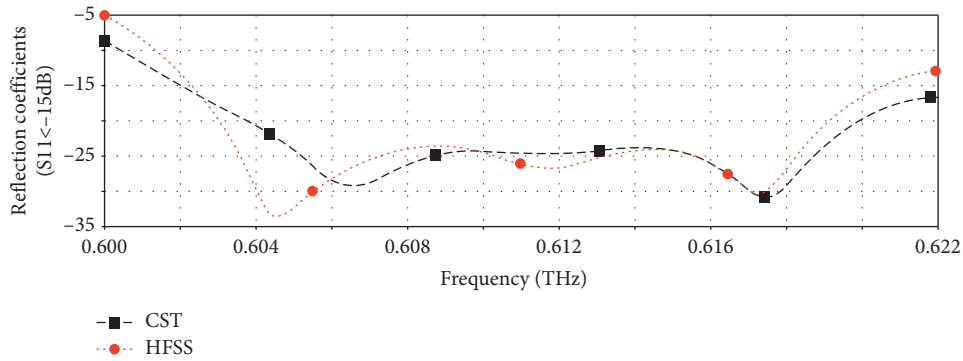


FIGURE 2: Reflection coefficient responses ($S_{11} < -15 \text{ dB}$) achieved by the CST and HFSS EM simulators.

TABLE 2: S-parameter responses of the proposed antenna.

CST microwave studio	
Frequency band	$0.6 - 0.622 \text{ THz}$
Bandwidth	22 GHz
Fractional bandwidth	3.6%
Resonance frequencies	$f_{r1} = 606.5 \text{ GHz}$ and $f_{r2} = 617.5 \text{ GHz}$
Impedance matching	25 dB
HFSS	
Frequency band	$0.601 - 0.622 \text{ THz}$
Bandwidth	21 GHz
Fractional bandwidth	3.43%
Resonance frequencies	$f_{r1} = 605 \text{ GHz}$ and $f_{r2} = 617.3 \text{ GHz}$
Impedance matching	25 dB

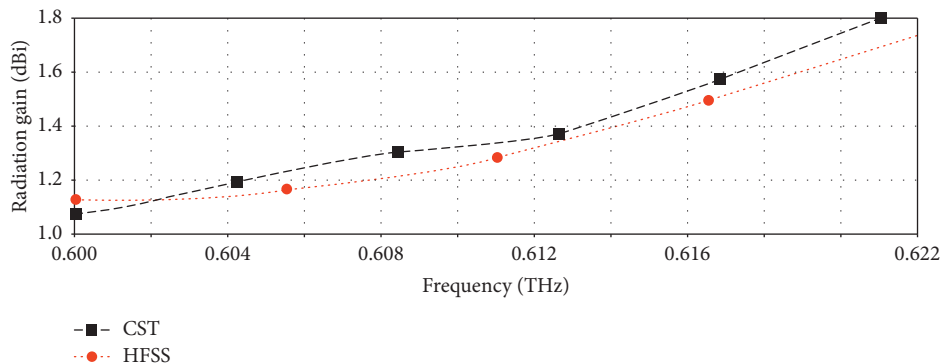


FIGURE 3: Radiation gain curves over the operating frequency band analyzed by the CST and HFSS EM simulators.

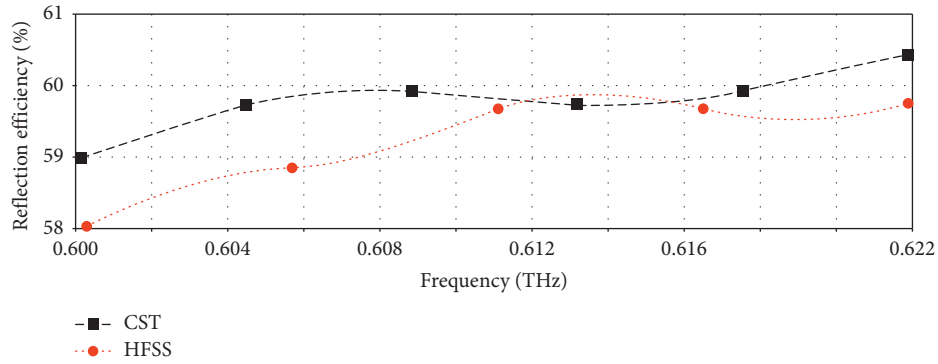


FIGURE 4: Radiation efficiency curves over the operating frequency band analyzed by the CST and HFSS EM simulators.

TABLE 3: Radiation gain specifications of the proposed antenna.

CST microwave studio	
Minimum gain	1.1 dBi
Maximum gain	1.8 dBi
Average gain	1.4 dBi
HFSS	
Minimum gain	1.14 dBi
Maximum gain	1.75 dBi
Average gain	1.35 dBi

TABLE 4: Radiation efficiency specifications of the proposed antenna.

CST microwave studio	
Minimum gain	59%
Maximum gain	60.4%
Average gain	59.8%
HFSS	
Minimum gain	58.3%
Maximum gain	59.9%
Average gain	59.2%

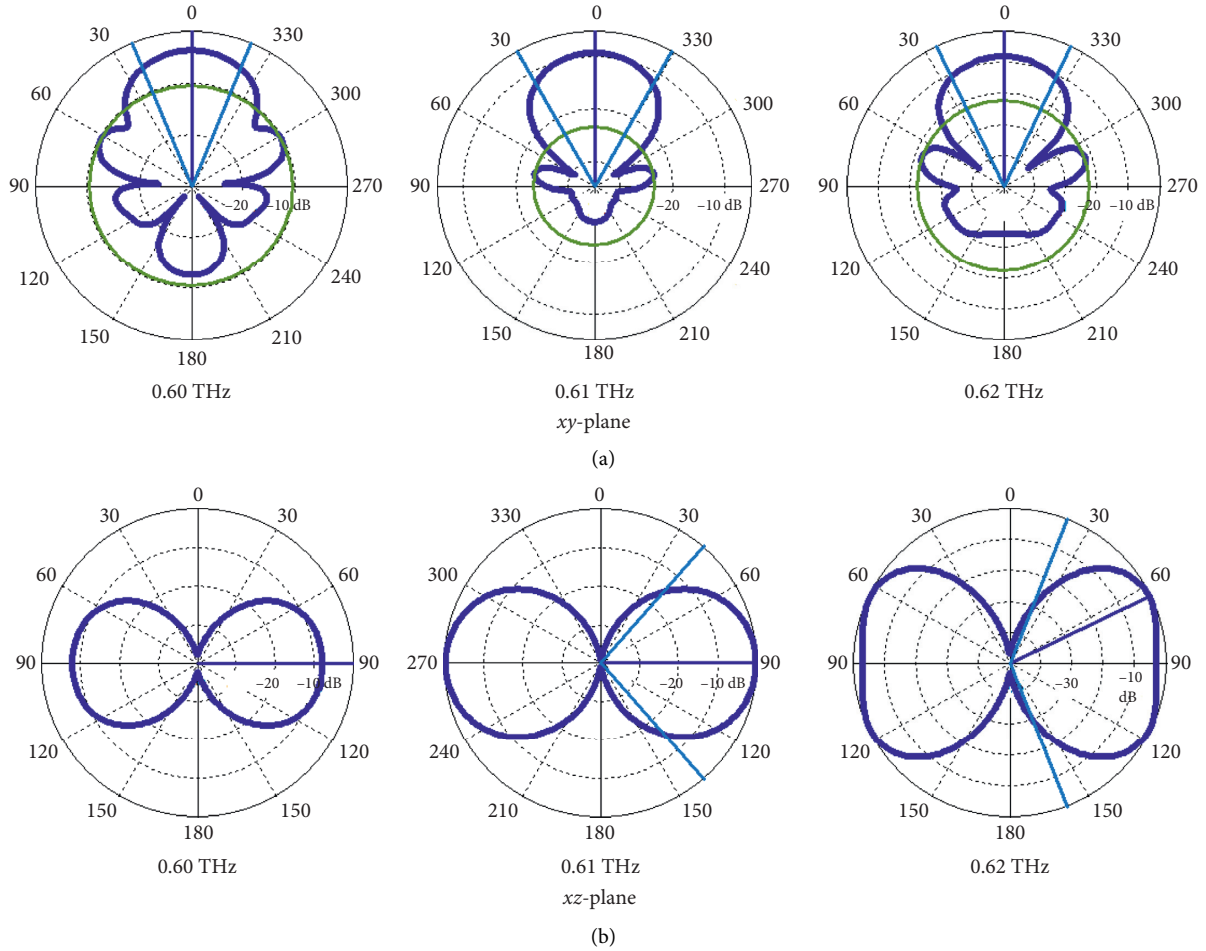


FIGURE 5: Radiation patterns (normalized) of the antenna in the xy -plane and xz -plane at spot frequencies of 0.60 THz, 0.61 THz, and 0.62 THz. (a) xy -plane (0.60 THz, 0.61 THz, and 0.62 THz). (b) xz -plane (0.60 THz, 0.61 THz, and 0.62 THz).

TABLE 5: State-of-the-art comparison.

References	Antenna type	Bandwidth (GHz)	Gain (dBi)	Efficiency (%)	Size (mm ³) or (mm ²)
[4]-a	OSAR antenna	317–330	1.4	41	0.5×0.5
[4]-b	1×2 antenna	303–320	4.1	38	0.5×1
[17]	Bowtie slot	90–105	≤−1.78	-	0.71×0.31×0.65
[18]	Differential-fed circularly polarized	50–70	≤−3.2	-	1.5×1.5×0.3
[19]	Ring-shaped monopole	50–70	≤0.02	≤35	-
[20]	Circular open loop	57–67	≤−4.4	-	1.8×1.8×0.3
[21]	AMC-embedded squared slot antenna	15–66	≤2	-	1.44×1.1
[22]	Monopole	45–70	≤4.96	-	1.9×1.9×0.25
[23]	Loop antenna	65–69	≤8	≤96	0.7×1.25
[24]	Dipole antenna	95–102	≤4.8	-	-
[25]	Tab monopole	45–75	≤0.1	≤42	1.5×1
[26]	Patch antenna	340 (working frequency)	−5.5	6.5	0.194×0.023
[27]	Circular-polarized SIW antenna	251–283	−0.5	21.41	0.99×0.99
[28]	SIW slot antenna	410 (working frequency)	−0.5	49.8	0.2×0.2
[29]	Dipole loaded AMC	200–281	0	63	0.25×0.41
[30]	DRA	340 (working frequency)	10	80	0.7×0.7×0.73
[31]	2×2 slot antenna array	320 (working frequency)	7.9	-	0.86×0.86
[32]	2×2 cavity-backed rectangular slot loop antenna array	340 (working frequency)	7.7	39	1.1×1.1
[33]	2×2 DRA array	334–350	8.65	54	1.1×1.5×1.269
This work	MTM and SIW	600–622	≥1	≥58	1×1×0.1

4. Conclusion

In this paper, the design process of a 50 μm polyimide layer based on-chip antenna has been proposed and demonstrated, which is working over the higher frequency band of terahertz area from 0.600 THz to 0.622 THz. The proposed structure has been constructed of five stacked layers. It has been excited by a simple coupling feeding mechanism, which is based on the transferring the EM signal from the bottom layer to the top layer throughout the middle GND layer having a coupling slot. To improve the performance parameters of the antenna, the feasible approaches based on the metamaterial (MTM) and substrate-integrated waveguide (SIW) concepts have been employed by realizing the tapered slots on the radiation patches and metallic via-holes on the edges of the structure throughout the GND layer connecting top- and bottom-polyimide substrates to each other, without increasing the physical dimensions of the structure. The proposed on-chip antenna with dimensions of $1000 \times 1000 \times 100 \mu\text{m}^3$ can operate over a wide frequency range of 0.600 THz to 0.622 THz, which is related to 22 GHz. Across the entire frequency band, the antenna has an average gain and efficiency of 1.5 dBi and 60%, respectively. The results affirm that the proposed antenna with low profile, simple design process, and cost effective can be applicable to use in THz integrated circuits.

Data Availability

The data used to support the findings of this study are available in the manuscript and from the corresponding author upon request.

Conflicts of Interest

The author declares no conflicts of interest.

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