

# A 254-276 GHz On-Chip THz Antenna Using Substrate Integrated Waveguide and Metamaterials for Short-Range Wireless Communications

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**Abstract**—This paper presents a novel, low-profile on-chip antenna (OCA) based on metamaterials (MTM) and substrate-integrated waveguides (SIW), operating in the frequency range of 254-276 GHz. It consists of five stacked layers: copper patch, polyimide, copper ground, polyimide, and a copper microstrip feedline. The top copper layer consists of a  $2 \times 2$  array of square patches with sub-wavelength-sized cross-sectional slots, which modify the array into a metamaterial. The antenna is excited by aperture coupling through the slot present in the ground layer. Both the top and bottom substrate layers are encapsulated by a series of metallic vias on either side. The proposed OCA is  $500 \times 500 \times 130 \mu\text{m}^3$  in size. Simulation results using Ansys High Frequency Structure Simulator (HFSS) indicate that the proposed OCA is promising for the integrated wireless system for short-range communications.

**Index Terms**—Substrate Integrated Waveguide (SIW), Metamaterials (MTM), On-chip Antenna (OCA).

## I. INTRODUCTION

The rapid adoption of mobile communications and the Internet of Things (IoT) necessitates a large operating bandwidth to support high-data-rate traffic. To cope with the immense amount of data, the currently allocated frequency spectrum will become congested for future communication systems. One possible solution is to use mm-wave communications, as in the fifth generation (5G) communication system, which has the ability to provide MHz to GHz bandwidth. However, it still cannot satisfy the data rate requirement. Edholm's law [1] states that “bandwidth and data rates double every 18 months,” so future wireless local area network (WLAN) and virtual reality (VR) systems would require data rates of at least 10 Gbps. In particular, the data rate requirement for three-dimensional (3D) videos would reach up to 100 GB/s [2], which necessitating the study of an even higher frequency band.

This problem could be solved by utilising the least-explored terahertz (THz) band, which lies between the microwave and infrared regions and ranges from 0.3 to 10 THz, according to the IEEE standard. Compared with the existing frequency band allocated to mobile communications, the THz band offers high spectral resolution and better system gains, making it applicable to various applications, such as biomedical and

chemical detection, imaging, spectroscopy, inter- and intra-chip communication [3], inter-satellite communication [4], and short-range wireless communications [5]. Although THz wireless systems are less affected by the atmosphere compared to optical wireless communication, there is a high path loss due to molecular absorption, resulting in a significantly reduced transmission distance. Therefore, a high-gain antenna is required to compensate for the transmission loss.

The quality of an antenna plays a crucial role in determining the properties of any wireless system, such as gain, bandwidth, and efficiency. Since the size of an antenna is determined by its operating frequency, for the terahertz band, the antenna size falls in the micron range. He et al. [6] provided a summary of basic THz antenna designs, which are listed below:

- **Metallic antennas:** This type of antenna is relatively easy to fabricate and offers high gain and efficiency. However, designing metallic antennas can be challenging due to mechanical complexity [7]. Typical designs in this category include horn antennas and traveling-wave corner cube antennas.
- **Dielectric antennas:** These antennas are easily accessible for coupling, and their connection to the circuit is relatively superficial. However, they are susceptible to the surface wave effect. Typical designs in this category include lens antennas.
- **New material antennas:** This category is still in development phase and relies on material science advancements. New designs in this category include carbon nanotubes and metamaterial antennas.

System-on-chip (SoC) technology enables further reduction in antenna size. By integrating both the receiver and transmitter on a single chip, SoC offers advantages such as increased repetition of radiating patches, smaller footprints, and the elimination of bond wires, flip-chips, and packaging. These benefits result in time and cost saving, as well as reduced loss and impedance mismatch at high-frequency operations. Figure 1, illustrates a wireless system comprising four modules: an amplifier, a detector, and RF circuit, and an antenna, all of which are integrated into a single substrate using SoC concept.

This led to the research and development of on-chip antennas (OCAs).

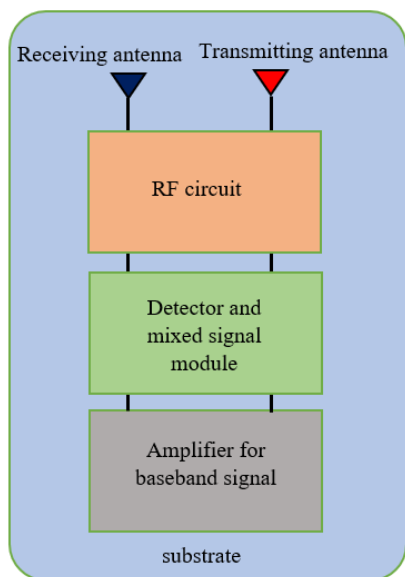


Fig. 1. System-on-chip (SOC) architecture

In this paper, we propose a low-profile and novel on-chip antenna (OCA) based on substrate-integrated waveguides (SIW) and metamaterials (MTM) for short-range wireless communications. The rest of the paper is organized as follows: Section II presents the related work, Section III describes the details of the proposed OCA design, Section IV presents the simulation and results, Section V compares the proposed OCA with existing OCAs reported in the literature, and Section VI concludes the paper.

## II. RELATED WORK

Various methods and techniques have been developed to enhance the directivity, gain, and radiation efficiency of antennas. One approach is to incorporate dielectric materials in the form of lenses onto the transmitting source [8]. Hemispherical and ellipsoidal lenses can be fabricated using low-loss dielectric materials. However, as the thickness of the lens increases, a significant portion of the radiated power is directed towards the substrate.

In the case of a dielectric resonator antenna [9], placing a dielectric material on top of the radiating layer allows the radiation component to separate from the metal layer, thereby reducing metal loss and surface loss. However, there is a risk that the thickness of the dielectric resonator may become compromised or misaligned during the fabrication process.

The artificial magnetic conductor (AMC) property [10] is similar to the perfect magnetic conductor (PMC) property in that it allows for zero-degree phase reflection at the resonant frequency. However, it requires an additional layer of metal, which complicates the metallization technique for on-chip antennas (OCAs). Defected ground structure (DSG) [11] is another technique that involves creating slots in the ground plane to increase radiation resistance. However, it requires a

high level of precision to fabricate those slots. The superstrate layer [12] is used to enhance directivity, gain, and radiation efficiency, while also providing protection to the antenna from the external environment. However, it requires additional layers such as teflon glass and polyimide on top of the radiating layers. Other methods used for antenna improvement include silicon-insulator (SOI), fractal antenna structure [13], benzocyclobutene (BCB) layer [14], and photonic band gap (PBG) [15].

These traditional methods suffer from drawbacks such as being time-consuming, expensive, and challenging to design from a manufacturing perspective. In recent years, alternative approaches like SIW and metamaterials (MTM) or metasurfaces (MTS) have gained significant attention for antenna miniaturization and integration with chips. Theoretical and experimental studies have demonstrated that SIW and MTM/MTS antennas [10] [16] [17] can effectively address the existing issues. These methods can also be applied to on-chip antennas (OCAs) for inter-chip communications in multi-core processors, enabling higher transmission rates among the cores. Currently, the transmission rates among the cores are limited by the inter-network bus [18].

SIW is a specialized rectangular waveguide designed for high-frequency operations. It utilizes a series of metallic or hollow vias on both sides, along with metal layers on the top and bottom, to confine the substrate materials. This design helps overcome issues such as mutual coupling and surface loss. Thanks to recent advancements in fabrication technology, the vias can be created with high precision.

When embedding SIW with OCA, the bandwidth (BW) of the system depends on two conditions:

$$BW \propto h \quad (1)$$

$$BW \propto \frac{1}{\sqrt{\epsilon_r}} \quad (2)$$

Where  $h$  and  $\epsilon_r$  are the SIW substrate's height and dielectric constant, respectively.

MTM and MTS are two-dimensional structures that are artificially designed materials. They possess electromagnetic characteristics that are not naturally found. This unique property of MTM is achieved by incorporating sub-wavelength slots in the radiating surfaces, which function as mini-resonators and facilitate the radiation of THz waves. The presence of these sub-wavelength slots enhances the radiation efficiency, gain, and bandwidth of the antenna [19]. Additionally, the lightweight nature of MTM simplifies the manufacturing process [20].

## III. PROPOSED ANTENNA GEOMETRY

The proposed layout of the On-Chip Antenna (OCA) is illustrated in Fig. 2. It comprises five layers stacked on top of each other: copper (radiating patches), polyimide substrate, copper (ground plane), polyimide substrate, and copper (feedline). In Fig. 2(a), the top layer is shown as a 2-by-2 array of square-shaped copper patches. To achieve the desired Metamaterial (MTM) properties, each element of the array undergoes cross-section-shaped etching, modifying the

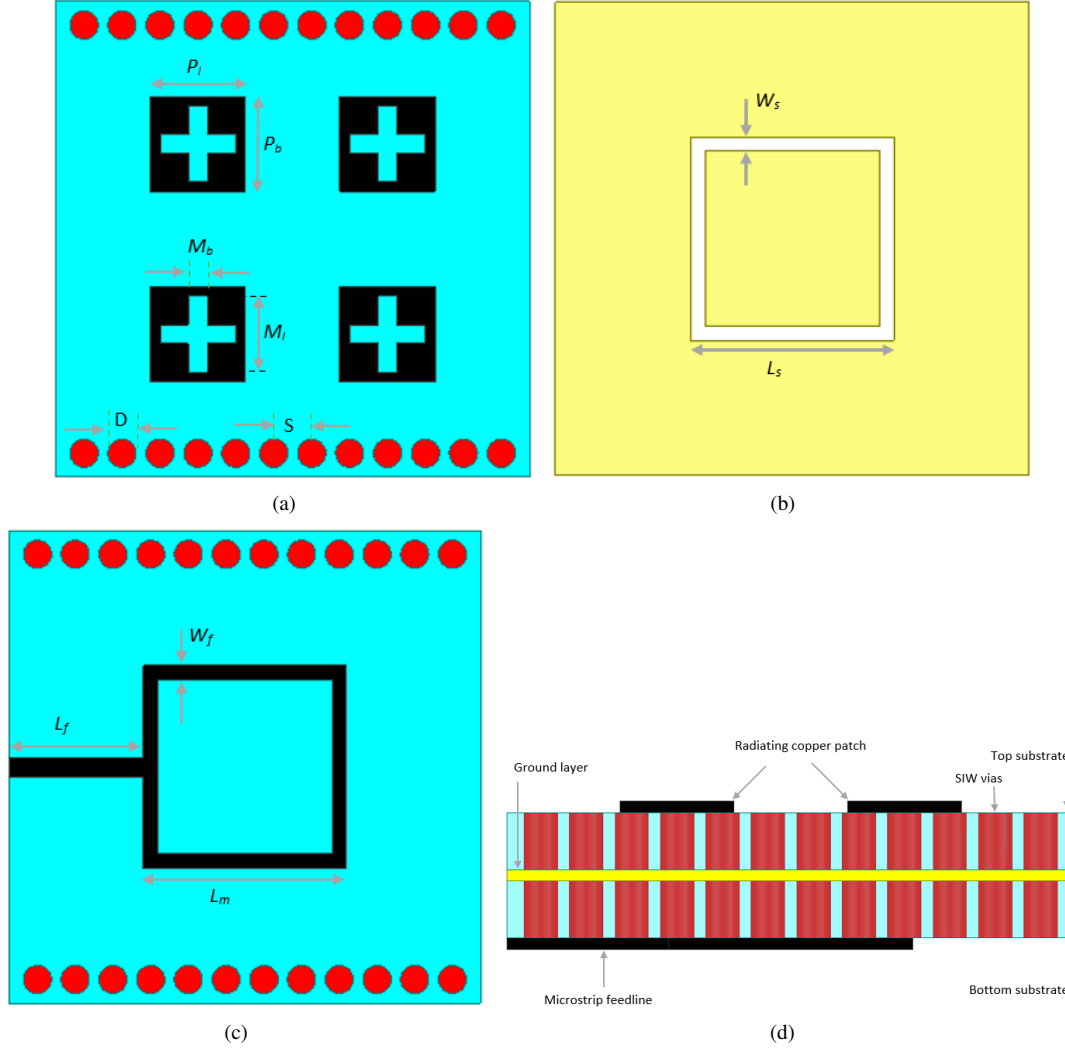


Fig. 2. On-Chip Antenna Architecture. (a) Top- view, (b) Ground-plane, (c) Back-view, and (d) side view

physical structure of the radiating surface. Fig. 2(b) depicts the placement of a ground plane beneath the top substrate layer. This ground layer serves to isolate the antenna structure from the lossy nature of the substrate layer [17]. Additionally, a square-shaped slot is etched on the ground layer to optimize the power transfer from the bottom feedline layer to the top radiating elements. This type of coupling method is known as aperture coupling and offers a higher level of flexibility for improving antenna properties by varying substrate materials and their dielectric constants. While other feeding mechanisms such as proximity, probe-fed, and line-fed exist, aperture coupling provides a moderate bandwidth [21]. 2(c) shows a square-shaped microstrip feedline positioned beneath the bottom polyimide layer, with one end serving as the excitation port. To minimize radiation leakage, two layers of SIW are applied on both sides of the top and bottom substrates. Initial parameters for the SIW width are calculated as per [22].

$$S_{width} = W_{eff} + p(0.766e^{0.4482\frac{d}{p}} - 1.176e^{-1.214\frac{d}{p}}) \quad (3)$$

Where  $d/p$  is the via diameter to via spacing ration with a range of 0.5 to 0.8,  $S_{width}$  represents the width of the SIW.

The effective waveguide width  $W_{eff}$  can be calculated using the equation below.

$$W_{eff} = \frac{c}{2f_c\sqrt{\epsilon_r}} \quad (4)$$

Only the transverse electric mode ( $TE_{10}$ ) is present as the dominant mode due to the metallic vias on either side of the SIW. The value of  $S_{width}$  determines the cut-off frequency ( $f_{cut}$ ), which can be calculated using the equation below.

$$f_{cut} = \frac{1}{2\pi\sqrt{\mu_o\epsilon_o}} \sqrt{\left(\frac{m\pi}{S_{width}}\right)^2 + \left(\frac{n\pi}{h}\right)^2} \quad (5)$$

where  $h$ ,  $\mu_o$ ,  $\epsilon_o$ ,  $m$ , and  $n$  are the height of the SIW, permeability of free space, permittivity of free space, and half-wavelength across the X and Y axes, respectively.

Copper is chosen as the material for this OCA design due to its high carrier mobility ( $5.8 \times 10^7$  siemens/m), which enables a high-frequency response in the THz band compared to materials such as aluminium ( $3.8 \times 10^7$  siemens/m) and gold ( $4.1 \times 10^7$  siemens/m). The silicon substrate is used to confine electromagnetic radiation and reflect back power radiation due to its low resistivity (10  $\Omega$ -cm) and high dielectric constant

( $\epsilon_r = 11.7$ ). For high-frequency performance, a polyimide substrate is selected with a high resistivity ranging from ( $10^{13}\Omega\text{-cm}$  to  $10^{19}\Omega\text{-cm}$ ) and a low dielectric constant ( $\epsilon_r = 3.5$ ). This choice minimizes substrate loss and power consumption.

The polyimide substrate is  $50\ \mu\text{m}$  thick and has a loss tangent of ( $\tan(\delta)$ ) 0.008. The size of the antenna is  $500\times 500\ \mu\text{m}^2$ , and rest of the antenna dimensions are shown in Table I.

TABLE I  
DESIGN PARAMETERS OF THE OCA

Parameter	Dimension
Area of square patch ( $P_l \times P_b$ )	$100 \times 100\ \mu\text{m}^2$
Length and breadth of MTM slot ( $M_l \times M_b$ )	$80 \times 20\ \mu\text{m}^2$
Diameter (D) of the SIW vias	$30\ \mu\text{m}$
Spacing (S) or pitch of vias	$40\ \mu\text{m}$
width of the etched slot in ground layer ( $W_s$ )	$2\ \mu\text{m}$
Area of the etched slot ( $L_s^2$ )	$202 \times 202\ \mu\text{m}^2$
width of the feedline ( $W_f$ )	$15\ \mu\text{m}$
Area of microstrip ( $L_m^2$ )	$215 \times 215\ \mu\text{m}^2$

#### IV. SIMULATION RESULTS

A full-wave, three-dimensional (3D) electromagnetic computational software called Ansys High-Frequency Structure Simulator (HFSS) is employed in the design and validation of the OCA parameters. HFSS utilizes the finite element method (FEM) and employs a tetrahedral mesh for its operations. Table II provides the necessary materials and simulation setup design for the proposed antenna. The parametric sweep feature in HFSS accelerates the design process, allowing for the attainment of the desired value of  $|S_{11}| < -10\ \text{dB}$ . This results in a frequency range of 254–276 GHz, corresponding to a bandwidth of 22 GHz. Fig. 3 illustrates that the utilization of SIW and MTM slots has significantly enhanced the impedance bandwidth. The presence of frequency-dependent components such as capacitance and inductance introduces an imaginary component, making it challenging to achieve the ideal voltage standing wave ratio (VSWR) of 1 (0 dB). Therefore, a VSWR slightly higher than 1 is desired. Fig. 4 illustrates that at the resonating frequency of 267 GHz, the VSWR is approximately 1.1 dB.

Fig. 5 displays the 2D radiation pattern (E and H planes) of the proposed OCA at the operating frequency of 267 GHz. The OCA exhibits bi-directional radiation in the H-plane and broad radiation in the E-plane. The theoretical relationship between the gain (G) and directivity (D) is given below:

$$G = \eta D \quad (6)$$

where  $\eta$  represents the dimensionless efficiency factor of the antenna, with values ranging from  $0 \leq \eta \leq 1$ . It is important to note that the antenna always has a value of  $D > 1$ , resulting in a lower gain compared to directivity. This can be observed in the simulation plot of gain and directivity comparison depicted in Fig.6.

#### V. PERFORMANCE COMPARISON

In Table III, the key features of the proposed OCA are compared with those of existing OCAs reported in the literature.

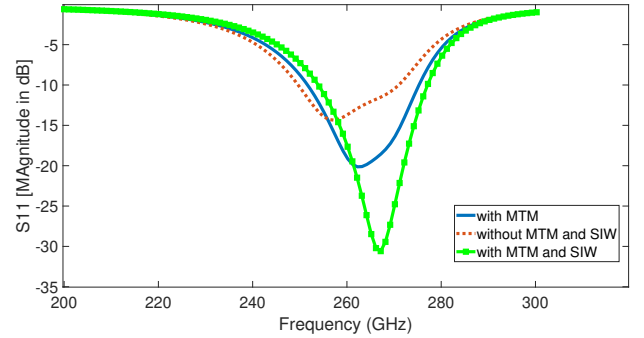


Fig. 3.  $|S_{11}|$  response of OCA (a) without MTM and SIW, (b) with MTM slots, and (c) with MTM and SIW

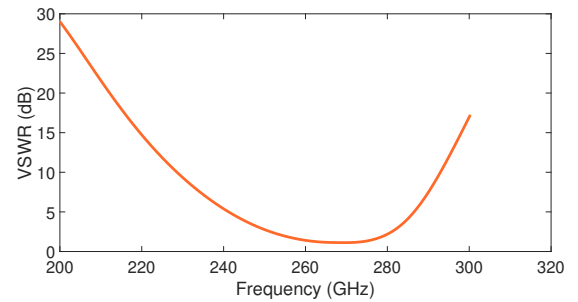


Fig. 4. VSWR of the proposed OCA

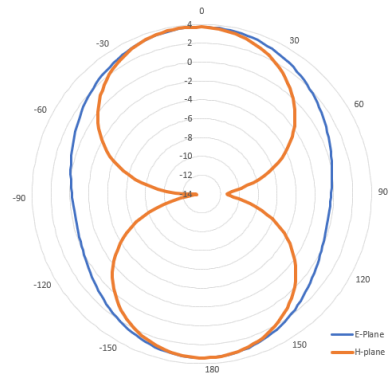


Fig. 5. Normalized radiation pattern at 267 GHz

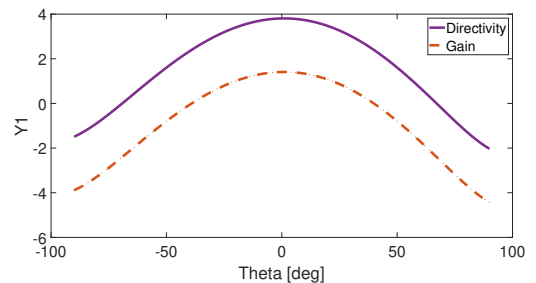


Fig. 6. Directivity and gain comparison at 267 GHz

It is observed that the OCA [23] exhibits a comparable gain to the proposed OCA, but it has a larger overall size in terms

TABLE II  
MATERIALS AND SIMULATION ENVIRONMENT OF THE PROPOSED OCA

Material	Properties	Simulation Environment
Copper	Thickness 10 $\mu\text{m}$	Software: Ansys HFSS v. 2022
	Conductivity $5.8 \times 10^7$ siemens/m	Terminal mode with lumped port excitation
Polyimide	Thickness 50 $\mu\text{m}$	Discrete frequency sweep: 200-300GHz Iterative mixed order solver
	Loss tangent ( $\tan(\delta)$ ) 0.008 Dielectric constant ( $\epsilon_r$ ) 3.5	

TABLE III  
PERFORMANCE COMPARISON OF OCAS

Antenna Reference	Parameters				
	Fabrication	Design method	Size	Operating frequency	Gain
[4]	0.13- $\mu\text{m}$ SiGe BiCMOS	Circular polarized array	$3.6 \times 3.6 \text{ mm}^2$	0.314-0.323 THz	8.7 dBi
[10]	100- $\mu\text{m}$ GaAs	SIW and MTM	$0.8 \times 0.8 \times 0.13 \text{ mm}^3$	0.45-0.50 THz	6.5 dBi
[14]	675- $\mu\text{m}$ low-resistivity silicon	Benzocyclobutene	-	0.27 THz	5.2 dB
[16]	125- $\mu\text{m}$ Silicon	SIW and MTM	$1 \times 1 \times 0.265 \text{ mm}^3$	0.2-0.22 THz	8.5 dBi
[17]	50- $\mu\text{m}$ Polyimide	SIW and MTM	$1 \times 1 \times 0.1 \text{ mm}^3$	0.6-0.622 THz	1.1-1.8 dBi
[23]	100- $\mu\text{m}$ Polyimide	MTS	$20 \times 10 \times 0.35 \text{ mm}^3$	0.3-0.32 THz	2.5 dBi
[24]	20- $\mu\text{m}$ Silicon	MTS	$0.2 \times 0.2 \times 0.045 \text{ mm}^3$	0.5-0.56 THz	4.58 dBi
[25]	0.13- $\mu\text{m}$ CMOS	SIW and MTM	$1.35 \times 1 \times 0.06 \text{ mm}^3$	0.285-0.325 THz	6.9 dBi
<b>This Work</b>	50- $\mu\text{m}$ Polyimide	SIW and MTM	$0.5 \times 0.5 \times 0.13 \text{ mm}^3$	0.254-0.278 THz	2.7 dBi

of area.

From a manufacturing standpoint, it is worth noting that the OCAs discussed in [10] consist of seven stacked layers, which introduces a high level of complexity and increases the risk of misalignment during fabrication. In the case of the OCA described in [25], it is fed by anti-podal fin-lines, which necessitates additional efforts to achieve impedance matching. Another example is the OCA outlined in [14], which requires multiple layers of benzocyclobutene, metal-organic chemical vapor deposition, and aluminum nitride (AlN) nucleation. Although these OCAs may offer higher gain compared to the proposed OCA, their manufacturing processes involve additional steps and materials.

## VI. CONCLUSION

This paper introduces a new and straightforward on-chip antenna designed for the frequency range of 254-276 GHz. The antenna's performance is enhanced by incorporating substrate-integrated waveguide (SIW) and metamaterial (MTM) techniques, which involve etching the cross-sectional shape into the patches to enlarge the radiating aperture area. Aperture coupling is employed to excite the antenna through a slot in the ground layer. Comparative analysis of the simulation results with existing on-chip antennas reveals that the proposed OCA offers a superior bandwidth.

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