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Design and analysis of metamaterial integrated modified golden spiral antenna for Terahertz applications

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Decagon metamaterial unit cell.

Abstract. The article presents a high gain metamaterial (MTM) integrated modified golden spiral antenna for THz (Terahertz) applications. The MTM unit cell is designed by two decagon SRRs (Split Ring Resonator). The proposed antenna has the dimensions of $100 \times 100\ \mu\text{m}^2$ with MTM decagon rings on the ground. The MTM integrated antenna resonates at 2.80 THz, 3.15 THz, and 3.46 THz with impedance bandwidths of 2.77 THz −2.88 THz and 3.00–3.70 THz.

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1. Introduction

The demand for mobile communications and innovative technologies has increased dramatically in recent years. The congested frequency bands in the Megahertz (MHz) as well as Gigahertz (GHz) frequency ranges for wireless communications, as well as the ever-increasing need for high bandwidth, have prompted researchers to hunt for the unexplored electromagnetic (EM) spectrum, such as the Tetrahertz (THz) region. THz is well suited to the development of a next-generation wireless telecommunication system capable of firing at a tremendous rate of 100 Gb/sec [1]. This use of the THz technology appears to be highly promising for high-speed data transfer between electronic devices. THz waves suffer from substantial free space path loss and atmospheric attenuation due to their shorter wavelengths than microwaves. This free space route loss can be mitigated by employing an antenna with strong directivity and gain. However, smaller antennas are required to transmit these lower wavelength signals [2]. THz waves exist in the EM spectrum between millimeter (mm) and far-infrared (FIR) waves [3]. THz waves are so named because they have a frequency

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range 300 GHz (0.3 THz) to 3 THz that corresponds to wavelengths 100 μm to 1000 μm. For diverse THz applications, several antennas had been designed and proposed [4,5].

There has been a great deal of interest in novel and innovative THz and optical material known as metamaterials (MTM). MTM, also known as Left-Handed Materials (LHMs) or negative index materials. MTM are intriguing because they allow for the artificial creation of unique material properties without relying on the fixed characteristics and properties of existing materials. There has recently been a surge in interest in the development of MTM antennas [6–15]. Many studies have been conducted to examine common antenna properties such as return loss (S_{11}), Voltage Standing Wave Ratio, directivity, radiation pattern, and gain.

In this paper a miniaturized MTM integrated modified golden spiral antenna for THz applications is presented. The antenna is designed by combining two golden spiral shapes and decagon MTM unit cells in the ground.

2. Antenna design and configuration

This section explains the concept of antenna design for THz frequency. The geometrical structure of the proposed antenna prototype is shown in Figure 1. The conducting patch is designed on a polyimide substrate of dielectric constant 3.5, loss tangent of 0.0027, and thickness of 10 μm which is noticed in optical systems. The conducting patch of an antenna is designed by placing two golden spirals and connecting them with arcs. The patch is modified by adding various leaf-shaped slots in the patch. The leaf shapes are designed by using the analytical curve of half-sine sinusoidal shape. The fractal slots and golden spirals with arcs are shown in Figure 1(b). The simulation of the proposed design is carried out using a CST microwave studio with a finite difference time domain method. The variation of the S-parameter with frequency is shown in Figure 2. The antenna resonates at 3.28 THz with impedance bandwidth ranging from 2.81 −3.58 THz. To validate the antenna design and to compare the results the antenna is designed in HFSS and S-parameter with frequency is plotted as shown in Figure 2(c) and (d). The antenna bandwidth is coming approximately the same in both designs with 0.2 THz of difference in the resonating frequency.

2.1. Antenna design concept and inspiration

The golden ratio ($\phi = (1 + 5)/2 = 1.681803...$) is commonly symbolized by the Greek letter ($\phi = (1 + 5)/2 = 1.681803...$) For a long time, there has been a lot of curiosity and attention on them, with claims that they are both aesthetically essential and widespread in nature [16]. Several actual examples in nature and biological systems support the notion that the golden ratio is more than just math. The golden ratio and Fibonacci pattern observed in the Fibonacci golden spiral inspired the antenna constructed and presented in this article. The golden rectangle is also known as rotating a square rectangle [17] because of its unique feature of subdividing into a reciprocal rectangle and a square. By drawing the arc with radius equals to the sides of the squares as shown in Figure 2(a) produces a Golden spiral, the main concept of the designed antenna.

From Figure 2(a) the ratio of a/b is equal to $(\phi) = 1.68$ = Golden ratio. The side length of each square follows the Fibonacci sequence number. The Fibonacci number begins from 1 and each new number of series is simply the sum of the previous two numbers. Thus the second number of the series is also 1, which is the sum of 0 and 1 (previous two numbers in Fibonacci

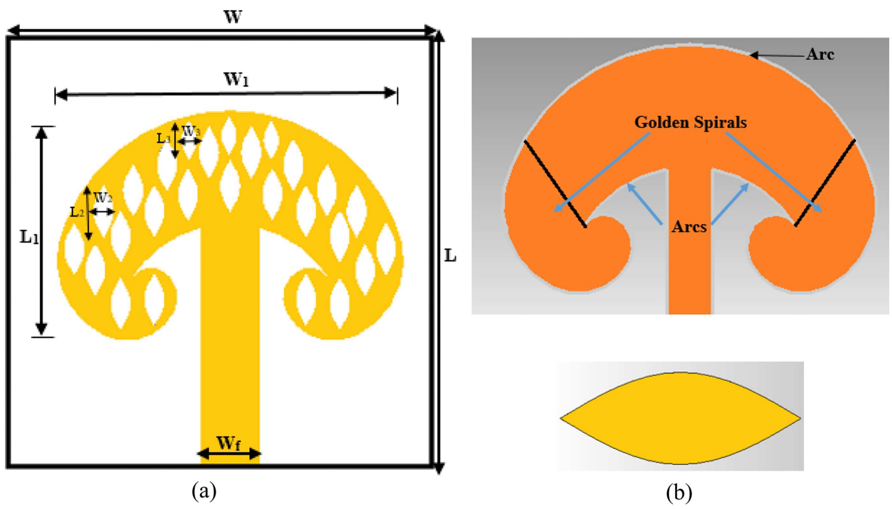

Figure 1. (a) Structure of the modified golden spiral antenna. (b) Conducting patch and fractal slot.

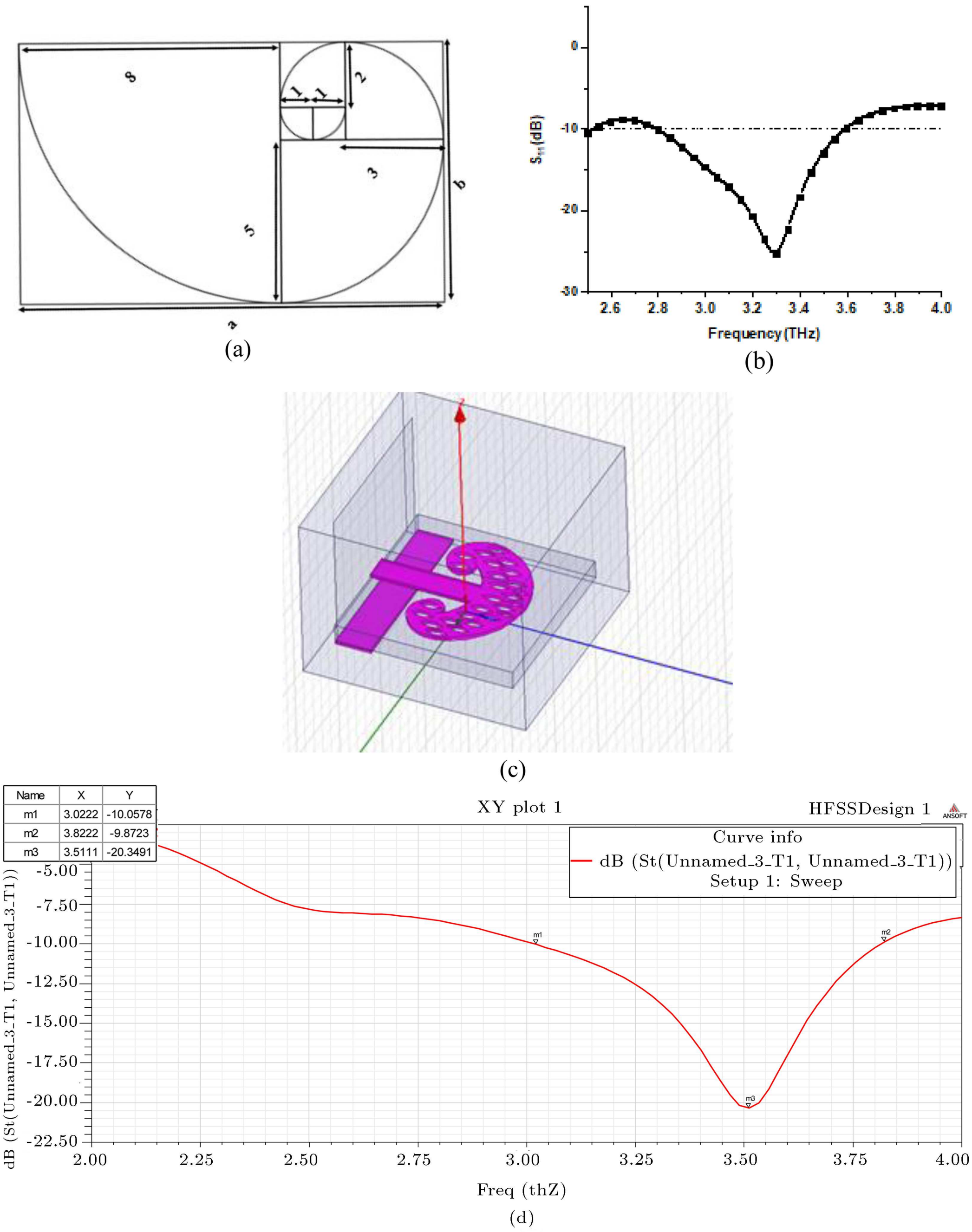

Figure 2. (a) Golden spiral for antenna design; (b) S-parameter variation with frequency (CST); (c) Antenna geometry on HFSS; and (d) S-parameter variation with frequency (HFSS).

sequence). Hence, the Fibonacci sequence numbers are given as follow [18,19]:

$$0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610,$$

$$987, 1597, 2584, ..., \text{ etc.}$$

3. MTM unit cell design and characterization

Permittivity (ε), permeability (μ), and conductivity are used in EM to describe the properties of a material. The propagation profile of the material at a given frequency is described by the extraction of these values for different frequencies. The MTM unit cell is composed of a polyimide substrate of refractive index 3.5 and a thickness of 10 μm. The MTM unit cell design is shown in Figure 3, which consists of two decagon split rings. The thickness of the decagon Split Ring Resonator (SRR) copper wire, gap, and width are 2 μm, 3 μm, and 3 μm, respectively. The conducting loop produces the inductance and the gaps between the two produce the capacitance [6]. The reflection coefficient

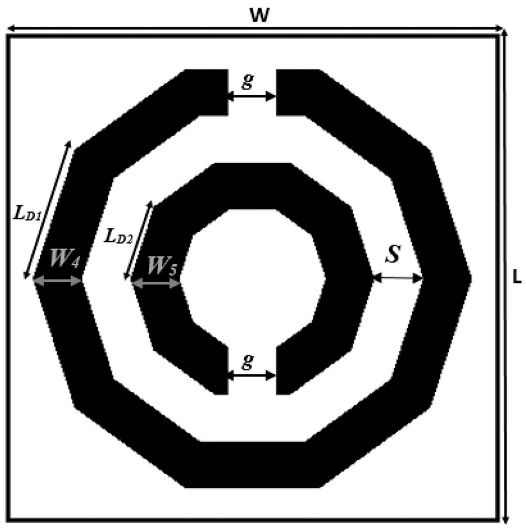

Figure 3. Decagon shaped metamaterial unit cell.

(S_{11}) and transmission (S_{21}) coefficient are obtained using simulation tool (CST Microwave studio). The permittivity (ε) and permeability (μ) of the material under test have been calculated using the refractive index (n) and impedance (z) of the material. The S parameters of this system can be written as [7]:

$$S_{11} = \frac{R_{01}(1 - e^{i2nk_0d})}{1 - R_{01}^2 e^{i2nk_0d}}, \tag{1}$$

$$S_{21} = \frac{(1 - R_{01}^2)e^{i2nk_0d}}{1 - R_{01}^2 e^{i2nk_0d}}, \tag{2}$$

where, impedance z is related to R_{01} as:

$$R_{01} = \frac{z-1}{z+1}. \tag{3}$$

From Eqs. (1), (2), and (3) by rearranging equations the (refractive index) and z (impedance) are obtained from S parameters as:

$$Z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}, \tag{4}$$

$$e^{ink_0d} = \frac{1}{2S_{21}(1 - S_{11}^2 + S_{21}^2)} \pm i\sqrt{1 - \left(\frac{1}{2S_{21}(1 - S_{11}^2 + S_{21}^2)}\right)^2}. \tag{5}$$

The value of refractive index n can be determined from the Eq. (5) as:

$$n = \frac{1}{k_0d}\left\{[\ln(e^{ink_0d})]'' + 2m\pi + i[\ln(e^{ink_0d})]'\right\}, \tag{6}$$

where k_0 is the wavenumber of the incident wave in free space, m is the branch index due to the periodicity of the sinusoidal function, $(.)'$ denotes the real part and $(.)''$ denotes the imaginary part operator. Permittivity (ε), permeability (μ), refractive index (n), and impedance (z) are related as follow:

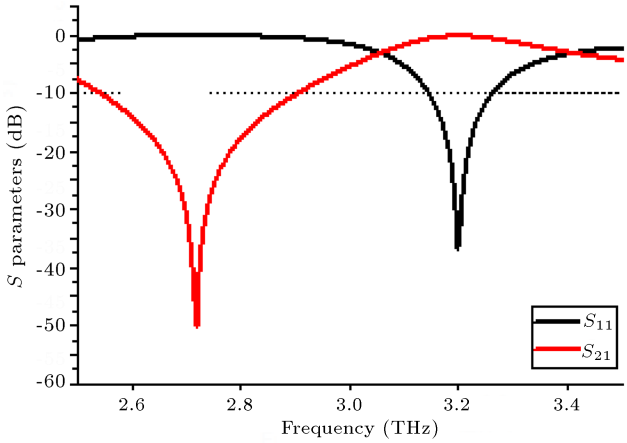

Figure 4. S-parameters variation of MTM unit cell.

$$\varepsilon = \frac{\text{refractive index}}{\text{impedance}} = \frac{n}{z}, \tag{7}$$

$$\mu = \text{refractive index} * \text{impedance} = n * z. \tag{8}$$

4. Results and discussions

The extracted S parameters are presented in Figure 4. In Figure 2 S_{11} displays resonance at 0.3.2 THz and S_{21} at 0.27 THz with values of -35.61 dB and -49.33 dBrespectively. From the extracted S parameters to obtain MTM properties, the Eqs. (1) to (8) were used to write code in MATLAB software. The μ, ε, n, and z for the MTM unit cell are extracted and plotted in Figure 5(a)–(d). As it can be observed from the obtained values of permeability and permittivity the negative behaviour at the resonance frequency.

The designed patch antenna is then loaded with MTM unit cells as shown in Figure 6. The six MTM unit cells are added in the ground of designed antenna. The optimized dimension of the proposed structure is presented in Table 1. Figure 7 shows the S-parameter comparision of antenna with MTM and without MTM. The tabular comparison of parameters for antenna with MTM is presented in Table 2. The excited surface current distribution on the proposed antenna at resonating frequencies are shown in Figure 8. In Figure 8(a) it is observed that the current distribution appears to be mainly concentrated on the full patch, upper middle and the lower three MTM unit cells at 2.8 THz. At 3.15 THz the current is distributed in the full patch, lower three rings and upper middle rings. On the other hand, current is distributed mainly in the lower part of the patch, ground and lower middle ring as compared to other parts of an antenna.

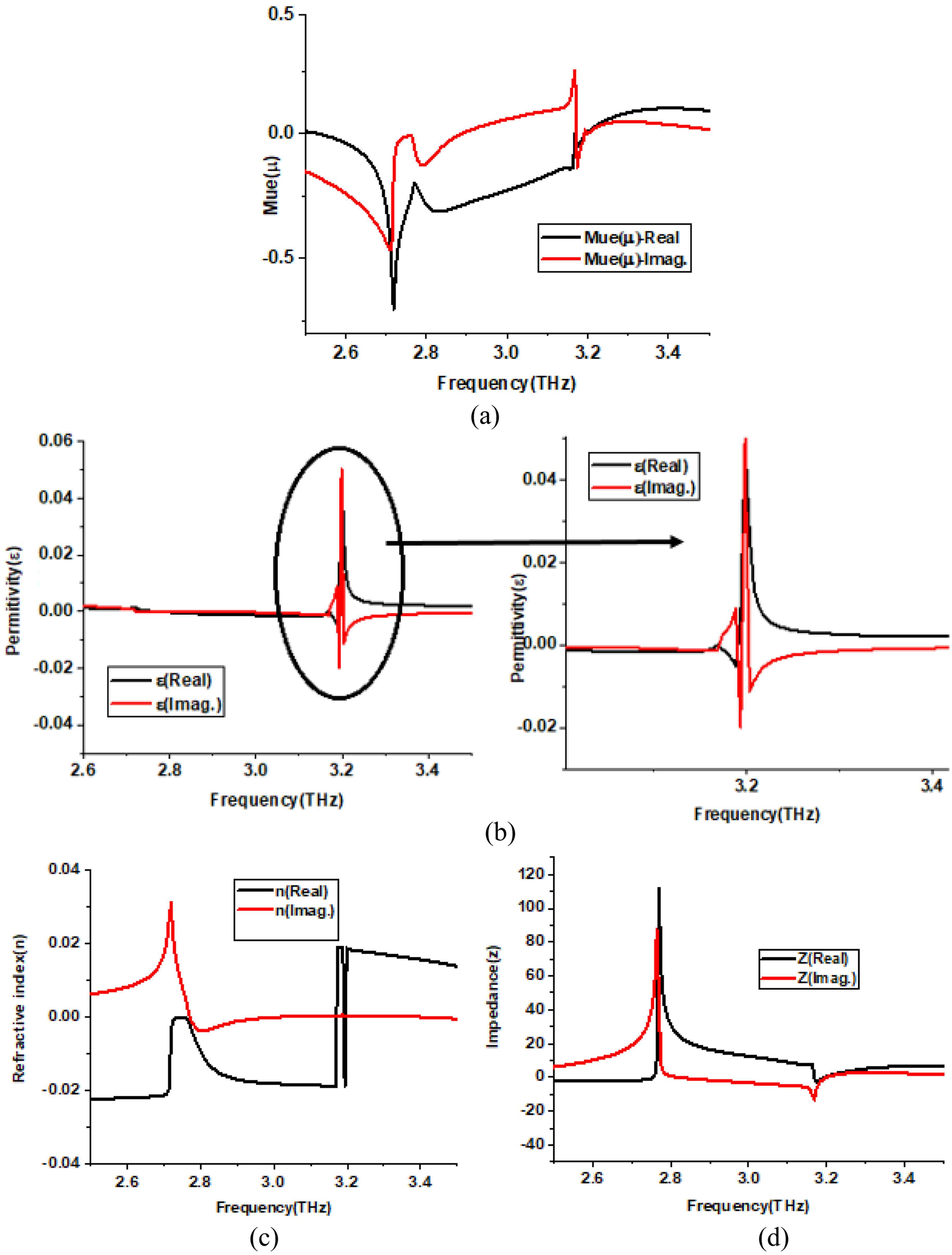

Figure 5. Metamaterial parameters: (a) Permeability (ε); (b) Permittivity (μ); (c) Refractive index (n); and (d) Impedance (z).

Figure 9 shows the E-plane ($\phi = 0^\circ$) and H-plane ($\phi = 90^\circ$) radiation pattern for the proposed antenna at resonating frequencies. At 2.8 THz distorted omnidirectional E-field has been obtained. On the other hand, a bidirectional radiation pattern can be observed at 3.15 THz and 3.46 THz. The H-fields are multilobe with main lobes pointing at 0°, 100°, and 215° for 2.8 THz, 3.15 THz, and 3.46 THz respectively. The comparison of the proposed antenna with the state of the art is shown in Table 3.

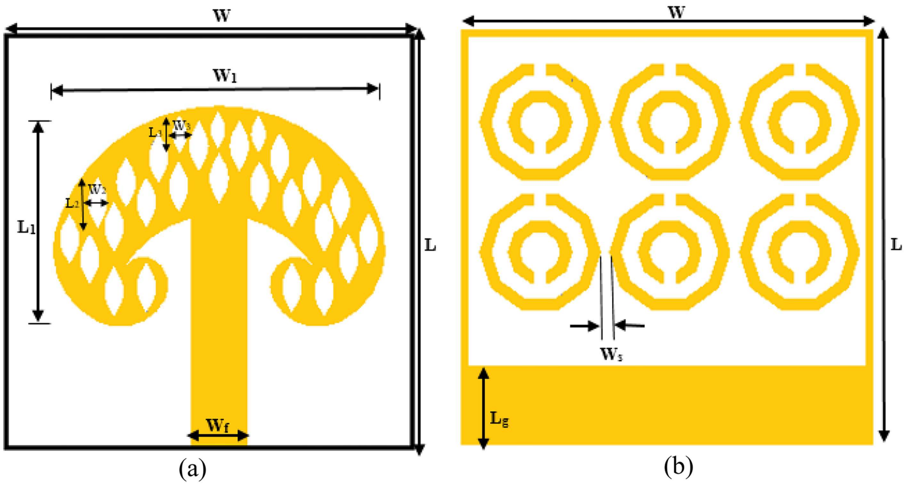

Figure 6. Proposed antenna structure with metamaterial: (a) Front view and (b) Back view.

Table 1. Optimized parameters of an antenna.

Parameters	Values (μm)	Parameters	Values (μm)	Parameters	Values (μm)
W	100	W_2	4.8	W_5	3
L	100	W_3	3.6	S	4
W_f	14	L_1	54	g	3
W_1	83	L_2	12.5	W_4	3
L_g	20	W_s	2	L_3	9.8
L_{D2}	5	L_{D1}	9.27	a	27.2
b	16.5				

Table 2. Comparison of parameters for antenna with metamaterial and antenna without metamaterial.

	f_1	f_2	BW	S_{11} (dB)
Antenna without metamaterial	2.80 THz	3.57 THz	0.77 ThZ	–25.14
Antenna with metamaterial	2.77 THz 3.00 THz	2.88 THz 3.70 THz	0.11 THz 0.70 THz	–17.5 –37.6

Table 3. Comparision of proposed antenna with existing antenna.

Reference	Substrate	Size	MTM unit cell shape	Resonant frequency (THz)	Fractional bandwidth (%)
[8]	Quartz	$128.5 \times 150\ \mu\text{m}^2$	Circular shaped split ring resonator	1.02 THz	4.12
[9]	Quartz	$180 \times 212\ \mu\text{m}^2$	Rectangular	1.08	8.2
[10]	Silicon	$136 \times 189\ \mu\text{m}^2$	Rectangular	0.46	7.60
[11]	Silicon	$1000 \times 1000\ \mu\text{m}^2$	Rectangular	1.00	2
[12]	RogersRT5880	$160 \times 150\ \mu\text{m}^2$	Rectangular TZ-shaped	0.62 1.1	15
Proposed antenna	**Polyimide**	**$100 \times 100\ \mu\text{m}^2$**	**Decagon**	**2.8** **3.15, 3.46**	**3.9** **21.18**

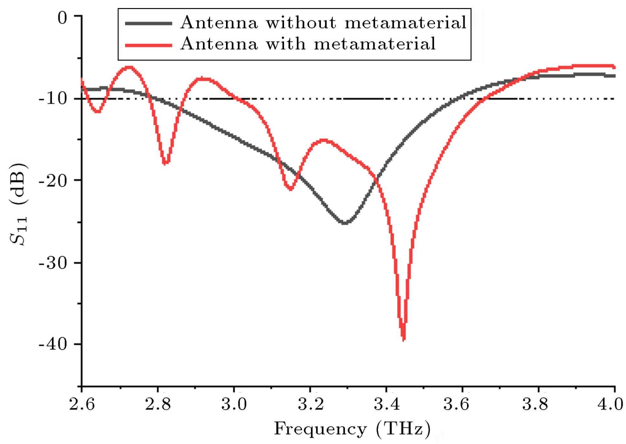

Figure 7. Comparision of S_{11} variation with frequency for metamaterial antenna.

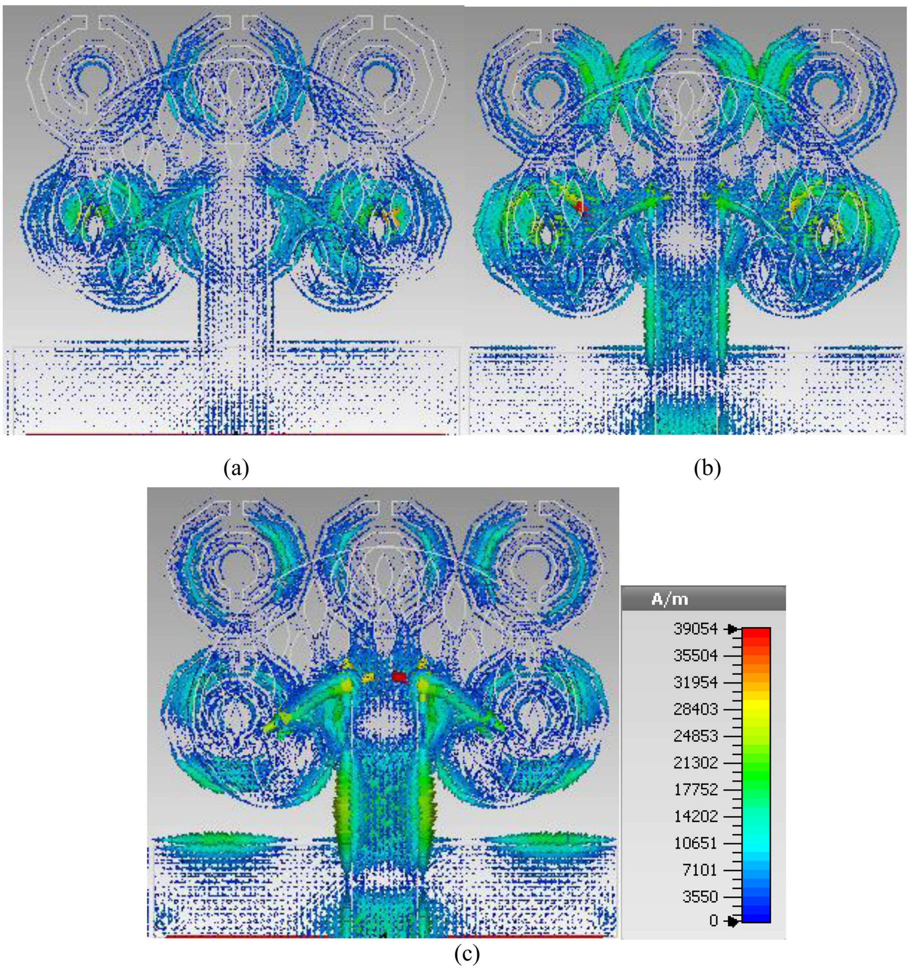

Figure 8. Surface current distributions (a) 2.8 THz; (b) 3.15 THz; and (c) 3.46 THz.

5. Conclusion

In this article, a modified golden spiral antennaintegrated with metamaterial (MTM) is presented for THz applications. The Golden spiral patch antenna is integrated with six decagon MTM unit cells in the ground plane. The antenna shows dual-band behaviour with bandwidths ranging from 2.77 THz−2.88 THz and 3.00–3.70 THz. The antenna resonates at 2.8 THz, 3.15 THz, and 3.46 THz with a return loss of −17.5 dB and −37.6 respectively. Thus the proposed antenna can be utilized for the THz applications.

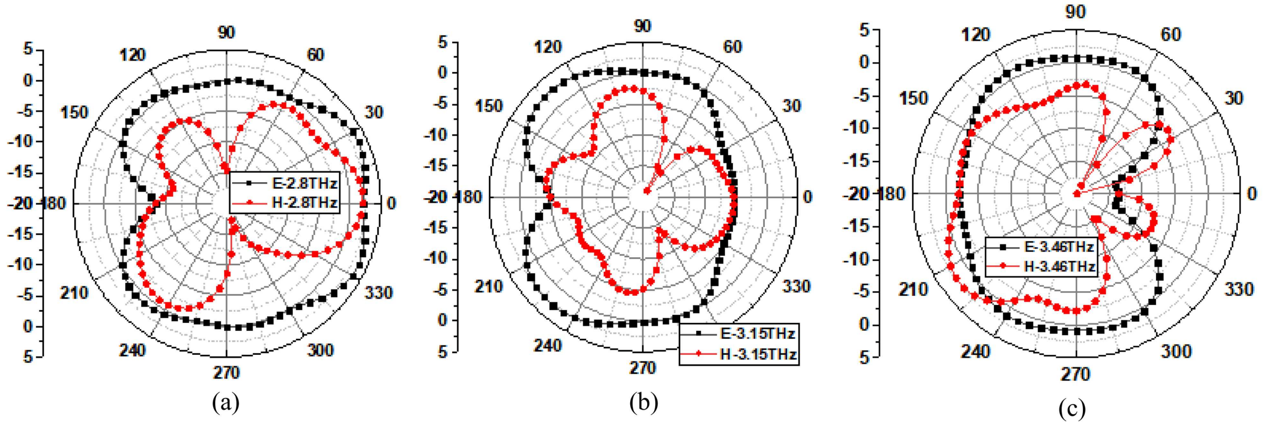

Figure 9. Radiation patterns at resonating frequencies: (a) 2.8 THz; (b) 3.15 THz; and (c) 3.46 THz.

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Kanad Ray (Senior Member, IEEE) received the MSc degree in physics from Calcutta University and the PhD degree in physics from Jadavpur University, West Bengal, India. He has been a Professor of Physics and Electronics and Communication, and is currently working as the Head of the Department of Physics, Amity School of Applied Sciences, Amity University Rajasthan (AUR), Jaipur, India. His current research areas of interest include cognition, communication, electromagnetic field theory, antenna and wave propagation, microwave, computational biology, and applied physics. He has been serving as an Editor for various Springer book series. He was an Associate Editor of the Journal of Integrative Neuroscience (The Netherlands: IOS Press).

Sanyog Rawat is presently associated with Electronics and Communication Engineering Department, Manipal University Jaipur. He has been into teaching and research for more than 16 years. He graduated with Bachelor of Engineering (B.E.) in Electronics and Communication, Master of Technology (M.Tech) in Microwave Engineering and PhD in the field of Planar Antennas. He has published more than 80 research papers in peer-reviewed International Journals, Book series, and IEEE conferences. He has supervised nearly 30 M.Tech Dissertations and 03 PhDs and guiding 06 PhD scholars. He has organized several workshops, seminars, national and international conferences. He has been empaneled in the editorial board of various national and International Journals. His current research interests include reconfigurable RF printed circuits, passive and active microwave integrated circuits. He has visited countries like Japan, Thailand, Malaysia, UAE and Indonesia for academic and research work. He is also a member of several academic and professional bodies i.e., Senior Member IEEE, Life Member IE and ISLE.