Investigation on Metamaterial Antenna for Terahertz Applications

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Abstract— **In this paper, the metamaterial based rectangular microstrip patch antenna is proposed and designed for THz applications. The circular split ring resonator is implemented as metamaterial. By incorporating metamaterial in the conventional microstrip patch antenna, the size is reduced and the performance of antenna is improved. The proposed antenna has the dimensions of 180 × 212 ×10 μm^3 which is designed on Quartz substrate which is fed by microstrip line feed technique. Additionally, the performance of the metamaterial antenna is analyzed by varying unit cell gap size and thickness. The antenna resonates at 1.02 THz which gives the return loss of -65 dB. Thus, the proposed antenna can be utilized in THz region.**

Index Terms— Metamaterial, Terahertz region

I. INTRODUCTION

Recent years, there is a demand on the unallocated frequency spectrum, the future communication systems focus on THz region for increased carrier frequency, higher data rates and high channel capacity [1]. THz is quite suitable to develop a current generation wireless telecommunication system, which can fire at a blazing fast speed of 100 Gb/sec. This utility of THz technique is quite promising for high-speed information transmission between electronic devices. Terahertz radiation gives a more engaged flag that could enhance the performance and reduce the power utilization of mobile towers. One of the key features of THz radiation is that many materials which block visible and IR spectra, that reveal to be transparent in THz frequency range. THz frequency range allows achieving a fairly good spatial resolution required for rendering quality imaging.

Since THz wave has shorter wavelengths than microwaves it suffers by high free space path loss and high atmospheric attenuation. This free space path loss can be overcame by using antenna with high directivity and high gain. However, to transmit this shorter wavelength signals miniaturized antennas are needed [2]. Microstrip patch antennas will meet all these requirements, because of its ease of installation, low cost and small size. The simple mechanism to improve the gain of the patch antenna is implementing metamaterial surface [3]. Especially the circularly polarized patch antenna has the ability to reduce the multipath effects [4]. Hence, radiation from these antennas are not depending on the orientation of transmitter and receiver. In order to reduce size, weight, and cost, there has been a growing interest in planar structures [5]. Patch antennas are incorporated with the

artificial metamaterials that have negative refractive index thus enable antenna miniaturization. Graphene layer over the dielectric substrate [6] can also be used as perfect absorbing element [7] in thermally based THz imaging devices [8], [9], because graphene resistivity decreases with the increase of electrostatic voltage [10]. Split-ring resonators (SRRs) have been the most commonly used meta-atom unit cell design at the microwave and terahertz frequencies [11]. The synergetic effect of both components of the composite (e.g., the MOFs and CNTs/ GO/ NPs/ biomolecules) should lead to an improvement in the electrocatalytic sensing of different species [12]. In THz region, metamaterial substrate enhances the performance of antenna by reflecting the signal in desired direction [13], and metamaterial substrate based on complimentary split ring resonator improves the impedance bandwidth [14]. The resonance of this metamaterials can be turned on/off by changing the capacitance of SRR [15], [16]. The array of resonators is able to decrease the resonance frequency and increase the realized gain of the antenna [17]. The utilization of the metamaterials in THz region have lot of applications including filters, observers, switches and modulators [18]. THz technology may be applied for the understanding of brain function in health and disease by providing biochemical profiling of various neurotransmitters in various conditions [19].

Recently, there has been growing interest in the design of metamaterial antenna. Many studies are done to analyze the common antenna parameters such as return loss, gain, directivity, VSWR and radiation pattern. Denizhan Sirmaciet et al. designed fishnet based metamaterial as a defected ground to enhance the bandwidth and return loss of the patch antenna. They achieved the bandwidth of 8.2% and return loss of -55 dB at 1.08 THz [1]. Pai-Yen Chen et al. investigated the tunable THz metamaterial consisting of graphene surface above the grounded surface. They suggested that this graphene can be used as the alternative design of the artificial metamaterial [6]. Jeet Ghosh et al. proposed the graphene metasurface which is implemented over the polysilicon layer and can be used to reduce the mutual coupling in the closely packed antenna array [7]. Zheng Xu et al. designed the graphene based MIMO antenna for THz communication. They examined that the proposed antenna has high spectral efficiency than the conventional MIMO antennas [10]. Maria Koutsoupidou et al. proposed THz antenna with four different type of split ring resonator (SRR) based metamaterial such as metasurface with single SRR, SRR with cross shaped structure, SRRs of linearly decreasing side length and SRRs of decreasing dimensions with a parabolic function. They analyzed that the metasurface with single SSR and SRRs of linearly decreasing side length produce better return loss at 1.3 THz and 1 THz, respectively [13]. Yoonjae Lee et al. proposed the design of compact high gain patch antenna using complementary split ring resonator (CSRR) as metamaterial surface. They used two different materials with different permittivity. They analyzed that the CSRR loaded on high permittivity surface improves the antenna performance over the THz region [14].

Ho-Jin Song et al propose one more type of THz antenna, which is implemented overSi-based substrate such as CMOS and SiGe. They reported THz waves could support data rates of 10 Gb/s. However, progress in speed is quite low [20]. Ameneh Nejati et al. designed patch antenna on Pyrex

material at THz range with frequency selective surface and photonic band gap structures. The proposed antenna has dimensions of 500 µm × 500 µm × 10 µm and the gain is increased by 2 dBi (32%) [21]. Yanbing Ma et al designed Square Sierpinski SRR (SS-SRR) for terahertz sensing application. They investigated the frequency response when the SS-SRR is implemented over the quartz substrate with the thickness as 130 µm [22]. Pozar et al. designed and analyzed two types of printed antennas for millimeter wave communication such as patch and dipole. He suggested that substrate materials like polytetrafluoroethylene, quartz and gallium arsenide [23].

Par et al. proposed the new idea of THz wave transmission over the slot antennas on various dielectric substrates. They reported that the resonance frequency of the THz transmission is shifted due to the changes in substrate refractive index [24]. Sae June Park et al. analyzed the performance of the THz antenna by changing the gap width of the metamaterial. They reported that when the metamaterial gap width decreased, the vertical range of metamaterial detection volume decreased [25].

Le et al. implemented the planar metamaterial surface on both upper patch and bottom ground to improve the performance of the antenna. They designed a conventional antenna in the size of 12 mm × 16mm. Maximum gain of 7.14 dB is achieved [26]. Gohar et al. designed fractal antenna and metamaterial based patch antenna to improve the antenna performance. The metamaterial based antenna with the size of 40 mm × 40 mm resonates at 2.4, 3.5 and 5 GHz. They achieved 24% of antenna miniaturization by the metamaterial unit cell [27]. Pankaj et al. designed log periodic with metamaterial. Metamaterial structure is a 2-D array of Square Spit-Ring Resonators. Maximum gain of 9.991 dB at 4.521 THz was achieved [28]. Adel et al. proposed the design of LH-MTM terahertz patch antenna. Metamaterial consists of SRR and thin wires. Gain, bandwidth and return loss were improved as 1.1 dB, 14.73 GHz and 12.62 dB respectively [29]. Qing et al. proposed a design of log periodic antenna with fishnet metamaterial. Antenna loaded with low refractive index metamaterial was analyzed at 0.339 THz, 0.340 THz and 0.341 THz. Maximum gain is 7.5 dB at 0.339 THz [30]. Mukesh et al. designed split ring resonator in four different shapes. They analyzed the characteristics on the FR4 substrate at 4.409 GHz, 4.249GHz, 4.139 THz and 3.833 THz. They achieved the compactness of 3.63%, 6.13% and 13.06% at 4.249GHz, 4.139 THz and 3.833 THz respectively [31].

From the literature survey, it is observed that designing the THz antenna performance improvement and miniaturization in size are the major challenges. In this paper, similar to other promising studies existing in literature, the metamaterial based THz antenna is designed. Conventional patch antenna with the size of 71.5 µm × 95 µm is proposed and circular shaped SRR structure is loaded in the ground plane. The functional parameters of the antenna are investigated by varying the split width and split ring thickness of the metamaterial.

The paper is organized as follows: In section II design and performance of microstrip patch antenna is discussed. The metamaterial unit cell structure and SRR design is discussed in section III. In section

IV simulation results are presented after loading metamaterials on the patch. The section V describes the conclusion of the paper.

II. PATCH ANTENNA DESIGN

The structure of the proposed rectangular microstrip patch antenna is shown in Fig. 1. The antenna is designed with the dimensions of 131.5 µm × 155 µm × 10 µm. The patch antenna is designed on quartz dielectric material with dielectric constant 3.78 and the loss tangent of about 0.001. Radiating patch has the dimensions as 71.5 µm × 95 µm. The layout consists of substrate, feed line and radiating patch. A rectangular patch is fed by a way of microstrip inset technique. The microstrip feed line is located 41 µm away from one end of the patch whose length and width are 83 µm and 24 µm, respectively. The feed line is inset to the patch with the value of slot length as 39 µm and slot width as 4.75 µm on each side of the feed line. The current is low at the ends of a half-wave patch and increases in magnitude towards the center, the input impedance could be reduced if the patch was fed closer to the center. In the proposed design, the feed is slightly away from the center for impedance matching. By adjusting the feed location along the circumference of the patch it is possible to match the antenna with a microstrip line of any impedance. Hence, the feeding is displaced from center. The detailed geometrical parameters of patch antenna are shown in Table I. The performance of the rectangular microstrip patch antenna depends on its dimensions. The proposed structure is designed and simulated by using Finite Element Method (FEM).
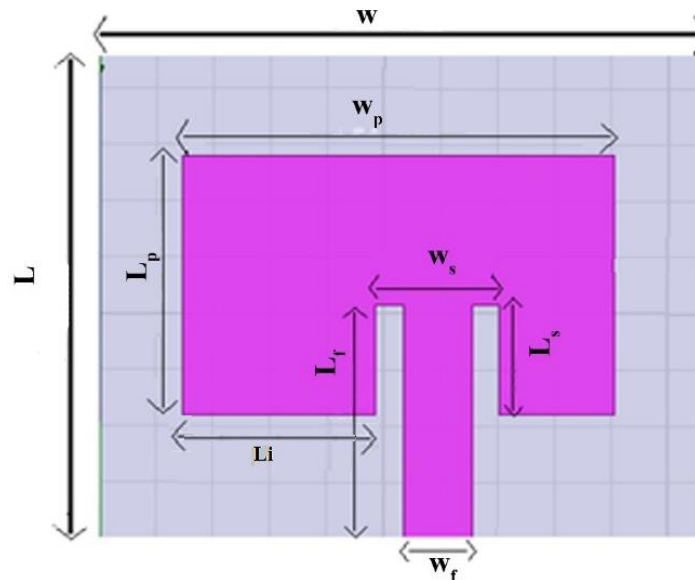

Fig. 1. Structure of the proposed microstrip patch antenna.
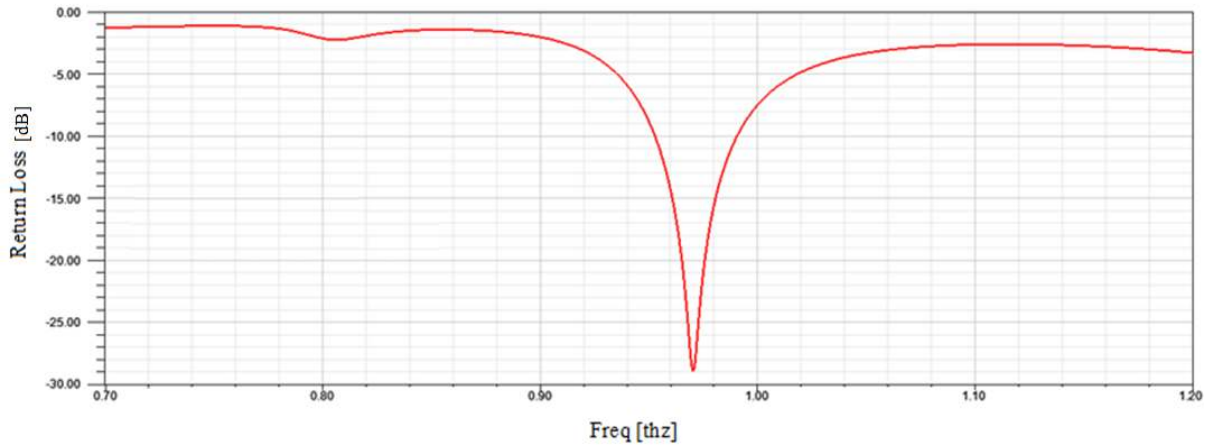
Fig. 2. Return loss for proposed patch antenna.

The proposed antenna has the resonance frequency of 0.97 THz. Generally, return loss indicates that the amount of power that does not return as reflection. The return loss of the proposed antenna without metamaterial structure is shown in Fig. 2. The proposed antenna has the better return loss (at least -10 dB) at frequencies from 0.96 THz to 0.99 THz. The antenna without metamaterial resonates at 0.97 THz and it produces the return loss as -28.76 dB. The fractional bandwidth of 4.12% is achieved.

TABLE I. GEOMETRICAL PARAMETERS FOR RECTANGULAR MICROSTRIP PATCH ANTENNA

Parameters	Dimensions (μm)
Substrate length (L)	180
Substrate width (W)	212
Substrate thickness (t)	10
Patch length (L_p)	75
Patch width (W_p)	100
Slot length (L_s)	39
Slot width (W_s)	43.5
Inset feed length (L_f)	83
Inset feed width (W_f)	24
Feed location (Li)	41

III.   METAMATERIAL UNIT CELL DESIGN

The circular shaped Split Ring Resonator (SRR) is used to construct the metamaterial surface. Fig. 3 (a) shows unit cell structure of circular SRR. The metallic part is printed on quartz substrate. The geometrical parameters of proposed SRR in Table II. The proposed SRR consists of two annular rings with outer radius of 20 μm and inner radius of 15 μm. The split width is taken as 5 μm and split ring thickness are 5 μm. Meta surface is constructed by arranging the circular SSR on the ground plane as shown in Fig. 3(b). The permeability and permittivity of the proposed circular SRR can be calculated directly by using the following equations [32], [33]:

$$\mu = nz \tag{1}$$

$$\xi = n / z \tag{2}$$

where n is the refractive index and Z is the impedance.

The S parameters can be related with refractive index and impedance by

$$Z = \sqrt{\frac{(1+S_{11}) - S_{21}^{2}}{(1-S_{11}) - S_{21}^{2}}} \tag{3}$$

$$n = \frac{1}{kd} \cos^{-1}\left[\frac{\left(1 - S^{2}_{11} + S^{2}_{12}\right)}{2S_{12}}\right] \tag{4}$$

Here, K and d denote the wave number of incident wave and SRR length respectively. Further, the value of refractive index n and impedance Z are determined by using (3) and (4).
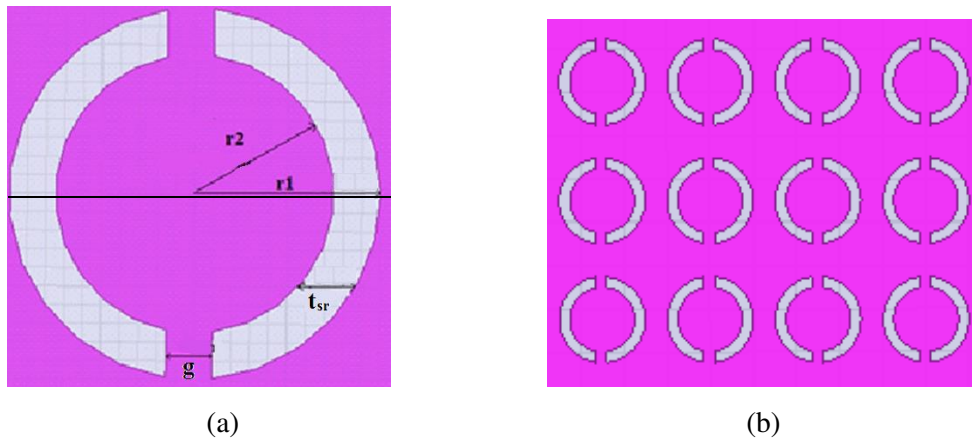

(a)   (b)

Fig. 3. Schematic representation of Circular split ring resonator (a) unit cell and (b) 3×4 unit cell formation.
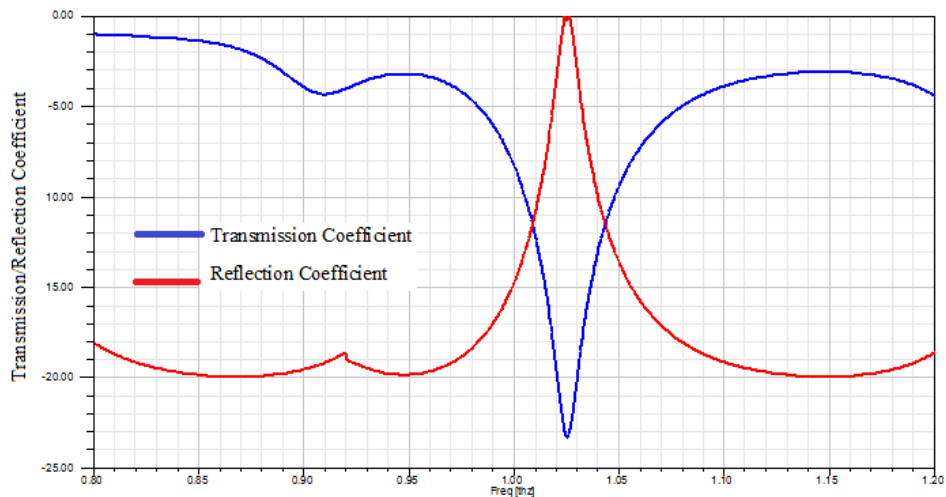

Fig. 4. Reflection and Transmission coefficient of Circular split ring resonator.
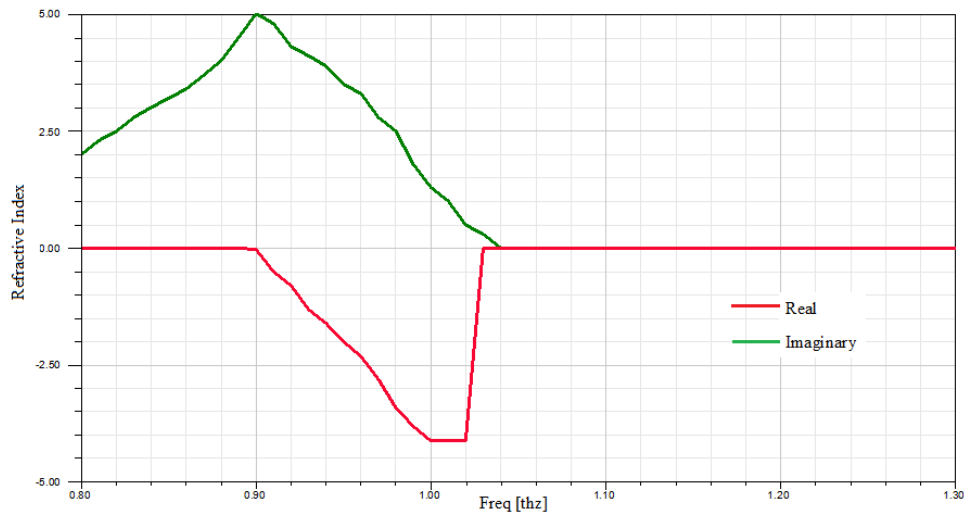
Fig. 5. Refractive index of Circular split ring resonator.

Reflection coefficient and transmission coefficient of the SRR is shown in Fig. 4. Generally, the transmission coefficient reaches minimum value in the resonance frequency of the SRR [1], [21], [24], [33], [34]. The transmission curve deeps at the frequency of 1.027 THz at the same point the reflection curve reaches its maximum. This indicates there is a resonance at 1.02 THz. Each unit cell is periodically arranged to behave as a microwave resonant circuit. The capacitance is made by the adjacent unit cells, which could be altered by varying the size of the unit cell. The periodic arrangement of these LC resonant elements is parameterized to significantly block surface wave's around the resonant frequency. Hence, the proposed unit cell provides negative permittivity and negative permeability around the resonance frequency. A capacitor-like 'split'structure regarded with a capacitance (C) couples to the electric field, and the two rings of the eSRR provide an inductance (L) to the circuit. Hence, the resonance frequency of the SRR can be changed either by varying the dimensions of the rings to alter the qualitative inductance or by varying the split to adjust the qualitative capacitance [35]. The proposed split ring resonator has negative refractive index at this resonance frequency, which is shown in Fig. 5. Due to the negative refractive index value, the metamaterial produces negative permittivity and negative permeability. The resonance frequency of the SRR purely depends on its size. By having splits in the rings, the SRR unit can be made resonant at wavelengths much larger than the diameter of the rings; that is, there is no half-wavelength requirement for resonance, as would be the case if the rings were closed [36]. The coupling effects between SRRs can be achieved by varying lattice arrangements of the meta-atoms. A SRR can be regarded as a LC circuit, its resonant frequency can then be simplified as $\omega_{LC} = \sqrt{\dfrac{2}{LC}}$ [37].

TABLE II. GEOMETRICAL PARAMETERS OF UNIT CELL

Parameters	Dimensions (µm)
Radius of the outer circle (r_1)	20
Radius of the inner circle (r_2)	15
Split ring Thickness (t_{sr})	5
Split width (g)	5

IV. RESULTS AND DISCUSSIONS

The designed metamaterial structure is loaded on the substrate of the proposed THz antenna whose dimension is 68.5×90 µm². Front and back view of proposed THz antenna with metamaterial is shown Fig. 6(a) and 6(b), respectively. The antenna with metamaterial is simulated and its results are shown in Fig. 7. It is noticed that the antenna with metamaterial resonates at 1.02 THz. Since the metasurface is designed to resonate at 1.02 THz the resonance frequency of the antenna with metamaterial is shifted to 1.02 THz [1], [14]. It seems that the size of the antenna is also reduced. Also, the return loss is further reduced as -65.26 dB at 1.02 THz. When the MTM is loaded with substrate this left handed material will act as reflecting surface and it will focus the maximum radiation energy in the desired direction. Also, it suppresses the surface wave of the antenna hence the return loss is highly improved. Gain of the proposed antenna with and without metamaterial are shown in Fig. 8(a) and 8(b) respectively. It is observed that the proposed antenna after incorporating metamaterial has the maximum gain of 5.75 dB.
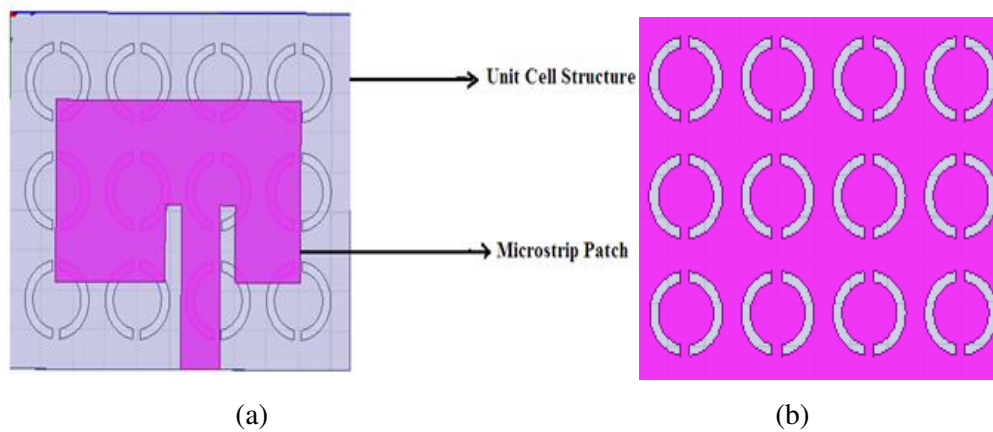

(a)   (b)

Fig. 6. (a) Front view and (b) Back view of proposed antenna with MTM.
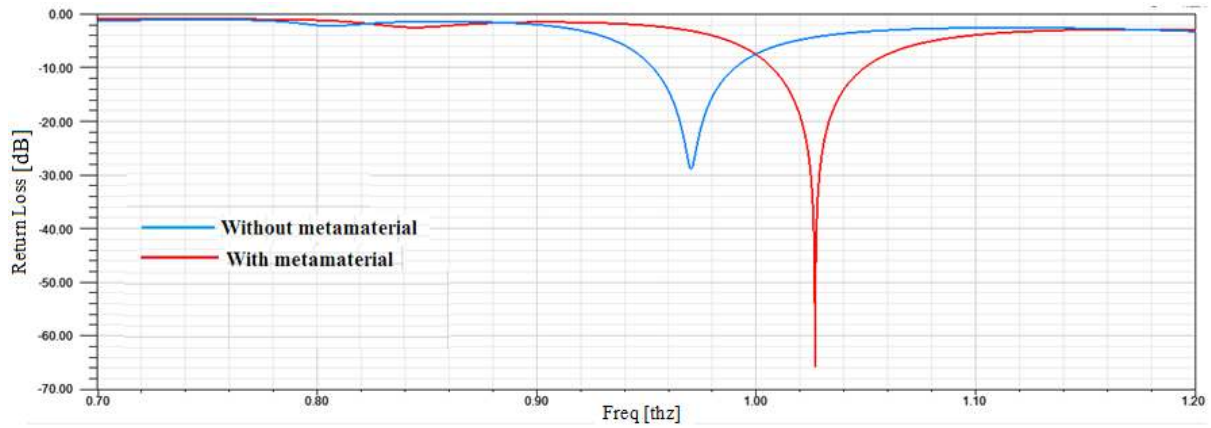
Fig. 7. Return loss of the proposed antenna with and without MTM.

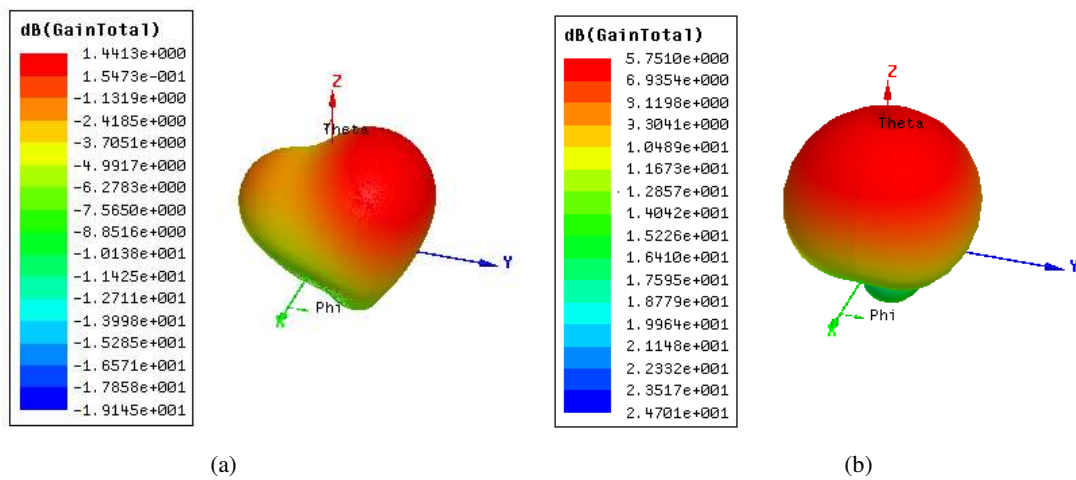(a)   (b)

Fig. 8. Gain of an antenna (a) without MTM (b) with MTM.

The conventional patch is produced the maximum gain of 1.44 dB. It is clearly noticed that, the MTM helps to radiate maximum radiation energy in the desired direction. Hence the directivity and gain are enhanced, but there is no change in bandwidth, the fractional bandwidth is maintained as 4.12%. Further, the performance of the antenna is analyzed by varying the ring width and split width in the metamaterial. Here six different split widths with a dimension of 2µm, 3µm, 4µm, 6µm, 7µm, 8µm are analyzed and its performance is shown in Fig. 9. The variation in resonant frequency, return loss and VSWR while changing the split width is listed in Table. III.

It is noted that the operating frequency is shifted slightly with respect to the split width. Normally, the resonance frequency of the metamaterial depends on both inductance and capacitance of the metasurface. Current path of SRR affects the inductance value and the capacitance is determined by both split width and dielectric constant of the substrate [14], [17]. When the split width is small high capacitance will be produced. Resonant frequency of the ring is inversely proportional to the value of ring capacitance. When the split width is 5 µm maximum return loss of -65 dB and for 4 µm split width -50.16 dB of return loss is achieved.

TABLE III. RESONANT FREQUENCY, RETURN LOSS AND VSWR FOR DIFFERENT SPLIT WIDTH OF CIRCULAR SPLIT RING RESONATOR

Split Width size (µm)	Frequency (THz)	Return Loss (dB)	VSWR
2	1.021	-33.71	1.02
3	1.023	-30.48	1.26
4	1.025	-50.16	1.02
5	**1.027**	**-65.26**	**1.00**
6	1.025	-39.17	1.04
7	1.024	-33.71	1.01
8	1.021	-44.62	1.02

TABLE IV. RESONANT FREQUENCY, RETURN LOSS AND VSWR FOR DIFFERENT RING WIDTH OF CIRCULAR SPLIT RING RESONATOR

Ring Width size (µm)	Frequency (THz)	Return Loss (dB)	VSWR
2	1.021	-39.67	1.30
3	1.023	-34.32	1.26
4	1.025	-41.23	1.04
5	**1.027**	**-65.26**	**1.00**
6	1.024	-36.81	1.03
7	1.023	-33.99	1.01
8	1.021	-34.32	1.02

Similar to the split width analysis, the ring width is varied and performance is analyzed. For the proposed unit cell outer ring and inner ring have the radius as 20 µm and 10 µm respectively. Hence it has the split ring width of 5 µm. Different width is changed by keeping the outer ring radius as constant. When the ring width is increased from 2 µm to 5 µm the return loss is enhanced after that, the return losses are reduced for 6 µm and 7µm. The variation in resonant frequency, return loss and VSWR while changing the split gap is listed in Table. IV.
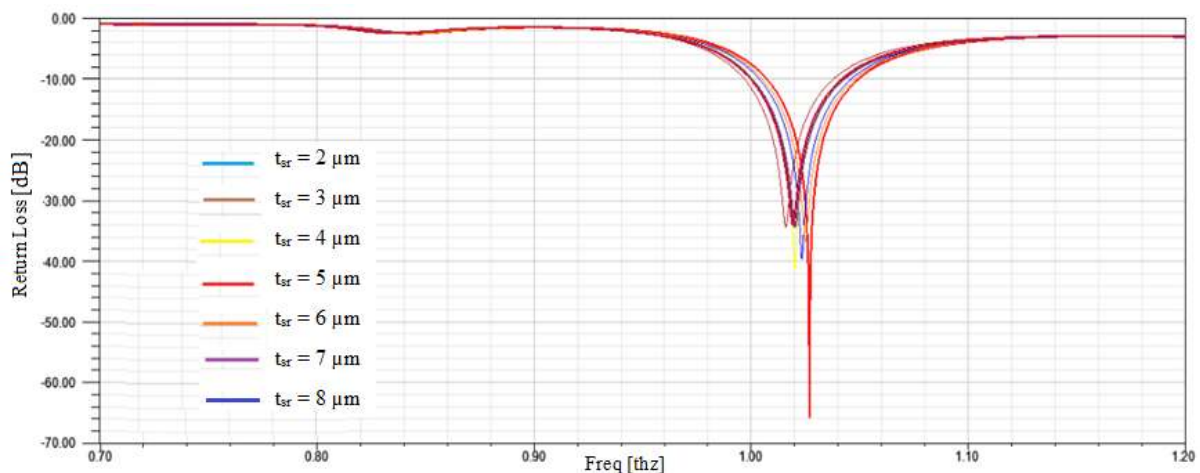

Fig. 9. Impact of return loss with respect to the ring width of the circular split ring resonator.

From the analysis, it is observed that the antenna loaded with metamaterial gives better results compared to conventional patch antenna. Parameters of the proposed THz antenna before and after loading the MTM are listed in Table. V. Bandwidth of the MTM antenna is improved from 13.91% to 17.95 %. Performance parameters of the proposed metamaterial based antenna is compared with reported antenna whose corresponding parameters are listed in Table VI.

TABLE V. COMPARISON RESULTS OF PARAMETERS FOR CONVENTIONAL AND WITH METAMATERIAL ANTENNA

Parameters	Conventional Antenna	MTM Antenna
Resonant frequency (THz)	0.97	1.02
Return Loss (dB)	-28.86	-65.26
Gain (dB)	1.44	5.75
VSWR	1.07	1.00
Fractional Bandwidth (%)	4.12 %	4.12%

TABLE VI. COMPARISON RESULTS OF PARAMETERS FOR PROPOSED METAMATERIAL ANTENNA WITH EXISTING ANTENNA

	Proposed antenna	Proposed antenna with SSR	Denizhan Sirmaciet et al, 2016 [1]	Jeet Ghosh et al, 2017 [6]	Maria Koutsoupidou et al, 2014 [10]	Li et al, 2010 [26]
Substrate	Quartz	Quartz	Quartz	Silicon Oxide,	Silicon	FR-4
Size	131×155 µm²	128.5×150 µm²	180×212 µm²	-	1000×1000 µm²	32×28 mm²
Patch Size	71.5×95 µm²	68.5×90 µm²	92×152 µm²	136×189 µm²	181×237 µm²	16×12 mm²
SRR	-	Circular	Rectangular	Rectangular	Square	Rectangular
Resonant frequency (THz)	1.02	1.02	1.08	0.46	1.00	0.006
Return Loss (dB)	-28.76	-65.26	-55	-17.08	-14.20	-22
Gain (dB)	1.44	5.75	3.57	-	1.99	7.14
VSWR	1.07	1.00	1.00	-	-	1.00
Fractional Bandwidth (%)	4.12	4.12	8.20	7.60	2	43.9

From the Table VI it is observed that Jeet Ghosh et al, proposed miniaturized antenna but it produced the return loss of -17.08 dB [6]. Antenna, which is proposed by Maria Koutsoupidou et al [10], has high directivity as 9.58 dB. The maximum return loss of -55 dB at 1.08 THz is produced by the antenna [1], which is designed by quartz material provided with the size of 180 µm × 212 µm. The proposed antenna is designed with same material and has same size as that of the antenna reported in [1]. Even though the bandwidth of the proposed antenna is comparatively low, the remaining parameters such as return loss and gain are enhanced. Hence, the proposed antenna could be suitable for terahertz applications.

V. CONCLUSION

In this paper, miniaturized metamaterial antenna with the dimension of 180 µm × 212 µm is presented for THz region. The proposed circular split ring resonator is integrated with patch as a ground plane. The results show that the return loss and gain are enhanced significantly at the resonant frequency of 1.02 THz. Particularly, the return loss is deep as -65.26 dB at the resonant frequency. It is also shown that the gain of the antenna can be enhanced with the help of negative refractive index metamaterial. Further the impact of return loss while varying the SRR width and thickness are investigated and identified that the maximum performance is obtained when the SRR split width and split ring thickness are kept as 5 µm. From this analysis, the proposed antenna can be used as

matching structure in the antenna design.

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