Meander-line-based defected ground microstrip antenna slotted with split-ring resonator for terahertz range

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In this article, the performance of a meander-line-based microstrip patch antenna with split-ring resonator (SRR)-based slots and defected ground is analyzed at the terahertz frequency range. The designed antenna shows a multiband application within a frequency range of 3.77 to 6.60 THz and operates over six different frequencies (viz. 3.83 THz, 4.24 THz, 5.12 THz, 5.50 THz, 5.95 THz, and 6.50 THz). A maximum return loss of 37 is achieved over the band of 5.85 to 6.18 THz, while a maximum realized gain of 7.54 dBi and a total efficiency of 54% is obtained at 4.24 THz. The ground and radiating elements of the antenna are made of gold. Silicon dioxide is used as a substrate material. The antenna simulation is performed and reported in this study. The proposed antenna finds its applications in the detection of colon cancer, skin cancer, brain tumor, drug detection, and communication fields for point-to-point communication purposes.

KEYWORDS
defected ground, meander line, microstrip antenna, SRR slot, terahertz range

1 INTRODUCTION

Wide bandwidth, small form factor, spatial resolution, and high data rate enhance the interest in the terahertz region having the frequency range of 0.3 to 30 THz.1-7 In biomedical sectors, terahertz frequency plays a vital role in the detection of drugs, tumors, cancer, etc.6-10 Along with these, the terahertz region shows the application in the communication field, especially in point-to-point communication.4-10 Several broadband applications have also been proposed in terahertz frequency range by the incorporation of lumped resistances in the equivalent circuit modelling.3,11-15 Split-ring resonators (SRRs), being asymmetric in nature, are sensitive to the polarization orientation of incidence due to the gap in the SRRs.16-21 High reflection or high efficiency can be achieved in the design based on SRRs by adjusting the geometrical parameters of the structures. The microstrip patch antenna possesses several advantages over conventional bulky antenna such as lightweight, small size, low cost to fabricate, easily integrated with circuits having some applications towards radio altimeters, satellite communication, missiles, remote sensing, biomedical radiators, etc.22-26 However, these antennas suffer from narrow bandwidth, low gain, and high value of ohmic losses in the feed of antenna, etc.22-26

In this article, to overcome the disadvantages of a conventional microstrip patch antenna, efficient design has been proposed so that multiband operations are observed in the terahertz domain within the frequency range between 3.77 THz and 6.60 THz. Meander-line slot-based patch antenna concept has been implemented with defected ground structure...
involving SRR-based slots. The side view of a conventional patch antenna is shown in Figure 1A. A meander-line geometry is shown in Figure 1B where the horizontal lines are acting as capacitor and vertical lines as inductor.27-33

To reduce the ohmic loss and enhance gain, the SRR-based slots have been incorporated within the patch which behaves as a simple RLC resonator with some constructive and destructive couplings (RLC resonator is an electrical circuit consisting of a resistor (R), an inductor (L), and a capacitor (C), connected in series or in parallel).16-23 The property of a metallic SRR depends on the plasma resonance frequency of the metal.34,35 When electric fields of light are directed between the two rings of SRR, the surface plasmons get excited and begin to resonate. The band intensity and wavelength of the surface plasmons are dependent on the properties of the particle which includes the shape, structure, metal type, size, and dielectric material including air.34-36 The SRR structure and equivalent circuit model of an SRR are represented in Figure 1C,D, respectively. In the single-ring SRR design, the equivalent circuit provides the resonant frequency as \( \omega_0 = \frac{1}{\sqrt{LC}} \), where \( L \) is equivalent inductance and \( C \) is the equivalent capacitance. The effect of coupling capacitance \( C_3 \) can be ignored due to the presence of a small gap between two rings of SRR. Hence, the equivalent circuit can be approximated in Figure 1D into a simple series RLC circuit by considering \( L_1 \approx L_2 \approx L \) and \( C_1 \approx C_2 \approx C \).26 In the proposed antenna, the ground plane width is reduced by involving semicircular slots to enhance the bandwidth.17-21 The proposed antenna operates over six different frequencies viz., 3.83 THz, 4.24 THz, 5.12 THz, 5.50 THz, 5.95 THz, and 6.50 THz with a fractional bandwidth of 3.86%, 7.31%, 4.58%, 4.94%, 5.68%, and 3.15%. The structure offers very good impedance matching at 5.95 THz with a return loss of 37 dB while the maximum realized gain of 7.54 dBi has been obtained at 4.24 THz. The power of this terahertz antenna is fed through the feed line in the optical range having an impedance of 50.06 Ω so that it is convenient to feed by SMA connector of 50 Ω impedance.22-24 The resonant frequency and other characteristics mainly depend upon the horizontal and vertical length of the meander line along with the separation between the twist arms, wire width, and the total physical length of the antenna.27-29 Besides that, the resonant frequency is also controlled by the shapes and dimensions of the SRR, which are the functions of capacitance and inductance.17-19,28 So, the resonant characteristics have been obtained by calculating their equivalent inductance and capacitance of the proposed antenna.25,28,29

### 2 | DESIGN OF MEANDER-LINE-BASED ANTENNA

The proposed antenna consists of a slotted meander line with six SRRs on a simple microstrip antenna where the ground is defected by introducing semicircular slots. The radiating patch of the proposed antenna is shown in Figure 2A. The side view and bottom view of the proposed antenna is shown in Figure 2B,C, respectively. Gold is used as a conducting material for the patch having a thickness (\( t \)) of 0.05 μm. The proposed antenna has been designed on Silicon dioxide (SiO₂) dielectric (relative permittivity of 3.9) with a thickness of 2 μm. All the optimized geometrical dimensions of the proposed antenna are mentioned in Table 1. The design of the proposed antenna has been obtained by optimizing a number of stages as shown in Figure 3. All the simulations have been carried out in CST Microwave Studio 2017; and the simulated results have been simultaneously compared. In the microstrip antenna, the feedline works as the transmission line. According to the transmission line concept, synchronization should be achieved between patch and feed to satisfy the maximum power transfer.25,26 The resonant frequency of the patch in TMₘₙ mode is given in Equation (1) showing...
FIGURE 2  (A) Top view, (B) side view, and (C) bottom view of the proposed antenna (geometrical dimensions mentioned in Table 2)

TABLE 1  Antenna dimensions used in Figure 2

| Antenna dimensions         | Value (μm) | Antenna dimensions         | Value (μm) |
|----------------------------|------------|----------------------------|------------|
| Length of patch ($L_p$)    | 145        | Outer radius of outer ring of SRR ($R_3$) | 10         |
| Width of patch ($W_p$)     | 92         | Inner radius of outer ring of SRR ($R_4$) | 8          |
| Thickness of patch ($t$)   | 0.05       | Length of substrate ($L_s$) and ground ($L_g$) | 210        |
| Space in meander line ($G$)| 5          | Width of substrate ($W_s$) and ground ($W_g$) | 160        |
| Outer radius of inner ring of SRR ($R_1$) | 5 | Thickness of substrate ($h$) | 2          |
| Inner radius of inner ring of SRR ($R_2$) | 3 | Width of feed ($W_f$) | 35         |

Abbreviation: SRR, split-ring resonator.

the dependence of the dimensions of the antenna upon the substrate and the operating frequency. Here $TM_{mn}$ mode is the electromagnetic field corresponding to ($m$, $n$). The $m$, $n$ values can take the values $m = 1, 2 \ldots$ and $n = 1, 2 \ldots$ and $L$ is the length of the waveguide ($0 < x < L, 0 < y < L$), $c$ is the velocity of light, $\varepsilon_{\text{eff}}$ is the effective permittivity of the waveguide, and $f_{mn}$ is the cut-off frequency of $TM_{mn}$ mode.

\[
 f_{mn} = \frac{c}{2f_0 \sqrt{\varepsilon_{\text{eff}}}} \sqrt{ \left( \frac{m}{L} \right)^2 + \left( \frac{n}{L} \right)^2 } . \tag{1}
\]

Simultaneously, the surface impedance $Z_{in}$ has been computed using Equation (2) where $Z_o$ is the characteristic impedance of the transmission line, $Z_L$ is the load impedance of the feed, and $\gamma$ is the propagation constant.

\[
 z_{in} = \frac{Z_o z_L + Z_o \tan \left( \frac{\gamma L}{2} \right)}{Z_o + z_L \tan \left( \frac{\gamma L}{2} \right)} . \tag{2}
\]

The detailed design evolution has been discussed below. The proposed design has been initiated from a simple rectangular patch antenna with a dimension of $145 \times 92 \, \mu m^2$ as shown in the CASE-I of Figure 3. Here this simple patch operates at the frequency of 5.54 THz along with fractional bandwidth of 3.66% and the gain of $-5.31$ dBi. This design cannot provide expected gain due to the low value of reactance present in the equivalent circuit of this design. Later, the gain has been
FIGURE 3    Design evolution for the proposed antenna with different modifications

enhanced to 3.99 dBi and the fractional bandwidth to 6.8% at the operating frequency of 4.24 THz after the introduction of the meander line having two continuous horizontal lines and one vertical line simultaneously, which is represented in CASE-II of Figure 3. The incorporation of meander line geometry increases the capacitance and inductance values, which cause an increment in realized gain and the simultaneous reduction in resonant frequency. To further increase the gain, a complex meander-line slot having six horizontal lines and five vertical lines is introduced in CASE-III of Figure 3.

Due to the enhancement of equivalent reactance value, an increment of gain and shift of resonant frequency has been observed. Here the gain is improved to 4.54 dBi with a fractional bandwidth of 6% at 3.73 THz. In CASE-IV of Figure 3, one SRR slot is added on the patch to enhance the gain by increasing the capacitance value. The gain is obtained as 4.95 dBi at an unaltered frequency of 3.73 THz with 5.57% fractional bandwidth. Two more SRR slots are added in the next step to introduce constructive coupling, which reflects realized gain as 4.97 dBi. Fractional bandwidth of 5.43% has been achieved. In CASE-VI, three more SRRs are implemented on either side of the meander line. Now it can be observed that the SRRs near the feed are the mirror image of the set of remaining SRRs. Thus, destructive coupling between them has occurred. As a result, its bandwidth is reduced to 5.35% and the operating frequency is increased to 5.95 THz from 3.73 THz. So, the defected ground concept is applied in CASE-VII of Figure 3 to increase the bandwidth and it is successfully improved up to 7.07% with a gain of 5.04 dBi. This bandwidth is within the desired range.

To fulfill the objective to design an antenna within 2 to 7 THz with better gain, some semicircular slots are added on the ground plane in CASE-VIII of Figure 3. The realized gain is finally observed as 7.54 dB at 4.25 THz frequency with a fractional bandwidth of 7.61%. This CASE-VIII of Figure 3 is finalized as the proposed antenna due to better performance.

3 | SIMULATED RESULTS

All the antennas shown in Figure 3 are simulated using CST Microwave Studio 2017 and the respective return loss responses with respect to the frequency is shown in Figure 4. The proposed antenna mentioned in Figure 2 operates at six different frequencies viz., 3.83 THz, 4.24 THz, 5.12 THz, 5.50 THz, 5.95 THz, and 6.5 THz with a fractional bandwidth of 3.86%, 7.31%, 4.58%, 4.49%, 5.68%, and 3.15% as shown in Figure 4. This antenna offers very good impedance matching at 5.95 THz with a return loss of 37 dB. It is observed that the introduction of SRR slots on the patch and defected ground structure results in multiband operation with improved bandwidth.
**Figure 4** Plot of $S_{11}$ (dB) with respect to frequency for different variations of antenna mentioned in Figure 3 along with the proposed antenna depicted in CASE-VIII.

The surface current distribution of the proposed antenna is shown in Figure 5. They are more intense around the antenna aperture corresponding to the operating frequencies of 3.83 THz, 4.24 THz, 5.12 THz, 5.50 THz, 5.95 THz, and 6.5 THz. The surface current is maximum at 5.95 THz to realize the best impedance matching.

The three-dimensional polar plot at different frequencies viz., 3.83 THz, 4.24 THz, 5.12 THz, 5.50 THz, 5.95 THz, and 6.5 THz are shown in Figure 6. It is observed that the proposed antenna exhibits the realized gain of 4.86 dBi, 7.54 dBi, 3.62 dBi, 3.15 dBi, 5.1 dBi, and 3.62 dBi at the corresponding operating frequencies. The realized gain is high over the band and the maximum gain of 7.54 dBi has been achieved at 4.24 THz.

The frequency response of the efficiency of the proposed antenna has been provided in Figure 7. The antenna yields a maximum efficiency of 54% at 4.24 THz. The efficiency of a photoconductive antenna is basically low due to impedance mismatch between the feeding system and the radiating element.

The E-plane ($\varphi = 0^\circ$) and H-plane ($\varphi = 90^\circ$) radiation characteristics of the proposed antenna at the operating frequencies of 3.83 THz, 4.24 THz, 5.12 THz, 5.50 THz, 5.95 THz, and 6.5 THz have been studied and shown in Figure 8A,B, respectively. Endfire radiation characteristics are observed at corresponding operating frequencies along E-plane while a nearly omnidirectional pattern is observed along H-plane. The crosspolarized level is found to be 15 dB below the copolarized level at all the operating frequencies as evident from Figure 8.
FIGURE 6  Simulated result of 3D gain of proposed antenna at different operating frequencies

FIGURE 7  Efficiency response with frequency for the proposed design

The proposed structure has been compared with the existing reported THz antenna structures as shown in Table 2. It is observed that the proposed design exhibits optimum fractional bandwidth and significant gain in comparison with the reported ones.

4  CONCLUSION

In this article, the performance of a meander line with SRRs-based slotted patch antenna along with defected ground structure is analyzed and studied. Gold is used as conducting material in ground and patch elements with SiO$_2$ substrate having a dielectric constant of 3.9. The proposed antenna operates over six different frequencies viz., 3.83 THz, 4.24 THz, 5.12 THz, 5.50 THz, 5.95 THz, and 6.50 THz with a fractional bandwidth of 3.86%, 7.31%, 4.58%, 4.49%, 5.68%, and 3.15%. The maximum return loss of 37 dB has been achieved over 5.85 to 6.18 THz at 5.95 THz. The maximum realized gain of 7.54 dBi is obtained at 4.24 THz. It is applicable in the detection of drugs and explosives, several medical applications like cancerous cell detection, tumor, and in many communication fields.
FIGURE 8  Copolarized and crosspolarized (A) E-plane and (B) H-plane at different operating frequencies within the proposed structure
| Antenna       | Max. fractional bandwidth (%) | Max. realized gain (dBi) |
|---------------|--------------------------------|-------------------------|
| Nag et al\textsuperscript{30} | 6.96                           | 5.95                    |
| Prince et al\textsuperscript{40} | 8.97                           | 4.25                    |
| Saini et al\textsuperscript{41} | 4.70                           | 7.35                    |
| Anand et al\textsuperscript{42} | 6.67                           | 5.71                    |
| George et al\textsuperscript{43} | 4.10                           | 6.03                    |
| Proposed antenna | 7.61                           | 7.54                    |

**TABLE 2** Comparison of the proposed THz antenna with existing THz antennas

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CONFLICT OF INTEREST
Authors have no conflict of interest relevant to this article.

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