An Integrated Switchable EM Absorber and Beam Switchable Radiator

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\[\text{ABSTRACT}\]

In this research work, a multifunctional metamaterial inspired surface is designed for two different applications, namely, electromagnetic (EM) absorber and radiator with pattern agility. The designed surface consists of periodic arrays of metallic loops and circular patches printed on a thin grounded dielectric slab. Lumped resistors are fixed in the outer ring where the inner patch is connected to the feeding network through metallic vias. Firstly, the basic unit cell of the surface is utilized as a dual-band EM absorber. Secondly, the same surface is utilized as a beam switching radiator. Each unit cell has two switchable feeding points which are connected to a single-pole double-throw (SPDT) switch designed on the bottom layer. The surface is symmetrical therefore the excitation of each unit cell at two feeding ports can produce a phase shift of 180°. By properly selecting the feeding point of the four elements, the surface can generate sum-beams and difference-beams. The surface exhibit low radar cross section (RCS), high gain, and high efficiency. A prototype of 4 × 4 elements array is manufactured and experimentally verified in an anechoic chamber.

\[\text{INDEX TERMS}\]

EM absorber, EM radiator, pattern agility, low RCS, high gain.

\[\text{I. INTRODUCTION}\]

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I. INTRODUCTION

In modern wireless communication technology, reconfigurable antennas have wide attention because of their flexibility on the pattern, frequency, or polarization. Especially, the pattern reconfigurable antennas can control the main lobe in a specific direction or place the nulls in the desired direction [1]. In the literature, frequency [2], polarization [3], [4], and radiation pattern [6] reconfigurable has been designed for 5G wireless systems [5]. The main advantage of these kinds of antennas is to avoid the noisy environment and also direct the signal toward the intended user. Further, many researchers have made an effort to design beam switchable antennas [7]–[13]. Reconfigurable reflectarray [7] and transmit-array [8] have been designed with high gains. In [7], reconfigurable reflectarray based on 1600 elements was designed with beam steering performance for Ku/X band application. In [9], [10], digitally coding metasurfaces have been designed to manipulate the far-field beams by using PIN switches. In [11], [12], the authors have made an effort to design an antenna array with radiation pattern agility based on PIN diodes in the feeding network. By selecting the PIN diode, the antenna array provides a sum or difference beams. A digital phase shifter was used in a complex feeding network to steer the beam of an regular patch antenna [13]. Compared to coding technique [9], [10], the beam switchable antennas using PIN diodes [11], [12] can provide more switching at low cost.

The applications of the traditional beam switchable antennas are limited to aerospace and military use due to high cost, complexity, and the size of the antenna. These traditional beam switchable planar antennas always contribute large radar cross section (RCS) to any stealth platforms. With the development of electronic technology for military applications, extensive research has been done to reduce the RCS of an antenna [14]–[20]. In [14], the RCS of the antenna was reduced by changing the shape of the radiator, wherein [15], the RCS of the antenna was reduced by loading the radar
absorbing materials [15], [19]. Other methods include RCS reduction by EM bandgap (EBG) [16], frequency selective surfaces (FSS) [17], and polarization conversion metamaterials [20]. Further, using the metamaterial absorber is another way to reduce the RCS of a regular patch antenna [18]. Due to excellent absorbing property, metamaterials are of great interest among the researchers in RCS reduction [18], [21]–[23]. In the previous research work, the metamaterial absorbers are combined to the regular patch antennas for RCS reduction. However, these combinations of the metamaterial absorber reduce the RCS but it may degrade the radiation performance, and also it has no contribution in wireless communication rather than RCS reduction.

The current trend in engineering and technology is multi-functional devices. Multi-functionality is the use of a single device for multiple applications by simply changing its operating parameters [24]. Few researchers have made an effort to design a surface for multiple applications [24]–[28], [30]–[32]. In [24], a metamaterial surface was designed for absorbing and sensing applications. Further, more multifunctional active FSSs are also proposed [28]–[30], which integrate multiple functions such as EM switching, polarization selection, and frequency tuning. To the best of author’s knowledge, surface with multiple functions such as switchable absorption and beam switchable radiation with low RCS, high gain, and high efficiency have not been presented so far.

In this research work, a multi-layered surface is designed having multiple functions. Firstly, the designed surface can be used as a dual-band EM absorber. Secondly, the same surface can also be used as a beam switchable radiator. A feeding network is designed on the bottom layer, to excite four elements of the surface. Each element is feed at two feeding points where the excitation of each point is reconfigured by using PIN switches. When PIN switches are switched OFF, the surface is regarded as a dual-band EM absorber. When the selected PIN switches are switched ON, the same surface is regarded as a beam switchable radiator. By properly selecting the feeding point of the four unit cells, the surface can generate sum beams and difference beams. Further, the surface exhibit low RCS, high gain, and high radiation efficiency.

II. THE SURFACE REGARDED AS AN EM ABSORBER

The perspective view of a single unit cell of the proposed surface is shown in Fig. 1 (a) front view and Fig. 1 (a) side view. The proposed unit cell is made of multi-layers. A square-shaped split ring and circular shape patch is placed on the metallic top layer. The width of the split is \( w_a = 2.7 \) mm, the radius of the patch is \( r_p = 4 \) mm, width of square ring is \( a = 15 \) mm and periodicity \( p = 24 \) mm. The resonator and the metallic backboard are separated by an \( h_1 = 3.0 \) mm thick F4B substrate with the permittivity of 2.65 and a loss tangent of 0.002. Four lumped resistors \( (R = 450 \Omega) \) are fixed in the rectangular shape split ring to increase the absorptivity of the surface. The proposed periodic surface has been simulated in CST Microwave Studio, a commercial full-wave EM solver based on finite integration technique. The simulations of the absorber were performed with the help of periodic boundary conditions and Floquet port excitation. The fabricated prototype was measured in an anechoic chamber. The experimental setup is shown in Fig. 1 (c) and its schematic view is shown in Fig. 1 (d). Where one horn antenna works as a transmitter and other work as a receiver, the sample is placed in front of them. The measurements were carried out in two steps. In the first step, perfect electric conductor (PEC) with equal the dimensions as the fabricated prototype was placed in front of horn antenna for calibration. In the second step, the designed prototype was placed in the same position to measure the reflection coefficient.

A. SIMULATED AND MEASURED RESULTS

To design an absorber with maximum absorptivity, the coupled incident power and EM wave should be comparable. To achieve low reflection from the proposed EM absorber, the impedance of the EM absorber needs to be well matched with that of free space impedance \( Z_0 = 377 \Omega \). The
The designed parameters of the proposed unit cell and the value of lumped resistors are carefully optimized to achieve the desired absorption. The maximum absorption ensures that the impedance of the metamaterial absorber nearly equals the characteristic impedance of free space within resonating frequency bands. Under normal incidence, the simulated and measured reflectivity and absorptivity for TE polarized incident wave are shown in Fig. 2. From Fig. 2(a), it can be seen that the reflectivity drops in the resonating bands i.e., from 7.5 GHz to 8.7 GHz and from 9.8 GHz to 10.2 GHz. These resonating bands denote the impedance matching with the free space. Further, the simulated and measured absorptivity is also calculated as a function of frequency as shown in Fig. 2 (a). The frequency characteristic of absorption can be calculated by $A(\omega) = 1 - T(\omega) - R(\omega)$, where the upper substrate metalized therefore we have considered the transmission nearly equal to zero i.e., $T(\omega) = 0$. The absorptivity can be rewritten as $A(\omega) = 1 - R(\omega)$. It can be seen from Fig. 2(b), that the designed surface has two absorbing peaks at 8 GHz and 10 GHz. The simulated and measured absorptivity are in good agreement.

In this work, to verify the angle stability of the proposed EM absorber, the absorptivity under oblique incidence is investigated in Fig. 2 (b). We can conclude that the absorptivity at resonance frequencies is remain same with the changing the polarization angles, which implies that the presented surface is also with good polarization-insensitive characteristic. The designed surface presents a high absorption for oblique incidence angles up to 30°.

The configuration of the unit element is a square loop and circular disk metal, which can be equivalent to a series RLC circuit. We assume that for an incident EM wave when the direction of $E$-field parallel along $x$-direction, the $E$-current will be induced on the metallic strip in $x$-direction, so the equivalent inductances are introduced. Where the capacitances are introduced to address the potential difference induced by the gap between adjacent units. The inductances are dependent on the length and width of the metallic line segments and the equivalent capacitances are dependent on the adjacent gap between two units.

The equivalent circuit analysis of the FSS and high impedance surfaces has been carried out in [33]–[38]. In Fig. 3, the $L_1$ denotes the equivalent inductance of the disk metal [37], where $L_2$, denotes equivalent inductance of the square loop [33]–[36]. The capacitance $C_1$ is the equivalent capacitance between the square loop and disk shape metal, where $C_2$ is the equivalent capacitance between two adjacent square loops. To get optimum results, the value of the inductor and capacitor were optimized in advanced design system (ADS). In the equivalent circuit, the loss resistor $R$ is also taken into account. The equivalence of periodic loop is given in Fig. 3 (a), where its final circuit equivalent circuit model is displayed in Fig. 3 (b). In Fig. 3 (b), the $Z_\circ = 377\Omega$. 
and $Z_{\text{in}} = \frac{Z_0}{\sqrt{\varepsilon_r}} = 231 \Omega$. The equivalent circuit model of the proposed unit cell is simulated in ADS, and its results are displayed in Fig. 2 (a). It can be seen that, simulated results obtained using ADS and CST MWS are coincides well, which confirm the validity of the proposed equivalent circuit model.

### B. ELECTRIC FIELD AND SURFACE CURRENT DISTRIBUTION

To better understand the absorption mechanism in the proposed dual-band absorber, the $E$-field distribution has been studied at both the absorption peaks i.e at 8 GHz and 10 GHz as shown in Fig. 4. It is observed from Fig. 4 (a) and (b), that at the absorption peak, the circular shape patch and square shape split ring with lumped resistors, are the main contributor to providing high $E$-field around the surface. Further in Fig. 4 (a) and (b), the strong $E$-fields are concentrated on the top layer and bottom layer. It is also observed that the $E$-field arrangements like symmetric shape on the top layer and bottom layer for both resonance frequencies i.e., at 8 GHz and 10 GHz, which performs as an electrical dipole.

The surface current distribution on the top and bottom layers are shown in Fig. 5 (a) and (b). At resonance frequencies, the current mainly exist on the resonator (top layer) and grounded metallic layer. The current on top layer flow along the incident $E$-field which provides the electric dipole. Further it also clear that the surface currents on the grounded metallic film and top layer flowing anti-parallel. The current flowing in opposite direction form an equivalent current loop, which demonstrates a magnetic resonance. The electric and magnetic resonances are achieved simultaneously at the resonant frequencies 8 GHz and 10 GHz, thus resulting in perfect absorption of electric and magnetic energy.

### III. LOW SCATTERING BEAM SWITCHABLE RADIATOR

To make the same surface as a beam switchable radiator, an additional F4B substrate with a dielectric constant of 2.65 and 1 mm thickness, is added to the bottom layer. The schematic view of the multilayer structure is shown in Fig. 6. In Fig. 6 (a), the top layer consist of resonators, the ground is sandwiched between two substrates. A feeding network, inspired by the Wilkinson power splitter is designed on the additional substrate (bottom layer). The feeding network is designed in a way that excites individual elements at two feed points. The SPDT switch is designed and integrated with the antenna element to switch between the two feeding ports. The layout of the SPDT switches are shown in Fig. 6(b). For switching a voltage-controlled PIN diode is a suitable candidate since, (i) it can block the current in the OFF state, and (ii) is equivalent to a low resistance to short the lumped resistance in the ON state. The equivalent circuit of PIN diode is shown Fig. 7 (a) ON state and (b) OFF state. A PIN diode SMP 1320 − 079LF in the SC-79 packages from SKYWORKS is selected, where its equivalent parameters are $R_{\text{OFF}} = 1 \, \text{k}\Omega$, $C_{\text{OFF}} = 0.35 \, \text{pF}$, $L_{\text{CHIP}} = 1.5 \, \text{nH}$ and $R_{\text{ON}} = 0.9 \, \Omega$, as these values were from the data sheet [39]. To isolate the DC and RF sections, an inductor and capacitor of amount 50 nH and 100 pF respectively, were fixed in the feeding network. The PIN diodes need to be turned “ON”, with DC source of voltage of 2 V and current of 100 mA is applied, on the contrary, no source is applied to make the PIN in off-state and the surface can be regarded as an EM absorber.
A. SIMULATED AND MEASURED RESULTS

To verify the designed surface an array of 16 elements is manufactured as shown Fig. 8(a) top layer and Fig. 8 (b) bottom layer. The excitation of the centered 2 × 2 elements is shown in Fig. 6. The individual element is connected to the feeding network at two feed points, through metalized via of diameter 0.7 mm, where each feed point is controlled through PIN diodes. For example, port 1 and port 5 are connected to diode D1, port 2, and port 6 are connected to diode D2, port 3, and port 7 are connected to diode D3 and finally, port 4 and port 8 are connected to diode D4. The simulation of the radiator was carried out by using CST MWS with the help of wave-guide port excitation and open boundary conditions in all directions.

The reflection coefficient (S11) of the fabricated prototype was measured by using Vector Network Analyzer (VNA).
The simulated and measured reflection coefficients (S11) are plotted in Fig. 9. In Fig. 9, the excitation at different feed points has the same impedance matching. In Fig. 9, when D1D3, D1D4, D2D3, and D2D4 are switched ON, the proposed surface resonates at 10 GHz, on the contrary, all diodes are switched the surface show mismatching or no element is excited.

The designed surface is symmetrical therefore the individual element excitation at the two feeding-ports can produce a 180° phase-shifting. The simulated current distribution is shown in Fig. 10 when D1D3 and D2D3 are switched ON. It can be seen from Fig. 10 (a), that (diodes) D1D3 are switched ON, the current flowing in the same direction as shown on circular patches. Similarly, when diodes (D2D3) are switched ON, the current flowing in the opposite direction. When current flowing in the same direction, the surface radiates with sum-beam while in case of opposite flowing current the surface radiates with difference-beam. The relationships between radiation beams and the feeding ports of the four antenna elements are tabulated in Table 1.

For both cases (i.e., sum and difference), the directivity and gain are shown in Fig. 11 (a). The directivity and gain increase within the resonance frequency band. However, in difference beam state, the gain and directivity are decreases. This decrement is because of the splitting of the main beam into two lobes. Further, the radiation efficiency can be defined as $\epsilon_{\text{rad}} = \frac{G}{D}$, where $G$ is the gain, and $D$ is the directivity. The radiation efficiency is shown in Fig. 11 (b), the radiation efficiency for both cases increases within the resonating band, and maximum radiation efficiency of 90% is observed at resonance frequency 10.2 GHz. Due to the symmetrical structure, the radiation efficiency for all cases is same.

To better understand the beam switching function, the 2D radiation patterns are shown in Fig. 12, where its different.
states are listed in Table 1. From Table 1, it can be seen that when feed port 1 and port 3 are excited means D1 and D3 are switched ON, the designed surface generates a sum beam as is shown in Fig. 12 (a). Similarly, when feed port 2 and port 4 are excited, the radiating surface also generates a sum beam. The designed surface is symmetrical, therefore the excitation of two ports, produce 180° phase shift. With the excitation of these ports i.e., port 1, port 4 or port 2, port 3, generates difference beams with two main lobes around +30° and -30° as shown in Fig. 12 (b). In the case of a difference-beam, the null depth at 0° is about -16 dB. The measured radiation patterns for both cases sum and difference beams are shown in Fig. 13 (a) and (b) respectively. It can be concluded that simulated results match more closely with the measured results.

The 3D radiation pattern is also shown in Fig. 14 (a) and (b). In Fig. 14 (a), the surface producing a sum beam with a maximum peak of 14.4 (11.6 dB). It is also noticed that the main lobe is directed toward the propagation direction.

Where Fig. 14 (b) shows a difference-beam with two maximum peaks of 10.4 (10 dB). Here we can also observe that the magnitude of the difference-beam is less sum-beam, this because the power is splitting in two different directions.

B. SCATTERING CHARACTERISTICS

To evaluate the low scattering performance, the designed surface has been simulated in a time-domain solver in CST MWS, while all the boundary conditions were set as an open boundary. The RCS reduction compared to the equal-sized metal as shown in Fig. 15. In Fig. 15 (a), the mono-static RCS reduction is plotted versus frequency by taking the difference between metal and designed structure’s RCS. A maximum reduction of 26 dB achieved at 8 GHz where 18 dB RCS reduction is achieved at radiating frequency i.e., at 10 GHz. In Fig. 15 (b) and (c), 2D scattering patterns are plotted at 8 GHz and 10 GHz frequencies. It can be seen that RCS reduces within the angular region, however, at some
angles, the RCS remains same or increases, such kind of side effect is due to anomalous scattering energy. Maximum RCS reduction is observed around about 0°. For more observation, the 3D RCS scattering pattern has been studied under normal plane wave incidence at 8 GHz and 10 GHz as shown in Fig. 16 (a) and (b). It can be observed that the incident energy has been mostly deflected towards multiple directions.

Table 2 compares some important performance parameters of the proposed designed surface to the previously reported published research work on the low scattering antennas. It is cleared from Table 2, that the designed surface in this research work exhibits, higher gain, high radiation, and much larger in-band, out-band RCS reduction. To be more persuasive, the proposed surface exhibit multiple functions such are EM absorption and beam switchable radiation.

**TABLE 2.** Comparison of the proposed research work to previously published works.

| Ref. | $f_c$ (GHz) | Gain (dB) | $\epsilon_{rad}$ (%) | Max. in-band RCS (dB) | Max. out-band RCS (dB) | Switchable beam | Multi-function |
|------|-------------|-----------|---------------------|----------------------|------------------------|----------------|---------------|
| [18] | 10.6        | 6.2       | 79.8                | 11.2                 | NA                     | NO             | NO            |
| [25] | 8.9         | 9.3       | NA                  | 4                    | NA                     | NO             | NO            |
| [26] | 11.5        | 13.2      | NA                  | 6                    | NA                     | NO             | NO            |
| [11] | 6           | 19        | 60                  | NA                   | NA                     | Yes            | NO            |
| [12] | 6           | 10        | 52                  | NA                   | NA                     | Yes            | NO            |
| Prop | 10          | 10        | 90                  | 18                   | 26                     | Yes            | Yes           |

**FIGURE 14.** The 3D radiation pattern for (a) sum and (b) difference beams.

**FIGURE 15.** The scattering characteristics (a) mono-static RCS, and (b) Bi-static RCS 8 GHz, (c) Bi-static RCS 10 GHz of proposed structure.
beam switchable radiation and absorption characteristics and cell. The designed surface exhibits low RCS but high gain. phase shift of 180° excitation of unit cell at two feeding ports can produce a it excites the radiating element at two feeding point. The array are connected to the feeding network designed on the bottom layer. The feeding network is designed in a way that utilzed as a radiating element. Four elements of the 4 cations namely, for switchable radiation and absorption. The surface exhibit a multi-layered structure. The basic unit cell is analyzed as an EM absorber. The unit cell exhibits two FIGURE 16. The 3-D scattering characteristics (a) 8 GHz and (b) 10 GHz of proposed structure.

IV. CONCLUSION
In this research work, a surface is designed for two applications namely, for switchable radiation and absorption. The surface exhibit a multi-layered structure. The basic unit cell is analyzed as an EM absorber. The unit cell exhibits two absorbing frequency bands. Further, the same unit cell is utilized as a radiating element. Four elements of the 4 × 4 array are connected to the feeding network designed on the bottom layer. The feeding network is designed in a way that it excites the radiating element at two feeding point. The excitation of unit cell at two feeding ports can produce a phase shift of 180°. The sum and difference beams were generated by selecting the feeding points of the four-unit cell. The designed surface exhibits low RCS but high gain. It is reasonable to believe the proposed method can provide an alternative way to design multi-functional surface having beam switchable radiation and absorption characteristics and also to solve the conflict between low RCS high and gain.

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