Abstract—In this paper, a low-profile broadband frequency selective surface (FSS) is presented for wideband shielding. The FSS consists of periodic patterns of circular loops connected among themselves through varactor diodes, which exhibit tunable operation. The novelty of the proposed design lies in its wideband tuning, where the bandstop response can be varied from 0.54 to 2.50 GHz under the reverse bias voltage, thereby exhibiting a tunable range of 363%. Moreover, the structure exhibits a wide 1.28 GHz stopband (fractional bandwidth of 152%), which is maximum as compared to other wideband FSSs. Additionally, the design is polarization-insensitive and angularly stable for both TE and TM polarizations. A prototype of the proposed structure has been fabricated where the varactor diodes are biased through a novel biasing technique. The sample is measured using parallel-plate waveguide setup as well as the free-space technique, where the measured results show good agreement with the simulated responses.

Index Terms—Electromagnetic shielding, frequency selective surface (FSS), varactor diode, wideband tuning.

I. INTRODUCTION

S INCE the last few decades, frequency selective surface (FSS) has attracted much attention due to its widespread applications in the fields of spatial filter, antenna, absorber, radar, and wireless technology [1]. Electromagnetic (EM) shielding is another important application of FSS, which has gained research attention due to emerging mobile phone and satellite communications [2], [3]. Several electrical/electronic equipment may malfunction in sensitive environments due to EM interference (EMI). These devices can be shielded by using metal foil or wire mesh, but it will also block all the transmissions regardless of their origin. An FSS, therefore, can be extensively used for shielding those components as it is free from such limitation. In addition, thin profile, ease of fabrication as well as low cost make the FSS a suitable candidate for such applications.

Several FSS configurations have been reported in the literature for shielding applications. In [4], an FSS consisting of cross-slot element has been designed for Ku-band (12–12.7 GHz) EMI shielding. Similarly, a dual-band FSS to shield GSM 900 and 1800 MHz bands having 20 dB attenuation is presented in [5]. A dual stopband FSS having slotted patch on both sides of the dielectric is reported in [6] to shield industrial, scientific and medical (ISM) and unlicensed national information infrastructure (UNII) frequency bands with 10 dB rejection. An anchor-shaped FSS has been proposed for WLAN applications [7]. A number of FSSs have also been designed to provide EMI shielding for X-band frequencies [8], [9]. With advent of time, wideband FSSs are reported in recent literature. A single-layer wideband FSS has been realized with 20 dB relative bandwidth of 36.5% in [10]. Several other geometries such as square loops, annular rings, and cross dipoles having fractional bandwidth of 52–100% have also been presented [11]–[13]; however, the stop bandwidth can be further improved.

In the last few years, rapid development in multistandard and multifunctional communication systems necessitates reconfigurable FSSs [14]. A switchable FSS based absorber/reflectors has recently been reported, where the incident wave can be absorbed in absorptive state, while it works as a reflector in complementary state [15]. Modification of the EM architecture of buildings is another important application, where propagation can be controlled using switchable FSS [16]. Various designs of tunable FSSs have also been proposed so far. In [17], tunable FSS is developed by using a magnetically tunable ferrite substrate. However, they suffer from slow tuning speeds. Graphene-based tunable FSS has also been reported, but realizing such a structure is challenging due to difficulty in controlling the surface conductivity [18]. Tunable FSS structures using liquid crystal have been designed, but the tuning ranges are relatively limited [19], [20].

Active components such as varactors and p-i-n diodes are an effective solution to resolve these problems, since they provide high speed and wideband tuning with compact size and low cost [21]–[24]. In [25] and [26], single-band tunable FSSs have been developed, where varactor diodes are embedded inside the unit cells along the direction of the incident electric field. Tunable dual-band and bandwidth-enhanced FSS designs have also been reported recently [27], [28]. However, most of these varactor-controlled tunable structures realized till now have asymmetrical designs, exhibiting polarization-sensitive behaviour. Besides, they suffer from small tuning range, which can also be increased.

In this paper, all the above-mentioned limitations have been resolved simultaneously. The proposed structure offers several significant novelties as compared to the earlier reported FSSs. First, the structure exhibits an attenuation of more than 20 dB for a wide stopband of 1.28 GHz (fractional bandwidth of 152%), which is the largest as compared to other broadband FSSs.
Second, the design provides a wide tuning range of 363% (0.54–2.50 GHz) under the application of reverse bias voltage of varactor diodes. The design is also fourfold symmetric, thereby showing tunable characteristics for all polarization angles. Furthermore, a novel biasing technique has been implemented for measuring the fabricated structure using both parallel plate waveguide and free-space techniques, where experimental results match well with the simulated responses.

The paper is organized as follows. Section II describes the design of the proposed structure along with the equivalent circuit model. The simulated response and parametric variation are presented in Section III. The fabrication and measurement results are discussed in Section IV. Finally, the conclusion is presented in the last section.

II. DESIGN OF THE STRUCTURE AND EQUIVALENT CIRCUIT MODEL

Fig. 1 illustrates the array and unit cell geometry of the proposed wideband FSS. The top metallic patch consists of a periodic arrangement of circular loops printed on a dielectric substrate. Each of the loops is connected with four other loops through semiconductor switches across the diagonals. The metal patch is made of copper with conductivity of $5.8 \times 10^7$ S/m and thickness of 0.035 mm, whereas FR4 is used as the dielectric substrate having relative permittivity ($\varepsilon_r$) of 4.4 and loss tangent $(\tan\delta)$ of 0.02. The geometric dimensions of the structure are optimized as $p = 12$ mm, $r = 3$ mm, $w_1 = 0.8$ mm, $w_2 = 0.6$ mm, $g = 1.3$ mm, and $t = 1$ mm. The switches chosen are SMV 1249-079 LF varactor diodes from Skywork Solutions, Inc. [29], which have variable capacitance under the reverse voltage. The incident field directions are also depicted in Fig. 1.

The varactor diodes, placed across the gaps in the diagonals, have variable capacitance depending on the reverse voltage. While increasing the reverse bias, the depletion region in the P-N junction expands, and the junction capacitance decreases. Similarly, the capacitance increases for reducing the bias voltage. The relation between the junction capacitance $C_J$ and the reverse voltage $V_R$ is given by [29]

$$C_J = \frac{C_{J0}}{(1 + V_R/V_J)^M} + C_P$$  

where the zero-bias junction capacitance $C_{J0}$ is 36.4 pF, junction potential $V_J$ is 80 V, grading coefficient $M$ is 70, and package capacitance $C_P$ is 1.68 pF. Therefore, the overall capacitance varies from 38.08 to 1.72 pF, when the reverse bias voltage changes from 0 to 8 V. In the full wave simulation, the varactor diode has been replaced by the corresponding capacitor model for simplicity.

The performance of bandstop FSS, aimed for shielding application, is often observed through shielding effectiveness (SE), which is defined as the ratio of the transmitted field component ($E_t$) to the incident field component ($E_i$) [3], [12] and is

\[ \text{SE} = \frac{E_t}{E_i} \]

Fig. 2. Simulated transmission coefficient of the proposed structure under different reverse bias voltages.
SE_{dB} = -20 \times \log \left| \frac{E_t}{E_i} \right|.

Given by Eq. (2)

Fig. 3. Simulated SE of the proposed structure under different reverse bias voltages.

The SE of the proposed structure is also shown in Fig. 3, which shows that at least 60 dB SE has been achieved while varying the reverse voltage.

To explain the tunable performance of the proposed FSS, an equivalent circuit model is developed in Fig. 4(a). The equivalent inductance ($L$) corresponds to the length of the circular loops along the direction of the incident electric field. Varactor diodes are realized by variable capacitance ($C_V$) and dielectric substrate is represented by the transmission line. The variable capacitance ($C_V$) value can be obtained from the data sheet, whereas the lumped inductor value can be determined as $L = 2.32 \text{ nH}$ using quasi-static analysis of microstrip line [30], [31].

Fig. 4(b) shows the comparison of SE of the proposed structure using full-wave and circuit model simulation. Two cases are considered: 0 volt and 8 volt reverse bias voltages, where good agreement is observed in both the cases.

III. SIMULATED RESULTS AND PARAMETRIC VARIATION

Since the biasing network of active FSS structures need to be carefully designed under different polarizations of incident waves, active polarization-insensitive FSSs are more difficult to realize compared to passive polarization-independent structures. The novelty of the proposed structure lies in its symmetrical design and, therefore, exhibits similar SE performance for all polarization angles, as observed from Fig. 5. The biasing networks applied across the varactor diodes have no considerable effect on the design symmetry as discussed in detail in the measurement section.

To examine the sensitivity of the proposed FSS under oblique incidence, the SE response is studied for both the upper and lower limits of the tuning range. The results are illustrated in Figs. 6 and 7 for TE and TM polarizations of the incident wave, respectively, where stable stopband frequency responses up to $60^\circ$ angle of incidence are observed. At TM polarization, the incident electric field vector changes with the incident angle, thus changing the equivalent inductance of the top FSS geometry. This effectively changes the resonance frequency, in particular, at higher incident angle as observed from Fig. 7. Since the equivalent inductance remains almost constant at TE mode, no noticeable frequency shift occurs as shown in Fig. 6.
The simulated SE of the proposed tunable FSS structure is also illustrated as a function of different parameters. When the period of the unit cell \((p)\) is varied keeping circular loop dimensions constant, the length of the diagonals will be increased to maintain the design symmetry. Then, the equivalent inductance \((L)\) will increase, thereby reducing the resonance frequency as observed from Fig. 8. The above-mentioned inference further confirms that the increase of radius of the circular loops \((r)\) will also decrease the resonance frequency in the similar way. Furthermore, the increase of the width of the circular loops \((w_2)\) will reduce the equivalent inductance and, consequently, the stopband frequency will be increased, as shown in Fig. 9.

In order to explain the resonance mechanism of the proposed design, the structure has been studied without the varactors, as shown in Fig. 10. It is observed that the bandstop frequency owing to the original passive structure occurs at 13.93 GHz,
whereas addition of varactors shifts the resonance to lower frequency range due to high value of junction capacitance. The surface current flows through the structure along the direction of incident electric field, thereby producing the equivalent inductance, which along with the diode capacitance generates the resonance [31]. While varying the reverse bias, capacitance value changes, and the resonance frequency tunes within a certain frequency range.

IV. FABRICATION AND MEASUREMENT

Since the biasing networks are to be provided in reconfigurable structures, it is difficult to design symmetrical FSS having unit cells arranged in periodic pattern. To describe the biasing network, an array of the unit cell of the proposed structure has been considered, as shown in Fig. 11. Two biasing lines are printed at the two sides of the sample. Circular loops present in the middle of the unit cell are connected to the right side bias line, whereas circular loops present above and below the central circular loops are joined with the left side bias line. The varactors are connected across the gap in the diagonals such that the anodes and the cathodes of the diodes are connected with the right and left side bias lines, respectively. HK 1005 series of inductors from TAIYO YUDEN having the value of 47 nH are used between the successive circular loops to achieve isolation as well as to protect the biasing lines from the EM wave [32]. The value of the inductors has been chosen in such a way that they exhibit bandstop characteristic over the entire tunable frequency range.

Therefore, when the left and right bias lines are connected with the positive and negative ends of the supply voltage, respectively, direct current will flow through the varactor diodes uninterruptedly as observed from Fig. 11. When the supply voltage is varied, the equivalent capacitance of the diodes will change and it will exhibit wideband tunable bandstop performance.

In order to verify the design of the proposed tunable FSS, two prototypes of different sizes are fabricated for two different measurement techniques. For the parallel plate waveguide technique, the fabricated sample consists of 12 unit cells in one direction, on which 48 varactor diodes are soldered, as illustrated in Fig. 12. In the parallel plate waveguide, there are two conductors lying at top and bottom, which support the transverse EM (TEM) wave propagation. If an one-dimensional array structure has been kept within the parallel plate waveguide, the top and bottom metal plates provide the periodic boundary condition and make the measurement equivalent to the measurement of a two-dimensional array in free space [33]–[35]. A photograph of the test setup is provided in Fig. 13. The waveguide is made of aluminium plates, where the separation between the plates has been maintained by using Teflon stands. The distance between the plates is kept in such a way that the higher order TE and TM modes cannot affect the performance of the fabricated structure.

Initially, the transmission coefficient of the empty waveguide is recorded as the background signal. Then, the fabricated prototype is placed and the transmission coefficient is measured. The original transmission coefficient has been obtained by subtracting the background signal from that of the structure. As the supply voltage is increased from 0 to 8 V, the capacitance decreases, and the stopband response is shifted to higher frequency range as observed from Fig. 14. The tunable range is maintained nearly 356.36% and 128.10% with respect to the lower frequency and the centre frequency, respectively, without any deterioration in the resonance shape. The measured results are also in good agreement with the simulated responses except some small deviation, which may be accounted due to finite size of the fabricated structure and fabrication tolerances.
Fig. 14. Comparison of measured and simulated SE of the proposed structure under different reverse bias voltages measured using parallel plate waveguide.

Since the purpose of the proposed FSS structure is mainly for free-space applications, a two-dimensional array has also been fabricated on the FR4 substrate using the printed circuit board technique. Besides, free-space measurement is more accurate than the parallel plate measurement. The overall structure contains $10 \times 10$ unit cells, where 400 varactor diodes are soldered using the surface-mount technology. The picture of the fabricated structure is depicted in Fig. 15.

The two-dimensional array structure is then measured in an anechoic chamber using the free-space technique. As the reverse bias voltage is increased from 0 to 8 V, the resonance frequency shifts from 0.55 to 2.52 GHz, thereby resulting tunability of 358.18% as observed from Fig. 16. Good agreement between the simulated and measured responses are observed for different bias voltages under normal incidence.

![Varactor diode and inductor](image)

**V. Conclusion**

In this paper, a wideband tunable FSS has been presented for EM shielding in different bands (GSM, ISM, UNII, WLAN, and so forth). The proposed structure exhibits wide tuning of band-stop response as a function of reverse bias voltage. The structure also exhibits broadband attenuation of 1.28 GHz, where the bandwidth remains almost constant while varying the bias voltage. The bandwidth of the proposed structure is the widest while compared with earlier reported FSSs in Table I. The structure also exhibits largest tuning range among the tunable FSSs, which is also observed from Table I. Furthermore, the structure has the advantages of simplified geometry, polarization-insensitivity, angular stability as well as experimental validation using a novel biasing network. The concept can further be extended to design the wideband tunable FSS structure with an embedded biasing network.

**TABLE I**

<table>
<thead>
<tr>
<th>FSS structure</th>
<th>Fractional bandwidth</th>
<th>Tunable range</th>
<th>Polarization insensitivity</th>
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<tr>
<td>[10]</td>
<td>36.5%</td>
<td>-</td>
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<td>[11]</td>
<td>52.4%</td>
<td>-</td>
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<td>[12]</td>
<td>73.17%</td>
<td>-</td>
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<td>[13]</td>
<td>100%</td>
<td>-</td>
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<td>Proposed structure</td>
<td>152.38%</td>
<td>362.96%</td>
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<td>[25]</td>
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**REFERENCES**


