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Design of dual-polarized and angular stable new bandpass frequency selective surface in X-band

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Abstract In this paper, a new geometrical shape of the bandpass modified circular ring frequency selective surface (FSS) structure with significant electrical response such as angular stability up to 50° of the angle-of-incidence (AOI) for both the perpendicular (TE) and parallel (TM) polarized waves has been discussed. The geometrical parameters of the proposed bandpass FSS is obtained by the transformation of bandpass single square loop FSS structure parameters. To achieve the frequency response of the proposed bandpass structure, commercially available 3D electromagnetic simulators such as CST Microwave Studio and Ansoft HFSS are used. The proposed bandpass FSS structure provides significant angular (i.e., up to 50°) and polarization (i.e., perpendicular and parallel) stability as compared to that of various other reported literatures. In addition to this, one of the important characteristics of the resonant structure is the quality factor (Q-factor), which has also been discussed for the proposed bandpass FSS structure at different AOI.

Keywords Oblique incidence · Perpendicular and parallel polarization · Q-factor · X-band

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1 Introduction

FSS structures have a potential to impart the bandstop and bandpass spatial filtering characteristics depending upon their requirements [1]. Ideally, the bandstop and bandpass FSS structures provide the total reflection and transmission characteristics at the resonant frequency, respectively [2]. However, various researchers have discussed the different geometrical shapes of bandstop FSS structures, which allow the propagation of direct current signals through it, which are not suitable for various applications as discussed in [1]. Therefore, the demand of designing the bandpass FSS structures has been increased and very significant in the modification of electromagnetic (EM) architecture of the buildings, which is essential in order to accommodate the advanced and imminent wireless technologies [3,4]. Moreover, several geometrical shapes of FSS structures such as square loop [5], circular ring [6], hexagonal and cross dipole [1] have been discussed in the microwave regime of the EM spectrum. Among these geometrical shapes of the FSS structures, the square loop and circular ring offer significantly less angular sensitivity for a wide range of AOI as compared to that of the other geometrical structures due to their symmetrical nature [7]. However, the angular and polarization stability is prime issue, which has to be explored in order to enhance the spectral performance of FSS structures. The circular ring FSS structure is the most significant in terms of the angular and polarization stability [1,6].

Various researchers/scientists have proposed different FSS structures to realize the significant angular and polarization stability. Kiani et al. [8] have explored two-layer absorb/transmit FSS structure in which the first layer consists of conducting cross dipole with a circular aperture in the centre and second layer uses resistive cross dipole element for perpendicular and parallel polarized wave, respectively, up to 45° of AOI. Recently, much attention has been focused to develop new geometrical shapes of FSS structure for single and multilayer FSS in order to realize the angular and polarization stability. In [9], the actively loaded (with varactor diode and surface mount capacitor) circular ring FSS structure has been discussed for perpendicular and parallel polarized wave, respectively. Further, the dual-band bandpass FSS with four symmetrical spiral patterns of metallic meander line printed on FR4 dielectric substrate [10], the single-band bandpass FSS [11] and a single-band bandpass FSS with four spiral rectangles connected to a cross-line element in the middle [12], have been explored for both the perpendicular and parallel polarized wave incident up to 60° AOI.

In this paper, a single-layer bandpass modified circular ring FSS structure, which provides very significant results in terms of the angular and polarization stability as compared to the reported cross-dipole with an aperture in the centre [8], tunable circular ring [9], and other new bandpass FSS structures as reported in [10–12], is discussed. In addition to this, the proposed bandpass FSS also provides the significant angular and polarization stable frequency response as compared to that of the classical geometrical shapes (i.e., square loop and circular ring) of the FSS structure as discussed in [2, 13–16]. The simple geometry of proposed bandpass FSS structure provides the ease of fabrication as compared to that of the tunable and fractal FSSs. The proposed bandpass FSS results an angular stable structure up to 50° of AOI for two principal orientations (i.e., perpendicular and parallel polarizations) relative to the incident plane wave in X-band regime of the EM spectrum. The proposed bandpass structure has been simulated through 3D EM commercially available simulators such as CST Microwave Studio and Ansoft HFSS. A prototype of the proposed bandpass FSS is fabricated and experimentally tested for s-parameters (i.e., reflection and transmission parameters). This paper is organized as follows. Section 2 describes the approach that is the transformation of bandpass single square loop FSS (SSLFSS) synthesis technique to obtain the geometrical parameters of the proposed bandpass FSS structure along with its material specifications. Section 3 explores the simulation as well as measured results. Finally, Sect. 4 concludes the work and explores the future prospective.

2 Generalized synthesis

In this section, the geometrical parameters of unit-cell element of proposed bandpass FSS, which is achieved through the periodic perforation of a thin conducting sheet and exhibit the transmission characteristics at the resonance frequency are discussed. It is very significant to study the unit-cell element of planar bandpass and bandstop FSS array because

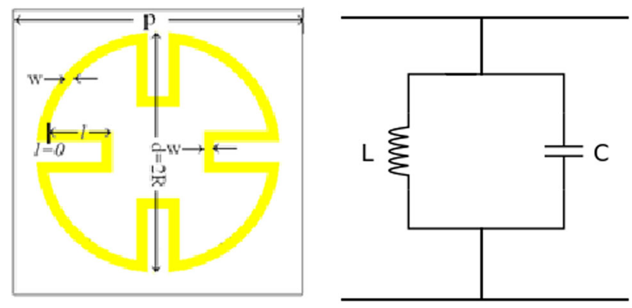


Fig. 1 The proposed bandpass modified circular ring FSS structure **a** unit-cell configuration and **b** its equivalent circuit (EC) model

according to the Floquet theorem, a single unit-cell efficiently describes the field through the FSS array [2]. In addition to this, several numerical techniques such as finite difference time domain (FDTD), finite element method (FEM), method-of-moment (MoM) and equivalent circuit (EC) technique are available for the analysis of various FSS structures. Among these numerical techniques, we have used the EC technique for the analysis of the proposed bandpass FSS because it provides simpler, rapid and accurate computation of the frequency response. The unit-cell element of proposed bandpass FSS structure as shown in Fig. 1a, has a metallic sheet of copper with thickness, $t = 0.02$ mm and electrical conductivity, $\sigma = 5.8 \times 10^7$ S/m through which a modified circular ring is etched out and backed with commercially available Arlon AD 320 (dielectric substrate) of thickness 0.762 mm, relative dielectric permittivity, $\varepsilon_r = 3.2$, loss tangent, $\tan\delta = 0.0038$ and simulated at 10.50 GHz using two different commercially available simulators. However, Fig. 1b has demonstrated the EC aspect of the proposed modified circular ring FSS structure, which is achieved using Advanced Design System (ADS) in which parallel LC circuit with 5.1 nH of lumped inductance, L and 44.45 fF of capacitance, C represents the unit-cell element. The effect of proposed bandpass FSS is adapted by adjusting the geometrical parameters such as periodicity (p), width of the slot (w), size of the unit-cell element (d) and length of the parallel straight slots (l), which has been discussed as follows.

2.1 Single square loop bandpass FSS structure

Recently, the synthesis technique of free-standing bandstop SSLFSS has been discussed in [17]. However, the effect of dielectric substrate on the resonant frequency of bandstop and bandpass FSSs is significantly different. Therefore, we have discussed the synthesis technique of bandpass SSLFSS, which is backed with dielectric substrate and has been interpreted in terms of its EC, which provides the normalized mathematical equation of its associated inductance as well

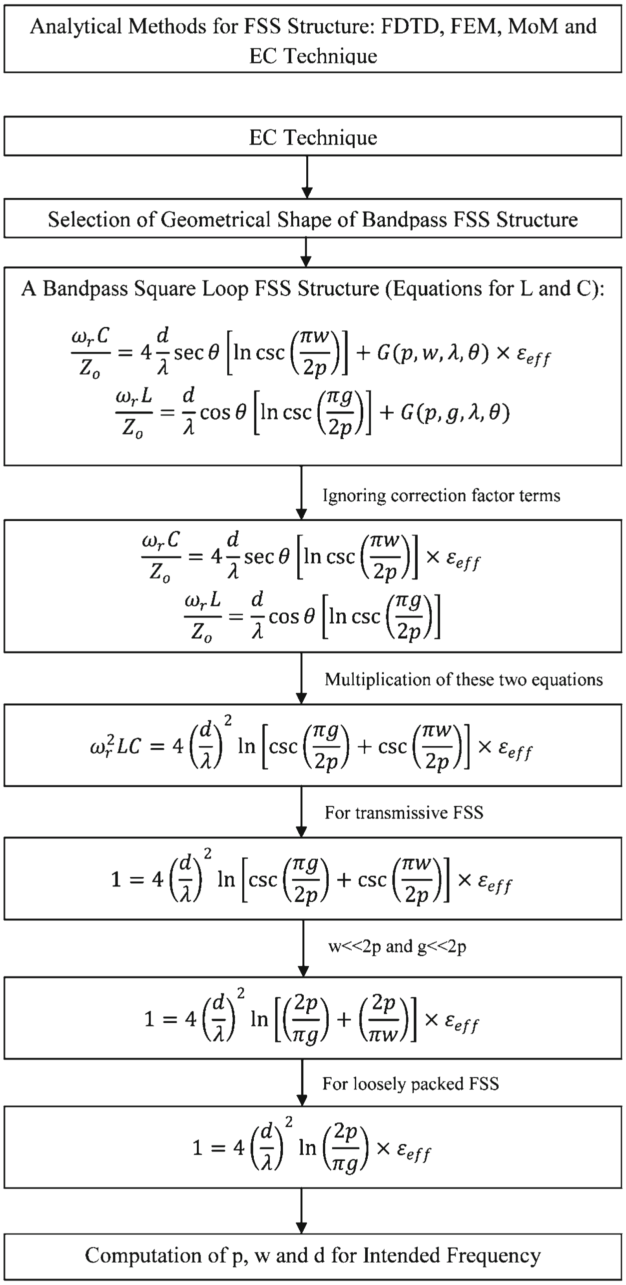


Fig. 2 The generalized synthesis approach for the bandpass SSLFSS

as capacitance [18] as shown in Fig. 2 (in block 4). On the multiplication of these normalized mathematical equations, we have achieved the resonance criteria. Theoretically, for achieving 100 % reflection and transmission from the patch and slot FSS structure, respectively, the $\omega_r^2 LC$ in the achieved mathematical equation is equal to 1 (i. e. the resonance condition), which is shown in Fig. 2. Moreover, in order to simplify the analysis of the bandpass SSLFSS structure, we have considered the loosely packed array of FSS structure with negligible width of the slot (w) of the unit-cell element and inter-element gap (g) between the unit-cell elements as compared

Table 1 The geometrical parameters of the proposed bandpass SSLFSS structure

w/λ	p (mm)	d (mm)	w (mm)
0.01	13.041	7.86	0.2857
0.02	13.041	8.85	0.5714

to twice of the periodicity (p). Moreover, the periodicity (p) of the bandpass SSLFSS structure has been given as [1]:

$$p(1+\sin\theta) < \lambda/2 \quad (1)$$

where, θ and λ is the AOI and wavelength corresponding to the operating frequency, respectively. In order to satisfy the Eq. (1), we have considered AOI, $\theta = 10°$ for normal wave incidence, therefore, Eq. (1) is modified as follows: $p\,(1+\sin\theta) = \lambda/2$. However, with this synthesis technique, at the intended frequency (10.50 GHz), we have obtained the geometrical parameters (i.e., p, w, d) of the bandpass SSLFSS structure, is shown in Table 1. The geometrical parameters given in second row of the Table 1 have been chosen to achieve significantly close frequency response to that of the intended resonant frequency in terms of the reflection and transmission parameters. In addition to this, we have considered the effect of the dielectric substrate on the individual parameter such as p, w, d and due to this, the geometrical parameters given in second row of Table 1. is as follows: $p = 9$ mm, $d = 6.10$ mm and $w = 0.40$ mm for $w/\lambda = 0.02$.

2.2 Modified circular ring bandpass FSS structure

The synthesis technique of bandpass SSLFSS is transformed over the circular ring FSS structure because it is more angular stable as compared to that of the SSLFSS. From the mode matching technique as reported in [19], illustrate that at the resonance frequency, the perimeter of a square loop and the mean circumference of circular ring FSS structure is approximately equal to the integer multiple of the operating wavelength. In other words, for the same value of p, d, and w, the SSLFSS resonates at a lower frequency as compared to that of the circular ring FSS, which has been discussed in [20]. For the transformation of proposed synthesis technique of bandpass SSLFSS over the circular ring FSS, it is required to resonate the circular ring FSS at the same frequency as that of the SSLFSS, which has been achieved by enhancing its d and p. However, this enlargement deteriorates the angular stability of the circular ring FSS structure and results the larger size [1]. Therefore, in order to overcome this limitation and to achieve better angular/polarization stability, the four pair of parallel straight slots of length (l) have been inserted in the circular ring FSS structure, as shown in Fig. 1a. The proposed bandpass FSS at 10.5 GHz with same geometrical

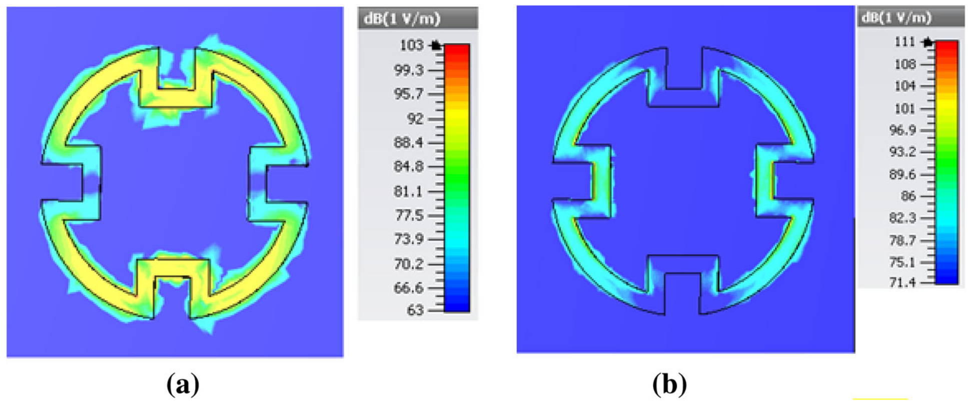


Fig. 3 The electric field distribution for normal wave incidence on the proposed FSS structure at 10.69 GHz for the **a** perpendicular polarized wave and **b** parallel polarized wave

parameters is designed, which are obtained from the synthesis technique of bandpass SSLFSS such as: $p = 9$ mm, $d = 6.10$ mm and $w = 0.40$ mm. In addition to this, we have computed the values of the inductance $L(nH)$ and capacitance C (pF) using respective EC approach of the proposed bandpass FSS and customized the values of L and$C$ in the EC, which has been achieved through ADS. By varying the values of $L(nH)$ and C (pF), the geometrical parameters of the proposed bandpass FSS are tuned as: $p = 9$ mm, $d = 6.9$ mm and $w = 0.46$ mm, to achieve the frequency response, which is closer to the intended frequency. Moreover, the length (l) of pair of parallel straight slot has been considered as 1.08mm.

3 Results and discussion

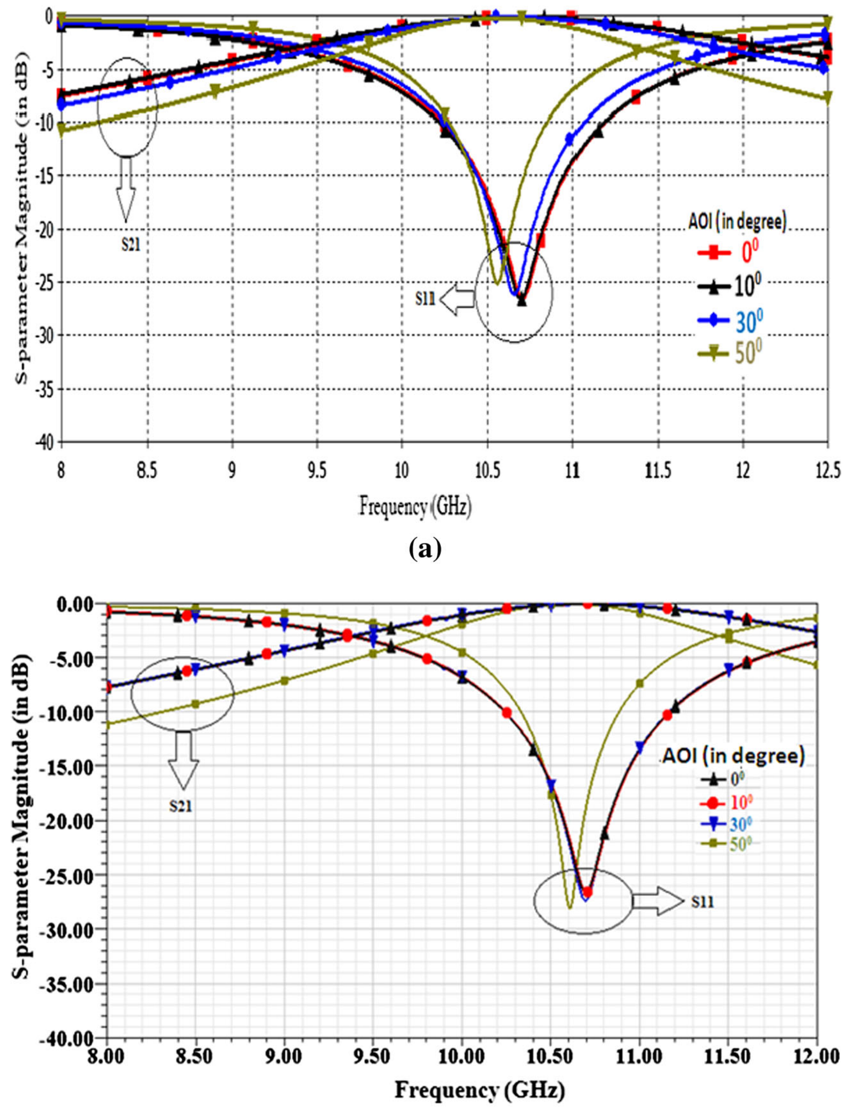
In this section, we have discussed the electric field distribution, angular stability, −3 dB reflection/transmission bandwidth and quality factor (Q-factor) of the proposed bandpass FSS for perpendicular and parallel polarized incident waves at X-band (8–12.5 GHz). We have simulated the proposed bandpass FSS structure using commercially available simulators such as CST Microwave Studio, which is based on finite integral technique and Ansoft HFSS, which is based on the finite element technique. The simulation has been performed through implementing the unit-cell boundary conditions along the x-as well as y-axis and open boundary condition along the z-axis in CST Microwave Studio [21] and master/slave boundary along x- as well as y-axis and Floquet boundary condition along z-axis in Ansoft HFSS [22] for the proposed bandpass FSS. The proposed bandpass FSS structure provides the resonance pole transmission at 10.69 GHz, for both the normally incidence perpendicular as well as parallel polarized wave. In order to clarify the bandpass resonance, we have provided the electric field distribution diagrams at 10.69 GHz for the normally incidence perpendicular and parallel polarized wave, which are demonstrated in Fig. 3a, b, respectively. In addition to this, Fig. 3a has depicted that for the perpendicular polarized wave, the electric field distribution for the component parallel to the direction of the wave propagation is weak. Moreover, Fig. 3b has demonstrated that for the parallel polarized wave, the electric field distribution for the component perpendicular to the direction of the wave propagation is weak. In addition to this, outside the proposed bandpass FSS structure, the electric field values are very weak and the passband arises from enhanced transmission assisted by the slot resonance for the normally incidence perpendicular and parallel polarized wave in the proposed bandpass FSS structure.

For the perpendicular polarized wave incidence up to 50°, the simulated resonant frequency of the proposed bandpass FSS downshifts with 0.85 and 0.84 % through CST Microwave Studio and Ansoft HFSS, respectively with respect to the normal incidence as demonstrated by Fig. 4a, b. In addition to this, Fig. 5a, b have illustrated that for the parallel polarized wave incidence up to 50°, the resonant frequency downshifts with 0.76 and 0.65 % through CST Microwave Studio and Ansoft HFSS, respectively, with respect to the normal incidence. Moreover, for the comparison of angular and polarization stability of the proposed FSS structure with several other FSS structures reported in literature are listed in Table 2.

However, in Fig. 6, the effect of different AOI on the Q-factor for the proposed bandpass FSS has been demonstrated. With the increase in the AOI up to 50° for the perpendicular polarized waves, the Q-factor increases with 26.81 and 16.41 % through CST microwave Studio and Ansoft HFSS, respectively, with respect to the normal wave incidence as shown in Fig. 6a.

In addition to this, for the parallel polarized wave, the Q-factor increases with 1.94 and 2.34 % through CST microwave Studio and Ansoft HFSS, respectively with respect to the normal wave incidence as shown in Fig. 6b. With increase in the AOI up to 50°, the 3-dB bandwidth decreases, which results increase in the Q-factor because 3-dB bandwidth is inversely proportional to the Q-factor. The proposed bandpass FSS structure provides significant

Fig. 4 The frequency response of S-parameters at different AOI on the proposed FSS structure at X-band for perpendicular polarized wave using **a** CST Microwave Studio and **b** Ansoft HFSS



angular stability for both perpendicular and parallel polarized waves and the simulation results have demonstrated 0 and 0.3 % shift in the resonant frequency for the perpendicular and parallel polarized wave at normal incidence, as achieved through CST Microwave Studio and Ansoft HFSS, respectively. For the generic use of the synthesis technique, based on the available infrastructure, a proposed bandpass FSS structure in X-band regime of the spectrum has been fabricated and tested. The measurement setup includes the two double ridge horn antennas, which are used as reference antennas. The proposed bandpass FSS structure fabricated on a single sided copper clad substrate of $18 \times 18\,\mathrm{cm}^2$ using the conventional chemical processing is placed between the two horn antennas and illuminated by the plane waves generated by the transmitting horn antenna, which is normal to the FSS structure. In addition to this, the transmitted waves through FSS structure have been collected by the receiving horn antenna and vector network analyzer (VNA) is used to calculate the frequency response. The structure parameters are given in Table 3. From Fig. 7, it is observed that the proposed FSS structure resonate at 10.69 and 10.70 GHz through simulation using CST Microwave Studio and Ansoft HFSS, respectively, where as in the measured result it resonates at 10.69 GHz. Therefore, the deviation in the resonant frequency achieved through CST Microwave Studio and Ansoft HFSS is 0.009 and 0.09 %, respectively as compared to the measured results, which demonstrate the practicality of the proposed FSS structure. Fig. 7 also demonstrates that −10 dB impedance bandwidth extends from 10.09 to 11.08 GHz and 10.22 to 11.18 GHz through CST Microwave Studio and Ansoft HFSS, respectively against the measured value of 10.37–10.96 GHz. The significant discrepancy is that the measured bandwidth is narrow than the simulated one, which is due to the following factors: (a) diffractions from the edge

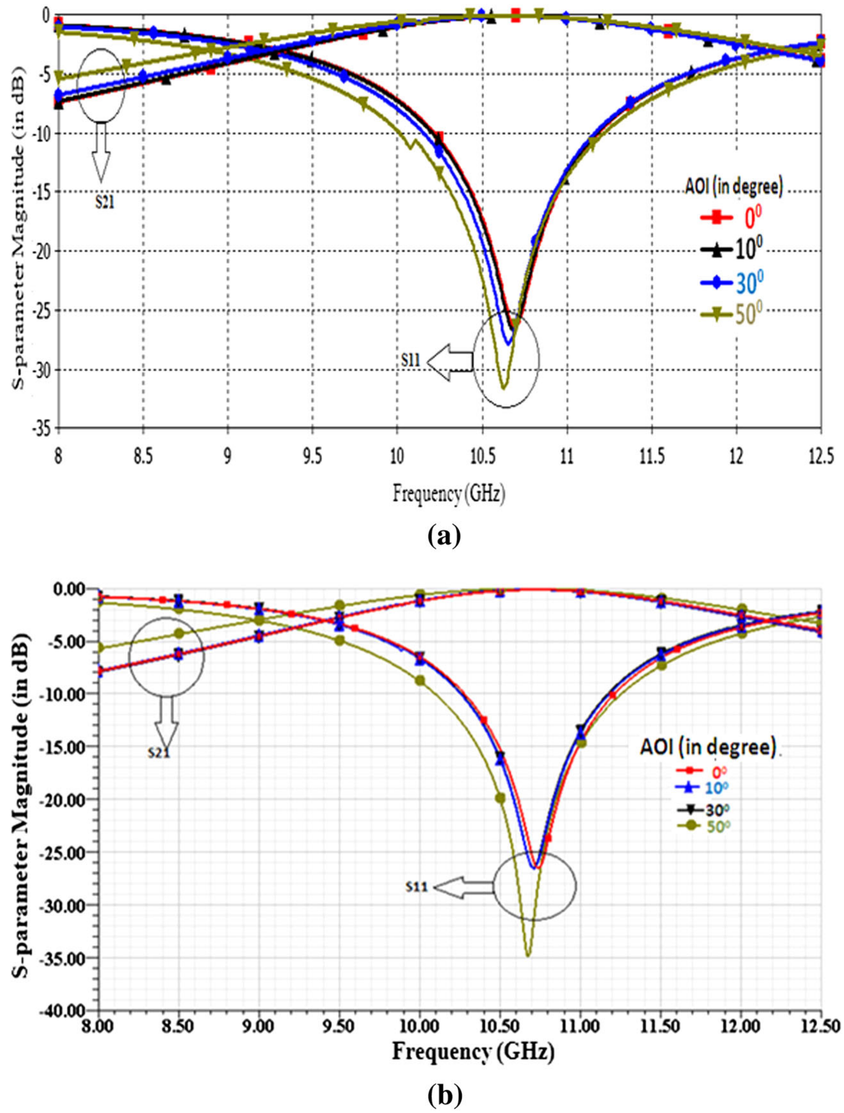


Fig. 5 The frequency response of S-parameters at different AOI on the proposed FSS structure at X-band for parallel polarized wave using **a** CST Microwave Studio and **b** Ansoft HFSS

of the finite FSS panel, (b) machining precision and (c) the measured conditions. At resonance, S_{11} in measured result is −24.15 dB against simulated value is −26.33 and −26.85 dB through CST microwave Studio and Ansoft HFSS, respectively.

4 Conclusion

In this paper, the electrical performance of the proposed inductive modified circular ring FSS structure for dual polarized and different oblique angle incidence of the EM wave is discussed in X-band. At the normal wave incidence, the simulation results achieved through CST Microwave Studio and Ansoft HFSS experiences only 0.009 and 0.09 % drift in the resonant frequency as compared to the measured results. In addition to this, the return loss obtained in the simulated results such as 26.33 and 26.58 dB through CST microwave Studio and Ansoft HFSS, is also comparable with the measured results (24.15 dB). However, at 0° AOI, the shift in the resonant frequency due to perpendicular and parallel polarized wave is 0 and 0.3 % as achieved through CST Microwave Studio and Ansoft HFSS, respectively, which is significantly small and provides the stable response in terms of the reflection and transmission parameters for dual polarization. Moreover, with the increase in the AOI up to 50°, for theperpendicular polarized wave, the resonant frequency downshifts with 0.85 and 0.84 %, respectively and for the parallel polarized wave, the resonant frequency downshifts with 0.76 and 0.65 %, through CST Microwave Studio and Ansoft HFSS, respectively. The proposedbandpass FSS structure provides the significantly better angular and polarization stability as compared to that of the active/tunable FSS and different complex geometry FSS structures as compared in the preced-

Table 2 Comparison of angular and polarization stability of the proposed FSS structure with other reported literatures

AOI (°)	FSS structure	% deviation of f_r
45	FSS structure in [2]	16.6
45	FSS structure in [8]	1.91 (TE incidence) and 1.12 (TM incidence)
45	FSS structure in [9]	3 (TE incidence) and10 (TM incidence)
60	FSS structure in [10]	Approximately 1 (TE and TM incidence)
60	FSS structure in [11]	Approximately 5 (TE and TM incidence)
60	FSS structure in [12]	0.52 (TE incidence) and 2.1 (TM incidence)
45	FSS structure in [13]	5.95
45	FSS structure in [14]	7.60
45	FSS structure in [15]	5.45
45	FSS structure in [16]	7 (TE and TM incidence)
50	Proposed FSS structure	0.84 (TE incidence) and 0.65 (TM incidence)

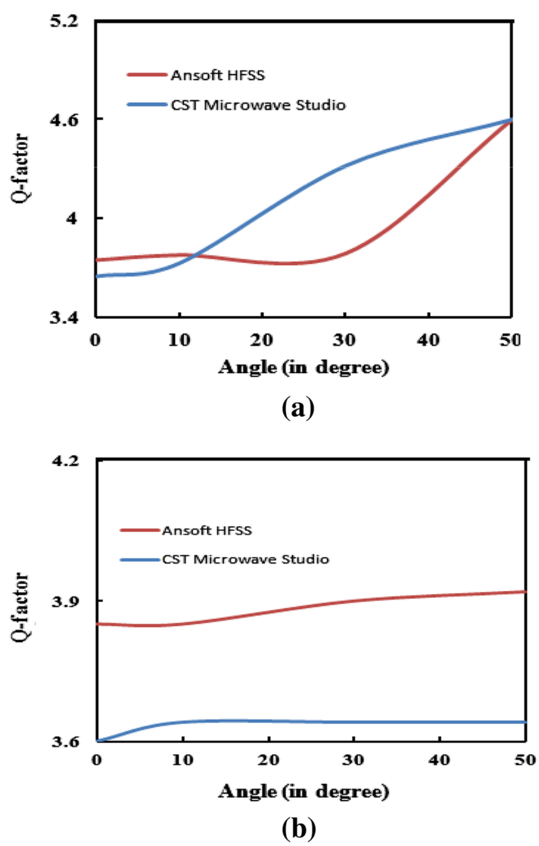


Fig. 6 The AOI versus quality-factor response of the proposed FSS structure through CST Microwave Studio and Ansoft HFSS for the **a** perpendicular and **b** parallel polarized wave

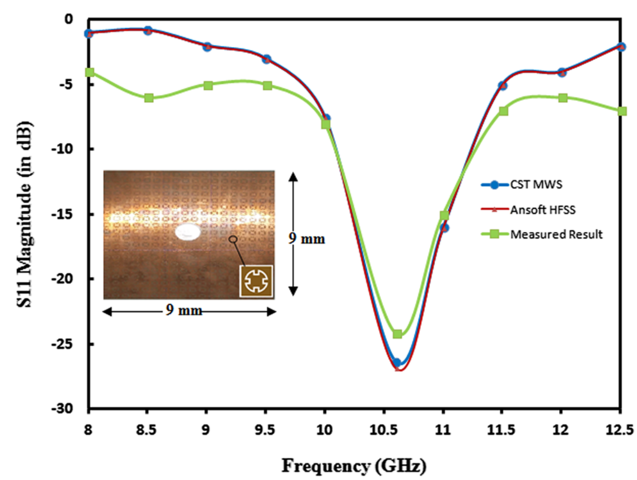


Fig. 7 The measured and simulated response of proposed FSS structure along with the fabrication prototype

Table 3 Geometrical parameters of proposed bandpass FSS structure at 10.50 GHz

p(mm)	d(mm)	w(mm)	t(mm)	$l(mm)$	ε_r	$\tan\delta$	Substrate thickness (h)
9	6.9	0.46	0.02	1.08	3.2	0.0038	0.762

ing sections. Moreover, the Q-factor is also increased and achieved the maximum value of 4.61, which enhances the frequency selectivity of the proposed modified circular ring FSS structure. The multi-band frequency response of this type of FSS structure is a potential issue which will be reported in future communication.

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