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Frequency Selective Surface with Improvised Ring-Resonator for Flexible Design

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Abstract—Ring resonators are very commonly used for the design of frequency selective surfaces (FSSs). But, for some particular design, the spacing between the resonators becomes very small. So it leaves no space to shift the reflection band towards the lower side of the spectrum. It also becomes very difficult to realize large PCBs. In this paper, an improvised design of the ring resonator using stubs is reported. This provides the designer with some flexibility. Two different configurations using this concept have been fabricated. Measured results are compared with the configuration using conventional ring resonators. These results indicate good performance with tune-ability in the response without major change in the design or in the substrate.

1. INTRODUCTION

Frequency selective surfaces (FSSs) find specialized application in the design of spacecraft antennas meant for deep-space missions. As the resources in a spacecraft become scarce, the antenna designers are compelled to explore the possibility of using the same antenna aperture for operations in multiple frequency bands. The frequency selective property of FSS of being totally reflective at a designed band and almost transparent in another, provides the designer with the opportunity to combine the energy radiated from different feed antennas onto the aperture of a single reflector antenna. Thus a compact antenna system can be realized leading to large savings in spacecraft mass.

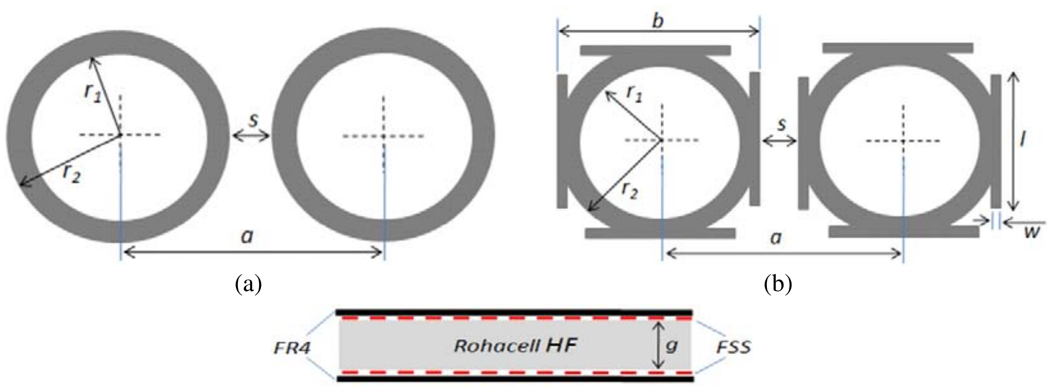

Figure 1. Schematic diagram of the FSSs under investigation: (a) conventional ring element, (b) ring element with stubs, (c) cross sectional view of the dual layer FSS.

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The FSSs are more interesting because, their frequency selective nature is not due to any material property but, due to some metallic patterns etched onto the sheet of a dielectric material. To be more precise, FSS per se does not need a substrate for its operation but for holding the repetitive metallic patterns together in the form of an array. There are different designs of the individual elements as well as of the array which are of particular interest of a designer.

The design aspects of FSS elements have been investigated by many researchers. Few of them are listed in [1–7] and most of the research works till the year 2000 have been discussed in [8]. Different configurations have been categorized under four groups [8] according to the topology of their geometry. Each of the elements has their specific advantages and application areas. Such is the case with the ring element [4, 6–9]. It provides more than 25% reflection bandwidth and maintains good polarization purity [4]. Sensitivity of the performance with varying angle of incidence of the electromagnetic (EM) wave is low for ring elements. Analysis of any general configuration of FSSs is discussed in [5] and that for the ring geometries is discussed in [10, 11]. Concentric ring resonators can be used for achieving multiband operations [7]. Active and/or lumped components can also be embedded within the ring to operate them at a different state or to realize a compact configuration [12, 13]. The design parameters of FSS using ring as elements are shown in Fig. 1(a). The detail of different aspects of their design can be found in [6].

While working with the FSS using ring elements, it is found that the geometry of some particular design do not offer any flexibility to lower the operating frequency of the reflection band. This is mainly due to the fact that it needs bigger rings which may not be possible to be accommodated within the space available.

Table 1. Substrate: FR-4: Thickness = 0.75 mm, $\varepsilon_r = 4.3$, and $\tan(\delta) = 0.013$. ROHACELL HF: Thickness, $g = 9$ mm, $\varepsilon_r = 1.04$ and $\tan(\delta) = 0.0017$. Metallization Thickness = 0.0175 mm.

config.	a (mm)	element parameters (mm)								stub param. (mm)	
		first layer				second layer				l	w
		r_1	r_2	b	s	r_1	r_2	b	s		
ring	9	4.1	4.3	---	0.4	3.6	4.3	---	0.4	---	---
stub-1	9	4.1	4.3	8.4	0.6	3.6	4.3	8.4	0.6	4	0.3
stub-2	9	4.1	4.3	8.4	0.6	3.6	4.3	8.4	0.6	5	0.3

In this paper, an improvised FSS design involving ring as the basic element is presented. Four rectangular stubs of dimension ($l \times w$) are attached to the rings as shown in Fig. 1(b). With this configuration the designer can have some flexibility in lowering the frequency of operation. This also allows varying the spacing between the rings 's' which is very important with respect to the fabrication of the printed surfaces.

2. NOMINAL DESIGN USING RING RESONATORS

The present design is targeted for application in an antenna that needs to cover the deep space communication at S- and X-bands. Keeping some margin for the design the pass-band for the FSS is taken as 2–2.7 GHz and the reflect band as 7–9 GHz. This is a very common requirement and can be met using nominal configuration of ring elements [6].

In here, a dual layer FSS has been designed using ring resonators in a square grid. The design parameters are provided in Table 1. The rings, printed on FR4 substrate, are sandwiched around Rohacell in such a way that the rings are covered by the dielectric material as shown in Fig. 1(c). The rings can be placed outside the surface of the sandwich also. In here this particular configuration is used to provide mechanical protection to the rings. Simulated response obtained using [14] of the configuration is shown in Fig. 2. Two different types of rings with staggered tuning are used to cover the entire band. It can be seen from Fig. 2 that the required bandwidth can be obtained if both the layers were identical to that of the first one (Table 1). But, it cannot cater to the lower side of the frequency range. To cover lower frequency range, the diameter of the ring needs to be increased which,

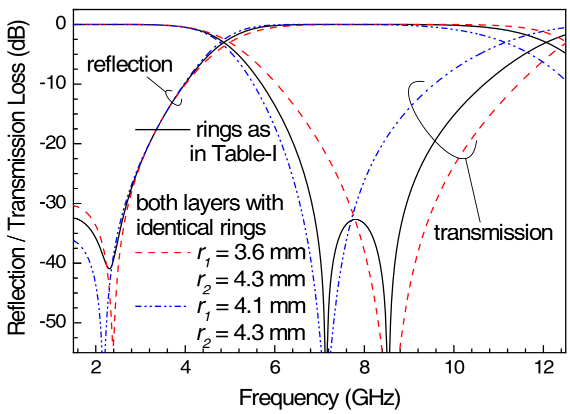

Figure 2. Simulated response of dual layer FSSs with different rings in the two layers as in Table 1 and with identical rings in both the layers.

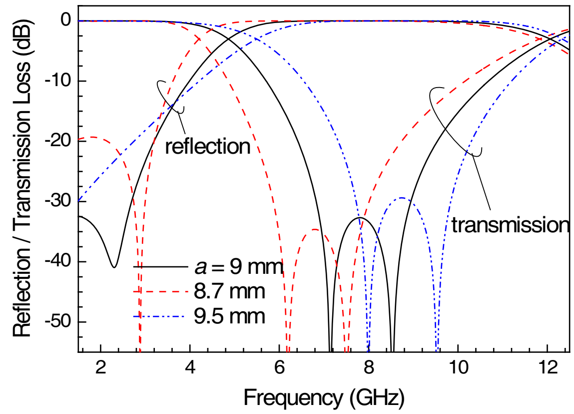

Figure 3. Simulated response of dual layer FSS with conventional ring elements for varying array spacing, a. Other parameters: in 1st row of Table 1.

in this situation is not possible because the available gap between the rings, s, is already very small. So only the inner radius (r_1) of the rings is increased such that the effective radius of the ring which lies between r_1 and r_2 is increased. This leads to the increase in the perimeter of the ring which lowers the resonant frequency. But, this also reduces the thickness of the ring ($r_2 - r_1$) which makes it a narrow band resonator. The simulated response of this configuration is also shown in Fig. 2. These results corroborate the observations made above. So, these two types of rings with their staggered resonant frequency are combined such that the required wide frequency band can be covered.

3. LIMITATION OF THE DESIGN USING RING

This design using conventional ring resonators meets the present requirements and can be used as such. But, a critical look at the design reveals that the designer has to work in a closed loop with contradicting requirements of the parameters a; the periodicity of the array and r_2; the outer radius of the ring. Value of a is determined by the highest frequency of operation and the angle of incidence of the EM wave, whereas, r_2 is related to the lower frequency side of the reflection band. Their values are geometrically related as $r_2 \leq (a - s)/2$. Thus for a given value of a, the choice of value of r_2 gets restricted to a maximum allowable limit. Hence, the lower range of operation for which the rings can be used also get restricted. The value of s is already very low, so the radius of the rings cannot be increased without increasing the value of a. But, it can be seen from the Fig. 3 that even any small increase in the value of a shifts the reflection frequency band towards the higher side of the spectrum. The spacing s between the rings also cannot be reduced beyond a certain limit for practical limitations in fabrication of large PCBs using chemical etching technique. In the present design the value of s is 0.4 mm which is already very close to the limit for a common PCB facility for a large size of board. This is more critical for the design operating at multiple and higher frequencies where value of a is reduced further.

So the only option seems to be left is to use a material with higher thickness or relative permittivity. But, it tends to increase insertion loss and excite surface wave. This also adds to the cost and mass of the hardware.

4. STUBBED RING: AN IMPROVISED DESIGN

The basic physics behind lowering of the operating frequency of the ring resonators is to increase their electrical length. Straight forward way is to increase the physical length itself by increasing the radius of the rings. When that is not possible then one tries to reduce the effective wavelength by introducing dielectric material. Such that though physical length remains the same, electrical length increases. Another way around is to introduce inductive and/or capacitive disturbances such that the phase of

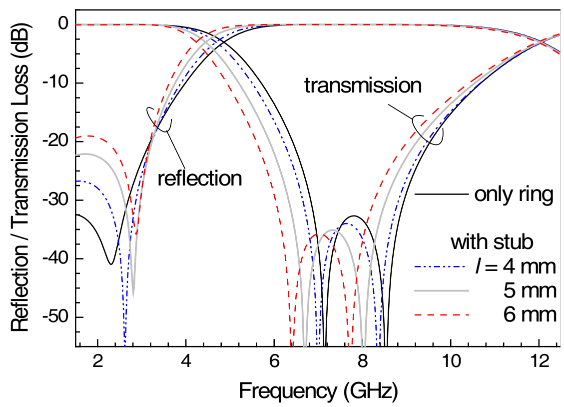

Figure 4. Simulated response (TE_{00} mode) of dual layer FSS with conventional rings and rings integrated with stubs of varying length, l. Other parameters: in Table 1.

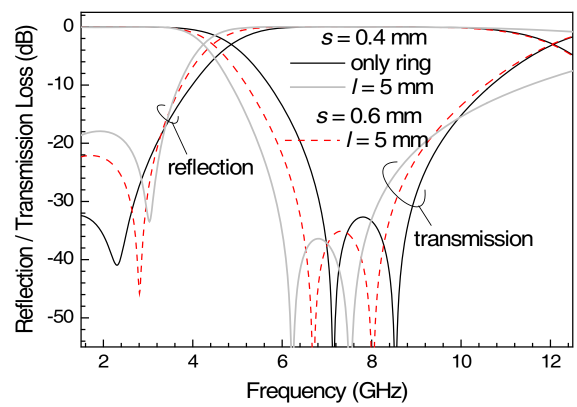

Figure 5. Comparison of the simulated response (TE_{00} mode) of dual layer FSS using ring element and new-element with 5 mm long stub for varying gap between the elements, s. Other parameters: in Table 1.

the currents in the ring is altered. As a result the electrical length of the rings is also changed. This concept has been implemented in this design.

As shown in Fig. 1(b), rectangular stubs of dimension $l \times w$ are attached to the ring resonators. Four of them are attached to a ring to maintain the symmetry in the square array in the present design. The location of these stubs is dependent on s. If enough space is available then the stubs can start tangentially to the outer edge of the ring, otherwise, as in the present case, stubs can move closer to the center of the ring such that a part of the stub overlaps with the ring. The parameter b in Fig. 1(b) controls the location of the stubs. If b becomes less than $(2 \times r_2)$, then the projection of the ring beyond the stubs may also be trimmed which increases the spacing, s. Three parameters namely b, l and w of the stub can be used to control the response of the FSS to some extent without altering the ring or the substrate parameters.

Simulated response of the configurations in Table 1 for varying length of the stub is shown in Fig. 4. It can be seen that with increased stub length the resonant frequency is lowered. However, the corresponding reflected power in the pass-band is also increased slightly which is more sensitive for the orthogonal, i.e., TM_{00} mode which will be addressed later. Considering this aspect it is found that for the present configuration a stub of length 5 mm can be used without much degradation in performance the corresponding shift in the frequency is about 600 MHz which is about 8% in terms of the fractional bandwidth.

In Fig. 4, the spacing between the resonator s is kept 0.6 mm by trimming the projection beyond the stubs as discussed above. This was to relax the PCB fabrication constraints. It can be seen from Fig. 5 that if this value was kept at 0.4 mm as that was in ring DGS, even more shift in frequency could have been achieved. The corresponding shift in frequency with respect to the conventional ring resonator is more than 1 GHz. However, degradation in reflection property in the passband is slightly more in this case. So with $s = 0.4$ mm a lower value of l could have been used. This provides the flexibility in the design.

But, due to the inclusion of the stubs, the circular symmetry of the ring is disturbed. This causes slight degradation in the performance specifically for wide angel incidence of the TM_{00} mode wave. This variation for the TE_{00} mode is very small for both the configurations, i.e., with and without stubs and they are not shown here. But, there are some variations for TM_{00} mode which has been investigated in Fig. 6. The response corresponding to TM_{00} mode of the FSS with conventional ring is shown in Fig. 6(a). From this figure, it can be seen that as such there is about 15 dB variation in the reflection property at passband for varying angle of incidence even without the stubs. The value of reflection coefficient reaches about -12 dB near the reflection band edge of 2.7 GHz for angle of incidence of 45°. For direct comparison, identical responses of the FSS integrated with the stub of length 5 mm is shown in Fig. 6(b). In here also large variation in reflection coefficient is observed with different angles of

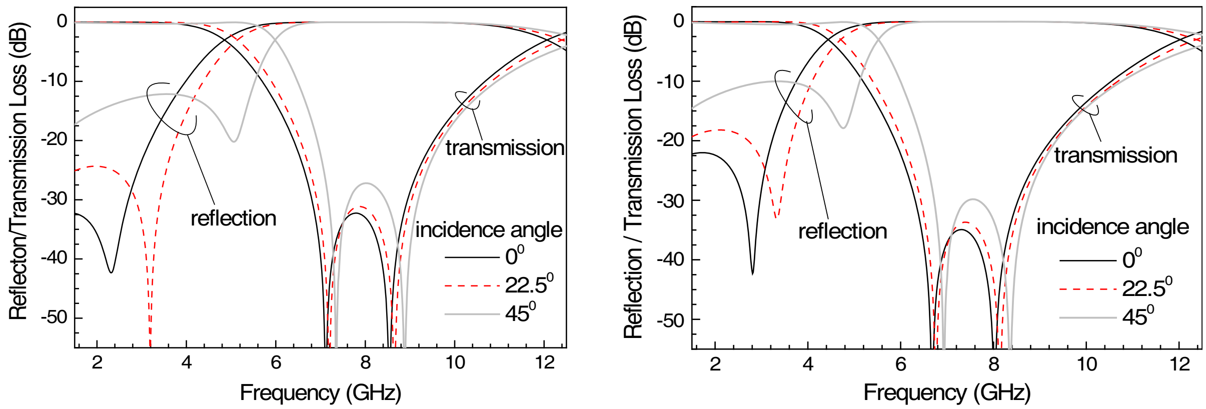

Figure 6. Simulated response (TM_{00} mode) of dual layer FSS for varying angle of incidence, (a) ring element, (b) ring integrated with stub ($l = 5$ mm); Other parameters: in Table 1.

incidence. Considerable reduction in reflectivity for the angles of incidence of 0° and 22.5° is observed compared to the FSS with conventional rings. But, still minimum of −19 dB of reflection coefficient is observed for these angles. However, for the incidence angles of 45° where the reflectivity was as such low with conventional ring, is reduced only by 2 dB. But, these variations cause hardly any significant change in the primary property at S-band, i.e., insertion loss of the FSS. Additionally, for any practical application, the power from the feed at a wide angle which illuminates the edge of the reflector is also less. Considering these aspects and the relative performance over the entire band, the design with stubs of reasonable length is still found to be acceptable.

5. MEASUREMENTS AND RESULTS

Three configurations of FSSs as mentioned in Table 1 were realized for experimental verification. Rectangular panels of dimension 430 mm × 535 mm incorporating 2773 resonators on each surface were fabricated using standard PCB fabrication technique using chemical etching. Commercially available, 0.75 mm thick FR4 substrate with relative permittivity of 4.3, and $\tan(\delta) = 0.013$ has been used. Two panels corresponding to a particular configuration were aligned face-to-face using alignment holes. ROHACELL HF foam with relative permittivity 1.04 and $\tan(\delta) = 0.0017$ has been placed between them in sandwich configuration. Photographs of the fabricated panels and one of the assembled FSS are shown in Fig. 7.

Both the surfaces of the FSS, realized using PCB fabrication technique have very high accuracy with respect to the dimensions of the rings and stub. However, there may be some deviation in the alignment of both the surfaces as it has been done manually. Effect of this has been studied using simulation results which indicate that a lateral mismatch of 0.5 mm in both the axes also does not have much effect. However, the performance is sensitive to the gap g between the two layers. Due to an increase of 0.5 mm in g the reflection coefficient at S-band shows a shift towards the lower side of frequency by about 150 MHz. The shift occurs towards higher side for reduction in g. But, the transmission property is not so sensitive to these changes. However, special care was taken by using spacers of exact thickness during assembly to maintain the spacing. The alignment between the two layers was ensured using multiple alignment pins.

The fabricated prototypes are characterized in an anechoic chamber in the transmission measurement mode. In this configuration the FSS is placed between two horn antennas one of which transmits the signal and the other one receives it. As one antenna was not able to cover the entire range of frequency, different sets of horn antennas were used for measurement. The FSS panel is held by a support and rotated manually to achieve different angles of incidence. The relative differences in the transmission coefficient (S_{21}) between the two antennas with and without the FSS are measured over the frequency using ZVB20 vector network analyzer. Measured results of the FSS with conventional ring

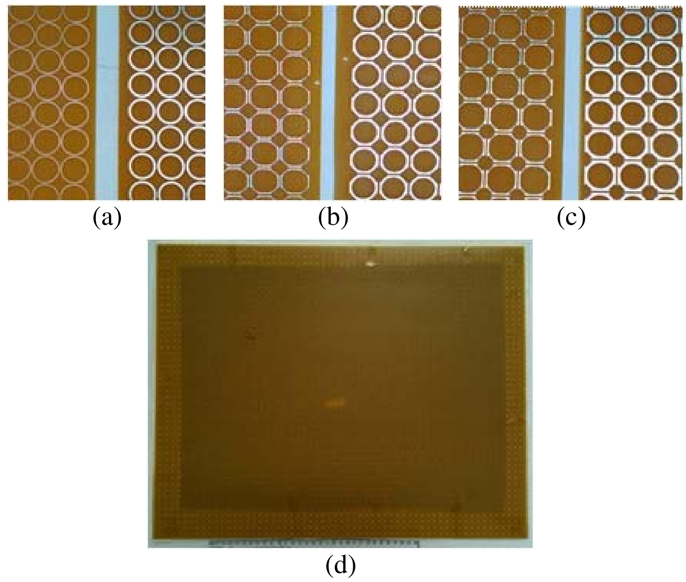

Figure 7. Photographs of the fabricated FSSs; zoomed view of the elements of both the surfaces shown side by side, (a) ring elements, (b) with 4 mm stub, (c) with 5 mm stub, (d) assembled view of the FSS with ring elements: Parameters: as in Table 1.

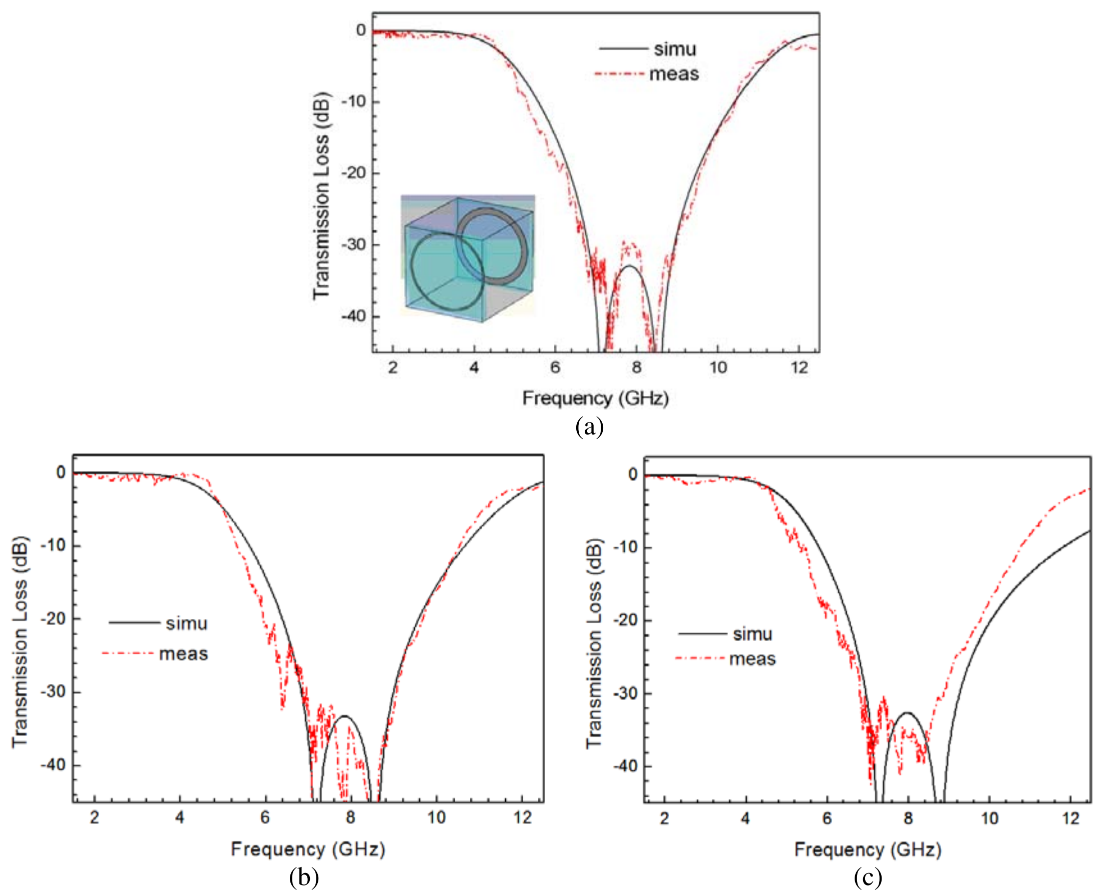

Figure 8. Measured and simulated frequency response of the transmission loss of dual layer FSS with ring elements. Parameters: in Table 1; angle of incidence: (a) 0°, (b) 20°, (c) 45°.

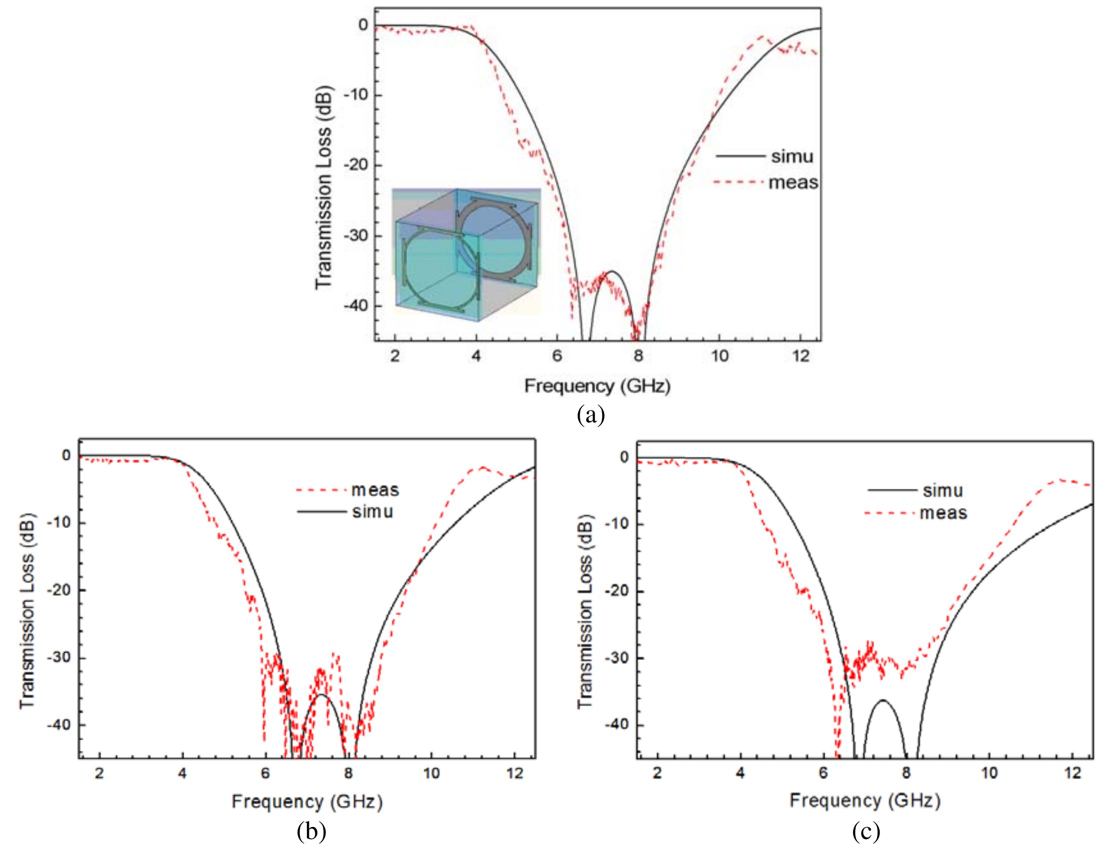

Figure 9. Measured and simulated frequency response of the transmission loss of dual layer FSS with the resonator integrated with 5 mm stub. Parameters: in Table 1; angle of incidence: (a) 0°, (b) 20°, (c) 45°.

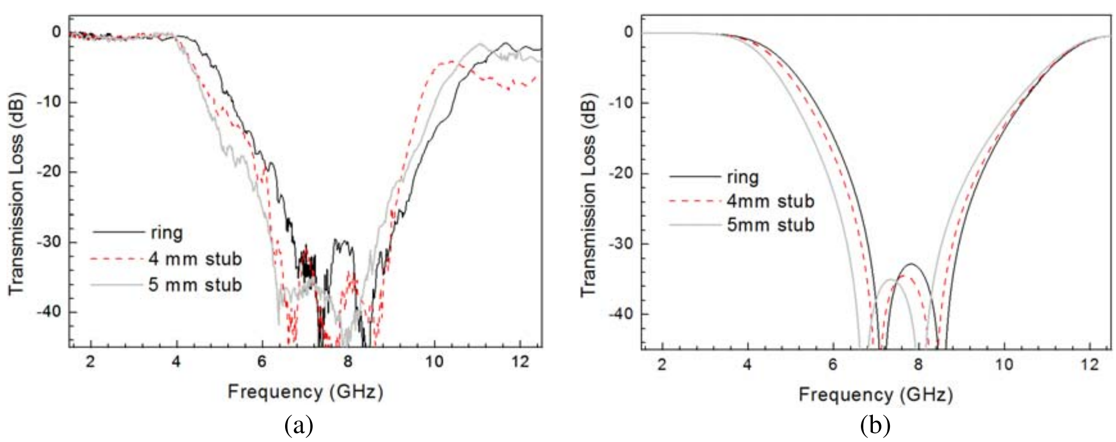

Figure 10. Frequency response of the transmission loss for 0° angle of incidence of dual layer FSS with three different elements as in Table 1. (a) Measured, (b) simulated.

configuration are shown in Fig. 8. These results are corroborated with the simulated results for general verification. Very good match between the measured and simulated results is observed for all the angles of incident. As the output power of the VNA is low, the actual received signal during measurement was weak. Due to this, the noise of the measurement chamber is reflected as small ripple riding over the actual response. The maximum insertion loss is measured to be about 0.6 dB at the pass-band, i.e., S-band. Its value is more than 30 dB at the reflection band, i.e., at X-band.

Similar set of results for the FSS using resonator with 5 mm stubs is shown in Fig. 9. Reasonably good match between the measured and simulated results are observed. As per the design the shift in frequency is evident in the measured results also. The stub moves the reflection band towards lower side of the frequency by about 600 MHz.

The transmission property of all the three configuration as in Table 1 is shown in Fig. 10. The corresponding simulated results are also incorporated there showing good matching with the measured results. Relative shift in the resonant frequency with the introduction of the stub of varying length is evident from these plots.

6. CONCLUSION

The design of FSS involving improvised ring resonators integrated with stubs is presented. This provides the designer with additional control to shift the resonant frequency towards the lower side of the spectrum without changing the basic design or the substrate parameters. Different parameters of the stubs can be varied to achieve the required shift. In another sense it provides some sort of tuning provision in the design. The disturbance in the rotational symmetry of the ring resonator shows slight degradation in the performance. This is manifested as small variation on the reflection property of the FSS in the pass-band for one particular mode of incident wave. These variations are practically very negligible. This design can also be used for reducing the size of the ring resonators for design at a particular band.

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