Progress In Electromagnetics Research C, Vol. 101, 13–28, 2020

Tuneable Frequency Selective Surface

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Abstract—This paper is presented to provide an overview on frequency selective surfaces and techniques to achieve tune-ability in frequency selective surface (FSS). FSS array element with specific arrangement on the dielectric surface either transmits (pass-band) or reflects (stop-band) partially or completely with resonance of the structure in tune with the frequency of electromagnetic wave. Tuning devices like PIN or Varactor incorporated in the structure tune the performance. The recent researches on FSS structures classifying them into structural classification and mechanisms to change the operating resonance frequency dynamically by changing the bias of the tuning devices like PIN or Varactor diode have been studied and detailed in this review article. Tune-ability allows the FSS layer filter to adapt to spectral changes and to compensate for the best performance in terms of bandwidth, gain, and directivity. We also focused on important performance parameters, particularly on how development in this field could facilitate invention in advanced electromagnetics.

1. INTRODUCTION

Multi-band operations is the necessity in all the radar and communication applications. Frequency Selective surfaces (FSSs) are the low cost and light weight solution for systems with multi-band application. FSSs are also known as meta-surfaces. These structures are mainly planar meta-materials, with subwavelength thickness. These can be easily fabricated with thin film printing techniques. Meta-materials or meta-surfaces find their use in spatially varying electromagnetic responses. The meta-surfaces are normally held above the radiating antennas. Meta-surfaces allow to pass or block the propagating waves of certain frequency band transmitted in the free space and are identified as frequency selective surfaces. The structure and principle of FSS is shown in Fig. 1. The improvement in performance especially in scattering phase, amplitude, and polarization can be achieved using tunable FSS. A good selection of material and the design of periodic structure brings down the unwanted losses in the wave propagation. Multi-band filter solutions for band selection have been used for various

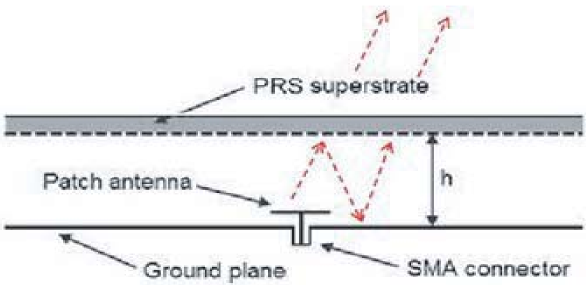

Figure 1. Structure and principle of FSS.

Received 31 December 2019, Accepted 27 March 2020, Scheduled 3 April 2020

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electronic warfare receiver applications with the use of diplexers, triplexers, quaduplexers, etc. Tunable FSS structures can be a low cost, light weight solution besides other attractive applications of the structures. Considering the response in polarisation, the meta-surfaces can be classified on the basis of operating principle of array cells of the FSS [1]. The FSS structures can be categorised for various applications on the basis of their functionalities [2].

From the theory of electromagnetics, meta-surfaces are high impedance surfaces. Thin resonant cavities created as periodic FSS cells are printed on the top surface of a dielectric slab [3–5]. These structures act as a perfect magnetic conductor (PMC) within a defined frequency range, thus they are often called as artificial magnetic conductors (AMCs) [6, 7]. FSS has been classified in various categories as shown in Fig. 2. Category 1 includes linear elements; Category 2 includes loop type of structures; Category 3 includes solid patch structures; and Category 4 includes mixture of linear and loop elements.

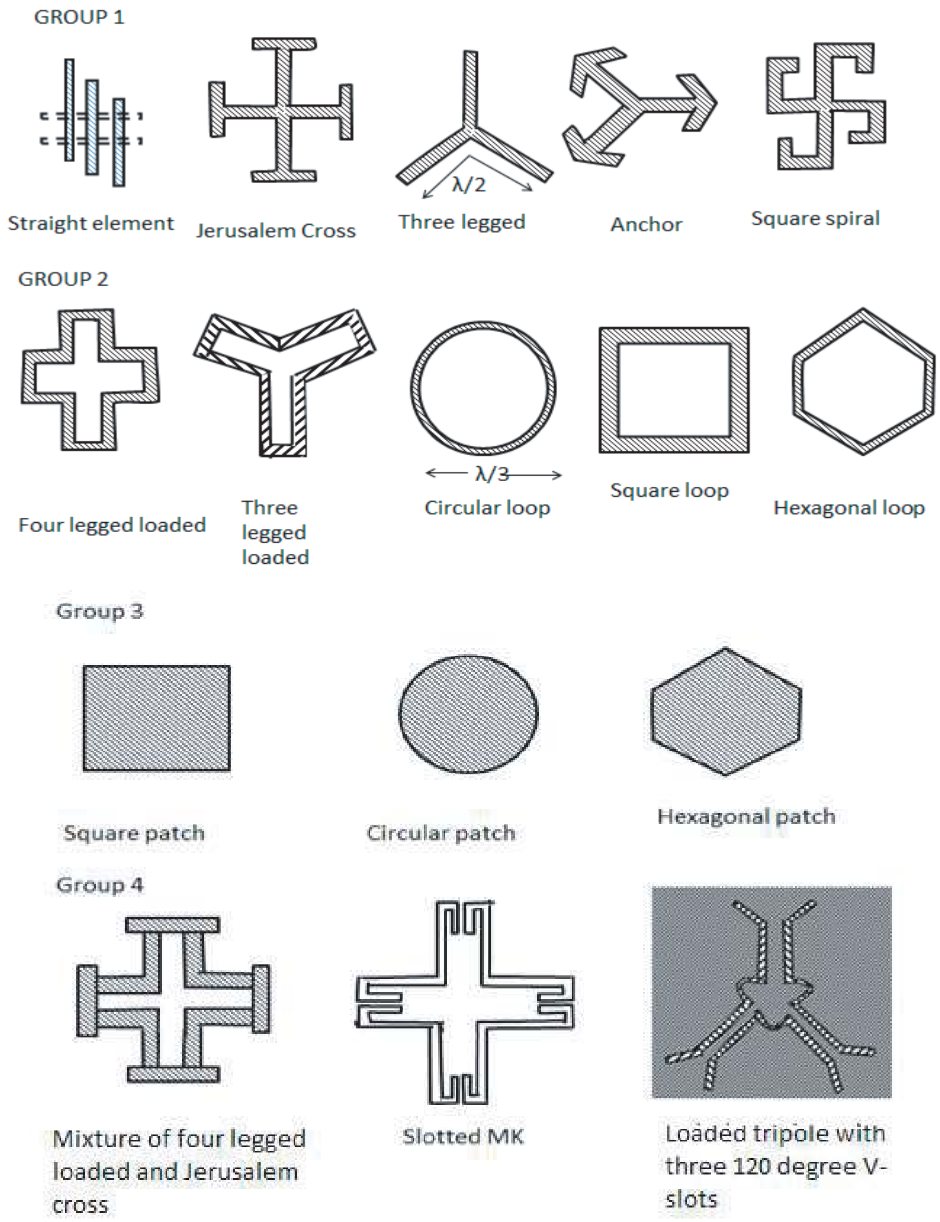


Figure 2. Different types of FSS.

Mostly, FSSs are designed to resonate at a particular frequency called resonant frequency. The resonant frequency or polarization characteristics cannot be changed once the FSS structure has been designed and fabricated. Recently, tuneable FSSs have been the subject of interest for researchers. This is because tune-ability permits the resonant cavity filters of FSS structures to adjust to spectral changes and enhancement in performance parameters.

There are several ways to tune FSS for changing its transmission or reflection properties, i.e., passband or stopband characteristics, using switching techniques. The dynamic use of FSS or the idea of tuneable FSS was proposed by Janaswamy and Lee [8] in 1980's. The authors analysed the scattering dipoles connected with diode by using active biasing technique.

2. TYPES OF TUNABLE FSS

In this paper, we analyse and present the researches on different types of tuneable FSSs. The study is presented based upon the structure design, array cells used, performance, and their applications [9]. FSS structures are basically planar periodic elements of metallic structures with different shapes and are generally classified either based on array elements or based on types of structures. We categorise the structures on the basis of structural designs and detail them here as:

2.1 Single side printed tuneable FSS
2.2 Double side printed tuneable FSS
2.3 Multi-layer/Three dimensional FSS

2.1. Single Side Printed Tuneable FSS

Single side printed tuneable FSSs consists of two-dimensional periodic resonant element with embedded control elements either PIN or varactor diodes. As well known, FSS acts as either passband or stopband filters based on the response of array elements. Control elements, PIN or Varactor, change the capacitive elements and correspondingly change the resonant frequency. Single layer FSSs with tuneable elements filter responses can be used in many applications for multi-band operations. Comparison on the basis of Performance Enhancement/Application for various reported authors have been detailed in Table 1 for single side printed tuneable FSS [10–16].

Reconfigurable Fabry-Perot cavity antenna design, in which meta-material is a composite phase varying material with active electronic components, has been presented by Ourir et al. [10] (see Fig. 3).

Table 1. Comparison table for single side tunable FSS.

Reference	Peak gain	Peak directivity	Frequency range	Tunning technique	Performance Enhancement /Applications
[10]	-	14.85 dB	7.9–8.2 GHz	Varactor diode	Directivity enhancement
[11]	21.5 dBi	-	5.725–5.875 GHz		Gain enhancement
[12]	-	-	1.6–8 GHz	PIN diode	Absorber application
[13]	-	-	9 to 13 GHz	PIN diode	Absorber application
[14]	-	-	2.4 and 5.2 GHz	Two metallic layers	WLAN application
[15]			2.42 GHz–5.94 GHz	Varactor diode	ISM signals
[16]	-	-	3.42 GHz	Varactor diode	Beam steering application

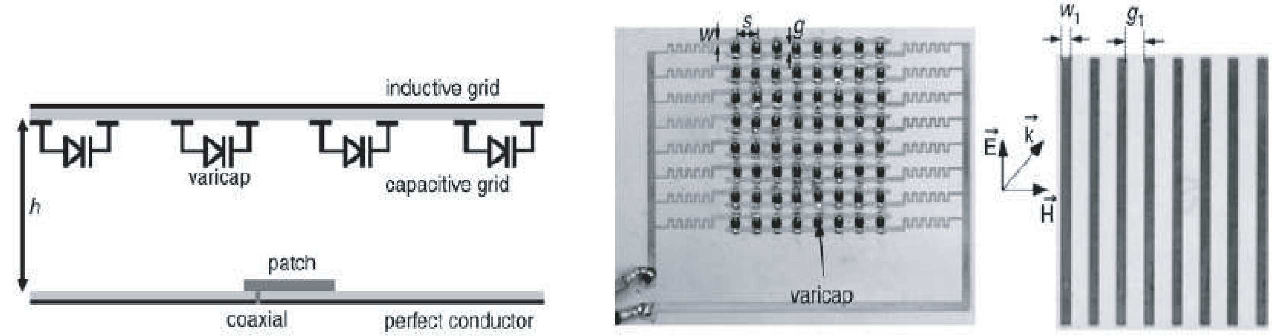
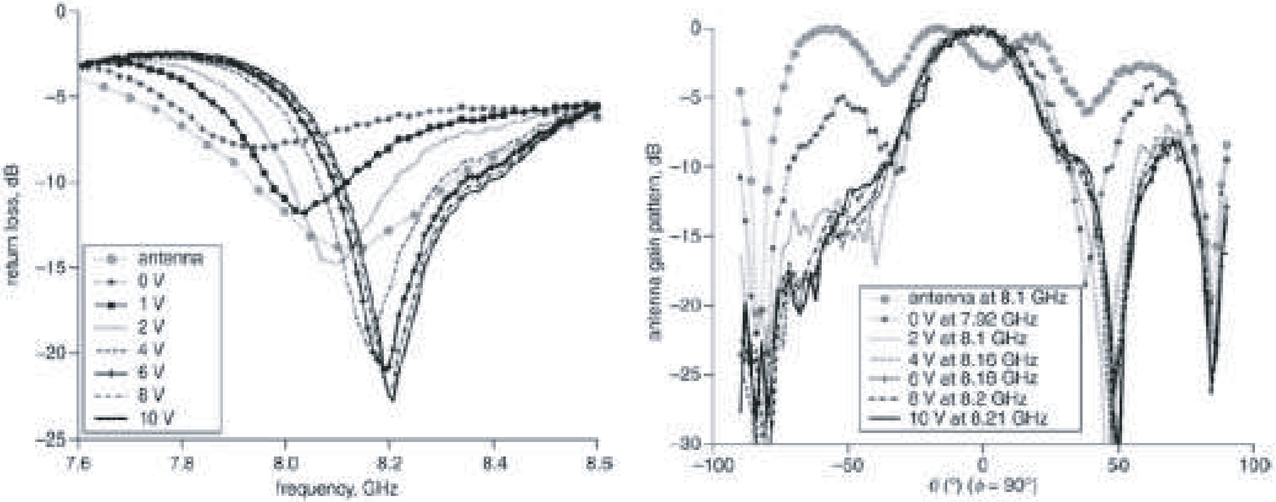


Figure 3. Composite structure of metamaterial [10].



(a) (b)

Figure 4. (a) Measured return loss [10]. (b) Measured antenna gain [10].

"An electronically controllable partially reflecting surface with a resonant cavity antenna between 7.9 and 8.2 GHz" has been presented in the work. The directivity enhancement of the antenna has been reported (see Fig. 4).

"High gain, low side lobe level Fabry Perot Cavity antenna with feed patch array" has been proposed by Vaidya et al. [11]. The microstrip antenna array is parasitically coupled square patches printed on an FR4 superstrate (see Fig. 5). The resonating parasitic patches exhibit constant high gain at frequencies 5.725–5.875 GHz in ISM band.

Figure 6 shows the gain variation less than 1 dB over the frequency range 5.725–5.875 GHz. The maximum gain of 21.5 dBi is at 5.8 GHz.

Wang et al. [12] have proposed FSS in Fig. 7, which includes a structure with an array of PIN diodes. "Progressively reduced equivalent resistor of PIN diodes has been presented with increasing DC voltage". The structure shows the absorber's performance in various frequency ranges shown in Fig. 8.

A single side printed layer of active microwave absorber is presented by Tennant and Chambers [13]. Planar absorber structure based upon the topology of a Salisbury screen has been presented. In the structure a conventional resistive layer is replaced by an active FSS. PIN diodes have been used for controlling the attenuation (see Fig. 9). The reflection response of the attenuating layer has been controlled over the frequency band from 9 to 13 GHz (see Figs. 10 & 11).

Single side tuneable frequency selective surface (FSS) has been reported by Hu et al. [14]. The structure is shown in Fig. 12 with small electrical elements and dual tuneable pass-bands for Wireless LAN application. The upper dielectric layer comprises single FSS cell (a loop wire), and its

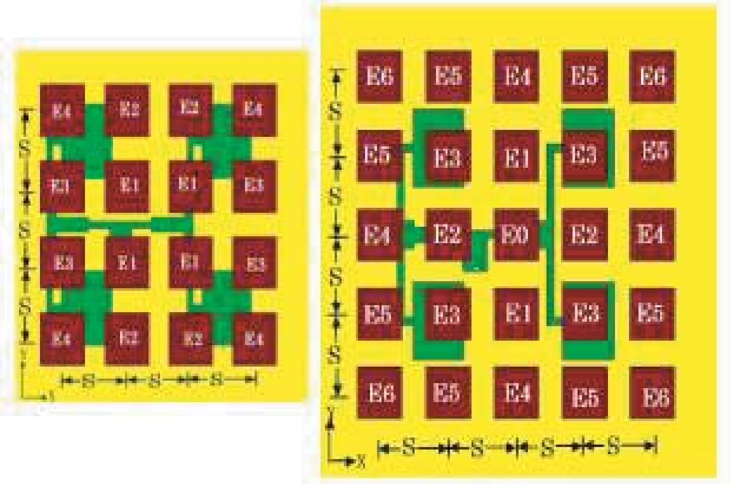


Figure 5. FSS layer [11].

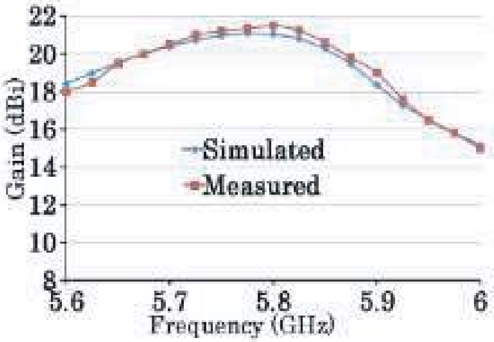


Figure 6. Measured antenna gain [11].

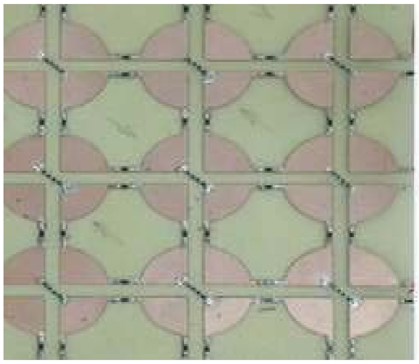


Figure 7. FSS Layer structure with an array of PIN diodes with biasing lines [12].

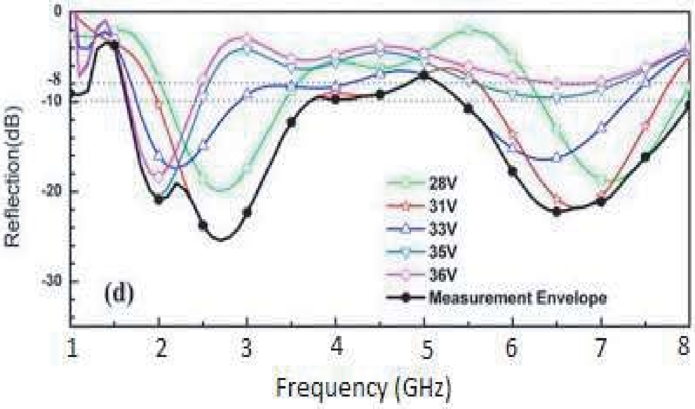


Figure 8. Absorber performance [12].

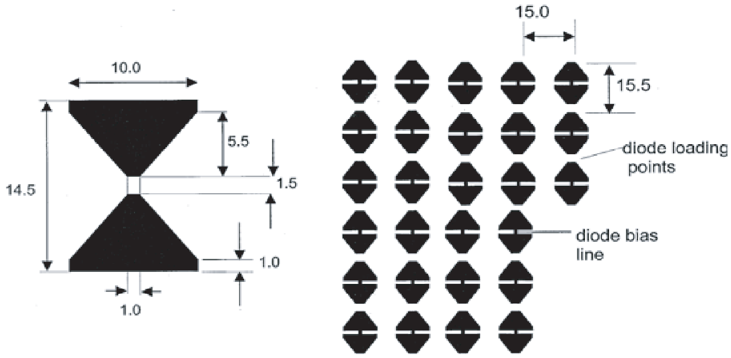


Figure 9. Active FSS geometry [13].

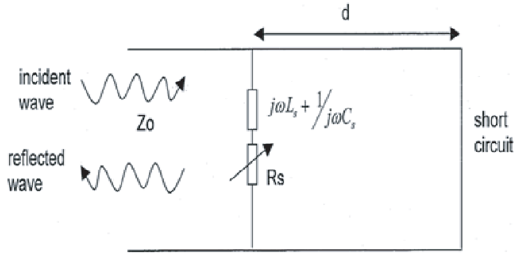


Figure 10. Equivalent circuit diagram [13].

complementary FSS element is etched in the bottom layer (see Fig. 13).

Bora Döken and Mesut Kartal [15] have proposed a tuneable FSS structure which is used for blocking ISM signals. The structure is adapted in order to attain wide tuning range with addition of varactor diodes. Frequency tuning range is enhanced by 11 percent, compared with the "Four Legged

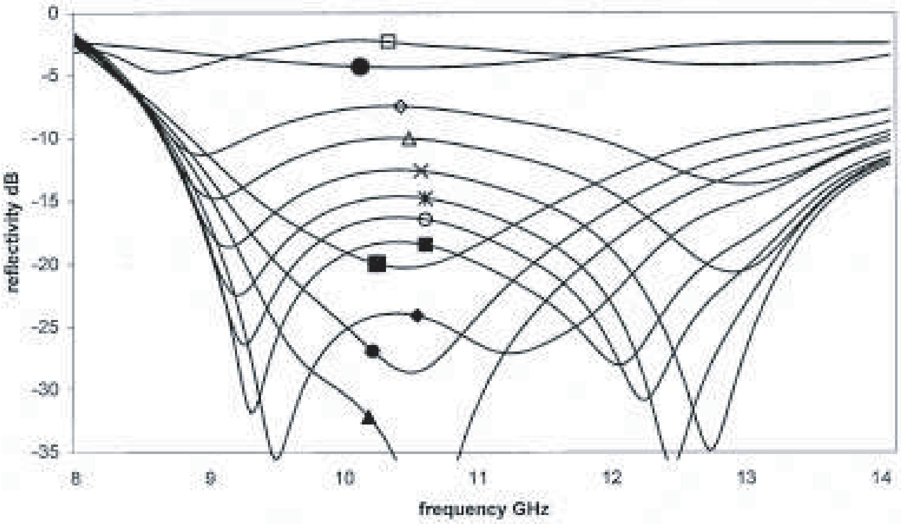
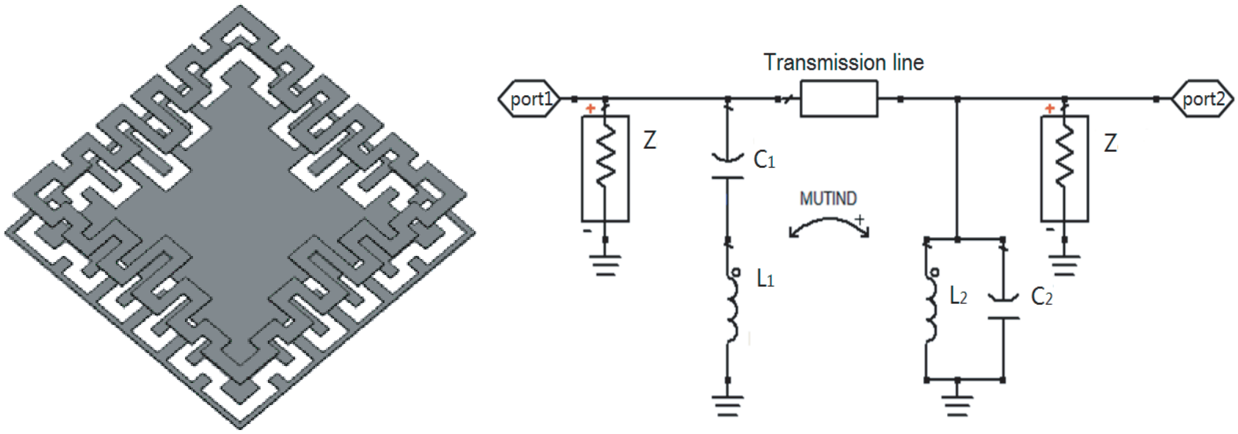


Figure 11. Measured reflection response with varying bias current [13].



(a) (b)

Figure 12. (a) Meandered loop FSS unit [14]. (b) Equivalent circuit [14].

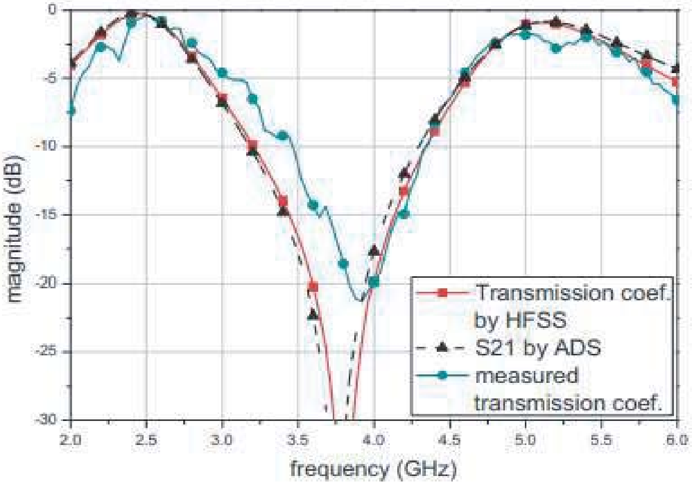
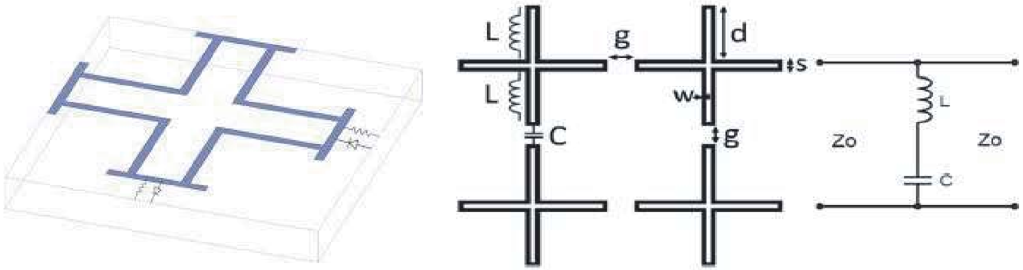
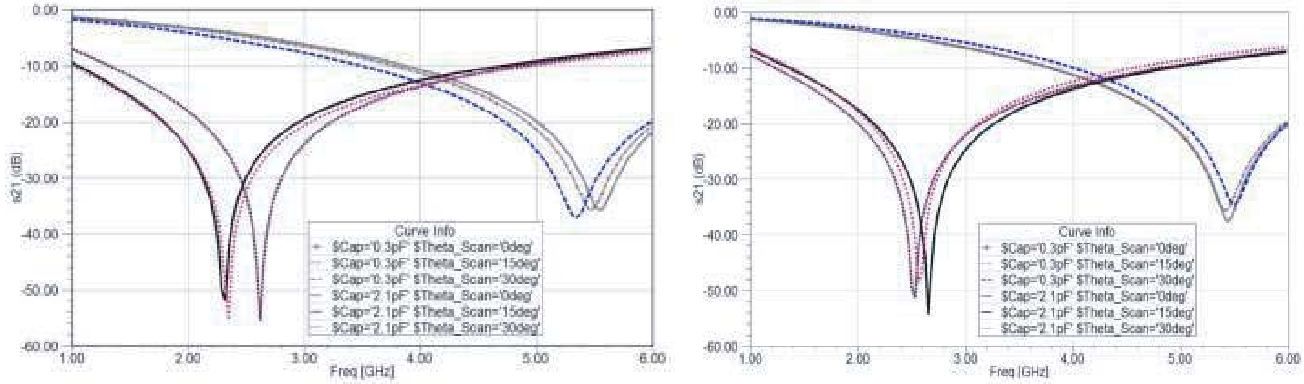


Figure 13. Transmission coefficients of the FSS [14].



(a) (b)

Figure 14. (a) Four legged loaded element geometry [15]. (b) Equivalent circuit [15].



(a) (b)

Figure 15. (a) S_{21} curves for TE polarization [15]. (b) S_{21} curves for TM polarization [15].

Loaded" structure (see Fig. 14). The presented structure gave tuning between 2.42 GHz and 5.94 GHz, shown in Fig. 15.

A thin tuneable and beam steerable Fabry-Perot antenna has been proposed by Costa and Monorchio [16]. The tuneable antenna comprises a low profile resonant cavity made up of a

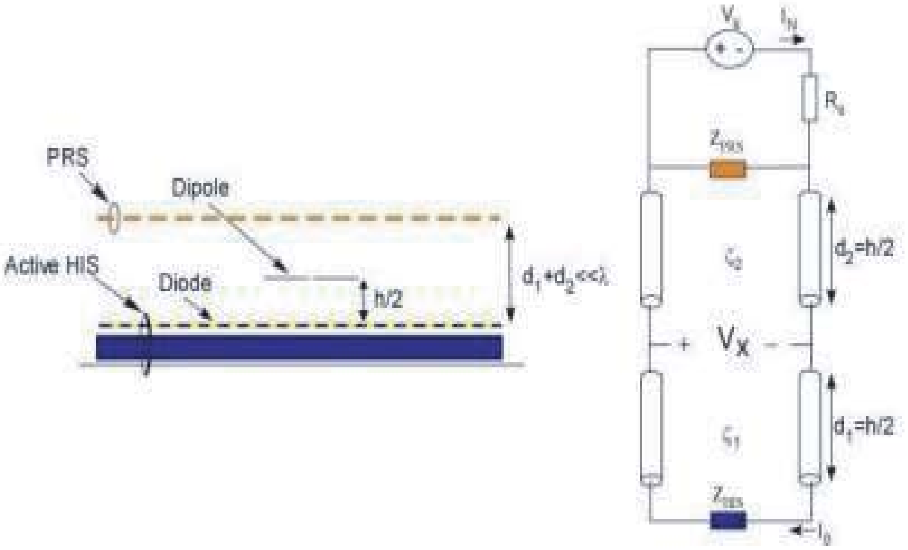


Figure 16. High impedance surface [16].

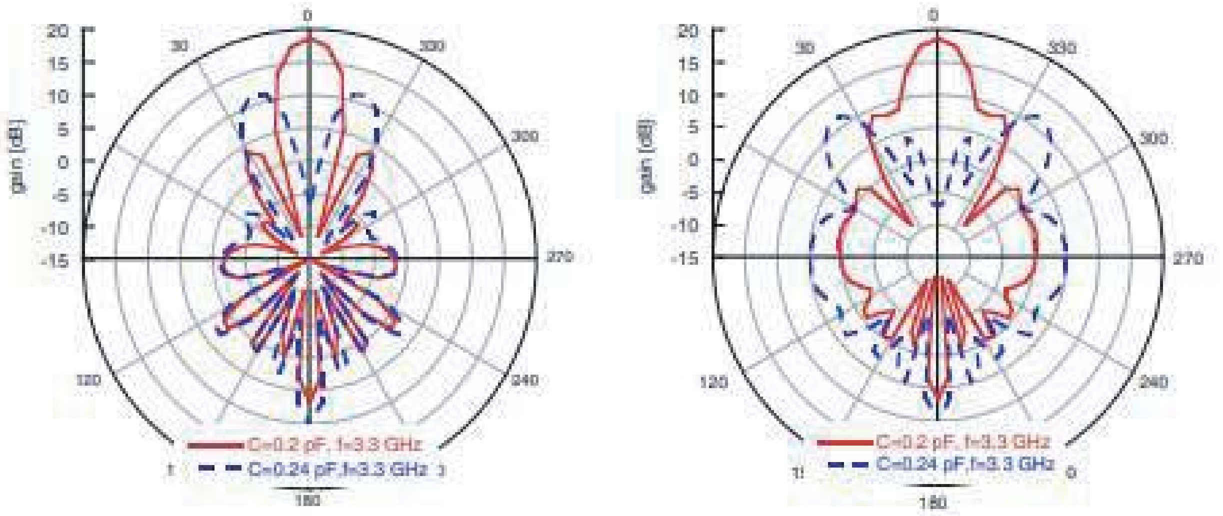


Figure 17. Beam steering application [16].

Partially Reflecting Surface (PRS) placed in close proximity of a tuneable high-impedance surface (see Fig. 16). The active ground plane has been created by loading a high-impedance surface with varactor diodes. Such a design allows both tuning the high gain operational frequency and obtaining a beam steering/shaping for each resonant frequency. Fig. 17 shows the steering of the beam at 3.3 GHz.

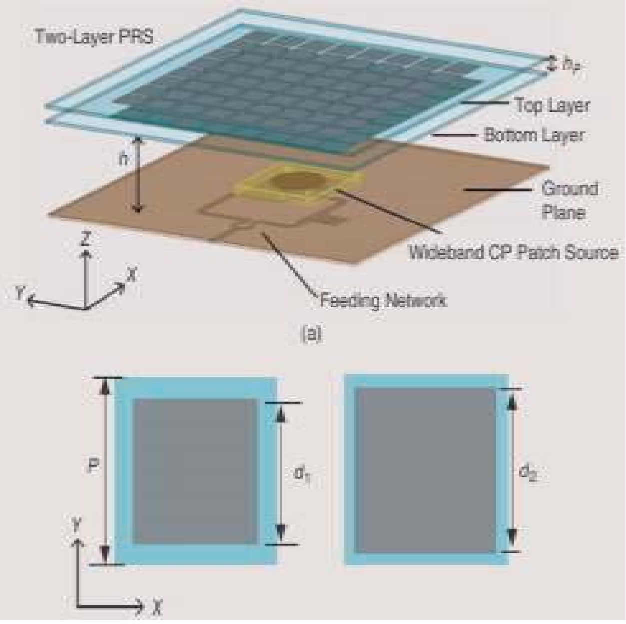
2.2. Double Side Printed Tuneable FSS

Double side tunable FSS has been analysed for improved bandwidth and tunability range by various authors. Table 2 details the comparison on the basis of Performance Enhancement/Application for double side printed tunable FSSs [17–21].

Table 2. Comparison table for double side printed tuneable FSS.

Reference	Peak gain	Peak directivity	Frequency range	Tunning technique	Performance Enhancement /Applications
[17]	14.7 dBi	-	8.8 to 11.7 GHz		Gain enhancement
[18]	-	-	2.28 GHz–4.66 GHz and 5.44 GHz–11.3 GHz	Varactor diode	Tuneable FSS
[19]	-	-	2.4 and 5.8 GHz	PIN diodes	ISM signals
[20]	14.85 dB	-	8 GHz to 8.5 GHz	Varactor diode	Beam steering applications
[21]	-	-	0.54 to 2.50 GHz	Varactor diode	EM shielding applications

Broadband and high gain, circularly polarized Fabry-Perot (CPFP) antenna (Fig. 18) is presented by Qin et al. [17]. The proposed antenna is a double layer FSS with a positive reflective phase gradient. The proposed structure has 28.3 percent improvement in 3 dB bandwidth from 8.8 to 11.7 GHz with highest gain of 14.7 dBi. The axial ratio (AR) is below 3 dB in this frequency range, and the reflection coefficient is lower than −10 dB (see Fig. 19).



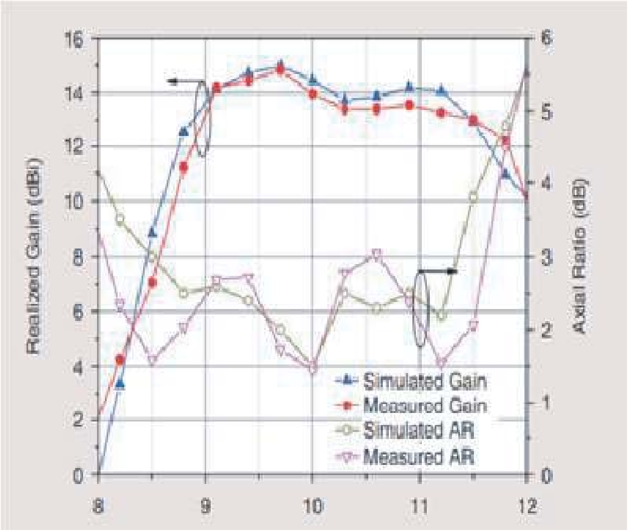
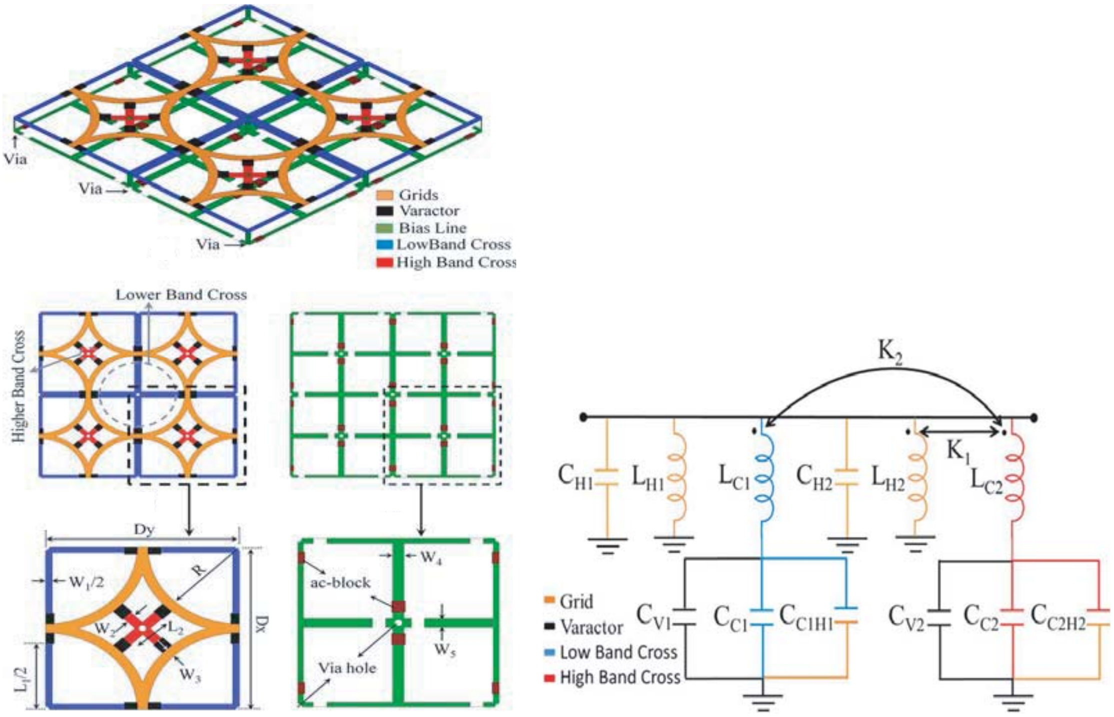


Figure 18. Double layer tunable FSS [17].

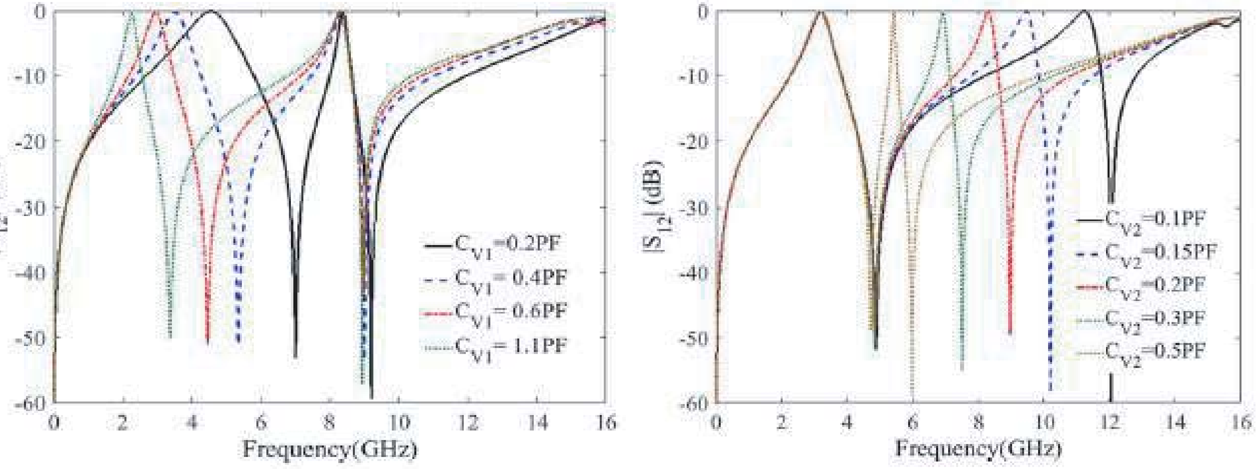
Figure 19. Gain plot [17].



(a) (b)

Figure 20. (a) FSS unit cell [18]. (b) Equivalent circuit diagram [18].

Rahmani-Shams et al. [18] have presented a FSS which is dual-band, dual-polarised with embedded bias network. The proposed structure is in low profile and compact antenna with tuneable varactor giving band-pass responses. The reported FSS consists of dual metallic sides printed on the substrate. Varactors are connected in between the cross strips and grids (see Fig. 20). The FSS structure has been

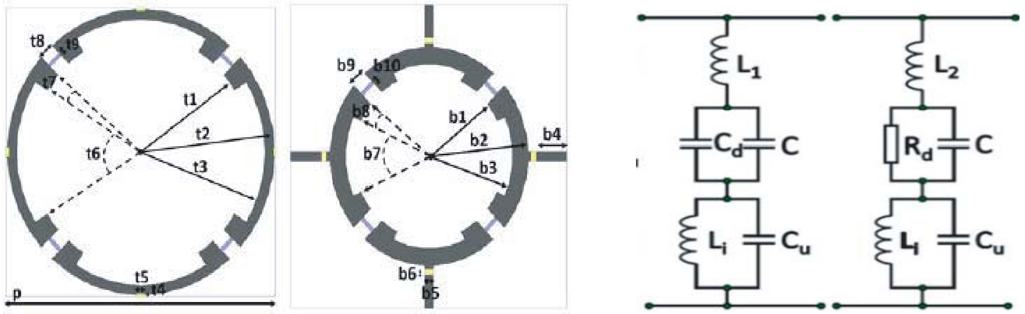


(a) (b)

Figure 21. (a) Band-pass variations [18]. (b) LPF variations from 11.3 GHz to 5.44 GHz [18].

presented for the frequency range from 2.28 GHz–4.66 GHz and −5.44 GHz–11.3 GHz. Transmission factors of the tuneable FSS for various values of varactors are presented in Fig. 21 [18].

"Tuneable FSS structure with various band-stop characteristics in 2.4 and 5.8 GHz in ISM bands" has been proposed by Döken and Kartal [19]. The structure is presented for Wireless LAN security and interference extenuating. The structure has four switchable frequency responses with the applied bias voltage. The proposed structure shows that 20 dB attenuation is attained in frequency bands (see Fig. 22). "The width of the structure is 1.6 mm which gives the opportunity of using this structure as a structural surface material for blocking the ISM signals" (see Fig. 23).



(a) (b) (c)

Figure 22. Active FSS design [19]. (a) Top layer. (b) Bottom layer. (c) Equivalent circuit.

Composite resonant meta-materials for highly directive subwavelength cavity antennas has been presented by [20]. These meta-materials consist of planar metallic structures periodically arranged over a dielectric giving frequency dispersive phase responses. These surfaces act as a resonant Fabry-Perot type cavity (see Fig. 24). The top surface gives a variable reflection phase by using a non-periodic metallic strips array for beam steering application. Fig. 25.

Broadband FSS with tune-ability has been proposed for shielding effectiveness in various frequency bands (for applications such as GSM, ISM, UNII, WLAN) by Ghosh and Srivastava [21]. The structure gives varied tuning of band-stop response with reverse bias voltages. The structure shows wideband attenuation (see Fig. 26). The comparison of simulated and measured shielding effectiveness of the structure as reported is shown in Fig. 27.

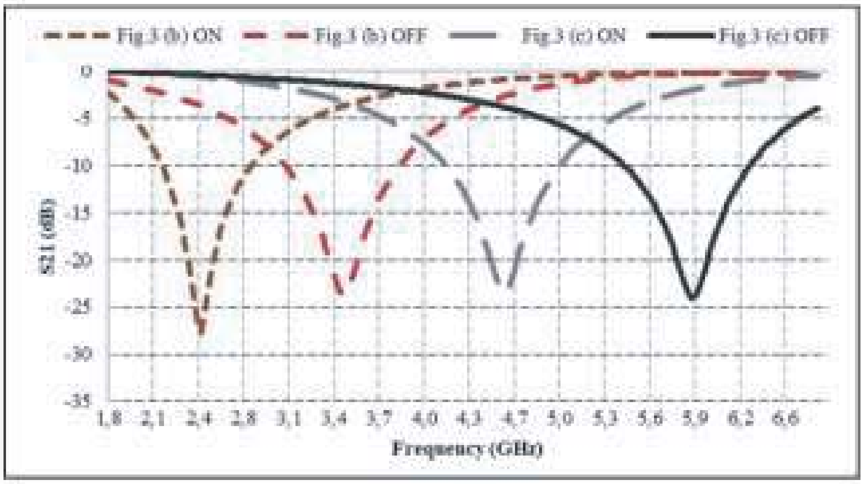


Figure 23. S_{21} frequency curves with switchable PIN diodes [19].

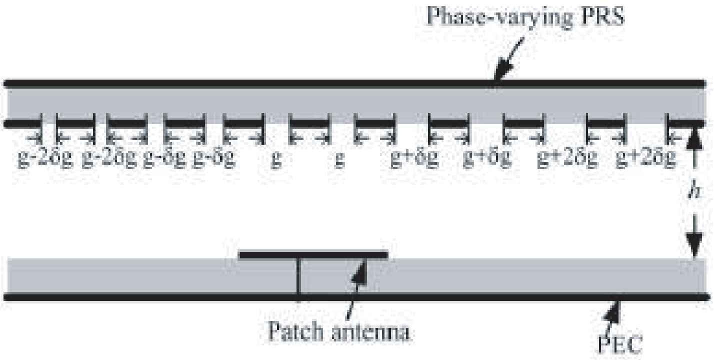


Figure 24. Resonant Fabry-Perot type cavity [20].

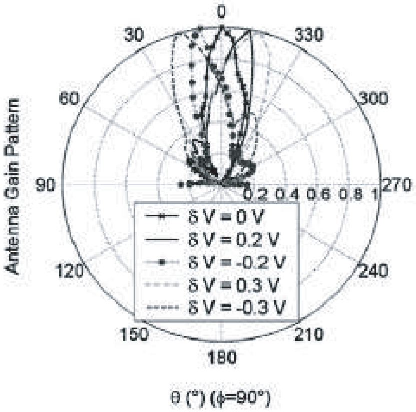


Figure 25. Beam steering [20].

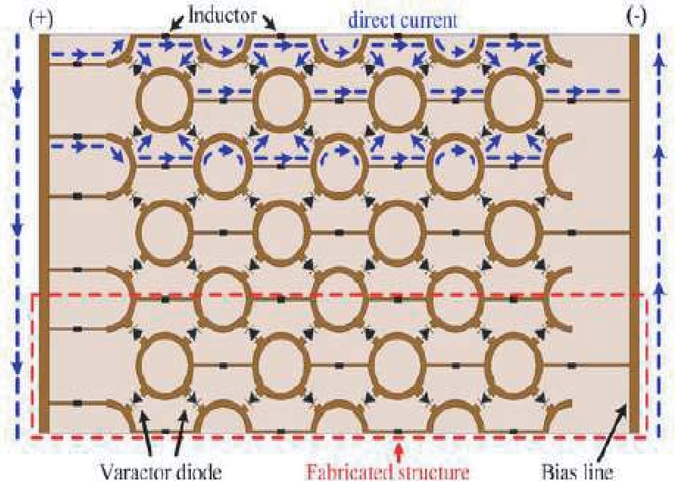


Figure 26. Wide band tuneable FSS [21].

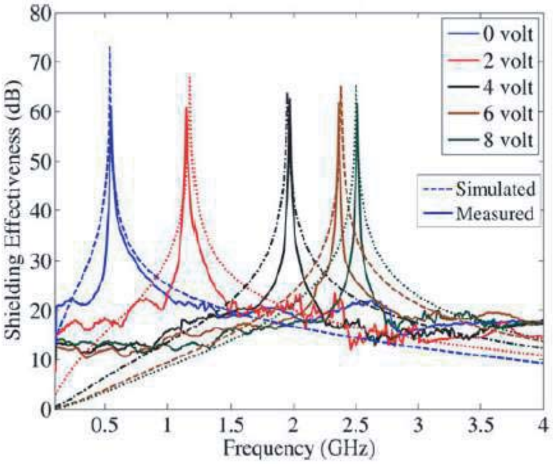


Figure 27. Measured and simulated shielding effectiveness of the FSS [21].

2.3. Multi-Layer/Three Dimensional Tuneable FSS

Multi-layer tuneable FSS provides better performances in terms of passband selectivity, phase dynamics, and bandwidth than double and single layer tuneable FSSs. Fractal FSS to some extent can improve narrow-band behaviour of single layer/double layer FSS but at the cost of insertion loss which limits the gain enhancement. Multi-layer tuneable FSS can further overcome the frequency response characteristics of the resonant structures as well. Table 3 details the comparison of multi-layer/three dimensional tuneable FSSs on the basis of Performance Enchancement/Applications [22–25].

Table 3. Comparison table for multilayer/three dimensional tuneable FSS.

Reference	Peak directivity	Frequency range	Tunning technique	Performance Enhancement /Applications
[22]	-	1.4 to 2.75 GHz	Varactor diode	Tunning performance
[23]	-	3.8–5.5 GHz band	Pin diode	Larger bandwidth and wide tunning capability
[24]	-	3.92 and 4.1 GHz	Varactor diode	Beam steering application
[25]	-	8.45 GHz to 11.5 GHz	-	RCS reduction, sub-reflector, polarizing grid and lens.

"Multilayer tuneable band-pass frequency selective structure (FSS) with broad tuning range" is presented in Fig. 28 [22]. The tuneable FSS comprises a periodic structure of printed circuit panels. The varactor-mounted quarter wavelength stepped impedance resonators (SIRs) are created and excited in the structure. The plots as reported for measured reflection and transmission responses are shown in Fig. 29.

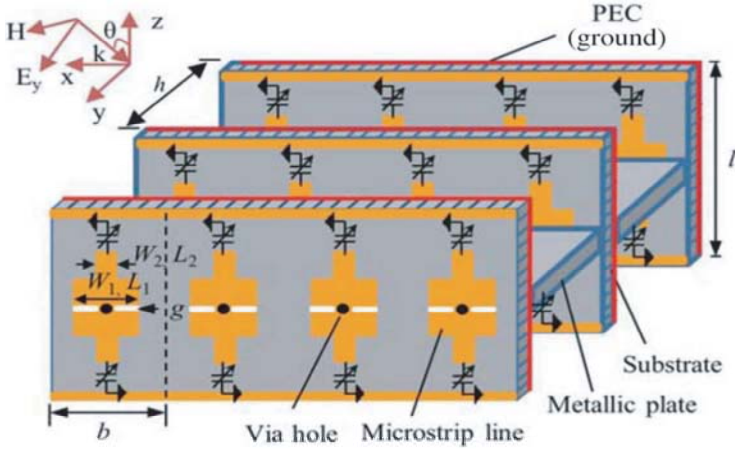


Figure 28. 3D tuneable FSS [22].

Tuneable FSS designs using switchable split ring resonators (SRRs) along with PIN diodes have been presented [23] (see Fig. 30). The split ring resonator-FSS design has been explored to include multiple FSS layers and is named as DSRR-FSS (Double split ring resonator FSS). DSRR-FSS offers large bandwidth and dual-band performance via switching Fig. 31.

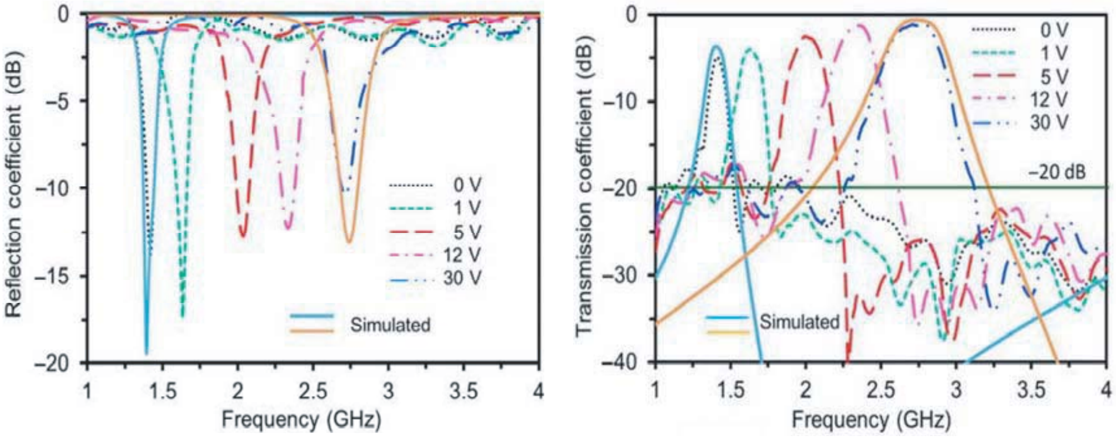


Figure 29. Reflection and transmission responses [22].

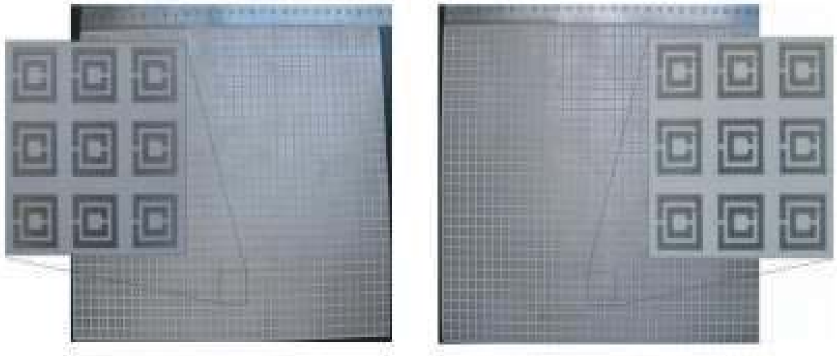


Figure 30. SRR-FSS design [23].

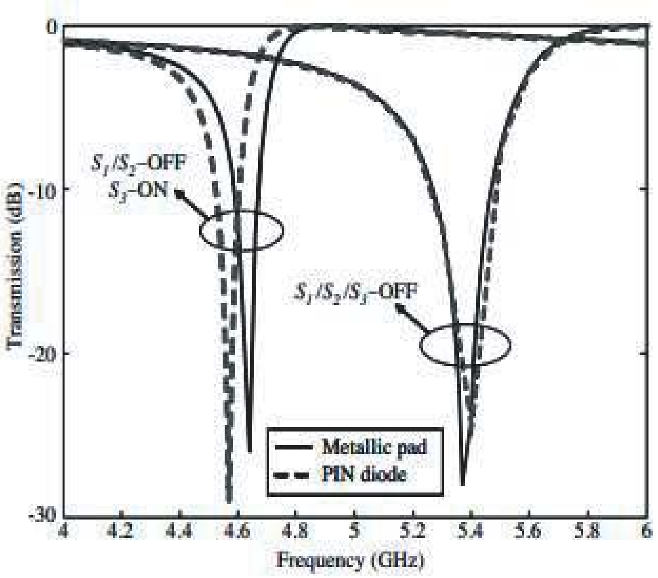


Figure 31. FSS performance with loaded PIN diodes [23].

"Tuneable frequency-selective surfaces (FSSs) for beam-steering applications" are shown in Fig. 32 [24]. Rectangular slots loaded with varactors have been examined and presented for steering of beam. The scattering characteristics of a multilayer passband FSS as obtained is shown in Fig. 33.

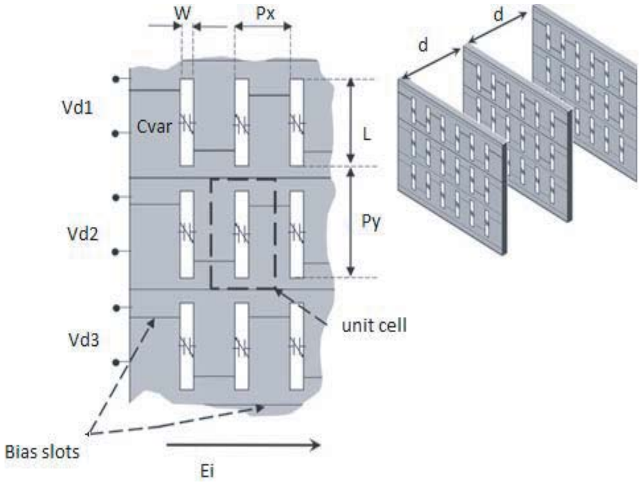


Figure 32. Multi layer pass band FSS [24].

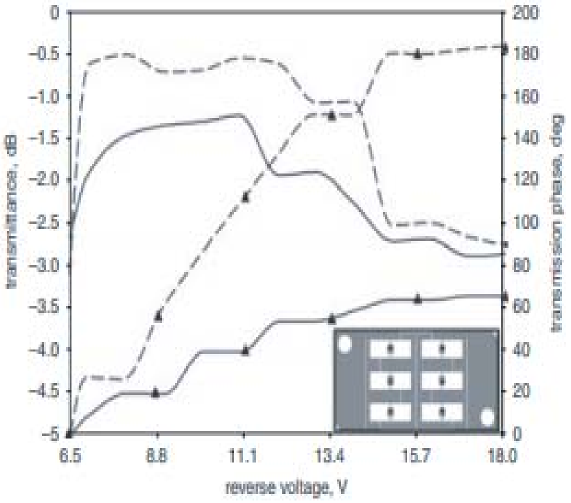


Figure 33. Measured transmission response against varactor voltage [24].

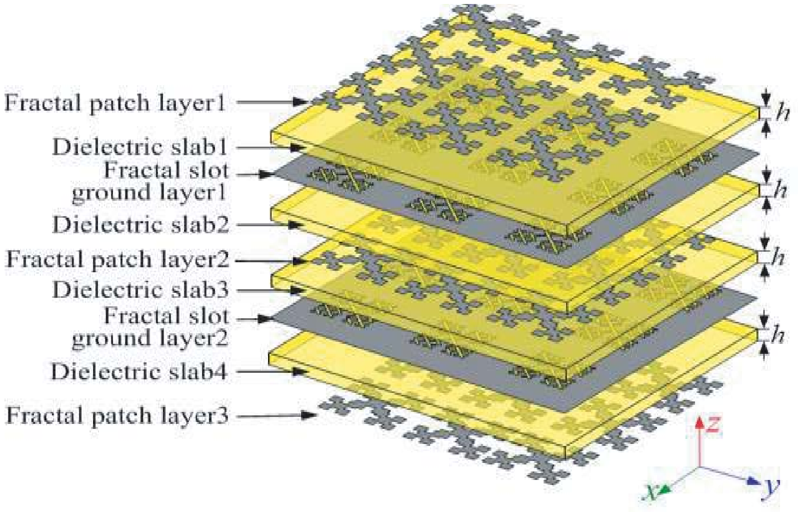


Figure 34. 3D view of proposed FSS [25].

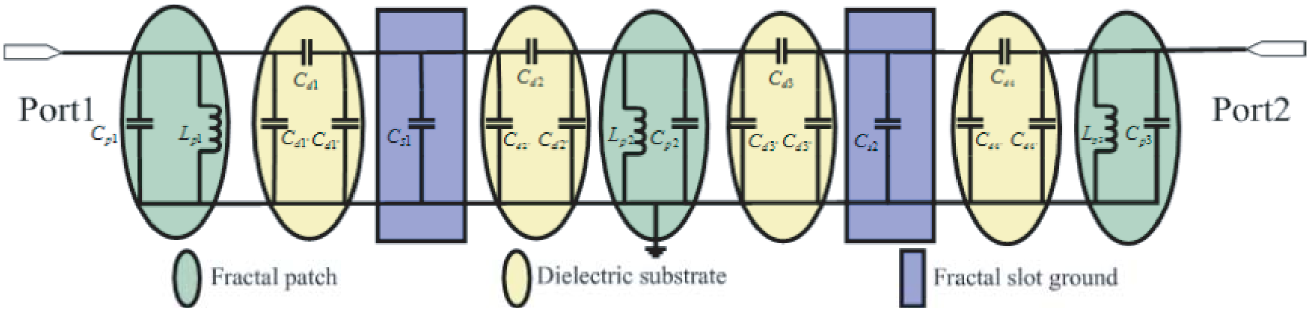


Figure 35. Equivalent circuit diagram [25].

Subwavelength three dimensional frequency selective surfaces (FSSs) with "antenna-filter antenna (AFA)" concept are proposed in this paper [25]. Top layer of fractal patches is inductive and non-resonant, and the fractal slots on the bottom ground layer give a capacitance (see Figs. 34 & 35). The structure is suitable for the applications such as RCS reduction, polarizing grid, sub-reflector, and lens.

3. CONCLUSION

Tuneable FSS changes the EM response dynamically and thus gives improved performance in terms of various antenna characteristics. Tuneable FSSs have been explored and used for potential applications such as band selection, beam steering, absorber, wireless communication, and antenna radomes. The study presented here provides an overview of the development of tuneable FSSs reported till today mostly on periodic arrays. It is proposed that more structures with non-periodic tuneable FSSs can be explored. Tunable FSS for ultra-wideband applications is also an area of open research.

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