Design and Development of Lowpass Filter and Harmonics Reduction

Tamasi Moyra[1], Susanta Kumar Parui[2], and Santanu Das[2]

[1]Department of Electronics and Communication Engineering,
College of Engineering and Management, Kolaghat
[2]Department of Electronics and Telecommunication Engineering,
Bengal Engineering and Science University, Shibpur, Howrah – 711 103, India
tamasi_moyra@yahoo.co.in, arkapv@yahoo.com & santanumdas@yahoo.com

Abstract: The shape of a popular split-ring defected ground structure (DGS) is modified by etching two concentric split-ring defective pattern which have different size and inverse split direction in the ground plane underneath a microstrip line. The frequency characteristics of proposed DGS unit show an attenuation zero close to the attenuation pole frequency. As a result, better transition sharpness is observed. An equivalent lumped L-C network is proposed to model the introduced DGS unit and corresponding L-C parameters are extracted. A 3rd order quasi-elliptic lowpass filter is designed by cascading the three investing DGS units under High-Low impedance microstrip line and the generated first harmonic has been removed with the help of defected microstrip structure (DMS) underneath the cascading DGS unit.

Keywords: Microstrip, split ring resonator, defected ground structure, defected microstrip structure, lowpass filter, elliptic filter.

1. Introduction

In 1999, defected ground structure was firstly proposed by Park et al. based on the idea of photonic band-gap (PBG) structure and had found its application in the design of planar circuits and low-pass filters [1-3] etc. A defected ground structure is realized by etching a defective pattern in the ground plane underneath a microstrip line which disturbs the shield current distribution in the ground plane and is a attractive solution for achieving finite passband, finite rejection band and slow wave characteristics. This disturbance can change the characteristics of a transmission line such as equivalent capacitance and inductance to obtain the slow-wave effect and band-stop property. Thus, it obtains wide stop band and compact size, which meet emerging application challenges.

Dumb-bell shaped DGS is explored first time by D. Ahn and applied to design a lowpass filter [1,2]. Unit cell has been described as a one-pole Butterworth filter, where the capacitance comes only from the gap and the inductance comes only from the loop. The study of dumbbell DGS with various head shape have appeared in the literature recently and they are used to design couplers, dividers and amplifiers [3-6] etc. It is well known that a filter with attenuation poles and attenuation zeros at finite frequencies shows higher selectivity compared to all pole filter. A DGS with quasi-elliptical response was proposed by Chen J.-X recently [7]. Various good filtering responses can be achieved with the different DGS units [8-12]

In this paper, a symmetric DGS pattern with reference to transmission line is proposed. Its unit cell consists of two concentric split-ring defective pattern which have different size and inverse split direction in the ground plane underneath a microstrip line. The investigated DGS unit produces an attenuation zero near to the attenuation pole frequency, which yields a very sharp transition band. A general equivalent circuit represented by cauer's Π -network is proposed for describing the DGS unit. Finally, good LPF with wide stopband is achieved with introducing cascaded DGS units underneath a Hi-Lo defected microstrip structure. The first

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harmonic has been removed by proper designing of defected microstrip structure (DMS) in addition with DGS units.

2. Frequency Characteristics of the DGS

Figure 1(a) shows the schematic diagram of the investigated DGS unit pattern etched off the backside metallic ground plane underneath a microstrip line. In the layout of DGS unit, an outer split - ring (of length and breadth L, width t, and split gap g) within which another split - ring with same split gap maintaining the separation ‘c’ is proposed and both split rings are concentric with inverse split direction. In order to investigate the frequency characteristics of the DGS unit, it is simulated by the MoM based IE3D EM-simulator. The different dimensions of the DGS unit are considered as L=8 mm, c=t=1 mm and g=h=1mm. The substrate with a dielectric constant of 3.2, loss tangent 0.0025 and thickness 0.79 mm is considered for the microstrip line. The width (w) of the conductor strip on the top plane is 1.92 mm corresponding to 50-ohm characteristic impedance.

The simulated S-parameters are plotted in Figure 1(b). The simulated values of 3-dB cutoff frequency (f_c) and pole frequency (f_p) are 3.1 GHz and 3.4 GHz, respectively. The attenuation zero is observed at 3.4 GHz, which is very close to the attenuation pole location (3.1 GHz). As a result, high sharpness factor is obtained in transition band. The passband insertion loss is almost 0.8 dB.

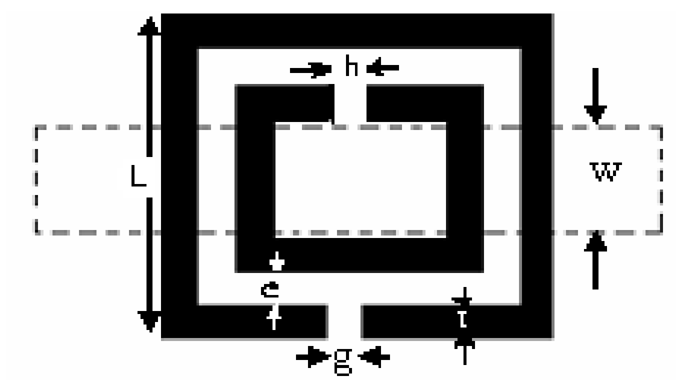


Figure1(a). Schematic diagram of proposed DGS

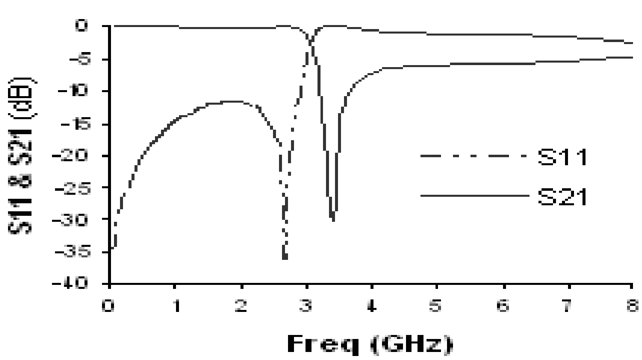


Figure 1(b). simulated S-parameters

3. Equivalent circuit and Parameter Extraction

Figure 2(a) shows the proposed loss-less equivalent circuit, which is represented by Cauer's Π-network. The introduced equivalent circuit consisting of series impedance *Y*a (of *L*g, *C*g) and shunt impedance Y_b (of *C*p) is connected in series with impedance Z_0 of a transmission line as illustrated in Figure 2(a).

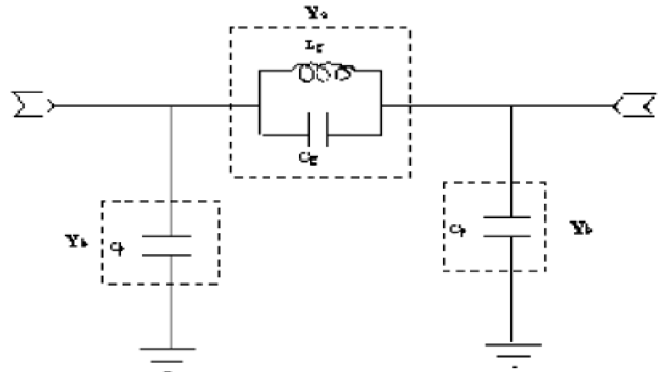


Figure 2 (a). Equivalent circuit (Cauer's Π-model)

Since the parallel capacitance might cause changing the characteristics impedance level and electrical length of DGS unit section, it should be considered as a part of equivalent circuit for more accurate modeling procedure. In this model, the equivalent circuit is not composed of resistors, as the losses resulting from the radiation and dielectric substrate are not considered. The proposed approach using Cauer's network with the complex S-parameter transform technique is only for two port equivalent circuit of DGSs. Parameter extraction begins with S-parameters of the DGS being modeled. The S-parameters of the unit DGS cell at reference plane should be calculated by a full-wave 3-D-EM frequency domain simulation. In the case of using the Cauer network synthesis technique, to represent the acquired information in a physically meaningful format, the S-parameters need to be directly converted to the impedance (or admittance) parameters, which are the rational function.

However, the proposed approach uses the complex S-parameter transform technique. Once the S-parameters are calculated at the complex cutoff frequency by using fullwave 3-D-EM frequency domain simulation by employing the S-parameter transform relation, the calculated S-parameters can be easily converted to the ABCD-parameters.

Then, the ABCD-parameters are converted to the admittance parameters as expressed in (1)–(4):

$$A = \frac{(1+S_{11})\times(1-S_{22})+S_{12}S_{21}}{2S_{21}} = 1+\frac{Y_b}{Y_a} \qquad (1)$$

$$B = \frac{(1+S_{11})\times(1+S_{22})-S_{12}S_{21}}{2S_{21}} = \frac{1}{Y_a} \qquad (2)$$

$$C = \frac{1}{Z_0}\times\frac{(1-S_{11})\times(1-S_{22})-S_{12}S_{21}}{2S_{21}} = 2Y_b + \frac{{Y_b}^2}{Y_a} \qquad (3)$$

$$D = \frac{(1-S_{11})\times(1+S_{22})+S_{12}S_{21}}{2S_{21}} = 1+\frac{Y_b}{Y_a} \qquad (4)$$

Here, *Y*a and *Y*b mean the series and parallel admittances of the proposed Π-type lossy equivalent circuit of Figure 2(a), respectively. The resulting relation between the equivalent circuit parameters of the Π-type symmetrical two-port circuit and the equivalent circuit parameters of the proposed DGS circuit are given by

$$Y_a = \frac{1}{B} = \frac{1}{R_g} + jB_r \tag{5}$$

$$Y_b = \frac{A-1}{B} = \frac{-1 \pm \sqrt{1+BC}}{B} = \frac{D-1}{B} = \frac{1}{R_P} + jB_P \tag{6}$$

Since the calculated S-parameters for the unit DGS circuit are complex, the resulting equivalent circuit parameters of the Π-type symmetrical two-port circuit are also complex. From these relations, the equivalent circuit parameters of the proposed DGS circuit are given by

$$C_g = \frac{B_r}{W_2\left(W_1/W_2 - W_2/W_1\right)} \tag{7a}$$

$$L_g = \frac{1}{W_2^2 C_g} \tag{7b}$$

$$C_p = \frac{B_p}{W_1} \tag{7c}$$

Where, W_1 and W_2 represent the cutoff frequency and the attenuation pole location in 3-D-EM simulation for the unit DGS circuit, respectively.

The achieved dimensions of the proposed DGS unit from the circuit model analysis are L_g = 1.385 nH, C_g = 1.582 pF and C_p = 0.967 pF The EM-simulated and circuit-simulated S-parameters are presented in Figure 2(b).

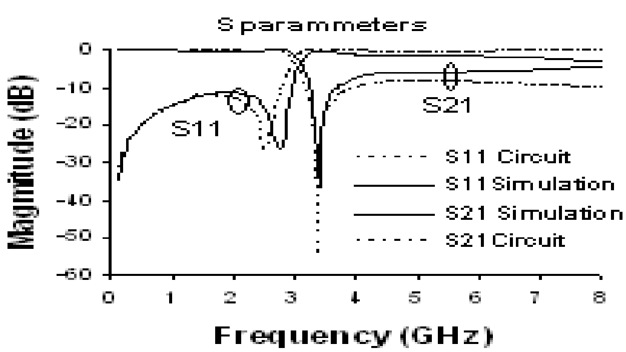


Figure 2 (b). S-parameters of the DGS from Circuit and EM- simulation

In Figure 2(b) the simulated S-parameter results are matched to the 3rd order elliptical lowpass filter response having attenuation pole at 3.4 GHz, attenuation zero at 3.1 GHz and stopband ratio of 1.16. The equivalent circuit parameters are calculated by using the prototype element values of the 3rd order elliptical lowpass filter. There is a good agreement between The EM-simulated and circuit-simulated S-parameters are noticed. The main reason for the discrepancy in attenuation at pole frequency is that ideal model has been adopted in circuit simulation and loss of resister and radiation haven't been taken into consideration..

4. Parametric study of the DGS for tuning the response

The elliptic- function response can be tuned with variation the values of the length 'L' and gap 'g'. The following Table:1 shows the variation of different parameters with different values of length.

Table 1. variation of different parameters with different values of split - ring Length 'L':

Split - ring Length 'L'(mm)	fc(GHz)	fp(GHz)
8	3.075	3.397
9	2.577	2.794
10	2.2	2.4
11	1.925	2.094
12	1.716	1.892

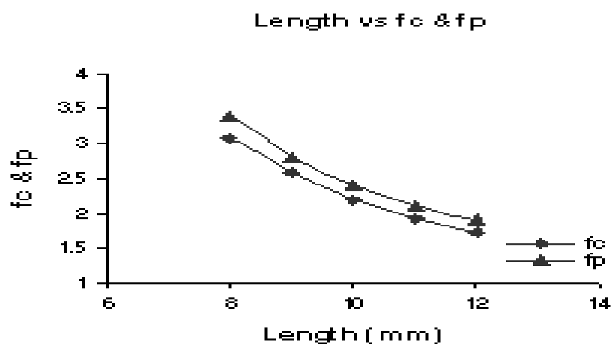


Figure 3(a). Graphical representation of table 1

Here, with the curve fitting it is observed that fc and fp follow the equations

$$y_1 = -0.0007x^4 + 0.0237x^3 - 0.2358x^2 + 0.1027x + 8.085 \quad (8a)$$

and

$$y_2 = 0.0057x^4 - 0.2371x^3 + 3.7258x^2 - 26.565x + 75.475 \quad (8b)$$

Where, y_1 is fc ; y_2 is fp and x is split-ring length 'L'.

The following graphs Figure 3(b) Figure 3(c) show the variation of the S11 and S21 parameters due to the variation of the length 'L' of the proposed DGS.

The attention has been also given towards the variation of the different parameters for the variation of the 'g' of the proposed DGS. The following table 2 shows the variation of different parameters with different values of gap, 'g'.

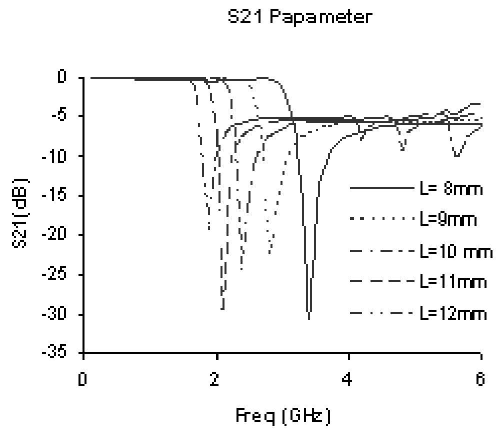


Figure 3(b). S11 parameters

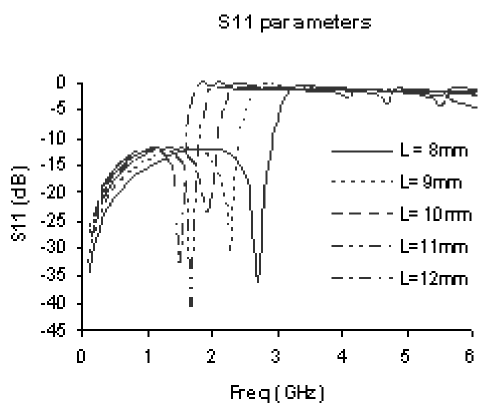


Figure 3(c). S21 parameters

Table 2. Variation of different parameters with different values of Gap:

Gap'g'(mm)	fc (GHz)	fp (GHz)
0.5	2.925	3.2
1.0	3.06	3.4
1.5	3.16	3.49
2.0	3.22	3.59
2.5	3.321	3.698

The variations of the attenuation pole and zero location with different gap ‘g’ can be shown as follows (Figure 4(a)):

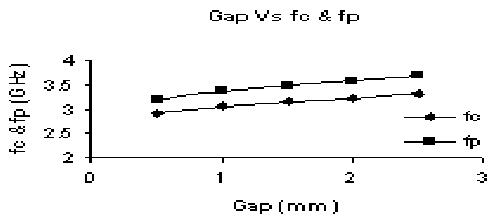


Figure 4(a). Graphical representation of table 2

Here, with the curve fitting it is observed that fc and fp follow the equations

$$y_3 = 0.0573x^4 - 0.2933x^3 + 0.4517x^2 - 0.0017x + 2.846 \quad (9a)$$
and

$$y_4 = -0.0813x^4 + 0.5667x^3 - 1.4117x^2 + 1.6783x + 2.648 \quad (9b)$$

Where, y_3 is fc ; y_4 is fp and x is Gap ‘g’.

5. DGS under HI-LO Line

The frequency characteristics of the DGS unit under microstrip line show a very sharp lowpass filtering characteristics but the insertion loss at passband is 0.8 dB, which is not too good and acceptable as a practical lowpass filter. To reduce the insertion loss at passband, the standard microstrip line is replased by High impedance and Low impedance line (HI-LO line) or compensated microstrip line. The low impedance line of width w_c having characteristics impedance 33 Ohm is chosen above DGS unit and high impedance line with standard characteristics impedance 50 Ohm is taken towards feed lines as illustrated in Figure 5(a). The width of w_c can be calculated as 4 mm using simple microstrip line formulas where the width of standard 50 Ohm line is 1.92mm. The simulated S-parameters of the proposed DGS with HI-LO line is shown in Figure 5(b). From the simulated S-parameters of the DGS under HI-LO line, the 3dB cutoff frequency at 2.9 GHz and pole frequency at 3.2 GHz with maximum attenuation of 28 dB are observed. The passband insertion loss is 0.06 dB.

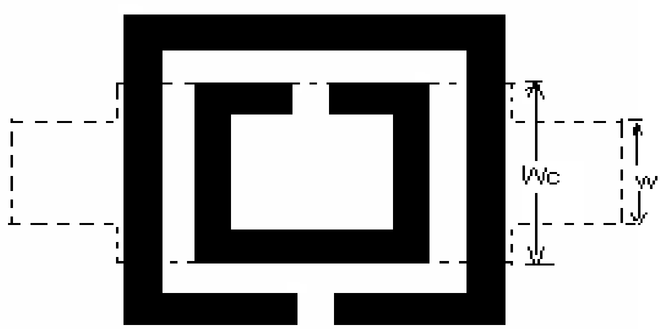


Figure 5(a). DGS unit underneath a HI-LO line

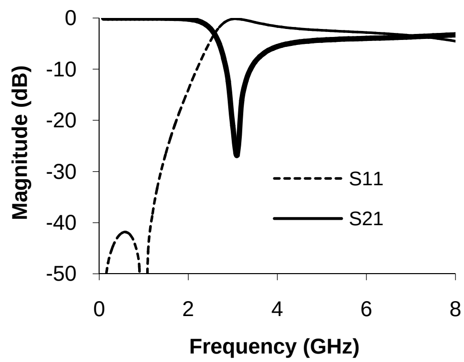


Figure 5(b). S-parameters of the DGS under HI-LO line

The 3dB cutoff frequencies are observed at 2.9 GHz for compensated line, whereas it is 3.15 GHz for 50 Ohm microstrip line. The pole frequency is observed at 3.4 GHz with maximum attenuation of 32 dB. The insertion loss in passband improves to 0.06 dB in compensate line, compares to 0.8 dB for microstrip line. Thus the insertion loss introduced in the microstrip line because of the incorporation of DGS may be reduced to 0.06 dB with the inclusion of compensated line.

6. Improvement of Stop band

This is also possible to improve the stopband of the filter with little modification of proposed structure. The band-stop phenomenon can be obtained from a more compact structure by milling only one array of DGSs in the ground plane of the microstrip line. The only condition for the structure to exhibit good band-stop transmission is that the array of DGSs must be centered under the microstrip line, as shown in Fig 6.

Figure 7 shows the simulated *S*11 and *S*21 responses of the filter with this new configuration.

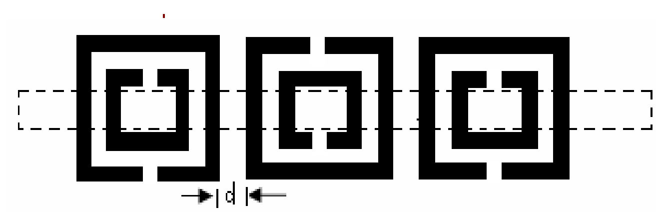


Figure 6. Proposed DGS to improve Stopband

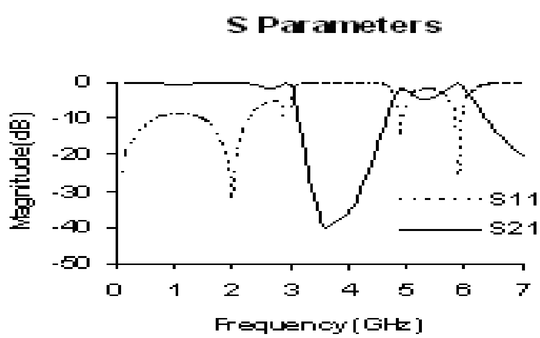


Figure 7. S-parameter of the proposed structure

7. Tuning of Stopband Frequency

It is possible to shift the stop band by changing the different dimensions of the proposed DGS.

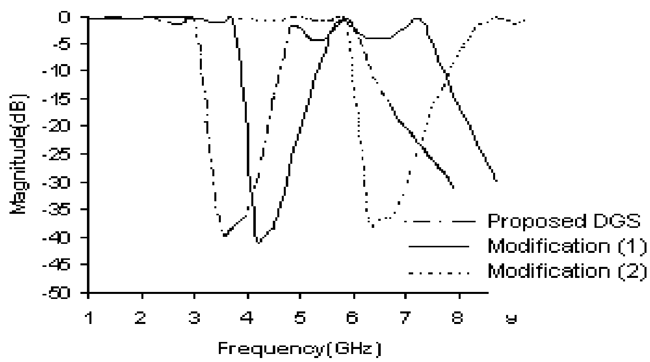


Figure 8. Tuning of stop band

Proposed DGS: L=8 mm, g=c=t=1mm, d=2mm
Modification (1): L=6 mm, g=c=t=0.6mm, d=1.5mm
Modification (2): L=4 mm, g=c=t=0.4mm, d=1mm

A study of the precision of the dimensions of the DGSs has also been made in order to discuss the slight shift in frequency obtained experimentally with the band-stop structure. Thus, we can see that when the different parameters of the DGS are decreased, the response of the band-stop structure shifts to higher frequencies.

8. Design of Lowpass Filter

From the above discussion it is observed that Figure 7 provides lowpass filtering characteristics with almost 1.3 GHz stop band at -20 dB with almost 0.8 dB passband insertion loss but there is a provision of transferring the frequency components of 5GHz to 7GHz also due to the appearing of the first harmonics around 5.6 GHz.

Therefore, the insertion loss is totally removed by replacing the 50 Ohm transmission line with compensated Hi-Lo microstrip line as discuss in section 5 and the harmonics suppression can be done with the help of a T-slot in the microstrip structure, known as Defective Microstrip Structure (DMS). The T-shaped DMS structure and its response are shown in the following Figure 9(a) and 9(b) respectively.

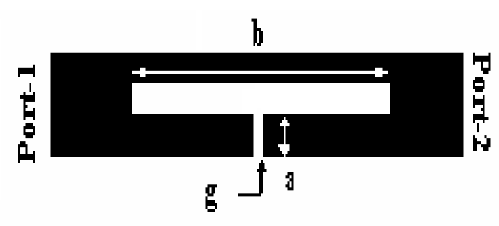


Figure 9(a). DMS Structure

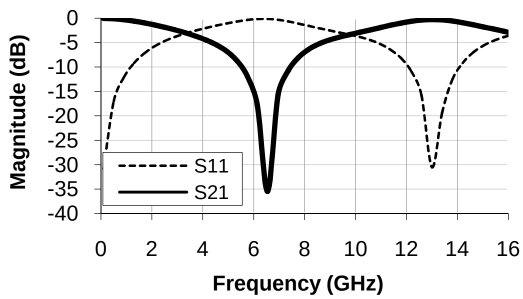


Figure 9(b). S-parameters of proposed DMS

Figure 9(b) shows that DMS act as a L-C tank circuit and provides one pole frequency. Now, the resonance frequency can be changed by varying any one parameter of the DMS keeping other parameters constant. Let, length 'b' of the DMS is changed, keeping a=g=0.5mm. The ariation of S21 parameters is shown in Figure 9(c) and variation of resonance frequency with 'b' is shown in the following Table 3 and Figure 9(d).

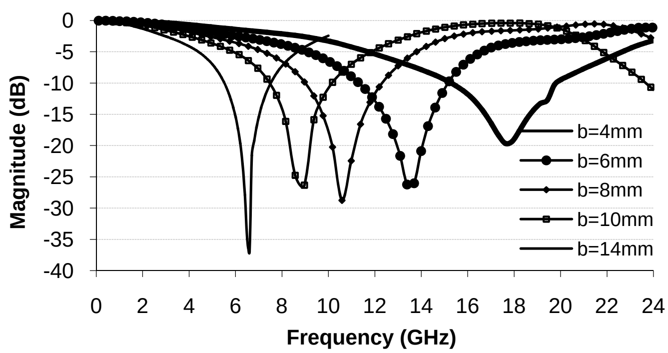


Figure 9(c). S21-parameters

Table 3. Variation of resonance frequency with 'b'

Length 'b'mm	4	6	8	10	14
Res freq 'f_0'(GHz)	17.62	13.4	10.58	8.97	6.6

Mathematically, with the curve fitting of the above graph it is possible to find out what will be the 'b' for specified value of 'fo' using the following polynomial equation.

$$b = -0.001 f_0^4 + 0.0412 f_0^3 - 0.4996 f_0^2 + 0.5005 f_0 - 22.542 \quad (10)$$

Similarly, by changing a and g resonance frequency can be tuned.

The graphical representation of Table 3 is shown in Figure 9(d) as follows

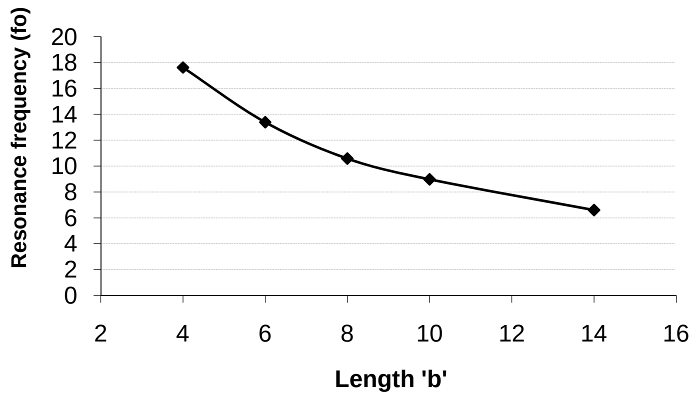


Figure 9(d). Variation of resonance frequency with ‘b’

It has been observed that the DMS (a=1mm, b=10mm, g=0.5mm) provides stop band near 6GHz which is sufficient for removing the first harmonics of the filter. Therefore, the modified DGS with DMS structure is shown in Figure 10.

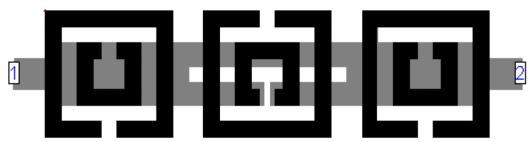


Figure 10(a). DGS with DMS structure

The performances of the modified structures with and without DMS have been compared and which has been shown in the Figure 10(b). It has been observed that the first harmonics is totally removed with the help of DMS structure.

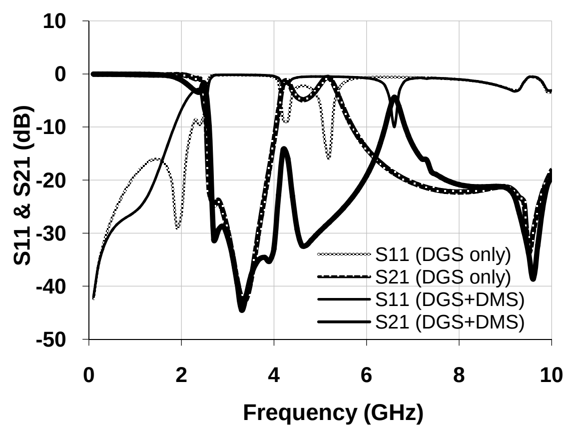
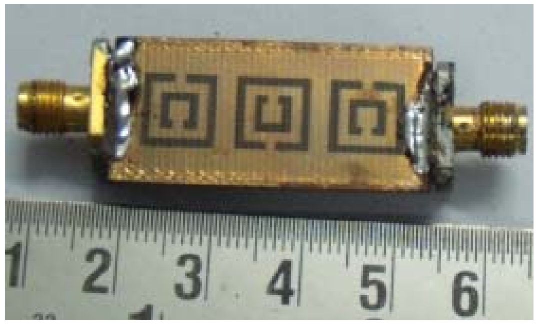


Figure 10(a). Scattering Parameters

The prototype structure (Figure 10(a)) is fabricated on Arlon PTFE substrate and measured with an Agilent make vector network analyzer of model N5230A. The photonic views of the Top plane and Ground plane are shown in the Figure 11(a) and 11(b) respectively. Both the simulated and measured S-parameters are plotted in Figure 12. The measured 3-dB cutoff frequency and pole frequency are 2.68 GHz and 2.8 GHz with sharpness factor 269.17dB/GHz, whereas, simulated values are 2.6 GHz and 2.72 GHz sharpness factor 235.1dB/GHz, respectively. The attenuation zero is observed is very close to the attenuation pole location. As a result, high sharpness factor is obtained in transition band. The passband insertion loss is almost negligible. The measured result complies with the simulated result to a great extent.



(a). Top plane

(b). Ground plane

Figure 11. The photonic views of the proposed structure

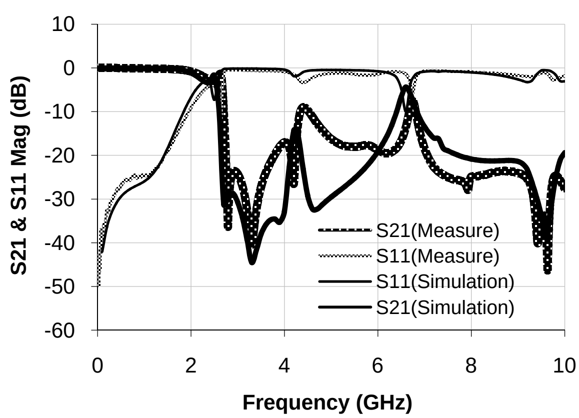


Figure 12. S-parameters (Simulated and Measured)

Conclusion

A new modified two concentric split ring DGS structure is proposed to achieve better sharpness compare to single split ring resonator. It exhibits the elliptic- function response and almost ideal lowpass filtering characteristics. The response can be tuned by varying the length and slot gap of the DGS unit. A considerable improvement in insertion loss has been achieved by incorporating compensated Hi-Lo microstrip line above DGS. By incorporating three DGS units under microstrip line, a good LPF is realized with a considerable improvement in steepness of the attenuation slope. A wide stopband bandwidth has been achieved by removing the first harmonic with the help of DMS structure in addition with DGS units. A study has also been made with regard to the precision of the milling process so as to show that the dimensions of the DGSs play a crucial role in determining the frequency response of the band. Due to the sharp transition between passband and stop band, negligible passband insertion loss and wide attenuation bandwidth this proposed structure is suitable in the modern microwave and millimeterwave communication systems.

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Tamasi Moyra (1978) received the AMIE (India) degree in Electronics and Communication Engineering from Institution of Engineers, India in the year 2003 and M.E. degree in the year 2007 from Bengal Engineering and Science University, Shibpur, India in the department of Electronics and Telecommunication Engineering. She is currently working toward the Ph.D degree in the department of Electronics and Telecommunication Engineering at Bengal Engineering and Science University, Shibpur, India. Presently, she is Assistant Professor of College of Engineering and Management, Kolaghat. Her current research interests include the planar circuits, Microstrip filters, antenna elements etc. She is a life member of Institution of Engineers, India.

Susanta Kumar Parui (1965) received the B.Sc. degree in Physics and B.Tech. degree in Radiophysics and Electronics from University of Calcutta in the year 1987 and 1990, respectively. He has done Master degree in Microwave Communication Engineering from Bengal Engineering College, India, in the year 1993. From 1993 to 2000, he worked as Instrument Engineer. Since 2000, he is associated with the Department of Electronics and Telecommunication Engineering of Bengal Engineering and Science University, India, and presently holds the post of Assistant Professor. His current research interests include the planar circuits, filters, antenna elements and electromagnetic band gap structures.

Santanu Das (1968) received the B.E.degree in the year 1989 in Electronics and Telecom. Engineering from Bengal Engineering College of Calcutta University (India) and M.E. degree in the year 1992 in Microwave Engineering from Jadavpur University, Calcutta. He obtained the Ph.D. (Engineering) degree in the year 1998 from Jadavpur University. He joined as Lecturer in the Electronics and Telecommunication Engineering Department of Bengal Engineering and Science University, India in the year 1998 and presently holds the post of Assistant Professor. His current research interests include the microstrip circuits, FSS, antenna elements and arrays. He is a life member of Institution of Engineers, India.