Design of a Quasi- elliptic Lowpass Filter using A New Defected Ground Structure and Capacitively Loaded Microstrip Line

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Abstract: The modern microwave and millimeter wave communication system demands good filtering characteristics with compact sizes. In this paper the attention has been given towards the design of a good elliptical lowpass filter with sharp transition between passband and stopband, negligible passband insertion loss and wide stop band. A new defected ground structure (DGS) consisting of two square slots connects with a rectangular slot by two thin transverse slots underneath a microstrip line is proposed. In the frequency characteristics of proposed unit pattern provides an attenuation zero close to an attenuation pole. As a result, better transition sharpness, lower passband insertion loss and broader stopband are observed compares to dumbbell DGS. 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 with 1.4 GHz cut-off frequency, 1.7 GHz attenuation pole frequency, negligible passband insertion loss, almost 100 dB/GHz sharpness factor and 1.56GHz passband bandwidth (at -15 dB) is designed by cascading three investigated DGS units of different dimensions under capacitively loaded microstrip line.

Keywords: microstrip, defected ground structure, elliptical, lowpass filter, capacitively loaded microstrip line.

1. Introduction

A defected structure etched in the metallic ground plane of a microstrip line is attractive solution for achieving finite pass band, rejection band and slow-wave characteristics. The defected structure effectively disturbs the shield current distribution in the ground plane and thus, introduces high line inductance and capacitance of the microstrip line. 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 filters, couplers, dividers and amplifiers [3-5] and [7-9]. 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 [6].

In this paper, an asymmetric DGS pattern with reference to transmission line is proposed. Its unit cell consists of two square headed thin slots connected with a rectangular slot under microstrip line transversely. 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. Three DGS cells are cascaded under capacitively loaded microstrip line realize a lowpass filter.

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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, a rectangular slot (of length a and breadth b) is connected with two square slots (of side length e) by two thin transverse slots (of length c and width g). The transverse slots increase the effective capacitance of the microstrip line whereas attached rectangular and square slots increase effective inductance. 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 b=10 mm, a=e=4 mm, d=c=2 mm, and g=0.4 mm. 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 prototype structure is fabricated on Arlon PTFE substrate and measured with an Agilent make vector network analyzer of model N5230A. Both the simulated and measured S-parameters are plotted in Figure 1(b). The measured 3-dB cutoff frequency and pole frequency are 3.16 GHz and 3.6 GHz, whereas, simulated values are 3.15 GHz and 3.5 GHz, respectively. The attenuation zero is observed at 2.83 GHz, which is very close to the attenuation pole location (3.5GHz). As a result, high sharpness factor (50 dB/ GHz) is obtained in transition band. The passband insertion loss is well below 1 dB. The measured result complies with the simulated result to a great extent.

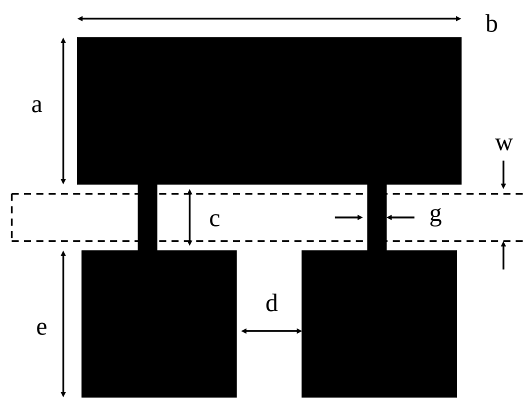


Figure 1(a). Schematic diagram of the proposed DGS unit pattern

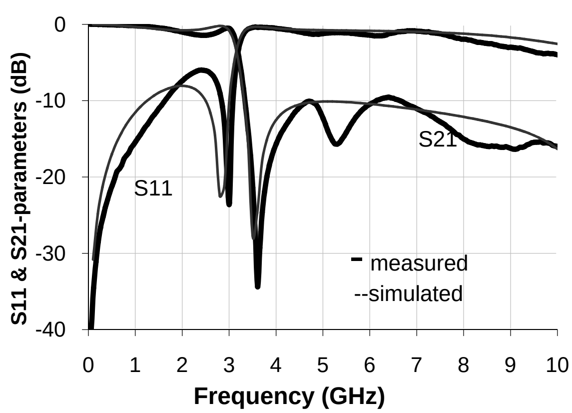


Figure 1(b). Simulated and measured S-parameters

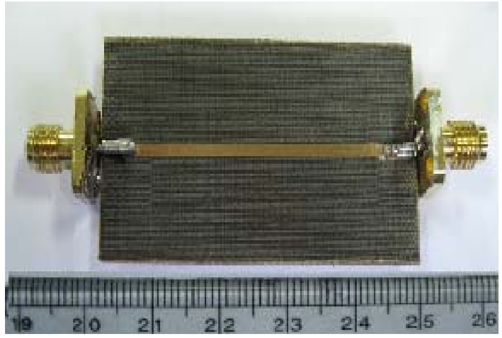


Figure 2(a). Photographic views of signal plane

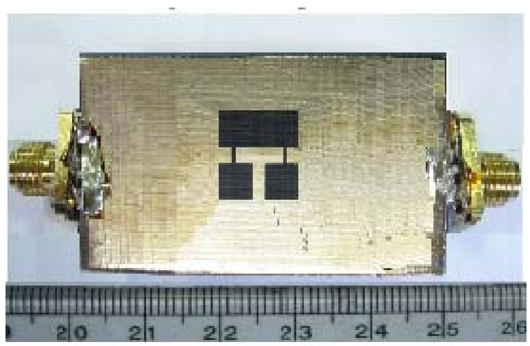
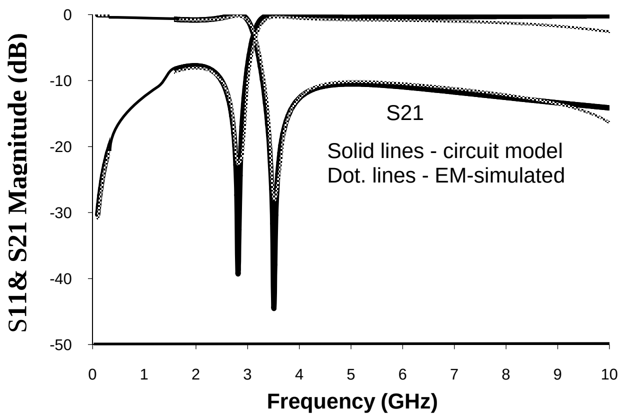


Figure 2(b). Photographic views of ground plane of DGS cell

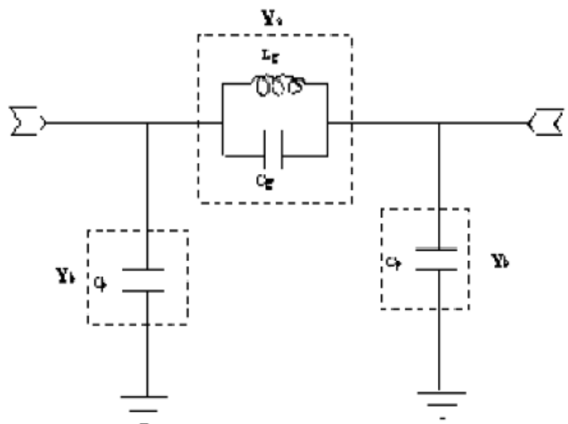
3. Equivalent circuit and Parameter Extraction

Figure 3(b) 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 Figure3(b). A DGS unit provides a cut-off and a attenuation pole frequency due to perturbation or disturbance of current distribution in the ground plane. Actually, the transverse slot increases the effective capacitance and the rectangular and square slots area improves the effective series inductance of the transmission line. Thus, the equivalent circuit, the etched defect in the metallic ground plane can be modeled as a parallel LC resonant circuit. But this parallel LC resonant circuit is not sufficient to explain the effect of discontinuities on the performance of the DGS. Here, the equivalent circuit includes the parallel capacitance *C*p that is due to the relatively large fringing field at the step discontinuity plane on the metallic ground surface.

The simulated S-parameter results are matched to the 3rd order elliptical lowpass filter response having attenuation pole at 3.5 GHz, attenuation zero at 2.83 GHz and stopband ratio of 1.1. The equivalent circuit parameters are calculated by using the prototype element values of the 3rd order elliptical lowpass filter. The EM-simulated and circuit-simulated S-parameters are presented in Figure 3(a) and good agreements between them 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. For the dimensions of the DGS unit as mentioned here, we can extract the parameters as L_g= 1.003 nH, C_g=2.0481 pF and C_p = 1.174 pF.



(a)



(b)

Figure 3(a). S-parameters of the DGS from circuit-model and EM- simulation
(b) Equivalent circuit

4. Optimization of the DGS shape and Comparison of Proposed DGS unit with Dumbbell DGS

The elliptic- function response is characterized by the following parameters:

(a) Stopband ratio (r_s) = f_s / f_p where f_s is the stopband edge frequency and f_p is the passband edge frequency
(b) Stopband attenuation (α_s) and
(c) Passband attenuation (α_p).

For almost ideal response, the value of r_s should be close to 1, α_p should be close to zero and α_s should be very high. The different dimension of the DGS unit is varied against r_s , α_p and α_s and obtained a relationship a=e; d=c=e/2; b=2a+d=2.5a for optimum values of r_s, α_p and α_s. It is also observed that r_s increases, i.e., sharpness decreases with increased value of g. So, low value of g is preferred. Finally we reach to a definite shape of the DGS unit with almost ideal elliptic- function response. Now, if any physical dimension (say, b) is known, other dimension (like a, e, d, c) can be determined from these relations. In our earlier example, b is taken as 10 mm and other dimension are calculated as a=4, e=4 mm, d=2, c=2 mm. The value of g is taken as 0.4 mm.

It is also possible to design one LPF of almost same resonance frequency using dumbbell DGS which first time proposed by D. Ahn. But the proposed DGS provides more satisfactory result compare to dumbbell DGS. The responses of the dumbbell DGS and proposed DGS are shown in the following figure 4.

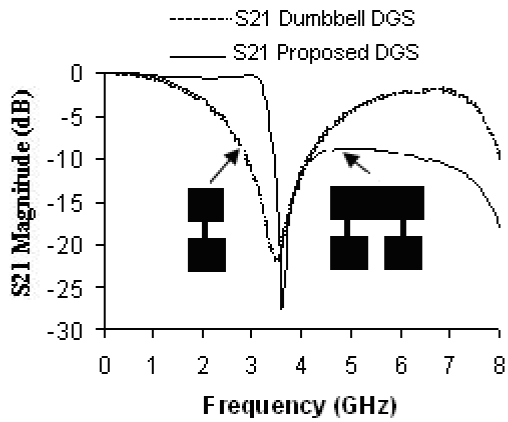


Figure 4. Comparison of Proposed DGS unit with Dumbbell DGS

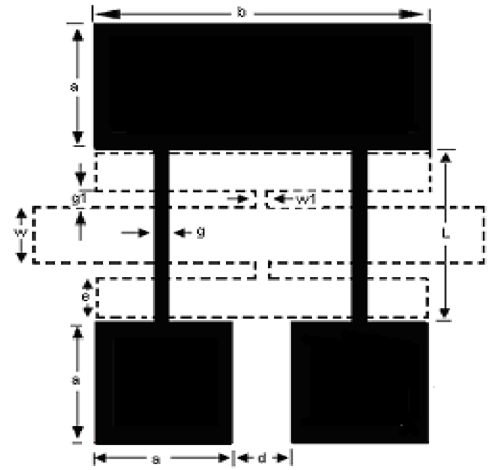
There is provision to generate attenuation pole at 3.52 GHz with Dumbbell DGS of two Square slots of 10mm length, 10mm breath and 0.4mm width connected by one transverse slot of length 2mm and width of 0.4mm underneath a 50 Ω microstrip line. But the proposed DGS structure provides some advantages.

From the above figure (Figure 4) it can be observed that dumbbell DGS provides attenuation pole at 3.52 GHz and attenuation zero at 1.95 GHz with very poor sharpness factor (11.4 dB/GHz) where as the proposed DGS provides high sharpness factor more than (50 dB/ GHz) in transition band i.e there is a good transition between the passband and the stop band of the proposed structure. As well as to get the same attenuation pole or resonance frequency near 3.6 GHz the Dumbbell DGS size require more than (10mm $\times$ 22mm) where as (10mm $\times$ 10mm) is sufficient for the proposed DGS i.e circuitry becomes more compact in size which is most important requirement in the modern microwave and millimeter wave mobile and wireless satellite communication system.

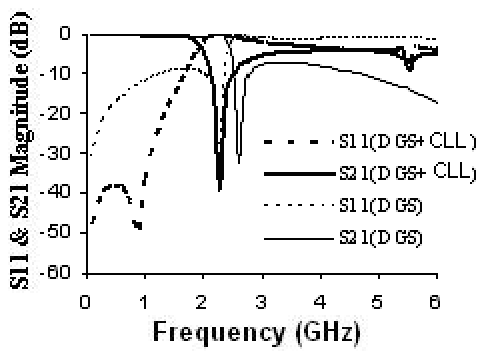
5. DGS under Capacitively loaded Line

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 acceptable as a practical lowpass filter. To reduce the insertion loss at passband, the standard microstrip line is replased by T-shape capacitively loaded alternative transmission line. The modified part of the microstrip line provides additional capacitance and acts as a low impedance line connected with high impedance line with standard characteristics impedance 50 Ohm and suitable for the reduction of the insertion loss.

The modified structure of the proposed DGS unit is shown in the figure 5(a). For the T-structure, patch have width, e=1.5mm with length, b=10mm, and stem have width, w1=0.4mm, length g1=0.5mm, is the optimized dimensions of the above DGS unit. In the layout of DGS unit, a rectangular ring slot (of length a=4mm, breadth b=10mm and width h=0.4mm) is connected with two square ring slots (of side length e=4mm and width h=0.4mm) by two thin transverse slots (of length L=6mm and width g=0.4mm). The simulated S-parameters of the proposed DGS with capacitively loaded line are compared **with DGS with standard 50 Ohm** line as shown in Figure 5(b). From the simulated S-parameters of the DGS the 3dB cutoff frequency at 2.45 GHz and pole frequency at 2.62 GHz with maximum attenuation of 35 dB are observed. The passband insertion loss is 0.65 dB but the DGS under capacitively loaded line, the 3dB cutoff frequency at 1.89 GHz and pole frequency at 2.2 GHz with maximum attenuation of 27.3 dB are observed with the passband insertion loss is 0.01 dB compares to 0.8 dB for microstrip line which makes the filter more practicable.



(a)



(b)

Figure 5(a). DGS unit underneath a capacitively loaded line (b) S-parameters of the DGS under standard (50 ohm) line and capacitively loaded line

Tuning of DGS with transverse slot width ‘g’:

The elliptic- function response can be tuned with variation the value of the transverse slot width ‘g’. The following table1 and Figure 6(a), 6(b), 6(c) shows the variation of different parameters with different values of transverse slot width width ‘g’ of the proposed DGS.

Graphical representation of the Table 1 shows as follows:

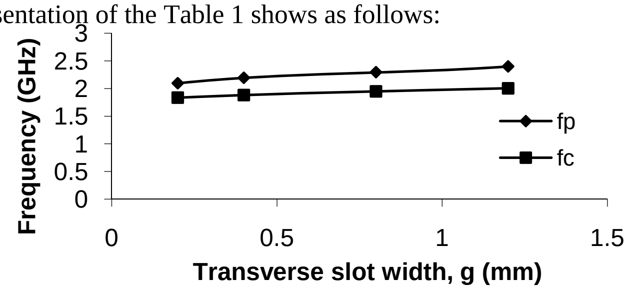


Figure 6(a). fp & fc characteristic with transverse slot width

Table 1. Variation of different parameters with different values of transverse slot width.

Transverse slot width g (mm)	Attenuation pole freq f_p (GHz)	Attenuation zero freq f_c (GHz)
0.2	2.096	1.836
0.4	2.195	1.883
0.8	2.2965	1.9502
1.2	2.3998	2.0049

From the above curve [Figure 6 (a)] and with the help of curve fitting it is possible to find the value of the require transverse slot width, g, of the DGS for the specified value of the attenuation pole frequency, fp, utilizing the following equation :

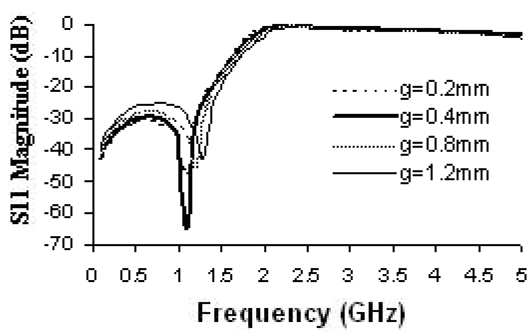
$$y = 0.4077x^3 - 0.9729x^2 + 0.9646x + 1.9387 \quad (1)$$

Where, Y and X signify the transverse slot width (g) and attenuation pole frequency (fp) respectively.

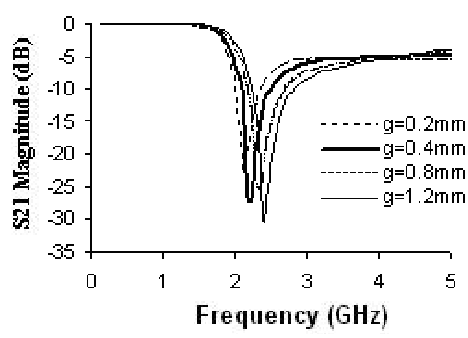
In the same way, from Figure 6 (a) require transverse slot width, g, can be tuned with attenuation zero (3 dB cut-off) frequency, fc, utilizing the following equation :

$$y = 0.0726x^3 - 0.2133x^2 + 0.3427x + 1.7754 \quad (2)$$

Where, Y and X signify the transverse slot width (g) and attenuation zero frequency (fc) respectively.



(b)



(c)

Figure 6(b). S11 & (c) S21 parameters for different values of transverse slot width ‘g’

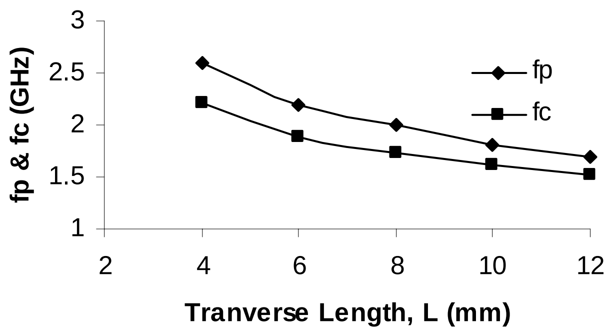
From the above discussion it is clear that it is possible to optimized the transverse slot width ‘g’ of the proposed DGS for a given fp and fc value with the help of equation (1) and (2).

Tuning of DGS with transverse slot Length ‘L’:

Table 2. Variation of different parameters with different values of transverse slot length:

Transverse slot length ,L (mm)	Attenuation pole freq f_p (GHz)	Attenuation zero freq f_c (GHz)
4	2.6056	2.2144
6	2.195	1.883
8	1.996	1.7313
10	1.7996	1.612
12	1.698	1.518

Graphical representation of the Table 2 shows as follows:



7(a) fp & fc characteristic with transverse slot length ‘L’

From the above curve [Figure 7(a)] and with the help of curve fitting it is possible to find the value of the require transverse slot length ‘L’, of the DGS for the specified value of the attenuation pole frequency, fp, utilizing the following equation:

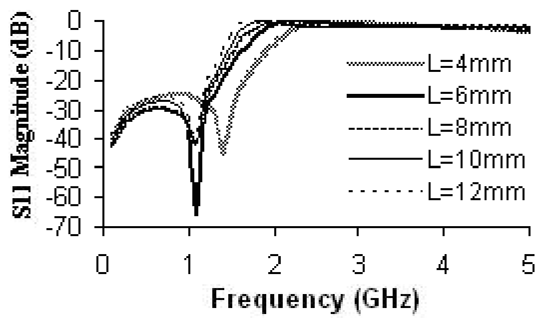
$$y = 0.0008x^4 - 0.0263x^3 + 0.3276x^2 - 1.889x + 6.4036 \quad (3)$$

Where, Y and X signify the transverse slot length ‘L’and attenuation pole frequency (fp) respectively.

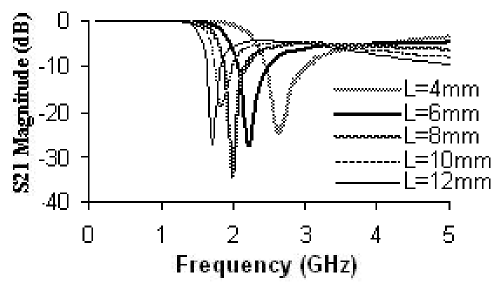
From Figure 7(a) require transverse slot length ‘L’, can be tuned with attenuation zero (3 dB cut-off) frequency, fc, utilizing the following equation :

$$y = 0.0004x^4 - 0.0133x^3 + 0.1814x^2 - 1.1593x + 4.7065 \quad (4)$$

Where, Y and X signify the transverse slot length ‘L’ and attenuation zero frequency (fc) respectively.



(b)



(c)

Figure 7 (b) S11 & (c) S21 parameters for different values of transverse slot Length 'L'

From the above discussion it is clear that it is possible to optimized the transverse slot Length 'L' of the proposed DGS for a given fp and fc value with the help of equation (3) and (4).

6. Realisation of Lowpass Filter

A lowpass filter has been realized using three DGS units of different sizes under capacitively loaded microstrip line or alternative transmission line as shown in Figure 8. The separation (x) between two DGS cell is taken as 2 mm. The overall length of DGS filter including microstrip line is 38 mm. The dimensions of the rectangular lengths of DGSs are 7.5mm, 10mm and 12.5mm respectively. The transverse slot lengths are 8mm, 6mm and 4mm respectively. The other dimensions are related with the relations of optimization as describe previously.

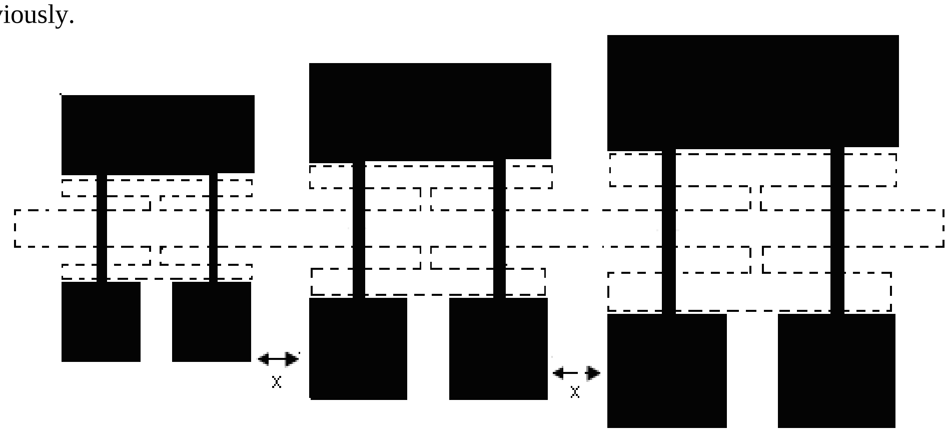


Figure 8. Layout of a DGS based lowpass filter

The equivalent circuit is obtained by cascading the equivalent circuits of the individual DGS units with 50 ohm transmission line is illustrated in Figure 9.

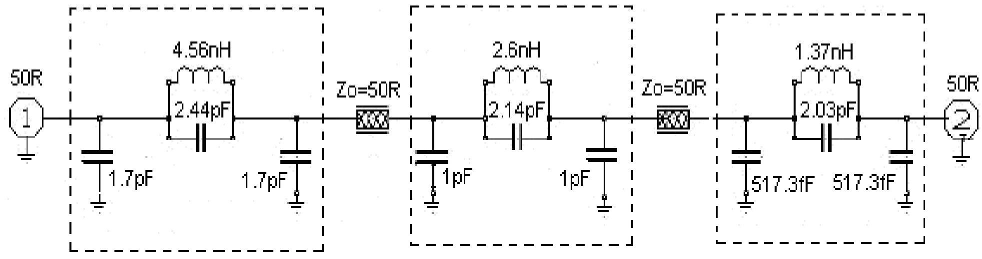


Figure 9 Equivalent Circuit

The simulation of the DGS for lowpass filter has been done with the help of IE3D EM-simulator and Circuit model analysis has been done by softwere RF sim99 and Filter Free Nuhertz technology. The simulated and circuit model responses are shown in Figure 10. It is observed that there is a good agreement between them.

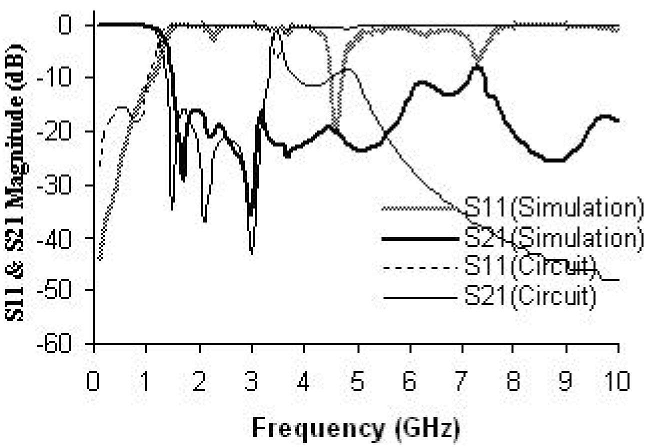


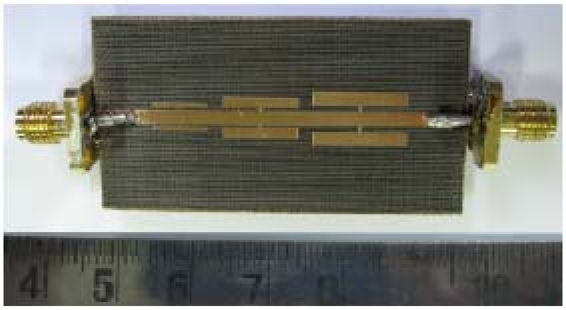
Figure10. S-parameters of DGS based low-pass filter simulated & circuit model

The fractional bandwidth (FBW) of stopband at -18dB is 0.688 or almost 69% and the attenuation bandwidth for EM-simulated and circuit-model are 1.6 GHz and 1.8 GHz respectively with center frequency 2.3 GHz. The insertion loss in passband is almost 0.02 dB in both simulated and circuit-model results. The sharpness at transition knee is more than 90 dB /GHz for both simulated and circuit-model results.

It responses provide the -3dB cut-off and attenuation pole frequencies at 1.38 GHz and 1.7 GHz respectively in simulation and 1.41GHz and 1.72 GHz in measurement results. Both responses provide 1.56 GHz passband bandwith at -15dB. The simulated and measurement response provides the sharpness factors of 93dB/GHz and 126dB/GHz respectively with almost zero passband insertion loss. Previously, from Figure10 it was found that both simulated and circuit model characterizes the almost identical responses and that is true for the simulated and measurement results as shown in Figure12. Therefore, from Figure10 and Figure12 it can conclude that there is a good agreement between simulated, circuit model and measurement results and the proposed structure is acceptable in practical applications. The passband band width can be tuned by controlling the separation between the adjacent DGS unites keeping the other dimensions constant. Thus, the structure shows a good quasi-elliptic lowpass filtering characteristics which is suitable for modern microwave and millimeter wave communication system.

The photonic view of the proposed DGS structure is shown in the Figure11.

(a)



(b)

Figure 11. Photographic views of (a) ground plane (array of DGS cells) and
(b) signal plane (Capacitively loaded transmission line)

The following response provides the comparative study of the simulated and measurement results.

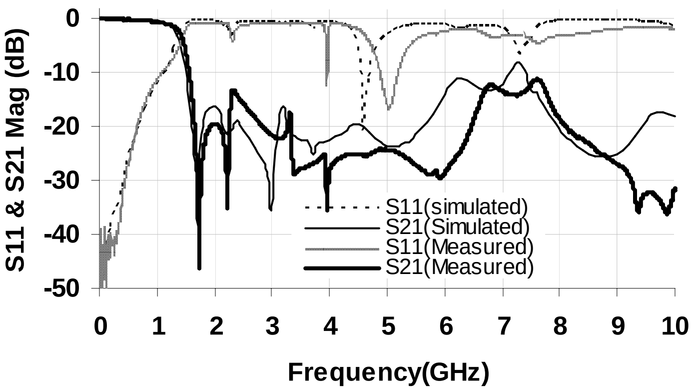


Figure 12. S-parameters of DGS based low-pass filter simulated & measured

7. Conclusion

A new modified Pi shaped microstrip DGS structure is proposed. It exhibits the elliptic-function response and almost ideal lowpass filtering characteristics. The stopband can be tuned by varying the length and width of connecting transverse slot. A considerable improvement in insertion loss has been achieved by incorporating capacitively loaded microstrip line or alternative transmission line above DGS. This approach leads also to a circuit size reduction. By incorporating three DGS units of different dimensions under capacitively loaded microstrip line, a three-pole LPF is realized. The stopband is tuned by changing the transverse slot width and the separation between the adjacent DGS units. A considerable improvement in steepness of the attenuation slope and fractional bandwidth has been achieved.

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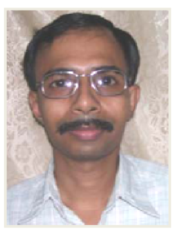

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