Modeling of Modified Split-Ring Type Defected Ground Structure and Its Application as Bandstop Filter

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Abstract. *The shape of a popular split-ring defected ground structure (DGS) is modified by selecting different width of the sides with respect to microstrip line. The frequency characteristics of proposed DGS unit show an attenuation zero close to the attenuation pole frequency. The unit cell is modeled by 3rd order elliptical lowpass filter and an equivalent circuit is presented accordingly. For proposed DGS, both pole and zero frequencies are obtained at lower values compared to split-ring DGS unit with uniform width. The variation of the width of the sides, parallel to microstrip line influences pole frequency. Two DGS cells with different pole frequencies cascaded under High-Low microstrip line realize a sharp and deep bandstop filter. Three-cascaded cells underneath a high-low impedance microstrip line produce sharper and wider bandstop filter characteristics.*

Keywords

Microstrip, defected ground structure, bandstop filter, elliptic filter.

1. Introduction

A defected structure etched in the metallic ground plane of a microstrip line is attractive solution for achieving finite passband, finite rejection band and slow-wave characteristics. Dumbbell shaped defected ground structure (DGS) has been proposed by D. Ahn first time and applied successfully to design a lowpass filter [1], [2], [3]. Such dumbbell DGSs with different head-slot were also proposed [4], [5]. Their frequency characteristics indicated one-pole response and they were modeled by Butterworth lowpass filter function. Thus, such dumbbell DGSs have been used for designing all pole type filters. A filter with high selectivity would be preferred owing to the demand for communication systems within finite spectrum resources. But we have to cascade a large number of dumbbell DGS to obtain sharp filtering response. A filter with attenuation poles and zeros at finite frequencies shows high selectivity characteristics. A DGS filter with elliptic function response may provide such features. Few DGSs with quasi-elliptic responses were reported [5], [6], [7], [8] in recent time. An asymmetric DGS consisting of three circular node-slots connected by two thin link-slots [9] showed attenuation zero and pole response and finally modeled by 3rd order elliptic filter function. Another asymmetric DGS consisting of two square slots connected with a rectangular slot by transverse slots underneath a microstrip line was proposed [10]. Two distinct attenuation poles were produced from its resonant elements and hence sharp bandstop filtering response was resulted.

In this paper, a modified split-ring DGS pattern is proposed where width of the sides, parallel to microstrip line is different to the sides, perpendicular to microstrip line unlike conventional split-ring DGS. The frequency characteristics of the proposed DGS show both attenuation zero and pole. The frequency characteristics looks like a 3rd order elliptic lowpass filter. Hence, the response exhibits very sharp transition knee due to the closeness of attenuation zero and pole frequencies. But it also introduces considerable amount of insertion loss in the passband. Replacing standard microstrip line of characteristic impedance (Z_0) of 50 Ω by high-low impedance (HI-LO) line, the insertion loss in the passband may be reduced.

Moreover, owing to increased equivalent inductances and capacitances, the required area of proposed DGS is seen to be smaller than dumbbell DGS and traditional split-ring DGS. By varying the ring width and split-gap, the pole frequency and cutoff frequency of the stopband can easily be tuned. Here two DGS cells with different pole frequencies are cascaded under a HI-LO microstrip line for realizing a sharp bandstop filter. Three or more cascaded DGS cells produce increased frequency bandwidth.

2. Frequency Characteristics of a Cell

Fig. 1(a) shows our proposed DGS cell etched off on the backside metallic ground plane underneath a microstrip line. The split-ring pattern is modified by increasing the width of the sides (m), parallel to the microstrip line with respect to the width of the sides (n), perpendicular to the line. Here, s is the width of the gap of the split-ring cell. The frequency characteristics are investigated by MoM based IE3D-simulator. The different dimensions of the DGS unit are considered as b = 6 mm, a = 4 mm, m =

3 mm, n = 1 mm and s = 0.4 mm, respectively. A substrate with a dielectric constant of 3.2, loss tangent 0.0025 and thickness 0.79 mm is considered. The width (w) of the conductor strip is taken as 1.92 mm, corresponding to characteristic impedance of 50 Ω as shown in Fig. 1(a).

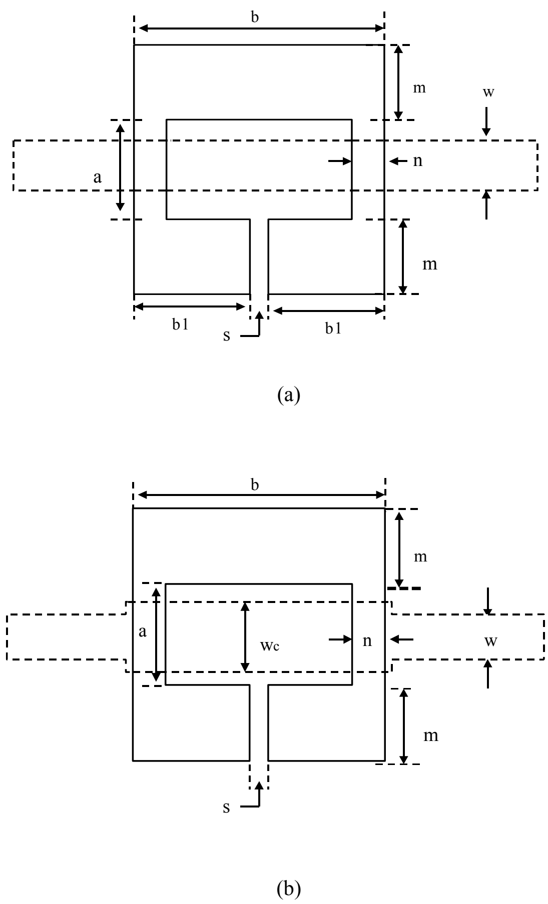


Fig. 1. Schematic diagram of split-ring DGS underneath (a) a standard microstrip line (b) a HI-LO microstrip line.

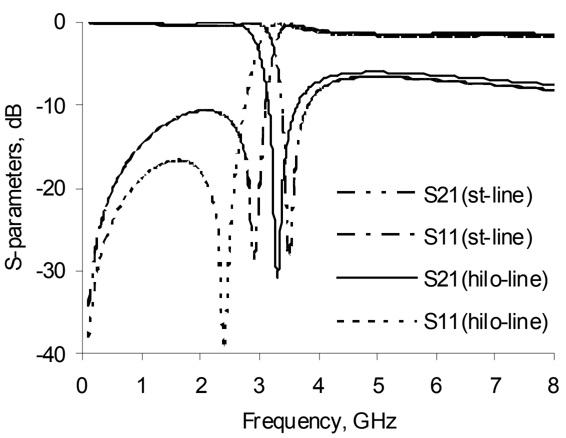


Fig. 2. Simulated S-parameters for standard microstrip line (st-line) and HI-LO line (hilo-line).

The simulated S-parameters of the DGS unit under a microstrip line (50 Ω) in Fig. 2 show an attenuation zero at 2.9 GHz and attenuation pole at 3.5 GHz. The response exhibits very sharp transition knee due to finite attenuation zero close to the attenuation pole frequency. But it also introduces considerable amount of insertion loss (0.43 dB) in the passband. The standard microstrip line is replaced by HI-LO line as shown in Fig. 1(b). For width w_c = 3 mm of the low impedance line having Z_0 of 40 Ω, the insertion loss reduces to 0.12 dB as observed in Fig. 2. Along with reduced insertion loss, 3 dB cut-off is lowered to 2.95 GHz and attenuation pole to 3.3 GHz. The sharpness factor at transition knee is obtained as high as 60 dB/GHz.

3. Modeling of DGS Cell

For practical circuit design, the equivalent circuit parameters need to be extracted. According to simulated S-parameters result, an equivalent circuit model represented by a ∏-type network, consisting of a parallel network composed of an inductance L and capacitance C and two parallel capacitances C_p as shown in Fig. 3. No resistance element is introduced as the radiation losses are very less in the stopband.

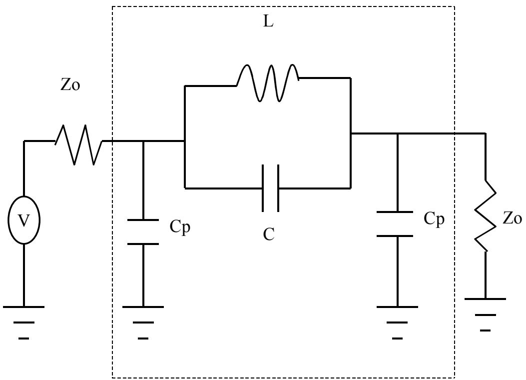


Fig. 3. Equivalent circuit of the DGS unit.

For the dimensions of the DGS unit as mentioned earlier, we have extracted the parameters using NuHertz make FilterSim software as L = 1.46 nH, C = 1.54 pF and C_p = 0.77 pF respectively considering cut-off at 2.95 GHz, stopband ratio of 1.2, passband ripple of 0.12 dB, and minimum attenuation of 7.4 dB.

From prototype filter design, we obtained L = 1.39 nH, C = 1.24 pF, C_p = 0.79 pF, considering theta of 56, stopband ratio of 1.206, minimum attenuation of -9 dB, ripple of 0.17 dB, passband edge frequency of 1.9 GHz and Z_0 = 50 Ω [11]. The results obtained from circuit-simulator are compared with elliptic prototype function as mentioned in Tab.1. The magnitude and phase characteristics of S-parameters obtained from proposed circuit model are compared with EM-simulation as illustrated in Fig. 4.

Method	Attn, dB	Ripp-le	S_band ratio	*L* (nH)	*C* (pF)	*Cp* (pF)
FilterSim	7.4	0.12	1.2	1.45	1.53	0.77
Prototype	9.0	0.17	1.2	1.39	1.24	0.79

Tab. 1. Filter parameters and equivalent LC parameters from FilterSim and filter prototype function.

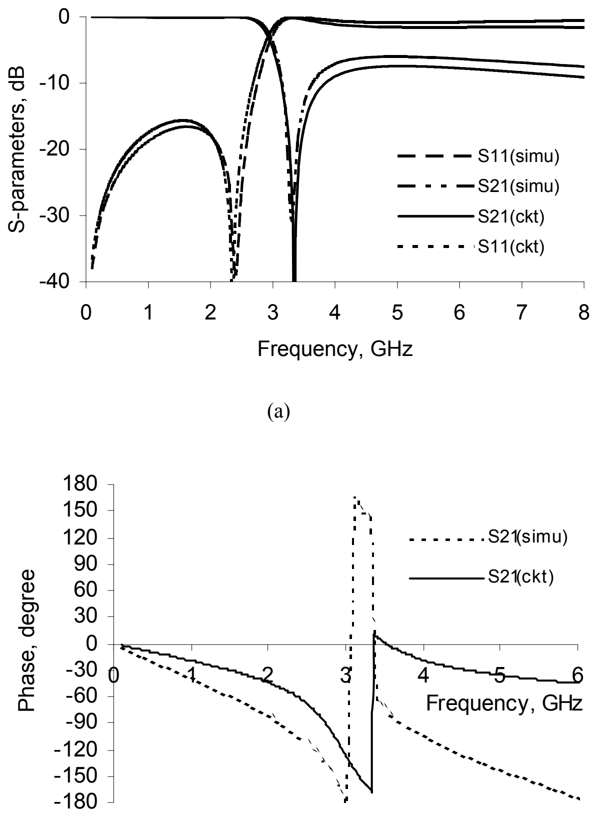


Fig. 4. S-parameters of the DGS from proposed circuit model and EM-simulation (a) magnitude, and (b) phase plot.

4. Influence of Ring-Width Variation

In order to investigate the influence of the width (*m*), the DGS unit is simulated with different values of *m*. The *m* is varied from 1 mm to 4 mm, keeping other dimensions like *n*, *s* and *b* fixed.

The simulated S-parameters are plotted in Fig. 5(a). It is observed that the pole frequency of the stopband is affected by *m* in appreciable amount. As *m* increases, pole location moves down to lower frequency. The sharpness factor, stopband attenuation and passband insertion loss of the filter remain at almost the same values.

The pole, zero and cutoff frequencies are plotted against *m* in Fig. 5(d). The extracted LC parameters for different value of *m* are mentioned in Tab. 2. With increasing *m*, the equivalent LC values increase, which confirms compactness.

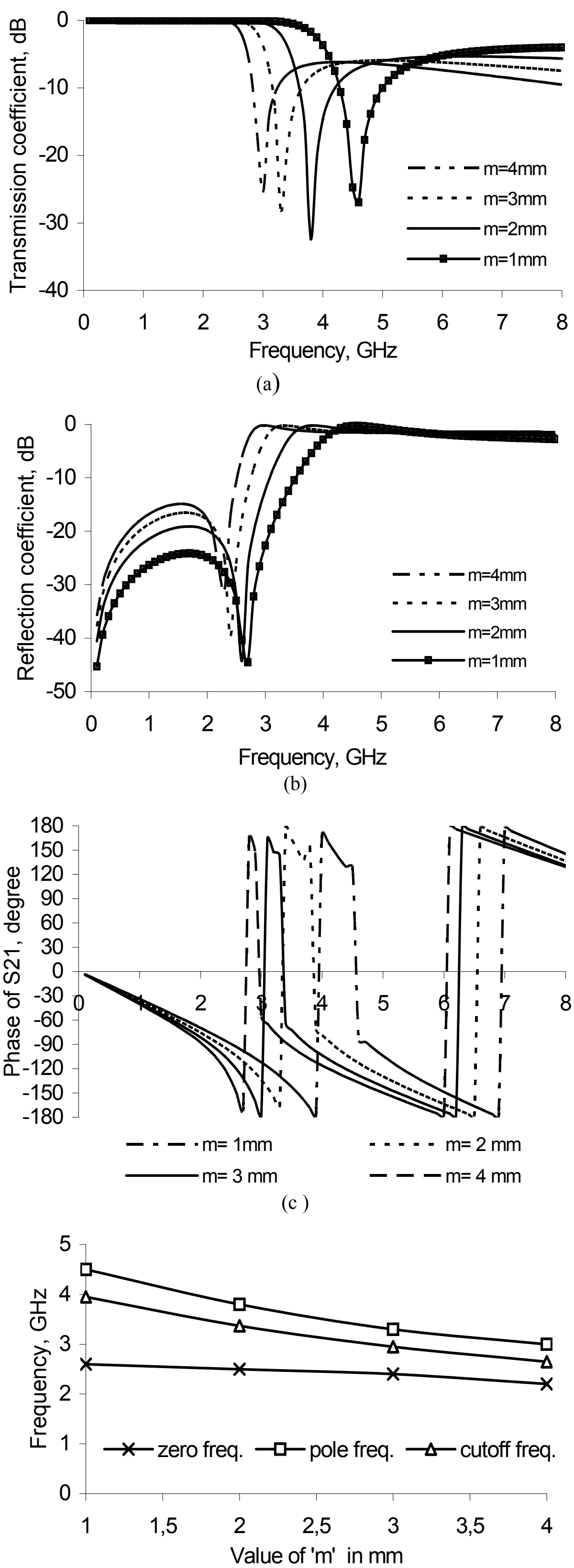


Fig. 5 The simulated S-parameters for different values of *m* (a) Magnitude of Transmission coefficient (b) Magnitude of Reflection coefficient (c) Phase of Transmission coefficient (d) Zero/pole/cutoff frequencies vs. *m* plots.

m (mm)	f_c (GHz)	f_p (GHz)	L (nH)	C (pF)	C_p (pF)
1	3.95	4.6	1.24	0.96	0.48
2	3.37	3.8	1.39	1.24	0.63
3	2.95	3.3	1.45	1.53	0.77
4	1.67	3.0	1.47	1.87	0.88

Tab. 2. Pole / cutoff frequency and extracted LC parameters of DGS cell for different value of *m*.

The pole frequency obtained as 3.3 GHz for proposed DGS with m = 3 mm and n = 1 mm is much lower than pole frequency (4.5 GHz) obtained for conventional split ring DGS with $m = n$ = 1 mm for almost same overall dimension as indicated in Tab. 2. Thus, proposed DGS is much more compact in comparison to coventional splitring DGS.

5. Realization of Band-Stop Filter

A bandstop has been designed by cascading a pair of cells with different set of pole frequencies as shown in Fig. 6.

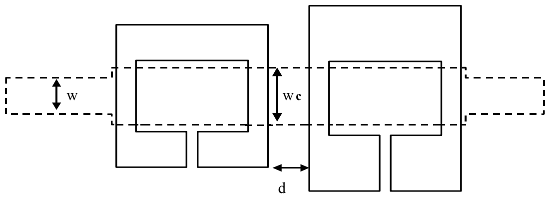


Fig. 6. Schematic diagram of two-cell DGS based band-stop filter with different set of *m*-value.

The pole frequencies are varied by width (m) of the DGS unit using the plot of Fig. 5(d). The separation between DGS cells (d) is taken as 3 mm. The other dimensions of the DGS units are taken as a = 4 mm, b = 6 mm and s = 0.4 mm. The width, w_c= 3 mm is taken for low impedance line.For different combinations of m values of the DGS we may realize stopband filters with different center frequencies and bandwidths as shown in Fig. 7.

It is observed that when both m values are very close, the stopband filter gives narrow bandwidth but deep stopband attenuation. But if m values differ a lot, the stopband filter gives wider bandwidth but with low stopband attenuation.

A prototype stopband filter has been fabricated on Arlon make PTFE substrate with a DGS pair having widths (m) of 1 mm and 2 mm. Other dimensions are the same for both DGSs as mentioned earlier. The photographic wievs of both planes is shown in Fig. 8. The total dimension of the circuit is 24 mm × 10 mm including feed line.

The circuit-simulated results are compared with EM-simulation and experimental measurement results in Fig. 9. The cut-off frequency is at 3.42 GHz, center frequency at 4.2 GHz and 20-dB rejection bandwidth of 0.82 GHz

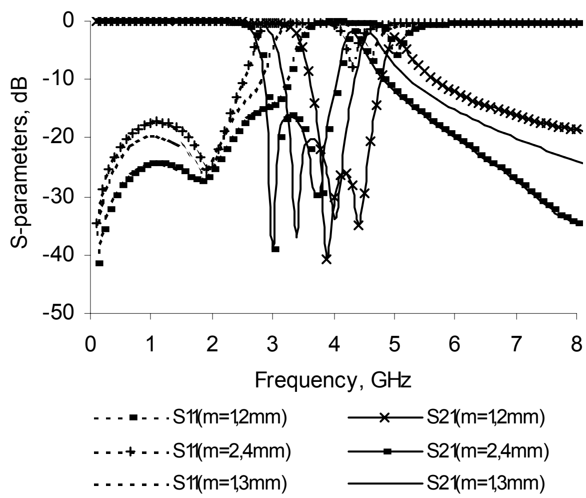
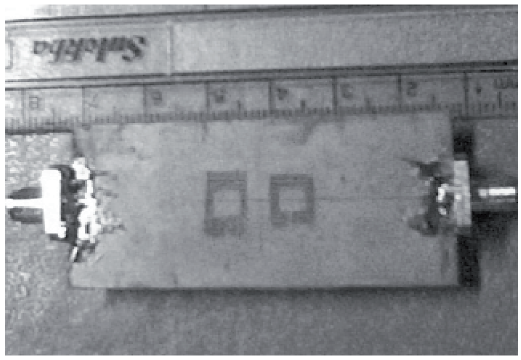
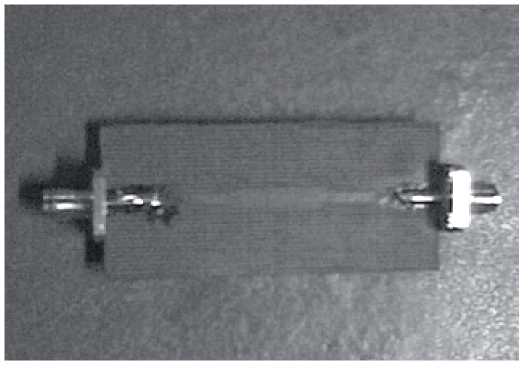


Fig. 7. S-parameters of bandstop filter for different pairs of cells.



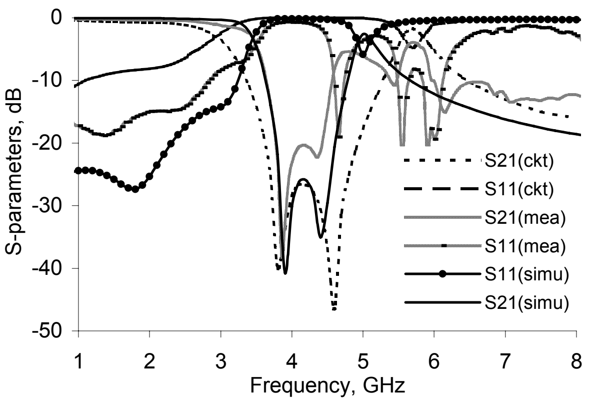
(a)



(b)

Fig. 8. Photographic views of a prototype filter: (a) ground plane (b) top plane.

(FBW= 19.5 %) are obtained in EM-simulation results. A sharpness factor of 50 dB/GHz is observed at lower transition knee and 42 dB/GHz at upper transition knee. The insertion loss in passband is maintained below 0.2 dB. The circuit-simulated results comply with the EM-simulated and experimentally measured values. The total dimension of the circuit is 24 mm × 10 mm including feed lines, which is equivalent to 0.425 λ × 0.127 λ, where λ is guided wavelength at center frequency.



(b)

Fig. 9. S-parameters for two-cell DGS filter (with m = 1mm and 2mm): EM-simulation (sim), circuit-simulation (ckt) experimentally measurement (mea) plots.

In another example, DGS pairs with m of 2 mm and 4 mm are chosen. Separation between two celss and other dimensions are the same as in previous considerations. The measured results in Fig. 10 show cut-off frequency at 2.61 GHz, center frequency at 3.16 GHz and 15-dB rejection bandwidth of 1.12 GHz (FBW = 35.4 %). The sharpness of 52 dB/GHz was obtained in lower transition and 41 dB/GHz in upper transition. The insertion loss is observed to be 0.1 dB in the passband. The EM-simulated results comply with the experimental measured results as shown in Fig. 10.

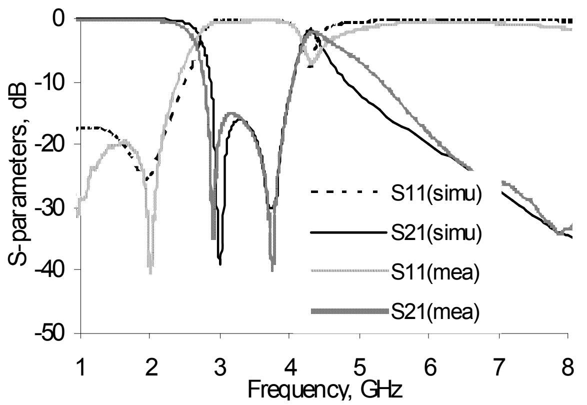
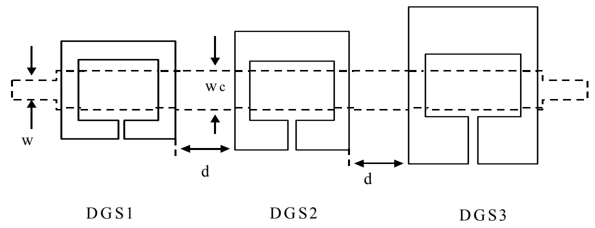


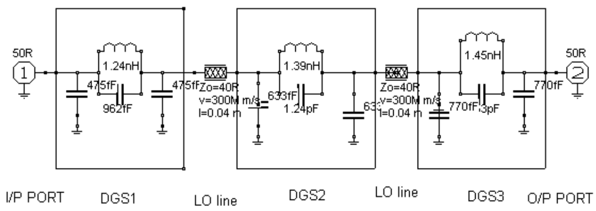
Fig. 10. S-parameters of bandstop filter for m = 2 mm and 4 mm

6. Realization of Wide-Band Filter

A bandstop is designed by cascading three DGS unit cells having closely spaced pole frequencies underneath a HI-LO line as shown in Fig. 11(a). DGS with a different pole frequency is obtained by varying the width (m) as illustrated earlier in Fig. 5(d). The DGS units having pole frequencies at 4.6 GHz, 3.8 GHz and 3.3 GHz are obtained with width (m) of 1 mm, 2 mm and 3 mm, respectively. Other dimensions are kept constant. Separation between all DGS cells (d) is taken as 4 mm. The total length including feed lines is 34 mm. The equivalent circuit of the filter consists of equivalent Π-circuits of each DGS unit, connected by transmission line sections of length 4 mm and Z_0 of 40 Ω. The LC values of each DGS unit are obtained from Tab. 2. The input and output ports have impedance of 50 Ω.



(a)



(b)

Fig. 11. A 3-cell DGS filter with m = 1 mm, 2 mm and 3 mm (a) schematic diagram, (b) LC equivalent circuit.

The circuit-simulated S-parameters are compared with EM-simulated results in Fig. 12. The cut-off frequency is observed at 3 GHz in EM-simulation and 3.1 GHz in circuit model. The 20-dB rejection bandwidth is 1.4 GHz (FBW = 35 %) in EM-simulation and 1.6 GHz (FBW = 40 %) in the circuit model. The center frequency is observed at 4 GHz in both the circuit and EM-simulated results. A sharpness factor of 80 dB/GHz is observed at transition knees and insertion loss maintained below of 0.1 dB all over the passband.. The circuit-simulated results almost comply with EM-simulated results. By cascading more DGS cells with different pole frequencies underneath a HI-LO line, a stopband filter may be realized with sharper and wider bandwidth.

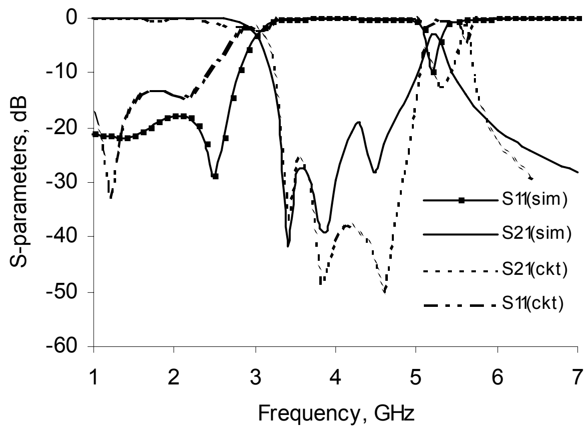


Fig. 12. S-parameters of 3-cell bandstop filter: EM-simulation (sim) and circuit-simulation (ckt).

The pole frequency of a DGS cell may be varied either by changing the width (*m*) of the vertical sides or by changing split-gap (*g*), keeping sharpness factor and passpand insertion loss unchanged.

7. Conclusions

The frequency characteristics of the proposed modified split-ring DGS cell show a very sharp transition knee due to attenuation zero close to attenuation pole frequency. It shows more compactness compared to dumbbell DGS and conventional split-ring DGS. The DGS was modeled by 3rd order elliptic lowpass filter function and proposed equivalent circuit accordingly. The LC parameters were extracted for different configurations of the DGS cells. A scheme for designing a bandstop filter by using two and more such DGS cells having different pole frequencies has been demonstrated. The pole frequency was varied by width of the vertical sides of the DGS unit. The stopband filters show high selectivity and compactness.

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