Improvement of Compactness of Lowpass/Bandpass Filter Using a New Electromagnetic Coupled Crescent Defected Ground Structure Resonators

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Abstract- This paper introduces a new compact defected ground structure (DGS) low pass filter (LPF) using a crescent shape structure etched in the ground plane. The filter response has improved dramatically by employing coupling of two DGS structures. Furthermore, the transformation to bandpass filter (BPF) is also investigated. The proposed configuration improved the lowpass response by widening the rejection band while significantly reducing the size. The behaviour of the filter has been investigated using HFSS as well as lumped element equivalent circuit model simulations using parallel L-C resonator. The proposed filter has been optimized.

Index Terms- Crescent, defected ground structure (DGS), low pass filter (LPF), band pass filter (BPF), frequency response.

I. INTRODUCTION

Defected ground structure technique is now applied in the design of microstrip filters. This helps to improve the filter performance and causes a size reduction, which is considered a major benefit. This technique is currently employed to meet the increasing demand for compact structure high performance [1] filters. Accordingly, numerous research has been done in order to achieve such goals. Lowpass and bandpass filters are enhanced by the use of such techniques [2-4].

The slots introduced at the backed ground plane layer (i.e, DGS) mainly improve the transition sharpness and widens the rejection band. This is due to the fact that the waves penetrating the structure are disturbed, causing equalization in the model phase velocity with respect to one another. This can also help in developing a more compact structure without the need to implement higher order filters with the same performance. In this paper, a new design for an LPF is investigated. The filter has a cutoff frequency of 1.9 GHz.

The filter performance has been improved by introducing two coupled elements as a defected structure in the ground plane. Furthermore, we have studied the effect of changing several parameters on the filter performance such as the coupling distance and the DGS area. Moreover, the implementation of a simple technique to transform the LPF into BPF is presented.

II. PROPOSED DGS STRUCTURE

The new proposed DGS structure, which is etched on the ground plane and shown in Fig. 1, has overall dimensions smaller than the predecessor H-DGS [5]. The crescent shape has the structure of a semi circle connected to a slot with a width g = 0.6mm, r = 5mm, t = 1mm and L=1.96mm. An RO4003 dielectric substrate of relative permittivity equals to 3.38 and thickness 0.813mm is used. The microstrip line on the upper layer in Fig. 2 has a width of 1.9mm which guarantees a 50 Ω matching impedance.

The presence of the DGS in the ground plane introduces an additional equivalent inductance, which in turn increases the characteristic impedance of the 50 Ω line on the top layer. This leads to a broader width of the 50 Ω line relative to that of the standard microstrip line [7-10].

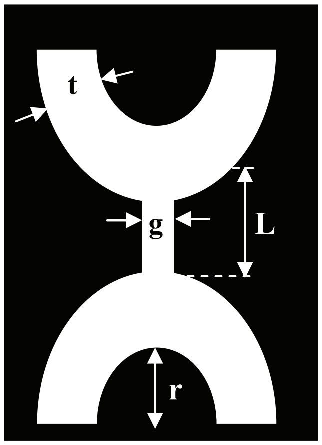

Fig. 1. Proposed single crescent DGS element.

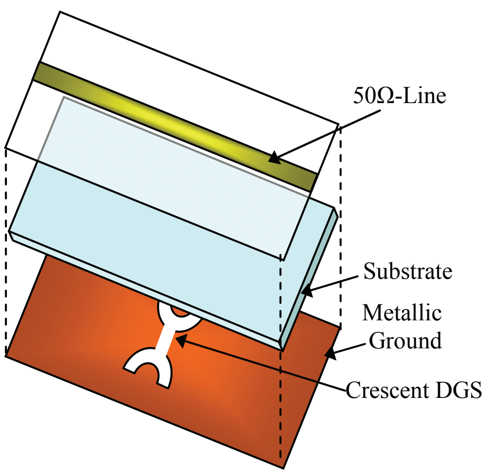

Fig. 2. 3-D view of the DGS resonator.

An equivalent circuit model for the crescent DGS element is shown in Fig. 3, which consists of simple L-C circuit [11,12]. The single crescent DGS LPF has been simulated using HFSS. The computed results were compared to that generated using the L-C circuit model. Good agreement between the equivalent circuit results and that of the simulated crescent element is shown in Fig. 4. As for the lumped elements used in the equivalent circuit, the capacitance (picofarads) and the inductance (nanohenrys) values are computed as using:

$$C_p = \frac{5 f_c}{\pi\left(f_0^2 - f_c^2\right)}\ pF \ \ and \ \ L_p = \frac{250}{C_p\left(\pi f_0\right)^2}\ nH \quad (1)$$

where f_c, is the cutoff frequency of the band reject response of the DGS at 3 dB and f_0, is the pole frequency [12].

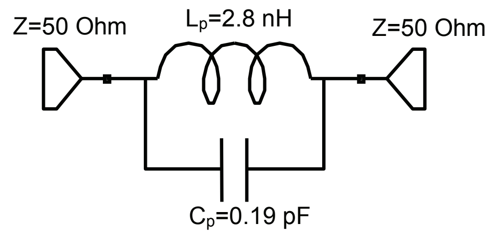

Fig. 3. Equivalent circuit of single DGS element.

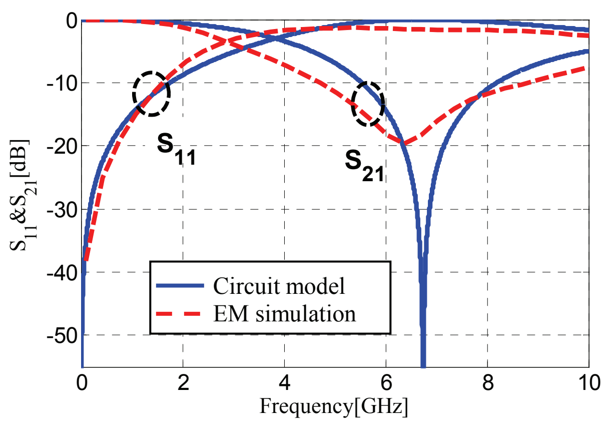

Fig. 4. Comparison between the S-parameters of the simulated crescent element and its equivalent circuit model.

III. COUPLED CRESCENT DGS FILTER

This section investigates the effect of etching two crescent DGS structures on the ground plane of the filter as shown in Fig. 5. The equivalent circuit model for the configuration of Fig. 5 is shown in Fig. 6. The proposed DGS shape has smooth edges and consequently less losses, which enhances its performance especially in the microwave range of frequencies where the filter is operating.

Moreover, the filter size is reduced dramatically, achieving a size saving of about 30%. This leads to a total filter size of $0.45\lambda_g \times 0.27\lambda_g$ having $\lambda_g = 58.3$ mm. The crescent LPF is

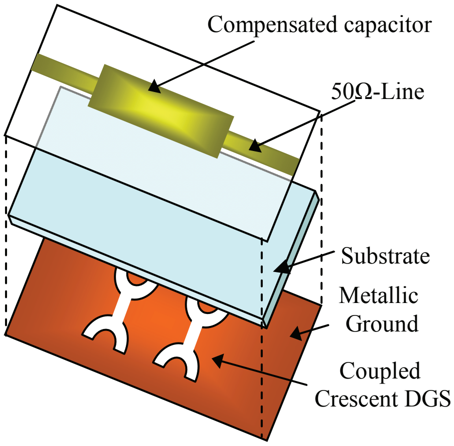

Fig. 5. 3-D view of coupled crescent DGS LPF.

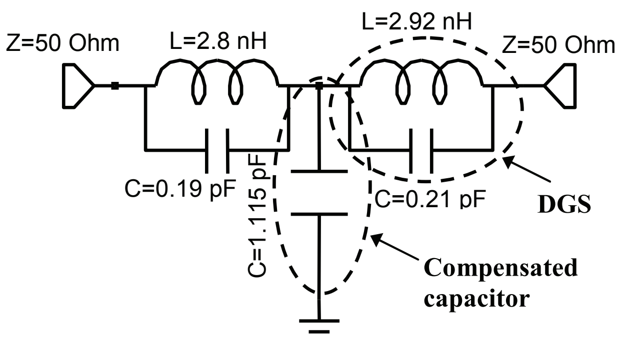

Fig. 6. Equivalent circuit of single DGS LPF.

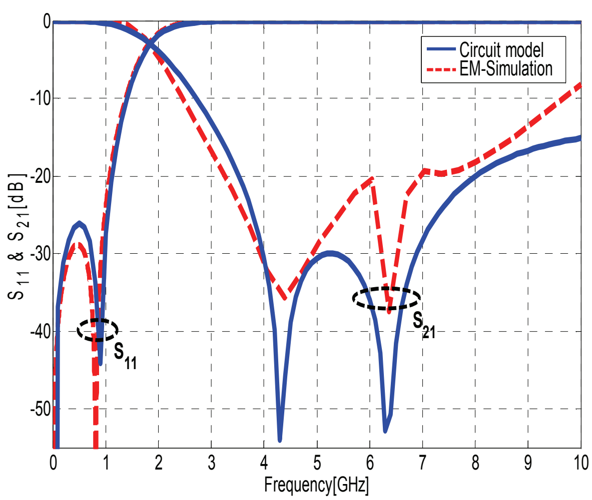

Fig. 7. Comparison between EM-simulation and circuit simulation results of the proposed filter structure.

simulated using microwave office. Figure 7 shows a comparison between the equivalent circuit model simulation and the microwave office simulation. The results show good agreement. The coupled crescent DGS filter shows a rejection band of about 6 GHz for an attenuation level less than 15dB providing an increase in the rejection band of about 50 % when compared to the H-DGS LPF [5].

A. Effect of Changing Coupling Distance on Filter Performance and Size at Crescent Radius of 5.0 mm

The coupling distance has a direct influence on the rejection band and also the filter size as shown in Table 1. Accordingly, there must be a trade off between performance and size to choose which suits best the application.

Table 1. Coupling distance versus rejection band and filter size.

Coupling distance(mm)	Rejection band < 20dB(GHz) Top Layer		Filter size (mm^2)
	50 Ohm line	Comp. capacitor	
3	3.6-5.8	3.2-5.4	23 x 16
4	3.6-5.9	3.25-5.7	25 x 16
5	3.6-8.1	3.2-7	26 x 16
6	3.6-8.1	3.2-7	27 x 16
7	3.8-8.1	3.2-7	28 x 16

Coupling distance(mm)	Sharpness Factor(fo/fc) Top Layer		Filter size (mm^2)
	50 Ohm Line	Comp. capacitor	
3	1.79	2.04	23 x 16
4	1.82	2.33	25 x 16
5	2	2.27	26 x 16
6	2.12	2.44	27 x 16
7	2.12	2.56	28 x 16

B. Effect of Changing Crescent Area at 5mm Coupling Distance

The crescent radius controls the inductance of its equivalent lumped circuit element model. Thus, increasing the radius value leads to an increase in the inductance value, which in turn decreases the cutoff frequency. This relation is clearly shown in Table 2.

A further investigation is conducted to study the effect of increasing the number of crescent elements in the DGS. Three coupled crescent elements are etched in the ground plane. The filter response in the presence of the 3 coupling crescent

Table 2. Crescent radius versus rejection band and cutoff frequency.

Crescent radius(mm)	Rejection band < 20dB(GHz)		f_c (GHz)	
	Top Layer		Top Layer	
	50 Ohm Line	Comp. capacitor	50 Ohm line	Comp. capacitor
3	9-14	8.6-11.4	4.1	2.8
4	5.4-7	4.7-7.6	3.19	2.44
5	3.6-8.1	3.2-7.7	2.4	1.9
6	3.8-8.2	3.2-7.7	2.25	1.75
Crescent radius(mm)	Sharpness Factor(fo/fc)		f_c (GHz)	
	Top Layer		Top Layer	
	50 Ohm Line	Comp. capacitor	50 Ohm line	Comp. capacitor
3	2.44	3.57	4.1	2.8
4	2.5	2.78	3.19	2.44
5	2	2.27	2.4	1.9
6	2.08	2.5	2.25	1.75

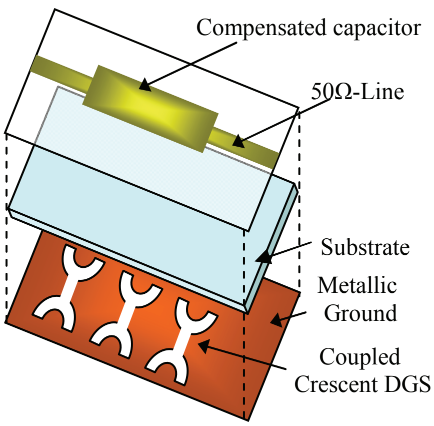

Fig. 8. 3-D view of coupled 3 crescents DGS LPF.

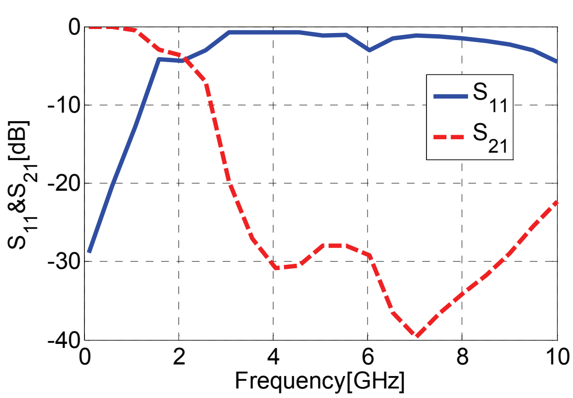

Fig. 9. Simulated S-parameters for the coupled 3 crescents DGS LPF.

elements is shown in Fig. 8. The relevant EM simulation is shown in Fig. 9. It can be noticed that the rejection band has increased dramatically due to the extended coupling. However, undesired effects have appeared in the pass band region. The equivalent filter size for the 3 crescent DGS LPF has increased to 41 × 16 mm^2.

IV. DISTRIBUTION OF ELECTRIC FIELD AT 4.4 GHz AND 1.0 GHz

The objective of this study is to prove the dependence of the equivalent circuit elements (capacitance and inductance) on the surface current distribution. This can be shown in Figs. 10, 11, and 12.

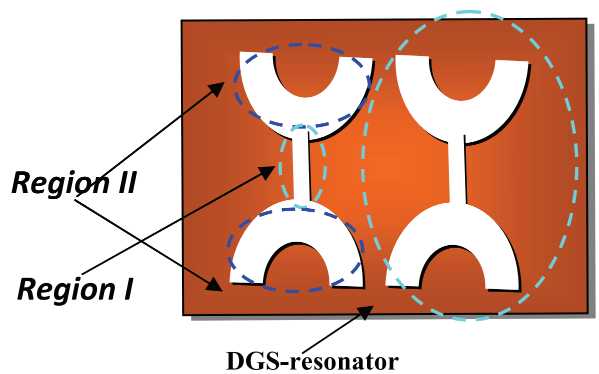

Fig. 10. Two-dimensional view of the proposed LPF.

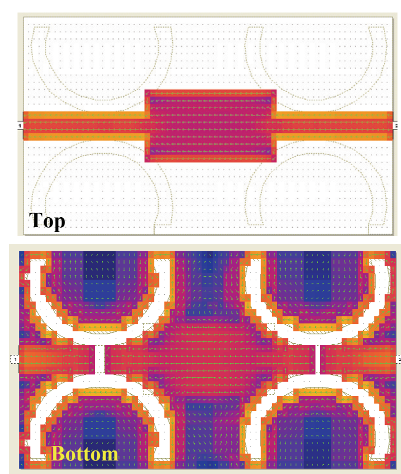

Fig. 11. Electric field distribution at f_0 = 1 GHz.

The structure is divided into two regions: region I, where the electric field is highly concentrated in the gap. Hence any change in the dimensions of the gap affects the effective capacitance of the structure. In region II, the electric field nearly vanishes [1-2]. This means that the length of the arcs does not affect the effective capacitance of the filter structure. The current is distributed throughout the whole structure. Therefore any change in the length of the arcs strongly affects the magnetic field distribution and hence the surface current, which in turn leads to a change in the effective inductance of the structure. Based on the previous illustration, region I corresponds to a capacitance, while region II corresponds to an inductance. Thus, the full structure corresponds to a parallel LC-resonator, which supports the circuit model shown in Fig. 6.

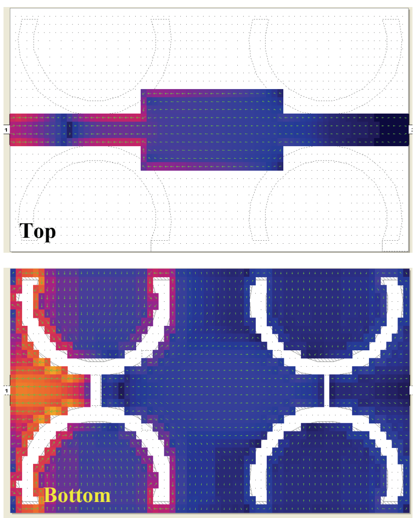

Fig. 12. Electric field distribution at f_0 = 4.4GHz.

V. THE TRANSFORMATION OF LPF TO BPF USING J-INVERTER-METHOD

It is well known that the transmission characteristics of microstrip low-pass filters have a periodic behavior. The periodicity is approximately four times the cutoff frequency f_c. This property of microstrip lowpass filters can be used to carry out a new and simple transformation from LPF to BPF [13]. Figure 13 shows the 3-D schematic view of the new compact BPF. The proposed BPF has a discontinuity in the feed microstrip line J-inverter as compared to continuous feed line of the LPF. In this case, the transmission characteristics is inverted, causing the structure to act as a bandpass filter with passband between f_c and 3 f_c and a stop-bands in DC- and [3 f_c - 4 f_c] intervals. The frequency response of the bandpass filter is shown in Fig. 14.

Figure 13 shows the microstrip BPF using end-coupled $\lambda/2$-microstrip resonators. Equivalent circuit of the gap-microstrip is shown in Fig. 13. The effect of the gap is equivalent to π-shunt (C_{IO}) and series (C_k) capacitances. The remaining capacitances and inductances are obtained from EM simulations of the single DGS element and the optimization method. The capacitances CIO and C_k are determined by:

$$for \;\; 2.5 \le \varepsilon_r = 3.38 \;\; \le \;\; 15.0$$

$$\frac{C_{even}}{w} = \left(\frac{\varepsilon_r}{9.6}\right)^{0.9} \left(\frac{s}{w}\right)^{m_e} e^{k_e} \left(\frac{pF}{m}\right) \tag{2}$$

$$\frac{C_{odd}}{w} = \left(\frac{\varepsilon_r}{9.6}\right)^{0.8} \left(\frac{s}{w}\right)^{m_o} e^{k_o} \left(\frac{pF}{m}\right) \tag{3}$$

$$for \;\; 0.1 \;\; \le \;\; \frac{s}{w} = 0.6 \;\; \le \;\; 1.0 \;\; \& \;\; \left(\frac{\mathrm{w}}{\mathrm{h}}\right) = \eta$$

$$\Rightarrow \mathrm{m}_0 = \left(\frac{\mathrm{w}}{\mathrm{h}}\right)\left[0.92 \log \eta \;\; - \;\; 0.38\right] \tag{4}$$

$$\Rightarrow \mathrm{k}_0 = \left[4.26 \;\; - \;\; 1.45 \log \eta\right] \tag{5}$$

$$\Rightarrow \mathrm{m}_\mathrm{e} = \left[\left(\frac{1.565}{\eta^{0.16}}\right) - 1.0\right]$$

$$\& \; \mathrm{k}_\mathrm{e} = \left[1.97 - \left(\frac{0.03}{\eta^{1}}\right)\right] \tag{6}$$

$$\Rightarrow \mathrm{C}_{\mathrm{IO}} = \left(\frac{\mathrm{C}_{\mathrm{even}}}{2.0}\right) \; \& \; \mathrm{C}_\mathrm{k} = \left(\frac{\mathrm{C}_{\mathrm{odd}}}{2.0} - \frac{\mathrm{C}_{\mathrm{even}}}{2.0}\right) \tag{7}$$

In order to improve the BPF behaviour, it is necessary to find the optimal distance between both DGS resonators. Through which the electromagnetic energy can be optimally utilized. Accordingly, the losses will be minimised in the pass-band, which leads to a better response. The coupling method and the coupling matrix will be used in order to calculate the gap distance (p = 0.2 λ_g),

$$\lambda_g = \left(2\pi \frac{c_0}{\omega_c \sqrt{\varepsilon_r}}\right) \qquad (c_0 \approx 3.10^8 \, ms^{-1}). \tag{8}$$

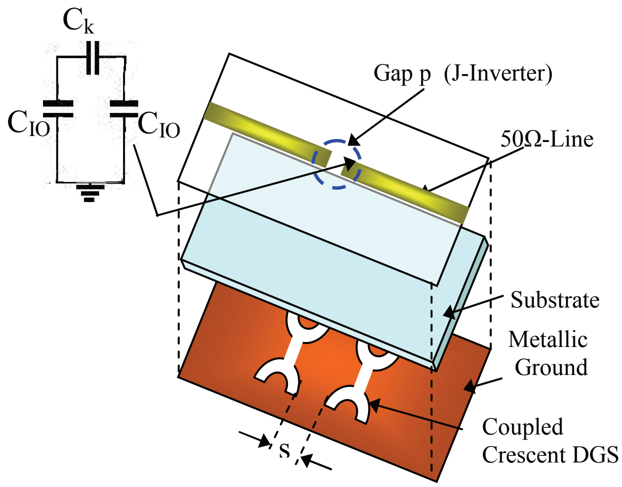

Fig. 13. Three-dimensional view of the proposed band-pass filter.

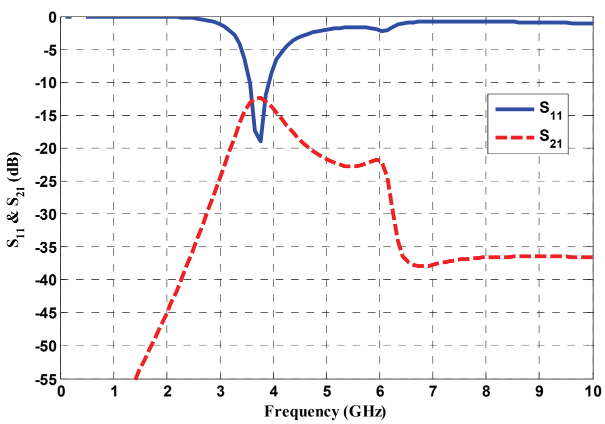

Fig. 14. Simulated S-parameters for the proposed crescent -DGS BPF.

VI. CONCLUSION

A new crescent DGS design has been implemented and its equivalent circuit was developed. The crescent DGS, when employed using coupling method, achieved very good results in terms of a rejection band of 6 GHz at an attenuation level less than 15 GHz. Furthermore, a size reduction of about 30 % was achieved relative to a predecessor design. Parametric studies were conducted to investigate the effect of coupling distance between crescent DGS elements and the crescent DGS area size on the filter performance. Moreover, an electric field analysis was performed on the proposed LPF. Transformation of the LPF to BPF was studied and employed using the technique of J-inverter.

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