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A Compact UWB Band Pass Filter Using Simple Defected Ground Structures

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Abstract—In this paper an ultra-wideband band (UWB) pass filter is introduced. The filter is composed of multiple shorted shunt stubs and some defected ground structures (DGS). The defected ground structures are composed of some circular-shape defects and diagonal-line patterns. The bend-shaped defected-ground structure is thoroughly studied and compared to some other defected structures. The filter features a simple structure and small dimensions ($12 \times 22\,\mathrm{mm}^2$). Meanwhile, a systematic design method is presented. The analysis method is based on numerical methods and is verified by a commercially available EM simulator. The 3 dB passband of the proposed wide band filter is between 2 GHz and 10 GHz.

1. INTRODUCTION

Microwave filters play a major role in telecommunication systems. There are major trends to reduce the dimension and improve the frequency response of the microstrip filters. Microstrip filters are planar circuits that can be easily integrated with other electronic circuits and components, and feature small dimensions. Microstrip band-pass filters suffer from higher frequency resonances and passbands due to the distributed effects. To suppress the unwanted passbands of a band-pass filter, some low-pass filters must be cascaded with the band-pass filter. As a consequence, the overall dimension of the filter increases. Defected ground structures have been used in microwave circuits and antennas for shaping the frequency response and improving the out of band performance [1, 2]. The addition of a DGS to a microwave filter improves the out of band rejection property of the filter without increasing the dimensions. In some cases the in band frequency response of the filter is affected too, and the net effect is an overall size reduction. A Low-pass and a band-pass filter with an H-shaped defected-ground structure have been introduced in [1]. The effect of a fractional pattern in the ground plane was studied in [2]. In both cases the frequency response of the filters was shaped through the DGS and major improvements observed. A DGS can be a simple cut in the ground plane or a void in the ground plane with the shape of an H or a dumbbell [3]. Although more complex patters can be used as a DGS, the analysis and design of these patters become complex [2, 4–6]. Not only does the out of band rejection of a microstrip filter improve through the presence of a DGS, the maximum frequency of the rejection band of a microstrip filter also increases as demonstrated in [7].

In this work several circular-shaped DGSs have been used to improve the frequency response of a band-pass filter. The analytical formulas, presented in the following sections, simplify the calculation of the resonant frequency introduces by a DGS.

2. THE DGS

The DGS is, in fact, a discontinuity or a cut in the ground plane of a microstrip line or microstrip circuit. The DGS affects the path of the current in the ground plane. The net effect is a resonant

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circuit in series with the primary microstrip line or circuit. In many applications the DGS is modeled by a parallel RLC resonator which is connected in series with the circuit. The parallel RLC resonator introduces transmission zeros in the transfer function of the circuit. A defected structure is simple to integrate with a planar circuit as microstrip filters and affects the frequency response of the circuit.

A diagonal cut in the ground plane of microstrip line is shown in Fig. 1. This is one of the easiest defected-ground structures. The discontinuity in the ground plane introduces a transmission zero for the current at DC and at a frequency, known as the resonance frequency of the circuit. For this reason the DGS is modeled as a parallel RLC resonator in series with a DC blocking capacitor. The value of this capacitor depends on the width of the gap and length of the cut in the ground plane.

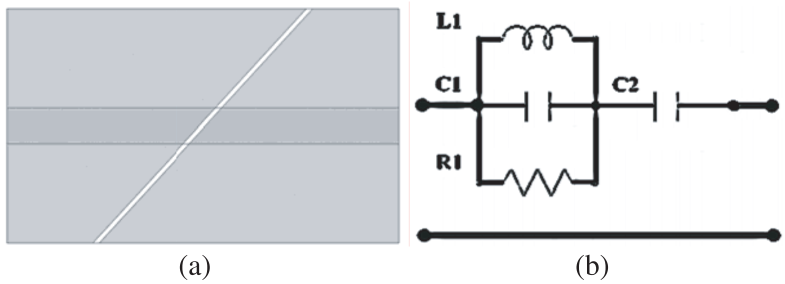


Figure 1. (a) A transmission line and a cut in the ground plane as a DGS. (b) The equivalent circuit of the DGS.

There are other types of DGS where some forms of defects in the ground plane are used to introduce a resonant circuit in the frequency response of the circuit. Fig. 2 shows some other shapes of DGSs. The transmission zero at DC disappears in these structures because of the finite dimension of the defects in the ground plane. These DGSs have the equivalent circuit of a parallel resonant RLC circuit (without the series capacitor C_2) in series with the transmission line.

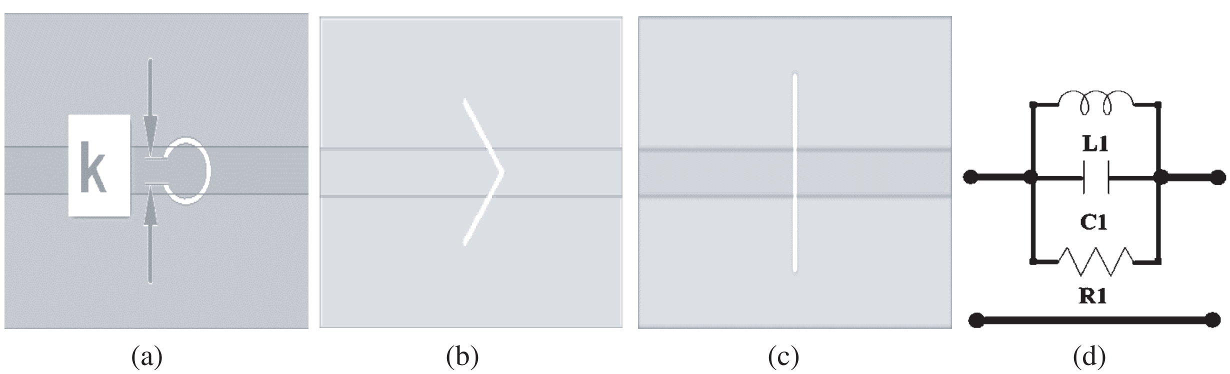


Figure 2. (a) Circular-shape DGS (type 1). (b) Broken-line DGS (type 2). (c) Straight-line DGS (type 3). (d) The equivalent circuit of three defected-ground structures.

The DGS in Fig. 2(a) is an open ring shaped cut in the ground plane of a microstrip line, and K is the spacing between the open ring ends. The DGSs in Figs. 2(b) and (c) are diagonal and straight cuts in the ground plane, respectively. The equivalent circuit of these defected ground structures is shown in Fig. 2(d).

These circuits are simulated in HFSS, which is a full wave simulator. The dimensions of the defects are such that a transmission zero results at 14.5 GHz. The frequency response of these DGSs are simulated and compared in Fig. 3.

The elements of the equivalent circuit of the DGSs shown in Fig. 2 have been calculated in [8] and [9]. Another useful method for deriving the equivalent circuit is to fit the S parameters of the equivalent

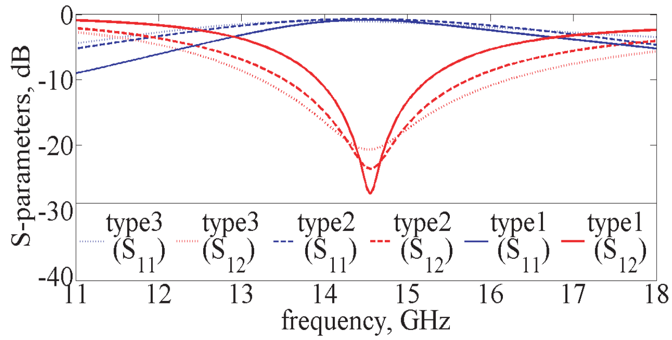


Figure 3. Simulated scattering parameters of three types of defected ground structures.

circuit to the simulation results. The S parameters of a DGS can be obtained with the aid of a full wave simulator as HFSS. The equivalent circuit parameters of the three DGSs of Fig. 2 have been derived by the fitting method. In the case of a defect of straight-line shape, $R_1 = 986\,\Omega$, $L_1 = 0.591\,\text{nH}$ and $C_1 = 0.203\,\text{pF}$. In the case of a V-shape cut in the ground plane, $R_1 = 1412\,\Omega$, $L_1 = 0.477\,\text{nH}$ and $C_1 = 0.251\,\text{pF}$. In the case of a defect in the ground plane of the semi-circular shape, $R_1 = 2273\,\Omega$, $L_1 = 0.269\,\text{nH}$ and $C_1 = 0.445\,\text{pF}$.

Comparing the frequency response of the three DGSs, the semi-circular cut in the ground plane has the highest quality factor for the same magnitude of transmission zero. The resonance frequency for the defected circular DGS with a spacing of K between the ring ends, as shown in Fig. 2(a), can be derived by calculating at first the arc length of the ring as:

$$L = 2R\left(\pi - \sin^{-1}\left(\frac{K}{2R}\right)\right) \tag{1}$$

where R is the radius of the ring. The resonant frequency of the ring is at a frequency, where the arc length equals one wavelength. For this reason the resonance frequency is

$$f_{\text{resonance}} = \frac{c}{L\sqrt{\varepsilon_r}} \tag{2}$$

where c is the speed of light, and ε_r is the dielectric constant of the substrate. The open ring is placed in the ground plane of the microstrip line. The speed of the wave and the wavelength are not easy to calculate analytically. An empirical fitting parameter is used to correct Eq. (2), and the corrected resonant frequency is given in Eq. (3).

$$f_{\text{resonance}} = \frac{\lambda c}{\left(\left(\sqrt{\varepsilon_r}\right) 2R\left(\pi - \sin^{-1}\left(\frac{K}{2R}\right)\right)\right)} \tag{3}$$

where $\lambda = 338$, and it is the empirical parameter. It has been obtained by simulating multiple semi-circular DGSs with different values of R and resonance frequencies. This method is valid for small values of K. Throughout this paper the opening of the rings is taken to be 1 mm.

3. DESIGNING THE UWB BAND PASS FILTER

To realize a wide-band band-pass filter, a 50 Ohm microstrip transmission line in conjunction with two shorted parallel stubs and four semi-circular defects on the ground plane has been used. The DGSs and two shorted stubs introduce some transmission zeros in frequency response. By controlling the dimension of the DGSs and shorted stubs, the passband and stopband of the filter can be shaped. The layout of the proposed band-pass filter is shown in Fig. 4. The shorted stubs with the diagonal cut in the ground plane are responsible for the transmission zeros in the lower stopband. The semi-circular shaped DGSs introduce zeros in the upper stopband of the filter.

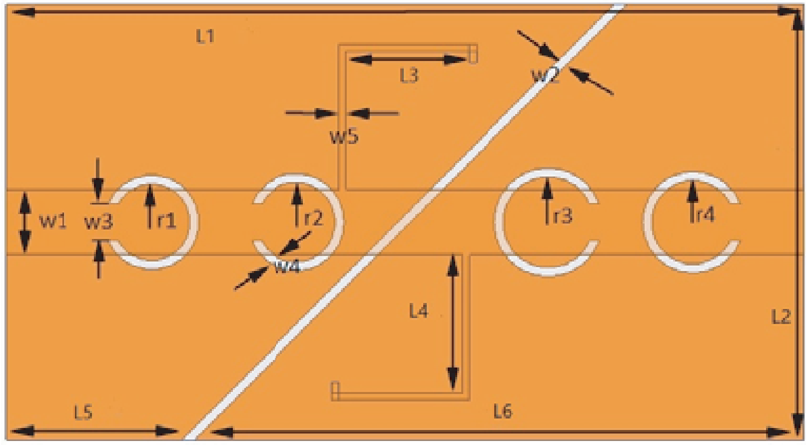


Figure 4. The layout of the proposed bandpass filter.

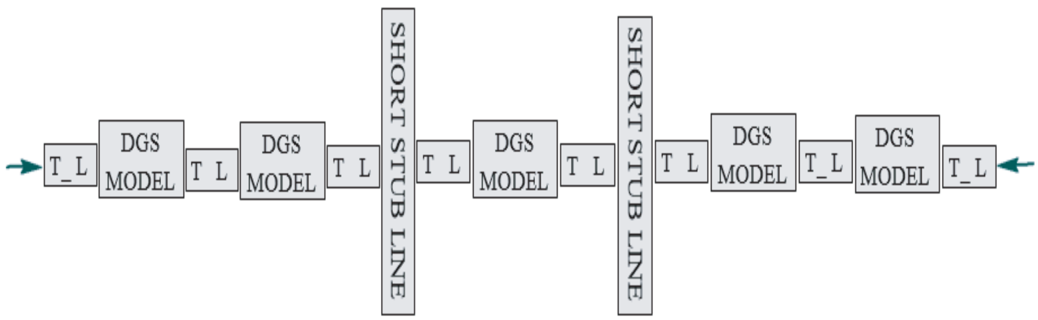


Figure 5. The band pass filter modeled by several sub components.

To compute the frequency response of the filter, each component in the layout is modeled as a block. These blocks are cascaded as shown in Fig. 5 and are connected by some 50 Ω transmission lines. The $ABCD$ matrix of each sub-component can be obtained by several methods.

It is worth noting that the dimensions of stubs and each DGS are unknown and must be obtained according to the desired overall frequency response.

The $ABCD$ matrix of the interconnecting 50 Ohms transmission line of length l is [10]

$$A = \begin{bmatrix} \cosh\left((\alpha + i\beta)\, l\right) & 50 \sinh\left((\alpha + i\beta)\, l\right) \\ \frac{1}{50} \sinh\left((\alpha + i\beta)\, l\right) & \cosh\left((\alpha + i\beta)\, l\right) \end{bmatrix} \tag{4}$$

where α and β are the attenuation and propagation constant of the transmission line, respectively.

The DGS and shorted shunt-stub are modelled as two port networks with the $ABCD$ matrices given in Eqs. (4) and (6), respectively.

$$A_1 = \begin{bmatrix} 1 & Z_{DGS} \\ 0 & 1 \end{bmatrix} \tag{5}$$

$$A_2 = \begin{bmatrix} 1 & 0 \\ Y_{stub} & 1 \end{bmatrix} \tag{6}$$

where Z_{DGS} and Y_{stub} are the equivalent series impedance of the DGS and parallel admittance of the shorted shunt stub, respectively. The corresponding expressions are given in Eqs. (7) and (8).

$$Z_{DGS} = R + \frac{1}{j\omega C} + j\omega L \tag{7}$$

$$Y_{stub} = -jY_0 \cot(\theta) \tag{8}$$

where R, C and L are the equivalent circuit parameters of the DGS. Y_0 and θ are the characteristic admittance and electrical length of the shorted stub, respectively.

The $ABCD$ matrix of the entire circuit is equal to the product of the $ABCD$ matrices of the individual sub-components. The proposed filter consists of fourteen different sub-circuits. The scattering parameters of the complete filter are computed from the elements of the overall $ABCD$ matrix using the following relations [10].

$$s_{11} = \frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D} \tag{9}$$

$$s_{12} = \frac{2\,(AD - BC)}{A + B/Z_0 + CZ_0 + D} \tag{10}$$

$$s_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D} \tag{11}$$

$$s_{22} = \frac{-A + B/Z_0 - CZ_0 + D}{A + B/Z_0 + CZ_0 + D} \tag{12}$$

4. MEASUREMENT AND SIMULATION RESULTS

The band-pass filter is synthesized from a pure all pass transmission line. The passband and out-of-band rejection of the filter are shaped by insertion of some transmission zeros. The DGSs and shorted stubs are responsible for these transmission zeros. The frequency of the transmission zeros is dependent on the passband and the desired out-of-band rejection. The transmission zeros can be deliberately distributed over the rejection band of the filter, and there is not a unique method for this type of design. The resonance frequency of each sub-circuit that comprises the band-pass filter is given in Table 1. A transmission zero is added in the frequency response of the filter due to each resonance frequency.

Table 1. The resonance frequency of each sub circuit.

Sub circuit	Resonance frequency (transmission zero)
Semi circular DGS with $R = 1.05$ mm	16 GHz
Semi circular DGS with $R = 1.1$ mm	15.3 GHz
Semi circular DGS with $R = 1.25$ mm	13.3 GHz
Semi circular DGS with $R = 1.15$ mm	14.5 GHz
Shorted stub	DC and 12.1 GHz
Cut in the ground plane	DC and 12.85 GHz

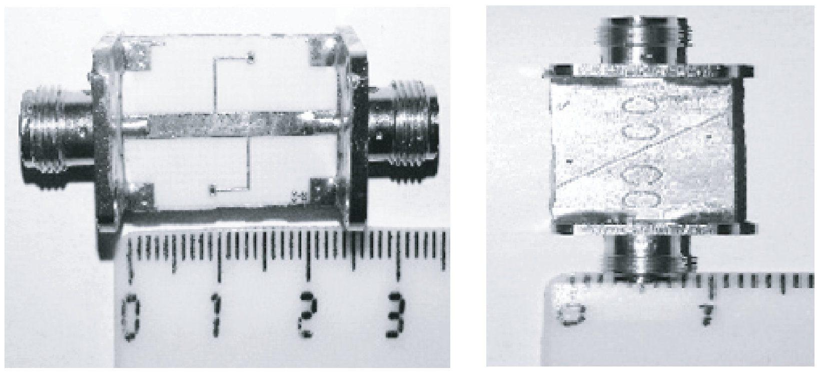
With the aid of a computer optimization in Matlab using the constraint that the passband should be within 2 GHz and 10 GHz, the unknown parameters will be determined. The unknown parameters that are determined are the characteristic impedances of the DGS and shorted stubs and the length of the interconnecting transmission lines.

Finally, a UWB band-pass filter with a passband of 8 GHz has been designed. The frequency of the transfer zeros are controlled by the DGSs. The 50 Ω transmission lines and shorted stubs help to match the input and output of each DGS to the rest of the circuit. The dimensions of the filter are listed in Table 2.

The filter was realized using an RO4003 substrate, which is a low-loss material with a dielectric constant and dielectric loss tangent of 3.38 and 0.0027, respectively. The substrate thickness is 0.032". Fig. 6 shows the top and bottom views of the fabricated UWB band-pass filter. For test purposes, two SMA connectors have been soldered to the circuit. The mounting panel of each SMA connector was soldered to the ground plane of the filter on the back side. To prevent possible cavity resonances, the filter was tested without a box. It is worth noting that a shielding box can degrade, under some circumstances, the out-of-band performance of the filter.

Table 2. The dimensions of the filter obtained by computer optimization.

W_1	W_2	W_3	W_4	W_5	L_1	L_2	L_3
1.8 mm	0.25 mm	1 mm	0.25 mm	0.2 mm	22 mm	12 mm	3.6 mm
L_4	L_5	L_6	R_1	R_2	R_3	R_4	
3.8 mm	4.8 mm	16.6 mm	1.05 mm	1.1 mm	1.25 mm	1.15 mm	



(a) (b)

Figure 6. Photograph of the proposed filter. (a) Top view. (b) Bottom view.

Figure 7 shows the measured S parameters of the wide band filter. Computer simulations using Matlab are compared with the measurements and simulation results of HFSS, which is a full wave simulator.

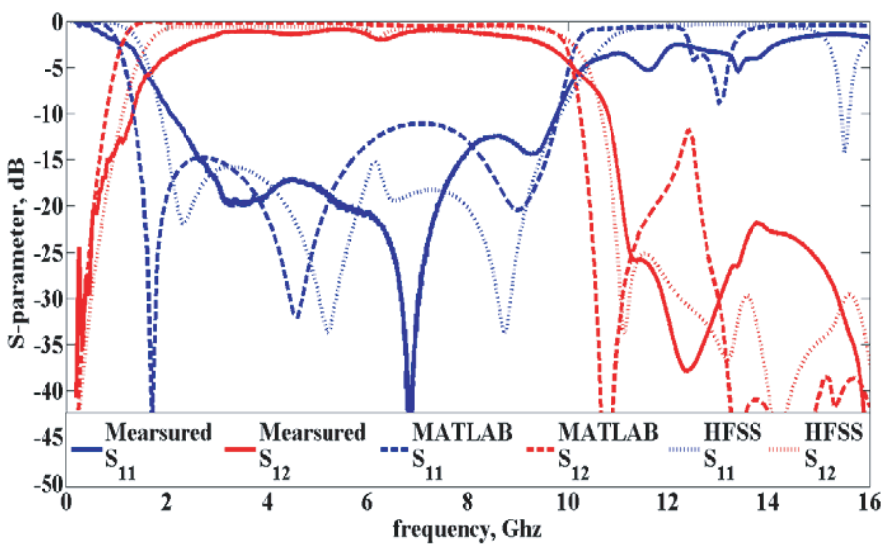


Figure 7. Measured and simulated frequency response.

The measured lower and upper cutoff frequencies of the filter are 2.27 GHz and 9.66 GHz, respectively, which are slightly different from design values. The discrepancy is due to imperfect modeling of the DGSs and the inter coupling between the DGSs. The equivalent circuit of a DGS is most accurate near the resonance frequency and loses its accuracy proportional to the distance from the resonance frequency. Furthermore, the equivalent circuit of a DGS does not account for other distributed effects as high frequency resonances and inter coupling. That is the reason for the discrepancy between the simulation and measurements in the out-of-band response.

The measured fractional bandwidth (FBW) of the filter is approximately 124% and is more than two octaves wide. In Table 3, the performances of the proposed filter and some other UWB filters are compared.

Table 3. The performance comparison of the proposed UWB filter.

Ref.	**3 dB fractional BW**	**size (mm^2)**	**Lower cutoff frequency (GHz)**	**Upper cutoff frequency (GHz)**	**Out of band rejection**
[7]	118%	16×30	2.8	11	−15 dB at 30 GHz
[11]	109%	17×37	3.1	10.6	−10 dB at 20 GHz
[12]	112%	19.4×20	3.4	10.9	−30 dB at 20 GHz
[13]	124%	34.4×55	2	4.7	−20 dB at 9.3 GHz
This work	**124%**	**12×22**	**2.27**	**9.66**	**−21.8 dB at 16 GHz**

5. CONCLUSION

In this paper a wideband, band-pass filter, with small dimensions has been introduced, which uses the response shaping properties of simple DGSs. The effect of the line bending in the shape of the defected-ground structure was investigated for three simple structures, and an empirical formula was presented that can predict the resonance frequency of the defected circular structures. The measured 3-dB fractional bandwidth is 124% compared to 146% obtained by simulation. The results obtained by measurements and simulations are in acceptable agreement. A UWB filter incorporating some DGSs can be modeled by cascaded connection of some DGSs.

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