A Compact Hairpin Filter With Stepped Hairpin Defected Ground Structure

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***Abstract*—A compact hairpin line bandpass filter is presented with two different defected ground structures (DGS). The DGS are used to reduce the distributive response of the microstrip filter. The harmonic at $2f_0$ is suppressed to below -20 dB. The filter has an insertion loss (IL) greater than -3 dB and return loss (RL) of 26 dB at the center frequency, 2.4 GHz. The designed filter has a sharp roll-off and a wide band of operation. The filter is fabricated using RO4350 substrate and measured results are compared with the simulations.**

***Index Terms*—Bandpass Filter, Defected Ground Structures, Hairpin Filter, Insertion Loss.**

I. Introduction

Filters are an essential part communication systems, measurement systems, and global positioning systems. Their purpose is to pass the wanted signals and block the unwanted ones in a given range of frequency. Due to the evolution of technology, modern communication systems have a dire need of compact components in order to further miniaturize the overall system. Miniaturization of filters have received great importance in the recent years. Along with compact size, ease of fabrication, high performance, and cost effectiveness are important parameters. Different microstrip filter designs have been used in the literature, for instance, stepped impedance filter, open stub filters, combline filters, parallel coupled resonators, hairpin resonators and inter-digital filters [1].

Researchers have tried many variation of the above mentioned filter designs and achieved good results. One of the drawback of using microstrip filters is their distributive response (spurious passbands). The even and odd modes propagate with different phase velocities, because of the inhomogeneous dielectric medium around the conductors, which in turn gives rise to these unwanted passbands. Scientists have used different techniques to reduce the effect of these spurious responses.

In order to minimize the effect of these harmonics, researchers have used various techniques. For example, authors in [2] have used defected microstrip structures for spurious response suppression. However, in this case the size of the filter is bigger than our proposed filter. In order to take care of the difference in phase velocities other techniques have also been proposed. For example, complementary split ring resonators [3], grooving the substrates [4], use of meandered lines [5], and ground plane apertures [6].

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Here, a conventional hairpin line filter DGS is proposed. The filter is designed on RO4350 substrate with dielectric constant, $\epsilon_r = 3.48$, loss tangent, tan$\delta = 0.0037$, and a height of 1.524 mm. Lumped component model is presented, followed by an initial design and the final design with DGS.

II. Filter Design

There are different types of filters that can be used to obtain our design requirements, e.g., end coupled, parallel coupled lines, and stepped impedance resonators. We are aiming for a compact design which is one of the reason hairpin design was selected for this study.

The filter design started with a fractional bandwidth (FBW), given by (1), specification of at least 25% with a center frequenyc (f_c) of 2.4 GHz. Here, f_u and f_l are the upper and lower cutoff frequency, defined by an insertion loss of less than 1 dB.

$$FBW = \frac{f_u - f_l}{f_c} \quad (1)$$

In order to start the lumped component analysis a 5th Order Chebyshev bandpass filter with 0.1 dB ripple was chosen, satisfying the following,

$$n \geq \frac{\cosh^{-1}\sqrt{\frac{10^{0.1\gamma}-1}{10^{0.1\chi}-1}}}{\cosh^{-1}\Delta_s} \quad (2)$$

where γ represents the required stop band attenuation in dB at Δ_s and χ is the required pass band ripple, i.e., 0.1 dB. For a filter with the given passband ripple the lowpass prototype parameters, given in Table I, are taken from [8],

TABLE I
ELEMENT VALUES FOR THE LOWPASS PROTOTYPE FILTER.

Elements	$g_0 = g_6$	$g_1 = g_5$	$g_2 = g_4$	g_3
Values	1	1.147	1.371	1.975

The following formulas are used to transform the lowpass prototype to a bandpass design,

$$Q_{e1} = \frac{g_0 g_1}{FBW}, \quad Q_{en} = \frac{g_n g_{n+1}}{FBW}, \tag{3}$$

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad \text{for} \quad i = 1, 2 \ldots n-1 \tag{4}$$

The external quality factor at the input and output resonators is given by Q_{e1} and Q_{en}, respectively, and the coupling coefficients of adjacent resonators are given by $M_{i,i+1}$. Our initial design started with lumped element model. Figures 1 and 2, respectively, show transformed and scaled circuit and simulation result. Lumped model is a good starting point

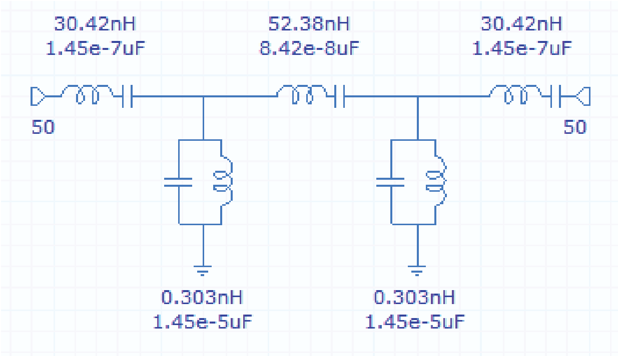

Fig. 1. Lumped element design for the Chebyshev 5^{th} order bandpass filter.

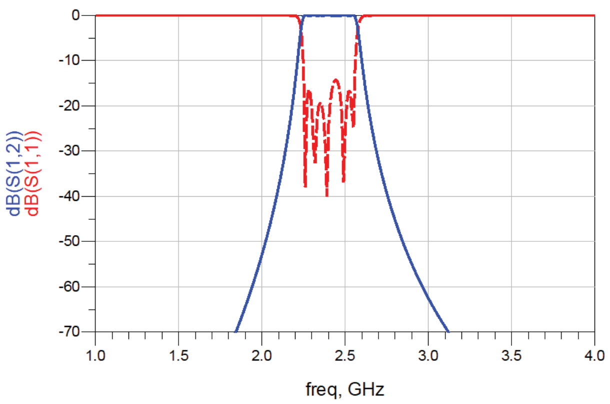

Fig. 2. S-parameters for the Lumped element design.

in order to analyze the filter response. However, this can be completely different from the microstrip design which has a distributive nature.

After the lumped element design the bandpass filter was designed in microstrip technology. The conventional hairpin

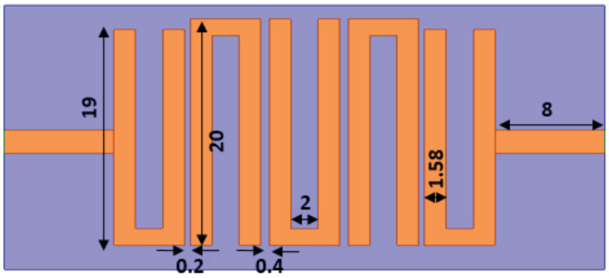

Fig. 3. Top view of the initial filter design along with the dimensions in mm.

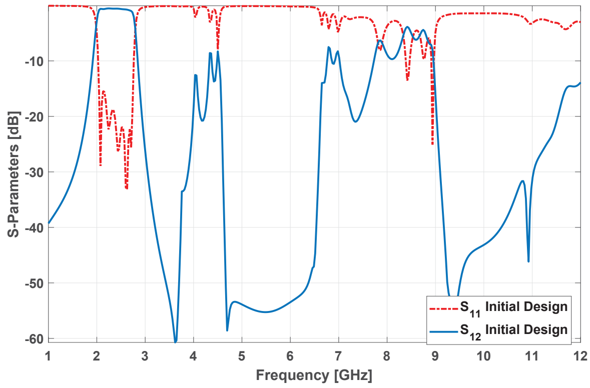

Fig. 4. S-parameters of the initial design shown in Fig. 3.

design was used to start the design. It is compact in size, simple to design and easier to fabricate. The design process starts from the parallel coupled line design equations which is then modified to get the hairpin design by bending the $\lambda/2$ resonator into $\lambda/4$ arms to form a U-shape [9]. An available electromagnetic (EM) simulator was used to perform a full three dimensional EM simulation of the initial design, shown in Fig. 3.

Figure 4 shows the reflection S_{11} and insertion loss S_{12} of the initial design. The return loss is better than -15 dB and the insertion loss is better than -1 dB in the desired band. However, the harmonics are showing up due to the distributive nature of the microstrip filter design. These harmonics need to be suppressed in order to obtain the desired filter response. The second harmonic in the range of $2f_0$ can cause interference with the system performance because it is the closest to the working band. In order to get rid of the harmonics DGS have been used.

III. EXPERIMENT AND MEASUREMENTS

A. Defected Ground Structures

As the name suggests, DGS is a defect, usually in the ground plane, in order to change the current distribution on the ground plane of an antenna or filter. The structure is etched on the ground plane which causes a change in the capacitance and inductance [10]. Various shapes can be used as DGS, e.g., dumbbells, split rings, meandered lines, and different shaped symbols. Changes in the length and width of the narrow slot

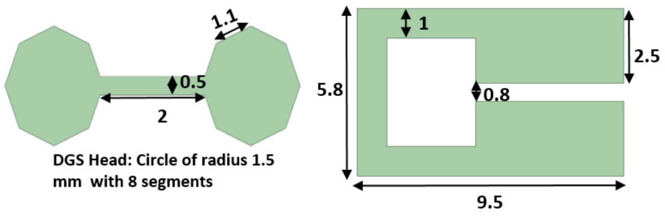

Fig. 5. Two different DGS with dimensions in millimeters. (*Left*) resonating at high frequency, (*right*) at low frequency.

varies the capacitance and variations in the wide slot allows to control the inductance, in case of a dumbbell DGS.

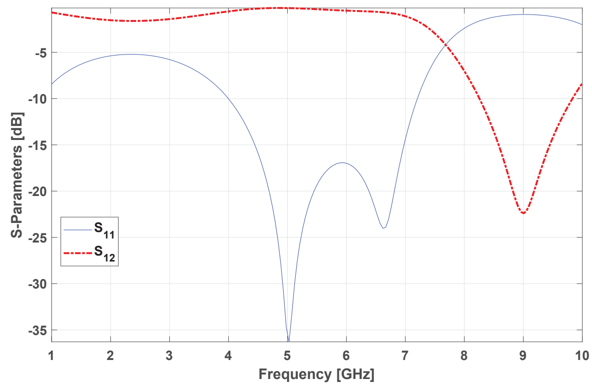

Fig. 6. S-parameters for the dumbbell shaped DGS to generate a null at 9 GHz.

In this design two different DGS structures resonating at different frequencies have been used to suppress the harmonics. The geometry of the dumbbell (left) shaped and stepped hairpin resonator (SHPR) (right) is shown in Fig. 5 and the results are shown in Figs. 6 and 7, respectively. The dumbbell

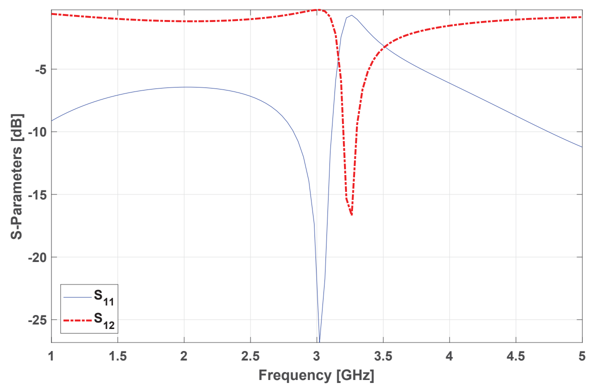

Fig. 7. S-parameters for the SHPR DGS to generate a notch at 3.25 GHz.

DGS is used to suppress the harmonics around 9 GHz while the SHPR suppresses the $2f_0$. By changing the lengths and widths of the DGS, the resonant frequency can be shifted to achieve the desired response. It should be noted that the reflection coefficient is sensitive to the placement of the DGS, which can cause the bandwidth, insertion loss, and the ripple in the passband to vary. In this study the DGS were placed such that the response in the passband is acceptable.

B. Proposed Design With DGS

The initial design of Fig. 3 was altered by placing the DGS on the ground plane. These structures cause the current flow on the ground plane to change, which in turn changes the response of the filter. The top and bottom sides of the proposed filter are shown in Fig. 8. The arm lengths of the resonators have changed in order to compensate for the current changes caused by the DGS on the ground plane. The overall size of the designed filter is 4.9×2.5 cm^2. Figures 9 and 10

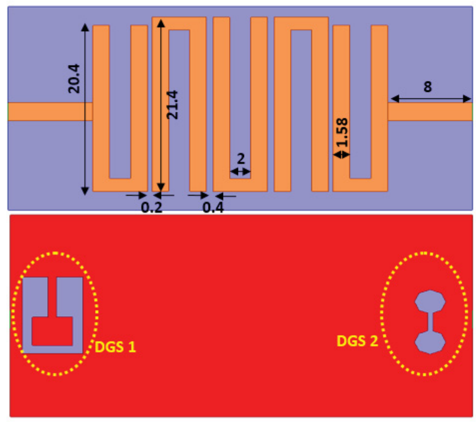

Fig. 8. Final filter design. (*Top*) filter with the dimensions in millimeters, (*bottom*) ground plane with two DGS.

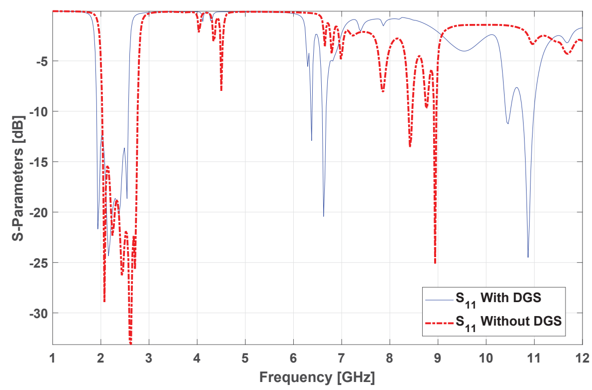

Fig. 9. Simulated return loss of the proposed filter shown in Fig. 8.

show the comparison of the S_{11} and S_{12}, respectively, of the proposed filter design. It can be seen that spurious passbands have been suppressed due to the effect of the DGS. The altered ground plane has also caused a shift in the response of the filter which is acceptable for this research work. However this can be optimized by varying the arm lengths of the resonators and

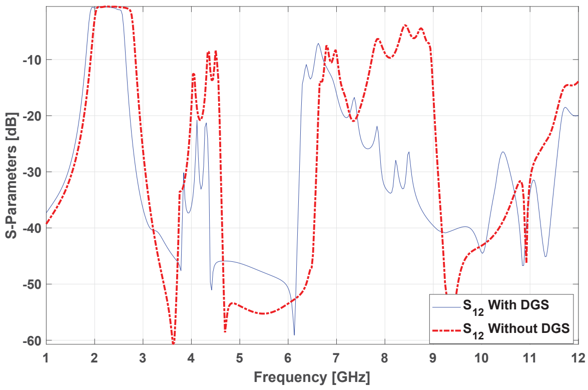

Fig. 10. Simulated insertion loss of the proposed filter shown in Fig. 8.

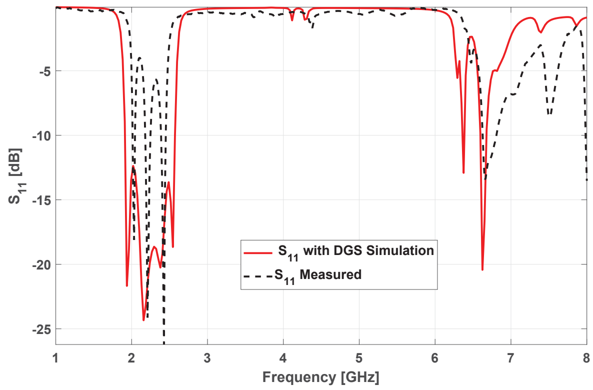

Fig. 12. Measured and simulated return loss of the proposed filter.

changing the placement of the DGS. If further suppression of other frequencies is required, a DGS at that specific frequency can be added on the ground plane.

C. Measured Results

After a round of simulations the design was fabricated using LPKF ProtoMat D104 milling machine. The top and bottom views of the design are shown in Fig. 11. The results were

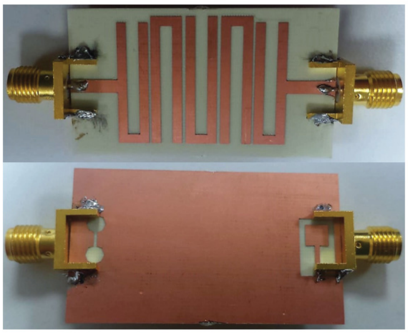

Fig. 11. Top and bottom view of the fabricated design.

measured using Rhode & Schwarz's vector network analyzer and are shown in Figs. 12 and 13. Measured results do not show a good agreement with the simulated results but follows the pattern. However, the simulations were verified in multiple EM simulators, which showed good agreement. The disagreement between the measured and simulated results can be explained by the improper grounding of the circuit. Another reason is that the DGS are close to the edges of the board. The SMA connectors, when connected, were close to the DGS and their effect was not included in the EM simulations. These are the potential reasons for the discrepancy.

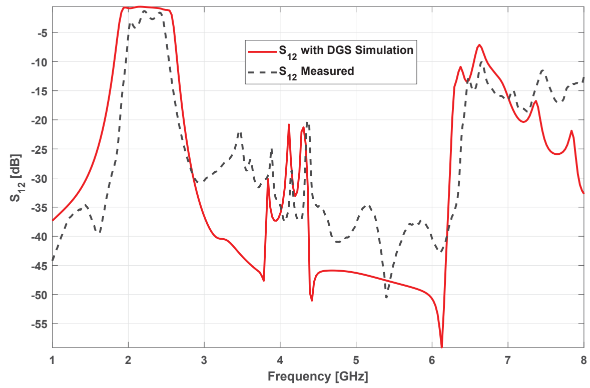

Fig. 13. Measured and simulated insertion loss of the proposed filter.

IV. Conclusion

The aim of this work was to come up with a compact microstrip hairpin line filter design using defected ground structures. The DGS are used to suppress the spurious passbands. The size of the designed filter is 4.9×2.5 cm^2 which is compact for this frequency band. This work can be used as a good reference for compact hairpin filters from 2.0–2.7 GHz, with a fractional bandwidth of 29%. In the recent studies, researchers are emphasizing on altering the resonator shapes to achieve further compactness, which is our next aim along with using improved DGS. This will help in achieving further compactness in size and better suppression of the harmonics.

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