DESIGN OF CASCADED THREE-CONDUCTOR COUPLED LINE FILTER

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ABSTRACT: *This article presents analysis approach and applications of symmetrical three-conductor coupled microstriplines with aperture in the ground plane for the design of microwave filters. Analysis is based on splitting the entire symmetrical three-conductor coupled line structure into simple two-conductor coupled lines. Various possible terminations have been shown in three-conductor coupled lines to derive a class of structures for the construction of filters. These coupled line structures are analyzed based on even- and odd-mode propagation characteristics to design filters in this article. An experimental cascaded three-conductor coupled line band stop filter with defected ground has been designed using the method of circuit model analysis. Defected ground has been used under the coupled lines to widen the filter's bandwidth. Measured results of the designed band stop filter have been compared against the circuit model analysis for the purpose of validation. Results are in good agreement between them.* Microwave Opt Technol Lett 56:2431–2436, 2014; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28615

Key words: *band stop; coupled line; defected ground; filter; three conductor*

1. INTRODUCTION

Coupled lines play an important role in the construction filters and couplers for microwave and millimeter wave systems. Filters are the key components in the front end of any communication links. Filters are essential part in the design of amplifiers, mixers, and antennas. Recent research focuses on investigation and analysis of various filter topologies for the requirement of various communication systems such as radars, radios, and commercial wireless links. Although conventional two-conductor parallel coupled lines shown in Figure 1 are widely used in the design of filters, it has few variant structures for the design of filters. Although this structure is easy to synthesis, it offers narrow band response in filters.

Modern wireless communication is continuously demanding for new filter structures to meet circuit miniaturization and cost reduction without the compromise in the performance. Hence, this article focuses on forming a class of coupled lines using three line structures for the design of filters. Such three line structure with aperture in the ground plane shown in Figure 2 offers tight coupling for the design of filters.

There are several approaches reported in literature to analyze coupled lines. Analytical modeling of multiconductor transmission lines is reported in Ref. [1]. In Ref. [2], normalized impedance matrix is used to solve the coupled line problems. Spectral domain approach, Fourier transforms approach, variational techniques, and integral equation method are some of the other methods for analyzing coupled lines [3–6]. This article uses the quasi-TEM approach for the analysis and design of three-conductor symmetrical coupled lines. The three-conductor coupled line structure is split into simple two-conductor coupled lines for the purpose of easy analysis. Different terminations are applied at the open end of coupled lines for the construction of filters. Section 2 reports the analysis procedure of three-conductor coupled lines with defected ground structure (DGS). Various filter structure formed using different terminations are reported in Section 2. Section 3 demonstrates a new design of band stop filter constructed using three-conductor cascaded coupled lines with DGS. Analytical calculations are performed based on the circuit models of each coupled line section for the computation of overall scattering parameters. Experimental results are presented along with circuit model simulation in Section 4. Section 5 concludes this present article.

Figure 1 Two-conductor coupled line section

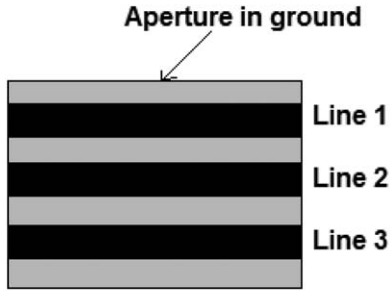

Figure 2 Three-conductor coupled line with aperture in the ground plane

2. CLASS OF THREE-CONDUCTOR COUPLED LINES

The three-conductor coupled microstrip line structure shown in Figure 3 is symmetrical and hence perfect magnetic conductor can be used at the center of the structure for the analysis. Now the resultant structure is asymmetrical coupled line section. This can be analyzed using the analysis of asymmetrical coupled lines explained in the literature [7]. The effect of slot in the ground plane is taken into the account using effective height h_{eff} (effective substrate thickness) in the place of h (substrate thickness) in the analysis of asymmetrical coupled lines [7] as explained in Refs. [8] and [9].

Various coupling arrangements for filter response obtained from a pair of three symmetrical coupled transmission lines by placing open circuit, short circuit, and loading stubs on terminal pairs are shown in Figure 4. Z_{i1} is the image impedance and θ is the length of coupled line section. Figure 4(a) is a band stop element which has input and output ports in the middle conductor. The other ends of lines in the input side are short circuited and other ends in the output side are open circuited. Band stop structure shown in Figure 4(b) is also a band stop element same as the one shown in Figure 4(a), but terminations are swapped at the port sides. These two structures offer band stop characteristics as shown in Figure 5(a). The physical dimensions of the

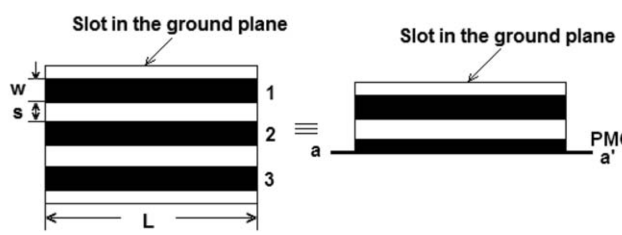

Figure 3 Analysis of three-conductor coupled line section

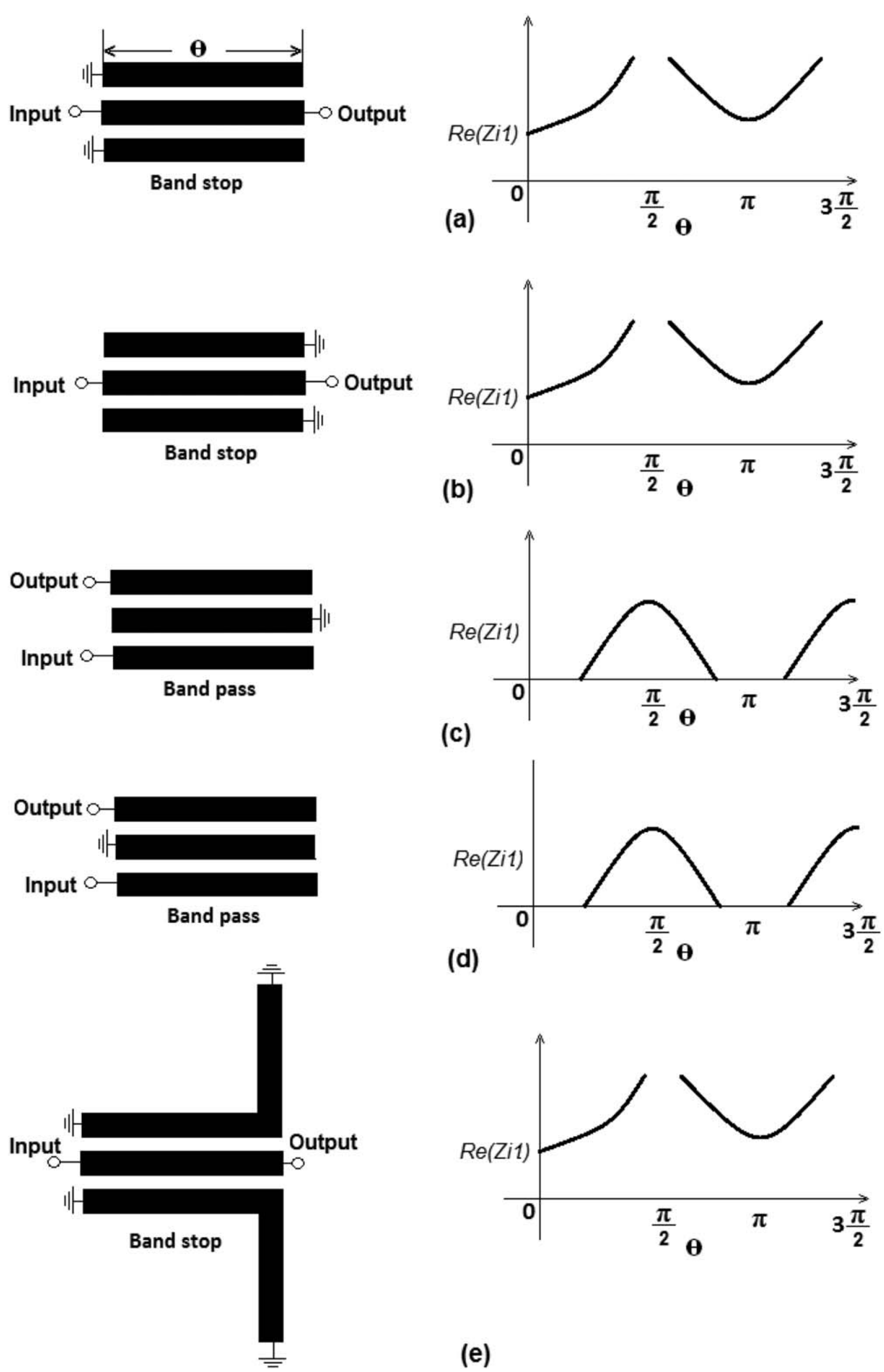

Figure 4 Various coupling arrangement of filter elements

coupled lines used for the purpose analysis are listed in Table 1 and the filter elements are analyzed at 3 GHz.

Figure 4(c) is a band pass element formed using three-conductor coupled lines and the end of the middle resonator is short circuited. As illustrated in Figure 5(b), this structure offers wide band response characteristics. Narrow band pass element having middle resonator short circuited at the input/output side of the circuit is shown in Figure 4(d). The response is shown in Figure 5(c). This structure can be used where very loose coupling is required in the design. Band stop structure constructed using additional short circuited stubs is illustrated in Figure 4(e). This structure offers band rejection characteristics as depicted in Figure 5(d).

3. DESIGN OF CASCADED THREE-CONDUCTOR BAND STOP FILTER

Various coupled line arrangements for band stop response obtained from a pair of two and three symmetrical coupled

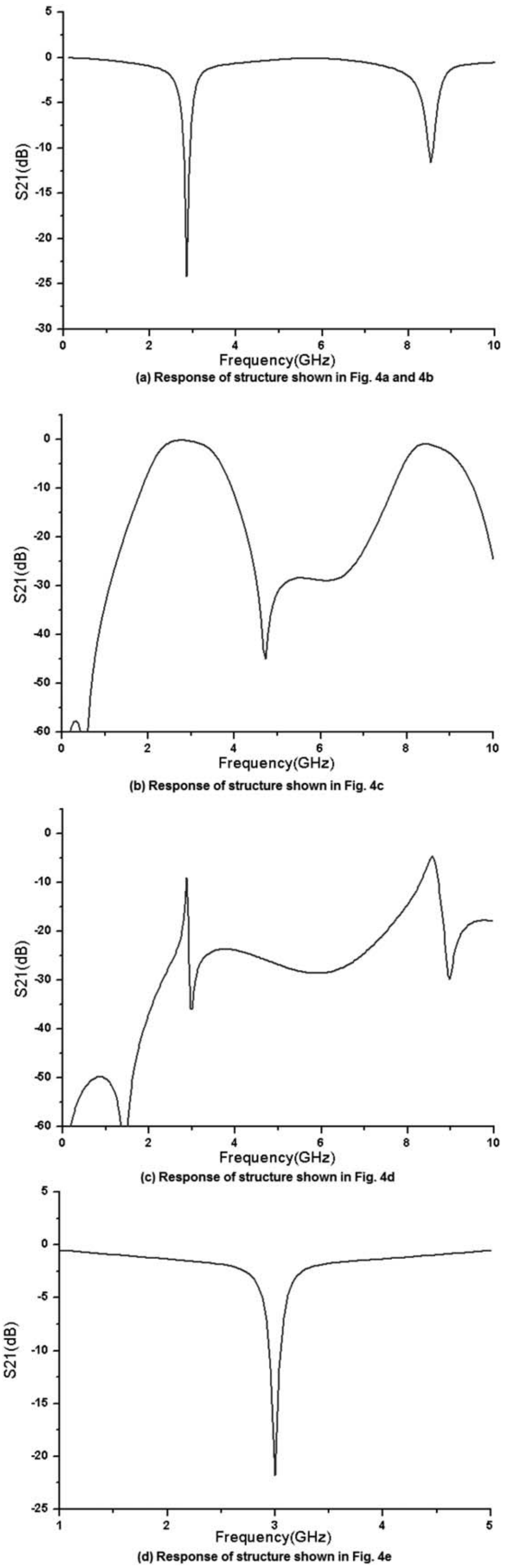

Figure 5 Response of various filter structures

transmission lines by placing short circuit stubs on terminal pairs are shown in Figure 6. Figure 6(a) is a popular band stop element configuration. This offers less rejection and narrow bandwidth. A proposed three-conductor coupled line band stop filter which offers better rejection than two-conductor coupled lines along with stubs is shown in Figure 6(b) [Fig. 4(e)]. Figure

TABLE 1 Coupled Line Parameters

Coupled line width, w (mm)	1
Coupled line spacing, s (mm)	0.2
Coupled line length, L (mm)	18.9
Substrate thickness, h (mm)	0.78
Substrate permittivity, εr	2.17

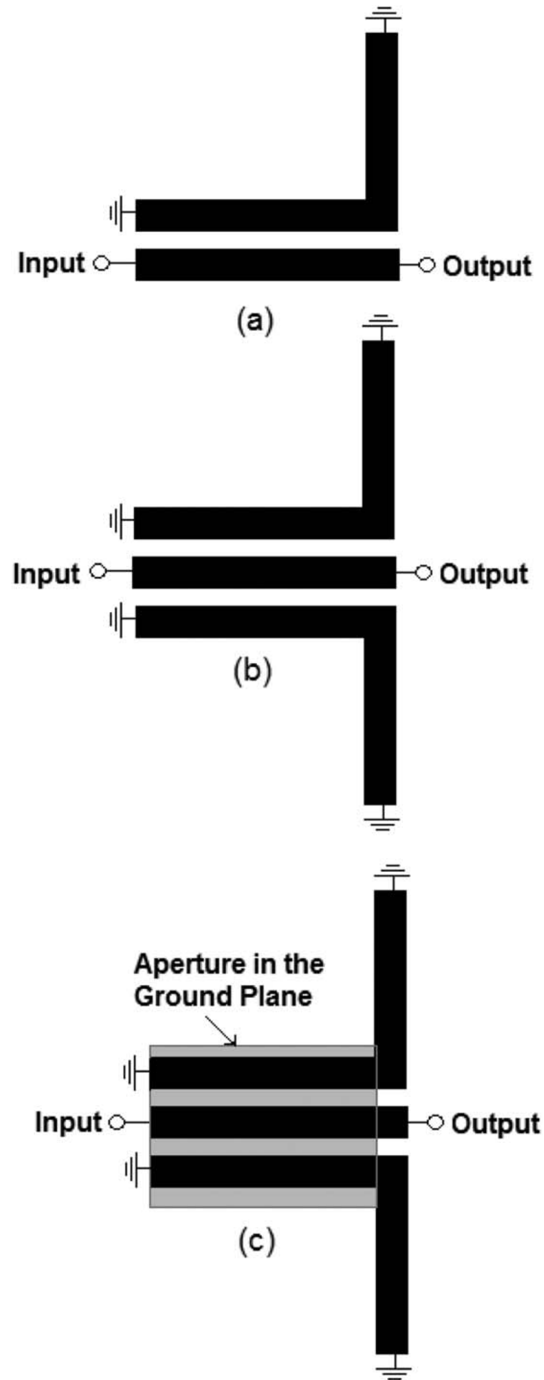

Figure 6 Various configurations of band stop filter (BSF) elements. (a) Conventional two-conductor coupled line BSF element, (b) proposed three-conductor coupled line BSF element, and (C) proposed three-conductor coupled line BSF element with aperture in the ground plane

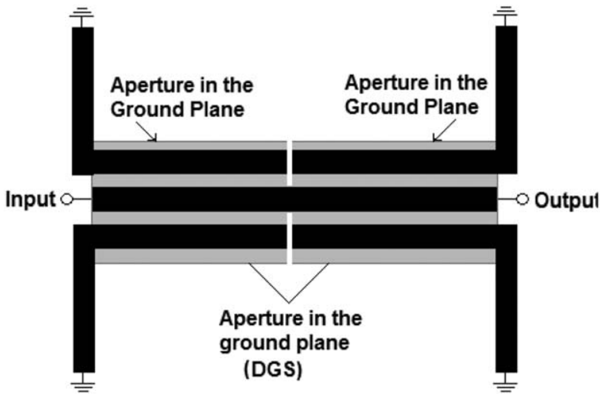

Figure 7 Analysis procedure of proposed band stop filter

6(c) is a modified version of band stop filter shown in Figure 6(b). Additionally, apertures are incorporated in the ground plane of the filter. This novel structure offers wide bandwidth than that of structure shown in Figures 6(a) and 6(b).

3.1. Circuit Analysis

The band stop filter is designed at 3 GHz in microstrip medium. Analysis of the entire band stop filter is based on splitting it into simple loaded two-conductor coupled line sections and analyzing each section. Figures 7 and 8 show such analysis procedure. Even- and odd-mode characteristic impedances and phase velocities are calculated using the expressions given in Refs. [7–9] and are used for the analysis of the coupled line sections shown in Figure 8.

Impedance matrix (Z) of each two line asymmetrical coupled line with aperture in the ground plane is calculated using the even- and odd-mode characteristic impedances and phase velocities. The 4 × 4 impedance matrix of the two-conductor coupled line is calculated using (1–4).

$$Z_{11}=Z_{22}=Z_{33}=Z_{44}=-j0.5(Z_{oe}\cot\theta_e+Z_{oo}\cot\theta_o) \quad (1)$$

$$Z_{12}=Z_{21}=Z_{34}=Z_{43}=-j0.5(Z_{oe}\cot\theta_e-Z_{oo}\cot\theta_o) \quad (2)$$

$$Z_{13}=Z_{31}=Z_{24}=Z_{42}=-j0.5(Z_{oe}\operatorname{cosec}\theta_e-Z_{oo}\operatorname{cosec}\theta_o) \quad (3)$$

$$Z_{14}=Z_{41}=Z_{23}=Z_{32}=-j0.5(Z_{oe}\operatorname{cosec}\theta_e+Z_{oo}\operatorname{cosec}\theta_o) \quad (4)$$

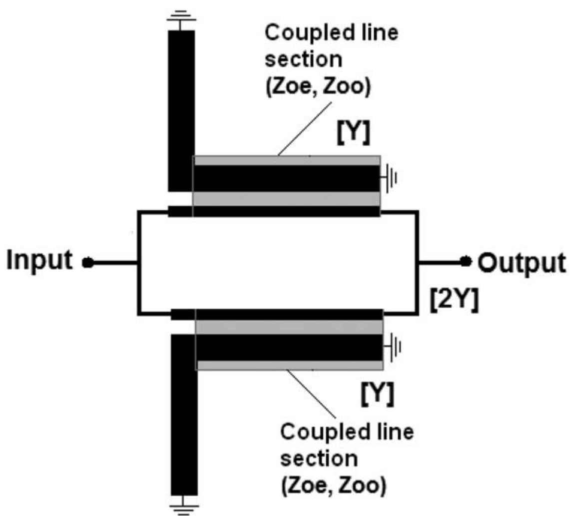

Figure 8 Different sections of the filter

TABLE 2 Coupled Line parameters

Coupled line width, w (mm)	0.5
Coupled line spacing, s (mm)	0.2
Coupled line length, L (mm)	18.9
Aperture dimensions, L, Wa (mm)	18.9, 2.5
Loaded stub length, L (mm)	18.9
Substrate thickness, h (mm)	0.78
Substrate permittivity, εr	2.17

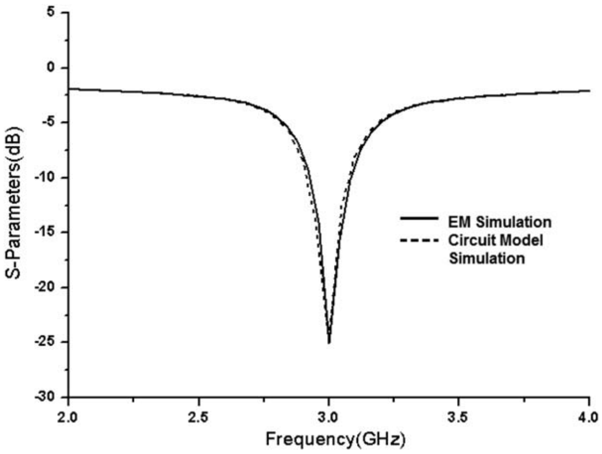

Figure 9 Analytical response of proposed BSF element along with EM simulation

Z_{oe} and Z_{oe} are the even-mode impedance and odd mode impedance of the asymmetrical two-conductor coupled line, respectively. The above impedance matrix is reduced to 2 × 2 impedance matrix after applying the terminations (open) and loading (half wavelength short circuited line) at the ports. The overall admittance matrix ($2Y$) is calculated using the admittance matrix Z. The overall admittance matrix is converted into final scattering parameters. The response characteristics of the band stop filter designed are derived from the final scattering parameters. The values of the even- and the odd-mode characteristic impedances (Z_{oe} and Z_{oo}) are 230 and 112 Ω, respectively. θ_e and θ_o are calculated based on physical length of coupled lines. Design parameters of the filter are listed in Table 2. A comparison is made between the analytical results (calculated in MATLAB) using the procedure explained above and

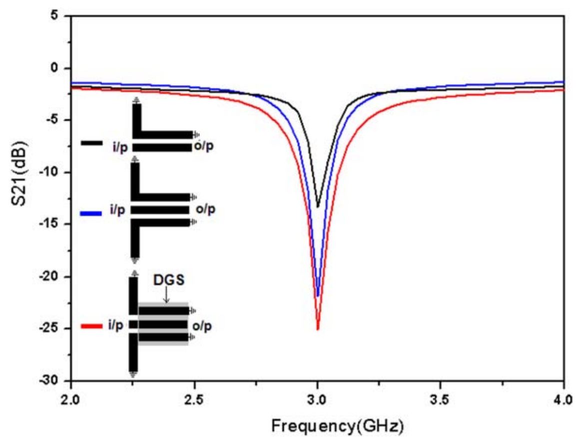

Figure 10 Response of various BSF elements. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

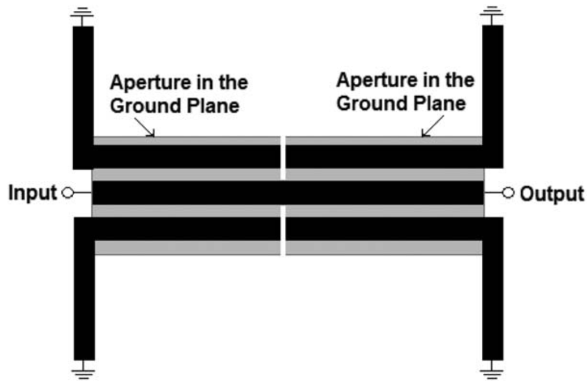

Figure 11 Proposed cascaded BSF

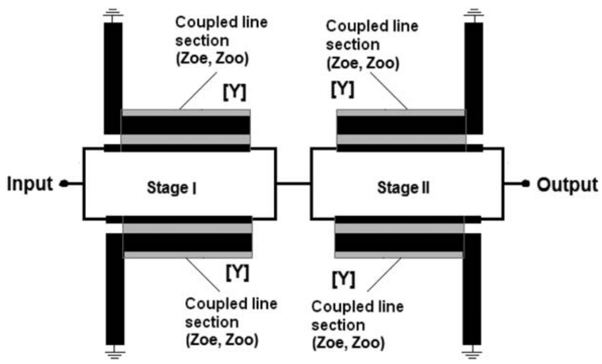

Figure 12 Different sections of the filter in the analysis of filter

fullwave simulations obtained using IE3D simulator from Mentor graphics [10]. As shown in Figure 9, a close agreement between them can be observed. The third harmonic of the fundamental band stop frequency appears at 9 GHz.

Analytical response of various BSF elements is shown in Figure 10. The BSF (band stop filter) element shown in Figure 6(a) offers 10 dB bandwidth of 2.3% and maximum rejection of 12 dB, whereas the proposed structure shown in Figure 6(b) yields 3.3% bandwidth and 23 dB rejection. The BSF element shown in Figure 6(c) offers 5.4% bandwidth which is approximately twice the bandwidth of two-conductor coupled line BSF [Fig. 6(a)].

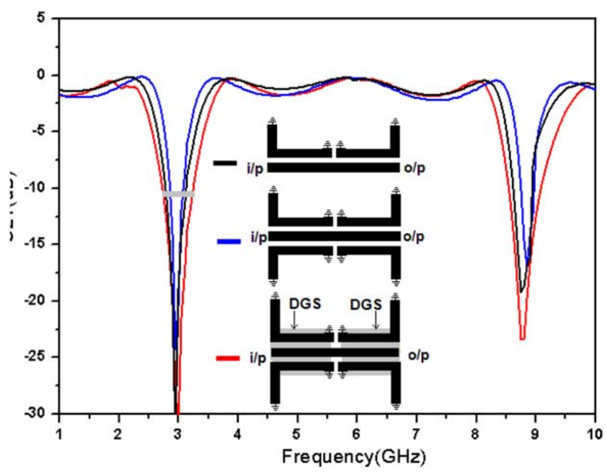

Figure 13 Circuit model simulation of proposed BSF with aperture in the ground plane along with other BSF. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

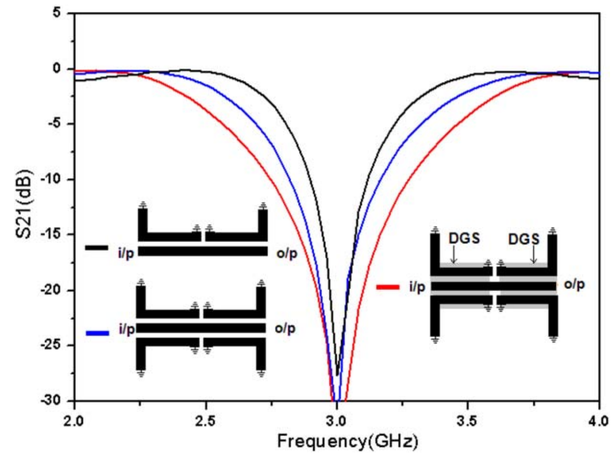

Figure 14 Inband response of proposed BSFs. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Two stages of three-conductor coupled lines with aperture in the ground plane are cascaded for the design of BSF as shown in Figure 11 to widen the bandwidth and to achieve better rejection. Various sections of the filter under analysis are shown in Figure 12. The transmission matrices of the stage I ($[ABCD]_{I}$) and stage II ($[ABCD]_{II}$) are derived from the admittance matrix of each stage. Then, overall transmission matrix ($[ABCD]_{T}$) can be given by (5).

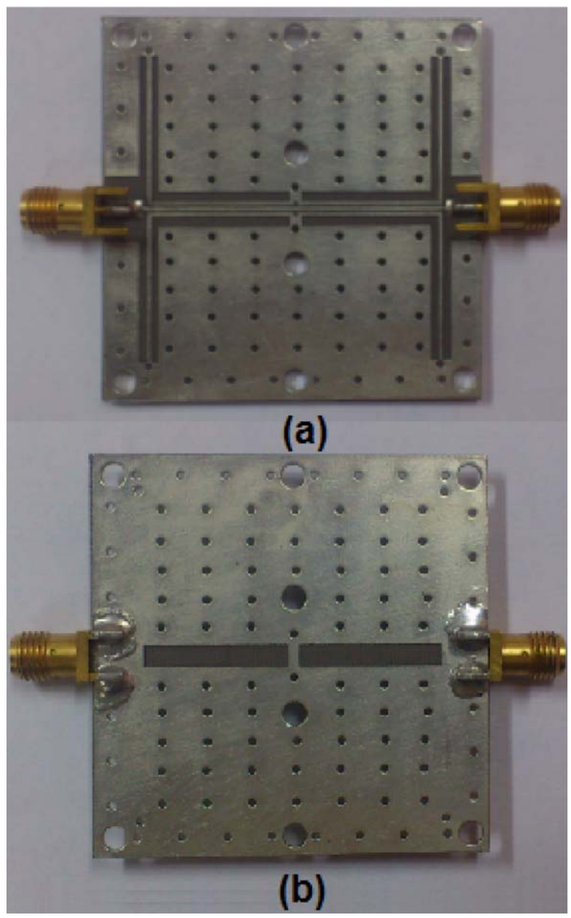

Figure 15 Band stop filter. (a) Top layer and (b) bottom layer. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

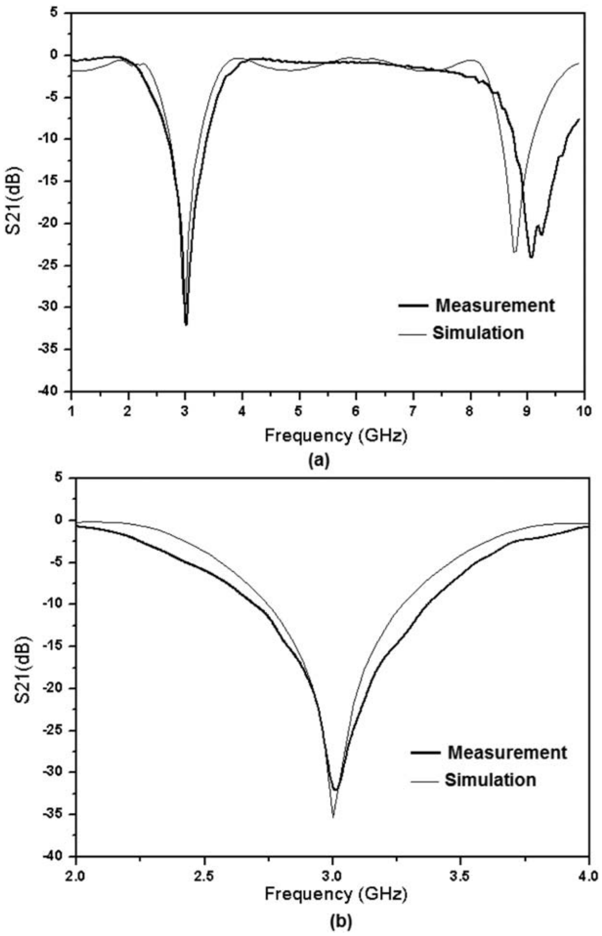

Figure 16 (a) Measured results of proposed BSF and (b) inband performance

$$[ABCD]_T = [ABCD]_I [ABCD]_{II} \quad (5)$$

Reflection and transmission parameters are extracted from the overall transmission matrix ($[ABCD]_T$). The calculated response (using MATLAB) of this structure is depicted in Figure 13.

The BSF offers 18% bandwidth (10 dB level), whereas the bandwidth of BSF without aperture in the ground plane is 12%. The bandwidth of the two-conductor coupled line BSF is 7%. It is understood that the three-conductor coupled line BSF with aperture in the ground plane offers more bandwidth (18%) than that of two-conductor coupled line BSF (7%). Figure 14 shows the inband response of the band stop filters.

4. EXPERIMENTAL DEMONSTRATION

Figure 15 shows the experimental band stop filter. The input and output feed lines are designed with line impedance of 50 Ω. Dimensions of the filter are $45 \times 40 \times 0.78$ mm^3. The filter is tested and measured using vector network analyzer. Figure 16 shows the measured results along with circuit model simulations. As shown in Figure 16, the measured stop band frequency of the filter is 2.73–3.31 GHz (19.2% bandwidth). The experimental results are satisfactorily matching with the analytical simulations (circuit model analysis) performed in MATLAB and this conforms the validity of the analysis.

5. CONCLUSIONS

This article presented a class of three-conductor coupled line based band pass and band stop elements for the construction of filter. Various coupling mechanisms with different terminations were used for the design of filter. These coupled lines can be used in numerous applications such as amplifiers, couplers, and matching circuits. Based on three-conductor coupled lines, a band stop filter has been designed in defected ground microstrip configurations. Defected ground plane (aperture in the ground plane) was used to widen the bandwidth of the filter. Analytical calculations based on even- and odd-mode propagation characteristics of coupled lines were performed to find out the response of the proposed band stop filter. An experimental filter has been developed to validate the design and analysis. Measured results are satisfactorily matching with analytical simulation and EM simulation.

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EXPERIMENTAL VERIFICATION 3D SUB-WAVELENGTH RESOLUTION BEYOND THE DIFFRACTION LIMIT WITH ZONE PLATE IN MILLIMETER WAVE

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ABSTRACT: *The results of experimental investigations of resolution power of millimeter-wave phase reversal binary Fresnel zone plate with short focal distance $F \leq 2\lambda$ are described. It has been experimentally shown that in the near-field of single diffractive lens with subwavelength focal distance $F \leq \lambda$ without the immersion medium a resolution of 0.3–*