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ANALYSIS AND DESIGN OF A COMPACT MULTI-LAYER ULTRA WIDE BAND FILTER

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Abstract—This paper presents analysis and design of a compact ultra wide band (UWB) filter using three parallel folded coupled lines in a defected ground structure in multi-layer structure. Defected ground has been incorporated under the coupled lines of the filter to improve the coupling over a wide bandwidth. The closed form expressions for even and odd mode impedances for the coupled lines with defected ground have been obtained to design a filter of desired bandwidth with the proposed structure. Based on circuit models, an UWB filter for 3.1–10.6 GHz has been analyzed and the results have been compared using full wave simulations. Analytical results are satisfactorily matching with simulations. Filter exhibits a constant group delay of $\pm\,0.08$ ns in the pass band. Size of the filter is $6.2\,\mathrm{mm} \times 3.4\,\mathrm{mm} \times 2.8\,\mathrm{mm}$.

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1. INTRODUCTION

Ultra wide band technology is gaining a lot of attention in applications such as medical imaging, through wall imaging and vehicular radar, etc due to its low power and high data rate features. Various topologies of band pass filters with specified pass bands are therefore required to progress in UWB technology. Filters used in UWB systems need to operate over a wide instantaneous bandwidth of 3.1–10.6 GHz with a constant group delay. Extensive work has been carried out to achieve wide band characteristics in the filter performance. A compact wide band filter has been designed based on impedance steps and coupled line sections [1]. Ground plane metallization is removed in these filters to achieve wide band response. Resonators based on slotted ground structures are used in [2] to design compact broad band dual band pass filters. This filter features compact size and frequency selective characteristics with adjustable lower and upper resonance frequencies by changing the size of the resonators. Ultra wide band filter based on quarter wavelength short circuited stubs has also been demonstrated [3]. This has minimal number of vias and improved frequency bandwidth. In [4], wide band and compact band stop filters using one dimensional mushroom like electromagnetic band gap (EBG) are proposed and only fewer EBG cells are used to achieve the desired filter response. The filter is compact with no backward radiation.

Wide band filters using metallization on both sides of suspended stripline substrate are realized in [5]. The required tight coupling is achieved due to increased coupling between lines of different metallization layers and hence wide band response is achieved. Dual mode ring resonator with stepped impedance open circuited stubs is used to design ultra wide band filter in [6]. Stepped impedances are used to excite band stop response for achieving good rejection characteristics. Circular shaped ring resonator with stepped impedances and open circuit stub is used to implement UWB filter in [7]. Attenuation poles are controlled using stub and ring impedances. A quadruple-mode UWB filter with sharp out-of-band rejection is reported in [8]. Short circuited stubs are introduced in the resonator to achieve transmission zeroes near the lower and upper cut-off frequencies of the filter to improve the rejection characteristics.

Besides wide band operation, modern wireless systems need compact and high performance circuits for miniaturization. Multi-layer structure such as low temperature co-fired ceramic (LTCC) is the potential technology [9–11] for designing miniaturized circuits in multi-layered ceramic. Multi-layer approach to design miniaturized passive components such as filters, couplers and baluns have been widely used.

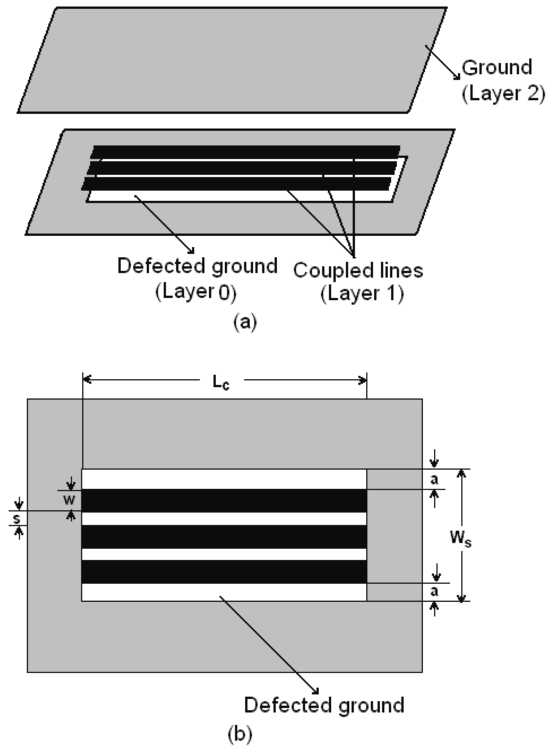


Figure 1. Basic band pass element.

In this paper, a set of three coupled lines shown in Fig. 1(a) having dimensions shown in Fig. 1(b) has been proposed as the basic band pass element to construct a compact UWB filter in multi-layer structure. Ultra wide band response characteristics are achieved using enhanced coupling between the lines in the defected ground. Analysis of this band pass element is explained in Section 2 and closed form expressions for even and odd mode impedances of coupled lines are given for the design of UWB filter. In Section 3, filter is analyzed based on circuit models and analytical results of UWB filter are compared against full wave simulation results for the validation. Section 4 concludes this paper.

2. ANALYSIS OF BAND PASS ELEMENT

Bands pass element shown Fig. 1 is formed using three uniform parallel coupled lines. Even and odd mode parameters for the three parallel

Figure 2. Cross section of layers.

coupled line section are extracted from IE3D [11] for the purpose of circuit analysis. Geometrical parameters given in Table 1 are used for the design of UWB filter. Cross section of layers of device is shown in Fig. 2. Layers 0 and 2 are ground conductors. Coupled lines are in layer 1. Layer 0 has defected ground to improve the coupling over wide bandwidth. Coupled line model given in [12] is used to synthesize coupled lines for the desired filter characteristics. Coupled lines are quarter wave long at the center frequency of the filter (6.85 GHz). Coupled line sections are characterized using $ABCD$ parameters, which are given by [12]

$$A = D = \frac{Z_{oe}\cot\theta_e + Z_{oo}\cot\theta_o}{Z_1} \tag{1}$$

$$B = \frac{j}{2}\frac{Z_{oe}^2 + Z_{oo}^2 - 2Z_{oe}Z_{oo}(\cot\theta_e\cot\theta_o + \csc\theta_e\csc\theta_o)}{Z_1} \tag{2}$$

$$C = \frac{2j}{Z_1} \tag{3}$$

where $Z_1 = Z_{oe}\csc\theta_e + Z_{oo}\csc\theta_o$ and Z_{oe} and Z_{oo} are even and odd mode impedances of coupled line section respectively. Using differential (positive and negative ports) and common mode (positive ports) excitation features of IE3D [13], even and odd mode impedances of the three parallel coupled line section were extracted and used to

Table 1. Geometrical parameters of band pass element.

Substrate thickness 'h_1' and 'h_2' ($b = h_1 + h_2$)	1000 µm, 200 µm
Substrate permittivity 'ε_r'	5.99
Conductor thickness	10 µm
Number of layers	3

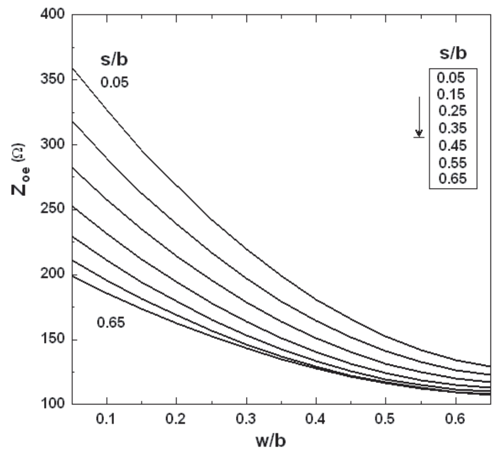


Figure 3. Even mode impedances.

obtain curve-fit expressions as

$$Z_{oe} = 420 - 787\frac{w}{b} + 528\left(\frac{w}{b}\right)^2 - 522.2\frac{s}{b}1017.56\left(\frac{w}{b}\right)\left(\frac{s}{b}\right) - 505.18\left(\frac{w}{b}\right)^2\left(\frac{s}{b}\right) + 312.7\left(\frac{s}{b}\right)^2 - 397.7\left(\frac{w}{b}\right)\left(\frac{s}{b}\right)^2 \quad (4)$$

$$Z_{oo} = 57.18 - 104.54\frac{w}{b} + 79.9\left(\frac{w}{b}\right)^2 + 154.9\frac{s}{b} - 108.27\left(\frac{w}{b}\right)\left(\frac{s}{b}\right) + 36.75\left(\frac{w}{b}\right)^2\left(\frac{s}{b}\right) - 62.45\left(\frac{s}{b}\right)^2 + 13.82\left(\frac{w}{b}\right)\left(\frac{s}{b}\right)^2 \quad (5)$$

for

$$0.05 \le \frac{w}{b} \le 0.65, \qquad 0.05 \le \frac{s}{b} \le 0.65,$$
$$a = 0.5\,\text{mm} \quad \varepsilon_r = 5.99 \quad \text{and} \quad b = 1.2\,\text{mm}.$$

θ_e is even mode phase velocity and θ_o is odd mode phase velocity. Equations (4)–(5) are accurate within ±4% tolerance. Z_{oe} and Z_{oo} for various w/b and s/b are shown in Figs. 3 and 4 respectively for the coupled line section shown in Fig. 1. Coupled line dimensions considered for the design of UWB filter are given in Table 2.

3. DESIGN OF COMPACT MULTILAYER UWB FILTER

An UWB filter operating from 3.1–10.6 GHz is designed by cascading two band pass elements as shown in Fig. 5. The band pass element as

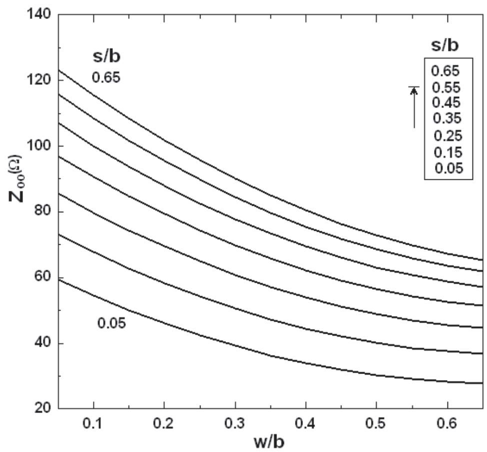


Figure 4. Odd mode impedances.

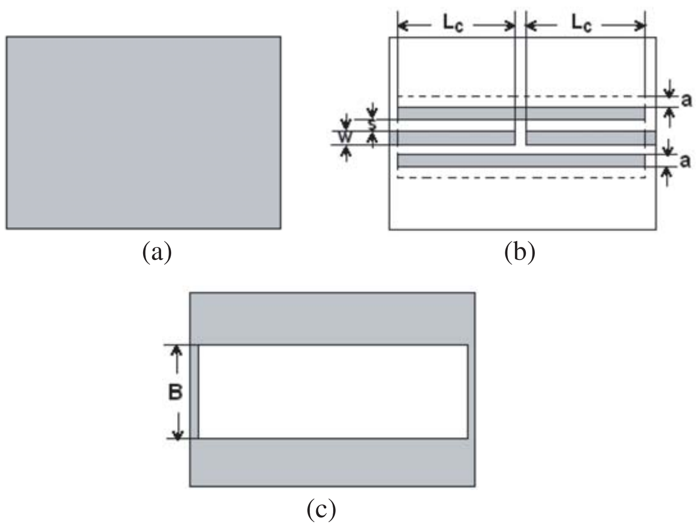


Figure 5. Metallization layers of UWB filter. (a) Top layer (layer 2), (b) middle layer (layer 1), (c) bottom layer (layer 0).

discussed in Section 2 has three parallel coupled lines over the defected ground. Multiple coupled lines are used to achieve tight coupling for the design of UWB filter. This UWB filter can be analyzed by splitting into coupled line sections as shown in Fig. 6. Each coupled line section is characterized using even and odd mode impedances given by

Equations (4)–(5). The values of capacitors in the equivalent circuit of the series gap are $C_a = 0.002\,\text{pF}$ and $C_b = 4\,\text{pF}$. The analytical results (using MATLAB) are obtained by cascading individual ABCD matrix of UWB filter sections.

Physical parameters defected ground extension 'a' and spacing 's' in the structure have influence on bandwidth of the filter. Parametric

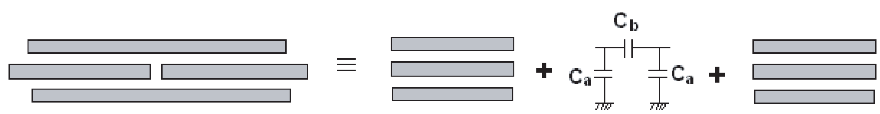
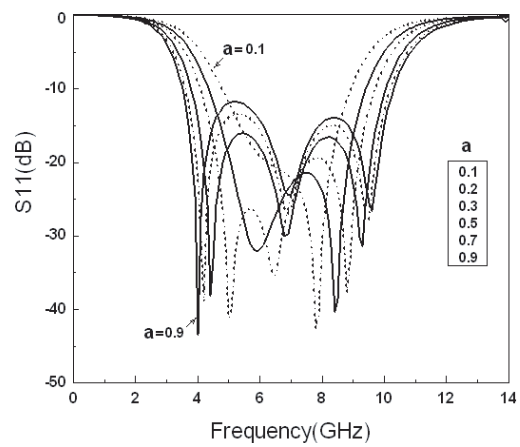
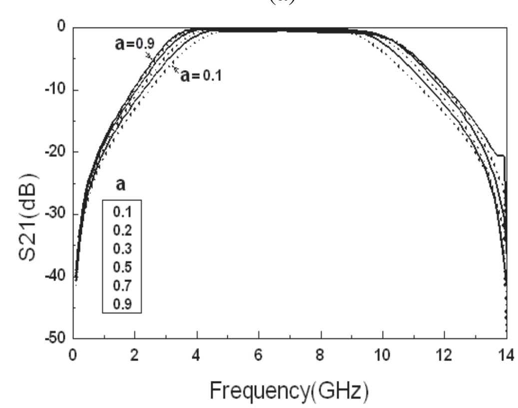


Figure 6. Equivalent of UWB filter.



(a)



(b)

Figure 7. Parametric study on 'a'. (a) Return loss, (b) Insertion loss.

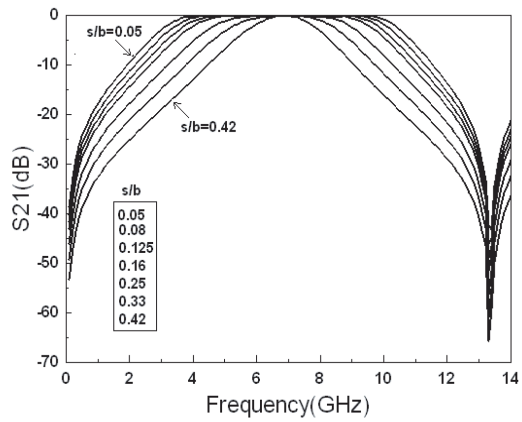


Figure 8. Effect of spacing 's' on bandwidth.

study is carried out to understand the effect of 'a' on bandwidth. Fig. 7 shows the results of this parametric study. It shows that bandwidth slightly shrinks as 'a' is reduced. Hence appropriate 'a' should be chosen while designing the filter with good performance. Spacing 's' in the coupled line sections plays vital role in determining the bandwidth of the filter. Effect of spacing 's' on bandwidth of the filter is shown in Fig. 8. When 's' s reduced, even mode impedance increases, odd mode impedance reduces and tight coupling occurs between the lines and thereby increases the bandwidth. In this paper, 'a' and 's' are chosen to be 0.5 mm and 0.1 mm respectively to achieve the required bandwidth of the filter.

Filter is designed using the parameters given in Table 2. Length of each coupled line 'L_c' is 4.5 mm and width of lines 'w' is 0.1 mm. Filter is simulated analytically and using full wave simulators [13, 14]. Results are compared in Fig. 9 and are satisfactorily matching with each other. Pass band of 3.1–10.6 GHz is observed in the filter. The minimum return loss of 15 dB and maximum insertion loss of 0.4 dB

Table 2. Coupled line dimensions.

w	100 µm
s	50 µm
$L_c(\lambda_g/4)$	4500 µm
a	500 µm
W_s	1400 µm

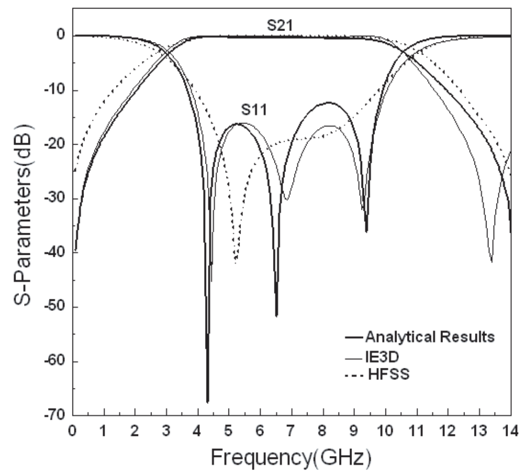


Figure 9. Characteristics of UWB filter.

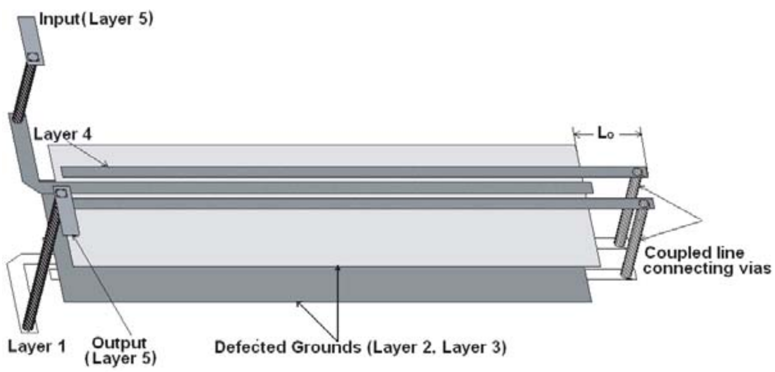


Figure 10. Multi-layer UWB filter.

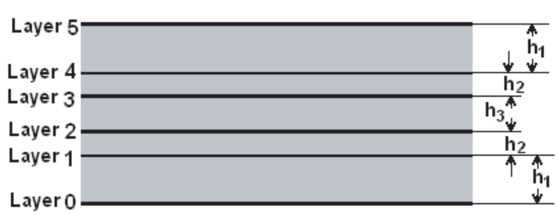


Figure 11. Cross section of layers in multi-layer UWB filter.

are obtained. The overall size of the filter is 11 mm× 3.4 mm×1.2 mm.

Coupled lines are folded in multi layer structure as shown in Fig. 10 to reduce the size of the filter. Vertical vias are used to interconnect the coupled lines and feed lines. The diameter of vias is 0.08 mm as normally used in LTCC process. Fig. 11 shows the cross section of layers and individual layers are shown in Fig. 12. Layers 0 and 5 are ground conductors and Layer 5 has input and output feed lines. Coupled lines are in layers 1 and 4. Defected ground conductors are in Layers 2 and 3. Connecting vias for the coupled lines are made between layers 1 and 4. Ground is isolated in layers 2 and 3 in square shape (0.15 mm × 0.15 mm) to isolate the vias as shown in Fig. 12. Substrate with thickness of 0.4 mm (h_3) is used between layers 2 and 3 to avoid the cross coupling between the coupled lines.

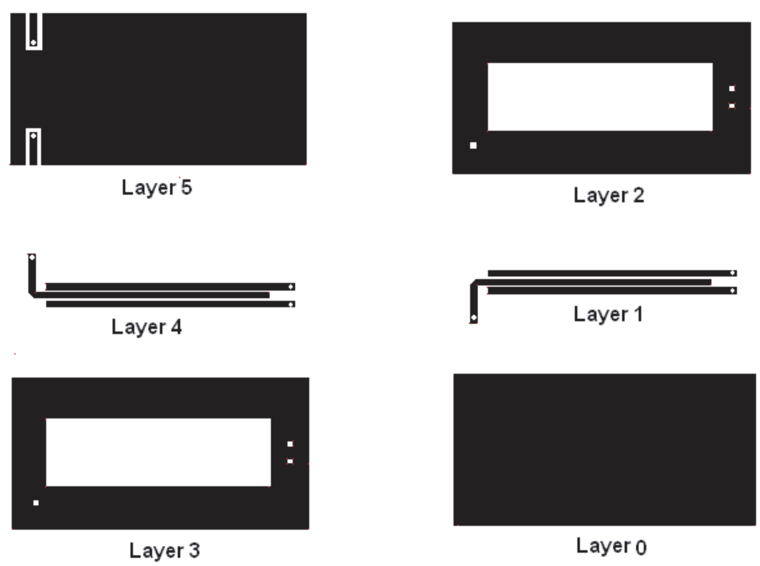


Figure 12. Layers of multi-layer UWB filter.

When coupled lines were folded into layers 1 and 4, a slight frequency shift and deterioration in impedance matching occurred due to connecting vias and multiple layers. This was corrected by fine tuning the coupled line length (L_c) and additional length (L_o) of filter. The length 'L_c' is reduced by 0.4 mm and length 'L_o' is increased by 1 mm. This multi-layer filter is simulated in full wave simulators to verify the analytical results using circuit models. Fig. 13 compares the analytical results against full wave simulations [13, 14] and results are satisfactorily matching with each other. Minimum return loss of the filter is 14 dB and maximum insertion loss is 1.0 dB. The filter is compact and size of the filter is 6.2 mm× 3.4 mm×2.8 mm.

Group delay is one of the parameters that characterizes UWB filter. Group delay is calculated using analytical results and full wave simulations and results are shown in Fig. 14. Group delay is constant over the pass band with ± 0.08 ns.

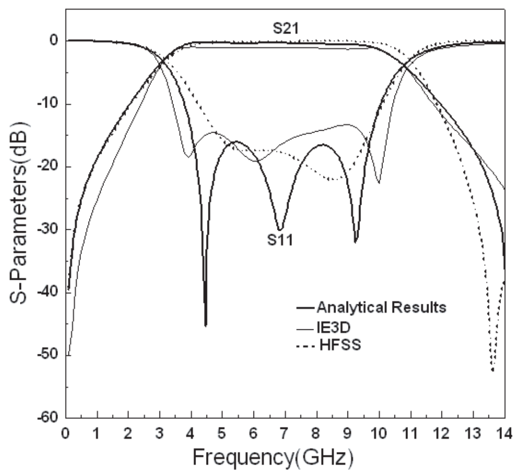


Figure 13. *S*-parameters of multi-layer UWB filter.

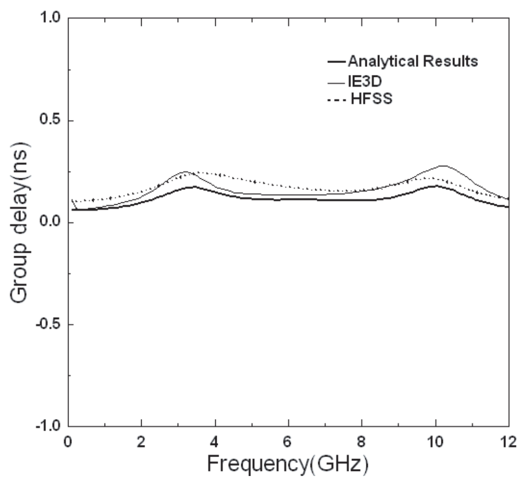


Figure 14. Group delay of multi-layer UWB filter.

4. CONCLUSIONS

A compact multi-layer UWB filter with the pass band of 3.1–10.6 GHz has been analyzed using folded three parallel coupled line section in defected ground structure topology. Closed form expressions for the coupled line sections were presented to analyze the filter in this paper. Vias were used to connect the folded coupled lines in different layers. This new structure offers wide band response and constant group delay in the pass band. The design of filter was analyzed using circuit models of coupled line and results obtained were validated against the full wave simulations.

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