

Small Size and Wide-Band Band Pass Filter with DGS/CRLH Structures

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Abstract — A small size and wide-band band pass filter with high performance for WiMAX applications is introduced. The filter is designed by utilizing one composite right left handed transmission line (CRLH-TL) metamaterial cell and two gap lumped capacitors. The filter has a center frequency of 5.3 GHz and a 3dB bandwidth from 4.2 GHz to 6.4 GHz. A lower than 0.5 dB insertion loss within pass-band is achieved. A single transmission zero at 6.52 GHz is achieved to increase the selectivity of the proposed filter. The rejection band is extended to be up to 10 GHz. A comparison between circuit simulation, EM simulation and measured results is introduced with good consistency between them. The filter has a small size ($26.8 \times 16.5 \text{ mm}^2$) which is smaller than recently reported wide band filters.

Index Terms — Band pass filter, CPW, CRLH-TL, DGS, gap capacitors.

I. INTRODUCTION

Band pass filters (BPFs) play a vital role in wireless communication systems. Special requirements must be achieved in microwave band pass filters such as compact size, low insertion loss, low cost, high selectivity and high attenuation in the rejection band [1]. In order to meet the high demand of increasing data rate in wide band communication systems, wide band microwave band pass filters are used. Many wideband BPFs with high performance, high selectivity and high attenuation in stop band have been reported such as using cross-coupled transmission line sections [2], ring resonators with open stubs [3], multimode resonators (MMRs) [4, 5], and cross-coupled MMRs [6]. The challenge in these

design methods is always the design complexity and the filter performance.

Composite right/left handed transmission line (CRLH-TL) metamaterial has been utilized in microwave passive components. CRLH-TL metamaterial has anti-parallel phase and group velocities [7, 8]. Consequently, CRLH-TL has non-linear positive/negative zero phase shift. Because of these good characteristics, passive components such as power splitter [9] resonators [10, 11], filters [12-18], and couplers [19, 20] are designed. Also, great effort has been focused in its applications in the active circuits such as oscillator, switches and amplifier [21–23].

Defected ground structure (DGS) are achieved by etching a slot in metallic ground plane; this slot disturbs the current distribution in the ground plane. This disturbance affects the microstrip line features, such as the inductance and capacitance [24]. Such properties have been used to design compact microwave filters [25–28], wide band filter [29-31] and also high selective filters [32]. However, up to the authors' knowledge, few attempts have been suggested to make use of CRLH metamaterial and DGS together in filter design [33].

In this paper, a compact size and wideband BPF is introduced. The filter is based on CRLH-TL metamaterial with two coupled lumped capacitors. The filter has a center frequency of 5.3 GHz and bandwidth of 2.2 GHz which is suitable for wide band wireless applications. Furthermore, the filter has single transmission zero at 6.5 GHz to improve the filter selectivity. Also, the filter has good filtering capabilities with good pass-band selectivity and stop-band attenuation. The filter is designed, fabricated, and measured to verify the simulated results.

II. THEORY OF THE PROPOSED FILTER

A. Operating principle of CRLH capacitive-gap coupled resonator BPF

A conventional coupled gap resonator is realized using N series transmission line sections (approximately $\lambda/2$) with $N+1$ capacitive gap between them, which can be realized as series capacitors. As shown in Fig. 1 (a), conventional capacitive coupled gap resonator band pass filter can be realized using one section of conventional transmission line coupled to filter output through two gap capacitors (C_1 and C_2). The electric length (θ_1) is a half wavelength.

The equivalent circuit of the CRLH capacitive-gap coupled resonator is shown in Fig. 1(b). It can be observed that the section of electrical length θ_1 is designed as a CRLH cell in T-configuration. Basically, the elements C_L and L_L are loading elements whereas C_R and L_R are usually parasitic elements. The main advantage of using this configuration is the utilization of the nonlinear behaviour of the progressive phase along the CRLH transmission line. As explained in [7], the design for one section filter can be expressed as:

$$\beta l = \pi. \quad (1)$$

The loading elements (series capacitance and shunt inductance) and parasitic elements are used to determine the negative left-handed and positive right-handed propagation constants, which can be expressed as [7]:

$$\beta_l = \left(\frac{-1}{\omega \sqrt{C_L L_L}} \right), \quad (2)$$

$$\beta_r = \left(\omega \sqrt{C_R L_R} \right). \quad (3)$$

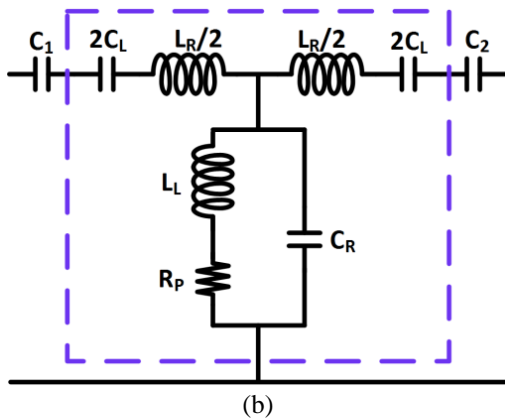
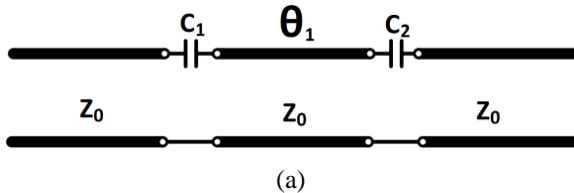


Fig. 1. (a) The schematic block diagram of the coupled resonator band pass filter, and (b) the CRLH version of the coupled gap resonator band pass filter.

B. Defected ground band stop filter for transmission zeros

The transmission zeros design was based on having a series defected ground structure that acts as a band stop filter. The equivalent circuit of the defected ground structure is the parallel L - C tank circuit. The values for pole lumped elements (L_P and C_P) are obtained in terms of the 3 dB cut off frequency (f_c) in GHz and pole frequency (f_p) in GHz as follows [24]:

$$C_P = \frac{5f_c}{\pi(f_p^2 - f_c^2)} \text{ pF}, \quad (4)$$

$$L_P = \frac{250}{C_P(\pi f_P)^2} \text{ nH}. \quad (5)$$

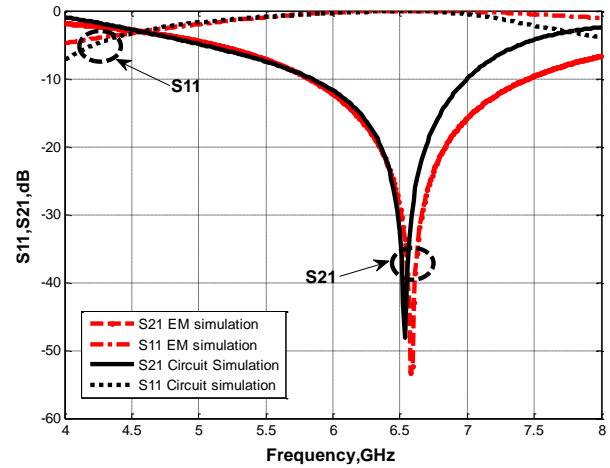


Fig. 2. The simulated S-parameters of DGS resonator filter (circuit model).

The DGS filter was designed to introduce a stop band centered at $f_p = 6.5$ GHz and a 3 dB cutoff frequency at $f_c = 4.5$ GHz. For testing purposes, a rectangular DGS resonator was etched in the ground plane and excited by a 50Ω coplanar waveguide transmission line. Consequently, the L_P and C_P extracted values are 1.851 nH, and 0.321 pF, respectively.

For verification purposes, the structure and circuit model were simulated using full wave simulations and circuit simulations, respectively. The simulated S-parameters are shown in Fig. 2. The two results in Fig. 2 demonstrate that there is a band stop filtering phenomenon. It can be noticed that the filter cut off frequency $f_c = 4.5$ GHz at which S_{21} magnitude is close to -3 dB. Also, the frequency f_p is 6.52 GHz at which the S_{21} magnitude is close to -50 dB.

III. CPW CRLH METAMATERIAL BAND PASS FILTER STRUCTURE

The geometry of the CPW CRLH band pass filter is shown in Fig. 3 (a) and Fig. 3 (b) with the detailed filter dimensions. The CPW CRLH filter is realized using one CRLH cell with T-configuration coupled to the two gap

capacitors. As it can be depicted from Fig. 3 (a) that the CRLH metamaterial unit cell is consisting of a series interdigital capacitor and shunt stub as an inductor. The filter is fed by 50 Ω transmission line and printed on RO4003 substrate ($\epsilon_r = 3.38$, thickness = 0.813 mm and dielectric loss tangent = 0.0027). The equivalent circuit of the band pass filter is shown in Fig. 3(c). The circuit consists of CRLH unit cell coupled to output terminals by the two coupled capacitors. Due to this coupling, the roll off attenuation in the filter is increased. Based on the design equations (6) and (7), the values of the equivalent capacitance and inductance of the CRLH cell are specified.

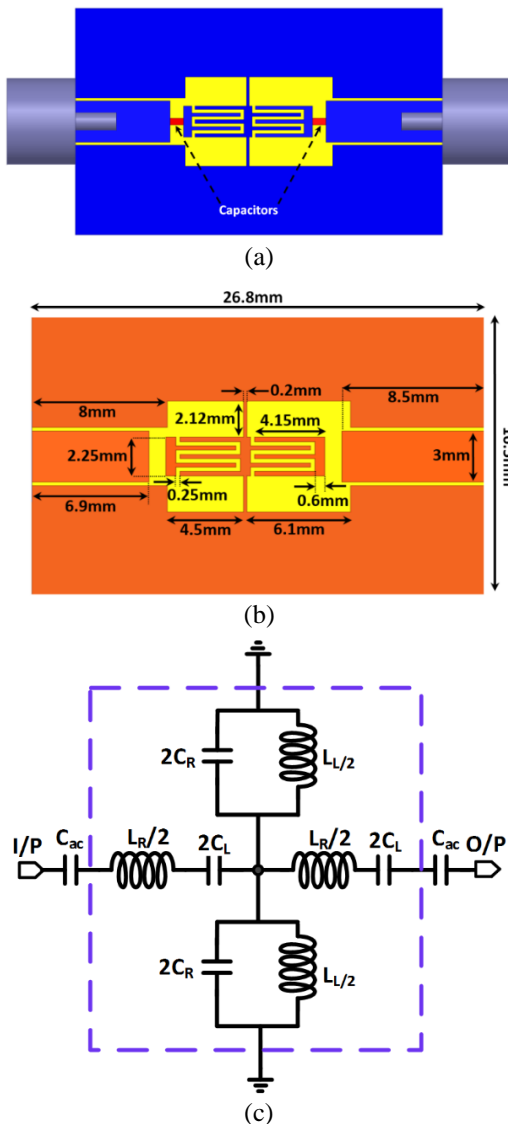


Fig. 3. The CPW composite right left handed band pass metamaterial filter: (a) 2-D layout, (b) filter dimensions and (c) the equivalent circuit model, $C_{ac}=0.6$ pF, $C_L=0.6$ pF, $L_R=1$ nH, $C_R=0.5$ pF, $L_L=2.56$ nH.

The interdigital capacitor and stub inductor dimensions were synthesized as [1]:

$$C_L = 3.937 \times 10^{-5} l_f (\epsilon_r + 1) (0.11(n - 3) + 0.252) \text{ pF}, \quad (6)$$

where l_f is interdigital capacitor length in micrometer:

$$L_L = Z_o \tan(\beta l_s) / \omega, \quad (7)$$

where l_s is the stub length, Z_o and β are the characteristic impedance and the propagation constant, corresponding to the stub width, respectively.

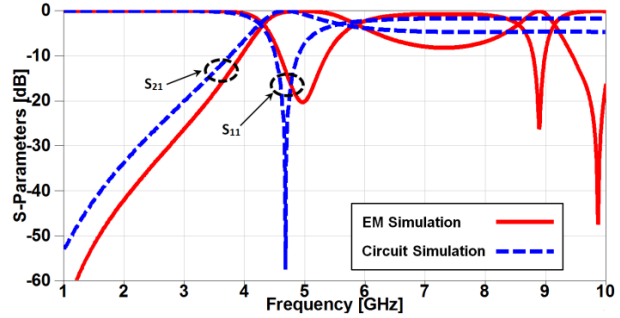


Fig. 4. The simulated scattering parameters magnitudes of the CPW CRLH filter.

The scattering parameters comparison between the circuit simulation and EM simulation of the CPW CRLH band pass filter is shown in Fig. 4. It can be noticed from the simulated EM results in Fig. 4 that the filter center frequency is 4.75 GHz and the 3 dB bandwidth is from 4.3 GHz to 5.5 GHz. The filter has good rejection band at lower frequency with more than -50 dB. However, it has lower rejection band at high frequency which reduces the filter selectivity at higher frequency band. Also, there is reasonable agreement between the achieved EM and circuit simulations.

IV. CPW CRLH METAMATERIAL FILTER WITH DGS

In order to enhance the filter performance and suppress the undesired peaks at the higher band of the CRLH metamaterial filter as shown in EM simulation of Fig. 4, two DGS-cells have been added to the filter structure. The idea is to utilize the DGS-resonators which have resonance frequency near the unwanted frequency band to achieve high rejection at high frequency band. The new filter is similar to the filter studied in the previous section with the difference of adding new structure consists of two DGS-units as illustrated in Fig. 5 (a). The two DGS resonators which are etched in the ground (top layer) have dimensions of 16×1 mm² as shown in Fig. 5 (b). The filter is printed on a Rogers RO4003 substrate with ϵ_r of 3.38 and a thickness h of 0.813 mm.

The simulated S-parameters of the BPF using EM and circuit simulations are illustrated in Fig. 6. It can be seen from the figure that the filter is operated at a center

frequency of 5.3 GHz with 3 dB bandwidth from 4.2 GHz to 6.4 GHz. The filter has insertion loss of lower than 0.5 dB and return loss higher than 12 dB over the achieved pass-band. Moreover, a transmission zero is achieved at frequency of 6.52 GHz to increase the filter selectivity. Also, a wide suppression level of approximately -10 dB is achieved in the higher frequency band from 7 GHz to 10 GHz.

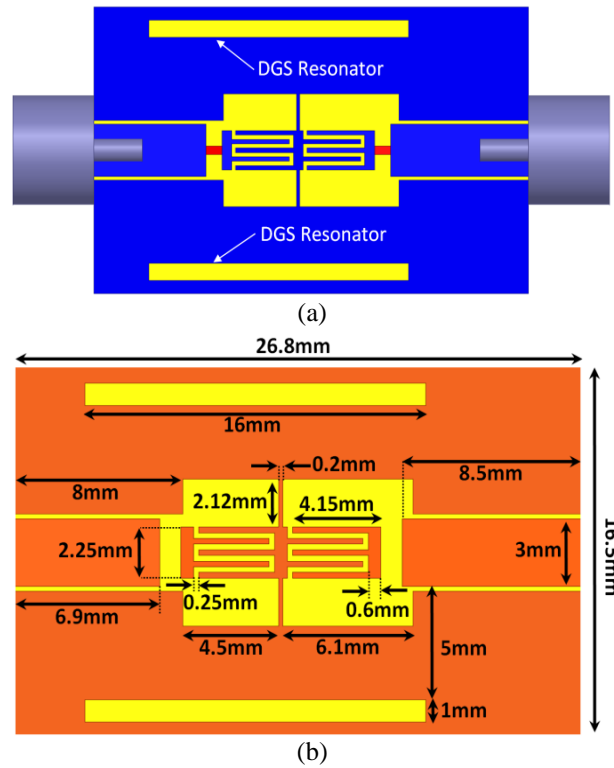


Fig. 5. The CPW CRLH filter with DGS: (a) 2-D layout and (b) filter dimensions.

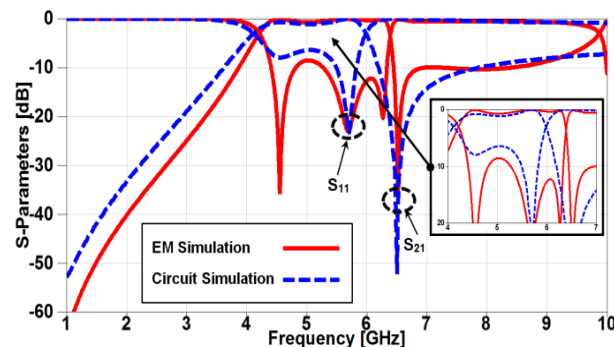


Fig. 6. The simulated scattering parameter of the CPW CRLH filter.

It is worth to comment from Fig. 4 and Fig. 6 that the DGS band stop has produced a transmission zero which eventually enhances the selectivity of the filter.

To study the effect of the values of the two lumped capacitors on the performance of the proposed filter, a parametric study is carried out. The simulated S-parameters of the proposed filter with different values of lumped capacitors are shown in Fig. 7. It is clear that the capacitance affects the matching of the proposed filter and the optimized value is chosen to be 0.6 pF.

V. EXPERIMENTAL RESULTS

Figure 8 shows the photograph of the fabricated CRLH band pass filter with DGS unit using a pair of 0.6 pF surface mounted capacitors. To confirm the simulation results from CST software, the proposed model of CPW CRLH filter is fabricated, tested and measured using ZVB-20 vector network analyzer (VNA).

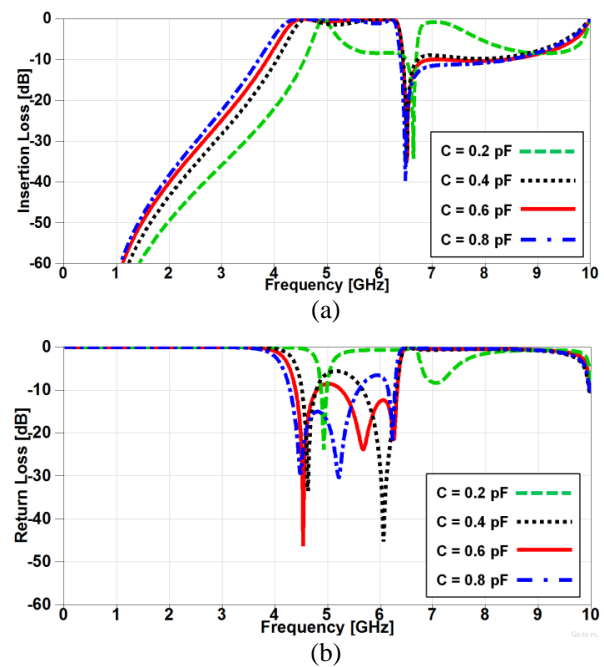


Fig. 7. The simulated scattering parameter of the proposed CPW CRLH filter: (a) insertion loss and (b) return loss.

The filter is printed on RO4003 substrate with thickness of 0.813 mm and dielectric constant of 3.38. Figure 9 shows a comparison between simulated and measured results of the proposed BPF. The measured results have insertion and return losses better than 0.5 dB and 12 dB, respectively. The stop band rejection is lower than -10 dB from 7 GHz up to 10 GHz. The filter has bandwidth from 4.5 GHz to 6.25 GHz with transmission zero at 6.3 GHz. It can be noticed from Fig. 9 that the simulated and measured results are in a good consistency. However, a frequency shift occurred due to the unpredictable fabrication tolerance and the soldering process of the SMA connectors and surface mounted capacitors. Table 1 summarizes the comparison of the proposed filter with other reported filters [2-6]. It is

obvious from table that the proposed filter has the minimum insertion loss ($|S_{21}|$) of 0.5 dB.

Furthermore, the proposed filter size has the smallest size of $16 \times 6.49 \text{ mm}^2$. From bandwidth point of view, the proposed filter bandwidth is competitive. However, it is worth to comment that the proposed filter has the minimum number of zeros.



Fig. 8. The fabricated prototype photo of the CPW CRLH filter.

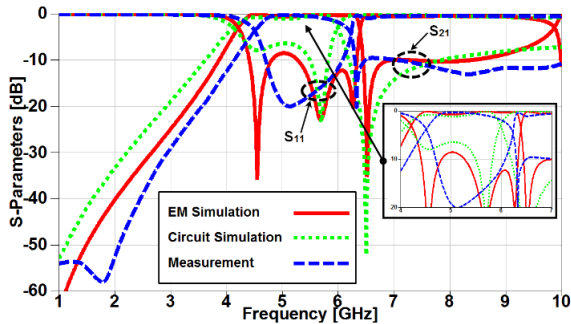


Fig. 9. The simulated and measured scattering parameter magnitudes of the CPW CRLH DGS filter.

Table 1: Comparison between the proposed filter with other reported wide band filters

Ref.	Freq. (GHz)	$ S_{21} / S_{11} $ (dB)	ϵ_r / Thick (mm)	FBW (%)	T. Zeros	Size (mm^2)
[2]	3	1/12	3.2/0.762	48	3	65×37
[3]	6.92	0.81/12	3.38/0.762	78	6	18.1×10
[4]	3.2	2.2/12	2.65/1	20.6	6	56.3×24.6
[5]	3	0.6/17	9.8/1.27	43.3	4	11×12
[6]	5.6	1.3/12	2.65/1	67.8	2	15.5×7.3
Prop. filter	5.3	0.5/12	3.38/0.813	41.5	2	16×6.49

VI. CONCLUSION

Compact size and high selective band pass filter for wireless applications has been presented. The CRLH-TL metamaterial is considered the main block of the filter with two gap capacitors. The proposed filter is suitable for wireless application (WiMAX). The filter has been operated at 5.3 GHz, bandwidth from 4.2 GHz to 6.4 GHz with insertion loss lower than 0.5 dB in the pass-band, return loss lower than -12 dB and with single transmission zero at 6.52 GHz in the stop band. The DGS has been used to enhance the rejection level. The

simulation results agree with the measured results which confirm the suitability of the proposed BPF for modern wireless communications.

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