

A Compact Triple Band Metamaterial Inspired Bandpass Filter Using Inverted S-shape Resonator

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Abstract. *This paper presents the compact metamaterial inspired triple-band filter using two inverted S-shape resonators and two C-shape stubs with via. The proposed filter is printed on FR-4 epoxy glass substrate with 1.6 mm thickness. The 3-dB measured fractional bandwidths are 40% (1.6–2.4 GHz), 16.5% (3.9–4.6 GHz) and 14.3% (5.2–6.0 GHz) at center frequencies 2.0 GHz, 4.25 GHz and 5.6 GHz, respectively. This filter offers electrical circuit size of $0.22\lambda_g \times 0.16\lambda_g$ where given λ_g is the guided wavelength at center frequency of the first passband 2.0 GHz. The performance parameter of the designed filter have been characterized by fractional bandwidth, insertion loss, dielectric constant, return loss, circuit size and group delay. Both simulated and measured results are shown to validate the proposed filter. Finally, the MTM properties of the proposed filter have been verified by extracting its dispersion diagram. It is suitable for GSM 1800, LTE 2300 and WiMAX (5.2–5.8 GHz) application.*

Keywords

Triple-band, bandpass filter, inverted S-shape resonator, C-shape stub

1. Introduction

In modern communication system, increasing demands of multiband services have attracted many researchers towards it. Triple-band filter with small size, low insertion loss, low cost and tremendous performance urges for multiband services [1], [2]. The main part of tri-band transceiver, a passband filter is permitted to pass on three different frequency band signals and filtering undesired frequency bands [3]. Further, various triple-band bandpass filters have been reported using different concepts [4–10]. The conventional triple-band filters were designed by cascading of multiple pair of microstrip resonators [4], which gives comparatively large size. Number of bands can be increased by using defected ground structure (DGS), which has been reported in [5]. Multiband filter has been reported

using stepped impedance resonator and meandered defected ground structure, which provides compactness and flexibility to design filter structure [6]. One passband can be generated due to DGS and other passbands due to stub loaded resonators. By using the grounded stepped impedance resonator triple band filter has been designed and the bandwidth is controlled by varying the distance between two vias [7]. To enhance the electromagnetic characteristics of multiband filter multi-mode resonators have been designed in [8]. A triple-band BPF has been designed based on stub loaded open-loop resonator, which improves stopband rejection and filter performance [9]. Communication system requires different passband with different bandwidths, so design compliance is required for triple bandpass filter. In [10], independent control of bandwidths has been realized by coupling effect.

Compactness of the filter can be achieved by using metamaterial (MTM) structure due to its effective-homogeneity condition [11]. MTM are artificial engineering electromagnetic structures with negative refractive index and zero phase constant. The planar structure of metamaterial has been planted on composite right/left handed transmission line (CRLH-TL) with series inductance and capacitance along with shunt parallel inductance and capacitance circuit [12]. A work has been reported based on composite MTM and parallel step impedance resonator to get triple passband filter in addition with TZs [13]. In [14], a MTM triple-band filter has been designed using meander line and rectangular stub which realizes virtual ground concept. A compact triple band bandpass filter has been proposed using complementary split ring resonator and Koch fractal shape transmission line [15].

This manuscript proposes a compact triple-band MTM inspired bandpass filter. The filter consists of two inverted S-shape resonators and two C-shape rectangular stubs with via. The electrical circuit size of the proposed filter is $0.22\lambda_g \times 0.16\lambda_g$ (20.9 mm \times 15.3 mm) at center frequency of the first passband 2.0 GHz. Center frequencies of each passband can be controlled by varying the length of S-shape resonator. Fractional bandwidth can be controlled by stub length and gap between S-shape resonators. Group delay of each passband is less than 1 ns.

2. Design of Triple Band Filter

In this paper a compact metamaterial inspired triple-band bandpass filter has been proposed and characterized using ANSYS HFSS 14.0 software. The configuration of the designed bandpass filter with optimized dimensions in caption has been displayed in Fig. 1. The equivalent LC circuit model of the designed filter has been presented in Fig. 2.

In the equivalent circuit, the series inductance L_p is generated due to input and output ports, tank circuit L_R, C_1 (due to gap, g_1) appears due to the first half portion of the inverted S-shape resonator, the inductance L_2 due to the second half portion of S-shape resonator and the coupling capacitor C_2 due to gap g_2 , the series left handed capacitance C_L mainly due to gap between two S-shape resonators. The LH inductance L_L is due to C-shape stub and via which connects stub to the ground plane. The RH capacitance C_R is the patristic capacitance between C-shape stub and ground plane. The extracted lumped element values of the proposed triple band bandpass filter based on equivalent circuit diagram using advanced design system software are as follows: $L_p = 5.5$ nH, $L_R = 0.29$ nH, $C_1 = 2.86$ pF, $C_L = 0.89$ pF, $C_2 = 0.63$ pF, $L_2 = 5.4$ nH, $C_R = 0.18$ pF, $L_L = 1.4$ nH.

The design procedure of the proposed triple band filter is divided into three major steps as shown in Fig. 3 and Fig. 4 along with scattering parameters and designed structures. The design steps are summarized as:

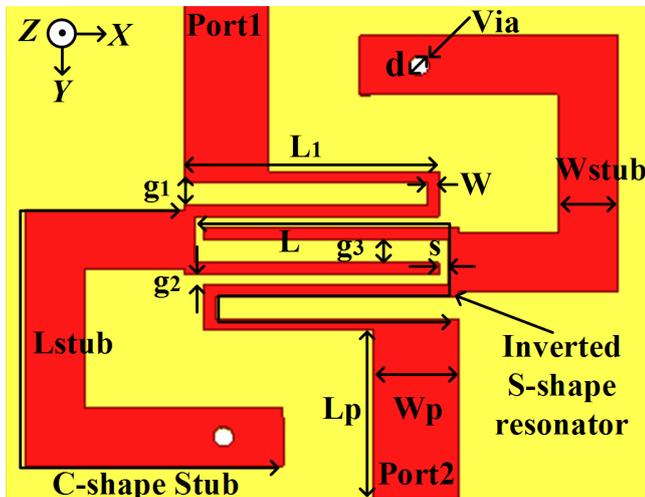


Fig. 1. Configuration of the proposed triple-band bandpass filter [All dimensions are in mm: $L = 14.7, L_1 = 9.0, L_p = 6.0, L_{stub} = 19.6, W = 0.4, W_p = 3.0, W_{stub} = 2.1, s = 0.3, g_1 = 0.8, g_2 = 0.4, g_3 = 0.8, d = 0.7$].

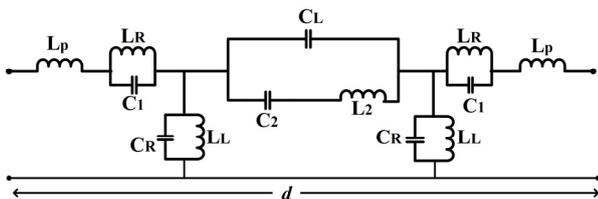


Fig. 2. Equivalent LC circuit model of the designed filter.

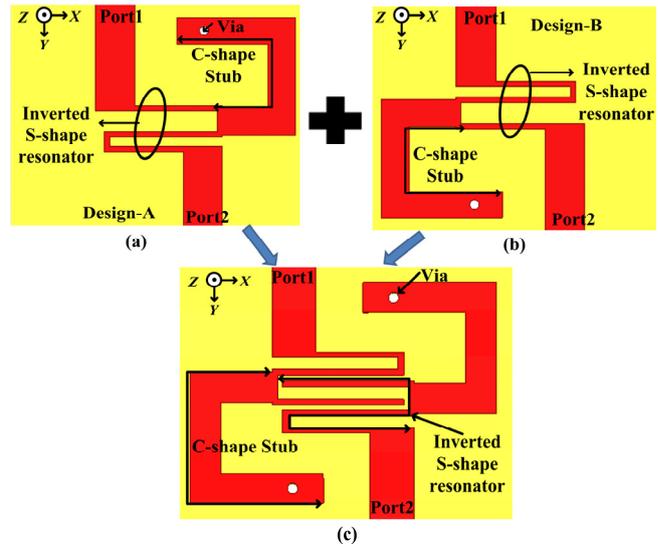


Fig. 3. Layout of different design steps of the proposed triple band filter: (a) Design-A, (b) Design-B, (c) Proposed Design-C.

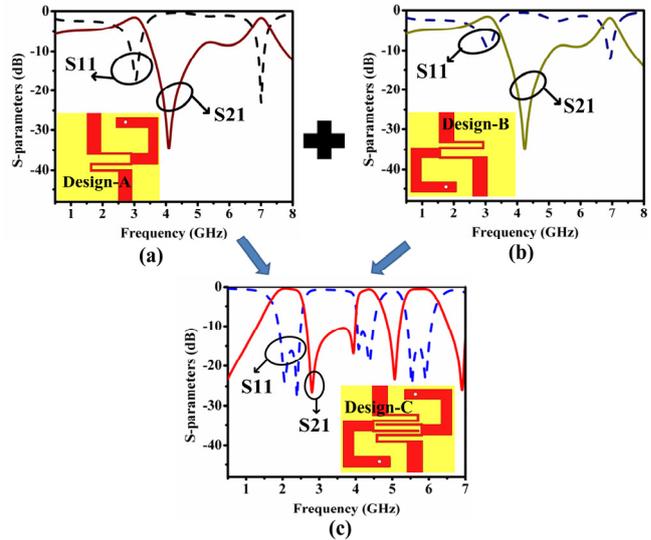


Fig. 4. Scattering parameters of different design steps of the proposed triple band filter: (a) Design-A, (b) Design-B, (c) Proposed Design-C.

(i) Step I: Initially, A dual band filter is designed with center frequencies 3.0 GHz and 7.0 GHz as shown in Fig. 3(a). This structure is called as Design-A and it is composed of single inverted S-shaped resonator and C-shaped rectangular stub. Via is also used in the design to connect the top and bottom copper parts. The scattering parameters of Design-A are shown in Fig. 4(a). It has insertion loss of 1.2 dB, 1.5 dB and return loss of 17.0 dB, 22 dB at center frequencies of the first and second pass-band, respectively. This design has low selectivity at lower cut-off frequency of the first passband.

(ii) Step II: In the next step, an inverted mirror image layout of Design-A is formed named as Design-B as shown in Fig. 3(b). The scattering parameters of Design-B are shown in Fig. 4(b), which offers the same operating frequencies, because of symmetry. It has insertion loss of

1.0 dB, 1.4 dB and return loss of 10.0 dB and 12.0 dB, respectively at center frequency of 3.0 GHz and 7.0 GHz. This design also offers low selectivity.

(iii) Step III: To improve the selectivity and impedance matching, Design-C has been proposed as shown in Fig. 3(c), which is the combination of Design-A and Design-B. The scattering parameters of Design-C have been depicted in Fig. 4(c), which shows a shift in center frequencies (2.0 GHz and 5.6 GHz) due to increase in mutual coupling between two inverted S-shape resonators formed after combining Design A and Design-B. It has also been noticed from the plot that an extra band is generated between them with center frequency of 4.25 GHz due to improved shunt inductance.

The metamaterial properties of the proposed filter are characterized by its dispersion diagram (ω - β curve), which is obtained by applying Bloch Floquet theory for a periodic distance (d) of Fig. 2 [16].

$$\beta d = \arccos(1 + Z_{se} Y_{sh}), \quad (1)$$

where $Z_{se} = Z_1 + Z_2,$ (2)

$$Z_1 = j\omega L_p + j\omega L_R / (1 - \omega^2 L_R C_1), \quad (3)$$

$$Z_2 = 1 / (j\omega C_L + j\omega C_2 / (1 - \omega^2 L_2 C_2)), \quad (4)$$

$$Y_{sh} = j\omega C_R + 1 / (j\omega L_L). \quad (5)$$

The dispersion diagram can also be found out using scattering parameters [17] as:

$$\beta d = \arccos\left(\frac{1 - S_{11} S_{22} + S_{12} S_{21}}{2 S_{21}}\right). \quad (6)$$

The refractive index of the designed filter using scattering parameters has been calculated using [18]

$$\eta = \frac{-j}{kd} \ln\left(\frac{S_{21}}{1 - S_{11} \frac{z-1}{z+1}}\right) \quad (7)$$

where k and z are the wave number and the impedance of the filter, respectively.

3. Analysis of Proposed Filter

The fabricated prototype of the proposed filter is depicted in Fig. 5. It is fabricated on FR-4 epoxy glass substrate with dielectric constant 4.4, loss tangent 0.02 and thickness 1.6 mm. Agilent Vector Network Analyzer N5221A has been used for scattering parameter and group delay measurement. The measured and simulated scattering parameters are presented in Fig. 6.

The measured and simulated results are in acceptable agreement with each other; there are minor frequency shift

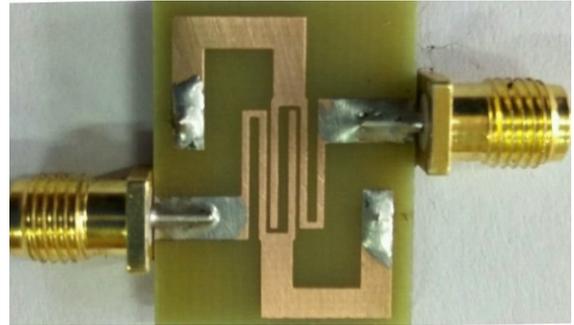


Fig. 5. Fabricated prototype of the presented filter.

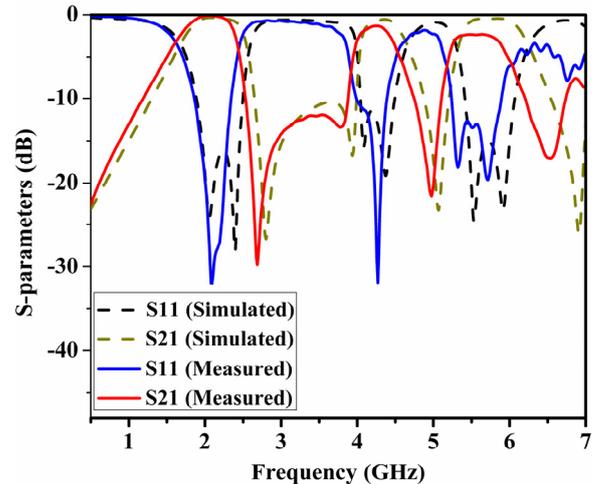


Fig. 6. Measured and simulated scattering parameters.

in center frequencies and more insertion loss in the second and third passband in comparison with simulation. These shifts have occurred due to imperfection of substrate and connector loss. The measured insertion losses have been found to be 0.1, 1.2, and 2.2 dB in triple-band at 2.0, 4.25, and 5.26 GHz respectively. The in-band return losses are greater than 32, 32, and 13 dB with fractional bandwidth 40.0, 16.5, and 14.3% respectively with respect to their center frequencies. In simulation total six poles are generated, two poles by each passband. They are situated at 2.05, 2.38, 4.0, 4.36, 5.52 and 5.9 GHz and their center frequencies at $f_{c1} = 2.1$ GHz, $f_{c2} = 4.32$ GHz, and $f_{c3} = 5.76$ GHz for the first, second and third passband, respectively.

The simulated surface current density of the proposed filter at six pole frequencies of passbands has been shown in Fig. 7. It depicts that the first and second pole frequency (2.05 and 2.38 GHz) of the first passband are mainly due to S-shape resonator and via, the third pole frequency (4.0 GHz) is due to whole structure and the fourth, fifth and sixth pole frequencies (4.36, 5.52, and 5.9 GHz) depend on S-shape resonator because high surface current density is concentrated on it. The simulated dispersion diagram of the designed triple band pass filter is shown in Fig. 8. It shows that passbands have both positive and negative slope, known as CRLH region. The passband from 1.6 to 1.85 GHz, 4.3 to 4.6 GHz, and 5.3 to 6.0 GHz with their negative slope termed as left handed (LH) region.

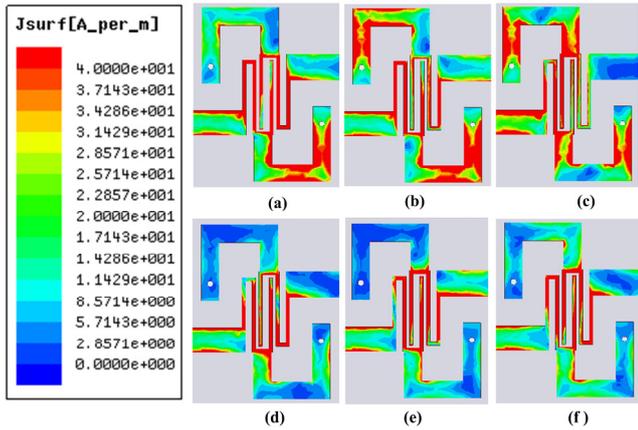


Fig. 7. Simulated surface current density of the proposed filter at pole frequencies of the triple band filter: (a) 2.05 GHz, (b) 2.38 GHz, (c) 4.0 GHz, (d) 4.36 GHz, (e) 5.52 GHz, (f) 5.9 GHz.

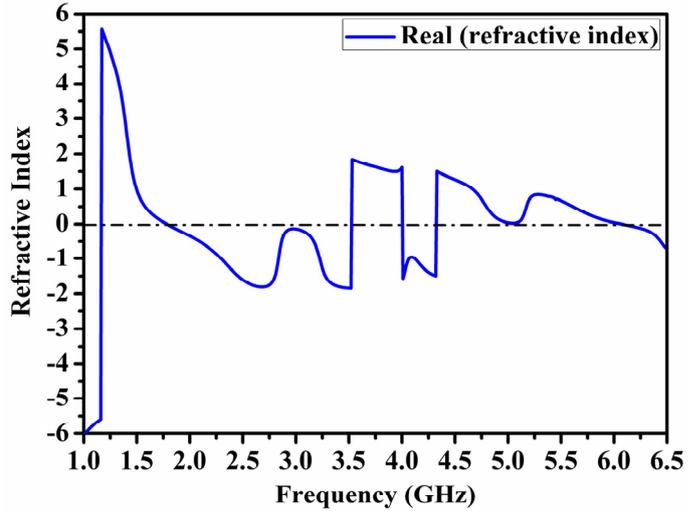


Fig. 9. Simulated refractive index of the proposed filter.

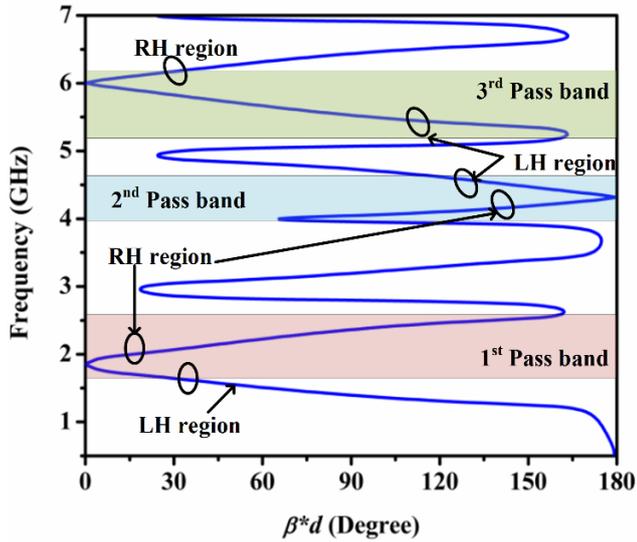


Fig. 8. Simulated dispersion diagram of the designed filter.

Similarly passbands from 1.85 to 2.55 GHz, 3.9 to 4.3 GHz, and 6.0 to 6.2 GHz are known as right handed (RH) region due to positive slope. This verifies the MTM properties of the designed filter, zero phase constant at frequency 1.85 GHz is known as the zeroth order resonance frequency.

The refractive index of the proposed filter is depicted in Fig. 9. It depicts that at resonance frequencies of the first and second passbands the real value of the refractive index is negative.

Group delay is the important parameter for bandpass filter. It measures the rate of change of transmission phase angle with respect to frequency. The group delay of the designed filter is depicted in Fig. 10. The measured variation of group delay within the passband varies from 0.5 to 1.0 ns. There has been a little difference of 0.3 ns between simulated and measured group delay due to imperfection in soldering and connector losses.

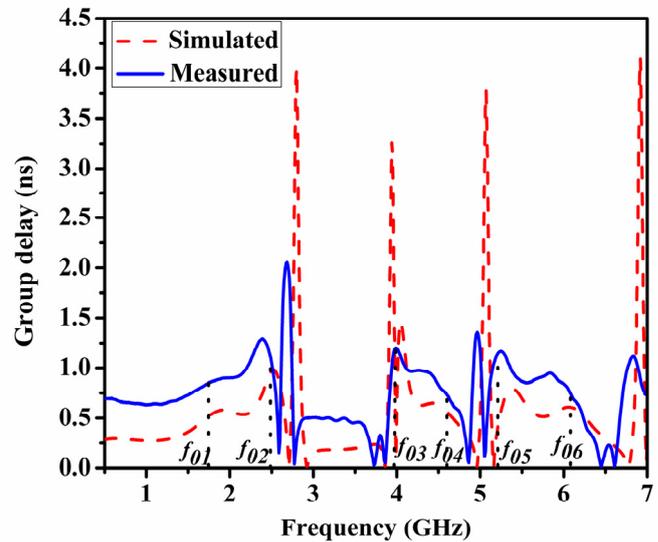


Fig. 10. Measured and simulated group delay.

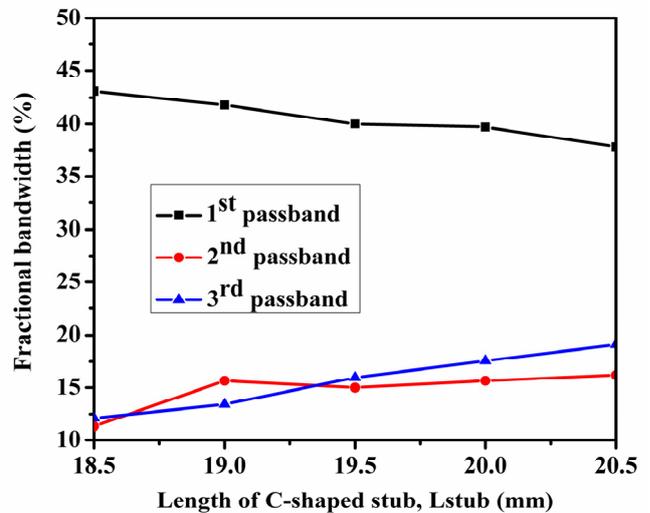


Fig. 11. Variation of fractional bandwidth with L_{stub} .

The 3dB fractional bandwidth is the important parameter of bandpass filter. It is defined as the ratio of bandwidth and center frequency. Variation of fractional bandwidth with different values of C-shape stub length is depicted in Fig. 11. As the length of L_{stub} increases from 18.5 to 20.5 mm the fractional bandwidth of the first passband increases from 43.1 to 37.8%, in the second passband it varies randomly and in the third passband it increases with the length of the stub. The dependency of fractional bandwidth with change in gap g_3 between S-shape resonator is shown in Fig. 12. By changing g_3 from 0.4 to 1.2 mm the fractional bandwidth decreases for the first and second passband and increases in the third passband.

The dependency of center frequencies on series inductance, L_R due to current flowing in the first arm of S-shape resonator is shown in Fig. 13. The center frequencies (f_{c1} , f_{c2} and f_{c3}) of all three passbands decrease by increasing the length L_1 . A comparison of measured values of the proposed triple band filter with earlier published triple band filters is summarized in Tab. 1. In terms of the center frequencies, return loss, insertion loss, 3dB fractional band-

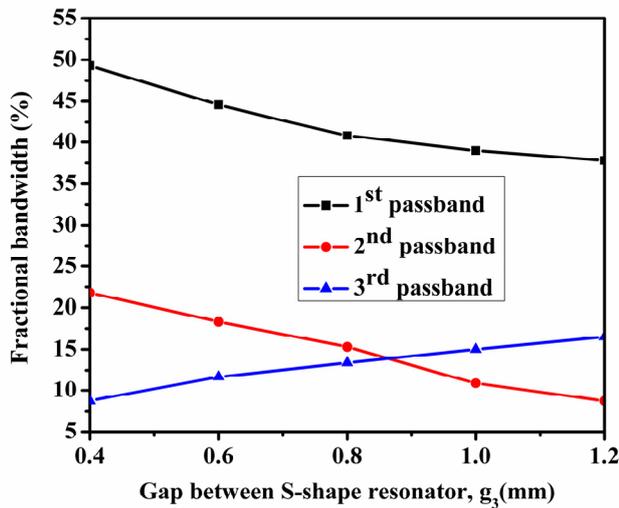


Fig. 12. Variation of the fractional bandwidth with gap g_3 .

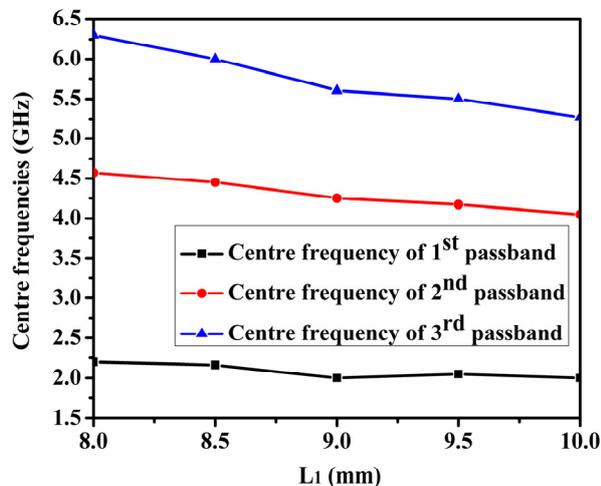


Fig. 13. Variation of the center frequencies with length L_1 .

	This work	[7]	[8]	[9]	[14]
CF (GHz)	2.0/4.25 /5.6	2.45/3.5 /5.3	1.95/3.65 /3.92	1.93/3.6 /4.89	2.1/5/7 /7.3
FBW (%)	40/16.5 /14.3	14/7 /4	8.5/3.7 /3.9	19.2/11.6 /2.86	57.1/8.7 /4.1
IL (dB)	0.1/1.2 /2.2	0.9/1.7 /2.1	0.46/1.96 /1.15	-	0.8/1.6 /2.4
RL (dB)	32/32/ >13	37/15/15	>16.7	15/15/22	25.5/15/ 23
DC	4.4	3.5	2.65	10.2	4.4
CS ($\lambda_g \times \lambda_g$)	0.22 × 0.16	0.43 × 0.35	0.38 × 0.28	0.33 × 0.23	0.23 × 0.21

CF = center frequencies, FBW = 3dB fractional bandwidth, IL =insertion loss, RL = return loss, DC = dielectric constant, CS = circuit size.

Tab. 1. Comparison of the designed filter with earlier published triple band bandpass filters.

width and electrical circuit size, it can be claimed that the proposed filter is very powerful candidate to earlier published performance.

4. Conclusion

A compact metamaterial inspired triple-band bandpass filter using S-shape resonator, C-shape stub and via has been proposed. The center frequency of all the three passbands depends on right handed inductance L_R . The dependency of fractional bandwidth on the length of C-shape stub has been explained. The proposed filter has good agreement with simulated and measured results. The proposed filter has three passbands from 1.6–2.4 GHz, 3.9–4.6 GHz and 5.2–5.6 GHz. It has compact electrical circuit size of $0.22\lambda_g \times 0.16\lambda_g$, at center frequency of the first passband. The proposed filter is suitable for GSM (1.8 GHz), LTE (2.3 GHz), WLAN (5.2 to 5.8 GHz) applications.

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