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A Compact Via-Less Metamaterial Wideband Bandpass Filter Using Split Circular Rings and Rectangular Stub

Dilip Kumar Choudhary and Raghvendra Kumar Chaudhary*

Abstract—A compact via-less metamaterial (MTM) wideband bandpass filter using split circular rings, meander-line and rectangular stub is reported in this letter. The split circular rings produce series capacitance and a meander line along with a rectangular stub gives shunt inductance and capacitance. The measured insertion loss has 0.60 dB and return loss above 15 dB with 3 dB fractional bandwidth 74.28% at centre frequency 3.25 GHz. The zeroth order resonance frequency of proposed filter is guarded by shunt parameters due to its open ended boundary condition. The electrical size of the suggested filter is $0.12\lambda_g \times 0.22\lambda_g$ at ZOR frequency of 2.3 GHz. The designed structure has been fabricated and experimentally validated. The designed filter offers group delay variation between 0.2ns to 0.7 ns within the passband. It is suitable for WLAN, WiMAX, Bluetooth applications.

1. INTRODUCTION

In last decade, ultra-wideband applications of wireless communication have encouraged the evolution of wideband filter. Low insertion loss, compact size and ease of integration are essential in modern wireless communication system to design a filter [1]. Recently, numerous bandpass filter have been proposed to accommodate the demand of wideband applications. Quadruple mode ring resonator based wideband filter gives high selectivity and high out-of-band rejection [2]. Wideband filter by using multiple ring resonator achieves low insertion loss and good sharpness factor [3].

Nowadays, the concept of electromagnetic metamaterial (MTM) has been used to design bandpass filter to improve the performance and achieve compactness. MTM is artificial engineered structure whose size is less than guided quarter wavelength [4]. It has negative refractive index and antiparallel group and phase velocities. Left-handed (LH) material was first investigated theoretically in 1968 by Russian physicist Viktor Veselago [5]. Backward wave generation appears by designing LH material due to triplet made between electric field, magnetic field and wave number. Unavoidable parasitic series inductance and shunt capacitance appears by designing LH Transmission line (TL) which made Composite right/left handed (CRLH) TL [6]. Filters based on MTM TL approach with CPW provides compactness and wide bandwidth [7]. Wideband bandpass filters are reported using open split ring resonator and double slit complementary split ring resonator for getting miniaturization and good selectivity [8, 9]. A wideband bandpass filter has been proposed by connecting high pass and low pass filter using open slot split ring resonator and compact microstrip resonating cell [10]. MTM based compact filter has been designed using fractal spiral resonator [11]. A compact band stop and bandpass filter have been proposed using small MTM cell using fractal resonators [12, 13].

In this paper, a compact wideband bandpass filter is proposed and characterized using HFSS 14.0, CST 11.0 and circuit simulator software. The proposed filter has been designed using various circular ring with a gap to provide series capacitance and a meander line with a rectangular stub. Due to its

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* Corresponding author: Raghvendra Kumar Chaudhary (raghvendra.chaudhary@gmail.com).
The authors are with the Department of Electronics Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand 826004, India.

open ended structure, zeroth order resonance (ZOR) frequency depends on shunt parameters only. The size of the designed filter is $0.12\lambda_g \times 0.22\lambda_g$, where λ_g is the guided wavelength at ZOR frequency of 2.3 GHz. The designed structure has been fabricated and validated experimentally. It is suitable for WLAN, WiMAX, Bluetooth applications.

2. FILTER DESIGN

The configuration of the designed wideband bandpass and its equivalent circuit diagram are shown in Figure 1 and Figure 2. The designed filter consists of five split circular rings, a meander line, and a rectangular stub. In series, C_L represents the left-handed (LH) capacitance due to split in circular rings, and right-handed (RH) inductance L_R is due to current flowing in circular ring and the top metallic patch. The coupling capacitance C_p has been generated due to mutual coupling between circular rings. The shunt LH inductance L_L due to meander line, RH capacitance C_R represents the parasitic capacitance between circular rings and ground plane, and C_{rs} is the capacitance of rectangular stub acting as virtual ground. The extracted LC values using circuit simulator are: $L_R = 0.56$ nH, $C_p = 0.38$ pF, $C_L = 1.3$ pF, $L_L = 2.53$ nH, $C_{rs} = 4.04$ pF, and $C_R = 1.54$ pF.

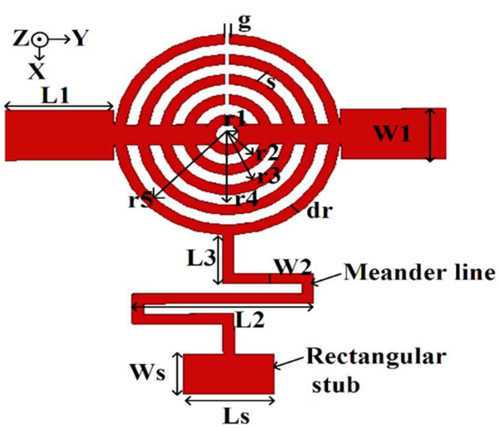

Figure 1. Configuration of designed wideband bandpass filter [All dimensions are in mm: $L_1 = 5.0$, $W_1 = 2.5$, $L_2 = 8.0$, $W_2 = 0.5$, $L_3 = 2.5$, $L_s = 4.0$, $W_s = 2.0$, $g = 0.2$, $s = 0.5$, $r_1 = 4.5$, $r_2 = 3.5$, $r_3 = 2.5$, $r_4 = 1.5$, $r_5 = 0.5$].

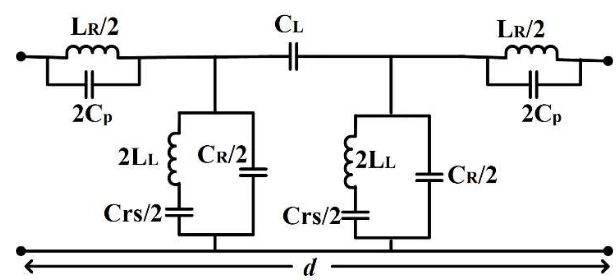

Figure 2. Equivalent circuit diagram of designed bandpass filter.

Equivalent circuit contains two series impedances $Z_{se1} = \frac{1}{j\omega 2C_p + \frac{2}{j\omega L_R}}$, $Z_{se2} = \frac{1}{j\omega C_L}$, and two shunt admittances, $Y_{sh} = \frac{1}{2j\omega L_L + \frac{2}{j\omega C_{rs}}} + \frac{j\omega C_R}{2}$. The $ABCD$ matrix of given network in Figure 2 is

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z_{se1} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_{sh} & 1 \end{bmatrix} \begin{bmatrix} 1 & Z_{se2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_{sh} & 1 \end{bmatrix} \begin{bmatrix} 1 & Z_{se1} \\ 0 & 1 \end{bmatrix} \tag{1}$$

By performing the matrix multiplication as given in Eq. (1), the transmission parameters of the designed filter will become

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} (1 + Z_{se1}Y_{sh})(1 + Z_{se2}Y_{sh}) + Z_{se1}Y_{sh} & (1 + Z_{se1}Y_{sh})(2Z_{se1} + Z_{se2}(1 + Z_{se1}Z_{se2}Y_{sh})) \\ Y_{sh}(2 + Z_{se2}Y_{sh}) & (1 + Z_{se1}Y_{sh})(1 + Z_{se2}Y_{sh}) + Z_{se1}Y_{sh} \end{bmatrix} \tag{2}$$

The metamaterial properties of CRLH TL structure can be verified by dispersion diagram which can be obtained by Bloch-Floquet theorem [14].

$$\beta = \frac{1}{d}\cos^{-1}\left[\frac{A + D}{2}\right] = \frac{1}{d}\cos^{-1}[A] \tag{3}$$

Bloch impedance is the characteristics impedance at the unit cell terminal [15]. The Bloch impedance in terms of transmission ($ABCD$) parameter is

$$Z_B = \frac{B}{\sqrt{A^2 - 1}} Z_0 \tag{4}$$

where, Z_0 is the characteristic impedance. The dispersion relation of the proposed bandpass filter can also be achieved using scattering parameters [16].

$$\beta = \frac{1}{d} \cos^{-1} \left[\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}} \right] \tag{5}$$

Using scattering parameters the Bloch impedance can be presented as [17]

$$Z_B = \frac{j2S_{21} \sin(\beta d)}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}} Z_0 \tag{6}$$

Zeroth order resonance (ZOR) frequency is the frequency at which the propagation constant (β) is equal to zero. The designed filter is an example of open ended structure, so the ZOR frequency depends only on shunt parameters. This can be evaluated as, for open ended input impedance (Z_{in}^{open}) of resonator is,

$$Z_{in}^{open} = -jZ_0 \cot(\beta l)^{\to 0} = -jZ_0 \frac{1}{\beta l} = -j\sqrt{\frac{Z(\omega)}{Y(\omega)}} \frac{1}{\left(-j\sqrt{Z(\omega)Y(\omega)}\right) l} = \frac{1}{NY(\omega)} \tag{7}$$

where, N is the number of unit cell and l the length of designed filter ($l = N \cdot d$). The group delay (T_d) is the rate of change of transmission phase angle with respect to frequency [15].

$$T_d = -d\varphi / d\omega \tag{8}$$

where, ϕ is the transmission phase angle and ω the frequency.

3. ANALYSIS OF RESULTS

The designed filter is printed on an FR-4 epoxy substrate ($\varepsilon_r = 4.4$, tan$\delta = 0.02$) with 1.6 mm thickness and its prototype shown in Figure 3. Scattering parameters and group delay of the proposed filter have been measured from Agilent PNA network analyzer N5221A. The scattering parameters of the proposed filter is presented in Figure 4. The measured 3 dB fractional bandwidth of passband is 74.28% with insertion loss 0.60 dB and return loss more than 15 dB throughout the passband. The proposed filter

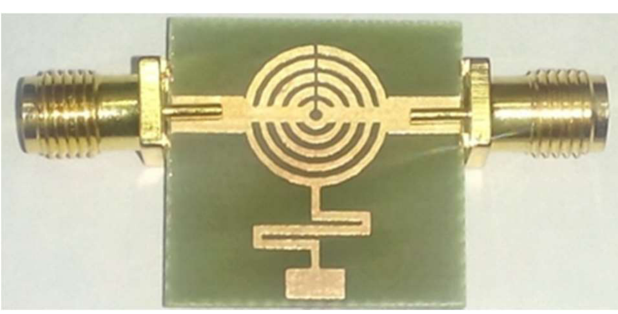

Figure 3. Fabricated prototype of proposed bandpass filter.

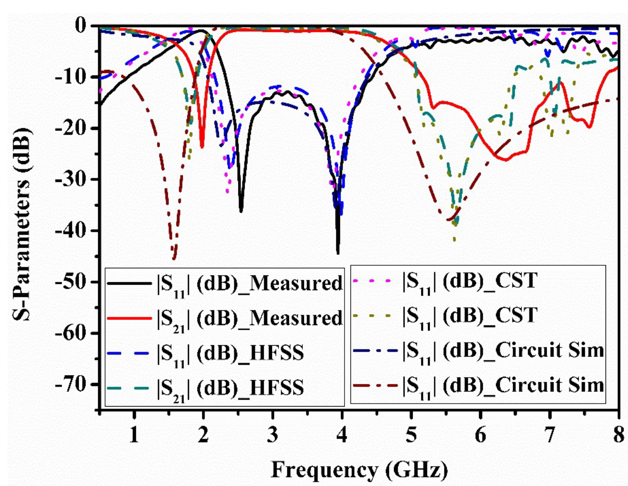

Figure 4. Scattering parameters of proposed bandpass filter.

Table 1. Measured output parameters of proposed filter.

Parameters	Simulated (HFSS)	Simulated (CST)	Circuit Simulator	Measured
Resonance frequencies (f_1, f_2)	2.3 GHz, 3.9 GHz	2.32 GHz, 3.9 GHz	2.26 GHz, 3.91 GHz	2.55 GHz, 3.95 GHz
3-dB Bandwidth (BW)	2.64 GHz	2.60 GHz	2.46 GHz	2.60 GHz
3-dB Fractional BW	80.48%	79.26%	76.63%	74.28%
Insertion loss ($\|S_{21}\|$)	0.35 dB	0.35 dB	0.12 dB	0.60 dB
Return loss ($\|S_{11}\|$)	$>$ 13.5 dB	$>$ 14 dB	$>$ 14.9 dB	$>$ 15 dB
Group delay (ns)	0.2	0.25		0.70
Out of Band rejection	at (3.25 ± 1.5) GHz better than 20 dB	at (3.25 ± 1.5) GHz better than 25 dB	at (3.25 ± 1.5) GHz better than 30 dB	at (3.25 ± 1.5) GHz better than 18 dB

has two poles at their resonance frequencies 2.55 GHz and 3.94 GHz, respectively. The measured results are approximately similar to simulated ones with a slight shift in ZOR frequency. This shift can occur due to imperfection of substrate and connector losses. The simulated results using HFSS 14.0, CST 11.0 and circuit simulator software are almost same. The simulated and measured results are compared in Table 1.

The simulated dispersion diagram is shown in Figure 5 which shows the frequency band from 1.9 to 2.3 GHz with negative slope known as LH band. The frequency band from 2.3 to 4.8 GHz with positive slope is called as RH band. The frequency 2.3 GHz is known as zeroth order resonance frequency. The

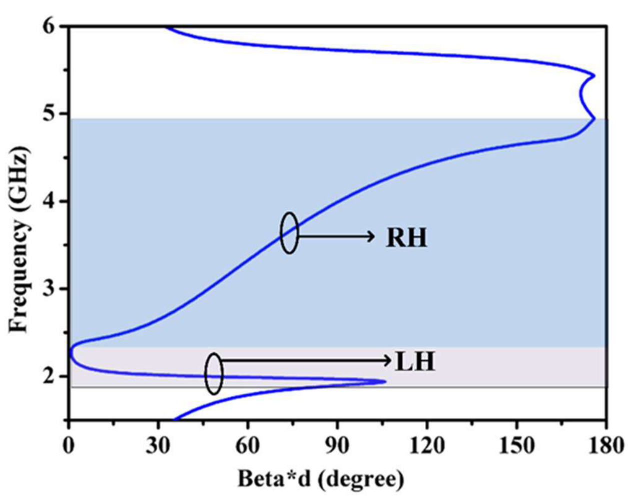

Figure 5. Simulated dispersion diagram of proposed filter.

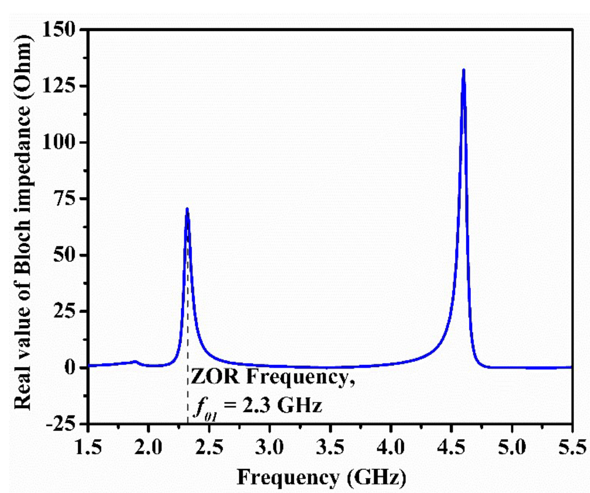

Figure 6. Simulated real value of Bloch impedance of proposed filter.

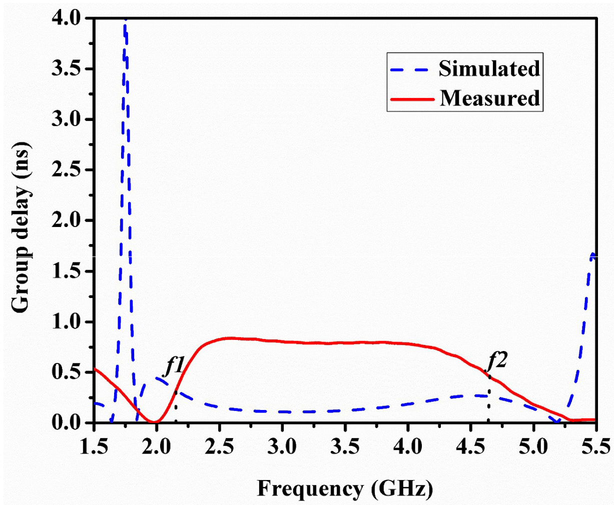

Figure 7. Group delay characteristics of proposed filter.

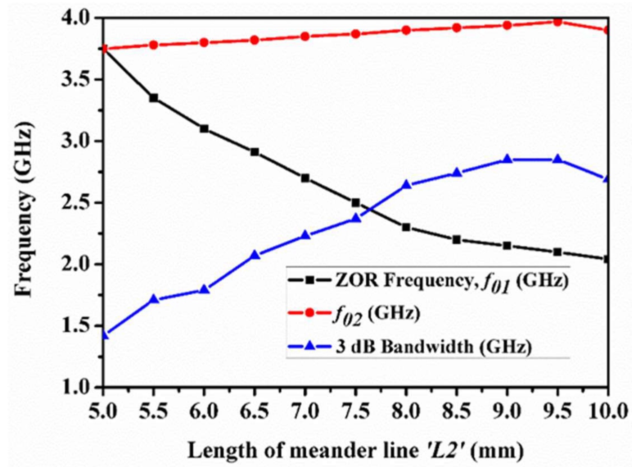

Figure 8. Variation in resonance frequencies and bandwidth by varying meander line length (L_2).

dependency of Bloch impedance on frequency is shown in Figure 6 which shows that the value of Bloch impedance is maximum at ZOR frequency, 2.3 GHz. Figure 7 shows the group delay characteristics of the proposed filter and shows slightly variation between simulated and measured group delay. The variation is about 0.5 ns. Results show that the group delay is nearly flat in the pass-bands. The proposed structure shows the average group delay of less than 0.70 ns in the passband.

Variation in resonance frequencies (f_{01}, f_{02}) and bandwidth with respect to meander line length (L_2) is shown in Figure 8. As the length of meander line increases, the shunt inductance L_L increases, which changes the ZOR frequency to lower value, and the other resonance frequency ($f_{02} = 3.9$ GHz) moves toward higher value with minor change. The bandwidth increases while increasing meander line length. Figure 9 depicts the variation in resonance frequencies (f_{01}, f_{02}) and bandwidth with different values of gap of circular ring (g). It shows the variation in the second resonance frequency (f_{02}) with change in the series capacitance (C_L) due to gap of circular rings (g). As the gap of circular ring increases, the series capacitance decreases, which shifts the second resonant frequency (f_{02}) towards higher value, but the ZOR frequency ($f_{01} = 2.3$ GHz) remains approximately same. Bandwidth varies

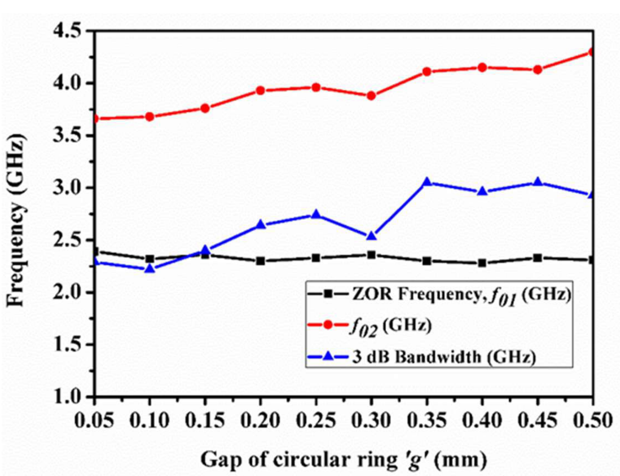

Figure 9. Variation in resonance frequencies and bandwidth by varying gap (g) of circular ring.

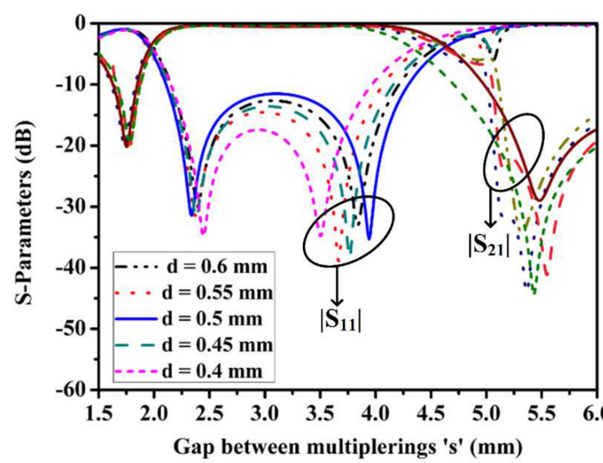

Figure 10. Scattering parameters with respect to gap between multiple ring 's'.

according to shift in the second resonance frequency, which confirms that for open ended boundary condition the ZOR frequency depends only on shunt parameters.

The effects of mutual coupling between the multiple rings on scattering parameters are shown in Figure 10. As the gap between multiple rings varies, the resonance frequency varies. The surface current plots for resonance frequencies 2.3 GHz and 3.9 GHz are included in Figure 11. It is noticed that ZOR frequency at 2.3 GHz is mainly affected by meander line, and the other resonance frequency 3.9 GHz is mainly due to the outer ring which connects feed line. Table 2 shows the comparison of filter parameters of suggested design with previous published wideband filters. It is clear from Table 2 that the proposed filter offers wider bandwidth and more compact size than previous presented work.

Table 2. Comparison of performance of proposed filter with earlier published work.

Parameters	This work	Earlier published work						
		[2]	[7]	[18]	[19]	[20]	[21]	[22]
Electrical size (λ_g)	0.12×0.22	0.23×0.72	0.38×0.61	0.25×0.45	0.22×0.29	0.26×0.36	0.26×0.30	0.55×0.3
Resonance frequency (GHz)	2.3	1.45	5.8	3.5	3.25	2.28	2.45	3.1
3-dB Fractional bandwidth (%)	80.48	57.9	32.5	70	21.2	-	3.5	20.9
Return loss (dB)	> 13.5	> 18.8	23	20	17	> 14	> 15	> 11
Insertion loss (dB)	0.35	0.66	2.5	0.7	1.0	1.58	2.3	2.55

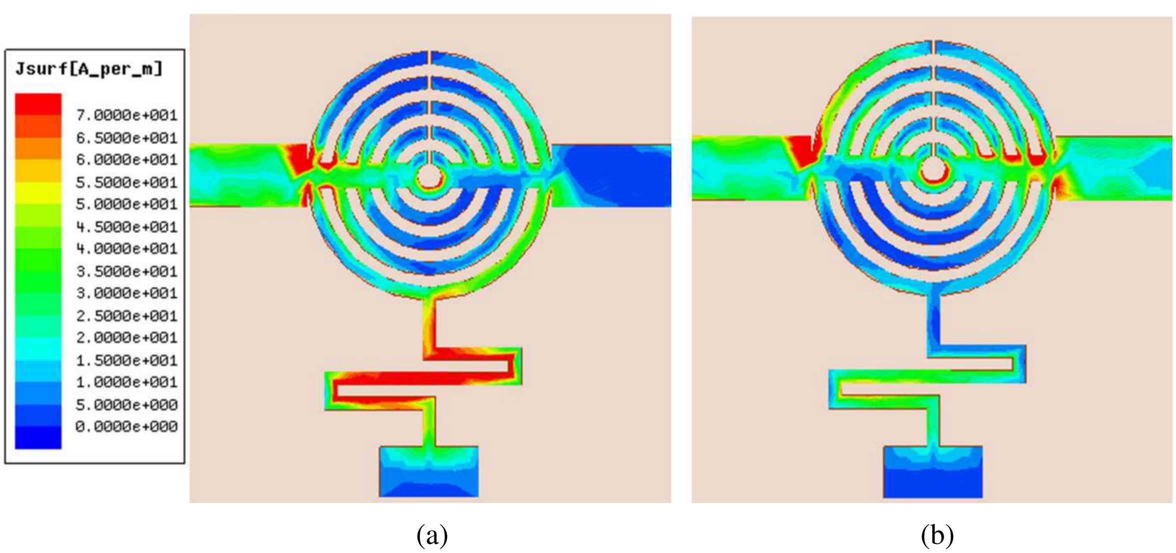

Figure 11. Surface current density of proposed filter at different frequencies: (a) 2.3 GHz and (b) 3.9 GHz.

4. CONCLUSION

In this paper a compact metamaterial wideband bandpass filter is proposed and printed on an FR4 substrate. Filter layout consists of circular rings with a gap to provide series capacitance and a meander line with a rectangular stub. The rectangular stub works as a virtual ground, which makes the structure vialess to avoid fabrication complexity. The proposed filter has a passband from 1.9 to 4.8 GHz with two poles at 2.3 GHz and 3.9 GHz with approximately 0.6 dB insertion loss and minimum 15 dB return loss using simulation. The fractional bandwidth is 80.48%. The filter size is only ($10 \times 18\,\text{mm}^2$), which is ($0.12\lambda_g \times 0.22\lambda_g$) at the ZOR frequency. The proposed filter is suitable for WLAN/Wi-Fi (2.4–2.49 GHz), WiMAX (2.5–2.69 GHz, 3.3-3.6 GHz) and Bluetooth (2.4–2.48 GHz) applications.

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