

Miniaturised ultra-wideband band-pass filter using quasi-lumped symmetrical EBG

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Abstract: This study presents a novel design of a miniaturised ultra wideband (UWB) band-pass filter (BPF) by integrating quasi-lumped structure with electro-magnetic band gap (EBG) cells. The proposed filter is designed to cover the UWB bandwidth of 3.1–10.6 GHz. The UWB BPF filter design is validated using both circuit simulation and electromagnetic full wave simulation. The compact UWB BPF is simulated, fabricated and the performance metrics are measured. A good agreement between simulated and measured results is obtained. Good performances such as return loss better than 14 dB, upper stop-band attenuation better than 20 dB and good selectivity are achieved.

1 Introduction

As radio systems evolve, they dictate the need for ultra wideband (UWB) filters with good performance while requiring compact size and reduced cost. However, the key challenge is the effect of parasitic capacitances with respect to transmission lines at high frequencies. The effect is even more pronounced for compact size up to 5 GHz. The micro-strip line short sections and stubs with physical length smaller than $\lambda_g/4$ are the basic units for approximate microwave realisation of lumped elements in micro-strip filter structures; these lumped elements are termed as quasi-lumped elements [1]. Micro-strip resonators present strong radiation loss [2] if they are used as filtering elements. Short circuit termination radiates less than open circuit termination and, therefore, can be considered a means to reducing radiation losses in micro-strip resonator structures [3].

In this paper, the focus is on quasi-lumped resonators such as compact planar resonators with dimensions much smaller than the operating wavelength, λ . The primary advantage is its full compatibility with planar technology [4, 5]. In the literature, several design techniques for realising UWB micro-strip filters are proposed. They are widely used in the form of multi-mode resonators (MMRs) [6]. Studies indicate that the length of the micro-strip MMR must be one-half of the wavelength at the centre frequency. This results in a filter with prohibitively larger dimensions. Thus, size reduction is one of the major issues in the design of UWB BPF. The researches on length reduction of UWB BPF have been reported in [7–12]. In [7], a compact UWB band-pass filter (BPF) using a dual stub loaded resonator (DSLRL) is presented. Four resonant modes which could be tuned by the DSLRL were allocated 3.1–10.6 GHz to obtain an UWB pass-band. In [8], the design of UWB BPF with dual band-notch performance is presented. This paper also proposes a filter which provides high selectivity and also improved out-of-band performance. In [9], a technique is proposed for the design of a compact UWB filter using one unit cell of a composite right/left handed transmission line (CRLH-TL). The series capacitance of the CRLH-TL is realised in the form of inter-digital lines and the shunt inductance is realised through a via hole connected to the ground. In [10], a multi-stub-loaded ring resonator is proposed for achieving a UWB BPF; the resonant characteristics are also analysed theoretically using the odd- and even-mode methods. In [11], a compact UWB-BPF based on broadside coupling of micro-strip-to-coplanar waveguide transition is presented. In [12], a method for the design of balanced UWB BPF is proposed which is not only compact but also provides good common mode suppression characteristics.

In this paper, a UWB BPF loaded with quasi-lumped EBG structures for improved performance is designed and fabricated. The rest of the paper is organised as follows. Section 2 presents the design of quasi-lumped structure with electro-magnetic band gap (QLS EBG) resonator; Sections 3 and 4 present the realisation of UWB BPF using QLS EBG, respectively; Section 5 presents the results, and conclusion of the present research is presented in Section 6.

2 Design of QLS EBG resonator

The lumped element model of the proposed EBG is shown in Fig. 1. The values of inductance L and capacitance C are determined by the geometry of the EBG. The band gap feature of the EBG structure is interpreted in terms of the EBG resonance behaviour.

EBG cells are characterised by self-resonance property. At high frequencies, the change of the characteristic impedance of transmission line is used for defining unit cells. Therefore, the effects of the self-resonances are expected to overlap the same frequency range. The unit cell of the periodic structure of the EBG has a wider frequency response and smaller Q factor compared with the frequency response of a resonator having a higher Q factor. The QLS EBG resonator unit cell exhibits slow wave pass-band and stop-band characteristics which are required to achieve low-pass performance and compact size. This EBG resonator is designed by taking the rectangular patch as the basic unit. The capacitive gap is introduced by creating four rectangular resonant slots at the edges of the patch. The dimensions of the edge resonators and capacitive gaps are tuned to optimum values. Fig. 2 shows the structure of the QLS EBG with three different tuning gaps, namely, G1, G2 and G3. Fig. 2a shows the QLS EBG resonator with four rectangular stubs at the corners of the rectangular patch with small capacitive gaps G1, G2 and G3. Fig. 2b shows the QLS EBG resonator with four rectangular stubs with large

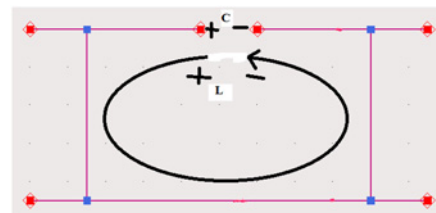


Fig. 1 Lumped L - C model for EBG analysis

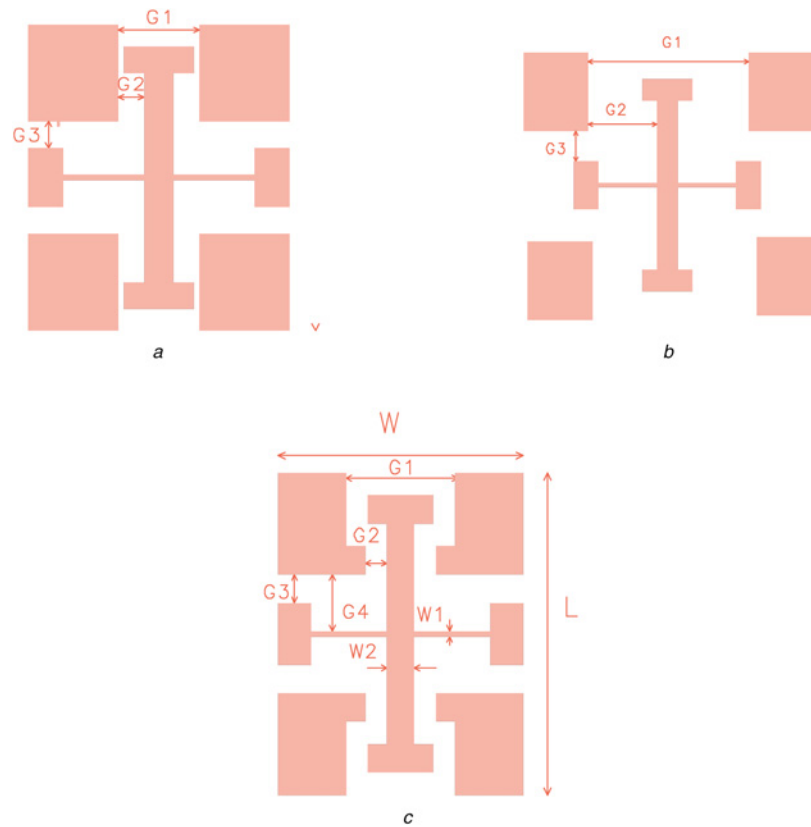


Fig. 2 Structure of the QLS EBG resonator

a QLS EBG resonator with rectangular stub unit cell structure ($G1 = 3$ mm, $G2 = 1$ mm, $G3 = 1$ mm)

b QLS EBG resonator with square stub and long gap unit cell structures ($G1 = 7.7$ mm, $G2 = 3.3$ mm, $G3 = 1.4$ mm)

c QLS EBG resonator L-shape unit cell structure ($G1 = 4$ mm, $G2 = 0.8$ mm, $G3 = 1$ mm, $G4 = 2$ mm, $W1 = 0.2$ mm, $W2 = 1$ mm, $W = 9$ mm, $L = 11.4$ mm)

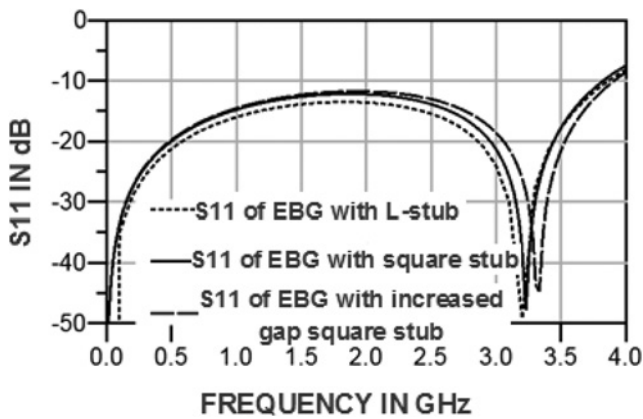


Fig. 3 Comparison of S_{11} parameter of QLS EBG resonator

capacitive gaps $G1$, $G2$ and $G3$. Fig. 2c shows the QLS EBG resonator with L-shape stubs at the edges of the rectangular patch with optimum capacitive gaps $G1$, $G2$ and $G3$. The simulated $|S_{11}|$ of Figs. 2a–c is compared in Fig. 3. The result shows that the resonant frequency is shifted towards the lower frequency range as the dimensions of the gap are decreased.

The equivalent circuit of the QLS EBG resonator is derived, and the parameters are determined through curve fitting method using full wave simulation results. The resultant values are $L1 = 10$ nH, $L2 = 9.5$ nH, $L3 = 0.1$ nH, $L4 = 0.1$ nH, $C1 = 0.2$ pF and $C2 = 0.5$ pF. The final optimised circuit is shown in Fig. 4. The characteristics of the pass-band and stop-band can be easily controlled using the elements in the circuit model of the

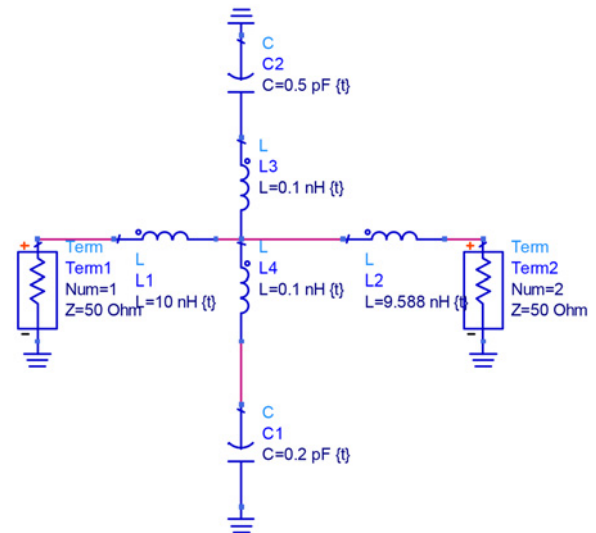


Fig. 4 Lumped L–C model for QLS EBG resonator

EBG resonator that has direct relation with the physical dimensions. The simulated $|S_{11}|$ of the QLS EBG using advanced design system (ADS) tool is shown in Fig. 5 along with equivalent circuits having three different $C2$ and constant $C1$. The result shows that, the resonance frequency is shifted towards the low-frequency range as capacitance $C2$ increases. It shows that the effect of $|S_{11}|$ with respect to the variation of capacitive impedance gap $G2$ and $G3$ of the stub is the same as the lumped capacitive element.

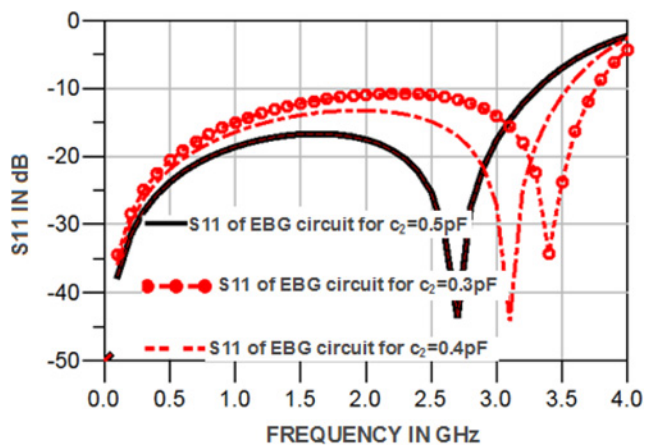


Fig. 5 Simulated $|S_{11}|$ for QLS EBG resonator equivalent circuit with three different C_2 values

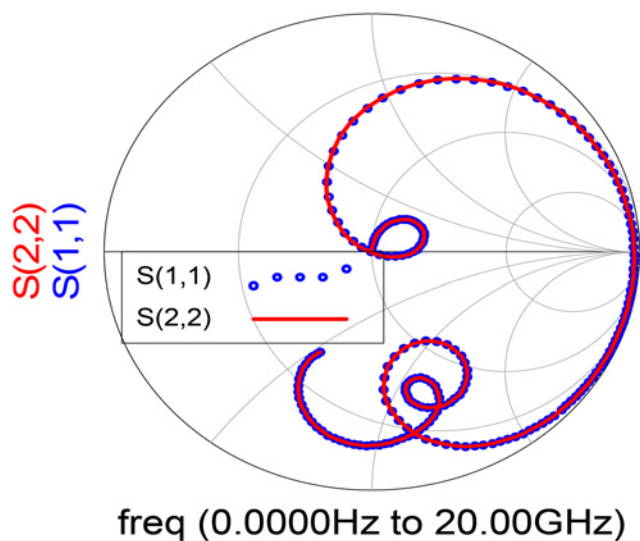


Fig. 6 Electrical symmetry property of QLS EBG resonator

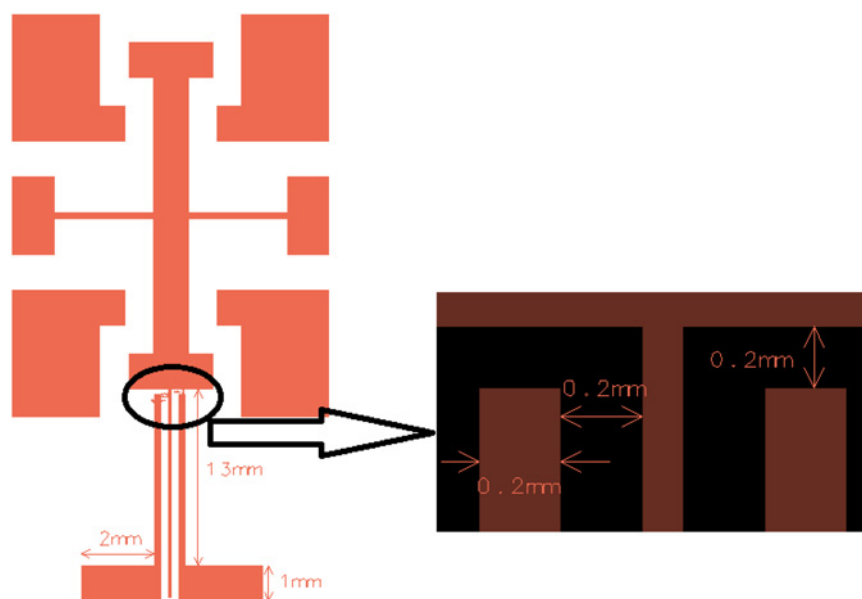


Fig. 7 Layout of unit cell QLS-EBG wideband BPF

The electrical symmetry property of QLS resonator is shown in Fig. 6.

3 Wideband BPF with unit cell QLS EBG structure

In this section, low-pass response is further modified to obtain the band-pass characteristics by embedding the resonator in the inter-digital coupled feed line as shown in Fig. 7. The inter-digital coupled lines used in BPF exhibit peak coupling at 6.85 GHz. The inter-digital pattern is perforated in the ground plane, and is connected to the shunt meander line to increase the loaded capacitance. The feed consists of three strips with a gap of 0.2 mm, end strip of 0.2 mm and centre strip of 0.2 mm. The cut-off frequency and pass-band frequency are inversely proportional to the longitudinal size of the QLS EBG resonator.

The QLS EBG based BPF is constructed with characteristic impedance $Z_0 = 50 \Omega$ using FR4 substrate with $\epsilon_r = 4.3$ having a thickness of 1.6 mm. The embedded QLS EBG is connected to inter-digital coupled feed lines. The layout is simulated using ADS. The transmission and reflection characteristics are shown in Fig. 8.

4 Design of UWB BPF with two unit-cell QLS EBG structures

A UWB BPF is designed by cascading two unit cells of QLS EBG structure. Each EBG unit cell having a length $\lambda_g/4$ and characteristic impedance 50Ω is cascaded as shown in Fig. 9. The cascaded resonators are connected to the inter-digital coupled feed lines at the centre of the cascaded stub. The lower part of the centre stub is shorted with series of via holes to avoid in-band ripple. The via-holes not only control the resonance frequency, but also produce a deformation in the local field around it. This depends on its size and position. It causes a major fringe capacitance null and local fields around it.

It is observed that the filter has a pass-band that covers the entire UWB frequency, i.e. 3.1–10.6 GHz. It has attenuation of more than 35 dB/octave in the stop-band. The insertion loss is as low as 0.4 dB and the return loss is also lower than 14 dB. Its upper stop-band rejection level is >10 dB up to 20 GHz.

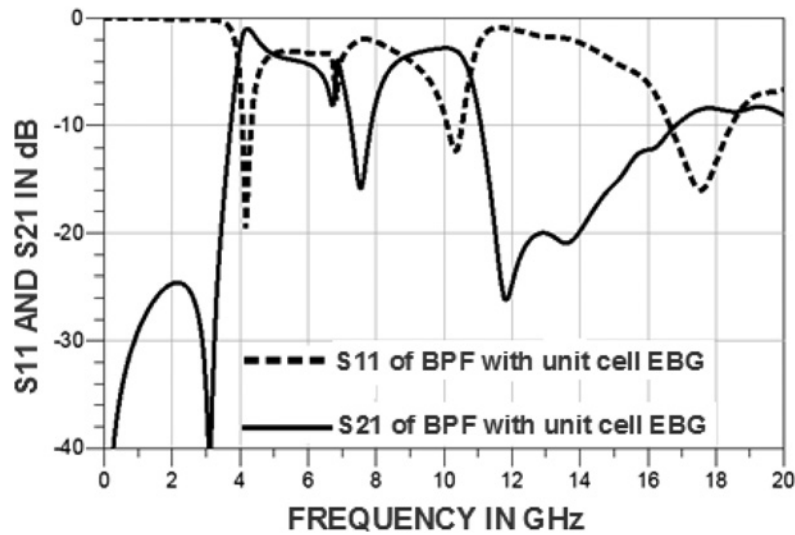


Fig. 8 Simulated transmission and reflection characteristics

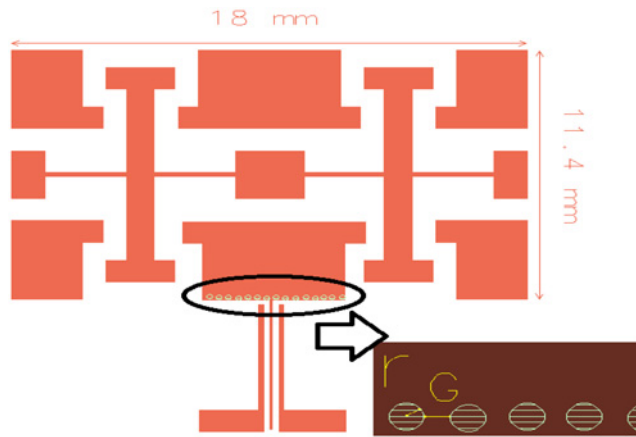


Fig. 9 Layout of complete UWB BPF with good in-band ripple

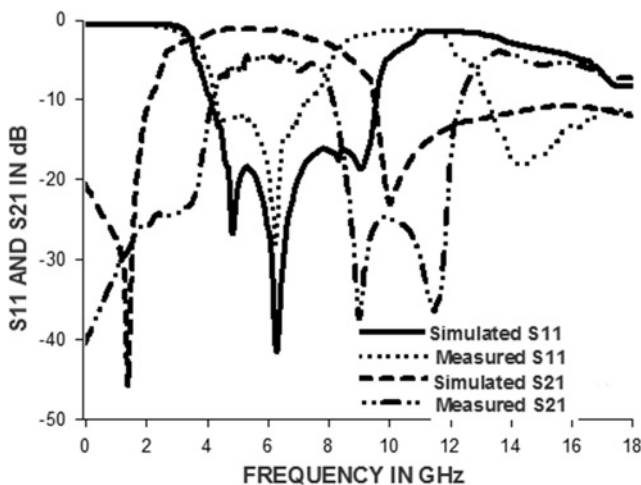


Fig. 10 Comparison of simulated and measured results of filter

5 Fabrication and measured results

The UWB BPF based on QLS EBG is fabricated using an FR4 material of thickness 1.6 mm and relative permittivity 4.3. The simulated and measured results are shown in Fig. 10. The

Table 1 Performance comparison table

Ref.	IL, dB	RL, dB	FBW, %	f_L , GHz	f_H , GHz	Size $\lambda_0 \times \lambda_0$
[7]	<1.5	>10	122	2.9	10.9	0.51×0.33
[8]	0.5	14	122	5.5	13.6	0.29×0.79
[10]	<0.9	>12.8	108	3.0	10.0	0.56×0.56
[12]	<1.5	>10	108	3	10	2.1×0.75
this work	0.4 (simulated)	15	110	3.1	10.6	0.45×0.38

IL, insertion loss over the pass-bands; RL, return loss over the whole pass-bands; f_L , the central frequency of lower band-notch; f_H , the central frequency of higher band-notch; FBW, fractional bandwidth; ϵ_r , substrate dielectric constant; h , substrate thickness; λ_0 , the free-space wavelength of the operating frequency at the centre of the pass-band (6.85 GHz).

fabricated filter is shown in Fig. 11. It can be seen that the simulated and measured results follow a similar trend; the deviations observed are attributed to the lossy nature of commercially available printed circuit board, connectors and the cables used in measurement setup. The performance of the proposed QLS-EBG based UWB BPF is given in Table 1. From the table, it is evident that the proposed design results in the most compact solution compared with the solutions available in literature.

Fig. 12 shows that there has been uniform distribution of the current of the filter and Fig. 13 confirms that the current density is maximum except on the edges.

6 Conclusion

A novel design approach is proposed for UWB micro-strip filter using QLS EBG unit cell for the reduction of the size and enhancing the performance of the filter. The measured results show that the proposed UWB filter exhibits significantly improved performance, and has smaller size when compared to other reported UWB filters. The filter has high selectivity, compact size (0.45×0.38) λ_0 . The filter exhibits an attenuation level >20 dB at both lower and upper stop-bands. Moreover, the filter has an insertion loss of 0.5 dB, a return loss better than 14 dB and a fractional bandwidth of more than 100% at 6.8 GHz centre frequency.

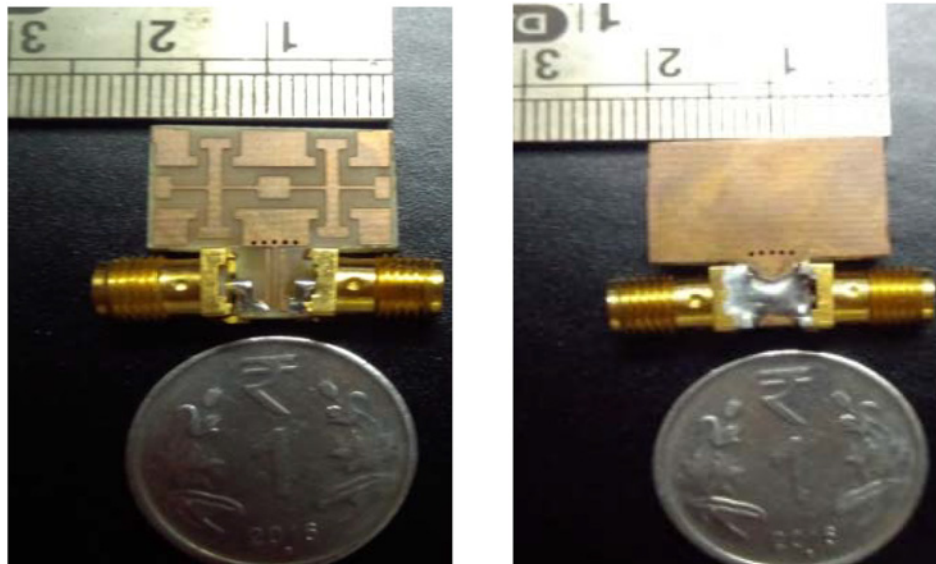


Fig. 11 Front side and back side photograph of the fabricated filter

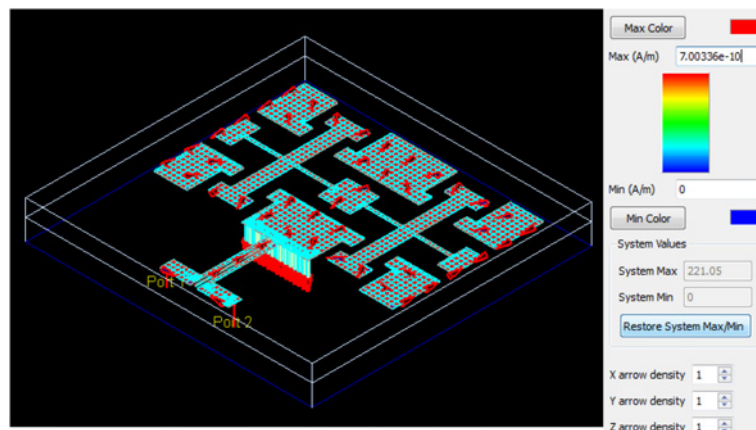


Fig. 12 Three-dimensional view of the filter showing current distribution and mesh

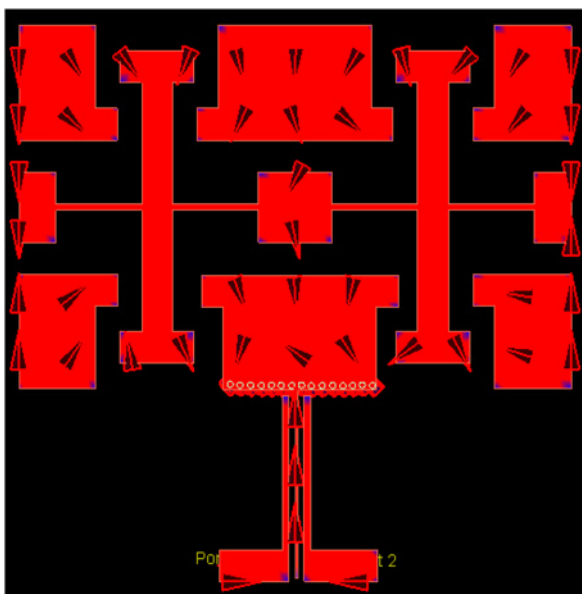


Fig. 13 Surface current density of the filter

7 References

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