



COMPACT ULTRA-WIDEBAND STEPPED-IMPEDANCE LOW PASS FILTER UTILIZING OPEN CIRCUIT STUB RESONATOR

Nur Baya Mohd Hashim, Mohammad Shahrazel Razalli, Siti Zuraidah Ibrahim and Fazlina Farid

School of Computer and Communication Engineering, d/a School of Manufacturing Engineering, Universiti Malaysia Perlis, 1st Floor, Pauh Putra Campus, Universiti Malaysia Perlis, Arau, Perlis, Malaysia

E-Mail: baya.hashim@gmail.com

ABSTRACT

A novel microstrip low pass filter based on stepped-impedance is presented with compact size and wide stop band. The properties of a single open circuit stub resonator is investigated and connected in parallel to a conventional stepped-impedance low pass filter. As a result, the performance of the conventional filter is significantly improved by exhibiting sharp response cut-off and better rejection level of stopband. The total size of the filter is only 21.48mm x 6.14mm with a cut-off frequency of 6.3GHz. On the other hand, wide stop band is achieved with attenuation level higher than 20dB is from 6.8GHz to 18GHz. The insertion loss is less than 1dB in the whole passband. The proposed filter is successfully verified in theory and simulated using full wave EM simulator.

Keywords: low pass filter, stepped-impedance, open stub resonator, wide stop band, insertion loss.

INTRODUCTION

Filter is a part of crucial components in microwave communication systems and radio frequency (RF) circuits. It provides a great opportunity for researchers around the world to explore the benefits of filter. Filters are used either to separate or combine the selected frequencies in the band to fulfil the required specifications. Low pass filter (LPF) is among the basic filter types that allow the lower frequency to pass into the signal while rejecting the higher frequency.

Hence, recent advances in wireless communication make the development and design of low pass filter becomes more challenging especially in ultra-wideband (UWB). The challenges are to overcome the suppression harmonics and spurious signals so that it performs well with minimum possible losses. Developing low pass filter that is compact in size and suitable to be integrated in UWB system that is operate between 3.1GHz to 10.6GHz has become the challenging research and offer diverse attraction from the researchers.

Basically, the conventional stepped-impedance LPF is suffering from narrow stopband, gradual transition and large dimension due to the high order filter in order to obtain sharp response (Hong and Lancaster, 2001). Therefore, several methods in designing low pass filter has been introduced by several researchers to overcome the sharpness of cut-off and the placement of transmission zeroes near to the cut-off. Sharp attenuation with three transmission zeroes is achieved by introducing microstrip ring resonator and two open stubs but the drawback of the design is not having wide stopband (Wuren *et al.*, 2008). The LPF with microstrip coupled-line hairpin unit, semi-circle defected ground structures and semi-circle stepped-impedance shunt stubs are cascaded to obtain sharp cut-off response and better rejection bandwidth (Wei *et al.*, 2010).

Defected ground structure (DGS) is also a part of the widely used method in low pass filter design. LPF exhibiting sharp cut-off response by employing split-ring resonator and elliptical defected ground structure is demonstrated to obtain good performance (Xi *et al.*, 2010). Further, a novel elliptic-function LPF consisting of a dumb-bell shaped, spiral shaped and microstrip DGS is employed to the design (Yang and Wu, 2008). The compact LPF is demonstrated by employing coupled gap-ring defected ground structure (CGRDGS) and the results show high selectivity and wider stopband (Zhang *et al.*, 2011). However, DGS method is suffering from fabrication difficulties and radiation loss.

Another method to be utilized is by using fractal shaped to enhance the performance of the pass band but narrow stop band and slow transition is occurred (Chen *et al.*, 2007). An effective size reduction technique is proposed by using Koch curve which is also part of fractal structure. The technique exhibit about 26% reduction compared to conventional LPF and not require complex calculation (Kumar and De, 2013).

Recent work on meta-material has shown potential result for low pass filter design by replacing the low impedance lines in conventional stepped-impedance LPF with rectangular split ring resonator (SRR) and etching rectangular complimentary split ring resonator (CSRRs) at the ground to obtain metamaterial low pass filter. The size of the filter is also reduced up to 30% and a compact size is achieved (Hameed *et al.*, 2014). New arrangement of meta-material has been designed by applying complimentary hexagonal-omega structures and exhibit compactness, sharp cut-off and low insertion loss. The hexagonal-omega structure is loaded to the ground of microstrip line in order to improve the sharpness of roll-off and the size of the filter (Sahu *et al.*, 2011).



Method presented by Verma (Verma *et al.*, 2013) has been chosen as the basis of this work, but the approach is different in obtaining the sharp cut-off and wide stopband for the low pass filter. In this paper, the roll-off and stopband characteristics of the conventional stepped-impedance LPF are significantly improved. The approach of this presented work is to apply the conventional step impedance with open circuit stub and it features both compact size and wide stopband. The low pass filter design is also meet the requirement of the UWB system.

STEPPED-IMPEDANCE LOW PASS FILTER DESIGN WITH OPEN CIRCUIT STUB

Structure of the proposed stepped-impedance LPF

Basically, the design is utilized from Chebyshev filter prototype with 0.1dB passband ripple with fifth order ($n=5$) and inductor is its first element. The general structure and the equivalent circuit for stepped-impedance microstrip low pass filter are shown in Figure 1(a) and (b). The structure is composed of alternating high and low impedance transmission line. High-impedance lines represent the series of inductor whereas the low-impedance lines act as a shunt capacitor.

Substrate used in this work is Roger 4003c with a relative dielectric constant, ϵ_r of 3.38 and a thickness, h of $35\mu\text{m}$. The characteristics impedance of high (Z_{0L}) and low (Z_{0C}) which referring to inductance and capacitance relatively are chosen as 110Ω and 24Ω .

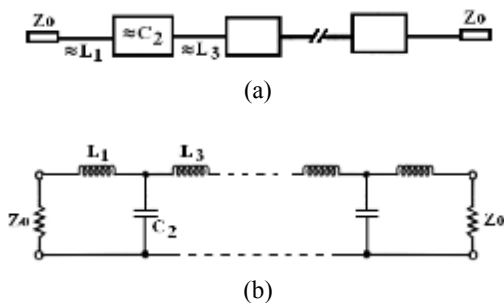


Figure-1. Stepped-Impedance LPF; (a)General structure (b) Equivalent circuit (Hong and Lancaster, 2001).

The fifth order ($n=5$) low pass filter with Chebyshev response is selected for this work and listed in Table-1.

Table-1. Element values for chebyshev lowpass response with the order of the filter.

n	g ₀	g ₁	g ₂	g ₃	g ₄	g ₅	g ₆
5	1	1.1468	1.3712	1.9750	1.3712	1.1468	1

For the normalized cutoff $\Omega_c = 1$, the value of lumped element in Figure 1(b) can be obtained from equations (1) and (2) where f_c is cut-off frequency and Z_0 is characteristics impedance.

$$L_i = \left(\frac{Z_0}{g_0} \right) \left(\frac{\Omega_c}{2\pi f_c} \right) g_i \quad \text{for } i = 1, 3 \text{ and } 5 \quad (1)$$

$$C_i = \left(\frac{g_0}{Z_0} \right) \left(\frac{\Omega_c}{2\pi f_c} \right) g_i \quad \text{for } i = 2, 4 \text{ and } 6 \quad (2)$$

Table-2 shows the calculated lumped element L and C values for the proposed filter design.

Table-2. Calculated lumped element values of inductor (L) and capacitance (C).

i	L (nH)	C (pF)
1	1.521	-
2	-	0.7274
3	2.6194	-
4	-	0.7274
5	1.521	-

The suitable design parameters to obtain the wavelength and impedances of microstrip lines are listed in Table-3.

Table-3. Design parameters of microstrip lines for a stepped-impedance LPF.

Characteristics impedance (Ω)	Z_{0L}	Z_{0C}	Z_0
	110	24	50
Guided wavelengths (mm)	λ_{gL}	λ_{gC}	λ_{g0}
	30.2	29.2	23.1
Microstrip line width (mm)	W_L	W_C	W_0
	0.2	3.25	1.14

Guided wavelength, λ_g can be calculated in mm directly by using equation (5) at 3 dB cut-off frequency



where the operation frequency is set at 6GHz and ϵ_{re} represent effective permittivity.

$$\lambda_g = \frac{300}{f(\text{GHz})\sqrt{\epsilon_{re}}} (\text{mm}) \quad (5)$$

The physical lengths of the high and low impedance lines in mm can be calculated using equations (6) and (7).

$$l_L = \frac{\lambda_{gL}}{2\pi} \sin^{-1} \left(\frac{w_c L}{Z_{ol}} \right) \quad (6)$$

$$l_c = \frac{\lambda_{gc}}{2\pi} \sin^{-1} (w_c C Z_{oc}) \quad (7)$$

All simulation results are accomplished using Advance Design System (ADS) 2013. The physical lengths dimension of high and low impedances line in mm for five-pole stepped-impedance LPF structure in Figure-2 can be summarized in Table-4.

Table-4. Physical lengths dimension of high and low impedances lines.

i	l_L (mm)	l_C (mm)
1	2.64	-
2	-	3.34
3	5.36	-
4	-	3.34
5	2.64	-

The response of the stepped-impedance LPF layout in Figure-2(a) is shown in Figure-2(b). The 3dB cut-off frequency of the initial low pass filter is 5.10GHz.

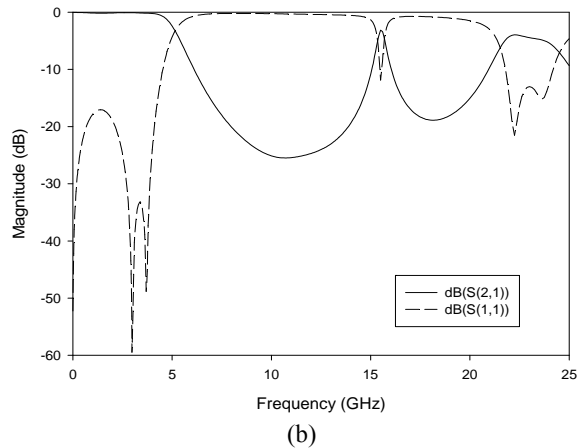
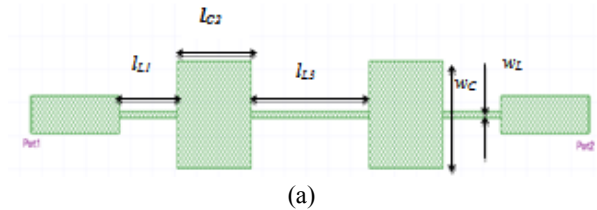


Figure-2. Proposed initial stepped-impedance LPF;

(a) Layout of microstrip structure (b) Simulated S-parameters result of microstrip structure.

Method of inductive line reduction to obtain accurate cut-off frequency

The response of the initial stepped-impedance LPF shows a 3dB cut-off frequency of 5.10GHz with initial length $l_{L1} = l_{L5} = 2.64\text{mm}$ and $l_{L3} = 5.36\text{mm}$. In order to get improved cut-off frequency, the initial lengths of the inductive line section need to be reduced while the capacitive line section is maintained (Verma *et al.*, 2013). Then, tuning need to be accounted into the design by further tuned on EM-simulator to get the final specified cut-off frequency.

The improved cut-off frequency can be computed from equation (8) after the length of inductive line section is modified.

$$l_{ind}^{mod} = \left(\frac{f_c^{initial}}{f_c^{specified}} \right)^2 \times l_{ind}^{initial} \quad (8)$$

where $f_c^{specified}$ is the specified frequency, l_{ind}^{mod} is the modified length of inductive line, $f_c^{initial}$ is the initial simulated cut-off frequency and $l_{ind}^{initial}$ is the initial inductive line length. Table V summarizes the value of the cut-off frequencies; initial, modified and final by



corresponding to the lengths of the inductive line; initial, modified and final.

As can be seen from Figure-2(b), the initial cut-off frequency is 5.10GHz which is about 15.0% less than the specified frequency. Figure-3 illustrates the simulated modified stepped-impedance LPF. When $L_1 = L_5 = 1.9\text{mm}$

and $L_3 = 3.9\text{mm}$, the result shows improvement about 3.33% less than the specified frequency. Figure 4 shows that by obtaining the correct cut-off frequency at 6GHz with corresponding to final correct inductive line length and the value of return loss in this range is higher than 30dB.

Table-5. Inductive line lengths; initial, modified and final at initial, modified and final cut-off frequency.

<i>i</i>	Initial l_L (mm)	Modified l_L (mm)	Final l_L (mm)	Cut-off frequency (GHz)		
				Initial l_L	Modified l_L	Final l_L
1	2.64	1.9	1.6	5.10	5.8	6.0
2	5.36	3.9	3.6	5.10	5.8	6.0
3	2.64	1.9	1.6	5.10	5.8	6.0

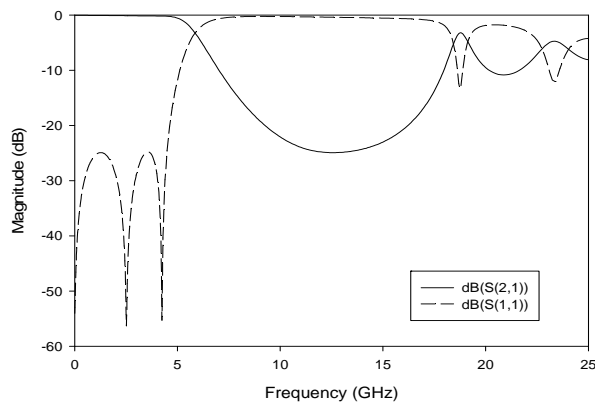


Figure-3. Simulated S-parameters result of the modified stepped-impedance LPF.

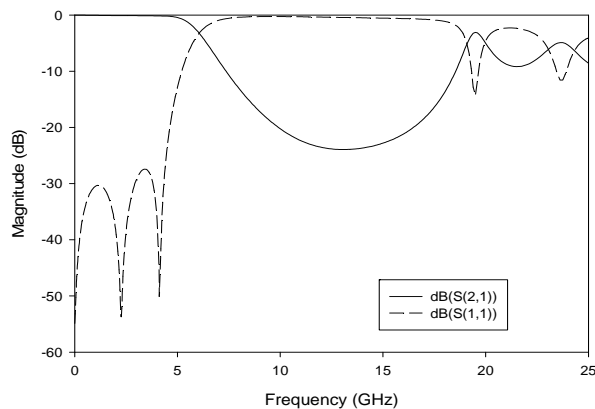


Figure-4. Simulated S-parameters result of the final stepped-impedance LPF.

Modification of stepped-impedance LPF

In order to achieve the sharp roll-off skirt instead of gradual attenuation, the resonance frequencies of a single open circuit stub are studied and implemented into the initial design of stepped-impedance LPF. According to the capability of the stepped impedance open stub that can create transmission zeros at the resonance frequency, hence this feature can boost up the function of the low pass filter to obtain wider stop band (Makki *et al.*, 2013).

The primary resonator design starts from the basic LC structure that can be calculated using (1) and (2). The value of the LC elements for this open circuit stub resonator is $L_1=2.45\text{nH}$, $L_2=2.45\text{nH}$, $L_3=0.7\text{nH}$ and $C_1=4\text{pF}$. The simulated result of the LC structure in Figure-5(a) can be obtained from Figure-5(b).

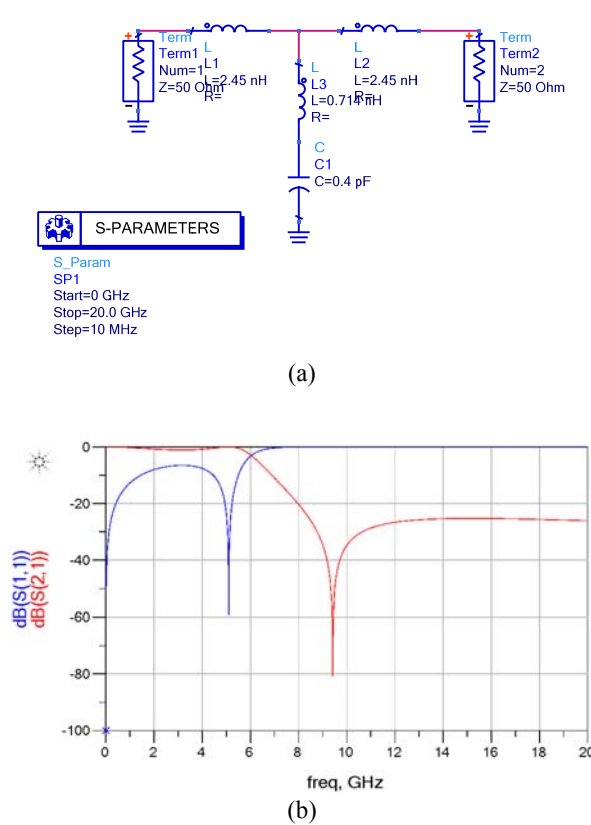


Figure-5. Proposed open circuit stub resonator; (a) LC model (b) Simulated S-parameters result of LC model.

The basic LC structure needs to transform into microstrip structure by converting each LC component to its equivalent microstrip line by using equations (3), (5), (6) and (7). Figure 6(a) shows the layout of the microstrip structure for the resonator. The same substrate is utilized with a relative dielectric constant, ϵ_r of 3.38 and a thickness, h of $35 \mu\text{m}$ while the characteristics impedance of high (Z_{0L}) and low (Z_{0C}) impedance are chosen as 110Ω and 24Ω . Dimension of the resonator that are used in the simulation is $l_1 = 9.58 \text{ mm}$, $l_2 = 1.16 \text{ mm}$, $l_3 = 3.25 \text{ mm}$, $l_4 = 1.72 \text{ mm}$, $w_1 = 0.2 \text{ mm}$ and $w_2 = 0.2 \text{ mm}$. It can be observed from Figure-6(b) that a transmission zero is generated at 7.1 GHz with attenuation level of -45.22 dB.

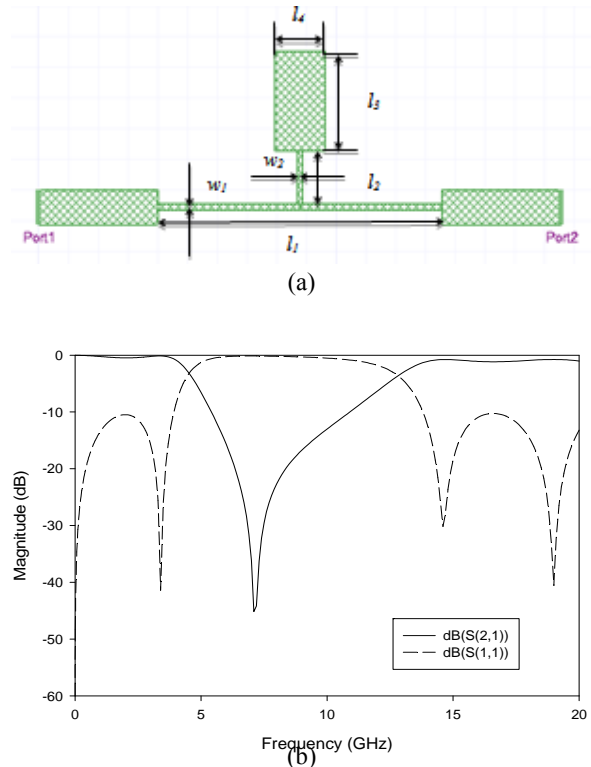


Figure-6. Proposed open circuit stub resonator; (a) Layout of microstrip structure (b) Simulated S-parameters result of microstrip structure.

In order to design a compact stepped-impedance LPF that can achieve sharp cut-off frequency response and wide stop band, an improved conventional stepped-impedance low pass filter as can be seen in Figure-2(a) is loaded with a single open circuit stub resonator. Figure-7(a) illustrates the layout of the proposed low pass filter that has been modified. Resonator is connected in parallel at high impedance transmission line which is inductive element. From the simulated result shown in Figure-7(b), by loading the resonator to the previous design of stepped-impedance LPF, the proposed filter formed attenuation pole near the pass band and on the other hand a sharp response cut-off is obtained instead of gradual attenuation characteristics near the pass band of the conventional stepped-impedance LPF.

The simulated 3dB cut-off frequency is at 6.3 GHz. Insertion loss is less than 1 dB ripple level in the pass band and the return loss is greater than 10 dB. Furthermore, the rejection level of the stop band with attenuation level better than 20 dB is from 6.8 GHz to 18 GHz. Attenuation pole is realized at 7.1 GHz with -41.4 dB response. The proposed filter has physical size of only $21.48 \text{ mm} \times 6.14 \text{ mm}$ which indicates a compact structure. Figure-8 exhibits the comparison between the modified stepped-impedance LPF and the stepped-impedance LPF utilizing open circuit stub resonator.

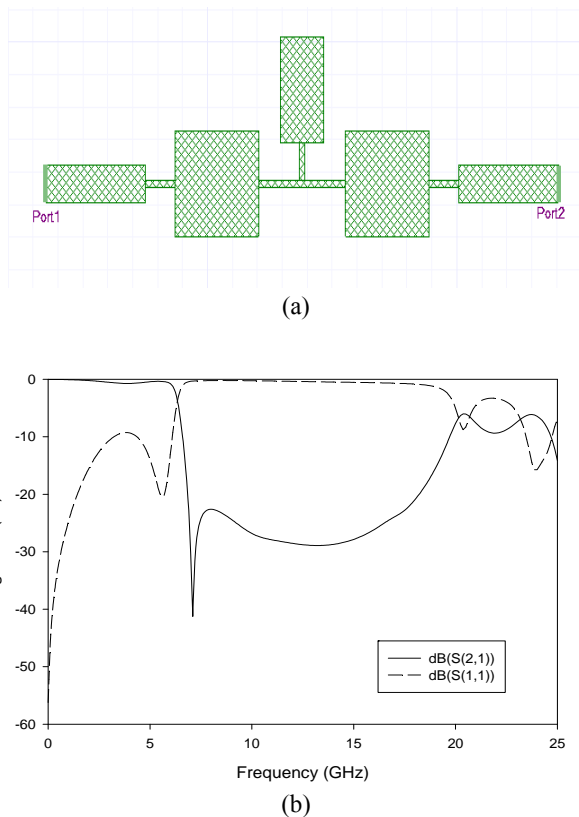


Figure-7. Proposed stepped-impedance LPF utilizing open stub resonator; (a) Layout of microstrip structure (b) Simulated S-parameters result of microstrip structure.

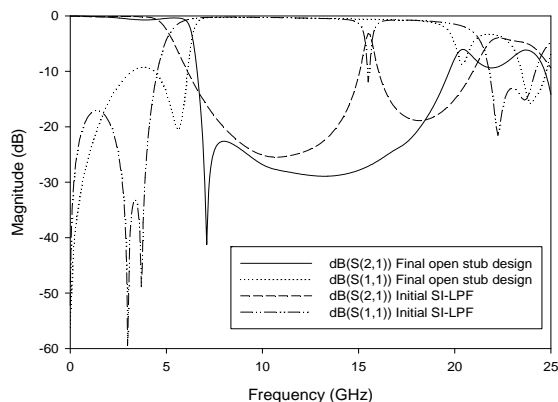


Figure-8. Comparison simulated S-parameters between stepped-impedance LPF utilizing open stub resonator and initial stepped-impedance LPF.

CONCLUSIONS

In this paper, a novel compact LPF using stepped-impedance and open stub resonator circuit has been proposed. The effect of adding open circuit stub resonator to high impedance line of conventional stepped-impedance LPF has exhibiting features that are sharp attenuation slope and wide stop band characteristics. The simulated result 3dB cutoff frequency is 6GHz with not less than 1dB ripple level in the pass band. The LPF has a rejection level better than 20dB from 6.8GHz to 18GHz. Therefore, with many desirable features as compactness, wide rejection level and easy fabrication make the proposed LPF has great potential applications in modern communication systems.

REFERENCES

- Chen, W. L., Wang, G. M., Chen, G. D., Yao, G. F., Han, Y. C., and Xiang, C. W. 2009. Enhancement of microstrip stepped-impedance lowpass filters using fractal shapes. *Microwave Journal*, 52(7), pp. 64-76.
- Hong, J. S. G., and Lancaster, M. J. 2004. *Microstrip filters for RF/microwave applications*. John Wiley and Sons, p. 167.
- Kumar, D., and De, A. 2013. Effective Size Reduction Technique for Microstrip Filters. *Journal of Electromagnetics Analysis and Application*, 5, pp. 166-174.
- Makki, S. V., Ahmadi, A., Majidifar, S., Sariri, H., and Rahmani, Z. 2013. Sharp response microstrip LPF using folded stepped impedance open stubs. *Radio Engineering*, 22(1), pp. 328-332.
- Reja, A. H., Alqaisy, M. A., Ahmed, S. N., Raheem, A., and Kasim, A. K. 2014. Design of metamaterial stepped-impedance microwave LPFs. *Computer Applications and Information Systems (WCCAIS)*, pp. 1-5.
- Sahu, S., Mishra, R. K., and Poddar, D. R. 2011. Compact metamaterial microstrip low-pass filter. *Journal of Electromagnetic Analysis and Applications*, 3, pp. 399-405.
- Verma, A. K., Chaudhari, N. P., and Kumar, A. 2013. Improved performance step impedance lowpass filter. *AEU-International Journal of Electronics and Communications*, 67(9), pp. 761-770.
- Wei, F., Chen, L., Shi, X. W., Huang, Q. L., and Wang, X. H. 2010. Compact lowpass filter with wide stop-band using coupled-line hairpin unit. *Electronics letters*, 46(1), pp. 88-90.



Wuren, T., Sakagami, I., Fujii, M., and Tahara, M. 2008, June. A miniaturized microstrip ring resonator lowpass filter with sharp attenuation. Microwave Symposium Digest, 2008 IEEE MTT-S International, pp. 535-538.

Xi, D., Yin, Y. Z., Wen, L. H., Mo, Y., and Wang, Y. 2010. A compact low-pass filter with sharp cutoff and low insertion loss characteristic using novel defected ground structure. Progress In Electromagnetics Research Letters, 17, pp. 133-143.

Yang, J., and Wu, W. 2008. Compact elliptic-function low-pass filter using defected ground structure. Microwave and Wireless Components Letters, 18(9), pp. 578-580.

Zhang, S., Liu, J., Zhai, Y., and Bian, T. J. 2011. Ultra-wide stopband low-pass filter using novel coupled defected ground structure. Microwave, Antenna, Propagation, and EMC Technologies for Wireless Communications (MAPE), pp. 384-387.