A Novel Compact Low-Pass Filter using Defected Ground Structure for Sharp Transition Band

A. Mohammadi and M. N. Azarmanesh

Microelectronic Research Laboratory, Urmia University, Urmia 57159, Iran
Khallegh60@gmail.com, m.azarmanesh@urmia.ac.ir

Abstract **─**This paper presents a simple technique to design a low-pass filter using defected ground structure (DGS) having a remarkable sharp response in transition band and rejection better than -20 dB up to 20 GHz. The fabricated filter has a 3 dB cutoff frequency at 3.4 GHz and it is as small as 22 mm × 12 mm. The insertion loss in the pass-band is less than 0.6 dB from DC to 3.1 GHz. The design of the filter is simple and it gives desired frequency response. Measured results show good agreement with simulated ones.

Index Terms **─** Bandpass, band-reject, defected ground structure (DGS), maximally flat prototype, and roll-off rate.

I. INTRODUCTION

Low-pass filters play an important role in RF circuits and systems, which rejects the higher harmonics and spurious responses of circuits. Conventional implementation of a low-pass filter (LPF) involves the use of open stubs or stepped-impedance microstrip lines. These structures have gradual cutoff response that only by increasing the number of sections, filter rejection characteristic can be improved. This improving method increases the passband insertion loss and filter physical size.

Defected ground structures (DGS) have been reported to improve the performance of traditional microstrip-based low-pass filters (LPF) [1-4] i.e., rejection properties of LPF have been improved. A DGS structure offers series connected quasi-lumped inductive element to a microstrip line. Its implementation reduces the length of LPF. The performances of low-pass filter, i.e., sharpness factor (the ratio of pole frequency to cutoff frequency), suppression of harmonics in the stop-band and low insertion loss in the passband; are significantly affected by the type of DGS slots.

The initial investigations on DGS have been carried out around simple geometrical shapes include square, circle, and triangle [1]. The simple geometrical shape DGS slots are modeled as a series-connected lossless inductor and capacitor (LC) parallel resonator [1]. Typical properties of LPFs can be obtained by using periodic defected ground structure (DGS) [2]. In periodic structures usually LPF is designed with conventional methods like Chebyshev [3] or Bessel [4] prototype. After that the equivalent LC circuit of DGS slots is used to realize the reactive elements of designed LPF [3]. In this method we need some diagrams, which show the equivalent inductance or capacitance versus the relative area of DGS [3].

In periodic DGS method we need to increase the number of sections for having a sharp response [5]. For example, to design a flat (low ripple) LPF with Chebyshev prototype, for a sharpness factor better than 1.1 and 20 dB attenuation in pole frequency we need a filter with order of nine or more [6]. As mentioned earlier by increasing the number of sections (to have a sharp response) the passband insertion loss and filter physical size is increased.

In this paper a new method to design a filterusing DGS slots is presented. In the proposed method we designed the top layer conventionally and after that by adding some DGS units to the bottom layer, we obtain desired filter responses. DGS units lead to some attenuation pole frequencies. By adjusting the dimensions of DGS units the pole frequencies can be controlled, consequently filter characteristics like sharpness factor and stop-band rejection can be adjusted.

Submitted On: Dec. 18, 2012
Accepted On: Jan. 27, 2014

II. INTRODUCING TWO DGS UNITS

It has always been a challenge for a defected ground structure (DGS) to obtain simultaneously a low resonant frequency and a small circuit area. Some papers have related the resonant frequency to the size of DGS (area which DGS is surrounded) [7]. But there are some results that show we can have lower resonant frequency with lower size [8]. In the following subsections two usual DGS are going to be introduced. The first one has a sharp attenuation pole in frequency response, which can be used to make transition band of LPF as sharp as possible. The second one has a wide attenuation pole, which can be used to extend band-stop.

A. First DGS unit resonator

Figure 1 (a) shows the schematic of DGS unit resonator. This DGS has two parallel stubs, which are bent. This resonator is excited by a 50 Ω microstrip line. This kind of DGS usually used for band-stop filter [8]. Band-stop filter can be designed by cascading several band-stop resonators. After that we should adjust the coupling amongst different resonators. If two or more of this DGS unit are used with a sufficient distance among them, the attenuation in pole frequency will be increased [8]. This DGS unit can be modeled by LC circuit shown in Fig. 1 (b). The parameters of this LC circuit model are obtained from frequency response.

The value of Lp and Cp are found from the following equations [1],

$$C_p = \frac{5f_c}{\pi[{f_p}^2 - {f_c}^2]} \quad pF \tag{1}$$

$$L_p = \frac{25}{C_p(\pi f_p)^2} \quad nH \ . \tag{2}$$

The symbol $f_p$is the pole frequency and $f_c$is the 3-dB cutoff frequency. The dimensions of Fig. 1 are as follows: L = 5.4 mm, L1 = 2.6 mm, L2 = 3.6 mm, L3 = 1.7 mm, L4 = 2.5 mm, L5 = 1.2 mm, L6 = 0.4 mm, G = 0.2mm and the width of microstrip line is 1.6 mm. The resonant frequency is affected by any changes in the dimensions of DGS. This unit has been designed on a substrate with dielectric constant 2.2 and thickness of 0.635 mm. The simulation results of this structure, which has been done by HFSS [9] are shown in Fig. 2.

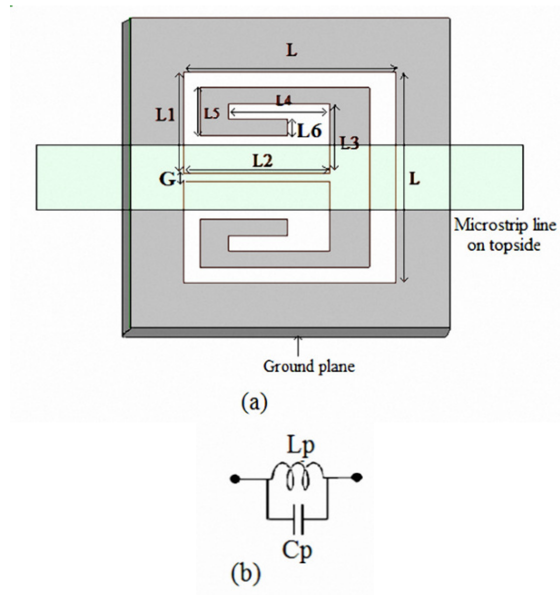


Fig. 1 (a) Schematic of the first DGS unit and (b) equivalent circuit.

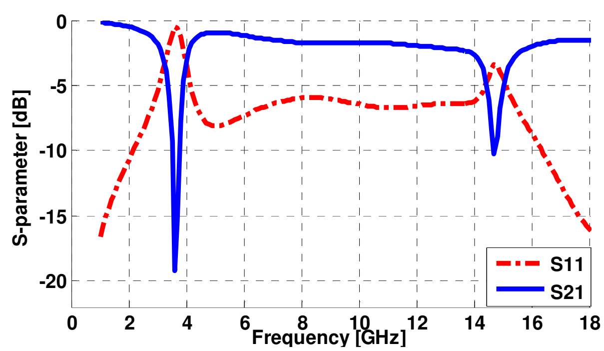


Fig. 2. Simulated S-parameters for DGS unit shown in Fig. 1.

As illustrated in Fig. 2 there are two attenuation poles in the frequency response of this DGS. One of them is in 3.6 GHz and the other one in 14.7 GHz. Totally if all dimensions become larger with the same scale (the area of slot becomes larger), the resonant frequency will decrease. This is because of an increase in the inductive reactance of the slot [3]. Simulation for different area has been done on a 50 Ω microstrip line. The first attenuation pole frequency versus different area of DGS is plotted in Fig. 3. The second pole is located beyond 7 GHz and does not affect our design procedure.

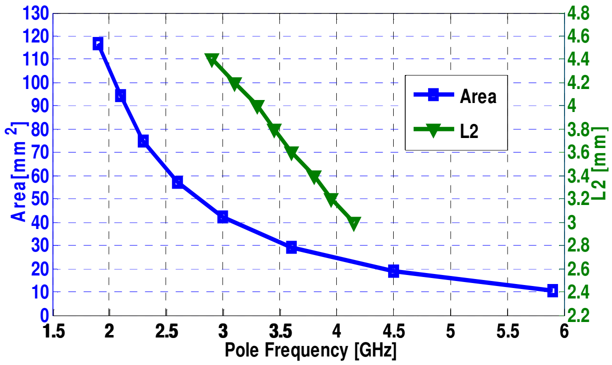


Fig. 3. First pole frequency versus DGS area (left axis) and L2 (right axis).

As Fig. 3 shows, by changing the area of DGS we would have a desired pole in a wide range of frequency from 1.8 GHz to 6 GHz. Moreover, by altering other dimensions of DGS unit, the attenuation pole frequency will change as well. In Fig. 3 we can also see increasing the length L2 causes a noticeable decrease in the attenuation pole frequency. Another parameter, which has a significant effect on pole frequency is the width G. Figure 4 shows that when G increases, the attenuation pole frequency increases as well. This is due to an increase in the capacitance property of the slot [10], [11].

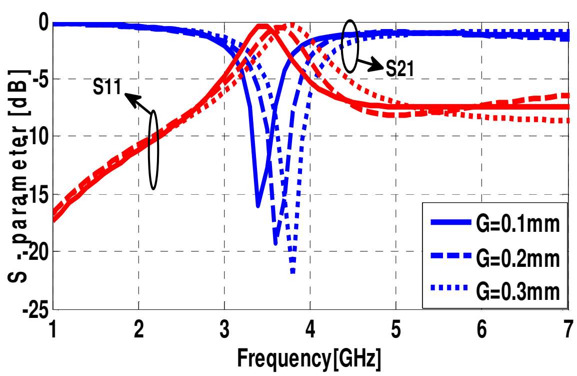


Fig. 4. Simulated S-parameter for G variation.

These results illustrate there are three or more degrees of freedom to design DGS slot and the selectivity is high enough to get the desired attenuation pole frequency.

B. Second DGS unit resonator

All DGS slots can be grouped in two categories: (i) simple DGS slot and (ii) complex DGS slot. In the first category there are simple geometrical shapes; such as square, triangle, circle and etc. In the second group the slot-heads of DGS have more complex geometrical shapes; such as H-shape, open-square [12], spiral [12], and inter-digital [12].

In this paper H-type DGS has been selected to produce the second pole of the LPF. The shape of H-type DGS is shown in Fig. 5. By adjusting values of a, b, c, L1, and W a desired resonant pole frequency could be obtained. The simulated S-parameters of this DGS as a function of L1 is shown in Fig. 6.

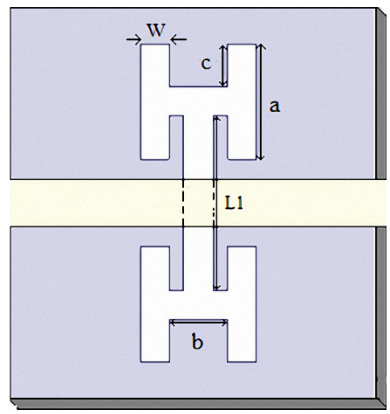


Fig. 5. Schematic of H-type DGS.

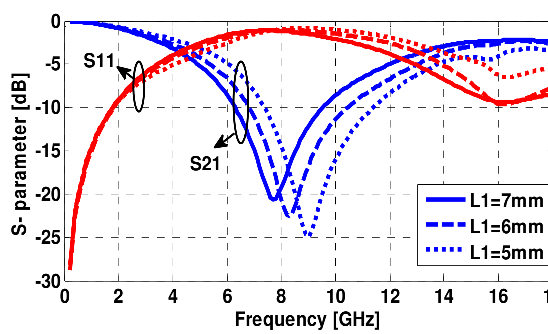


Fig. 6. Simulated S-parameter of H-type DGS for L1 variation.

Other dimensions of H-type DGS are as follows: a = 4 mm, b = 2 mm, c = 1.5 mm, and W = 1 mm. It is evident from Fig. 6 that as L1 decreases the attenuation pole frequency increases. Furthermore, we can see that the second DGS have a wide rejection around pole frequency, approximately from 5 GHz to 13 GHz, and it leads to a better stop-band rejection in LPF.

III. DESIGN LOW-PASS FILTER

A. Maximally flat low-pass filter

In the proposed design method, the desired band-rejection and sharpness of the LPF has been obtained by the use of DGS; therefore, it is better to use a prototype for top side, which gives a flat response through pass-band and maximally flat low-pass filter prototype with low order is the best choice. Since by increasing the order of filter, the size, the passband insertion loss, and nonlinearity of phase response will increase [6], we should choose low orders.

A LPF with cut-off frequency of 4.5 GHz, using conventional method, without ripple factor in the pass band (maximally flat response) has been designed [6]. The prototype has the following normalized components: g_1 = 0.6180, g_2 = 1.6180, g_3 = 2, g_4 = 1.6180, g_5 =0.6180. Three series inductances and two shunt capacitances of the prototype are computed by,

$$l_i = \frac{g_i Z_0}{\omega_c} \quad (3)$$

$$c_j = \frac{g_j}{\omega_c Z_0}, \quad (4)$$

where Z_0 = 50 Ω, ω_c= $2\pi f_c$, i=1, 3, 5 and j=2,4. The LC circuit and its equivalent distributed elements is shown in Fig. 7.

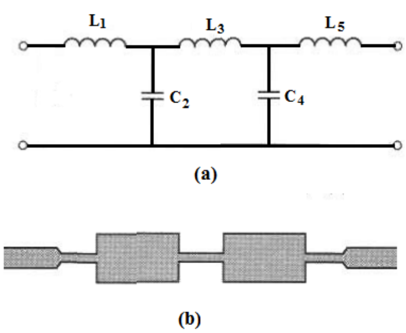


Fig. 7. (a) LC circuit and (b) equivalent distributed circuit.

The schematic of the designed LPF is shown in Fig. 8. To find the dimensions of the distributed element we can use following formulas,

$$\text{(inductor)} \qquad Bl \approx \frac{LR_0}{Z_h} \quad (5)$$

$$\text{(capacitor)} \qquad Bl \approx \frac{CZ_l}{R_0}, \quad (6)$$

where Bl is the electrical length of capacitor and inductor, R_0 is the filter impedance, Z_h and Z_l are the highest and lowest characteristic impedance that can be practically fabricated, L and C are normalized components (g_i).

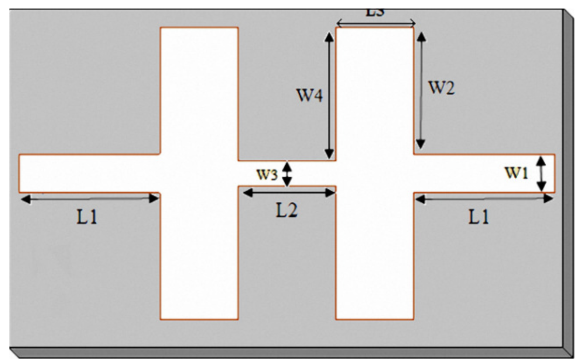


Fig. 8. Schematic of primary LPF.

After computing Bl, the length of distributed elements (l) can be calculated. The width of distributed elements, which refers to Z_h and Z_l can be calculated by following formulas [13]. For narrow strips (i.e., when Z_0 > (44-ε_r) Ω),

$$\frac{w}{h} = \left(\frac{\exp H}{8} - \frac{1}{4\exp H}\right)^{-1} \quad (7)$$

$$H = \frac{Z_0\sqrt{2(\varepsilon_r+1)}}{119.9} + \frac{1}{2}\left(\frac{\varepsilon_r-1}{\varepsilon_r+1}\right)\left(ln\frac{\pi}{2} - \frac{1}{\varepsilon_r} ln\frac{4}{\pi}\right). \quad (8)$$

And for wide strips (i.e., when Z_0< (44-2ε_r) Ω),

$$\frac{w}{h} = \frac{2}{\pi}\left[\left(d_{\varepsilon_r} - 1\right) - \ln\left(2d_{\varepsilon_r} - 1\right)\right] + \frac{(\varepsilon_r-1)}{\pi\varepsilon_r}\left[ln d_{\varepsilon_r-1} + 0.293 - \frac{0.517}{\varepsilon_r}\right] \quad (9)$$

$$d_{\varepsilon_r} = \frac{59.95\pi^2}{Z_0\sqrt{\varepsilon_r}}, \quad (10)$$

where h is the thickness of substrate and ε_r is the relative permittivity. Filter implementation from LC circuit to distributed elements is mentioned completely in [6]. In Table 1 the calculated dimensions of distributed elements are shown.

The LPF has been designed on the substrate having ε_r= 2.2 and thickness h = 0.635mm. The frequency response of the designed LPF is shown in Fig. 9. As it can be seen the roll-off rate is low and there is a small insertion loss in pass-band. Also after frequency of 14 GHz the rejection property is going to decrease. In the next part we will see that high roll-off rate, low insertion loss in pass-band and wide stop-band (up to 20 GHz) could be obtained simultaneously by using proper DGS in correct position.

Table 1: Calculated dimensions of distributed elements.

section	Z_i=Z_l,Z_h(Ω)	$Bl_i(deg)$	$W_i\,(mm)$	L_i(mm)
1	57	30	1.6	5.8
2	12	21	12	3.2
3	110	52	1	4
4	12	21	12	3.2
5	57	30	1.6	5.8

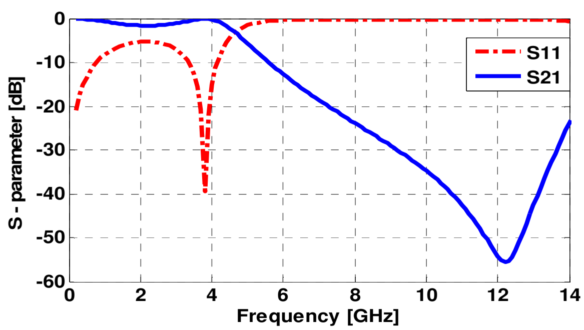


Fig. 9. Frequency response of primary LPF.

B. Adding DGS to primary designed LPF

In this part we want to show by adding DGS units to primary LPF the desired characteristics would be obtained. To design a LPF having a cutoff in 3.4 GHz and a 20 dB rejection band up to 20 GHz the following structure in Fig. 10 is proposed. As it can be seen from Fig. 10 three DGS units (in white color) have been used. Two of them are the same, which are located in a symmetry form. Some parts of DGS units, which are located behind the top layer components are shown with dashed line. The dimensions of the top layer components are like previous section.

The frequency response of the designed LPF is plotted in Fig. 11. It is evident from Fig. 11 that the sharpness of the transition band is really good. The first pole is designed to be located in 3.7 GHz. It has a rejection better than 45 dB. This pole leads to a 3 dB cutoff frequency in 3.4 GHz. By adjusting this pole frequency, which refers to the first DGS unit, the cutoff frequency can be controlled. As shown in Fig. 6, H-type DGS has a wide-band rejection response. By adjusting the pole of H-type DGS, a desired and wide rejection band will be obtained, consequently spurious frequency will be omitted.

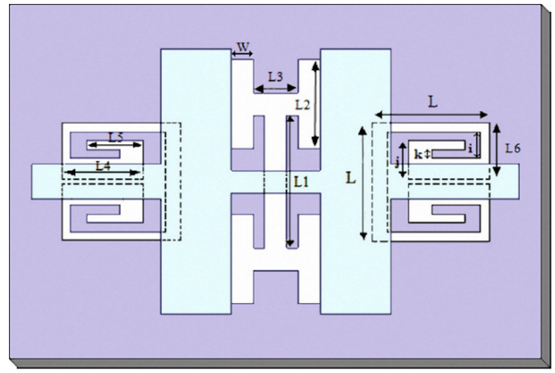


Fig. 10. Schematic of designed LPF.

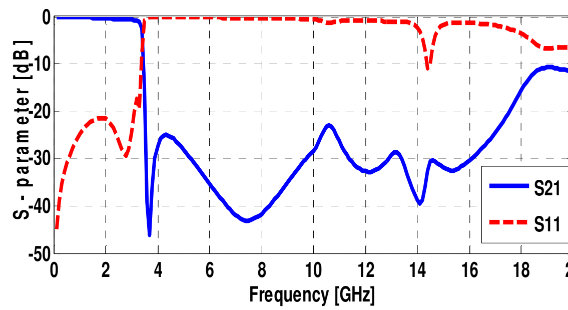
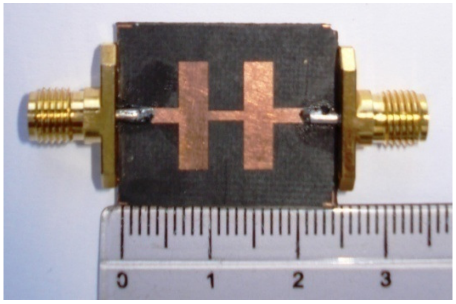


Fig. 11. Simulated frequency response of designed LPF.

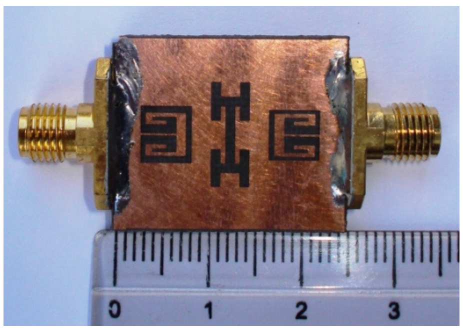
IV. FABRICATION AND MEASURMENT

Figure 12 shows the photograph of the fabricated filter. Top view of LPF is in Fig. 12 (a), the dimensions of top view are those, which were designed in section III, part A. The dimensions of DGS unitsin bottom view according to Fig. 10 are as follows: L = 5.3 mm, L1 = 6 mm, a = 4 mm, b = 2 mm, c = 1.5 mm, d = 3.6 mm, e = 2.55 mm, f = 2.5 mm, W = 1 mm, i = 1.2 mm, j = 1.7 mm, k = 0.4 mm.

The proposed LPF has been fabricated on Rogers 5880 substrate having relative permittivity of 2.2 and thickness of 0.635 mm. The measurements have been done by using vector network analyzer Agilent E8363C. Figure 13 shows the comparison between the EM simulation, which is done by HFSS [9] and the measured S-parameters of the designed LPF. Good agreement between them is observed. After frequency of 18 GHz there is a spurious stop-band in simulated results while this spurious stop-band in fabricated LPF is completely suppressed, which is evident in measured results.



(a)



(b)

Fig. 12. Photograph of the fabricated LPF, (a) top view and (b) bottom view.

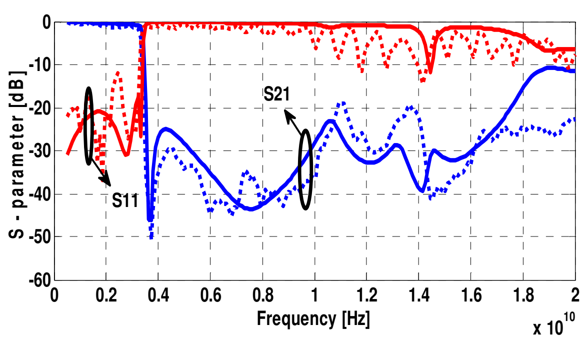


Fig. 13. Simulation (continuous line) and measured (dashed line) results.

V. CONCLUSION

A simple technique has been proposed to design a compact LPF. In this method both advantages of conventional filter design prototype and DGS suppression property are used simultaneously. Finally, a LPF with a really good sharpness and rejection level better than 20 dB up to 18 GHz has been designed and fabricated.The effective size of LPF is 22 mm × 12 mm. Measured results show good agreement with simulated ones.

ACKNOWLEDGMENT

Authors would like to thank the Iran Telecommunication Research center (ITRC) for their technical support.

REFERENCES

[1] A. Rahman, A. Verma, A. Boutejdar, and A. Omar, "Control of bandstop response of Hi-Lo microstrip lowpass filter using slot in ground plane," *IEEE Trans. Microw. Theory Tech.*, vol. 52, pp. 1008-1013, 2004.

[2] J. Lim, C. Kim, D. Ahn, Y. Jeong, and S. Nam, "Design of low-pass filters using defected ground structure," *IEEE Trans. Microw. Theory Tech.*, vol. 53, pp. 2539-2545, 2005.

[3] A. Kumar and A. Verma, "Design of compact seven poles low pass filter using defected ground structure," in *International Conference on Emerging Trends in Electronic and Photonic Devices & Systems*, Varanasi, 2009.

[4] A. Kumar and A. Verma, "Compact low pass bessel filter using microstrip DGS structure," in *Proceedings of Asia-Pacific Microwave Conference*, Yokohama City, 2010.

[5] S. Ting, K. Tam, and R. Martins, "Miniaturized microstrip lowpass filter with wide stopband using double equilateral U-shaped defected ground structure," *IEEE Microwave and Wireless Components Lett.*, vol. 16, no. 5, pp. 240-242, 2006.

[6] D. Pozar, *Microwave Engineering*, New York, John Wiley & Sons, Inc., pp. 392-398, 2005.

[7] A. Verma and A. Kumar, "Synthesis of microstrip lowpass filter using defected ground structures," *IET Microw. Antennas Propag.*, vol. 5, no. 12, pp. 1431-1439, 2011.

[8] S. Rehman, A. Sheta, and M. Alkanhal, "Compact bandstop filter using defected ground structure (DGS)," in *Electronics, Communications and Photonics Conference (SIECPC), Saudi International*, Riyadh, 2011.

[9] Ansoft HFSS V13.

[10] A. Safwat, S. Tretyakov, and A. Raisanen, "Defected ground and patch-loaded planar transmission lines," *IET Microwaves, Antennas & Propagation,* vol. 3, no. 2, pp. 195-204, 2009.

[11] M. Sharkawy, A. Boutejdar, F. Alhefnawi, and O. Luxor, "Improvement of compactness of lowpass/bandpass filter using a new electromagnetic coupled crescent defected ground structure resonators," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 25,

no. 7, pp. 570-577, 2010.

[12] A. Verma and A. Kumar, "Design of low-pass filters using some defected ground structures," *International Journal of Electronics and Communications (AEÜ)*, vol. 65, no. 10, pp. 864-872, 2011.

[13] T. Edwards and M. Steer, *Foundations of Interconnect and Microstrip Design*, John Wiley & Sons, Ltd., pp. 93, 2000.

Abdolkhalegh Mohamadi was born in Shiraz, Iran, in 1987. He received the B.S. degree in Electrical Engineering from Shiraz University, Iran, in 2009. He got his M.Sc. degree in Telecommunication Engineering from Urmia University, Iran, in 2012. He has participated in several research projects with Microelectronic Research Laboratory and Iranian companies. His research interests include adaptive filter, design and optimization of patch antenna and microstrip filter.

Mohammad Azarmanesh was born in Tabriz, Iran, in 1950. He received his B.S. degree in physics from Tabriz University, Iran, in 1973, his M.S degree inelectrical engineering from the University of Paris VI in 1976, his Ph.D degree in electrical engineering from Poly Technique De Toulouse, France. In 1979, he joined Applied Physics Department in Urmia University, where he worked effectively in founding ElectricalEngineering Department in 1983. In 1998, he worked with three other colleagues in developing Microelectronics Research Center in Urmia University. He is currently the head of Microelectronics Research Center. Dr. Azarmanesh is a member of Iranian Society of Electrical Engineers and a member of IEEE, Institute of Electronics, Information and Communication Engineers (IEICE) of Japan. He has published a book, Electromagnetic Field Theory (Urmia: Urmia University, 1996).