Design and Improvement of Compact Half-Wavelength Band Pass Filter Employing Overlapped Slotted Ground Structure (SGS) and Multilayer Technique

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Abstract **─** This paper deals with a compact Chebyschev 3rd hairpin band pass filter design, using the Richards-Kuroda transformation method. Afterwards, a combination of slotted ground structure (SGS) and multilayer technique is applied. Filters using quarter-wavelength stepped-impedance resonator without and with SGS technique are investigated. Finally, two band pass filters are designed, simulated, and partially measured. A compact SGS band pass filter operated at 4.35 GHz is demonstrated. The proposed band pass filter has low insertion loss, high rejection in both the stop bands and a compact size of (20 × 23) mm^2 (0.075 λg × 0.058 λg) with a guide wavelength λg = 0.359 m. Additionally, the structure has generated two transmission zeros on both sides of the pass band at 3.1 GHz and 4.9 GHz. The simulated results as well as the experimental results are satisfactory with the filter requirements. The introduced structure can be a good alternative to a conventional parallel-coupled half wavelength, as well as quarter-wavelength stepped-impedance resonator band pass filter.

Index Terms **─** Band pass filter, compactness, multilayer, and slotted ground structure.

I. INTRODUCTION

Modern personal communication systems require miniaturized high performance band pass filters having high selectivity in the pass band and low insertion loss in the stop band. This type of filter design is of key importance for the radio frequency engineer, since they are currently used in communication applications to reject spurious signal, and to separate different channels in multichannel communication systems. Microstrip line band pass filters with these characteristics should be designed with direct coupling in order to minimize the dispersion and radiation losses [1-5]. Other filters with $\lambda/2$ resonators may be used to realize the selectivity, but the disadvantage is that they are long and therefore cannot be used in all applications [6-9]. To eliminate this disadvantage and thus to manufacture a band pass filter, which is compact and useful in personal communication systems, we suggest a class of band pass filters, which consist of four coupled microstrip lines. Two are connected to a shorted ground inductive microstrip line. The two remaining ones are coupled together by means of a J-immitance inverter (see Fig. 1). This structure is improved and simplified through transformation of the short-circuit to the equivalent open end microstrip line, therefore, short-circuits are avoided. The proposed band pass filter employing Richards-Kuroda transformation method and short-open-circuit geometric trick is simulated, optimized, and finally fabricated. In order to improve the compactness of the structure, other ideas have been used so-called SGS and overlapped techniques. Good performance, low cost, and compact size are usually demanded in modern microwave communication systems. In order to alleviate these

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problems Karshenas et al. [10], Boutejdar et al. [11-13] proposed DGS or SGS, which is designed by connecting the middle thin channel slot with two identical defected areas. SGS bases on new ground plane hole (GPH) technique. GPH focuses not only on its application but also on its own proprieties. SGS can be designated as an etched periodic or non-periodic cascaded configuration holes in metallic ground plane of a microstrip structure, which causes a disturbed current distribution in the ground plane. This disturbance leads to an increase in the effective capacitance and inductance, thus unwanted second harmonic and circuit size reduction could be obtained [14-17]. SGS adds an extra degree of freedom in high frequency circuit design and opens a wide door to the RF, microwave, and millimeter-wave applications.

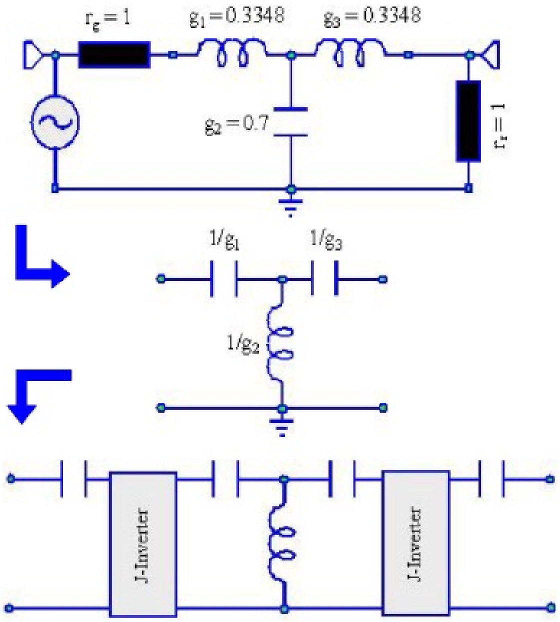

Fig. 1. LPF-HPF-BPF- transformation (first step, second step, and third step).

II. THE TRANSFORMATION FROM LPF TO BPF

In order to design a band pass filter cascaded coupled resonators, through inverters, have been used. An optimization process of filter dimensions will be carried out to get the desired filter parameters. In order to minimize the time outlay and to design a filter systematically, another method so-called LPF-HPF-BPF has been used in this work, where the low pass filter with known parameters has been first transformed to high pass filter. Moreover, the unit elements (inverter) and Kuroda transformation lead to realization of a band pass filter with desired properties [18].

In order to design a band pass filter with desired characteristics (f_c) using systematic and accurate process analysis, the cutoff frequency of a low pass filter must be nearly around $f_c/2$. Based on this idea a proposed low pass filter is a Chebyschev filter of 3rd order, with a cutoff frequency ($f_c/2$) of 2.1 GHz. The normalized element values for this low pass structure are $g_2 = 0.712$ and $g_1 = g_3 = 3.345$. In order to realize this LPF-BPF transformation (see Fig. 1), the lumped elements of the 3rd circuit have been calculated using normalized element values of lumped elements and characteristic impedance Z_0 [18, 19]. Using low-high pass transformation, Kuroda-identity and method of coupled line procedures (see Fig. 2), a required band pass circuit has been realized. Finally, the circuit is supplemented mutually with a unit-element (J-inverter), which represents the gap between the quarter length resonators (see Fig. 1).

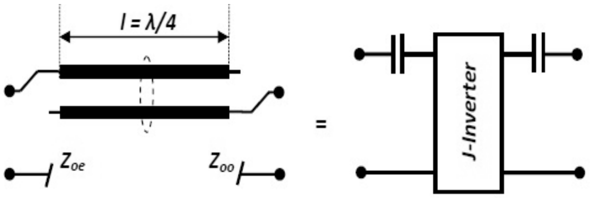

Fig. 2. Equivalent circuit to microstrip coupled lines transformation.

III. DESIGN OF THE COUPLED-LINE BANDPASS FILTER

The first proposed band pass filter (structure 1) is composed of two microstrip half-wavelength resonators and a shorted stub with metallic ground as shown in Fig. 3. All dimensions are shown in Table I, while the filter characteristics are shown in Table II. The response of the first structure is shown in Fig. 4. The second structure is proposed to avoid via holes short-circuits as shown in Fig. 5, this was done by extending the microstrip line by λ/2. The new length is then extended by means of the following length correction [2],

$$\Delta l = \frac{\xi_1 \cdot \xi_2 \cdot \xi_5}{\xi_4} h \tag{1}$$

$$\xi_1 \approx 0.44 \frac{\varepsilon_{r_{eff}}^{0.81} + 0.26 \cdot \eta^{0.85} + 0.24}{\varepsilon_{r_{eff}}^{0.81} - 0.19\eta^{0.85} + 0.87}, \quad (2)$$

$$\xi_2 \approx 1 + \frac{\eta^{0.37}}{2.35 \cdot \varepsilon_r + 1}, \quad (3)$$

$$\xi_3 \approx 1 + \frac{0.53 \tan^{-1}[0.1\eta^{\frac{1.94}{\xi_2}}]}{\varepsilon_{r_{eff}}^{0.924}}, \quad (4)$$

$$\begin{aligned} \xi_4 \approx\ & 1 + 0.04 \tan^{-1}[0.07\eta^{1.46}] \\ & \times [6 - 5\exp[0.04(1-\varepsilon_r)]], \end{aligned} \quad (5)$$

$$\xi_5 \approx 1 - 0.22\exp[-7.50\eta] \quad \text{with } \eta = \frac{W}{h}, \quad (6)$$

where h and W are the substrate thickness and microstrip width, successively.

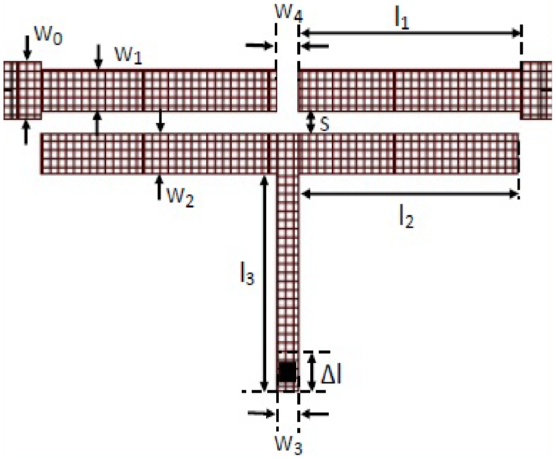

Fig. 3. Layout of the transformed band pass filter (structure 1).

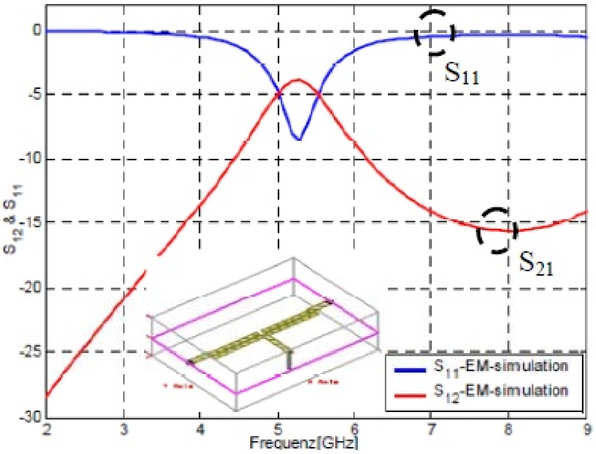

Fig. 4. Simulation results of the first proposed band pass filter (structure 1).

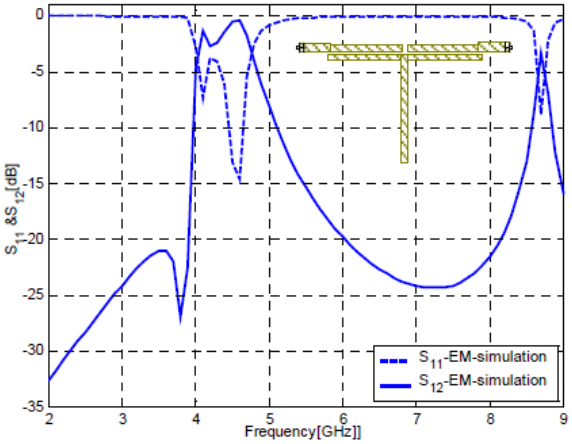

Fig. 5. Simulation results of the second proposed band pass filter (structure 2).

These corrections are applied simultaneously to the three microstrip lines l1, l2, and l3. In structure 2, the open stub has several important characteristics. By changing the length of the open stub, the center frequency in the pass band can be controlled. In order to prove the validity of the proposed structure, the equivalent circuit network is provided as shown in Fig. 6. This network is valid for structures 2 and 3 (structure 3 is proposed in the next section) regardless the gap between the upper two microstrip lines. Comparison between the EM simulation and the circuit simulation is shown in the next section. In order to improve the filter characteristics, several structures have been designed and developed. The passage from structure 1 to structure 2 was carried out with the goal to avoid the shorting problem. Due to the loss in the pass band was non negligible, the coupling (gab = inverter) between the resonators has been changed to enhance the electrical coupling, and thus to minimize the losses in the pass band. For this purpose, structure 3 has been designed, simulated, and manufactured as shown in Fig. 7. The comparison between the simulation and measurement results are presented in Fig. 8. Structures 2 and 3 are similar to each other but with different coupling distances, which is determined using empirical method. The values of coupling distances (s) in structure 2 and 3 are 0.3 mm and 0.2 mm, respectively. In order to improve the filter characteristics a removing of the short circuit (via) (structure 3) and a minimizing of the filter structure, using the overlapping idea (structure 4) are used.

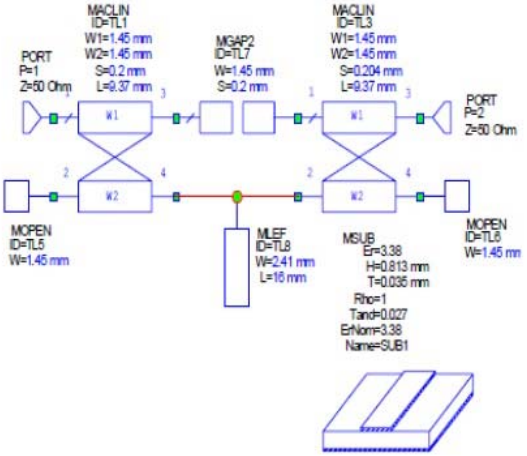

Fig. 6. Equivalent circuit model of the proposed band pass filter (structures 2 and 3).

IV. FABRICATION AND MEASUREMENT RESULTS

As shown in Fig. 7, the band pass filter (structure 3) has been designed, optimized, fabricated, and tested on a (20 × 23 mm^2) RO4003 microwave substrate with a relative dielectric constant ε_r of 3.38, a loss tangent tgδ of 0.0027, and a thickness h of 0.813 mm. The characteristic impedance of the microstrip lines used as resonators is Zoe = 74 Ω, Zoo = 70 Ω and that of the open stub is 64 Ω. The band pass filter was designed to have a center frequency of 4.5 GHz and a fractional bandwidth of 22.2 %. The detailed dimensions are shown in Table I. The EM and circuit simulations are carried out using the commercial microwave office software AWR. As Fig. 8 depicts, both simulation and experimental results show good agreement.

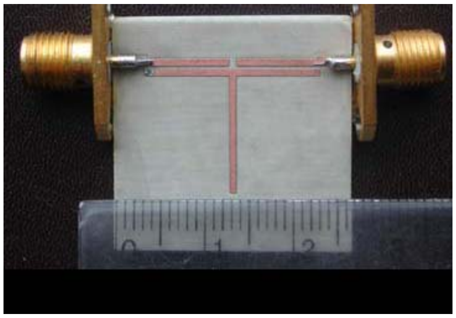

Fig. 7. Photograph of the fabricated optimized band pass filter.

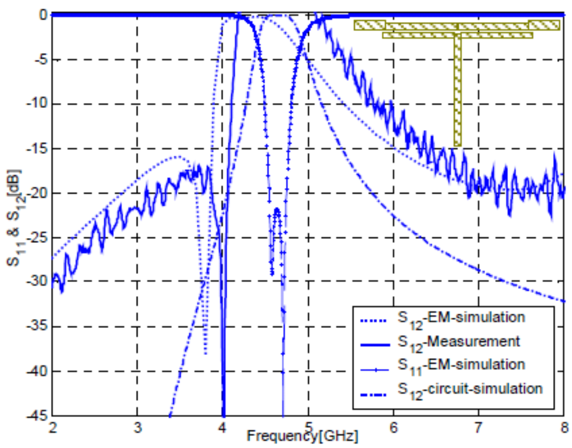

Fig. 8. The comparison of S-parameters of EM-, circuit simulations and measurement results of BPF (structure 3).

The observed deviation between both results is due to the mismatches and fabrication errors. Turning the filter arms around λ/2 reduces the dimension of the filter by approximately 49 %, which introduces the fifth structure. Moreover, the space of coupling becomes smaller, which causes good results and high compactness. In order to obtain the optimal coupling distance between the filter arms and thus to control the results in pass band, an empirical method [16, 18] is used instead of the procedures based on the coupling coefficient and the external quality factor [11, 20]. In our case, the insertion losses in the pass band reaches 1.2 dB resulted by an optimal gap width of 0.5 mm as shown in Fig. 9 for structure 4.

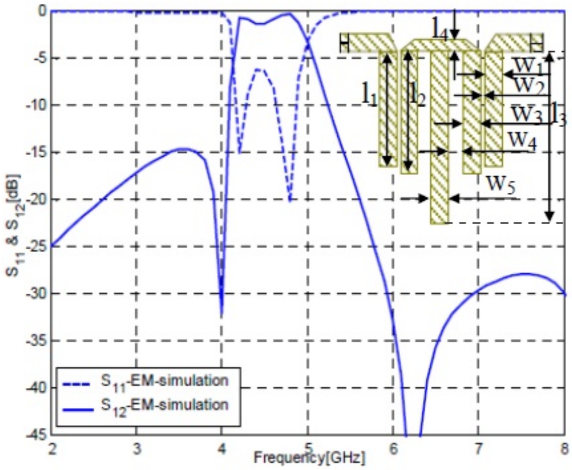

Fig. 9. S-parameters of the compact overlapped BPF (structure 4).

V. DESIGN AND IMPROVEMENT OF NEW OVERLAPPED SGS-BAND PASS FILTER

As the compactness of devices is an important characteristic, which is frequently considered in various technologies and particularly in wireless communication and microwave applications, a new structure topology has been designed and optimized employing defected slotted ground (SGS) and multilayer techniques (structure 5). The simulation results have been carried out using microwave studio^{TM} software under the same conditions as before. The filter structure of the proposed compact SGS band pass filter is shown in Figs. 10 and 11. It consists of two compensated coupled microstrip capacitors on the top layer, while three overlapped slot cannels presents a SGS resonator in the metallic ground plane. Through the substrate, the SGS is electromagnetic coupled with the top compensated capacitors. The gap between the microstrip capacitors corresponds to J-inverter and controls the inter-stage (w_2) coupling, which also determines the filter bandwidth.

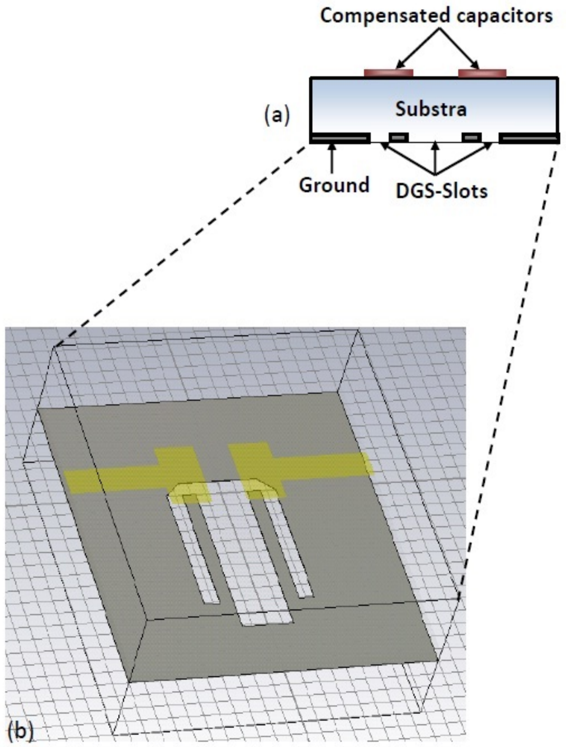

Fig. 10. 3D view of the new proposed SGS band pass filter (structure 5).

All dimensions of the new structure are depicted in Table I. In order to guarantee the matching between the ports (SMA) and the structure, the width of the feed lines (w_0 = 1.88 mm) has been computed using a microstrip line calculator [21]. This filter exhibits two transmission zeros at 3.1 GHz and 4.9 GHz, thus a relative response symmetric is achieved. From the simulated results shown in Fig. 12, it can be seen that the simulated overlapped structure has a pass band center frequency at 4.35 GHz as required. The insertion loss is as low as 0.24 dB in the pass band of the BPF, the upper stop band is using SGS and slow wave effect suppressed below 20 dB from 4.7 GHz to 8 GHz. Using overlapping and SGS techniques, the size of the new SGS BPF is 49 % less than conventional BPF (structure 3).

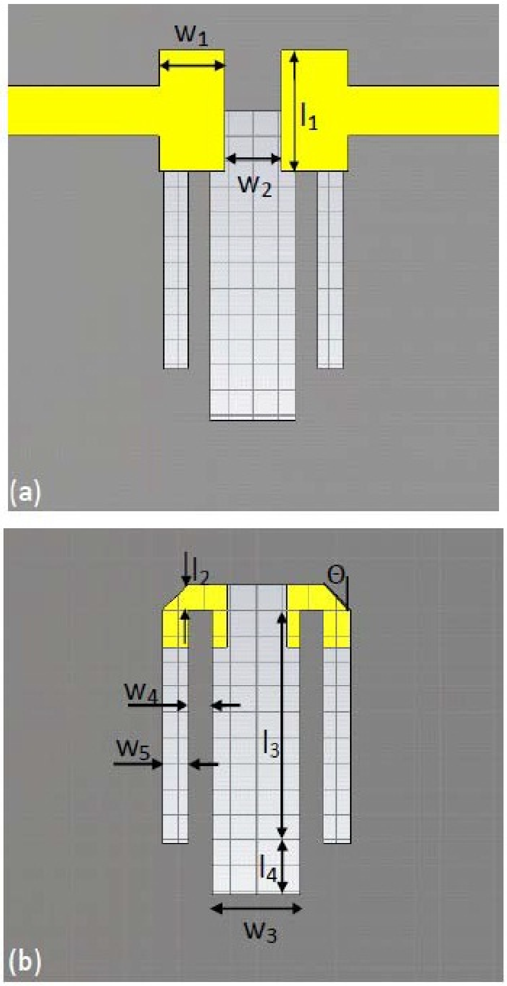

Fig. 11. 2D view of the new SGS BPF; (a) top and (b) bottom layers.

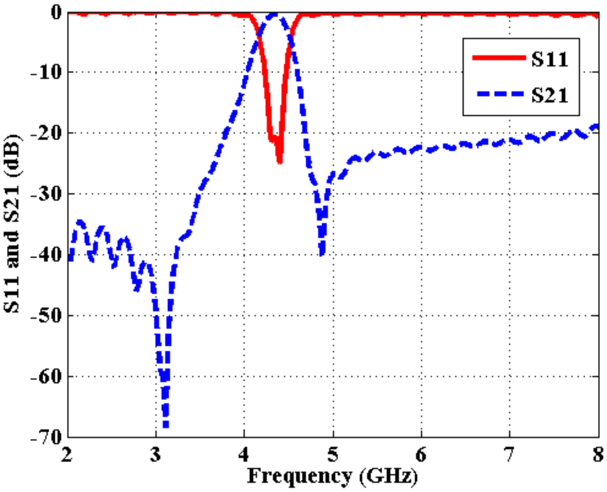

Fig. 12. Simulation results of the compact SGS BPF (Structure 5).

Table I: The dimensions (in mm) of the different proposed structures' topologies.

Structure 1	Structure 2	Structure 3	Structure 4	Structure 5
l_1= 9.37	l_1= 9.00	l_1= 9.00	l_1= 11.75	l_1= 4.75
l_2= 9.37	l_2= 9.00	l_2= 9.00	l_2= 12.66	l_2= 1.00
l_3= 5.37	l_3= 13.5	l_3= 13.5	l_3= 17.73	l_3= 9.15
w_1= 1.45	w_1= 0.80	w_1= 0.80	l_4= 1.250	l_4= 2.00
w_2= 1.25	w_2= 0.80	w_2= 0.80	w_1= 2.400	w_1= 2.60
w_3= 1.85	w_3= 0.80	w_3= 0.80	w_2= 0.500	w_2= 2.30
w_4= 0.8	w_4= 0.50	w_4= 0.50	w_3= 2.150	w_3= 3.35
			w_4= 1.650	w_4= 0.90
			w_5= 2.4	w_5= 1.00
				Θ= 45°

VI. CONCLUSION

In this work, the required λ/2–microstrip BPF and its equivalent circuit have been realized starting from a known low pass filter and using kurodas' and Richards' transformations. In order to show the validity of the proposed BPF and the derived equivalent circuit, the BPF have been designed, fabricated, and measured. Numerical simulations using microwave office AWR show a satisfactory agreement between simulated and measured responses. In order to minimize the size of the structure and to improve the filter responses, SGS and multilayer technique are used. The simulation results of the proposed compact SGS-overlapped BPF have demonstrated the optimum performances in pass band and stop band. This additional electric coupling between the compensated microstrip capacitors allows the generation of 2 finite transmission zeros instead of one near the pass band. Comparison between the proposed BPF and the enhanced filter show a significant size reduction up 49 %. Simulation results of the proposed compact structure show that the SGS and overlapping ideas work very well. It is expected that this proposed method and this filter topology can be applied to improve the compactness and stop band performances of other microwave filters, and thus could be used in mobile communication systems and RF/microwave applications.

Table II: The characteristics of the different investigated structures.

Structure	1	2	3	4	5
Characteristics					
fc_1, fc_2 (GHz)		4.05, 4.70	4.20, 4.95	4.10, 4.95	4.15, 4.50
f_0 (GHz)	5.20	4.60	4.50	4.52	4.35
S_{21},max.(dB)	15.5	24.0	35.0	50.0	41.5
S_{21},max.,losses(dB)	4.20	2.30	0.30	1.20	0.24
BW (GHz)		0.75	0.75	0.85	0.35
FBW (%)		16.0	16.6	18.8	8.00
SF_1, SF_2		0.88, 1.02	0.93, 1.10	0.90, 1.09	0.95, 1.03

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REFERENCES

[1] G. L. Matthaei, L. Young, and E. M. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, Norwood, MA: Artech House, 1980.

[2] J.-S. Hong and M. J. Lancaster, *Microwave Filter for RF/Microwave Application*, New York: Wiley, 2001.

[3] W. Bächtold, *Mikrowellentechnik*, Vieweg Verlag, 1999.

[4] H. Yabuki, M. Sagawa, M. Matsuo, and M. Makimoto, “Stripline dual-mode ring resonators and their application to microwave devices,” *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 723-728, May 1996.

[5] K. Wada, Y. Yamamoto, O. Hashimoto, and H. Harada, “A design method of a 2-pole tapped resonator BPF with multiple attenuation poles and its miniaturization,” *Proc. Asia-Pacific Microwave Conf.*, pp. 1111-1114, Nov. 2001.

[6] J. T. Kuo, S. P. Chen, and M. Jiang, “Parallel-coupled microstrip filters with over-coupled end stages for suppression of spurious responses,” *IEEE Microwave and Wirless Components Letters*, vol. 13, no. 10, Oct. 2003.

[7] B. Easter and K. A. Merza, “Parallel-coupled-line filters for inverted-microstrip and suspended-substrate MIC’s,” *11th Eur. Microwave Conf. Dig.*, pp. 164-167, 1981.

[8] A. Riddle, “High performance parallel coupled microstrip filters,” *IEEE MTT-S Symp. Dig.*, pp. 427-430, 1988.

[9] I. J. Bahl, “Capacitively compensated high performance parallel coupled microstrip filters,” *IEEE MTT-S Symp. Dig.*, pp. 679-682, 1989.

[10] F. Karshenas, A. R. Mallahzadeh, and J. R.-Mohassel, “Size reduction and harmonic suppression of parallel coupled-line bandpass filters using defected ground structure,” *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 25, no. 2, pp. 149-155, Feb. 2010.

[11] A. Boutejdar, A. Batmanov, A. Elsherbini, A. Omar, and E. Burte, “A miniature 3.1 GHz microstrip bandpass filter with a suppression of spurious harmonic using multilayer-technique and defected ground structure open loop-ring (DGS),” *Proc. EUROEM European Electromagnetic 2008*, Lausanne, Switzerland, 21-25 July 2008.

[12] A. Boutejdar, A. Abdel-Rahman, A. Batmanov, et. al., “Miniaturized band stop filter based on multilayer-technique and new coupled octagonal defected ground structure with interdigital capacitor,” *Microwave and Optical Technology Letters*, vol. 52, no. 3, pp. 510-514, March 2010.

[13] A. Boutejdar, N. Mohamed, B. Edmund, O. Abbas, and S. Parui, “Design of novel 4-GHz bandpass filter using a combination of defected ground structure resonators and admittance J-inverter,” *Recent Patents on Electrical Engineering Journal, Bentham Science Publishers*, vol. 4, no. 1, pp. 42-49, Jan. 2011.

[14] G. Al-Omair, S. Mahmoud, and A. Al-Zayed, “Lowpass and bandpass filter designs based on DGS with complementary split ring resonators,” *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 26, no. 11, pp. 907-914, Nov. 2011.

[15] S. Rehman, A. Sheta, and M. Alkanhal, “Compact bandpass filters with bandwidth control using defected ground structure (DGS),” *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 26, no. 7, pp. 624-630, July 2011.

[16] M. Al 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, July 2010.

[17] N. Garmjani and N. Komjani, “Improved microstrip folded tri-section stepped impedance resonator bandpass filter using defected ground structure,” *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 25, no. 11, pp. 975-983, Nov. 2010.

[18] A. Boutejdar, “Design, development and optimization of compact microstrip RF filters using "Defected Ground Structure" (DGS) technology”, *PhD dissertation, University of Magdeburg, IESK, Magdeburg, Germany*.

[19] A. Boutejdar, A. Elsherbini, and A. Omar, “Design of a novel ultra-wide stop band low pass filter using H-defected ground structure,” *Microwave and Optical Technology Letters*, vol. 50, no. 3, pp. 771-775, March 2008.

[20] S. Amari, “Synthesis of cross-coupled resonator filters using an analytical gradient based optimization technique,” *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 1559-1564, Sept. 2000.

[21] http://www.emtalk.com/

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