Progress In Electromagnetics Research Letters, Vol. 54, 129–135, 2015

Design of Miniaturized Planar SIW Diplexers Using Dual-Mode Resonators

Homayoon Oraizi* **and Elham Bidaki**

Abstract—In this paper, two planar diplexers using dual-mode resonators are designed, which have achieved significant size miniaturization. The first diplexer is made of a simple single dual-mode resonator as a square cavity in the substrate integrated waveguide technology. The two degenerate modes with 90° rotation are perturbed by the placement of metallic via and CPW lines as input and output ports. A prototype model of this diplexer is designed and fabricated in the X-band. Its simulation results and measurement data agree very well. An isolation of 22 dB is achieved between two ports, which is quite suitable for receiving systems. For the improvement of isolation and bandwidth, the degree of structure is increased, whereby dual-mode resonators are used to connect the channel filters to the input port. Those types of channel filters are used which generate a transmission zero in the frequency band of the other channel. The isolation and bandwidth of the diplexer have been improved significantly, where its size is much smaller than the common diplexers.

1. INTRODUCTION

Diplexers are used in applications where an input signal is to be separated into its two components having two distinct frequencies, which may be contiguous or separated. One application of diplexers is in duplex systems. The frequency diplexers may be realized as series or shunt connections of two band-pass filters, which may be designed for various types of transmission lines [1]. The common designs of diplexers use a T-junction to which two band-pass filters are connected to separate the two channels with the required isolation and impedance matching [2, 3]. However T-junctions occupy a large space in the system. Furthermore, the required tuning of diplexers may be difficult [2]. Another design for the diplexer uses ferrite circulators for the connection of the two output filters to the input port [4]. Designs of circulators with acceptable performance are quite costly. In [5] a dual-mode cavity is employed as the common resonator to replace the T-junction. By using multilayer technology a high isolation is achieved, but the structure is not planar. There are also some realizations based on the waveguide technology A waveguide diplexer using a dual-band resonator is presented in [6]. Due to the absence of junctions the size of diplexer reduces but it requires precise fabrication On the other hand, in [7] a resonant Y-junction is introduced as the first block of a rectangular waveguide diplexer. However it is very sensitive and its optimization is very difficult.

Recently various planar diplexers are proposed due to their favourable characteristics. They are designed for various technologies, such as low temperature co-fired ceramic (LTCC), thin film technology (PCB), planar waveguides and substrate integrated waveguides (SIW) [5, 8]. The SIW is fabricated in a microstrip medium by placing a row of metallic vias in a low loss substrate, which exhibits low insertion loss, high power handling capacity and high Q factor compared to other planar waveguides.

In this paper, two planar diplexers are presented, which use single SIW resonator having dual-mode operation. The structures of the proposed dual-mode SIW diplexers are quite simple and achieve a significant miniaturization and narrow profile compared to the available diplexers.

Received 11 April 2015, Accepted 15 May 2015, Scheduled 12 August 2015
* Corresponding author: Homayoon Oraizi (h_oraizi@iust.ac.ir).
The authors are with the Department of Electrical Engineering, Centre of Excellence in Railway Transportation, Iran University of Science and Technology, Tehran, Iran.

2. DUAL-MODE RESONATOR

The dual-mode resonators operating at two resonance frequencies are quite effective in filter designs, which lead to the reduction of number of resonators and the eventual size reduction of filter. In such systems, the resonance frequencies of degenerate modes may be separated by producing a perturbation on the symmetry axis of its field pattern. Consequently, a suitable bandwidth will be generated for the appropriate operation of the filter. As the perturbation increases, the resonance frequencies will be further separated.

The resonance frequencies of degenerate modes (TE_{p0q} and TE_{m0n}) of a rectangular SIW resonator are made equal [9]:

$$f_r = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a_{eff}}\right)^2 + \left(\frac{n}{b_{eff}}\right)^2} = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{p}{a_{eff}}\right)^2 + \left(\frac{q}{b_{eff}}\right)^2} \tag{1}$$

where [10]

$$b_{eff} = b - \frac{d^2}{0.95s} \tag{2}$$

$$a_{eff} = a - \frac{d^2}{0.95s} \tag{3}$$

and **m, n, p, q** are the order of resonance modes. $\boldsymbol{\varepsilon_r}$ is the dielectric constant of the substrate material, $\mathbf{c}_o$ the speed of light in free space, **d** the diameter of metallic vias, **s** the distance between vias, and **a** and **b** are the width and height of rectangular resonator, respectively. The dual-mode operation of SIW resonator appears for the case of ($m \neq p$, $n \neq q$). Therefore, the resonance frequencies of the square resonator, namely TE_{102} and TE_{201}, have the same resonance frequency.

Two vias are made on the diagonal of the SIW resonator to produce the two electric field patterns of the diagonal TE_{201} and TE_{102} modes, as shown in Figure 1. The displacement of vias along the diagonal of SIW resonator for the first mode does not appreciably affect its resonance frequency, because they are placed on the region where the standing electric field is zero, as shown in Figure 1(a). Its resonance frequency depends in the dimension of SIW resonator. On the other hand, for the second mode shown in Figure 1(b), the vias are made on the diagonal, where the standing electric field is not zero. Consequently, the electric field will be forced to zero at the position of inserting the metallic vias. In such a case, the displacement of the vias along the diagonal towards the centre of resonator tends to increase the resonance frequency of second mode.

3. PLANAR DUAL-MODE RESONATOR SIW DIPLEXER

The field distributions of the two degenerate resonance modes of the SIW square resonator are rotated by 90° relative to each other. That is the zero field points of one mode coincides with the maximum

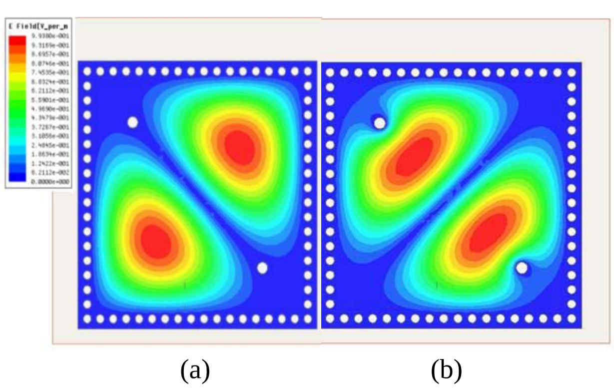


Figure 1. Electric field distribution of the diagonal TE_{201} and TE_{102} modes.

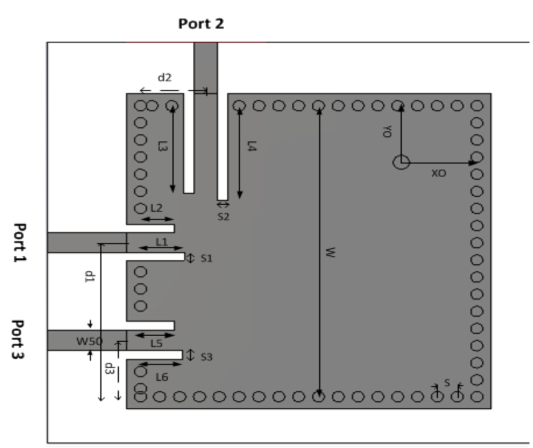


Figure 2. The configuration of the diplexer.

field region of the other, and vice versa. We intend to make use of the field rotation of such resonance modes to design a single dual-mode resonator diplexer. Consequently, we place one output port of the diplexer at the point where the field of one mode (namely diagonal TE_{201}) is maximum and we place the other output port of diplexer where the field of the other mode (namely diagonal TE_{102}) is maximum. In such a manner, the isolation between the two output ports is maximized. The frequency separation of diplexer may be adjusted by variation of the perturbations (namely position of vias).

The configuration of the single dual-mode resonator SIW diplexer is shown in Figure 2, where the output ports 2 and 3 and input port 1 are designated. The dimensions of diplexer are determined according to the guidelines in previous section. Due to the presence of the CPW lines for the output and input ports, only one via is sufficient to generate the two modes (see Figure 2). The CPW lines between SIW and 50 ohm lines should operate as an impedance transformer.

The design of diplexer is optimized by CST software. Its optimum geometrical dimensions are given in Table 1. The Rogers R04003 substrate is used with dielectric constant 3.55, height 0.508 mm and loss tangent 0.0027. The diameter of metallic vias is 0.6 mm and their spacing is 1 mm. By this design the field leakage is negligible [11]. The width of CPW line is 1.15 mm to produce the characteristic impedance of 50 ohms.

3.1. Measurement Data and Simulation Results

The performance of the diplexer is obtained by CST and HFSS softwares. However, in order to avoid overcrowding the figures, only the CST data are reported. The results obtained by CST and HFSS coincide. The scattering parameters S_{11} (reflection coefficient at the input port), S_{21} and S_{31} (transmission from the input port to the output ports) are shown in Figure 3(a). The isolation between the two output ports (S_{32}) is drawn in Figure 3(b). The various characteristic of the diplexer as obtained

Table 1. Geometrical dimensions of the single dual-mode resonator SIW diplexer.

W	17.1 mm	L_3	6 mm	d_2	1.5 mm	L_2	2.9 mm
XO	3.55 mm	L_4	6 mm	d_3	1.9 mm	d_1	9 mm
YO	3.94 mm	L_5	2.9 mm	S_1	0.54 mm	S_3	0.57 mm
L_1	2.9 mm	L_6	2.8 mm	S_2	0.55 mm		

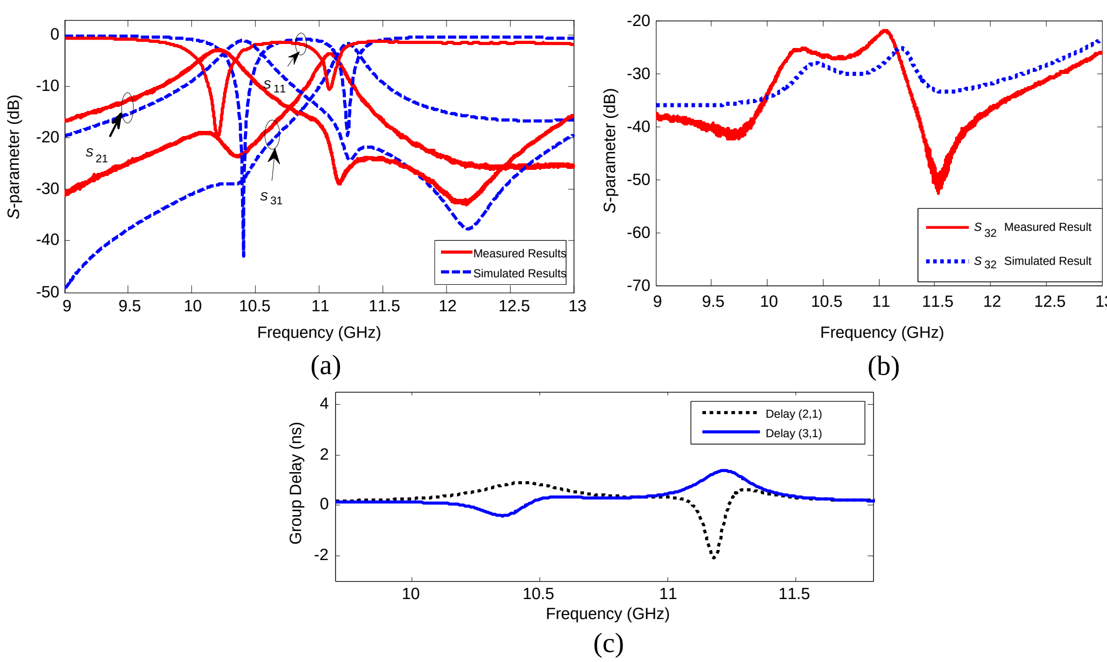


Figure 3. Simulated and measured scattering parameters. (a) Reflection and transmission; (b) isolation; (c) group delay.

by CST and HFSS are given in Table 2 for comparison. Figure 4 presents a photograph of the circuit.

The two measured passbands are centered at 10.21 and 11.08 GHz. The frequency shift is considered to be mainly caused by the substrate dielectric constant variations. The measured insertion losses (IL) are 2.79 and 3.51 dB at the two center frequencies respectively, while the simulated ones are 1.03 and 1.64 dB. The measured isolation is larger than 22 dB from 9 to 13 GHz. However, there are some deviations between the simulation result and measured data of diplexer which are due to the workmanship of the fabrication of diplexer and measurment instruments. Since ports 1 and 3 are close together and the lack of availability of small connectors to fit them, the connectors could not be made very tight to obtain accurate results. The frequency shift is considered to be mainly caused by the substrate dielectric constant variations.

Figure 5(c) shows the group delay for both channels of the diplexer. The group delay from input port 1 to output port 2 in the passband with the center frequency 10.4 GHz is between 0.6 to 0.9 ns. The group delay from input port 1 to output port 3 in the passband with the center frequency 11.22 GHz is between 0.9 to 1.4 ns. These group delays are acceptable for the common modulation systems.

Table 2. Comparison between simulation results and measurement data.

	f_o (GHz)		IL (dB)		S_{32} (dB)	RL (dB)	
	Channel 1	Channel 2	Channel 1	Channel 2		Channel 1	Channel 2
CST simulation	10.40	11.22	1.03,	1.64	> 25.5	42	19.2
HFSS simulation	10.51	11.23	1.14,	1.43	> 27	24.7	22.6
Measured Result	10.21	11.08	2.7	3.51	> 22	20	10.5,

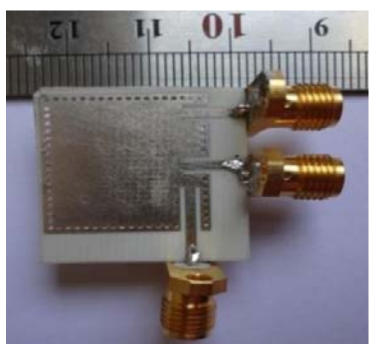
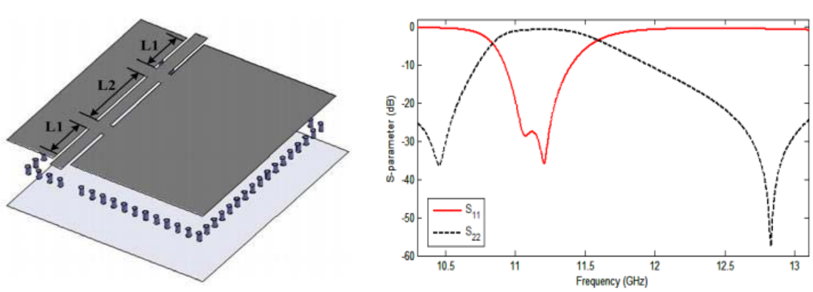


Figure 4. Photograph of the fabricated diplexer of degree 1.



(a) (b)

Figure 5. Dual-mode filter with non-resonating node, (a) 3D view of the filter [12], (b) its response at the upper cannel filter.

The designed diplexer has a simple structure and design showing the capability of the dual-mode resonator for the generation of diplex signal and is of degree one, but its transition band has a sharp slope. Its output ports are perpendicular to each other, which results in high isolation between them. Such isolation is sufficient for receiver applications. Simplicity can be a positive point, although it could be improved. However, higher isolations are required for transmission applications. Consequently, for broader bandwidths and increased isolation between the output ports, the device order may be increased, so that dual-mode resonators may be used for connecting channel filters to input port which does not have the shortcomings of the older versions, such as Y- and T-Junctions.

4. PLANAR SIW DIPLEXER OF DEGREE 3

For the design of diplexer, the dual-mode resonator with three ports is used for the first and second channel filters. In order to achieve high isolation between the output ports, the filter and its channel passband should coincide in their design, but should have high rejection on the other channel. In other word, there should be a transmission zero in the other channel pass band. These points are considered for the design of filters for the planar SIW diplexer. For this purpose, we use the Dual-mode filter with non-resonating node (NRN) which is designed in [12]. Since the channel filters require two transmission zeros on the two sides of the pass band and their size should also be small, the non-resonating nod (NRN) filter in the form of a CPW structure is selected.

4.1. Dual-Mode Filter with Non-resonating Node

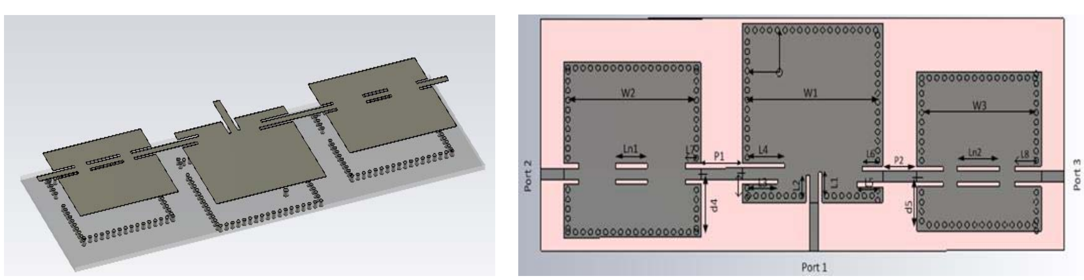
The filter is designed based on a dual-mode resonator with a non-resonating node (NRN), which is realized by a coplanar waveguide mode on the top metallic surface. This method leads to an indirect mutual coupling between the source and load, which generates two transmission zeros in the filters [12]. NRN is a parallel element in the network model, which makes possible the design of cross-coupled filters with the maximum number of transmission zeros without mutual coupling between the source and load. NRN leads to a constant phase shift and prepares new paths for the signal. Its other frequency response is drawn in Figure 5. The position of transmission zeros may be adjusted by varying the lengths L_1 and L_2.

4.2. Diplexer Design

Three port square resonators are used for diplexer design, where its output ports are perpendicular to its input port. Resonators are connected to the common resonator through CPW line. Considering the resonance frequencies of the dual-mode resonator, the centre frequencies of channel filters and transmission zeros are determined. The structure of planar SIW diplexer is shown in Figure 6.

4.3. Simulation Results

Figure 7 shows the simulation result of the proposed diplexer of degree 3 with geometrical dimensions given in Table 3. This diplexer is designed by CST software. The centre frequencies of the first and



(a) (b)

Figure 6. The proposed diplexer of degree 3. (a) 3-D view of proposed diplexer; (b) top view of proposed, dual-mode resonator connects channel filters to input port.

Table 3. Geometrical dimensions of the diplexer of degree 3.

W_1	17.2 mm	d_3	3.14 mm	L_5	3.4 mm	P_2	4.5 mm
W_2	17.2 mm	d_4	6.5 mm	L_6	2.67 mm	P_1	5.3 mm
W_3	15.3 mm	d_5	5 mm	L_7	2.3 mm	d_1	8.53 mm
L_1	3.15 mm	L_2	2.9 mm	L_8	3.5 mm	Ln_1	4.6 mm
L_3	4.7 mm	Ln_2	5.6 mm	d_2	2.44 mm	L_4	5.57 mm

Table 4. Comparison between the proposed diplexers and the References.

	Size (λ_0^3)	$\lvert S_{21}\rvert$ or $\lvert S_{31}\rvert$ (Insertion loss)		$\lvert S_{21}\rvert$ or $\lvert S_{31}\rvert$ (Suppression) dB		$\lvert S_{32}\rvert$ (Isolation)
		Channel 1	Channel 2	Channel 1	Channel 2	
Diplexer of degree 1 (Measured)	$0.12 \times 0.094 \times 0.057$	2.7 dB	3.5 dB	24@10.21 GHz	26@11.08 GHz	> 22 dB
Diplexer of degree 3 (Simulated)	$4.1 \times 1.2 \times 0.057$	1.2 dB	1.4 dB	48@10.39 GHz	48@11.22 GHz	> 48 dB
Ref. [13] (Measured)	$0.103 \times 0.103 \times 0.004$	1.25 dB	1.49 dB	26@1.03 GHz	25@1.37 GHz	> 22.5
Ref. [5] (Measured)	$0.83 \times 0.83 \times 0.064$	2.86 dB	3.04 dB	52@8 GHz	43@9 GHz	> 40 dB
Ref. [8] (Measured)	$0.187 \times 0.30 \times 0.003$	2.8 dB	3.2 dB	38@1.50 GHz	39@1.79 GHz	> 30 dB

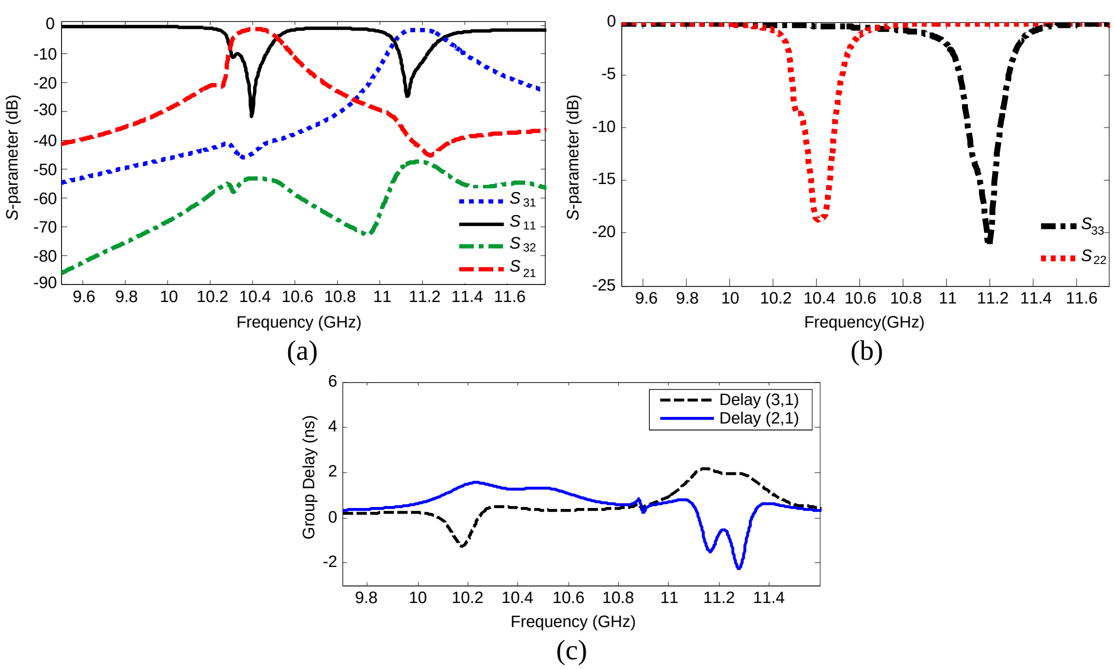


Figure 7. Simulation result of the diplexer of degree 3.

second channels are 10.39 and 11.2 GHz, respectively. The insertion and return losses of the first channel are 1.2 dB and 35 dB, respectively. Those of the second channel are 1.4 dB and 28 dB, respectively. As expected, the bandwidth and isolation of diplexer have improved by increasing its degree. Observe that the isolation between the two output ports (S_{23}) is better than -46 dB. Figure 7(c) shows the group delay for both channels of the diplexer. The group delay from input port 1 to output port 2 in the passband with the center frequency 10.39 GHz is between 1.3 to 1.55 ns. The group delay from input port 1 to output port 3 in the passband with the center frequency 11.22 GHz is between 1.7 to 2.23 ns. The performances of the proposed SIW diplexers are compared in Table 4 to those of other diplexers reported in the literature.

5. CONCLUSION

Two novel planar diplexers of first and third degrees are designed with SIW technology, which use dual-mode square resonators. The SIW diplexers have simple and small structures, which may be readily designed by the available computer simulator softwares. A prototype model is fabricated in the X band. Its measurement data agree very well with the simulation results, which indicates its effective application in microwave circuits. Observe that the bandwidth, output port isolations and return losses of the third degree diplexer have been significantly improved compared to the first degree diplexer.

REFERENCES

1. Rizii, P. A., *Microwave Engineering, Passive Devices*, Prentice Hall, 1988.
2. Tang, H.-J., W. Hong, J.-X. Chen, G. Q. Luo, and K. Wu, "Development of millimeter-wave planar diplexers based on complementary characters of dual-mode substrate integrated waveguide filters with circular and elliptic cavities," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 55, No. 4, 776–782, Apr. 2007.
3. Athanasopoulos, N., D. Makris, and K. Voudouris, "Development of a 60 GHz substrate integrated waveguide planar diplexer," *2011 IEEE MTT-S International Microwave Workshop Series on Millimeter Wave Integration Technologies (IMWS)*, 128–131, Sep. 15–16, 2011.
4. He, J., K. Gao, and Z. Shao, "A novel compact Ka-band high-rejection diplexer based on substrate integrated waveguide," *2012 International Conferenceon Computational Problem-Solving (ICCP)*, 193–197, Oct. 19–21, 2012.
5. Cheng, F., X. Lin, K. Song, Y. Jiang, and Y. Fan, "Compact diplexer with high isolation using the dual-mode substrate integrated waveguide resonator," *IEEE Microwave and Wireless Components Letters*, Vol. 23, No. 9, 459–461, Sep. 2013.
6. Li, Z., R. R. Mansour, and M. Yu, "A compact waveguide diplexer employing dual-band resonators," *2014 IEEE MTT-S International Microwave Symposium (IMS)*, 1–4, Jun. 1–6, 2014.
7. Bastioli, S., L. Marcaccioli, and R. Sorrentino, "An original resonant Y-junction for compact waveguide diplexers," *IEEE MTT-S International Microwave Symposium Digest, MTT' 09*, 1233–1236, Jun. 7–12, 2009.
8. Chen, C.-H., T.-Y. Huang, C.-P. Chou, and R.-B. Wu, "Microstrip diplexers design with common resonator sections for compact size, but high isolation," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 54, No. 5, 1945–1952, May 2006.
9. Pozar, D. M., *Microwave Engineering*, 3rd Edition, Wiley, New York, 2004.
10. Cassivi, Y., L. Perregrini, P. Arcioni, M. Bressan, K. Wu, and G. Conciauro, "Dispersion characteristics of substrate integrated rectangular waveguide," *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 9, 333–335, Sep. 2002.
11. Bozzi, M., F. Xu, D. Deslandes, and K. Wu, "Modeling and design considerations for substrate integrated waveguide circuits and components," *8th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services, TELSIKS 2007*, P-VII–P-XVI, Sep. 26–28, 2007.
12. Shen, W., X.-W. Sun, W.-Y. Yin, J.-F. Mao, and Q.-F. Wei, "A novel single-cavity dual mode substrate integrated waveguide filter with non-resonating node," *IEEE Microwave and Wireless Components Letters*, Vol. 19, No. 6, 368–370, Jun. 2009.
13. Xue, Q. and J.-X. Chen, "Compact diplexer based on double-sided parallel-strip line," *Electron. Lett.*, Vol. 44, No. 2, 123–124, 2008.