HIGH ISOLATION DIPLEXER USING THE HYBRID COAXIAL AND MICROSTRIP RESONATORS FOR RF/MICROWAVE COMMUNICATION SYSTEMS

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Abstract:

One of the major passive components, which affected the performance of broadband RF/microwave communication systems, is the diplexers. This paper presents a new approach for designing a high selectivity diplexer, which is based on compact and high unloaded quality factor hybrid coaxial and microstrip resonator bandpass filters (BPFs). Additional transmission zeros (TZs) on both sides of the passband response, which are created by mixed electromagnetic (EM) coupling scheme, can be easily realized to high isolation of the proposed diplexer. A designed diplexer prototype at center frequencies 2.6 and 3.1 GHz with 3-dB bandwidth of 220/180 MHz, respectively, is designed and simulated by HFSS software. The proposed diplexer has been exhibited to have excellent filtering selectivity, low insertion loss, and improved channel-to-channel isolation.

Keywords:

Diplexer, hybrid coaxial and microstrip resonator, transmission zeros, RF/microwave communication systems.

Tóm tắt:

Bộ song kênh là một trong những thành phần thụ động chính ảnh hưởng đến hiệu suất của hệ thống thông tin liên lạc vô tuyến hiện đại có băng thông rộng. Bài báo này đề xuất một giải pháp để thiết kế bộ song kênh có độ chọn lọc tốt, dựa trên các bộ lọc thông dải cộng hưởng đồng trục kết hợp vi dải có cấu trúc nhỏ gọn và hệ số phẩm chất không tải cao. Các điểm truyền không trên cả hai dải chặn của đáp ứng tần số, được tạo ra bởi cấu trúc cộng hưởng ghép điện từ hỗn hợp giúp nâng cao độ cách ly của bộ song kênh được đề xuất. Bộ song kênh được thiết kế và mô phỏng bằng phần mềm HFSS với hai tần số trung tâm là 2,6 và 3,1 GHz và băng thông 3-dB, tương ứng là 220/180 MHz. Bộ song kênh được đề xuất có những ưu điểm như độ chọn lọc cao, suy hao trong dải thấp và cải thiện độ cách ly giữa các kênh tín hiệu.

Từ khóa:

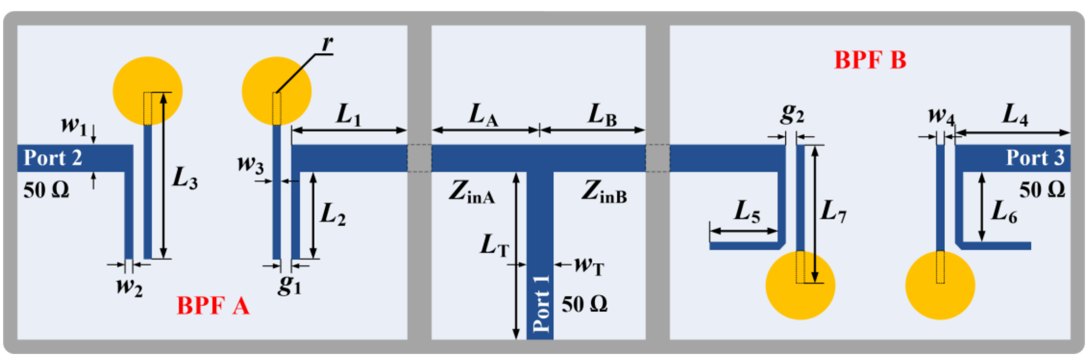
Bộ song kênh, cộng hưởng đồng trục kết hợp vi dải, điểm truyền không, hệ thống thông tin cao tần.

1. INTRODUCTION

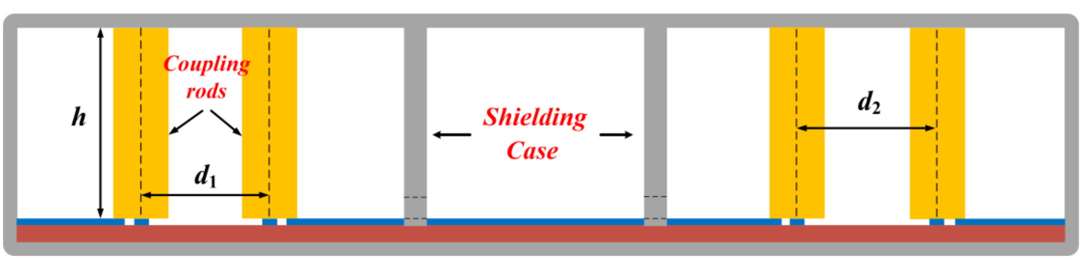
Recently, many research works about diplexers have been reported in various literatures. The diplexer designed based on waveguide technology to provide high selectivity, low insertion loss is introduced [1-6]. However, this design has common drawbacks such as being heavy, difficult to fabricate, and incompatible with planar integrated circuits. Recently, several planar diplexers predominantly based on Printed Circuit Board (PCB) or Low-Temperature Co-fired Ceramic (LTCC) technology have been developed to overcome such problems [7-9]. In [7] and [8], two high performance diplexers were designed, but such resonators of these diplexers suffer from relatively low unloaded quality factor (Q_u < 200). Although the designs in [9] got a more compact circuit size, they were with poorer frequency selectivity and they need multilayer fabrication process that requires higher cost.

In our previous work [10], a prototype of compact and low loss bandpass filter (BPF) was designed successfully by utilizing the unique hybrid resonator structure, which introduces a high-unloaded *Q*-factor. These resonators were then applied to the implementation of low loss and miniaturized bandpass filters. In this paper, the compact hybrid resonator technique is used to design a novel high selectivity diplexer. With maximum space utilization of the structure, the proposed filters configuration are not only enabling significantly miniaturized design but also give an improvement unloaded *Q*-factor of the resonator. Consequently, two compact and high rejection BPFs by using the hybrid coaxial and microstrip resonators (HCMR) are investigated and analyzed, and then, a high selectivity diplexer is designed for verification.

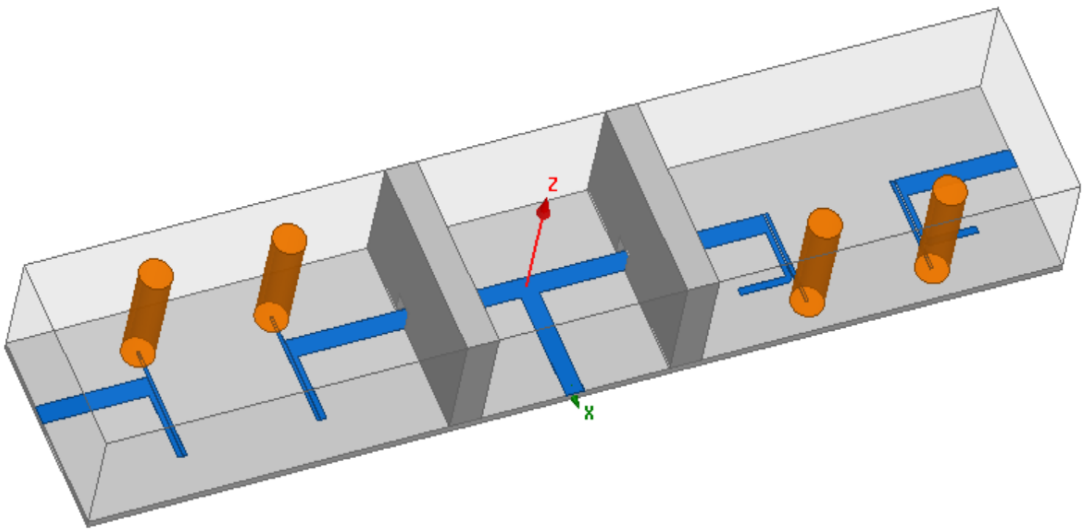
2. DIPLEXER DESIGN PROCEDURE



(a) Top view



(b) Side view



(c) 3-D view

Figure 1. Structure of the proposed diplexer based on hybrid coaxial and microstrip resonators

Figure 1 shows the structure of the proposed diplexer. It consists of two second-order BPFs and a T-junction microstrip lines connecting the individual BPFs to the common input. Let lower- and upper-frequency channel filters be bandpass filter A (BPF A) and bandpass filter B (BPF B), respectively. These filters are constructed by the hybrid coaxial and microstrip resonators structure, which is composed of two sections of transmission line, microstrip line on the substrate and the coaxial line. The bottom part of the filter is formed from printed circuit whose layout is shown in Figure 1(a). The diameter and the length of each of the copper rod is r and h, respectively, as shown in Figure 1(b). The center-to-center distance between two copper rods is d, which mainly determines internal coupling between the resonators.

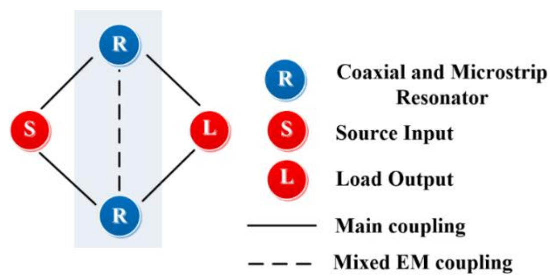


Figure 2. Coupling structure for the proposed hybrid coaxial and microstrip resonator

The coupling topology of the proposed hybrid coaxial and microstrip resonator as shown in Figure 2, where the node S denotes the source or input, the node L denotes the load or output, respectively. This investigated general topology contain not only the input and output coupling to resonator nodes, but also a mixed electromagnetic coupling between resonator nodes. For this coupling structure, a $(N+2)\times(N+2)$ coupling matrix [11] for a second-order BPF without source–load coupling is given by:

$$m = \begin{bmatrix} 0 & m_{S1} & 0 & 0 \\ m_{1S} & m_{11} & m_{12} & 0 \\ 0 & m_{21} & m_{22} & m_{2L} \\ 0 & 0 & m_{L2} & 0 \end{bmatrix} \quad (1)$$

Where the coupling coefficients k_{ij} are replaced by $m(i,j)$ corresponding to resonant modes in the coupled HCMR, respectively. m_{S1} and m_{L1} denote input and output external couplings, respectively, and m_{12} represents inter-resonator coupling. m_{11} and m_{22} stand for the detuning of each resonator's resonant frequency from the center frequency of the filter's frequency response. The $m_{11} = 0$ (or $m_{22} = 0$) indicates that the first resonator (or second resonator) is tuned to the center frequency of the filter response.

For demonstration of our proposed technique, a two-pole Chebyshev HCMR filter centered at 2.6 GHz with in-band return loss of 20 dB and 0.1 dB-ripple fractional bandwidth (FBW) of 8.5% is designed. According to the low-pass prototype and calculation [12], the element values of the lowpass prototype can be found to be $g_0 = 1$, $g_1 = 0.8431$, $g_2 = 0.6220$. The external quality factor Q_e and coupling efficient $m(i,j)$ can be defined as follows:

$$Q_{e1} = Q_{e2} = \frac{g_0 g_1}{FBW_A} \approx 9.9188 \quad (2)$$

$$m_{12} = m_{21} = \frac{FBW_A}{\sqrt{g_1 g_2}} \approx 0.1173 \quad (3)$$

The coupling coefficients m_{Si} and m_{Li}, which denote the couplings between the source and load to each resonant mode, can be extracted from external quality factors [12] by:

$$Q_{e,Si} = \frac{1}{m_{Si}^2 \cdot FBW} \quad (4)$$

$$Q_{e,Li} = \frac{1}{m_{Li}^2 \cdot FBW} \quad (5)$$

According to Equation (2)-(5), the calculated inter-stage coupling matrix of the implemented filter according to the low-pass prototype is given by:

$$m_A = \begin{bmatrix} 0 & 1.089 & 0 & 0 \\ 1.089 & 0 & 0.1173 & 0 \\ 0 & 0.1173 & 0 & 1.089 \\ 0 & 0 & 1.089 & 0 \end{bmatrix} \quad (6)$$

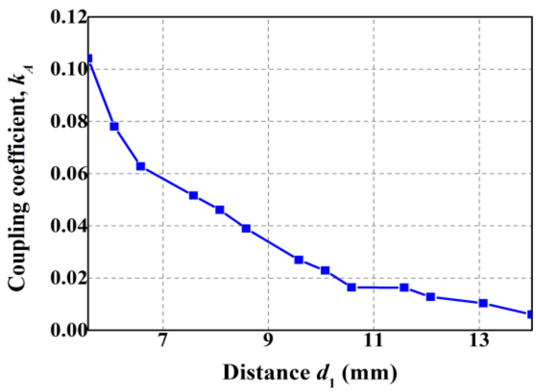
Implementing the similar calculations with a two-pole Chebyshev hybrid resonator BPF B centered at 3.1 GHz with in-band return loss of 20 dB and 0.1 dB-ripple FBW of 5.7%. The calculated inter-stage coupling matrix of the implemented filter according to the low-pass prototype is derived by:

$$m_B = \begin{bmatrix} 0 & 1.089 & 0 & 0 \\ 1.089 & 0 & 0.0787 & 0 \\ 0 & 0.0787 & 0 & 1.089 \\ 0 & 0 & 1.089 & 0 \end{bmatrix} \quad (7)$$

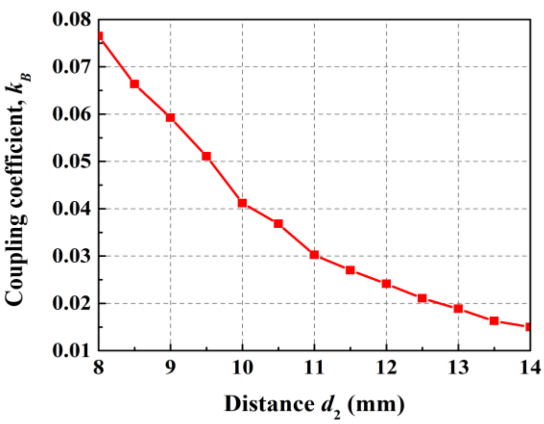
The coupling coefficient of the coupled hybrid coaxial and microstrip resonator [12] is:

$$k_A = \frac{f_{2A}^2 - f_{1A}^2}{f_{2A}^2 + f_{1A}^2} \qquad (8)$$

Where f_{1A} and f_{2A} are the two resonant peaks of BPF A, respectively. Full-wave



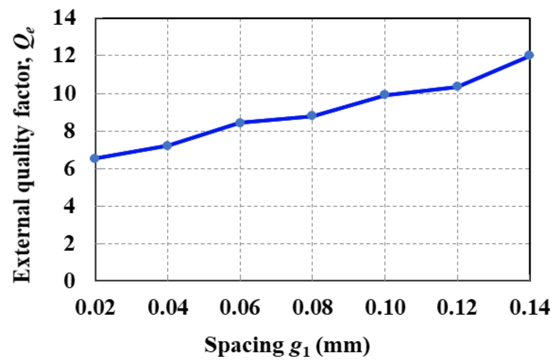
(a)



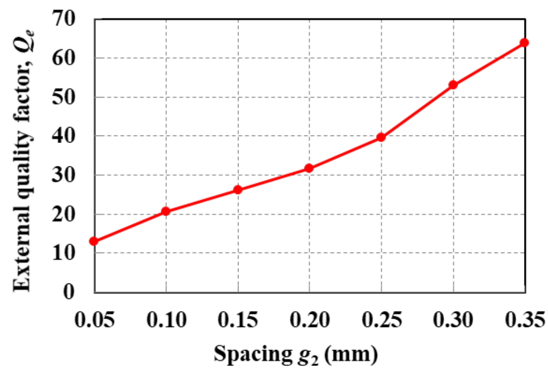
(b)

Figure 3. Extracted coupling coefficient k_A, k_B with regard to different values distance d_1 and d_2, respectively

EM simulations are carried out to extract the desired external quality factor and coupling coefficient. The coupling strength of the proposed HCMR is mainly controlled by the spacing *d* between the two copper rods. Figure 3 shows the design curve for the coupling coefficient k_A and k_B, respectively. It is obvious that the coupling decreases as the spacing d_1 between the coupled resonators increases. The filter of bandwidth can be enlarged with small d_1.



(a)



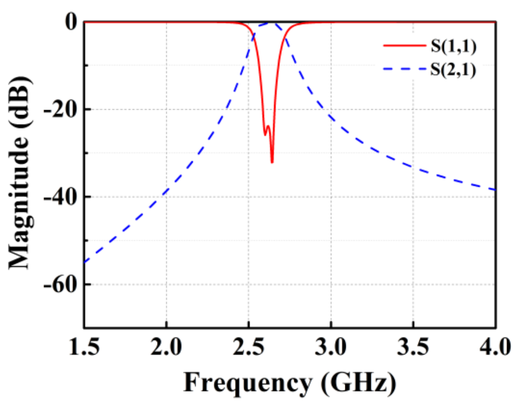
(b)

Figure 4. Design curve for external quality factor Q_e with different spacing g_1 and g_2, respectively

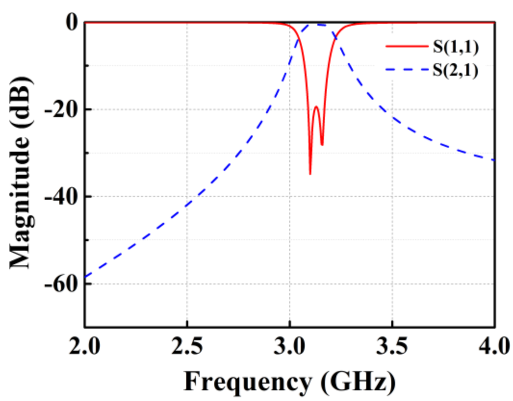
A design curve for Q_e against distance g_1 and g_2 can be obtained, as shown in Figure 4. In this case, as g_1 and g_2 increases, the coupling from the source is weaker so that Q_e increases.

3. DIPLEXER IMPLEMENTATION AND RESULTS

The proposed diplexer is realized on 0.635 mm thick Taconic substrate (ε_r = 2.65, tanδ = 0.0019) and the microstrip has a thickness of 0.035 mm. The simulations are carried out by using a full-wave electromagnetic (EM) simulator HFSS. The EM simulated responses of the BPF A at 2.6 GHz center frequency are shown in



(a)



(b)

Figure 5. Simulated frequency response of (a) BPF A, and (b) BPF B

Figure 5 (a). The filter shows an upper side of the operating frequency with an overall out-of-band rejection, better than 32.5 dB. The return loss is better than 20 dB within the passband over a bandwidth of 8.5% (2.53–2.72 GHz). The minimum insertion loss is 0.36 dB. The same procedure is used to design the upper-frequency channel bandpass filter at 3.1 GHz center frequency. This filter requires a high rejection at 2.6 GHz lower-frequency channel filter. Figure 5 (b) shows the corresponding simulated responses of the filter B. A lower side of the operating frequency with an improved out-of-band rejection, better than 37.4 dB. The 3-dB bandwidth is 5.7% (3.04–3.22 GHz) and the minimum insertion loss is 0.59 dB. The return loss is better than 18.5 dB within the passband.

Lastly, to obtain satisfactory impedance matching, the input impedance at the “T”-junction needs to satisfy the following conditions:

$$Z_{inA} = \begin{cases} \infty & \text{at } 3.1 \text{ GHz} \\ 50\Omega & \text{at } 2.6 \text{ GHz} \end{cases} \quad (9)$$

$$Z_{inB} = \begin{cases} 50\Omega & \text{at } 3.1 \text{ GHz} \\ \infty & \text{at } 2.6 \text{ GHz} \end{cases} \quad (10)$$

Where Z_{inA} and Z_{inB} are the input impedances of the diplexer at the junction looking into the upper and lower path, respectively, as illustrated in Figure 1. These conditions can be easily satisfied by connecting the junction to each filter with a microstrip line, which ensures an open circuit at the frequency of the other passband. Finally, the dimension optimization of the proposed diplexer that referred to Figure 1, which is carried out by using the quasi Newton method available ANSYS HFSS simulator and listed in Table 1.

Table 1. Physical size of the proposed diplexer (in mm)

Parameters	Value	Parameters	Value
w_1	1.74	L_A	16.8
w_2	0.5	L_B	18.8
w_3	0.3	L_T	10.1
L_1	10.5	w_T	1.74
L_2	6.4	h	10
L_3	4.6	r	1.5
L_4	10.8	d_1	12.6
L_5	4.5	d_2	11.8
L_6	4.4	L_7	9

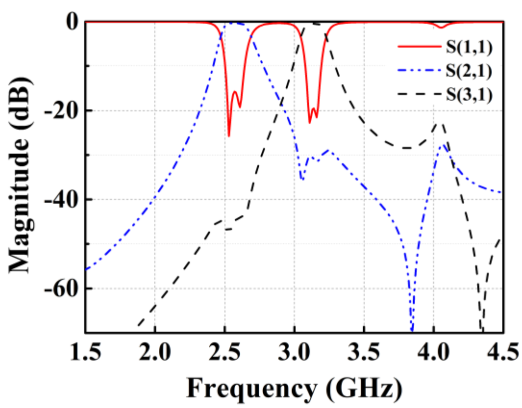


Figure 6. Simulated result insertion losses and return loss of the proposed diplexer

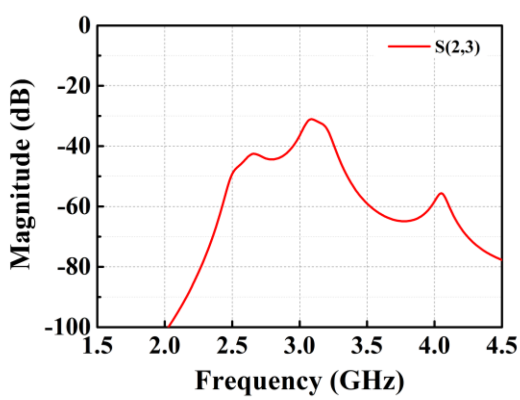


Figure 7. Simulated result isolation of the proposed diplexer

Figure 6 shows the electromagnetic simulated S-parameters of the proposed diplexer. The diplexer presents insertion losses (S_{21}, S_{31}) of 0.41 dB and 0.47 dB; and return loss (S_{11}) better than 15.7 dB and 19.5 dB, at 2.6 GHz and 3.1 GHz, respectively. There are two transmission zeros at each side of the passband are located at 2.65 and 3.05 GHz, respectively, thus allow this proposed diplexer to achieve good isolation between two filtering channels as highly expected. In particular, two transmission zeros appear at 3.8 and 4.4 GHz, respectively, in the higher frequency channel then give much better out-of-band rejection for the proposed diplexer. The isolation (S_{23}) performance of the proposed diplexer is illustrated in Figure 7. As a result, the high isolations at the lower band and higher band are 41 dB and 31 dB, respectively.

Table 2 shows a comparison with other differential diplexer designs developed by using the microstrip-Slotline, microstrip resonator, and LTCC. Comparing to the diplexer in [5] and [7], the simulated insertion loss of proposed design is better than 0.5 dB and the isolation is better than 30 dB. In [9], the diplexer are fabricated using LTCC techniques and the isolation is better than 35 dB. However, the multilayer structures will increase the cost of product processing. In sum, the proposed diplexer offers a better trade-off between insertion loss, return loss and isolation.

Table 2. Comparison with some other diplexers

[Refs.]	Type of diplexer	$1^{st}/2^{nd}$ Passband (GHz)	Insertion Loss (dB)	Return Loss (dB)	Isolation (dB)	FBW (%)
[5]	Microstrip- Slotline	2.51/3.48	1.25/0.28	18/20	35/28	13.9/4.3
[7]	Microstrip Resonator	2.3/3.5	3.23/2.3	9.6/10.6	N/A	4.3/14.0
[9]	LTCC	3.55/5.55	1.7/2.3	15/16	40/36	11.5/8.6
[This work]	Hybrid coaxial and microstrip resonator	2.6/3.1	0.41/0.47	15.7/19.5	41/31	8.5/5.7

4. CONCLUSION

In this paper, a new simple design approach for compact and high isolation diplexer using low loss hybrid coaxial and microstrip resonators bandpass filters with high isolation and simple circuit has been proposed and designed. The proposed diplexer has the advantages of flexible design approach, good selectivity, high isolation as well as easy to integrate with other printed circuits. Mixed electromagnetic coupling is formed by the copper rods and the gaps between the resonators, transmission zeros are produced and the isolation of the diplexer is improved. The EM simulation results diplexer shows that each filtering channel has its own transmission zeros in either the lower- or upper-stopbands to realize its high filtering selectivity, and high isolation better than 31 dB has been achieved. The designed diplexer has a broad application prospect in Tx/Rx front-end transceivers of weather radar, surface ship radar, and wireless communications systems.

REFERENCES

[1] Ofli E, Vahldieck R, and Amari S, "Novel E-plane filters and diplexers with elliptic response for millimeter-wave applications", IEEE Transactions on Microwave Theory and Techniques, vol. 53, no. 3, pp. 843-851, 2005.

[2] L. Nouri, S. Yahya and A. Rezaei, "Design and fabrication of a low-loss microstrip lowpass-bandpass diplexer for WiMAX applications", China Communications, vol. 17, no. 6, pp. 109-120, 2020.

[3] S. I. Yahya, A. Rezaei, L. Noori and M.H. Jamaluddin, "A Novel Harmonic Attenuator Quad-Channel Microstrip Diplexer for Multi-Service Communication Systems", 2019 IEEE Asia-Pacific Microwave Conference (APMC), pp. 1676-1678, 2019.

[4] Yao H.W., Abdelm A.E., Liang J. F., Liang X.P. and Zaki K., "Wide-band waveguide and ridge waveguide T-junctions for diplexer applications", IEEE Transactions on Microwave Theory and Techniques, vol. 41, pp. 2166–2173, 1993.

[5] B. Ren, Z. Ma, H. Liu, M. Ohira, P. Wen, X. Wang and X. Guan, "Design of a compact diplexer using microstrip and slotline dual-mode resonators", 2017 Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP), pp. 1-3, 2017.

[6] P. Deng, R. Liu, W. Lin and W. Lo, "Design of a Microstrip Low-Pass-Bandpass Diplexer Using Direct-Feed Coupled-Resonator Filter", IEEE Microwave and Wireless Components Letters, vol. 27, no. 3, pp. 254-256, 2017.

[7] M.A. Sazali, N.A. Shairi and Z. Zakaria, "Hybrid Microstrip Diplexer Design for Multi-band WiMAX Application in 2.3 and 3.5 GHz Bands", International Journal of Electrical and Computer Engineering (IJECE), vol.8, no.1, pp. 576-584, 2018.

[8] H.-W. Liu, W.-Y. Xu, Z.-C. Zhang and X.-H. Guan, "Compact diplexer using slotline stepped impedance resonator", IEEE Microwave and Wireless Components Letters, vol. 23, no. 2, pp. 75 – 77, 2013.

[9] J. Xu and X.Y. Zhang, "Compact High-Isolation LTCC Diplexer Using Common Stub-Loaded Resonator With Controllable Frequencies and Bandwidths", IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 11, pp. 4636-4644, 2017.

[10] Trong-Hieu Le, Chuan Ge and Xiao-Wei Zhu, "Two-pole bandpass filter using new hybrid resonator", IEEE Asia-Pacific Microwave Conference (APMC), vol. 1, pp. 233-235, 2015.

[11] R.J. Cameron, "Advanced coupling matrix synthesis techniques for microwave filters", IEEE Transactions on Microwave Theory and Techniques, vol. 51, pp. 1- 10, 2003.

[12] J.S. Hong, "Microstrip Filters for RF/Microwave Applications", second edition, New York: Wiley, 2001.

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