International Journal of Electrical and Computer Engineering (IJECE)
Vol. 8, No. 1, February 2018, pp. 576~584
ISSN: 2088-8708, DOI: 10.11591/ijece.v8i1.pp576-584

Hybrid Microstrip Diplexer Design for Multi-band WiMAX Application in 2.3 and 3.5 GHz Bands

M. A. Sazali, N. A. Shairi, Z. Zakaria
Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer, Universiti Teknikal Malaysia Melaka (UTeM),
Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia

Article Info

Article history:

Received Sep 27, 2017
Revised Dec 20, 2017
Accepted Jan 4, 2018

Keyword:

Diplexer
Multi-band
Resonator
WiMAX

ABSTRACT

In this paper, a design of hybrid microstrip diplexer is proposed for multi-band Worldwide Interoperability for Microwave Access (WiMAX) application in 2.3 and 3.5 GHz bands. The diplexer consists of a combination of two different filter designs. These filters were designed based on microstripline coupling techniques in order to obtain minimum insertion losses and achieve the desired frequency bandwidth. Therefore, a coupled open loop ring resonator was chosen for the filter design in 2.3 GHz band and a folded coupled line resonator was chosen for the filter design in 3.5 GHz band. Then, these filters were combined with a ring manifold matching network to be a hybrid microstrip diplexer. Based on the results, good agreements were achieved between the simulation and measurement results in terms of insertion loss, return loss and bandwidth in the 2.3 and 3.5 GHz bands.

Corresponding Author:

Noor Azwan Shairi ,
Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK),
Universiti Teknikal Malaysia Melaka (UTeM),
Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia.
Email: noorazwan@utem.edu.my

1. INTRODUCTION

In multi-band and multi-standard wireless communication systems, there is a requirement of designing a multi-band RF and microwave circuit to support modern wireless technologies such as WiFi, WiMAX and LTE [1], [2]. From the literatures, several examples can be found in certain designs such as antenna [3-6], filter [7-9], switch [10-12], mixer [13] and low noise amplifier [14], [15]. Besides, the demand has also led to the challenge in RF and microwave circuit design to support the requirements of different frequency bandwidths for different bands.

With the current demand of multi-band WiMAX, this technology has been implemented in four different spectrum bands worldwide, which are in 2.3, 2.5, 3.5 and 5 GHz bands [16], [17]. Although it has been implemented worldwide, the spectrum allocations are also based on the country regulations [18]. Table 1 shows the WiMAX operation in certain spectrum allocated to various countries which are recognised by the International Telecommunications Union (ITU).

In order to support multi-services simultaneously, as reported in [19], [20] diplexers in the WiMAX application were implemented using a Low Temperature Co-fired Ceramic (LTCC) technology to fullfil the current technology requirements. The authors in [21] also designed diplexer for WiMAX application but in different fabrication technology; which is Monolithic Microwave Integration Circuit (MMIC). The performances of the diplexers achieved good agreements between diplexers responses and the application requirements. However, the development of the diplexers on such technology has given more complexity in the design stage and increased costs during the manufacturing process compared to the design in [22] which used a microstrip structure. Besides, the diplexer can also give good performances for WiMAX application which is similar to the MMIC technology. The key advantages of designing a diplexer using the microstrip structure are cheaper cost and ease to manufacture.

Therefore, in this paper, hybrid microstrip diplexer design is proposed for multi-band WiMAX application in 2.3 and 3.5 GHz bands. The proposed diplexer design consists two different bandpass filter and a matching network. These two bandpass filters were designed based on the microstripline coupling technique due to ease of controlling the frequency bandwidth during the design processes [23], [24]. Thus, a coupled open loop ring resonator was chosen for the filter design in 2.3 GHz band and a folded coupled line resonator was chosen for the filter design in 3.5 GHz band. Then, these filters were combined with a ring manifold matching network as a hybrid microstrip diplexer. The diplexer was designed and simulated in the Advanced Design System (ADS) for analysis and fabricated on an FR4 board for verification.

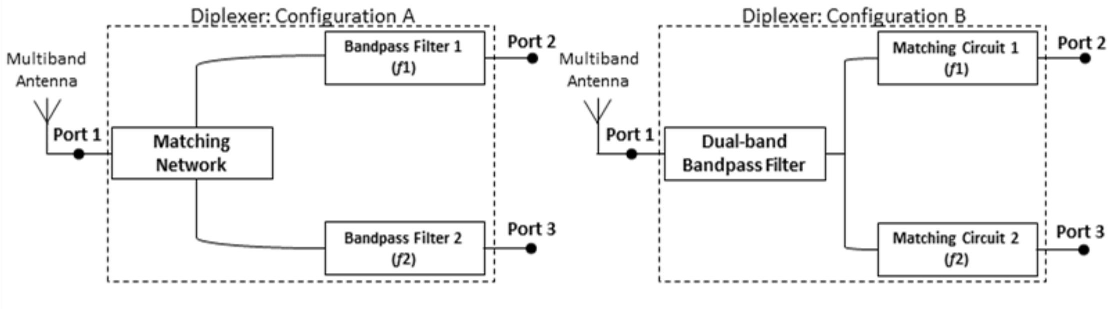
Table 1. WiMAX Spectrum Allocation [18]

No	Country	Spectrum Allocation
1	Asia Pacific	2.3, 3.3, 3.5, 5 GHz
2	Canada	2.5, 3.5, 5 GHz
3	Central & South America	2.5, 3.5, 5 GHz
4	Europe	3.5, 5 GHz
5	Middle East & Africa	3.5, 5 GHz
6	Russia	2.3, 2.5, 3.5 GHz
7	United States	2.5, 3.5, 5 GHz

This paper is organized as follows. Section 2 discusses the selection and analysis of the bandpass filter for hybrid diplexer. Then, Section 3 continues with the explanation and discussion of the proposed hybrid diplexer designs. The experimental results and discussion are reported in Section 4. Finally, the overall conclusion of this paper is presented in the last section.

2. SELECTION OF DIPLEXER

In selecting the configurations of a diplexer design, there are two different configurations (Configuration A [25] and Configuration B) as depicted in Figure 1. The differences between the configurations are the location of the matching network and the bandpass filters. In Configuration A, it requires a matching network before the bandpass filters. This filter is a single bandpass filter. Meanwhile, in Configuration B, two matching networks are required and placed over the filter. This filter must be a dual-band bandpass filter to support multi-band applications. In this paper, Configuration A was selected due to the flexibility of the selection of two different types of bandpass filter in 2.3 and 3.5 GHz band, thus meeting different bandwidth requirement in multi-band WiMAX application.

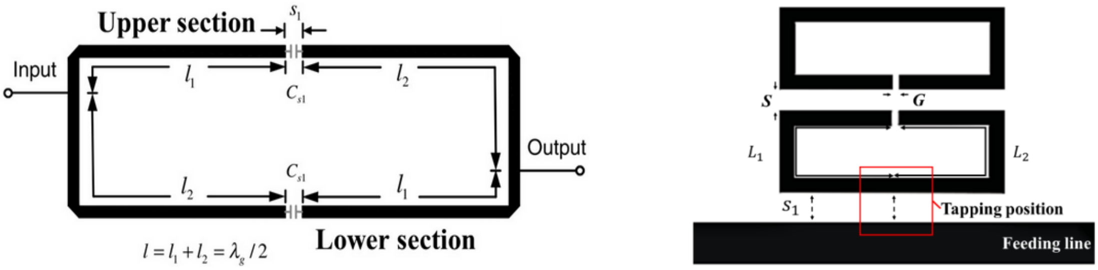


(a) (b)

Figure 1. Diplexer designs, (a) Configuration A [25] and (b) Configuration B.

2.1. Bandpass Filter Design in 2.3 GHz Band

Generally, the open ring resonator was chosen to achieved a high selectivity characteristic as reported in [24] and depicted in Figure 2. In order to realise the passband response, Equation (1) was used and a coupling technique was applied between the feeding line and resonators; the location of the coupled feeding line was to suppress the harmonic of bandpass [26]. Besides, another parameter that needed to be considered was the *Q* factor. Thiswas because the coupled line of resonator created the loading effect to produce coupling mechanism such as magnetic, electric or both in order to connect the circuit and thus causing some losses such as insertion loss, dielectric loss, or radiation loss [24], [27].



(a) (b)

Figure 2. (a) Single open open loop ring resonator [24] (b) Coupled open loop ring resonator.

By refering Figure 2(a), an *ABCD* matrix analysis is applied in order to realize the bandpass filter using single open looped resonator technique. The *ABCD* matrix is defined as an individual two-port networks. Therefore, in this proposed bandpass filter, there are two matrixes used to determine the open looped resonator and they are upper and lower loops. Equation in (1) indicates the matrixes

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{upper} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{lower} = M_1 M_2 M_3 \tag{1}$$

where M_1,M_2 *and* M_3 are the ABCD parameters of the two-port networks for transmission lines (l_1 and l_2) and the gap (C_{s1}) [24]. The parameters of the M_1, M_2 and M_3 are simplified and transformed to the Y- parameter using conversion between two-port networks as referring in [27] thus Equation (2) is obtained as

$$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}_{upper} + \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}_{lower} = \begin{bmatrix} D_j/B_j & (B_j C_j - A_j D_i)/B_j \\ -1/B_j & A_j/B_j \end{bmatrix} \tag{2}$$

From (2), the insertion loss, S_{21} of the bandpass filter using open looped resonator can be found by using the Y-paramter to S-parameter convertion [27],

$$S_{21} = \frac{j4\left(Z_0 \sin\beta l - \frac{\cos\beta l_1 \cos\beta l_2}{\omega C_{s1}}\right)Y_0}{\left[2 \cos\beta l + \frac{Y_0 \sin\beta l}{\omega C_{s1}} + j\left(Z_0 \sin\beta l - \frac{\cos\beta l_1 \cos\beta l_2}{\omega C_{s1}}\right)Y_0\right]^2 - 4} \tag{3}$$

where β is the propagation constant, $Z_c = {}^{1}/_{j\omega C_{s1}}$, is the impedance of gap capacitance or separation *Cs1*, ω is the angular frequency, and $Z_0 = {}^{1}/_{Y_0}$ is the impedane of the resonator.

In this paper, another analysis was conducted as shown in Figure 3. The passband response showed a study for the coupled open loop ring resonators based on an FR4 substrate with a dielectric constant of 4.3 and board thickness of 1.6 mm. The focus of this study was at the coupling separation between the resonator and tapping position as shown in Figure 2(b). It was found that the optimum separation between the resonator and tapping position was 0.5 mm. The bandwidth achieved was a 100 MHz from 2.3 to 2.4 GHz with transmission zeros at out of the band were very close to the passband response. However, for s = 0.3 and 0.7 mm, it showed that a hump response was produced and the transmission zeros were slightly far from the passband response. Beside that, it was found that the passband response shifted to the lower frequencies. For WiMAX application at 2.3-2.4 GHz, the passband response required a 100 MHz bandwidth.

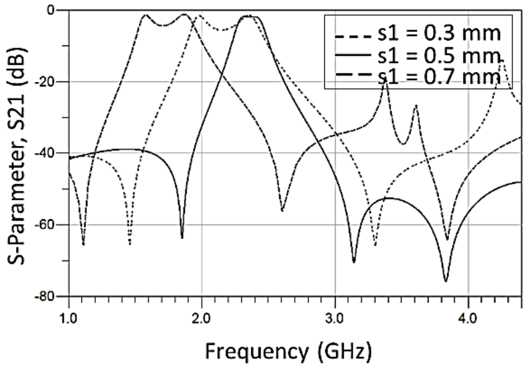


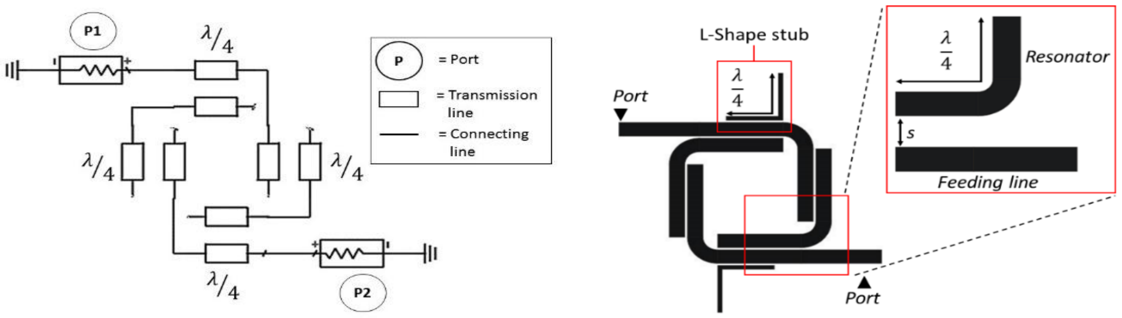
Figure 3. Analysis of coupled open loop ring resonator on FR4 subtrate

2.2. Bandpass Filter Design in 3.5 GHz Band

For the bandpass filter operating in 3.5 GHz band, 700 MHz bandwidth was targeted in the design. Therefore a folded coupled line resonator as reported in [28] was selected due to a wider bandwidth passband response with smaller or compact filter size. Since this type of bandpass filter was a parallel coupled line originally, there were dual modes (even- and odd-) of coupled mechanism that occurred between the resonators. These modes were important factors to match the bandpass filter. The values of dual mode can be calculated by

$$Z_{oe}n = Z_o(1 + Z_oJ_n + (Z_oJ_n)^2), Z_{oo}n = Z_o(1 - Z_oJ_n + (Z_oJ_n)^2) \quad (4)$$

where Z_o is the real impedance of the transmission line, while J_n is the imaginary part of the transmission line. After calculated the values, the bandpass filter is developed in schematic form as shown in Figure 4.

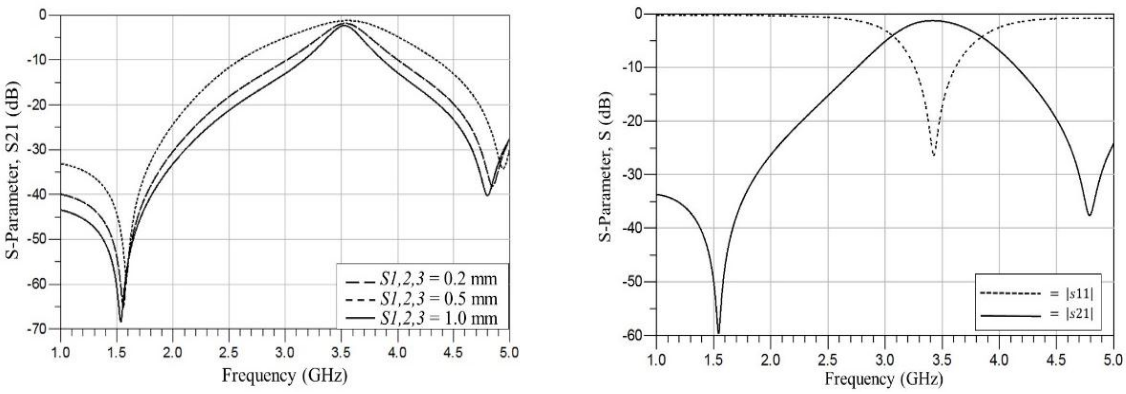


(a) (b)

Figure 4. (a) The schematic of bandpass filter [28] (b) The structure of folded coupled line resonator in filter design

As depicted in Figure 4(a), folded coupled lines are based on the transmission line modelling or schematic which was constructed in the ADS software. In Figure 4(b), four coupled lines were bent in a form of ring structure to miniaturize the size of the bandpass filter as introduced in [28]. Figure 5(a) shows a relationship of the coupling separation between the folded coupled line resonators. The passband response showed that the narrower the separation of the coupling the larger the bandwidth achieved. This analysis also tallies with the analysis in [29].

However, the bandpass filter in 3.5 GHz band also produced a wider attenuation slope. Thus, to obtain an improved attenuation slope, L-shaped stubs were introduced in the design as additional stub-loaded resonators. These stubs produced additional notches at the upper and lower out of the band in the filter design as reported in [24], [29]. Figure 5(b) shows the finalized passband response before integrating with other circuits in the hybrid microstrip diplexer design.



(a) (b)

Figure 5. (a) The analysis of coupling separation (b) The finalized bandpass filter response in 3.5 GHz band

3. DIPLEXER DESIGN

Figure 6 shows a block diagram of the hybrid microstrip diplexer design. The configuration of the proposed diplexer was a combination of two bandpass filters operating from 2.3 to 2.4 GHz and 3.3 to 3.8 GHz. These two filters were combined by using the ring manifold matching network (denoted as M1 in Figure 7) because it was easy to construct and provide a better performance for narrow to medium band frequency responses [30].

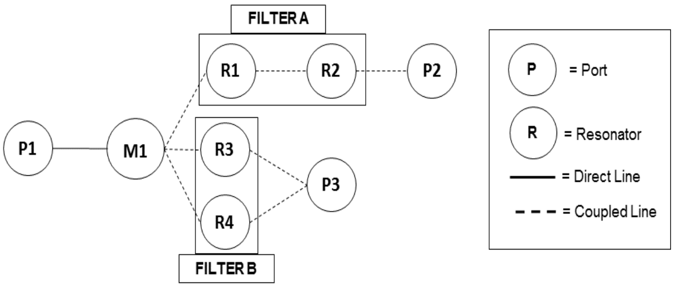
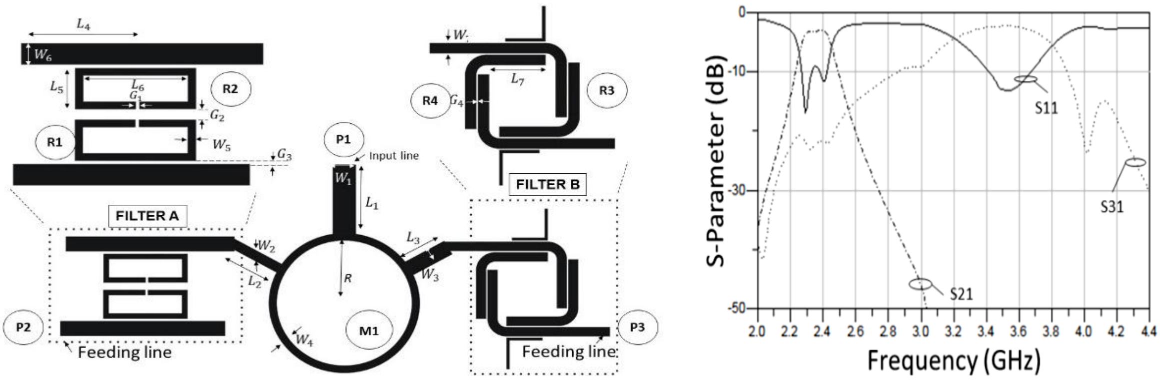


Figure 6. Block diagram of hybrid microstrip diplexer design

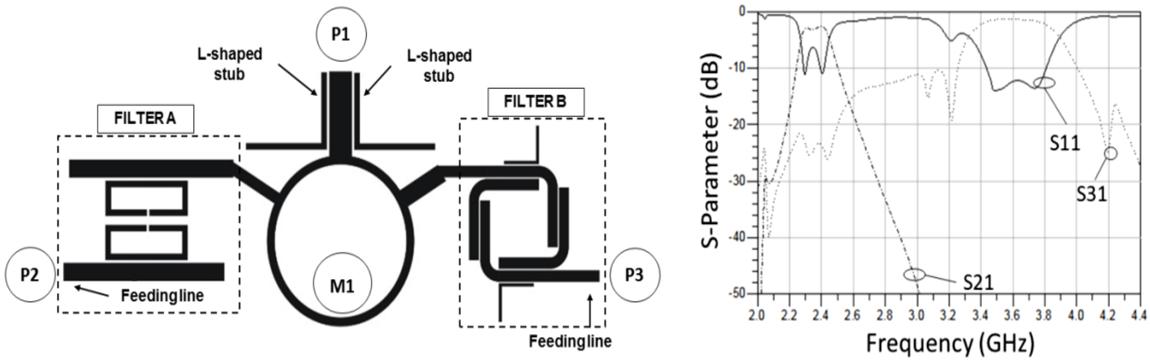


(a) (b)

Figure 7. (a) Layout of hybrid microstrip diplexer design (b) The simulation response of diplexer

Figure 7(a) shows the layout of hybrid microstrip diplexer design. It was constructed in ADS software based on the FR4 substrate (ε_r = 4.6, h = 1.6 mm, $tan\ \delta$ = 0.019). The characteristic impedance of the input and the output was set to 50 Ohm. Therefore, the dimensions of the matching network are W_1=4.2 mm, W_2=1.9 mm, W_3=2.98 mm, W_4=1.4 mm, L_1=13.61 mm, L_2=10.11 mm, L_3=8.3 mm and R=13.17 mm; the dimensions of Filter A are W_5= 1 mm, W_6=2.9 mm, L_4=15 mm, L_5=5.6 mm, L_6=13.4 mm, G_1, G_3=0.5 mm and G_2=1.5 mm; and the dimensions of Filter B are W_7=1.8 mm, L_7=10 mm and G_4=0.3 mm.

The *S*-parameter simulation is shown in Figure 7(b). The simulated results of the first diplexer showed -3.23 dB of the insertion loss, IL at 2.35 GHz, and -2.30 dB at 3.51 GHz. By referring to *S21*, the bandwidth at the output of P2 was 100 MHz and for *S3*, the bandwidth at the output of P3 was 300 MHz. Obviously, the bandwidth of Filter B in the diplexer is smaller than the initial performance of the single filter design in Section 2.2. Besides, the smaller bandwidth was affected by the additional phase delay due to the matching network since it is a 180^0 hybrid ring [23], [27].



(a) (b)

Figure 83. (a) Improved design of hybrid microstrip diplexer (b) The response of the diplexer

Therefore, to increase the bandwidth of the passband response in Filter B, L-shaped stubs were added to be additional notch responses [29]. On the other hand, it also improved the band attenuation. As shown in Figure 8(a), the L-shaped stubs were constructed based on the quarter wavelength of microstriplines [18], [19] where the selected width of the L-shaped stubs was 0.5 mm. The L-shaped stubs were resonated at 3.2 and 4.1 GHz. The improved performance of the hybrid microstrip diplexer is depicted in Figure 8(b). It showed that the performance of the improved design of the diplexer can be used for multi-band WiMAX from 2.3 to 2.4 GHz (100 MHz bandwidth) and 3.3 to 3.8 GHz (500 MHz bandwidth).

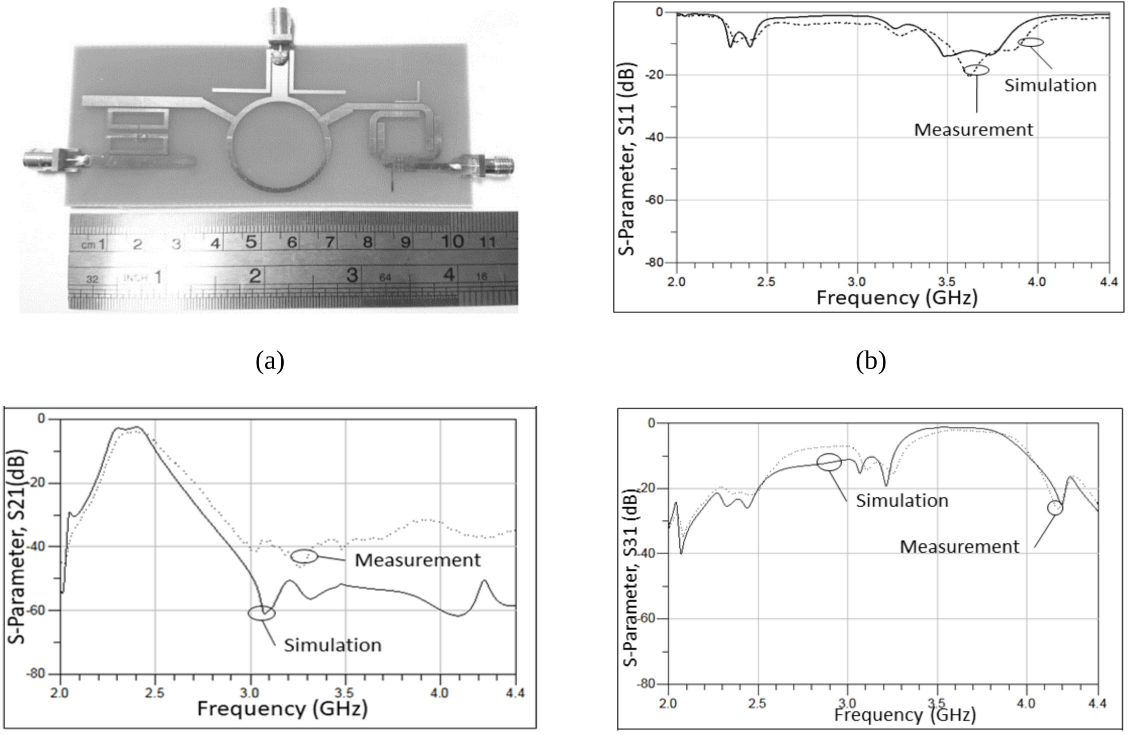
4. EXPERIMENTAL RESULT AND DISCUSSION

The prototype of the hybrid microstrip diplexer was fabricated on FR-4 board with ε_r = 4.6, h = 1.6 mm, $tan\ \delta$ = 0.019. The photograph, measured and simulated results of the hybrid microstrip diplexer are shown in Figure 9. The dimension of the fabricated diplexer is 105 x 45 mm as depicted in Figure 9(a).

Figure 9(b) showed return loss at port P1 where an acceptable S11 was achieved in 2.3 and 3.5 GHz band. The measurement results (in Figure 9(c) and (d)) showed the lowest insertion loss of -4.12 and -2.42 dB at frequencies of 2.39 and 3.7 GHz respectively. Meanwhile, the measured output of the diplexer bandwidths was 130 MHz (in 2.3 GHz band) at port P2 and 400 MHz (in 3.5 GHz band) at port P3.

A good agreement between simulation and measurement results can be seen even thoughit was a bit different in the out of band response. The differences between simulated and measured results were due to many factors such as the limitation and additional losses in the fabrication process, calibration of measurement devices, and the additional parasitic inductive elements of the soldering process. In addition, the FR4 board might have tolerances that contributed to the differences.

In general, the acceptable insertion loss of the bandpass of the hybrid microstrip diplexer was about -3 dB as referred in [27] and the return loss is greater than -10 dB. For the measurement results, the insertion loss was better that -4.12 dB, while the return loss was greater than -10 dB and acceptable for the filter application [35]. Table 2 shows a comparison with other diplexer designs. Obviously, the proposed diplexer has the qualification to be implemented in WiMAX application. The focus was the bandwidths of the diplexer which covered the WiMAX (IEEE 802.16 standards). The performances of the proposed diplexer also showed acceptable results.



(a) (b)

(c) (d)

Figure 9. (a) Photograph of the proposed diplexer (b) Return loss, S11 (dB) (c) Bandpass of Filter A at port P2, S21 (dB) (d) Bandpass of of Filter B at port P3, S31 (dB)

Table 2. comparison of the diplexer to the other diplexer design

	Type of diplexer	Substrate Materials	*fo (GHz)*	*RL (dB)*	*IL (dB)*	FBW (%)	Bandwidth (MHz)
This work	Microstrip coupled lines	FR-4	*2.3, 3.5*	-9.58, -10.63	-4.12, -2.42	4.3, 14.0	100, 500
[8]	Microstrip open loop	FR-4	*3.2, 5.8*	-21, -2 7	-1.86, -2	8.9, 9.75	312, 515
[26]	Microstrip open loop	RT/Duroid 6010LM	*2.3, 3.7, 5, 6.1*	<-20	-2.2, -2.5, -1.8, -2.1	5, 4, 7, 4	100 to 300
[31]	Microstrip	RT/Duroid 5880	2.6, 6	-11.3, -12.4	-0.6, - 0.9	4.2, 5.2	110, 310
[32][33]	Mcrostrip balun	RT/Duroid 5880	2.46,3.65	<-18	1.5, 2	8.1, 4.9	100 to 300
[34]	Microstrip coupled lines	Arlon_AD270N	1.8, 2.1	> - 16	2, 1.8	5.5, 6.2	100, 130

5. CONCLUSION

In this paper, a hybrid microstrip diplexer for multi-band WiMAX application (2.3 and 3.5 GHz band) was designed by combining two different types of microstrip filter with a single 180^0 matching network (ring manifold). In order to achieve acceptable insertion losses and good bandpass bandwidths, two coupling techniques in the filter designs were chosen which were coupled open loop ring resonator and folded coupled line resonator. The proposed hybrid microstrip diplexer was designed and simulated in the ADS software. Then it was fabricated on an FR4 board. Results showed that a good agreement between simulation and measurement results was achieved and it validated the overall performance for multi-band WiMAX application in 2.3 and 3.5 GHz bands.

ACKNOWLEDGEMENT

Sincerely to express the appreciation to Centre for Research & Innovation Management (CRIM), Centre for Telecommunication Research & Innovation (CeTRI), Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM) and MyBrain15 under Ministry of Higher Education (MOHE) for funding this work under the research grant no.: PJP/2017/FKEKK/HI13/S01543

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BIOGRAPHIES OF AUTHORS

Muhammad Aizat Sazali is a Msc student from Universiti Teknikal Malaysia Melaka (UTeM) in Department of Telecommunication Engineering, Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK) . Currently, he is doing research on diplexer and triplexer for multi-band WiMAX application. His technical interest is mainly focused on RF and Microwave Engineering

Noor Azwan Shairi, PhD, MIEEE - was born in Malaysia in 1978. He received the Bachelor in Engineering (Electrical–Telecommunication) and the Master in Electrical Engineering (By Research) from Universiti Teknologi Malaysia (UTM), in 2002 and 2005, respectively. In 2015, he obtained his Doctorate from Universiti Teknikal Malaysia Melaka (UTeM) in the field of Electronic Engineering (RF and Microwave). Currently, he is a Senior Lecturer at the Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK), UTeM, Malaysia. His research areas are mainly focused on RF and Microwave Engineering.

Zahriladha Zakaria, PhD, MIEEE - was born in Malaysia in 1975. He received the B. Eng. and M. Eng. in Electrical and Electronic Engineering from the Universiti Teknologi Malaysia in 1998 and 2004 respectively. He obtained his Doctorate from The University of Leeds in 2010 in the field of Microwave Engineering. He is currently an Associate Professor at the Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK), UTeM, Malaysia. His research interests include a variety of microwave device developments such as planar and nonplanar microwave filters, amplifiers and antennas.