Microwave Diplexer Purely Based on Direct Synchronous and Asynchronous Coupling

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Abstract. *A diplexer realized purely based on direct coupling is presented. No cross-coupling is involved in the design process. The microwave diplexer is achieved by coupling a dual-band bandpass filter onto two individual channel filters. This design eliminates the need for employing external junctions in diplexer design, as opposed to the conventional design approach which requires separate junctions for energy distribution. A 10-pole (10th order) diplexer has been successfully designed, simulated, fabricated and measured. The diplexer is composed of 2 poles from the dual-band filter, 4 poles from the Tx bandpass filter, and the remaining 4 poles from the Rx bandpass filter. The design was implemented using synchronously and asynchronously tuned microstrip square open-loop resonators. The simulation and measurement results show that an isolation of 50 dB is achieved between the diplexer Tx and Rx bands. The minimum insertion loss is 2.88 dB for the transmit band, and 2.95 dB for the receive band.*

Keywords

Bandpass filters, diplexer, dual-band filter, coupling, microstrip, square open-loop resonators (SOLR)

1. Introduction

Microwave diplexer has attracted a lot of interest due to its ability to allow two separate devices to share one communication medium. The need for miniaturization, as well as reduction in the design complexity of microwave and millimeter-wave components, while maintaining (or even improving on) the quality of such components has recently drawn a lot of attention from researchers in this research area. The aforementioned advantage makes the diplexer a cost effective and less bulky alternative to communicating via separate channels. Diplexers have got a variety of applications; hence, researchers have been coming up with novel and better design methods to cope with the ever increasing demands of modern communication systems.

Diplexers are devices used for either splitting a frequency band into two sub-bands or for combining two sub-bands into one wide band [1]. They are popularly used in satellite communication systems to combine both the transmit and the receive antennas on space crafts. This can reduce the mass and volume of the space craft to a considerable amount [2]. In general, microwave diplexers are used for connecting two different networks with different operating frequencies to a single port. Microwave diplexer is commonly used in the Radio Frequency (RF) front end of cellular radio base stations to separate the transmit and the receive channels as shown in Fig. 1.

Conventionally, microwave diplexers are achieved by connecting two separately designed filters together via an external energy distribution device. This connecting device could be a T-junction [1–5], a Y-junction [6–8], a circulator [9–11], a manifold [12–15] and recently, a common resonator [16–19]. The external junctions utilized in the conventional approach to diplexer design had resulted in more complex and larger size diplexer devices. The complexity of the conventional design is due to the fact that the external junction (or connecting device) needs to be continuously adjusted and optimized in order to achieve a desired result. Also, the large size issue with conventional diplexer is because the connecting device does not contribute to the number of poles contained in the resultant diplexer. Meaning that the connecting device has very little function in the selectivity of the diplexer and only present to split the channel and, hence, result in slightly larger size. To remedy these drawbacks, the work presented in this paper has successfully eliminated the need for an external junction in achieving a microwave diplexer and replacing it with resonators which provide resonant poles in the diplexer response. This paper will show that with a good mastery of the basic principles involved in bandpass filter (BPF) design [20] and dual-band filter (DBF) design [21], engineers can achieve diplexers purely based on existing formulations rather than developing complex optimization algorithm to achieve the same function. Hence, the diplexer design complexity is averted. Also, since the resultant diplexer in this paper is formed by coupling a section of the BPF resonators, onto a section of the DBF resonators, a reduced sized diplexer is achieved. This is because the energy distributing resonators (that is, the two DBF resonators) contribute one resonant pole to the diplexer transmit channel and one resonant pole to the

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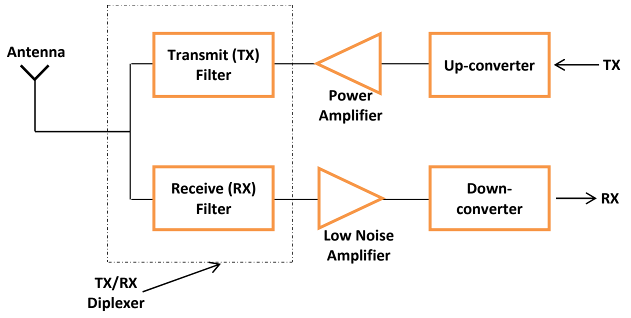

Fig. 1. RF front end of a cellular base station.

diplexer receive channel. Therefore, the large size issue with the conventional diplexer design approach can be avoided, as external junctions (or external/common resonator) are not required.

The proposed approach involves cascading a section of a DBF, with a section of two BPFs. A DBF passes two bands of frequencies while attenuating frequencies outside the two bands. A BPF, on the other hand, passes frequencies within a single band while rejecting all other frequencies outside the band. The dual-band filter resonators present in this proposed diplexer can be viewed as an energy distributor which distribute energy towards the transmit and the receive bands of the diplexer; as they replace the external junctions or the common resonator used in other diplexer designs found in literature. The actual function of the dual-band filter is to establish the two pass-bands of the diplexer. To verify this design method, a test diplexer is presented with the following specifications: center frequency, f_0, 1849 MHz; center frequency of the transmit band, $f_{0,\mathrm{TX}}$, 1800 MHz; center frequency of the receive band, $f_{0,\mathrm{RX}}$, 1900 MHz; fractional bandwidth of the transmit band, FBWTX, 4%; fractional bandwidth of the receive band, FBWRX, 4%; passband return loss, RL, 20 dB.

2. Diplexer Circuit Model

To illustrate the novel diplexer design method, a design example with the specification presented in previous section will be used to describe the design procedure. The diplexer design is started off by designing two individual 5-pole bandpass filters (BPF1 and BPF2) using the conventional method presented in [20]. BPF1 has a center frequency corresponding to that of the proposed diplexer transmit band while BPF2 has a center frequency corresponding to that of the received band. Both channel filters were designed with 20 dB return loss and 50 Ohms termination. Each has a fractional bandwidth (FBW) of 4% to match the proposed diplexer transmit and receive bands. The numerical design parameters for both BPF1 and BPF2 are shown in Tab. 1. As explained in [20], L, C and J are inductance, capacitance and J-inverter values, respectively. F is the filter centre frequency.

A 10-pole dual-band filter (DBF) was also designed using the method presented in [21]. The DBF was designed to operate at the center frequency of the proposed diplexer, with a combined FBW of 8% (with equal split of 4% each, for the upper and the lower passbands). The upper and lower passbands of the DBF, respectively, agrees with BPF1 and BPF2 in terms of number of poles, FBW and center frequency. The DBF is also designed to have a 20 dB return loss and 50 Ohms termination. Table 2 shows the numerical design parameters for the DBF.

BPF n	F n [GHz]	L [nH]	C [pF]	Jn_{01}	Jn_{12}	Jn_{23}
1	1.8	0.183	43.23	0.02	0.017	0.012
2	1.9	0.171	40.32	0.02	0.017	0.012

Tab. 1. 5th order Chebyshev bandpass filter design parameters.

Filter	F [GHz]	L [nH]	C [pF]	J_{01}	J_{12}	J_{23}	J'_{11}
DBF	1.85	0.354	20.90	0.02	0.017	0.012	0.013

Tab. 2. 10th order Chebyshev bandpass filter design parameters.

The diplexer circuit model was established by coupling the first pair of dual-band resonators of the DBF, onto the last four resonators of the transmit channel filter (BPF1) and the last four resonators of the receive channel filter (BPF2). In other words, the first resonator of each of the 5th order BPF of Tab. 1 is replaced with a dual-band resonator from the DBF of Tab. 2 as shown in Fig. 2 (c). D1 and D1' are the first pair of dual-band resonators from the DBF; T2, T3, T4, T5 and R2, R3, R4, R5 are the last four resonators of BPF1 and BPF2 respectively. Figure 2 (a), (b), and (c) show the coupling scheme for a conventional diplexer, a common resonator diplexer and the proposed diplexer, respectively. The proposed diplexer is composed of 10 resonators, making it a 10th order diplexer

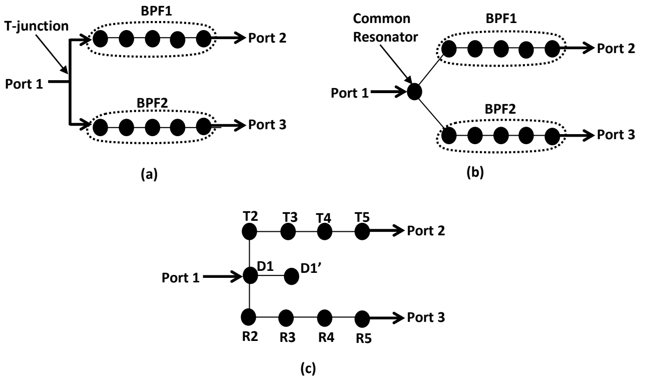

Fig. 2. 10-pole diplexer coupling structure. (a) Conventional. (b) Common resonator. (c) Proposed.

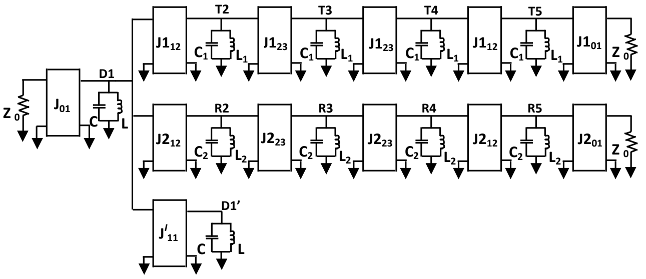

Fig. 3. Diplexer circuit model with identical LC resonators and J-inverters.

as shown in Fig. 3. The coupling between resonators in the proposed diplexer circuit model is mainly asymmetrical coupling since the diplexer is made up of three different filters, namely the DBF, BPF1 and BPF2, which all have different center frequencies as shown in Tab. 1 and 2.

$$J'_{11} = \sqrt{\frac{C}{L}}\left(\frac{f_{0,\mathrm{Rx}}^2 - f_{0,\mathrm{Tx}}^2}{f_{0,\mathrm{Rx}}^2 + f_{0,\mathrm{Tx}}^2}\right) \qquad (1)$$

The design parameters for the diplexer are the same as those contained in Tab. 1 and 2. J'_{11} is the J-inverter that exists between the two DBF resonators that form the energy distributor for the proposed diplexer. The apostrophe is used here to differential it from the single bandpass filter J-inverter rather than having the mathematically meaning of derivative J-inverter. The numerical value for J'_{11}, as indicated in Tab. 2, is determined using (1) [21], where $f_{0,\mathrm{TX}}$ and $f_{0,\mathrm{RX}}$ are the center frequencies for the diplexer transmit and receive bands respectively. The diplexer circuit model was simulated using the Agilent Advanced Design System (ADS) Circuit Simulator. Before performing the simulation, the couplings between resonators were modeled using the method presented in [23].

The simulation results of the diplexer circuit model are shown in Fig. 4. The results clearly show that the diplexer has a center frequency of 1.85 GHz as designed. The minimum return loss is approximately 19 dB across the band. These are in close agreement with the original design specification.

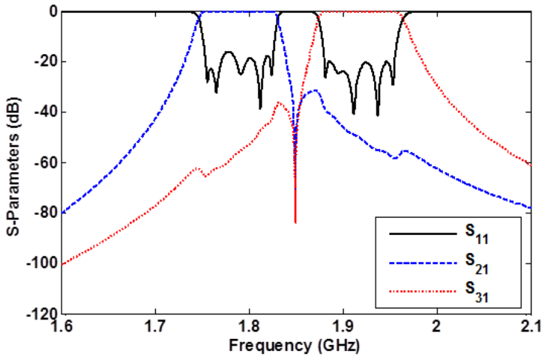

Fig. 4. Simulations responses of the diplexer circuit model.

3. Microstrip Diplexer

The microstrip square open-loop resonator (SOLR) technique presented in [23] has been utilized in the implementation of the diplexer circuit. The SOLRs utilized in achieving the diplexer presented in this investigation were designed to have the dimensions shown in Fig. 5. The transmit resonator (Tx), the receive resonator (Rx), and the energy distributor resonator (ED), all correspond to the BPF1, the BPF2, and the DBF component filters, respectively. All dimensions were achieved based on the component filters center frequencies.

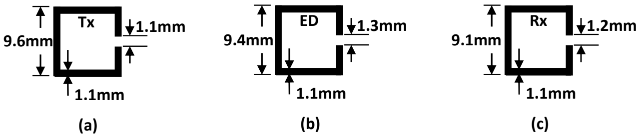

Fig. 5. Resonator dimensions. (a) Transmit. (b) Energy distributor. (c) Receive.

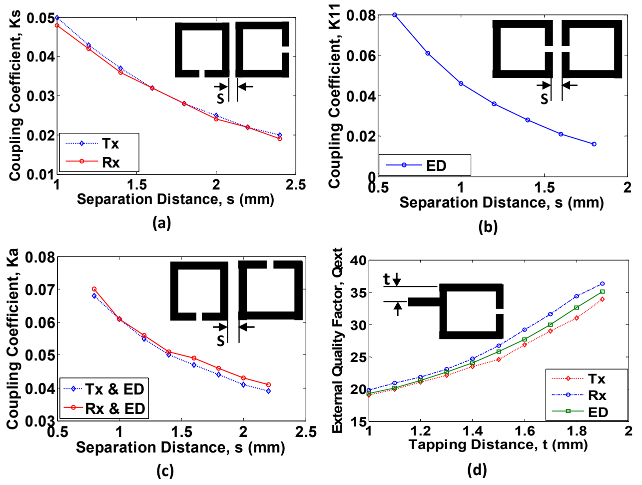

Fig. 6. Coupling coefficients and external quality factors. (a) Tx/Tx and Rx/Rx couplings. (b) ED/ED coupling. (c) Tx/ED and Rx/ED couplings. (d) External quality factor.

Using the Agilent ADS Momentum simulator, the coupling coefficients and the external quality factors for the diplexer were determined and presented in Fig. 6. The coupling between a pair of Tx or Rx resonators (Fig. 6 (a)) where synchronously tuned since they are of equal dimensions. Similarly, the coupling between the ED resonators (Fig. 6 (b)) was also synchronously tuned. On the other hand, the couplings between Tx and ED resonators or Rx and ED resonators (Fig. 6 (c)), were asynchronously tuned because of the variations in the resonator dimensions, i.e. the resonators were resonating at different frequencies. The coupling coefficients of Fig. 6(a), (b), and (c), were determined from simulating a coupling pair of resonators and using (2) [20], where f_1 and f_2 are the eigenmodes from simulating a pair of resonators, f_{r1} and f_{r2} are the self-resonant frequencies of resonators 1 and 2, respectively, and K_s and K_a are for synchronous and asynchronous couplings, respectively.

$$K_\mathrm{s} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}\,, \qquad (2a)$$

$$K_\mathrm{a} = \frac{1}{2}\left(\frac{f_{r2}}{f_{r1}} + \frac{f_{r1}}{f_{r2}}\right)\sqrt{\left(\frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}\right)^2 - \left(\frac{f_{r2}^2 - f_{r1}^2}{f_{r2}^2 + f_{r1}^2}\right)^2} \qquad (2b)$$

Using (2a) and the graph shown in Fig. 6 (a), S_1, S_2, S_3, S_5, S_7, S_8 and S_9 were achieved. S_4 and S_6 were also achieved using (2b) and Fig. 6 (c). The diplexer layout, indicating all the desired S-values is shown in Fig. 7.

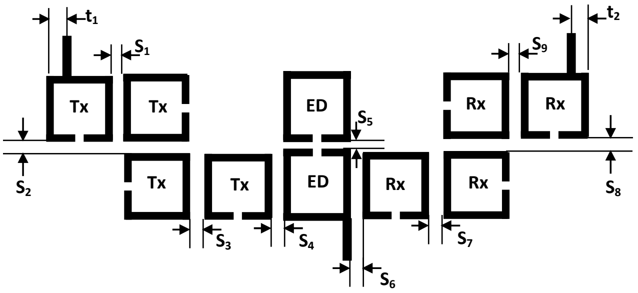

Fig. 7. Diplexer layout (S_1= 1.5 mm, S_2= 2.0 mm, S_3= 2.0 mm, S_4 = 1.6 mm, S_5= 0.9 mm, S_6= 1.65 mm, S_7 = 1.95 mm, S_8= 2.0 mm, S_9= 1.45 mm, t_1= 1.45 mm, t_2 = 1.35 mm).

The external quality factor, Q_{ext}, was theoretically determined using (3), where J is the J-inverter value between the 50 Ohms feedline and the resonator. Using (3) and applying the specifications for this design, three external quality factor values 24.285, 24.285 and 12.143 for the Tx, Rx, and ED resonators of the diplexer were obtained, respectively. These Q_{ext} values were achieved using the Agilent ADS Momentum simulator by adjusting the tapping distance, t, as shown in Fig. 6 (d). The t values that achieved the diplexer specifications are 1.45 mm, 1.35 mm, and 0.0 mm for Tx, Rx, and ED resonators, respectively.

$$Q_{ext} = \frac{\omega_0 C}{J} \tag{3}$$

4. Layout Simulation

The diplexer layout is based on Fig. 2(c). Ten multi-coupled resonators were used in achieving the final diplexer layout as shown in Fig. 7. Four of the resonators are resonating at the Tx frequency, another four are at the Rx frequency, while the last two resonators are at the center frequency of the diplexer (which is the same as the DBF center frequency for energy distribution). The design was simulated using RT/Duroid 6010LM substrate with a dielectric constant of 10.8. The electromagnetic (EM) simulation was carried out using the Agilent ADS Momentum simulator and the simulation results shown in Fig. 8 are in good agreement with the circuit model simulation results.

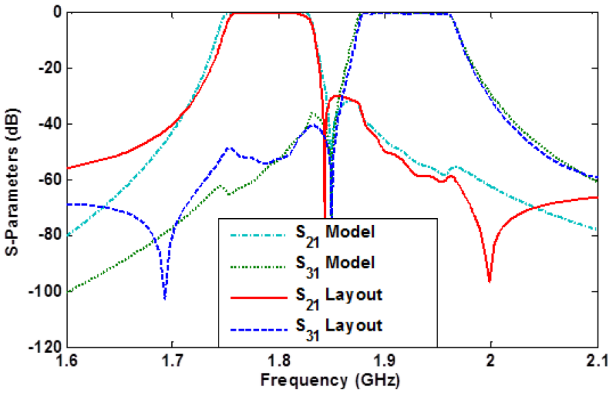

Fig. 8. Comparison of the Tx and Rx bands of the circuit model and the layout diplexer.

Comparing the EM simulation results to the circuit model simulation results, one can clearly see that there is a very good agreement between them. For ease of comparison, the Tx and Rx bands of both the circuit model and the EM model of the diplexer have been plotted and presented in Fig. 8. Both design models are in their ideal conditions, i.e. lossless. The Tx and Rx bands are represented by the S_{21} and the S_{31} plots, respectively.

5. Fabrication and Measurement

The microstrip diplexer was fabricated using the same material employed in the EM simulation. The fabrication was based on printed circuit board (PCB) milling process. The photograph of the microstrip diplexer is shown in Fig. 9. In order to facilitate measurement of the diplexer, three SMA (Sub-Miniature version A) connectors were fitted onto the three input/output ports as shown. The testing and measurement was carried out using the Agilent Vector Network Analyzer. Figure 10 shows the measured results indicating that an isolation (S_{32}) of 50 dB was achieved between the transmit (S_{21}) and the receive (S_{31}) bands. The measured minimum insertion loss of the transmit band is 2.88 dB, while that of the receive band is 2.95 dB.

EM simulations with losses were also performed. Conductor and dielectric loss parameters were included in the loss simulations. The RT/Duroid 6010LM substrate with a dielectric constant of 10.8, a loss tangent of 0.0023, and a substrate thickness of 1.27 mm was used for the loss simulation. A copper conductor with thickness of 16 micron (µm) and conductivity, $\sigma = 5.8 \times 10^7$ S/m was assumed for both the top and bottom metals of the microstrip. However, surface roughness and thickness variation of the substrate material were not considered.

The measured results and the EM loss simulation results are both presented in Fig. 11 for ease of comparison. The graphs clearly show a good agreement between the simulation and measurement. The additional transmission zeros shown in Fig. 11 is the result of unwanted cross-couplings between non adjacent resonators which is an artefact.

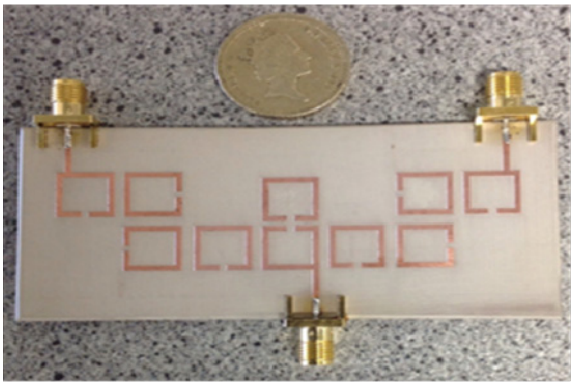

Fig. 9. Photograph of the fabricated microwave diplexer.

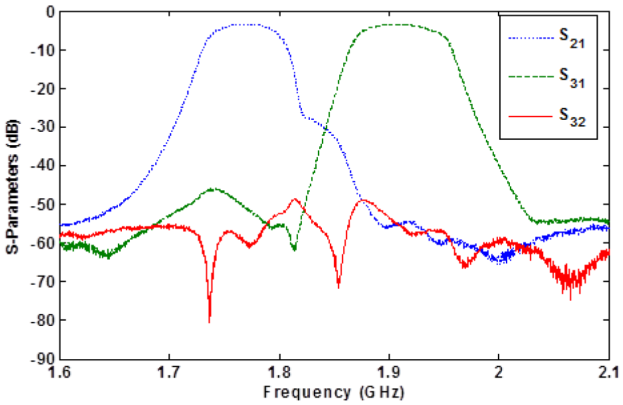

Fig. 10. Measured results of the microwave diplexer.

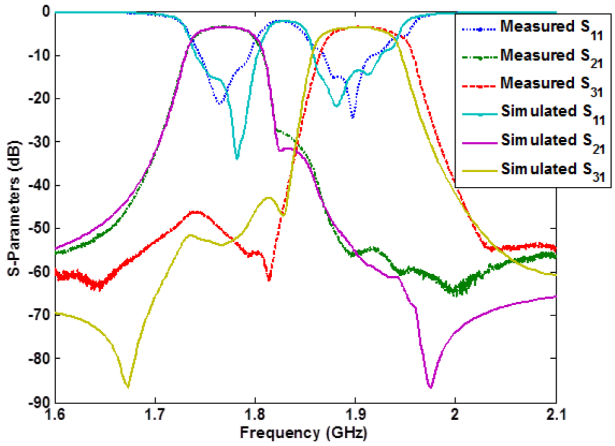

Fig. 11. Comparison of the simulated and measured diplexer.

6. Conclusion

A microwave diplexer achieved by coupling a dual-band bandpass filter with two single-bands bandpass filters has been presented. No cross-coupling is involved in the design. Despite the straight forward methodology, the design is also shown to have an additional advantage in comparison to other designs in the literature which is the energy distributing circuit itself contributes two resonant poles to the diplexer response. Whereas in other designs, the energy distributing circuit is mainly for channeling the energy to correct band but serves very little function in the selectivity of the diplexer. The design has been experimentally validated and the performance of the diplexer presented. Measured results indicated that the isolation between the Tx and Rx bands is about 50 dB, which is very encouraging. The measured minimum insertion loss of the Tx and the Rx bands are 2.88 dB and 2.95 dB, respectively. As a result of the very good bands isolation of the diplexer, only a very small amount of signal is expected to deflect into the wrong direction. The simulated and measured results show good agreement. The diplexer can be used for either splitting a frequency band into two sub-bands or for combining two sub-bands into one wide band. Although the example presented employed microstrip resonators and is at mobile communication frequencies, the methodology is applicable at higher frequencies and can be used for designing diplexers for satellite applications and also applicable using other resonators, i.e. dielectric resonators, waveguide resonators, etc.

Table 3 compares the proposed diplexer to the conventional and the recent common resonator diplexers.

Conventional Diplexer	Common Resonator Diplexer	Proposed Diplexer
Requires a T-junction [1–5], a Y-junction [6–8], a circulator [9–11] or a manifold [12–15] for energy distribution between the transmit and the receive channels	Uses an external / additional resonator [16–19] for energy distribution between the transmit and receive channels	No external device is required for energy distribution as the design is purely based on direct couplings
Relatively large in size due to the involvement of an external junction as shown in Fig. 2(a)	The additional resonator (as shown in Fig. 2(b)) contributes to the size of the diplexer, though to a lesser extent when compared to the conventional diplexer	Relatively small size as no external junction or resonator is required. The two DBF resonators that distribute energy to the transmit and receive bands contribute one resonant pole to the diplexer transmit channel and one resonant pole to the diplexer receive channel as shown in Fig. 2(c)
Complex design as the external junction (or connecting device) needs to be continuously adjusted and optimized in order to achieve a desired result	The common resonator design is mostly based on the evaluation of polynomial functions, and the optimization of error functions to achieve couplings [19]. Though this is a good improvement on the conventional design, the proposed design is even simpler.	Simple design based on the basic principles and formulations involved in BPF design [20] and DBF design [21]

Tab. 3. Comparison of the proposed diplexer to the conventional and the common resonator diplexers.

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Kenneth S. K. YEO received the B.Eng. (Hons.) in Electronic and Communication Engineering from Birmingham University, UK, in 1996. He received the Ph.D. degree in 2000 for researching into high temperature superconducting microwave devices. He was a research fellow with the University of Birmingham from 2000 to 2004 researching on MEMS and ferroelectrics applications. In 2004, he spent 2 years as Principal RF Engineer with CryoSystems Ltd, Luton, UK where he led the RF development of high temperature superconductor mobile phone mast head/tower mount amplifier systems. His current research interests include microwave filters, phase shifters, waveguide components and amplifiers implemented using high temperature superconductor, MEMS/micromachining, ferrite, ferroelectrics, and low temperature co-firing ceramics. He currently works as a Senior Lecturer at the University of East London. He is a member of the Institution of Engineering and Technology (IET). He is a Chartered Engineer. He is also a Fellow of the Higher Education Academy, UK.