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A four-port diplexer for high Tx/Rx isolation for integrated transceivers

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Abstract: A four-port diplexer consisting of two back-to-back three-port diplexers combined with a 180° phase shifter in one branch is presented. The technique achieves high Tx/Rx isolation with relatively low degree filters. Two experimental diplexers are demonstrated, one with equal Q resonators in all filters and the other with dissimilar Q factors, enabling miniaturization and cost reduction. Measured results of Tx/Rx diplexer devices at 2.13/1.73GHz are presented and 40dB Tx/Rx isolation is achieved with only second-order filters.

1. Introduction

Diplexer, which are usually set in the form of filters, are three-port networks and commonly used to combine or separate different signal frequencies. RF front-ends in a radio cellular network uses bandpass filters to discriminate two different frequency bands for transmitting (Tx) and receiving (Rx) channels when a single antenna is shared in the base station. Generally, relative high-power signals, with an order of 30W, are generated and flow in the Tx channel. These high-power signals generated in the Tx branch can easily interfere the Rx channel and can even destroy some Rx components, e.g. low-noise amplifiers and etc., if the signal isolation between Tx and Rx channels are not sufficiently high [1]. Therefore, a design technique to increase signal isolation while offering ease of design and superior figure-of-merit, e.g. low signal losses as well as low cost and small size, is required.

Normally, the most common diplexer structure is to combine bandpass filters through a three-port impedance matching network. Most diplexer designs with high Tx/Rx isolation require high degree filters, resulting in a very complicated filter design and fabrication. Consequently, these complicated higher-order filter architectures increase overall signal losses as well as high fabrication cost and large diplexer size. Diplexer designs based on microstrip structure can achieve low cost, small filter size and ease of integration but provide low power handling and high signal losses due to dielectric and ohmic losses [2-5]. An alternative technology to reduce overall signal losses and increase power handling with the same or better isolation compared to the microstrip technology is combline coaxial resonator structures [6-7]. However, the main drawback of this design technique is that the degree of the filters increases linearly when higher signal isolation is required because this conventional diplexer structure design is still based on three-port networks. To achieve higher signal isolation, higher-order conventional diplexer design technique can be used but at the costs of higher signal losses, complexity, cost and bigger size.

In this paper, a new design technique of a non-conventional four-port diplexer for high Tx/Rx isolation with relatively low-order filter topology for integrated high-power transceivers is introduced. The new design technique is based on two back-to-back second-degree diplexers,

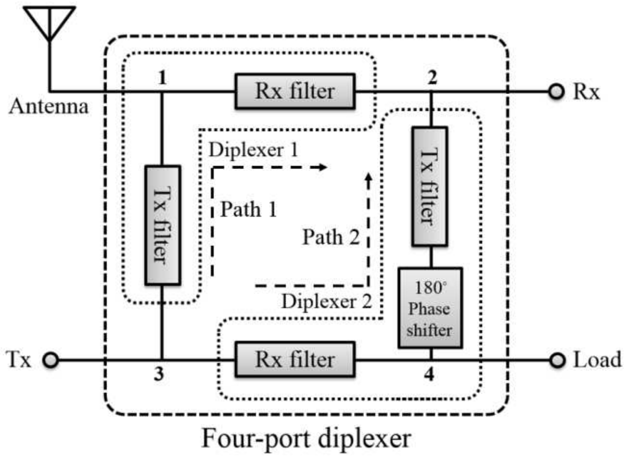


Fig. 1. *Schematic diagram of four-port diplexer using two back-to-back three-port diplexers with amplitude and 180° phase cancellation technique between Rx and Tx channel*

which are combined to form a four-port diplexer as shown in Figure 1. The design frequencies of the four-port diplexer are 1.73GHz and 2.13GHz for Rx and Tx module, respectively. Two different designs of four-port diplexer prototypes, based on filter designs with similar and dissimilar Q-factors, are fabricated and measured to verify the new design technique. High signal isolation between Tx and Rx module is achievable by only using second-order filter topology and the design technique is based on amplitude and phase cancellation between two diplexer branches of the four-port diplexer.

This paper is extended from the published conference paper by the authors [8]. In the conference paper, the mathematical model was developed and some analytical and simulation results were obtained to verify the model. In this paper, we show complete diplexer designs and fabricated diplexer prototypes with extensive measurement results to verify the designs. Moreover, in this paper, we also introduced an additional design technique based on dissimilar Q-factors for each three-port diplexer branch, which is verified by measurement results, to decrease the overall size and cost of the diplexer system, while still offering superior figure-of-merits, e.g. high Tx/Rx isolation.

2. Four-port diplexer analysis and synthesis

For a lossless and reciprocal network, the unitary condition of network can be shown as [1]:

$$[S][S^*]=[1] \quad (1)$$

The solution for a four-port diplexer from [8] can replace a conventional diplexer. Hence, we examine a four-port network as shown in Fig. 1.

Let $S_{11},\ S_{22},\ S_{33},\ S_{44} = 0 \quad \forall\omega$
Let $S_{23} = 0 \quad \forall\omega$

we consider Tx frequency,

By setting γ and ϵ, which are arbitrary numbers, then we define

$$S_{12}=\gamma \ll 1,\ S_{13} = \Delta \cong 1,\ S_{34}=\epsilon \ll 1,\ S_{14}=0 \quad (2)$$

In order to determine S_{24}, we consider from four-port S-parameters

$$\begin{bmatrix} 0 & \gamma & \Delta & 0 \\ \gamma & 0 & 0 & S_{24} \\ \Delta & 0 & 0 & \epsilon \\ 0 & S_{24} & \epsilon & 0 \end{bmatrix}\begin{bmatrix} 0 & \gamma^* & \Delta^* & 0 \\ \gamma^* & 0 & 0 & {S_{24}}^* \\ \Delta^* & 0 & 0 & \epsilon^* \\ 0 & {S_{24}}^* & \epsilon^* & 0 \end{bmatrix}=[1] \quad (3)$$

A solution from [8] is

$$S_{24} = -\Delta^* \text{ and } \gamma = \epsilon^* \quad (4)$$

For real quantities

$$\Delta=\sqrt{1-\epsilon^2}, \quad \gamma = \epsilon,\ S_{24} = -\sqrt{1-\epsilon^2} \quad (5)$$

When $\epsilon \ll 1$

Therefore, the scattering parameters of four-port network at Tx frequency can be given as

$$[S] = \begin{bmatrix} 0 & \epsilon & \sqrt{1-\epsilon^2} & 0 \\ \epsilon & 0 & 0 & -\sqrt{1-\epsilon^2} \\ \sqrt{1-\epsilon^2} & 0 & 0 & \epsilon \\ 0 & -\sqrt{1-\epsilon^2} & \epsilon & 0 \end{bmatrix} \quad (6)$$

And at Rx frequency

$$[S] = \begin{bmatrix} 0 & \sqrt{1-\epsilon^2} & \epsilon & 0 \\ \sqrt{1-\epsilon^2} & 0 & 0 & -\epsilon \\ \epsilon & 0 & 0 & \sqrt{1-\epsilon^2} \\ 0 & -\epsilon & \sqrt{1-\epsilon^2} & 0 \end{bmatrix} \quad (7)$$

In (6) and (7), S_{13} is equal to $-S_{24}$, i.e. the same value but different sign or 180° out of phase. Therefore, it is noticeable that, between Port 2 and 4, exactly 180° phase shift must be introduced while keeping the signal amplitudes equal in order to obtain an infinite Tx/Rx signal isolation.

To investigate the signal from Tx to Rx, we consider two sinusoidal signals propagating in two paths: Path 1 and Path 2, as shown in Fig. 1. The superposition of these two sine waves with the same amplitude, A, but different phases between point 2 and 4 can be expressed as $A\sin\theta + A\sin(\theta + \emptyset)$, where θ is the phase of sinusoidal signals and $\emptyset$ is the phase difference between these two signals. Then, the relationship between signal phases of these two sinusoidal signals and Tx/Rx signal isolation are simulated and plotted, as shown in Fig. 2. To obtain the best Tx/Rx isolation, the two sinusoidal signals in Paths 1 and 2 must have the same amplitude and the signal phases between Ports 2 and 4 must be out of phase, 180° difference. To fulfill these requirements we, therefore, use two resonators with equal Q-factors (Q_1=Q_2) and add an additional 180° phase shifter in our diplexer designs, which is shown in Fig. 1.

To decrease the overall size of the four-port diplexer, resonators with dissimilar Q-factors between Paths 1 and 2

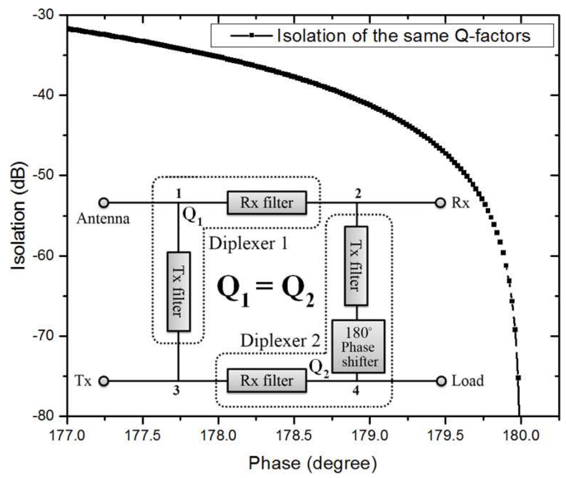


Fig. 2. *Simulated Tx/Rx isolation versus phase differences between port 2 and 4 of two-diplexers (Path 1 and Path 2) with the same Q-factors. The best Tx/Rx signal isolation is achievable at 180° phase shift*

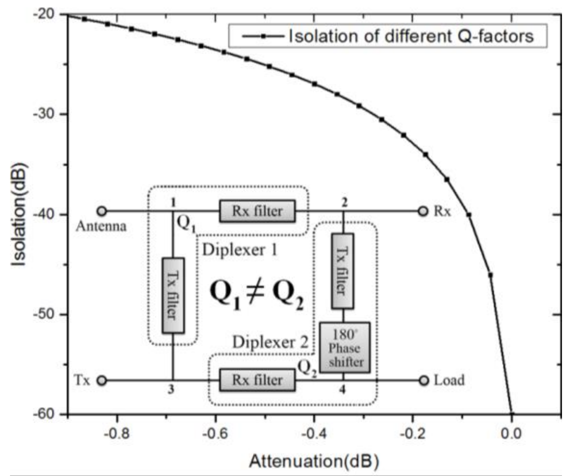


Fig. 3. *Simulated Tx/Rx signal isolation versus attenuation of two diplexers with different Q-factors. The reasonable Tx/Rx signal isolation of better than 40 dB is obtained when the attenuation difference between the two diplexers is less than 0.1 dB*

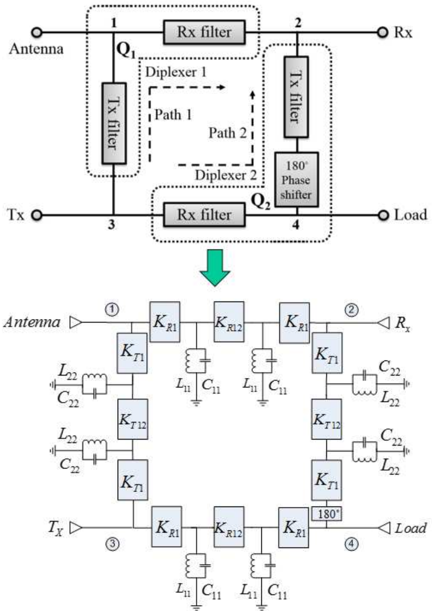


Fig. 4. Four-port diplexer topology and its equivalent circuit based on second-order filter consisting of external coupling, internal coupling coefficients and element values of resonators with a 180° phase shifter between Port 2 and 4

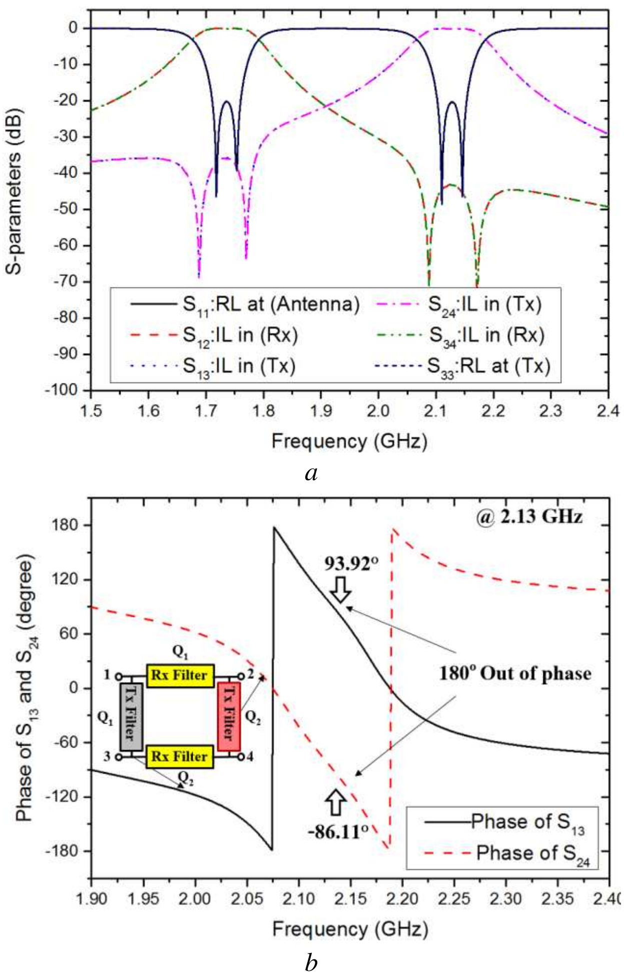


Fig. 5. Simulation results

(a) S-parameters of the four-port diplexer design at Tx=2.13 GHz, Rx=1.73 GHz,

(b) Phases of S_{13} and S_{24} with 180° phase difference at 2.13 GHz

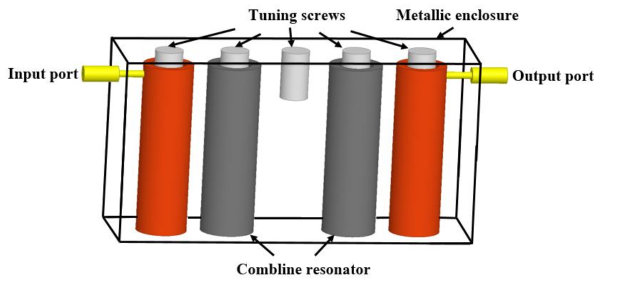
may be used. For the resonators with dissimilar Q-factors, $Q_1 \neq Q_2$, we also consider the superposition of two sinusoidal signals with different amplitudes and phase different of 180° as $A\sin\theta + B\sin(\theta + 180°)$, where A and B are the signal amplitudes in both signal paths and we assume $A < B$ ($Q_1 < Q_2$). The relationship between signal attenuation, differences between B and A, and the Tx/Rx signal isolation is calculated and plotted in Fig. 3. To maintain a reasonable Tx/Rx signal isolation, e.g. better than 40 dB, the amplitude attenuation between the two diplexers must be kept smaller than 0.1dB.

3. Lumped element model

The key design parameters of lumped-element Chebyshev four-port diplexer are specified as the centre frequency, passband bandwidth, stopband attenuation, passband insertion loss and passband return loss. Both four-port diplexers with the equal Q (Q_1=Q_2=1800) and dissimilar Q-factors (Q_1=1800, Q_2=3600) are designed at the centre frequency of 1.73 GHz and 2.13 GHz for Rx and Tx module, respectively, with 20-dB bandwidth of 50 MHz. The equivalent circuit of the four-port diplexer, for both equal and dissimilar Q-factors is shown in Fig. 4. The loaded normalized lowpass prototype filter element values (g_i) can be calculated as in [9]. The calculated design element values of the equal Q and dissimilar Q-factors with 0.044 dB ripple are given as g_0=1, g_1=0.6682, g_2=0.5462 and g_3=1.2222. The impedance inverter for external coupling coefficients are K_{T1}= 0.322 and K_{R1}= 0.289. The impedance inverter for internal coupling coefficients are K_{T12}= 0.084, K_{R12}= 0.082. Therefore, K_T and K_R refer to the impedance converters at the input and output port of each filter. The element values of shunt resonator are L_{11}= 2.3784 nH, L_{22}= 2.9284 nH, C_{11}= 2.3474 pF, C_{22}= 2.8902 pF. Both equal Q and dissimilar Q factor diplexer designs have exactly the same parameters as the key design parameters and the only difference between these two designs are the Q factors.

From Fig.4, two diplexers, which can have either similar or dissimilar Q-factors, with a phase difference of 180° are combined together by using back-to-back technique to achieve an optimum Tx/Rx signal isolation. The simulation results of the four-port diplexer circuit analysis simulated by AWR Microwave Office is plotted in Fig. 5(a). For the similar Q-factor diplexer design, Diplexer 1 and 2 are designed with the same Q-factors of 1800. The simulation results show that the passband insertion loss (IL) in Tx band is less than 0.25 dB while, in Rx band, it is less than 0.32 dB. For dissimilar Q-factor diplexer design, Diplexer 1, is designed with a Q factor of 1800 while the second diplexer, Diplexer 2, is designed with a Q factor of 3600. From the simulation results, the passband IL in Tx band is less than 0.19 dB and the passband IL in Rx band is less than 0.23 dB. The return loss (RL) of the diplexer design for both similar and dissimilar Q-factors in both Tx and Rx channels are better than 20 dB in the passband.

According to (6) and (7), the phase responses of S_{12} and S_{34} have the same phase but, for S_{13} and S_{24}, phase difference between these parameters are 180° or out of phase. Fig. 5(b) depicts the phase responses of S_{13} and S_{24}. To achieve an optimum Tx/Rx isolation, the phase of S_{13} and S_{24} are designed to be 93.92° and -86.11°, respectively,



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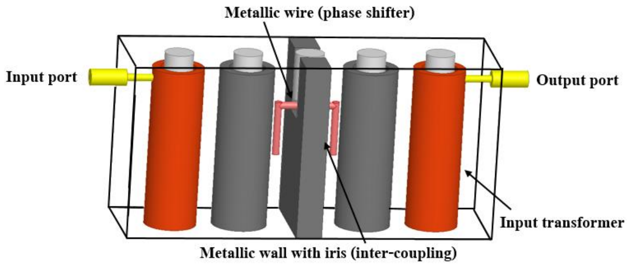

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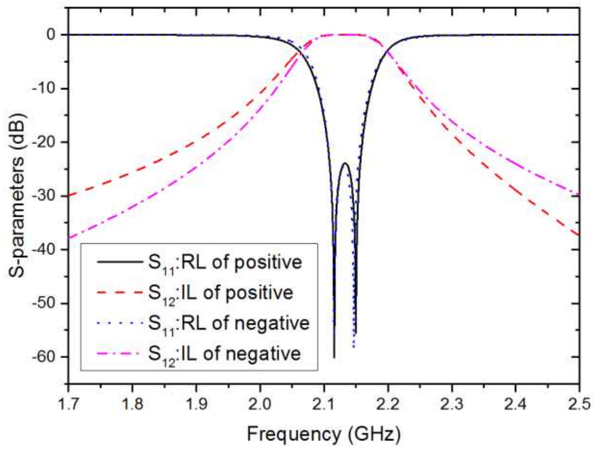
Fig. 6. *Geometrical structure of combline filters*
(a) Positive coupling introduced via an iris/window,
(b) Negative coupling (phase shifter) achieved by an opening in the upper part of the wall and a metallic wire suspended in the iris between the resonators



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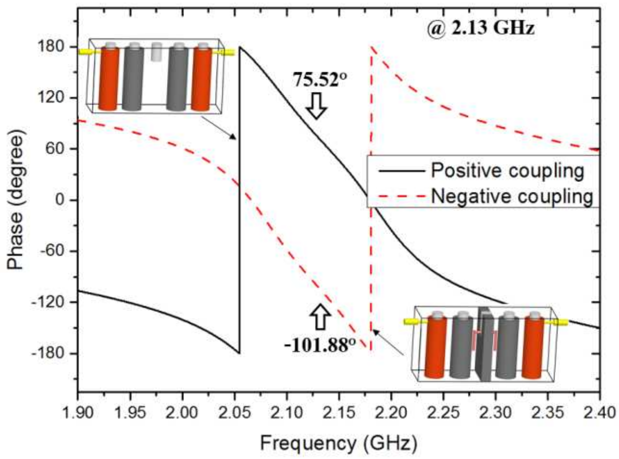

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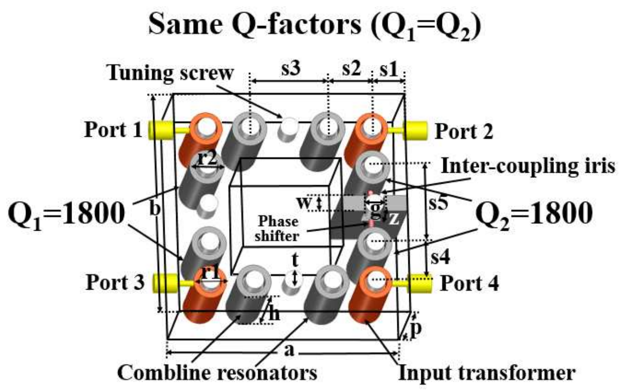
Fig. 7. *Simulation results*
(a) S-parameters of combline filter designed by positive and negative coupling structures at Tx band of 2.13 GHz,
(b) Phase responses of S_{13} and S_{24}



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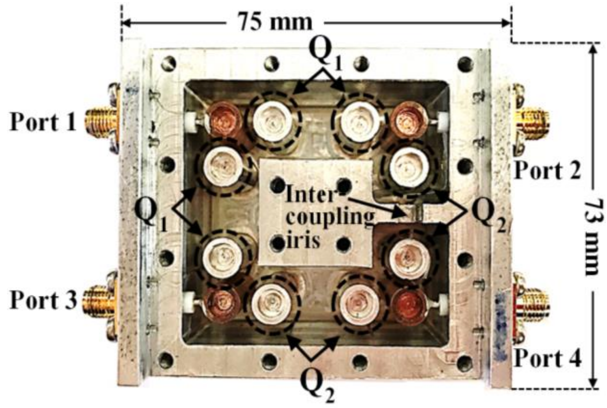

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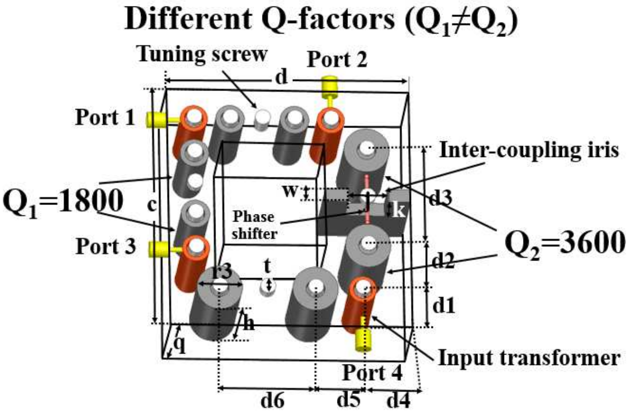
Fig. 8. *Geometrical structure of four-port combline filters*
(a) The geometric structure of four-port diplexer with the similar Q-factors (Q_1=Q_2=1800),
(b) Top view without lid of the fabricated four-port diplexer prototype with the similar Q-factors

and, thus the phase difference between them is 180° at f_0 =2.13 GHz, which fulfil the requirements as stated in (6) and (7). The phase of S_{13} and S_{24} are not fixed by these values. The combination of phase should be ±180°. Ideally, when the filter is designed with 180° phase shift and equal amplitudes, the resulting isolation becomes infinity. However, it is not necessary to achieve exact 180° phase shift. If the required isolation of the diplexer is better than 40 dB, the phase between S_{13} and S_{24} does not require to be exactly 180° difference. The phase shift can easily be tuned using single phase shifter in second diplexer branch without introducing further complexity.

4. Diplexer designs and fabrication

Based on the mathematical synthesis and lumped-element model, the individual filter branches consist of second-order Chebyshev diplexer design are fabricated by using combline resonators. To achieve the filter design with 180° phase shift between two diplexer branches, the 90° positive inverter and -90° negative inverter coupled filter are required. The positive and negatively coupled combline filters are designed by using Ansys HFSS with the physical structure presented in Fig. 6. The negative coupling in Fig. 6(b) can be designed with an opening in the upper part of the wall, by which the electric field coupling is strongest,



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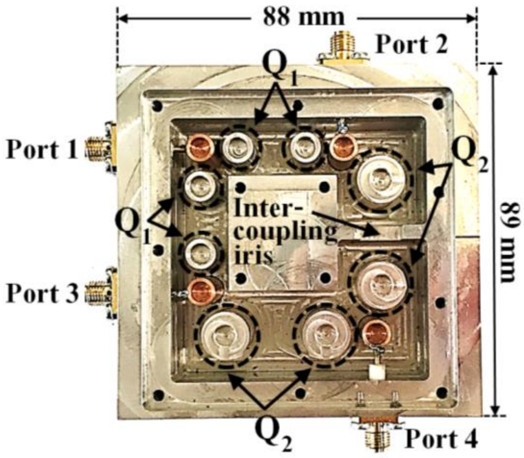

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Fig. 9. *Geometrical structure of four-port combline filters*
(a) The geometric structure of four-port diplexer with dissimilar Q-factors (Q_1=1800, Q_2=3600),
(b) Top view without lid of the fabricated four-port diplexer prototype with dissimilar Q-factors

while the positive coupling can be implemented by using an iris/window, as shown in Fig. 6(a). To increase the efficiency of the negative coupling, an inversed U-shape metallic wire is suspended above the iris between the resonators as shown in Fig. 6(b). In practice, the metallic wire is supported by Teflon with a dielectric constant 2.1 or any other dielectric materials, which have a dielectric property close to air. Simulation results of second-order combline filters with positive and negative couplings are shown in Fig.7. From the simulation results, the positive and negatively coupled combline-filter designs have the same resonant frequency but with the phase difference of 177.4°, which is only 2.6° phase error from the mathematical model. However, the phase error of combline filters can be varied due to fabrication accuracy but can be compensated by tuning coupling-screws as shown in Fig. 6.

The combination of four-filters is used to complete the four-port diplexer design. The 3D geometrical structure and the fabricated prototype of the four-port diplexer with all filters designed with equal Q-factors are show in Fig. 8(a) and (b), respectively. Likewise, Fig. 9(a) represents the 3D structure of the four-port diplexer with dissimilar Q-factors for each filter pair while Fig. 9(b) shows the fabricated prototype of the dissimilar-Q-factor for-port diplexer. The optimized parameters for both four-port diplexers, with equal and dissimilar Q-factors, are listed in table 1. The prototypes of both four-port diplexers are fabricated by using computer numerically controlled (CNC) machine and Aluminum and Copper are used as structural materials. Tuning screws are implemented between each resonator to compensate manufacturing errors as well as to optimize the resonant frequencies and inter-resonators couplings.

Table 1 Parameters of geometric structure of four-port diplexer according to Fig. 8(a), 9(a) and 12

Parameters	Values (mm)	Parameters	Values (mm)
a	50.6	d	63.80
b	48.8	c	65.45
h	24.2	r3	12.00
t	4.00	d1	11.20
r1	7.20	d2	11.20
r2	7.60	d3	23.40
w	3.00	d4	12.80
g	4.40	d5	12.48
s1	7.2	d6	25.28
s2	9.55	j	10.4
s3	17.1	k	10.7
s4	8.6	p	26.2
s5	17.2	q	26.2
z	8.7		

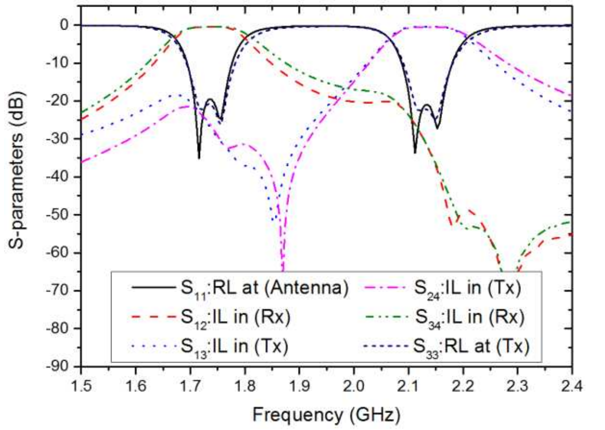
5. Measurement results and result comparisons

5.1. Measurement results of for-port diplexer with equal Q-factors

The S-parameter measurement is achieved by using Agilent E5071C Network Analyzer. Four-port calibration is performed using Agilent N4431-60006 Electronic Calibration Module prior to the measurement. The measured S-parameters of four-port diplexer with the same Q-factors in all branches are shown in Fig. 10. From Fig. 10(a), the passband ILs of both Tx and Rx bands are less than 0.46 dB and 0.48 dB, respectively. The RLs of both Tx and Rx channels are better than 20 dB in the passband with the 20-dB bandwidth of 50 MHz. Fig. 10(b) represents the comparison of measured Tx/Rx isolation of a conventional 3-port diplexer and the new four-port diplexer design. At the centre frequency of 1.73 GHz and 2.13 GHz for Rx and Tx module, the measured Tx/Rx isolation of the conventional three-port diplexer is 26.28 dB and it is 35.15 dB for the four-port diplexer. Fig. 10(c) depicts the measured phase response of Tx filter branches, S_{13} and S_{24}, at the centre frequency of 2.13 GHz. From the measurement results, the phases of S_{13} and S_{24} are 15.05° and -162.6°, respectively. Therefore, the phase difference between the Tx and Rx branches is 177.65°, which is only 2.35° error compared to the analytical model.

5.2. Measurement results of four-port diplexer with different Q-factors

The measurement results of the second-order four-port diplexer with unequal Q-factors for each diplexer branch is shown in Fig. 11. From Fig. 11(a), the passband ILs of the Tx and Rx bands are less than 0.42 dB. The RLs in both channels are better than 20 dB in the passband with the 20-dB bandwidth of 50 MHz. From Fig. 11(b), the



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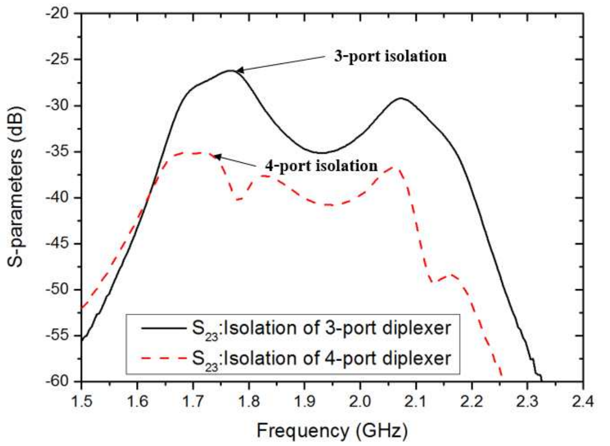

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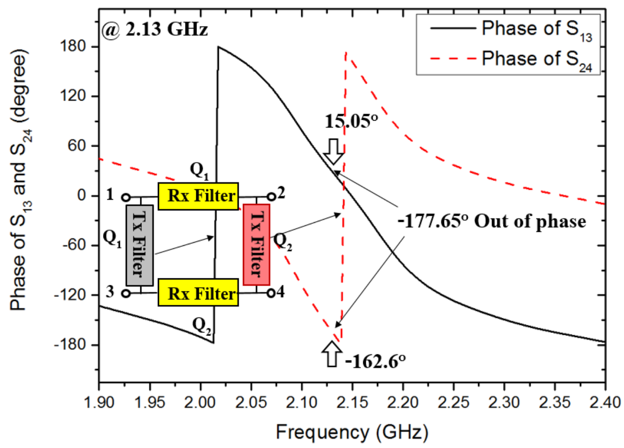

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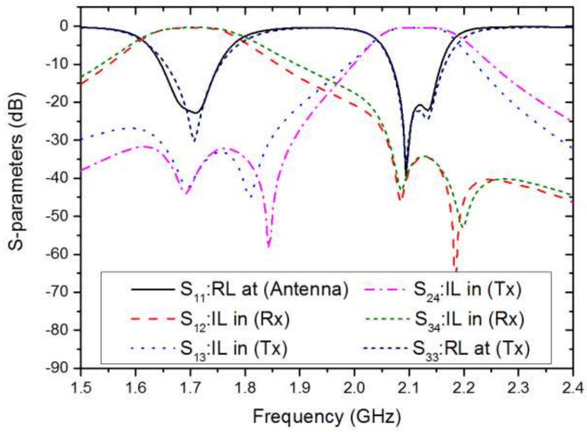
Fig. 10. *Measurement results:*
(a) S-parameters of four-port diplexer with the similar Q-factors where Q_1= Q_2=1800 at Tx=2.13 GHz, Rx=1.73 GHz,
(b) Signal isolation, S_{23}, of four-port diplexer with the similar Q_1-factors (35.15 dB) and three-port diplexer (26.28 dB),
(c) Phases of S_{13} and S_{24} with 177.65° phase difference at 2.13 GHz



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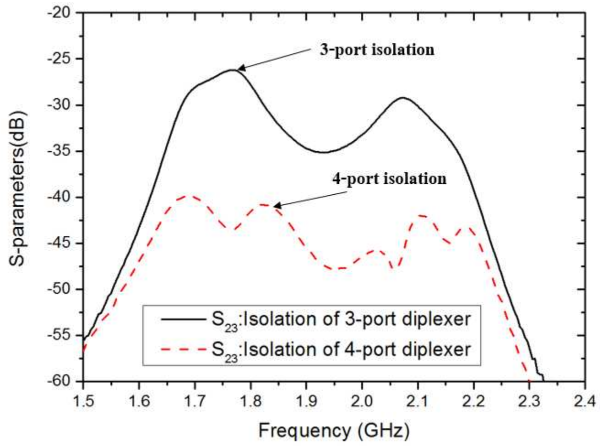

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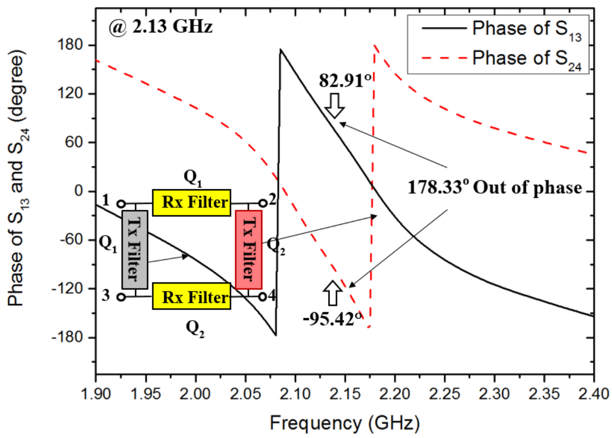

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Fig. 11. *Measurement results:*
(a) S-parameters of four-port diplexer with dissimilar Q-factors where Q_1= 1800, Q_2=3600 at Tx=2.13 GHz, Rx=1.73 GHz,
(b) Signal isolation, S_{23}, of four-port diplexer with dissimilar Q_1-factors (40.11 dB) and three-port diplexer (26.28 dB),
(c) Phases of S_{13} and S_{24} with 178.33° phase difference at 2.13 GHz

Table 2 Comparison of four-port diplexer with the state-of-the arts diplexer

Ref.	Architecture	Degree	Insertion Loss (dB) Tx/Rx	1st/2nd Passband (GHz)	Types	Power Handling	Size	Isolation (dB)
[5]	3-port	2	1.83/1.52	1.1/1.3	Dual-mode Microstrip ring resonator	Low	$0.82\lambda_g \times 0.82\lambda_g$ (λ_g^2)	>26
[10]	3-port	3	1.6/2.1	9.5/10.5	Substrate integrated surface (SIW)	Low	58.4 × 18.7 (mm^2)	>35
[11]	3-port	5	0.6/0.6	2.52/2.67	Coaxial resonators	High	95×28×25 (mm^3)	>55
[12]	3-port	12	0.96/1.22	2.54/2.67	Triple-Mode Dielectric Loaded resonators	High	10×10×5 (mm^3)	>50
Three-port diplexer (This work)	3-port	2	0.46/0.48	1.73/2.13	Combline resonators	High	75×73×26 (mm^3)	>26.28
Four-port with the same Q_s (This work)	4-port	2	0.46/0.48	1.73/2.13	Combline resonators	High	75×73×26 (mm^3)	>35
Four-port with dissimilar Q_s (This work)	**4-port**	**2**	**0.42/0.42**	**1.73/2.13**	**Combline resonators**	**High**	**88×89×26 (mm^3)**	**>40**

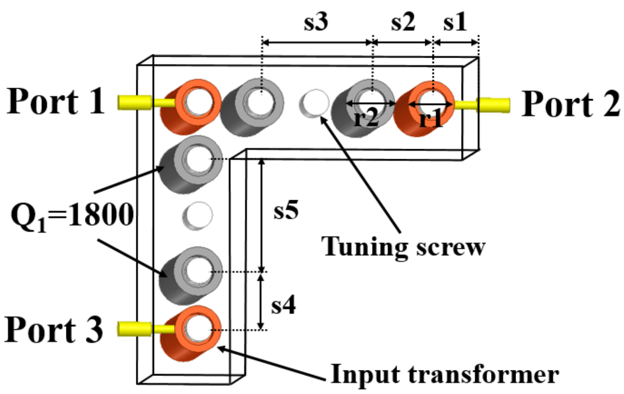

Fig. 12. Geometrical structure of three-port combline filters

measured isolation of the conventional three-port diplexer is 26.28 dB and it is 40.11dB for the four-port diplexer. The phase responses of S_{13} and S_{24} at the centre frequency of 2.13 GHz are plotted in Fig.11(c). The measured phases of S_{13} and S_{24} are 82.91° and S_{24} -95.42°, respectively, resulting in a phase difference of 178.33° which is only 1.67° phase error compared to the mathematical model. Table 2. represents the figure-of-merits and extensive comparisons between the novel four-port diplexer designs and the published research works with different diplexer architectures.

Theoretically, infinite signal cancellation is achievable if the signals propagating through both branches have the same amplitude and 180° phase difference. Practically, the amplitude and phase errors result from fabrication and tuning screws as well as negative coupling. Therefore, the four-port diplexer with different Q-factors has slightly better isolation than the design with the same Q-factors.

5.3. Comparisons to three-port diplexer

To compare the isolation of the proposed four port diplexer, a conventional three-port diplexer is implemented by shorting out all the tuning screws in the diplexer 2 as shown in Fig.12. The measured isolation of three-port diplexer is 26.28 dB as compared in Fig. 10(b) and 11(b).

6. Conclusions

A new method for achieving high Tx/Rx isolation using a four-port diplexer is proved in here. The technique achieves high isolation with two back-to-back low degree diplexers. However, one diplexer can have significantly lower Q than the other. The four-port diplexer is designed at the centre frequency of Tx at 2.13 GHz, Rx at 1.73 GHz with BW=50MHz. The new technique design can enhance the isolation (S_{23}) more than 14 dB from the conventional diplexer. Finally, this RF interference rejection technique can be used in wireless communication systems where small size, low losses and low complexity are required.

Currently, work is progressing on investigating the effects of a mismatched antenna port. Clearly, if the antenna port impedance is not 50 Ω, then the isolation reduces. However, methods for compensating for this automatically adjusting the isolated port load impedance are being investigated.

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