A 1.32 to 1.89 GHz Diplexer/Filtering-Switch for Reconfigurable FDD/TDD Operations

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***Abstract*—Time division duplexing (TDD) and frequency division duplexing (FDD) are two typical duplexing techniques in modern wireless systems. Adopting appropriate duplexing mode in specific scenarios can effectively improve the communication efficiency. In this paper, a novel reconfigurable diplexer/filtering-switch (RDFS) for reconfigurable TDD/FDD operations is presented. It is constructed by seven varactor loaded half-wavelength microstrip resonators. Common resonator technique is adopted to divide the seven resonators into two signal channels, while the controllable mixed electromagnetic coupling (CMEC) technique is employed for inter-stage couplings. With the proposed methods, not only the intrinsic reconfigurable diplexer and filtering-switching functions can be easily achieved, multiple transmission zeros are also introduced to improve the channel isolation in FDD operation and stopband suppression in TDD operation. A circuit prototype with a tunable center frequency covering 1.32-1.89 GHz is designed, fabricated and measured to validate the proposed method. Good agreement between the simulated and measured results can be observed.**

***Keywords*—bandpass filter, diplexer, frequency division duplex, single-pole double-throw switch, time division duplex.**

I. Introduction

Frequency division duplexing (FDD) and time division duplexing (TDD) are two of the most classical duplexing techniques which have been extensively used in various wireless systems. Due to their differences in working mechanisms, the FDD and TDD modes are generally used in different scenarios. For instance, the TDD mode is of more superiority for short-range point-to-point communication and asymmetric transmission, while the FDD mode is preferred for applications requiring good isolation between transmitting (Tx) and receiving (Rx) paths [1]. For achieving higher flexibility and efficiency, wireless system is expected to possess reconfigurable TDD/FDD operations and tunable operating frequency. In the radio frequency (RF) domain of the system, the FDD and TDD operations are commonly realized by using a diplexer and a single-pole double-throw (SPDT) switch (usually cascaded with a predefined bandpass filter for interference rejection), respectively. Integrating the diplexer and SPDT switch (plus bandpass filter) together and making them reconfigurable could eventually enable the system with reconfigurable FDD/TDD operations, as shown in Fig. 1.

In literature, a number of diplexers with embedded switching function have been reported [2] - [5]. For instance, a switchable diplexer based on stepped-impedance distributed coupling feeding technique was proposed in [2]. Ref. [3] described a switchable filtering diplexer employing a reused

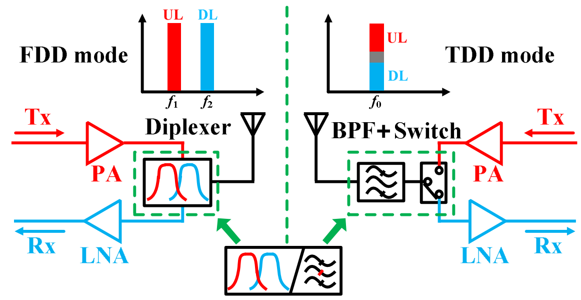


Fig. 1. Schematic diagram of the proposed reconfigurable diplexer/filtering switch for reconfigurable TDD/FDD operations.

switchable L-shaped resonator. In [4], Xu *et al*. proposed a diplexer-integrated SPDT switch by using distributed coupling tri-mode resonators. However, since the operating frequencies of the uplink and downlink channels are always different in these diplexers, they are unable to support TDD operation (which requires the same frequencies for both uplink and downlink channels). The switchable diplexer in [6] achieved the ability of supporting simultaneous TDD and FDD functions by increasing the number of channels to four, but it has a relatively complex structure and can only afford fixed frequency.

In this paper, a novel reconfigurable diplexer/filtering-switch (RDFS) with tunable working frequency is proposed. It consists of seven coupled microstrip resonators, where the first resonator serves as a common resonator to connect its two channels. By adjusting the coupling coefficients and resonant frequencies of the resonators, the proposed RDFS can be configured to work as a standard diplexer or an SPDT filtering switch, thus enabling the flexible switching between TDD and FDD operations in a single system. Moreover, both the operating frequencies of the diplexer mode and filtering-switch mode are tunable, further improving the flexibility of the system.

II. Design of the Proposed Reconfigurable Diplexer/Filtering Switch

Fig. 2 shows the physical layout of the proposed RDFS. It has two channels that are built by seven short-ended half-wavelength microstrip resonators (i.e. R_1 - R_7). Each resonator has a varactor-loaded stub at its center plane, which is utilized to achieve the resonant frequency tuning. The resonator R_1 is employed as the common resonator for both Tx and Rx channels. The resonators R_2 and R_5 are connected to the

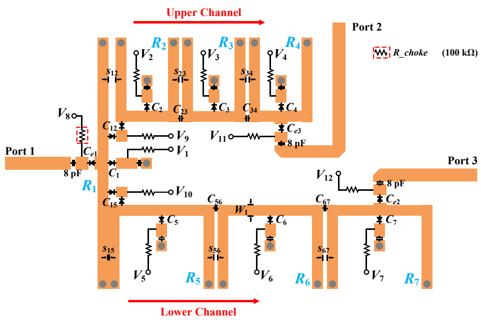
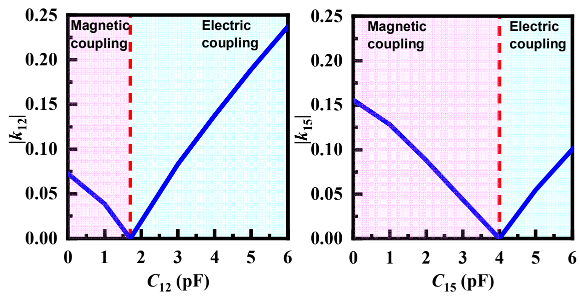


Fig. 2. Physical layout of the proposed RDFS.



(a) (b)

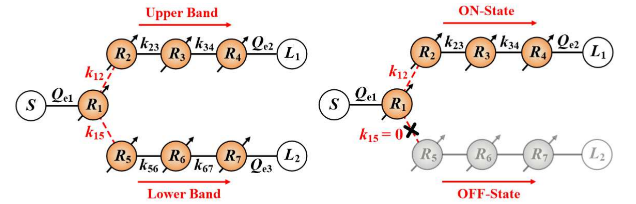
Fig. 3. (a) Simulated coupling coefficient $|k_{12}|$ versus C_{12} with s_{12}=0.8 mm. (b) Simulated coupling coefficient $|k_{15}|$ versus C_{15} with s_{15}=0.1 mm.

resonator R_1 through a pair of back-to-back varactors (i.e. C_{12} and C_{15}), respectively, and the rest resonators are connected by fixed capacitors (i.e. C_{23}, C_{34}, C_{56} and C_{67}). Varactors C_{e1}, C_{e2} and C_{e3} at the input and output feedlines are employed to control the strength of external couplings, and each of them is connected to an 8 pF fixed capacitor for dc blocking.

The loaded varactors C_{12} and C_{15} are used to introduce controllable electric couplings which will be combined with the intrinsic magnetic couplings between resonators, thus forming the controllable mixed electromagnetic couplings (CMECs). The total coupling coefficient of the mixed electromagnetic coupling can be calculated as [7],

$$|k| = \left| \frac{M_C - E_C}{1 - M_C E_C} \right| \tag{1}$$

with M_c and E_c being the strength of magnetic coupling and electric coupling, respectively. The electric coupling E_c is directly related to the coupling capacitance between resonators, and hence the total coupling coefficient k can be effectively controlled by the loaded varactors. Fig. 3 shows the simulated coupling coefficients of $|k_{12}|$ and $|k_{15}|$ with different coupling capacitances of C_{12} and C_{15}. As can be seen, with the increase of coupling capacitances, both $|k_{12}|$ and $|k_{15}|$ decrease first to zero and then increase monotonically. This is because when there are no coupling capacitances loaded (i.e. $C_{12} = C_{15} = 0$), the coupling between resonators is dominated by the intrinsic magnetic coupling. Then, with the increase of C_{12} and C_{15}, the electric coupling E_c is enhanced and then cancel with the magnetic coupling, and hence $|k_{12}|$ and $|k_{15}|$ decrease gradually. When the strength of electric coupling reaches the same level of magnetic coupling (i.e. $E_c = M_c$), $|k_{12}|$ and $|k_{15}|$ become zero. After that, the dominated coupling turns to be electric coupling, and $|k_{12}|$ and $|k_{15}|$ would increase with the increased C_{12} and C_{15},



(a) (b)

Fig. 4. Coupling topologies of the proposed RDFS working as (a) diplexer and (b) filtering switch.

respectively. When the total coupling coefficient is zero, transmission in the corresponding channel will become zero and the corresponding channel will be turned off. This zero-coupling method is utilized to achieve the integrated switching function for the proposed RDFS in this work.

On the other hand, when the total coupling coefficient is non-zero at the operating frequency bands for both diplexer channels in FDD operation and for the on-state channel in TDD operation, the canceling effect of the mixed coupling can introduce a transmission zero (TZ) in the stopband, which can be used to improve the selectivity of the filter. The location of the TZ is related to E_c and M_c as [7],

$$f_z = f_0 \sqrt{\frac{M_C}{E_C}} \tag{2}$$

where f_z and f_0 represent the frequency of TZ and center frequency of the filter passband, respectively. Eqn. (2) indicates that the TZ could be placed at the upper stopband or lower stopband of the filter, depending on the relative ratio between M_c and E_c. In this design, the $|k_{12}|$ is located in the channel for upper band of the diplexer, while $|k_{15}|$ is in the channel for lower band. Therefore, the TZs introduced by $|k_{12}|$ and $|k_{15}|$ should be placed in the lower stopband and upper stopband of their corresponding passbands, respectively, so as to enhance the isolation between the two passbands of the diplexer in FDD operation. For this purpose, the coupling gaps s_{12} and s_{15} are carefully optimized, so as to make the $|k_{12}|$ and $|k_{15}|$ operates in electric coupling-dominated mode (i.e. $\frac{M_c}{E_c}$<1) and magnetic coupling-dominated mode (i.e. $\frac{M_c}{E_c}$>1), respectively.

A. Operating Principle of the Diplexer in FDD Operation

Fig. 4(a) depicts the coupling topology of the proposed RDFS when operating as a diplexer in FDD operation. In this operation, the resonators R_2, R_3, R_4 construct the upper band of the diplexer and R_5, R_6, R_7 built the lower band. The resonator R_1 is employed as the common resonator for both two channels. The benefit of such topology is that a good impedance matching for the two channels can be realized by directly adjusting the coupling coefficients k_{12} and k_{15}, thus removing extra matching networks and lowering the complexity of the circuit. The initial state of the diplexer is designed to have an upper band centered at 1.85 GHz and a lower band centered at 1.45 GHz. The absolute bandwidths (ABWs) of the upper and lower bands are set to be 82 MHz and 110 MHz, respectively, and the return loss levels for the two bands are both 15 dB. The corresponding coupling matrix for the diplexer can be given as,

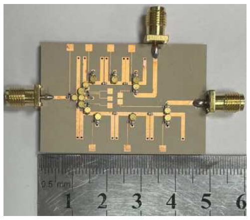


Fig. 5. Photograph of the fabricated RDFS.

Table 1. Physical dimensions of the fabricated RDFS. (Unit: mm)

W_1	s_{12}	s_{23}	s_{34}	s_{15}	s_{56}	s_{67}
1	0.8	0.3	0.1	0.1	0.2	0.2

The total lengths of R_1, R_2-R_4, R_5-R_6 are 24 mm, 20 mm and 24 mm, respectively.

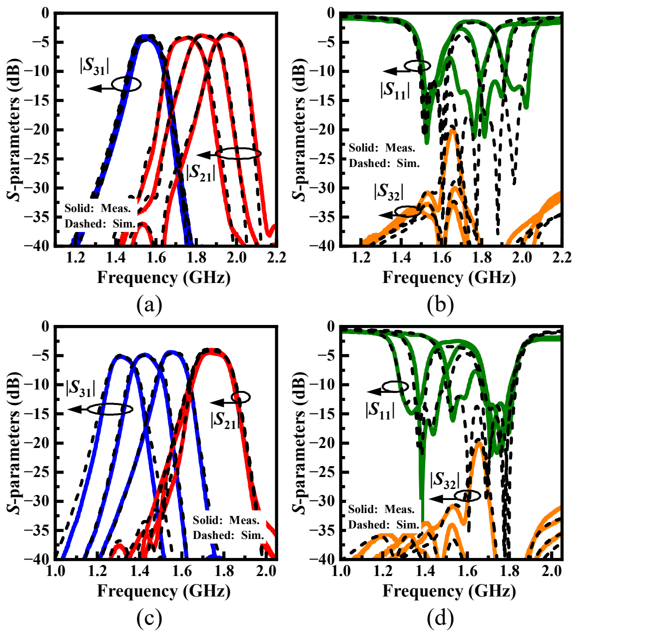


Fig. 6. Simulated and measured results of the designed RDFS operating as diplexer. (a) $|S_{21}|$, $|S_{31}|$ and (b) $|S_{11}|$, $|S_{32}|$ when the upper channel is tuned and lower channel is fixed. (c) $|S_{21}|$, $|S_{31}|$ and (d) $|S_{11}|$, $|S_{32}|$ when the upper channel is fixed and lower channel is tuned.

$$M = \begin{array}{c|cccccccccc} & S & 1 & 2 & 3 & 4 & 5 & 6 & 7 & L_1 & L_2 \\ \hline S & 0 & 1.36 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1.36 & 0 & 0.56 & 0 & 0 & 0.58 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0.56 & 0.76 & 0.16 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0.16 & 0.81 & 0.17 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 0 & 0.17 & 0.81 & 0 & 0 & 0 & 0.41 & 0 \\ 5 & 0 & 0.58 & 0 & 0 & 0 & -0.75 & 0.17 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 0 & 0.17 & -0.80 & 0.17 & 0 & 0 \\ 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0.17 & -0.80 & 0 & 0.42 \\ L_1 & 0 & 0 & 0 & 0 & 0.41 & 0 & 0 & 0 & 0 & 0 \\ L_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.42 & 0 & 0 \end{array} \quad (3)$$

The required coupling coefficient k_{mn} (m, n = 1, 2, 3, 4, 5, 6, 7) can then be calculated from the normalized coefficient M_{mn} as,

$$k_{mn} = M_{mn} \times FBW \quad (4)$$

where FBW represents the fractional bandwidth. To obtain a constant ABW during the frequency tuning process of the diplexer, the coupling coefficient k_{mn} should be decreased with an appropriate slope as the center frequency increases. This is achieved by carefully optimizing the gap distances and the values of fixed capacitors between resonators.

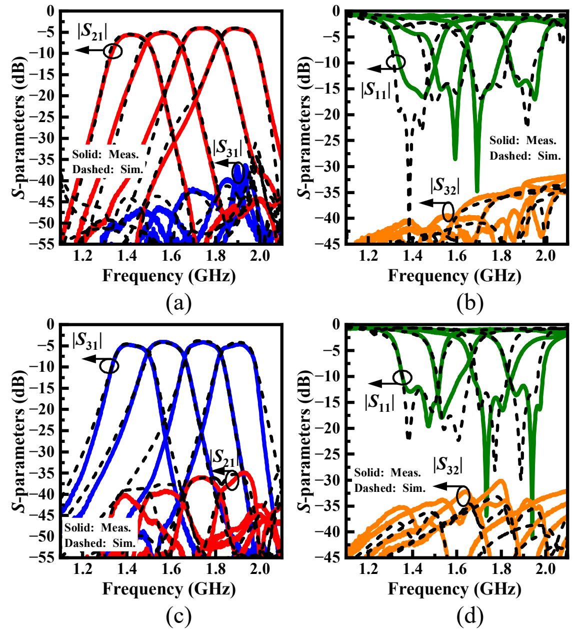


Fig. 7. Simulated and measured results of the designed RDFS operating as filtering switch. (a) $|S_{21}|$, $|S_{31}|$ and (b) $|S_{11}|$, $|S_{32}|$ when upper channel is switched on and lower channel is switched off. (c) $|S_{21}|$, $|S_{31}|$ and (d) $|S_{11}|$, $|S_{32}|$ when upper channel is switched off and lower channel is switched on.

B. *Operating Principle of Filtering Switch in TDD Operation*

Fig. 4(b) shows the coupling schemes of the proposed RDFS working as a filtering switch in TDD operation. In this operation, the two channels share the same operating frequency band, while there is only one channel operating in ON-state at a time (the other channel is in OFF-state). The switching-off operation is achieved by setting the CMEC in the corresponding channel (k_{12} for upper channel or k_{15} for lower channel) to zero. The zero coupling cuts off the signal transmission in the OFF-state channel, which makes it approximate to an open circuit to the main path. To further improve the isolation between the two channels, the resonant frequencies of the resonators in the OFF-state channel are also tuned to be far away from the passband. It is worth noting that, for the filtering switch in TDD operation, the resonator R_1 becomes one of the main resonators to construct the filter channel instead of the common resonator for impedance matching in FDD operation, and hence a fourth-order bandpass filtering performance can be obtained in the ON-state channel. The initial center frequency of the filter is set at 1.6 GHz with a 1-dB ABW of 110 MHz. The corresponding coupling matrix (which is essentially a fourth-order in-line bandpass filter topology) can be easily determined by using the classical synthesis method [8].

III. Results and Discussion

For experimental demonstration, the designed RDFS is fabricated on substrate *Rogers* 6010 with a thickness of 1.27 mm, and its photograph is shown in Fig. 5. The corresponding physical dimensions are given in Table 1. All the varactors use the MA46H202 from MACOM Corporation. The final

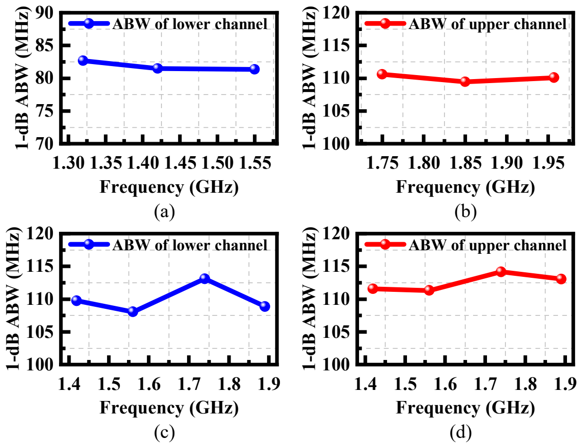


Fig. 8. Measured 1-dB ABW of the designed RDFS. (a) 1-dB ABW of lower channel and (b) 1-dB ABW of upper channel in diplexer mode. (c) 1-dB ABW of lower channel and (d) 1-dB ABW of upper channel in filtering switch mode.

optimized values for the fixed-value capacitors are: C_{23} = 0.5 pF, C_{34} = 0.8 pF, C_{56} = 0.7 pF, C_{67} = 0.7 pF.

Fig. 6 shows the simulated and measured results of the proposed RDFS operating as a diplexer in FDD operation. As can be seen, the designed RDFS demonstrates a good diplexer performance, and the operating frequencies of the two channels can be independently tuned. Specifically, the center frequency of the upper channel can be tuned from 1.75 GHz to 1.96 GHz with the lower channel being fixed at 1.55 GHz, and the corresponding measured insertion loss is varied from 3.75 dB to 4.24 dB. When the upper channel is fixed at 1.75 GHz, the center frequency of the lower channel can be tuned from 1.32 GHz to 1.55 GHz, with a measured insertion loss varying from 4.36 dB to 5.18 dB. The measured in-band isolation between the two channels (i.e. $|S_{32}|$) is better than 25.7 dB during the whole tuning process. Fig. 7 shows the simulated and measured results of the proposed RDFS operating as a filtering switch in TDD operation. In this operation, the operating frequencies of the two channels are the same, both of which can be continuously tuned from 1.42 GHz to 1.89 GHz. When the upper channel is on and lower channel is off, the measured in-band insertion loss (i.e. $|S_{21}|$) is varied from 4.01 dB to 5.5 dB, and the measured in-band isolation (i.e. $|S_{32}|$) keeps better than 35.9 dB. When the lower channel is on and upper channel is off, the measured in-band insertion loss (i.e. $|S_{31}|$) is varied from 4.04 dB to 4.74 dB, and the measured in-band isolation (i.e. $|S_{32}|$) maintains better than 35.1 dB.

Fig. 8 gives the measured 1-dB ABW of the RDFS with different operating frequencies. For the diplexer in FDD operation, the measured 1-dB ABWs of the upper channel and lower channel maintain at 110 ± 1 MHz and 82 ± 1 MHz respectively, during the frequency tuning process. For the filtering switch in TDD operation, the 1-dB ABWs of both the two channels keep at 110 ± 4 MHz during the frequency tuning process.

Table 2 shows the comparisons between this work and other state-of-art switchable diplexers. As can be seen, compared with the listed switchable diplexers in Table 2, the proposed RDFS is the only one which possesses frequency tunability, and it also achieves constant ABW during the frequency tuning process. More importantly, different from these switchable diplexers reported in literature, the proposed RDFS in this work can flexibly assign the operating frequencies for the two channels according to the required working mode (i.e. different frequencies for the two channels when operating as diplexer and same frequencies for the two channels when operating as filtering switch), and hence it is capable of supporting system with reconfigurable FDD/TDD operations.

Table 2. Comparison between this work and other switchable diplexers.

Ref.	Working mode	Center frequency (GHz)	Insertion loss (dB)	Frequency tunability	Supporting switchable TDD/FDD?
[2]	Switchable diplexer	1.2/1.5	2.1/2.2	×	×
[3]	Switchable diplexer	2.35/3.5	1.3/1.3	×	×
[4]	Switchable diplexer	0.89/1.82	2.04/1.97	×	×
This Work	**Diplexer**	**1.32-1.55 / 1.75-1.96**	**4.36-5.18 / 3.75-4.24**	√	√
	Filtering switch	**1.42-1.89**	**4.01-5.5**		

IV. Conclusion

A novel RDFS which aims for realizing system with reconfigurable TDD/FDD operations is presented. The proposed RDFS employs an all-resonator coupled topology which requires no extra impedance matching networks. By further introducing CMEC technique to the circuit, it successfully achieves the flexible switching between the functions of standard diplexer and filtering switch in a single device. Both the operating frequencies of the two working modes can also be continuously tuned. The proposed RDFS, featuring with flexible reconfigurability, may offer a promising solution for mode-reconfigurable wireless system.

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