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Diplexing Filtering Power Divider with a Lowpass and Dual-Band Bandpass Response

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ABSTRACT: In this paper, a novel diplexing power divider with a lowpass and two bandpass channels is presented. The lowpass channel is constructed by using a 7th-order quasi-elliptical transfer function, while the dual-band bandpass response is obtained by using co-directional split-ring resonators. A lowpass-bandpass diplexer is first designed by integrating the lowpass and bandpass filters directly. In order to achieve the power division within the entire frequency range, a multi-section power divider is located at the end of both filter structures. The proposed lowpass-bandpass diplexing power divider is fabricated and measured in very good agreement with the predicted results. The measured frequency range of the lowpass channel is between 100 MHz and 2 GHz. The measured center frequencies of the bandpass channels are at 3.4 and 3.9 GHz with the 3-dB fractional bandwidths of 7 and 6.6%, respectively.

1. INTRODUCTION

In recent years, the utilization of multifunction radio frequency (RF)/microwave circuits in modern communication systems has gradually increased. This is because of the advantages of multifunction circuits in terms of compactness, low loss, and reduced integration complexity within the whole system. Filtering power dividers are used to decrease reflection/transmission losses and impedance mismatch resulting from multiple circuits and phase and amplitude imbalance. Moreover, multiplexing devices having different types of filtering functions and power dividing applications are also good candidates for future communication systems since they can provide so many functions within a single circuit board.

To date, researchers have studied different types of filtering power dividers having compact circuit size, high isolation, harmonic suppression, etc. [1–11]. Stepped impedance resonators, coupled lines, multi-mode and stub-loaded resonators have been used to achieve filter sections, where multi-mode resonators can be especially used to obtain multiple passbands. For instance, a dual-band bandpass filter can be designed by using co-directional split-ring resonators that can exhibit dual-resonance behavior [12]. Wilkinson power dividers are often preferred in power division sections depending on their high isolation and compact circuit size properties [13, 14]. On the other hand, lowpass-bandpass diplexers have attracted great attention in the last decade [15–19]. In such designs, elliptical lowpass filters are especially used to obtain the lowpass filter since they can allow high isolation [18, 19]. Lowpass-bandpass multiplexers with multiple passbands also stand out in the literature [20, 21]. However, it is expected that the number of diplexing filtering power dividers is going to increase in the near future to resolve the requirements of multifunction communication systems. For this purpose, several types of multiplexer integrated filtering power dividers have been introduced in [10, 11, 22–25]. However, to the best of the authors' knowledge, lowpass-bandpass diplexing power dividers have not yet been studied in the literature.

In this paper, a diplexing power divider with a lowpass and two bandpass channels is proposed. A quasi-elliptical lowpass prototype is used to achieve the lowpass channel, while co-directional split-ring resonators are employed to form two bandpass channels. A multi-section power divider is located at the end of both filters to have a wideband covering all channels. Thus, a low-pass channel from 100 MHz to 2 GHz and two bandpass channels centered at 3.4 and 3.9 GHz are created. It is expected that the designed diplexing power divider can be used in the applications of sub-2 GHz, WiMAX, 5G C-band, and n77/n78 frequency bands. The designed prototype has been implemented and successfully tested to validate the predicted results.

2. DESIGN PROCEDURE

In order to design the lowpass-bandpass diplexing power divider, lowpass filter, bandpass filter, and multi-section power divider should be separately designed. The lowpass and bandpass filters can form a diplexing process, while the multi-section power divider is integrated to the output ports of the diplexer to provide a wideband response. In all design steps, a Rogers 4003C dielectric substrate with a relative dielectric constant of 3.55 and a thickness of 0.813 mm is used. Parameter sweeps should be performed by using the Full-Wave Electromagnetic (EM) Simulator, Sonnet software, for all design steps, including lowpass filter, bandpass filter, and diplexing

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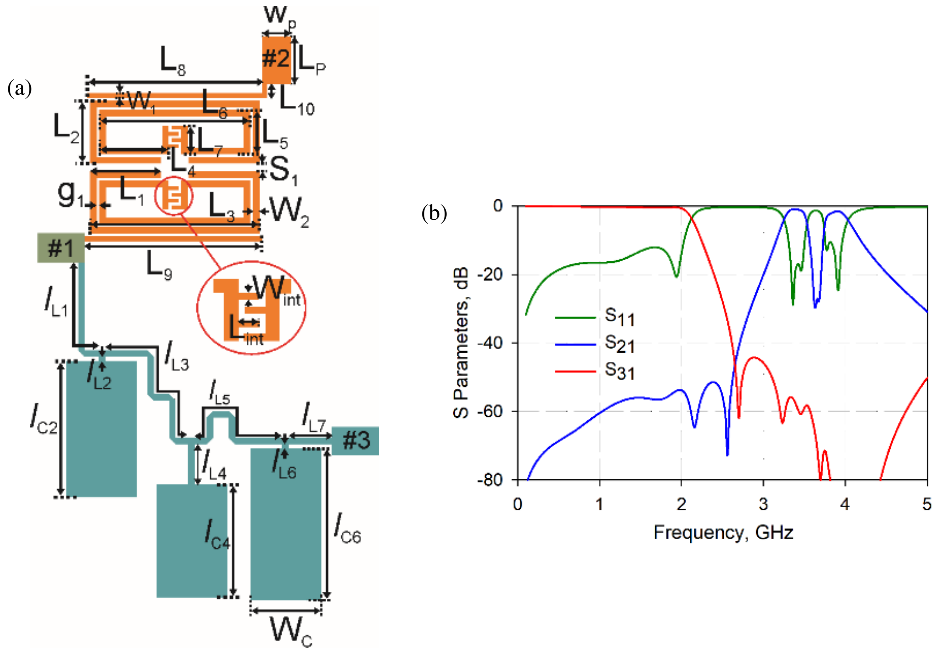

FIGURE 1. (a) Layout of the lowpass-bandpass diplexer, (b) EM-simulation results ($W_p = 1.8$, $L_p = 3$, $W_1 = 0.3$, $W_2 = 0.4$, $g_1 = 0.2$, $S_1 = 0.5$, $W_{int} = 0.2$, $L_{int} = 0.6$, $L_1 = 4.5$, $L_2 = 4$, $L_3 = 10.8$, $L_4 = 4.4$, $L_5 = 2.8$, $L_6 = 9.6$, $L_7 = 1.8$, $L_8 = 11.2$, $L_9 = 11.3$, $L_{10} = 0.9$, $l_{L1} = 7$, $l_{L2} = 0.3$, $l_{C2} = 8.7$, $l_{L3} = 11.3$, $l_{L4} = 2.6$, $l_{C4} = 7.2$, $l_{L5} = 9.2$, $l_{L6} = 0.3$, $l_{C6} = 9.7$, $l_{L7} = 3$, $W_c = 4.5$ mm).

power divider, respectively. The design steps for the lowpass-bandpass diplexing power divider can be summarized as follows.

1. A lowpass filter design is firstly designed using a 7th-order elliptical transfer function.
2. A dual-band bandpass filter is designed using an interdigital capacitor-loaded co-directional split-ring resonator according to the approach in [12].
3. The diplexer is constructed by connecting the lowpass and bandpass filter structures to the input port directly.
4. A conventional multi-section power divider operating between $f_1 = 500$ MHz and $f_2 = 5$ GHz is designed so as to cover the entire frequency range of the lowpass and bandpass filters.
5. The lowpass-bandpass diplexing filtering power divider is constructed by integrating the multi-section power divider to the output ports of the lowpass-bandpass diplexer. Final dimensions can be found at this stage by means of EM simulations.

2.1. Lowpass-Bandpass Diplexer

For the diplexer design, lowpass and bandpass filters can be separately designed. A 7th-order elliptical transfer function is initially chosen for the lowpass filter design to achieve high selectivity. Although it is possible to use a higher-order transfer function to increase the selectivity, the circuit size and complexity would have increased accordingly. The design parameters are determined to obtain a stopband attenuation of greater than 45 dB and to have the minimum possible Ω_s. The minimum Ω_s is needed for high selectivity and high isolation between the outputs of the diplexer to be designed. The initial element values for the lowpass filter prototype are $g_0 = 1$, $g_1 = 1.0252$, $g_2 = 1.2157$, $g_2' = 0.1940$, $g_3 = 1.5811$, $g_4 = 0.9939$, $g_4' = 0.5816$, $g_5 = 1.2382$ and $g_6 = 0.5243$, $g_6' = 0.5816$, $g_7 = 0.4369$ [26]. The cut-off frequency of the lowpass filter is 2 GHz, and the low and high characteristic impedances to be used in the transformation are selected as $Z_{0L} = 27$ and $Z_{0H} = 107$ ohm. In order to observe the best possible performance, the element values have been mathematically investigated, and some of them are revised as follows: $g_2 = 0.283$, $g_6 = 0.6943$. The initial physical lengths of the lowpass filter calculated from the above element values are as follows: $l_{L1} = 6.9$, $l_{L2} = 0.3$, $l_{L3} = 10.9$, $l_{L4} = 2.6$, $l_{L5} = 9$, $l_{L6} = 0.3$, $l_{L7} = 2.8$, $l_{C2} = 8.7$, $l_{C4} = 7.2$, $l_{C6} = 9.7$, $W_c = 4.5$ mm.

For the bandpass response, an interdigital capacitor loaded co-directional split-ring resonator is used to obtain two passbands centered at 3.36 and 3.92 GHz. According to [12], the interdigital capacitor-loaded co-directional split-ring resonator exhibits dual-resonance behaviour, and the frequency bands can be adjusted by changing both the split-ring resonator and interdigital finger lengths/numbers. Fig. 1(a) depicts the layout of the lowpass-bandpass diplexer, which can exhibit two channels at the bandpass output. It is clear that the diplexer can be constructed by connecting the lowpass and bandpass filter structures to the input port directly. EM simulation results of the proposed circuit are depicted in Fig. 1(b).

2.2. Multi-Section Wilkinson Power Divider

The multi-section Wilkinson power divider is required for a wideband response since the lowpass and bandpass filter channels cover the frequency range between DC and 4 GHz. Therefore, the power divider should also cover this frequency range

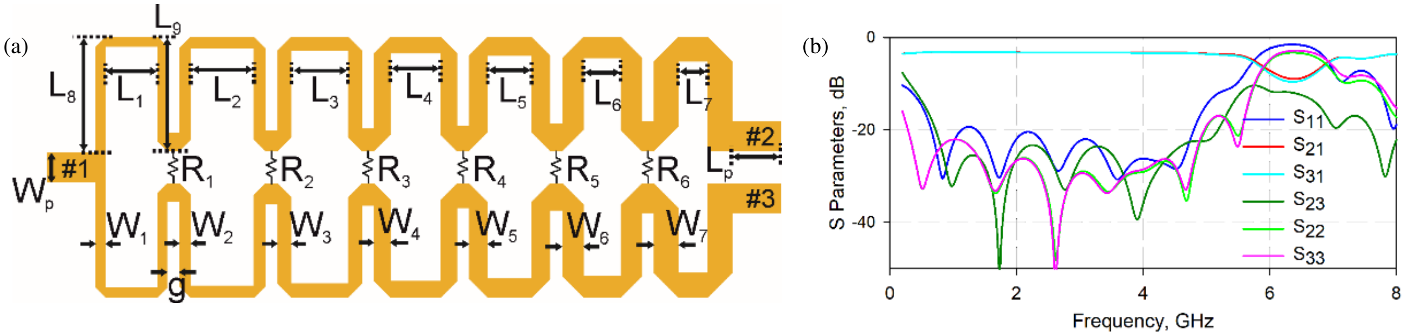

FIGURE 2. (a) Layout of the multi-section power divider, (b) EM simulation results ($L_1 = 3.2$, $L_2 = 3.9$, $L_3 = 3.5$, $L_4 = 3.1$, $L_5 = 2.7$, $L_6 = 2.3$, $L_7 = 1.8$, $L_8 = 7.1$, $L_9 = 7$, $L_p = 3$, $W_p = 1.8$, $W_1 = 0.6$, $W_2 = 0.7$, $W_3 = 0.85$, $W_4 = 1$, $W_5 = 1.15$, $W_6 = 1.3$, $W_7 = 1.5$, $g = 0.75$, $R_1 = 220\,\Omega$, $R_2 = 120\,\Omega$, $R_3 = 220\,\Omega$, $R_4 = 330\,\Omega$, $R_5 = 470\,\Omega$, $R_6 = 560\,\Omega$).

to observe good reflection/transmission losses within the related frequency range. For this purpose, a conventional multi-section power divider operating between $f_1 = 500$ MHz and $f_2 = 5$ GHz is firstly designed [27]. As it is known, the number of sections can be determined by the frequency ratio of f_0/f_1, where $f_1 = 500$ MHz is the minimum frequency, and $f_0 = 2.75$ GHz is the center frequency that can be found from $(f_1 + f_2)/2$. Since the frequency ratio is calculated as 5.5, a 7-stage design can be preferred [27]. Since lowpass and bandpass filter channels cover a wide frequency range, a wideband 7-stage power divider is preferred to achieve good return loss and insertion loss within the entire frequency range.

Each transmission line in the upper and bottom paths is chosen as $\lambda/4$, where λ is the wavelength at the midband frequency of the wideband response, 2.75 GHz. Although the lowpass filter starts from DC, the lowest frequency of the multi-section power divider is chosen as 500 MHz to reduce the section number. The layout of the conventional multi-section power divider is shown in Fig. 2(a). The physical dimensions of the circuit are given in the caption of Fig. 2(a), which may be revised during the design of the diplexing filtering power divider. It can be noted that resistive elements are used to ensure the isolation between the stages, as in [27]. However, the last resistor is cancelled in order to make the circuit ready for practical measurements, so that the distance between the output ports can be increased. S-parameters of the designed circuit are also depicted in Fig. 2(b). As can be seen from the figure, the input return loss can be obtained as better than 19 dB, while the isolation is lower than 24 dB.

3. LOWPASS-BANDPASS DIPLEXING FILTERING POWER DIVIDER

As mentioned in the previous section, the lowpass-bandpass diplexing filtering power divider is constructed by integrating the multi-section power divider to the output ports of the lowpass-bandpass diplexer, as shown in Fig. 3(a). However, the final dimensions need to be revised for performance optimization. The optimizations can be realized by using Full-Wave EM Simulator, Sonnet, with the following goals:

1. *Lowpass channel insertion loss below 2 GHz < 0.5 dB.*
2. *Bandpass channels insertion losses < 2 dB.*
3. *Multiplexer isolations (S_{24}, S_{25}, S_{34}, S_{35}) > 40 dB.*
4. *Power divider isolation (S_{23}, S_{45}) > 20 dB.*
5. *Lowpass return loss from 300 MHz to 2 GHz > 15 dB.*
6. *Bandpass channels return losses > 15 dB.*

Due to the high number of design goals, some conditions may need to be ignored to achieve the best possible performance. For this purpose, the goal for the power divider isolation can be decreased to 15 dB. In order to capture the above values, some dimensions given before should be swept in EM simulations. Therefore, the lengths of L_{12} and W_8 in Fig. 3(a) are revised for the final dimensions. All dimensions shown in Fig. 3(a) are as follows: $l_{L1} = 6.9$, $l_{L2} = 0.3$, $l_{C2} = 8.8$, $l_{L3} = 11.1$, $l_{L4} = 2.6$, $l_{C4} = 7.8$, $l_{L5} = 9$, $l_{L6} = 0.3$, $l_{C6} = 9.7$, $l_{L7} = 2.8$, $W_c = 4.5$, $W_1 = 0.6$, $W_2 = 0.7$, $W_3 = 0.85$, $W_4 = 1$, $W_5 = 1.15$, $W_6 = 1.3$, $W_7 = 1.5$, $W_8 = 1.8$, $W_9 = 0.3$, $W_{10} = 0.4$, $g = 0.75$, $g_1 = 0.2$, $L_1 = 3.2$, $L_2 = 4.1$, $L_3 = 4$, $L_4 = 3.9$, $L_5 = 3.8$, $L_6 = 3.7$, $L_7 = 7.6$, $L_8 = 3.6$, $L_9 = 8.1$, $L_{10} = 7.7$, $L_{11} = 7.6$, $L_{12} = 3$, $L_{13} = 4.5$, $L_{14} = 4.5$, $L_{15} = 4$, $L_{16} = 10.8$, $L_{17} = 4.4$, $L_{18} = 2.8$, $L_{19} = 9.6$, $L_{20} = 1.8$, $L_{21} = 12.1$, $L_{22} = 11.3$, $L_{23} = 5$, $W_{int} = 0.2$, $L_{int} = 0.6$, $S_1 = 0.5$ mm, $R_1 = 220\,\Omega$, $R_2 = 120\,\Omega$, $R_3 = 220\,\Omega$, $R_4 = 330\,\Omega$, $R_5 = 470\,\Omega$, $R_6 = 560\,\Omega$. Moreover, as mentioned previously, the last section of the conventional power divider shown in Fig 2(a) is revised, and the last resistance is removed to make the circuit ready for the measurement in the Network Analyzer. In addition, Fig. 3(b) shows the effects of the section number of the power divider on the frequency response. As can be seen from the figure, better return losses at both of the lowpass and bandpass channels can be observed, depending on the use of a multi-section power divider. It should also be noted that the lowpass channel could be started from DC if more sections are used. However, in the proposed design, in order to reduce the circuit complexity, the section number is limited by 7, which can also cover a significant part of the lowpass frequency band.

For demonstration, a diplexing power divider was fabricated and measured using a Power Network Analyzer of Keysight N5222A. A photograph of the manufactured circuit is shown in Fig. 4(a). The comparison of the simulated and measured S-parameters is given in Fig. 4(b) in terms of transmission and reflection coefficients. It is obvious that the simulated and measured responses show excellent agreement. Small differences

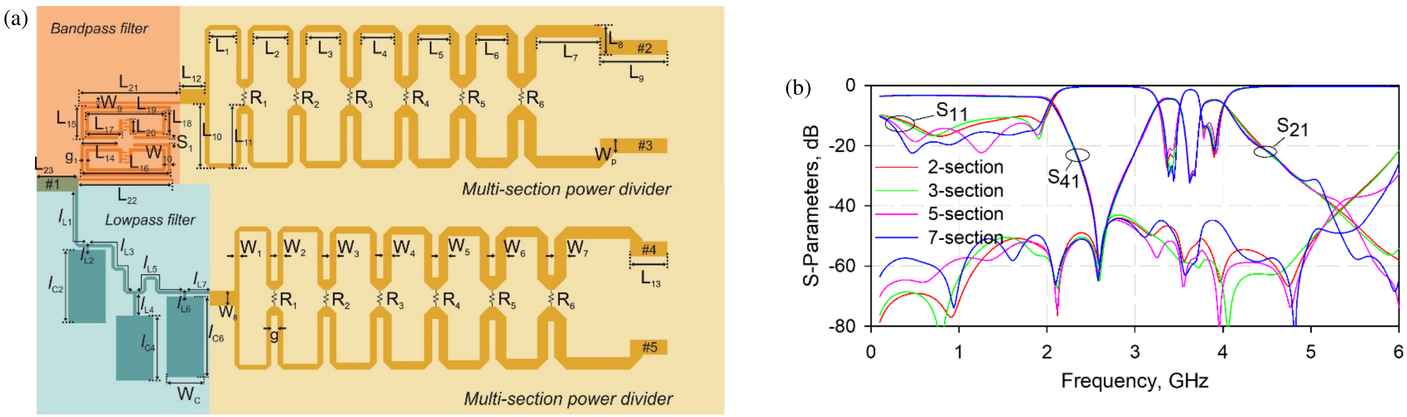

FIGURE 3. (a) Layout of the diplexing filtering power divider, (b) effects of section numbers on the frequency response.

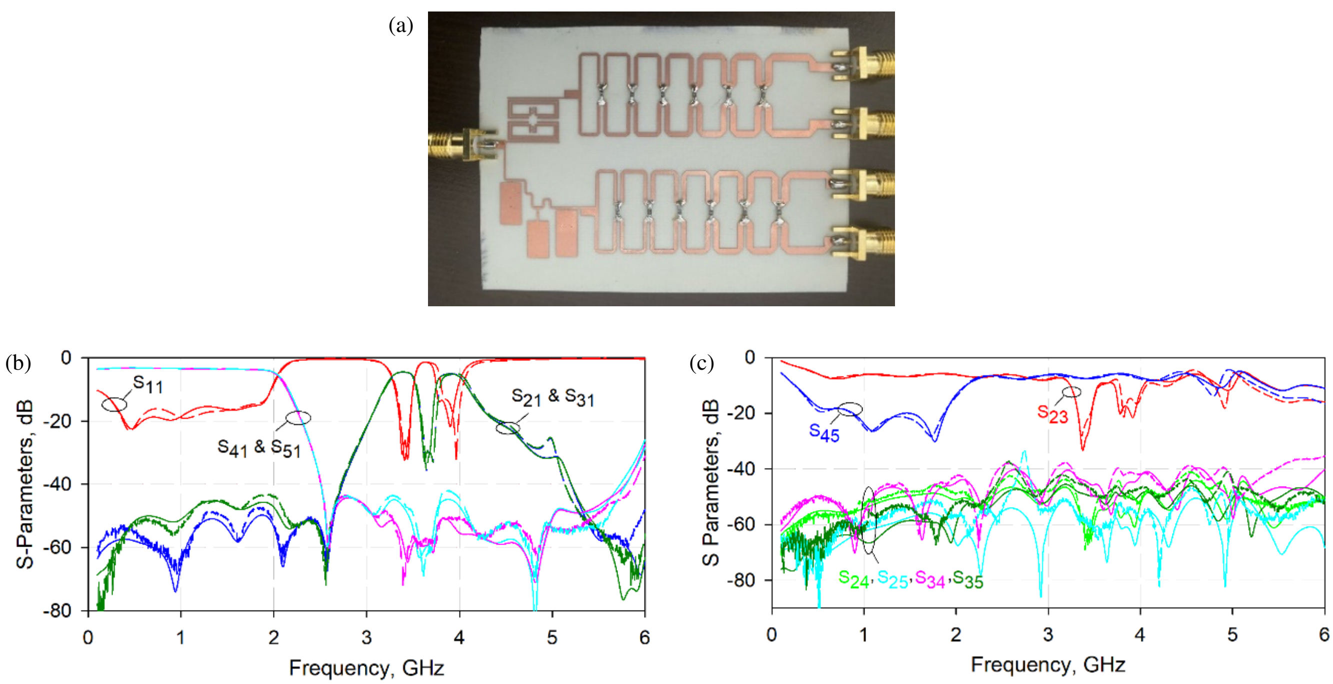

FIGURE 4. (a) Photograph of the manufactured circuit, (b) EM-simulated and measured input return losses and insertion losses of the diplexing power divider, (c) EM-simulated and measured isolations (Solid lines: Simulated. Dashed lines: Measured.)

between the EM-simulated and measured responses are especially observed in the second passband, which result from the fabrication tolerances of the interdigital capacitors.

In the lowpass channel, the excess insertion loss, which comprises the ideal splitting loss and an excess loss from the filter structure, is better than 3.9 dB up to 1.9 GHz. The return loss was measured as better than 15 dB from 300 MHz to 1.8 GHz. It is also better than 10 dB from 100 MHz to 1.95 GHz. On the other hand, center frequencies of the bandpass channels were measured at 3.4 and 3.9 GHz with the 3-dB fractional bandwidths of 7% and 6.6%, and the excess insertion losses are 4.5 and 4.93 dB, respectively. Fig. 4(c) illustrates the isolation performance of the implemented circuit. The multiplexer isolation between the channels is better than 33 dB within the entire frequency range. However, the maximal isolations between the power divider ports from 400 MHz to 1.95 GHz and within the passbands were measured as 15, 25, and 15 dB, in the lowpass and bandpass channels, respectively.

The balanced performance of the designed diplexing power divider is also promising, as depicted in Fig. 5. The magnitude imbalance at the frequencies of the lowpass channel is less than 0.12 dB. It is also better than 0.15 dB at the frequencies of the bandpass channels. Moreover, the measured phase imbalances of the lowpass and bandpass channels were observed as better than 0.6° and 1°, respectively.

The designed diplexing filtering power divider is compared with similar works in the literature, as given in Table 1. It should be noted that the proposed circuit is the only one that exhibits lowpass and bandpass channels. Moreover, the circuit performance in terms of return loss (RL), insertion loss (IL), and isolation (I) is competitive.

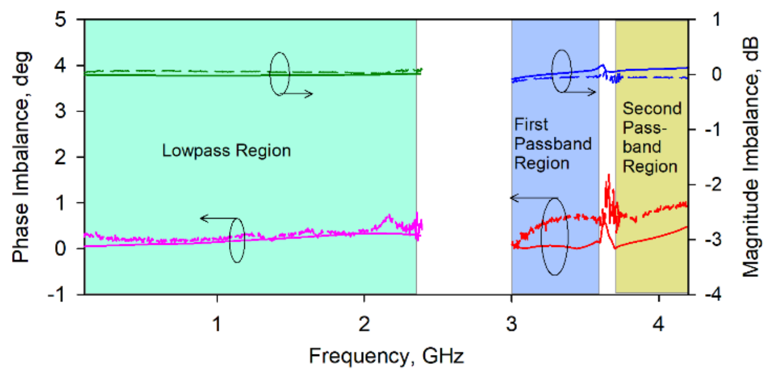

FIGURE 5. EM-simulated and measured magnitudes and phase imbalances (Solid lines: Simulated. Dashed lines: Measured.)

TABLE 1. State of art.

Ref.	Type	No of Band	CF (GHz)	FBW	IL (dB)	RL (dB)	IPD (dB)	ID (dB)
[10]	Balanced-to-balanced Diplexing PD	4	5.38/5.96/6.68/7.3	3.35/2.84/3/2.48%	1.79/1.83/1.67/1.82	> 10	-	-
[11]	Diplexing PD	2	1.81/2.4	6.3/6.3%	4.76/4.75	-	20.2/23	> 41
[22]	Diplexing PD	2	1.8/2.4	4.4/2.7%	3.74/3.95	-	30/32	> 18.7
[23]	Triplexer PD	3	1.64/2.35/3.03	0.3/0.26/0.25 GHz	3.2/3.5/3.49	20.5/17.6/18.7	20.6/17.6/13.5	-
[24]	Diplexing PD	2	28.2/29.2	650/650 MHz	0.9/ 0.9	20	-	-
[25]	Diplexing PD	2	2.43/2.91	8.2/9.6%	1.69/1.78	24.8	> 20	> 39
TW	LP-BP Diplexing PD	1 LP 2 BP	LP Ch: 0.1–1.95 BP Ch: 3.4–3.9	BP: 7/6.6%	3.9/4.5/4.93	> 10	15/25/15	> 33

LP: Lowpass, BP: Bandpass, IPD: Isolation between the output ports of the power divider (S_{23}, S_{45}),
ID: Isolation between the output ports of the diplexer.

4. CONCLUSION

A novel diplexing power divider has been designed by using a quasi-elliptical lowpass filter with 7th order and co-directional split-ring resonators to achieve a dual-band bandpass response. A prototype of the designed circuit has been manufactured and successfully tested in very good agreement with the EM-simulation results. The insertion losses within the lowpass and bandpass channels are better than 0.9 and 1.93 dB, respectively. The maximal isolation is better than 15 dB for the lowpass filter, while it is better than 25 and 15 dB for the bandpass channels. The diplexer isolation performance is better than 33 dB from DC to 6 GHz.

The designed lowpass-bandpass diplexing power divider can become a good candidate for the applications of sub-2 GHz communication systems and 5G n77/n78/C bands. It exhibits a promising performance in terms of insertion loss, isolation, and compactness. It is expected that the integration of lowpass filters with bandpass filters in a power divider configuration may have great attraction in the research and industry.

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