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DIPLEXERS BASED ON MICROSTRIP LINE RESONATORS WITH LOADED ELEMENTS

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Abstract—In this paper, microstrip line resonators with loaded elements are proposed and studied to design microstrip diplexer. To demonstrate the design ideas, the equivalent circuits of the proposed resonators are built and studied. It is found that the different loads on different positions of the proposed half-wavelength resonator make the resonator have different features, which will easily control the characteristic of the diplexers. And here, resistor, open stub, and shorted stub are used as loaded elements. It is found the resistor loaded on the center of the microstrip line resonator can extremely reduce the unloaded quality factor of even-mode resonant frequency, which can be used to suppress the harmonics of the diplexer. The loaded open stub not only can reduce the size of the diplexer, but also can control the frequency ratio between the fundamental frequency and second harmonic of a resonator, which can increases the frequency ratio between the two passbands of the diplexer. As for the loaded shorted stub, it can enlarge the size of the diplexer. To demonstrate the design ideas, three diplexers are presented. The comparisons between the loaded and unloaded diplexers are given. The experimental results agree well to the theoretical predictions and simulations.

1. INTRODUCTION

Modern wireless communication systems demand RF devices operating in multiple frequency bands. A diplexer, as an essential component in multi-service and multi-band communication systems, is a three-terminal device that separates the input signals to two output ports. A well designed diplexer should have low cost and high performance. Microstrip diplexers as low cost ones can be easily mounted on the

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dielectric substrate and can provide a more flexible design of the circuit layout [1]. For microstrip diplexers, much effort has been paid to reduce the size and improve the performance.

To compact the microstrip diplexer, resonators such as stepped-impedance open-loop resonators [2], miniaturized open-loop resonator [3], square open loop with stepped-impedance resonator [4], stepped impedance coupled-line resonator [5], H-type resonator [6] and artificial transmission line [7], have been utilized in diplexer design. In [8, 9], microstrip diplexer based on dual-passband filter is also designed to reduce the size of the diplexer, however the large size of the matching networks limit the effect of size reduction. In [10], compact diplexer based on double-sided parallel-strip line is realized, but this diplexer is based on multilayer structure. Besides the size reduction, high performance for microstrip diplexer is also important. In [2–10], each diplexer still has one or two drawbacks of the performance of the diplexers, such as selectivity, isolation, harmonic suppression, and frequency-ratio range of the two passbands.

In [11, 12], folded coupled-line structure and dual-mode stripline ring resonators are utilized to produce transmission zeros to improve the selectivity of the diplexer, respectively. In [13], microstrip electromagnetic band gap structure is used to get wide stopband of the diplexer, but the selectivity is not good. Microstrip diplexer/filter based on the common resonator section [14], modified stepped-impedance resonators [15–17], dual-mode stepped-impedance resonators [18] and defected ground structure [19–21] realize good selectivity, high isolation and wide stopband. Actually, for the diplexer with wide stopband, it is easy to control the frequency ratio of the two passbands of the diplexer, because the harmonic of the lower passband is far away from the higher passbands, so it will not affect the high passband when the lower passband moves down. The other method to control the frequency ration of the two passbands is to make the harmonic to be fixed on a frequency when the lower passband moves down.

In microstrip diplexer design, some harmonics probably appear near or inside the two passbands, which will degenerate the performance of the diplexer [2, 5, 7, 10, 11, 13]. Therefore, if the unloaded quality factor of these harmonics can be greatly reduced, then these harmonics can be suppressed very well.

In this paper, the microstrip line resonators with different loaded elements are proposed to design microstrip diplexers, which will show different characteristics of the diplexers. Here, resistor, open stub, and shorted stub are used as loaded elements, respectively. The characteristics of the proposed resonators at the fundamental frequency and the second harmonic are studied. It is found the resistor-loaded resonator can extremely reduce the unloaded quality factor at even-mode resonant frequency, which can used to suppress the harmonics of the diplexer. The loaded open stub not only can reduce the size of the diplexer, but also control the frequency ratio between the two passbands of the diplexer, which is because the second harmonic will not move when the fundamental frequency moves. As for the loaded shorted stub, it can enlarge the size of the diplexer. To demonstrate the design ideas, three diplexers are presented. The comparisons between the loaded and unloaded diplexers are given. The experimental results agree well to the theoretical predictions and simulations.

2. ANALYSIS OF THE PROPOSED RESONATOR

Figure 1 shows the proposed open-ended transmission line resonators with different loaded elements. Based on transmission line theory, the electromagnetic field of the resonator can be represented by voltage wave [22]. As shown in Fig. 1(a), the normalized voltages at the fundamental frequency and the second harmonic of the open-ended

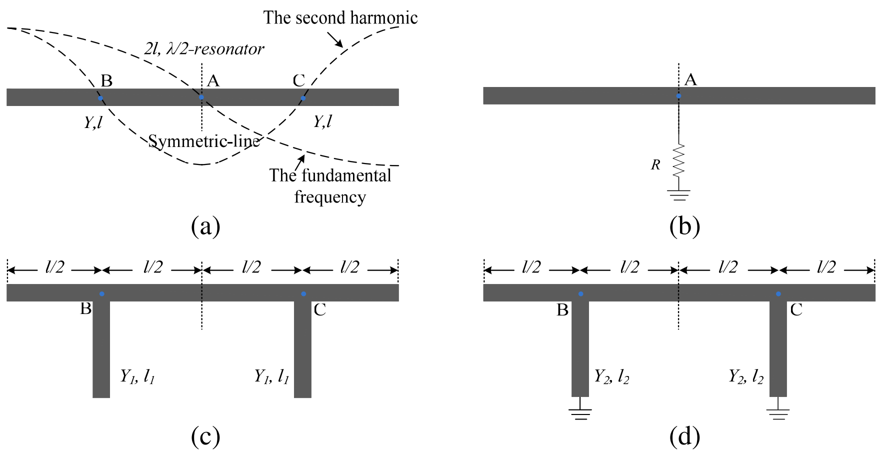


Figure 1. The proposed resonators with loaded elements. (a) Normalized voltage wave along the unloaded half wavelength resonator at fundamental frequency and the second harmonic. (b) Proposed resonator with center-loaded resistor. (c) Proposed resonator with two open stubs loaded on zero-voltage points (A and B). (c) Proposed resonator with two shorted stubs loaded on zero-voltage points (A and B).

half wavelength resonator can be expressed as half cosine curve and one cosine curve, respectively. Therefore, for the half wavelength resonator, there is a zero-voltage point at the center (point A) for the fundamental signal, while there are two zero-voltage points (B and C) for the second harmonic. Thus, when the elements are loaded on the zero-voltage point (A) of the fundamental signal, the feature of the resonator for the second harmonic will be changed and controllable. Whereas, the feature of the resonator at the fundamental frequency can be varied by loading the element on the zero-voltage points (B and C) for the second harmonic.

In this paper, the resistors, open stubs, and shorted stubs are utilized as the loaded elements to realize different feature of the resonator. The analysis, simulation and fabrication are all based on the substrate Taconic RF-60A-0310 (with a thickness of 0.82 mm, a dielectric constant of 6.03 and the loss tangent of 0.0038). Fig. 1(b) shows the half wavelength resonator with center-loaded resistor. Since the center point is the maximum-voltage point for the second harmonic, some part of the energy will be absorbed by the resistor. Thus the unloaded quality factor at the second harmonic will be dramatically reduced. Fig. 2 shows the simulated unloaded quality factor of the resistor-loaded resonator at the second harmonic and the fundamental frequency. For the resonator without resistor, the unloaded quality factor of the resonator is about 218 at both the fundamental frequency and the second harmonic. When the resistor is loaded, for the second harmonic, the unloaded quality factor will be greatly reduced.

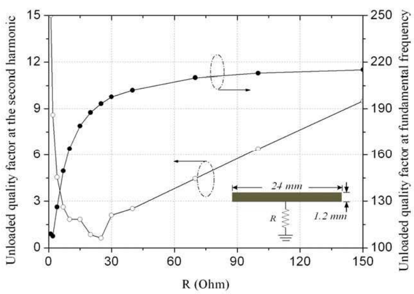


Figure 2. Simulated unloaded quality factor at the fundamental frequency and the second harmonic of the half wavelength resonator with center-loaded resistor.

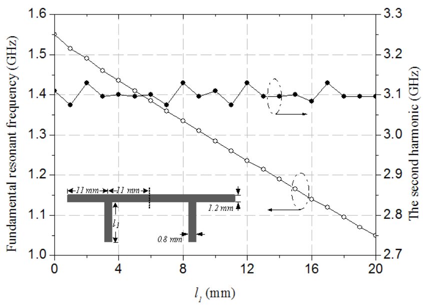


Figure 3. Simulated fundamental resonant frequency and the second harmonic of the proposed resonator loaded with open stubs.

And, there exists an optimum resistance that can make the proposed resonator to have the minimum unloaded quality factor. While for the fundamental frequency, the reduction of the unloaded quality factor is very slow when the resistance is larger than 25 ohm; however when the resistance is smaller than 25 ohm, the unloaded quality factor will be rapidly reduced. This means that the resistor can be used to suppress the second harmonic in filter or diplexer, but the resistance should not be too low to reduce the performance of the filter at the fundamental frequency. This is also suitable for other even-order harmonics.

Unlike the resistor-loaded resonator, the proposed resonator loaded with open stubs, which is shown as in Fig. 1(c), is utilized to control the fundament resonant frequency. Since the two open stubs are located at the zero-voltage points (B and C) for the second harmonic of unloaded resonator, the frequency of the second harmonic will almost not change. Fig. 3 shows the simulated fundamental resonant frequency and the second harmonic of the proposed resonator with two open stubs. It can be seen that the fundamental resonant frequency moves down when increasing the length of the loaded open stubs, however the frequency of the second harmonic almost doesn't change. Therefore, the loaded open stubs can compact the size of the resonator, because this kind of resonator usually is folded into open-loop shapes, then the length of the loop will decide the size of the resonator. Also, the frequency ratio between the fundamental frequency and the second harmonic can also be controlled by the loaded open stubs.

Figure 1(d) shows the proposed resonator loaded with shorted stubs, which can also control the fundament resonant frequency, while the frequency of the second harmonic will almost not change. Fig. 4 shows the simulated fundamental resonant frequency and the second harmonic of the proposed resonator loaded with two shorted stubs. It is obvious that the fundamental resonant frequency also moves down when increasing the length of the loaded shorted stubs; and the frequency of the second harmonic almost doesn't change. However, there is a great difference from the resonator with open stub. When l_2 is between 0 to 6 mm, the fundamental resonant frequency is larger than the fundamental resonant frequency of the unloaded resonator (1.55 GHz). When l_2 is larger than 6 mm, the fundamental resonant frequency is smaller than 1.55 GHz. Therefore, the loaded shorted stub can either enlarge or reduce the size of the resonator. However, for size reduction, the resonator with open stub is better than the resonator with shorted stub, because the resonator with shorted stub brings more harmonics near the fundamental resonant frequency than the resonator with open stub. Therefore, the resonator with shorted stub is much better to utilized to enlarge the circuit size. Also, the frequency ratio

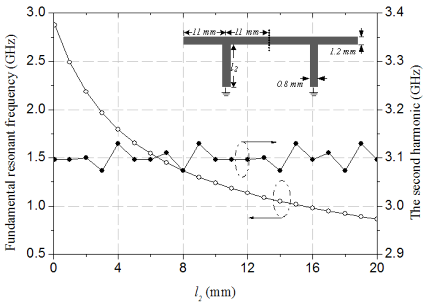


Figure 4. Simulated fundamental resonant frequency and the second harmonic of the proposed resonator loaded with shorted stubs.

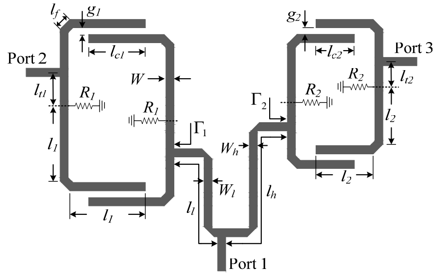


Figure 5. The layout of the diplexer using resistor-loaded resonators.

between the fundamental frequency and the second harmonic can also be controlled.

The above investigations of loaded resonators can be utilized to design the microstrip diplexers. Three kinds of diplexers have been designed. The first one utilizes the resistor-loaded resonator. The second one uses the resonator loaded with resistor and open stubs. The third one is the diplexer using the resonator loaded with resistor and shorted stubs. Details of the design procedure and features of the diplexers will be given.

3. THE DIPLEXER WITH RESONATORS LOADED WITH RESISTORS

Figure 5 shows the layout of the diplexer using the resistor-loaded half wavelength resonator. Each path of the diplexer is a two-order bandpass filter. In order to obtain the physical dimensions of the two filters, IE3D has been used to extract the coupling coefficients and the external quality factors. For each filter, the coupling coefficient is decided by the gap g_1 and g_2, respectively. The coupling coefficient can be evaluated from the two dominant resonant frequencies for two coupled resonators. If f_{p1} and f_{p2} are defined to be the lower and higher of the two resonant frequencies, respectively, the coupling coefficient can be obtained by [23]

$$K_{ij} = \frac{f_{p2}^2 - f_{p1}^2}{f_{p2}^2 + f_{p1}^2} \tag{1}$$

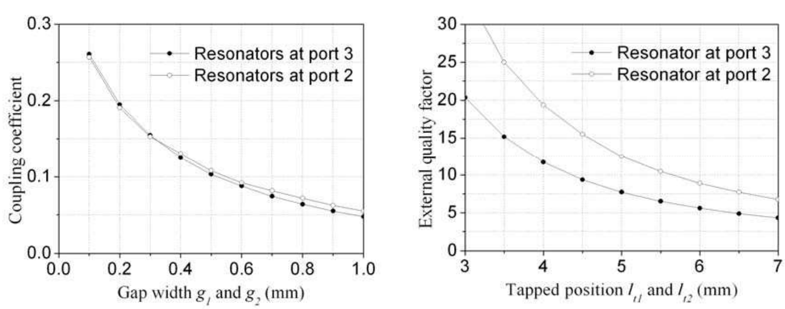
where K_{ij} represents the coupling coefficient between resonators i and j. Fig. 6(a) shows the simulated coupling coefficients versus the gap width between the resonators. The external quality factors can be obtained by the equation [23]

$$Q_e = \frac{f_0}{\Delta f_{\pm 90^\circ}} \tag{2}$$

f_0 is the resonant frequency and can be determined from the peak of the group delay response. $\Delta f_{\pm 90^\circ}$ is the frequency difference between the two frequencies, the phase of which shifts $\pm 90^\circ$ with respect to the phase of resonant frequency from the phase response. Fig. 6(b) shows the external quality factor versus the tapped position of the feed line. To make the diplexer have two passbands located at 1.55 and 2.015 GHz with fractional bandwidth of 9% and 8%, respectively for paths at the left and right side. The initial coupling coefficient and external quality factor for the filter at left side are $k_{12} = 0.116$ and $q_e = 10.33$; while for the filter at the right side, $k_{12} = 0.103$ and $q_e = 11.63$. Therefore, according to the given coupling coefficient and external quality factor, the initial gap width and tapped position can be selected from Fig. 6. To design the diplexer, the reflection coefficient should satisfy

$$\Gamma_1(f_1) \approx 0, \quad \Gamma_1(f_2) \approx 1, \quad \Gamma_2(f_2) \approx 0, \text{ and } \Gamma_2(f_1) \approx 1 \tag{3}$$

where f_1 and f_2 are the center frequencies of passbands for paths at the left and right side, respectively. After optimized in IE3D and ADS, the final geometric parameters of the diplexer are determined as follows: $l_1 = 11.14$ mm, $l_2 = 8.44$ mm, $l_{t1} = 4.8$ mm, $l_{t2} = 3.7$ mm, $l_f = 2$ mm,



(a) (b)

Figure 6. Coupling coefficients and external quality factors of the diplexer using resistor-loaded resonators. (a) Coupling coefficients versus the gap width between the resonators. (b) External quality factor versus the tapped position of the feed line.

$l_{c1} = 8.35\,\text{mm}$, $l_{c2} = 5.65\,\text{mm}$, $g_1 = 0.51\,\text{mm}$, $g_2 = 0.46\,\text{mm}$, $W = 1.2\,\text{mm}$, $W_l = W_h = 1.2\,\text{mm}$, $l_l = 18.14\,\text{mm}$, and $l_h = 24.64\,\text{mm}$.

Figure 7 shows the simulated results with and without loaded resistors. When there were no resistors, some harmonics with strong response will exist at about 0.68 and 3 GHz, which will reduce the selectivity and isolation of the diplexer. These harmonics can be suppressed to some extent by using the center-loaded resistors, because the resistors can greatly reduce the unloaded quality factor at the even-mode harmonics. However, the unloaded quality factor at the fundamental frequency will also be reduced when the resistance becomes small as shown in Fig. 2. Therefore, the resistance should not be too low. For this diplexer, $R_1 = 47\,\text{ohm}$, and $R_2 = 180\,\text{ohm}$ are selected. From Fig. 7, it can be seen that the suppression is greatly improved after loading the resistors, especially for the isolation of the diplexer.

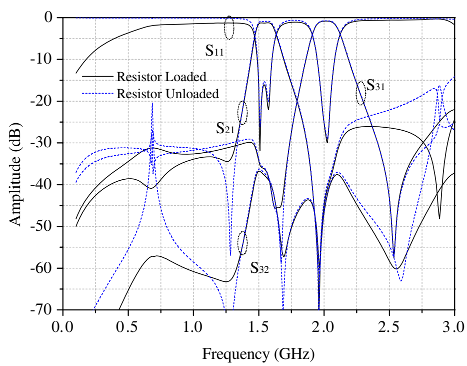


Figure 7. Simulated response of the diplexer with and without loaded resistors.

The measured results of the diplexer with center-loaded resistors, including the group delay, are shown in Fig. 8. Measurement was carried out using an Agilent N5230A network analyzer. It can be seen that the isolation is larger than 35 dB between the two channels. It should be noted that the larger the order of the resonators, the better the isolation with the tradeoff of the size and insertion loss. The lower and higher bands are located at 1.555 and 2.017 GHz with their respective insertion loss of 1.5 and 1.23 dB. The measured return losses at lower and higher bands are less than −16.5 dB. Each band of the diplexer has two transmission zeros, which improves the selectivity of the diplexer. The measured results agree well with the simulated ones.

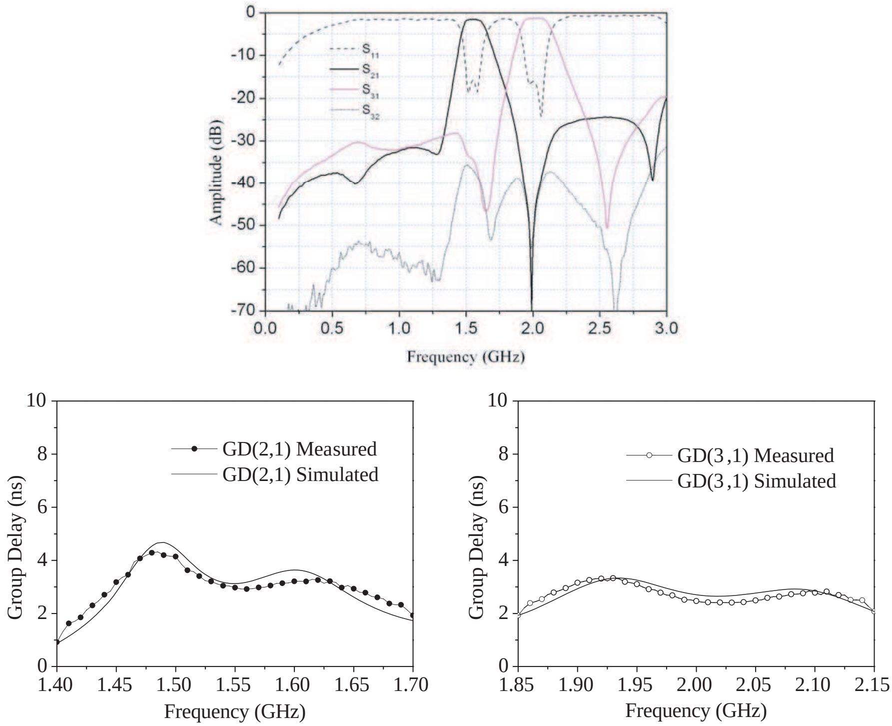


Figure 8. Measured response of the diplexer with loaded resistors.

4. THE DIPLEXER WITH RESISTORS AND OPEN STUBS

Figure 9 shows the layout of the second diplexer, one path of which uses resonators with open stubs and resistors. To demonstrate the compactness, the right side filter is identical to the right one in Fig. 5 with center frequency of the passband located at 2 GHz, while for the resonator of the left side path, two open stubs are added with the outer length (l_1 and l_f) of the resonator to be identical to that of the resonator of the left side path in Fig. 5. With the effect of the loaded open stubs, the center frequency of the passband of the left side path will be moved down, while the size also does not change. Therefore, it can be seen as that the loaded open stubs can compact the size of the diplexer. Besides the compactness, the proposed resonator with open stubs can increase the frequency ratio between the second harmonic and the fundamental frequency, which can be utilized to increase the frequency ratio between the two center frequencies of the

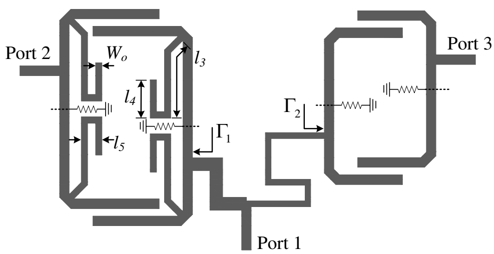


Figure 9. The layout of the diplexer with one path using resistor-loaded resonators and the other path using resonators with resistor and open stubs.

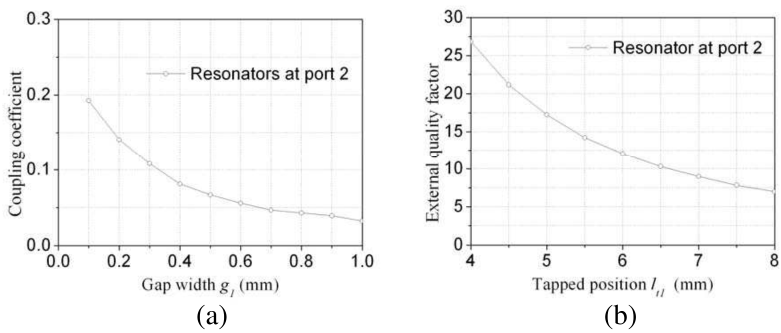


Figure 10. Coupling coefficient and external quality factor of the left path with loaded resistor and open stubs in Fig. 9. (a) Coupling coefficient versus the gap width between the resonators. (b) External quality factor versus the tapped position of the feed line.

two passbands of the diplexer, because the second harmonic of the left side passband will not move down when decrease the center frequency of the left side path, so the passband of the filter at right side will not be affected; otherwise the second harmonic of the left side path will affect the passband of the right path.

To make the left side path of the diplexer has a passband locating at 1.22 GHz with fractional bandwidth of 5.5%. The initial coupling coefficient and external quality factor are $k_{12} = 0.0708$ and $q_e = 16.91$, respectively. Fig. 10(a) shows the simulated coupling coefficient versus the gap width between the resonators. Fig. 10(b) shows the external quality factor versus the tapped position of the feed line. Therefore, according to the given coupling coefficient and external quality factor, the initial gap width and tapped position can be selected from Fig. 10. For the line at the common port of the diplexer, it should also satisfy

Equation (3). After optimization, the geometric parameters of the diplexer can be determined as follows: $l_1 = 11.14\,\mathrm{mm}$, $l_2 = 8.44\,\mathrm{mm}$, $l_{t1} = 4.8\,\mathrm{mm}$, $l_{t2} = 3.7\,\mathrm{mm}$, $l_f = 2\,\mathrm{mm}$, $l_{c1} = 8.35\,\mathrm{mm}$, $l_{c2} = 5.65\,\mathrm{mm}$, $g_1 = 0.26\,\mathrm{mm}$, $g_2 = 0.46\,\mathrm{mm}$, $W = 1.2\,\mathrm{mm}$, $W_l = 1.61\,\mathrm{mm}$, $W_h = 0.72\,\mathrm{mm}$, $l_l = 11.8\,\mathrm{mm}$, $l_h = 28.42\,\mathrm{mm}$, $W_o = 0.8\,\mathrm{mm}$, $l_3 = 10.64\,\mathrm{mm}$, $l_4 = 4.8\,\mathrm{mm}$, and $l_5 = 2.6\,\mathrm{mm}$.

Figure 11 shows the simulated results with and without loaded resistors of the diplexer in Fig. 9. It can be seen that compared with the diplexer without open stubs, the low passband of the diplexer moves from 1.55 to 1.22 GHz, while the second harmonic of the left side path almost does not change and is still at about 3 GHz. This means that the second harmonic of the filter with lower passband will not move and not affect the other passband of the diplexer when the lower passband moves down. Therefore, the proposed resonator with open stubs can widen the realizable frequency ratio between the two passbands of the diplexer. It also can be found that there are still some other harmonics at about 0.64 and 2.54 GHz when no resistors added. Therefore, the resistors should be added to suppress these harmonics. After loading the resistors with $R_1 = 33\,\mathrm{ohm}$, and $R_2 = 180\,\mathrm{ohm}$, these harmonics are greatly suppressed.

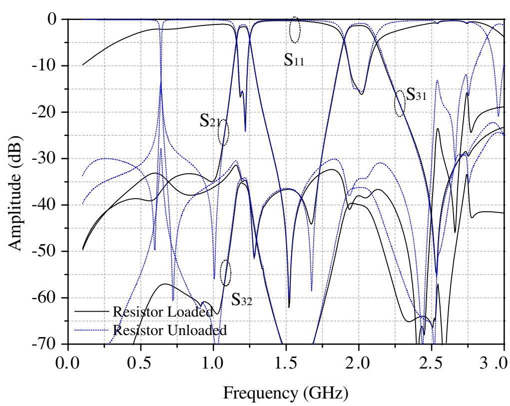


Figure 11. Simulated response of the diplexer in Fig. 9.

The measured results of the diplexer in Fig. 9, including the group delay, are shown in Fig. 12. It can be seen that the isolation is larger than 35 dB between the two paths. The lower and higher bands are located at 1.225 and 2.025 GHz with their respective insertion loss of 1.96 and 1.41 dB. Each band of the diplexer has two transmission zeros. The measured results agree well with the simulated ones.

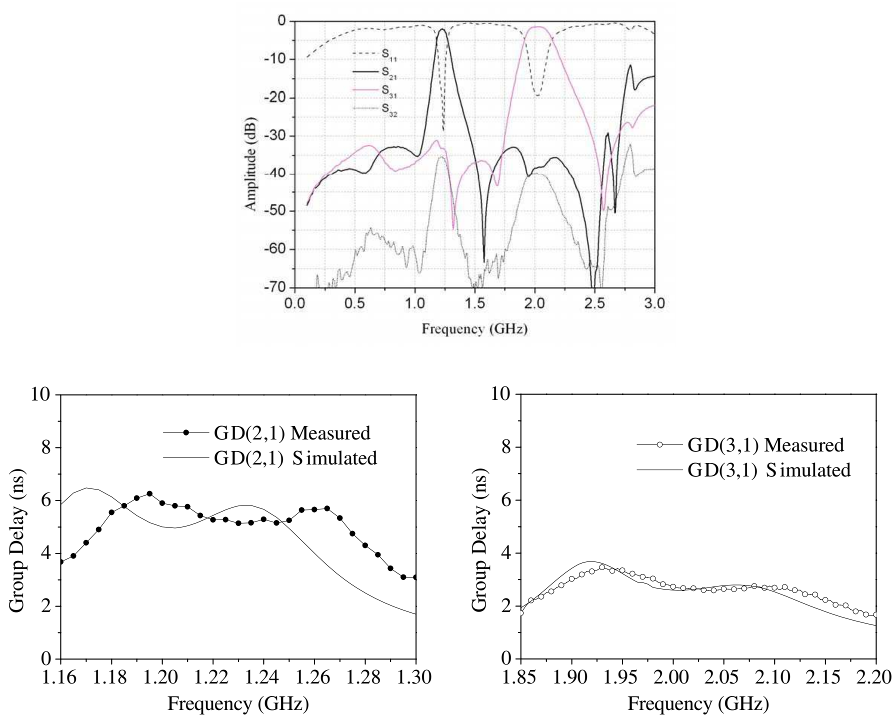


Figure 12. Measured response of the diplexer in Fig. 9.

5. THE DIPLEXER WITH RESISTORS AND SHORTED STUBS

Figure 13 shows the layout of the third diplexer. The right side path of the diplexer using resistor-loaded resonators with the center frequency located at 1.8 GHz. The left side path of the diplexer using resonators with resistor and shorted stubs, where the center frequency locates at 2.44 GHz when shorted stubs are loaded, otherwise the center frequency locates at 2 GHz. To make the two passbands locate at 1.8 and 2.44 GHz with fractional bandwidth of 8% and 7%, respectively. The initial coupling coefficient and external quality factor for the filter at left side are $k_{12} = 0.09$ and $q_e = 13.3$; while for the filter at the right side, $k_{12} = 0.103$ and $q_e = 11.63$. Fig. 14(a) shows the simulated coupling coefficient versus the gap width between the resonators. Fig. 14(b) shows the external quality factor versus the tapped position of the feed line. The initial gap width and tapped position can be selected from Fig. 14, according the given coupling

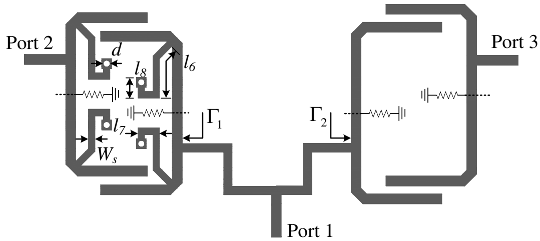


Figure 13. The layout of the diplexer with one path using resistor-loaded resonators and the other path using resonators with resistor and shorted stubs.

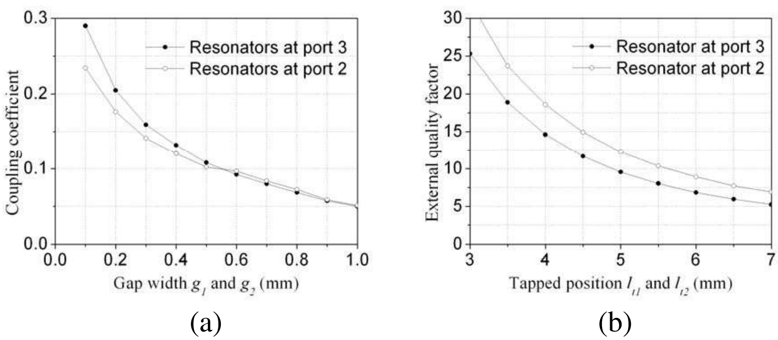


Figure 14. Coupling coefficient and external quality factor of resonators of the diplexer in Fig. 13. (a) Coupling coefficient versus the gap width between the resonators. (b) External quality factor versus the tapped position of the feed line.

coefficient and external quality factor. For the line at the common port of the diplexer, it should also satisfy Equation (3). After optimization, the geometric parameters of the diplexer are as follows: $l_1 = 8.44\,\text{mm}$, $l_2 = 9.54\,\text{mm}$, $l_{t1} = 4.2\,\text{mm}$, $l_{t2} = 4.2\,\text{mm}$, $l_f = 2\,\text{mm}$, $l_{c1} = 5.65\,\text{mm}$, $l_{c2} = 6.75\,\text{mm}$, $g_1 = 0.56\,\text{mm}$, $g_2 = 0.46\,\text{mm}$, $W = 1.2\,\text{mm}$, $W_l = 1.01\,\text{mm}$, $W_h = 1.05\,\text{mm}$, $l_l = 16.5\,\text{mm}$, $l_h = 14.13\,\text{mm}$, $W_s = 0.8\,\text{mm}$, $l_6 = 7.14\,\text{mm}$, $l_7 = 2.6\,\text{mm}$, $l_8 = 2.5\,\text{mm}$, and $d = 0.8\,\text{mm}$.

Figure 15 shows the simulated results with and without loaded resistors of the diplexer in Fig. 13. It can be seen that the higher passband locates at 2.44 GHz, while the passband will be located at 2 GHz if the shorted stubs will not be loaded. This means that the loaded shorted stubs move the center frequency up, so the loaded shorted stub can enlarge the size of the diplexer. By adding the resistors with optimized values $R_1 = 22\,\text{ohm}$, and $R_2 = 82\,\text{ohm}$, the suppression and isolation of the diplexer is greatly improved. The

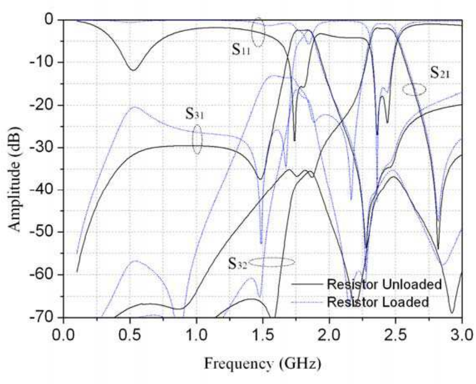


Figure 15. Simulated response of the diplexer in Fig. 13.

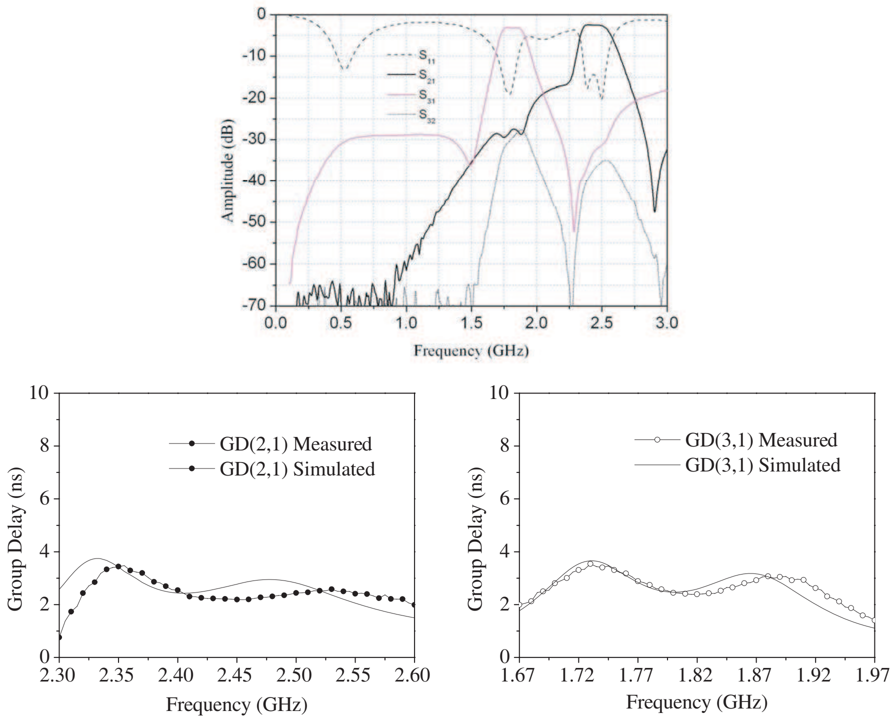


Figure 16. Measured response of the diplexer in Fig. 13.

measured results of the diplexer in Fig. 13, including the group delay, are shown in Fig. 16. It can be seen that the isolation is larger than 33 dB between the two paths. The lower and higher bands are located at 1.81 and 2.44 GHz with their respective insertion loss of 3 and 2.4 dB. Each band of the diplexer has two transmission zeros. The measured results agree well with the simulated ones.

To clear the design procedure of diplexer with loaded elements, it is summarized as follows. First, according to the diplexer specification, we can select the type and parameter of the resonator. Second, according to the bandwidth, center frequency, return loss, out-of-band suppression, etc, the coupling matrixes for the two filters at each path can be gotten by the method of synthesis. Third, the geometric parameters of the two filters can be extracted by EM simulation using Equations (1) and (2). Then, the length of the lines between the common port and two filters can be gotten according Equation (3), and can be optimized in simulation soft. Finally, the resistance should be optimized to remove the harmonics.

6. CONCLUSION

In this paper, open-ended transmission line resonators loaded with resistors, open stubs or shorted stubs have been studied. The characteristics of the resonators have been given. Three demonstrative diplexers were designed, fabricated and measured. The diplexer with resistor-loaded resonator can suppress harmonics near the two passbands. The diplexer with resonators loaded with open stubs can compact the diplexer size and make the frequency ratio between the two passbands controllable. The diplexer with resonators loaded with shorted stubs can enlarge the diplexer size. All the diplexers have transmission zeros besides the passbands, which can improve the selectivity of the diplexers. The experimental results agree well to the theoretical predictions and simulations.

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