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Design of a Dual-Band Bandpass Filter Using a Cross Ring Resonator

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Abstract—In this paper, a new dual-band bandpass filter (BPF) using a cross ring resonator is designed. The cross ring resonator is modified from a typical dual-mode ring resonator and has four parallel coupling gaps (g). The resonant modes of the proposed cross ring resonator is investigated first. It is found that the first mode and the second mode can be tuned individually. The filter performances are simulated by using full-wave simulator IE3D. A filter example having two passbands operated at 2.4/5.2 GHz of wireless local area network (WLAN) applications is described to verify the design concept. The fabricated filter has measured characteristics including average insertion losses of 2.0 dB and 1.8 dB and return losses larger than 22 dB and 10 dB for 2.4/5.2 GHz, respectively. Two transmission zeros with high frequency selectivity of 40 dB and 42 dB are obtained near the first passband at 2.2 GHz and 2.7 GHz, respectively. This design is very simple as compared to other design methods, and the measured results prove the design concept of the proposed structure.

1. INTRODUCTION

Newly, the multi-service mobile wireless communication systems, such as the wireless local area network (WLAN) or 5G communications, have become more and more attractive for commercial products. Bandpass filter (BPF) is an important element in RF front end, and it is required to provide two or more passbands for multi-communications under this progress [1]. There are several methods to design dual-band BPFs, for example, by combining bandpass and bandstop filters [2], coupling of two sets of filters with different passbands [3], and using the stepped impedance resonators (SIRs) [4].

In various types of the resonators, dual mode ring resonator is popular due to its simple structure and design method [5]. However, it is difficult to tune the second resonant mode of the conventional dual mode ring resonator due to the natural harmonics. In [6], a step impedance dual-mode ring resonator is applied to control the second resonant mode for the dual band application. In a previous work [7], two types of dual-mode ring resonators were used to achieve a dual-band BPF. The dual-mode cross-shaped resonator was used for providing the first passband response, and three dual-mode ring resonators were designed for providing the second passband response. In [8], a dual-mode ring resonator with stacked-loop structure was used to obtain dual-band responses. In [9], two dual-mode ring resonators fed by the coplanar-waveguide (CPW) input/output (I/O) ports were designed for dual passbands. In [10], a quadruple-mode square ring loaded resonator (SRLR) was reported to achieve a dual band response. In [11], a quadruple-mode stepped-impedance square ring loaded resonator (SI-SRLR) was used to obtain a dual-band differential BPF. Most of the above methods have complex structures and only tune the second resonant modes. Therefore, for filter designers it is needed to design a high performance dual-band BPF with a simple structure and an easy way.

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In this paper, a simple method is developed to realize a dual-band BPF using a cross ring resonator. The cross ring resonator is modified from a typical dual-mode ring resonator. The resonant modes of the proposed cross ring resonator is discussed. It is investigated that the first mode and the second mode can be controlled individually by resonator structure parameters. The first resonant mode is tuned by the parallel coupling gap, and the second resonant mode is shifted by the impedance of the ring line. The design procedure is described clearly in this paper. A filter sample at 2.4/5.2 GHz is designed for the WLAN. The designed filter is fabricated and measured to prove the design concept. The filter is simple and compact without using any other assisted structures, such as CPW or defected ground structure (DGS).

2. DESIGN PROCEDURE

Figure 1 shows the schematic of the dual band BPF. The filter basically consists of a cross ring resonator coupled to a pair of I/O ports. The A-A′ line is a symmetric line of the filter structure. The proposed cross ring resonator with four parallel coupling gaps (g) is modified from the conventional square ring resonator. The length parameter (d) at the four corners is used to modify the impedance of the ring resonator, and the length parameter (p) at top corner is used to add a perturbation element for the cross ring resonator. The coupling spacing (s) between the cross ring resonator and the I/O ports is used to adjust the external coupling strength. For the design and fabrication, an FR4 substrate having a thickness of 1.6 mm, dielectric constant ε_r of 4.4, and loss tangent of 0.02 is used. The design is achieved by a full-wave EM simulator IE3D [12].

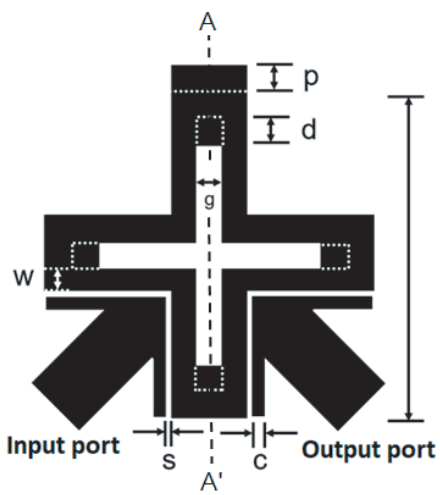

Figure 1. Structure diagram of the designed dual-band BPF using a cross ring resonator.

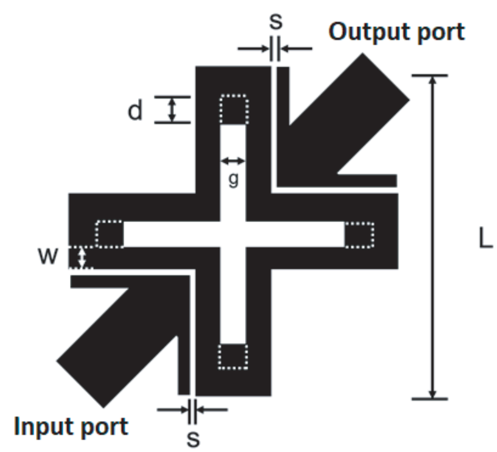

Figure 2. Structure diagram of the proposed cross ring resonator.

Figure 2 shows practical layout of the proposed cross ring resonator. Before designing the dual mode filter, the resonant modes of the proposed cross ring resonator without any perturbation element shall be investigated first. When analyzing the characteristics of resonant modes, weak coupling by using the coupling spacing (s) of 0.4 mm is used to excite the cross ring resonator. Fig. 3 shows simulated resonant mode responses of the proposed cross ring resonator with different side lengths (L), as setting $g = 2$ mm, $d = p = 0$ mm. Namely, the cross ring resonator is a uniform impedance resonator without a perturbation element. The side length (L) is equal to a quarter guided wavelength (λ_g). For designing at the 2.4 GHz, the side length (L) is around 20 mm. As the side lengths (L) are 20 mm, 22 mm, 24 mm, the first resonant modes are at 2.5, 2.2, 2.0 GHz, while the second resonant modes are at 5.0, 4.4, 4.0 GHz, respectively. Namely, the second resonant mode is twice of the first resonant mode and is a natural harmonic mode of the cross ring resonator.

To investigate the effect of the parallel coupling gap (g) on the resonant modes, the four coupling gaps (g) are varied. Fig. 4 shows simulated resonant mode responses of the proposed cross ring resonator

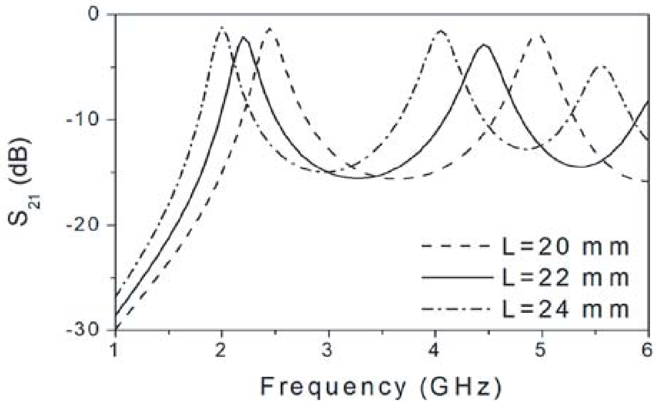

Figure 3. Simulated resonant mode responses of the proposed cross ring resonator with different side length parameters (L). (Setting $g = 2\,\text{mm}$, $d = p = 0\,\text{mm}$).

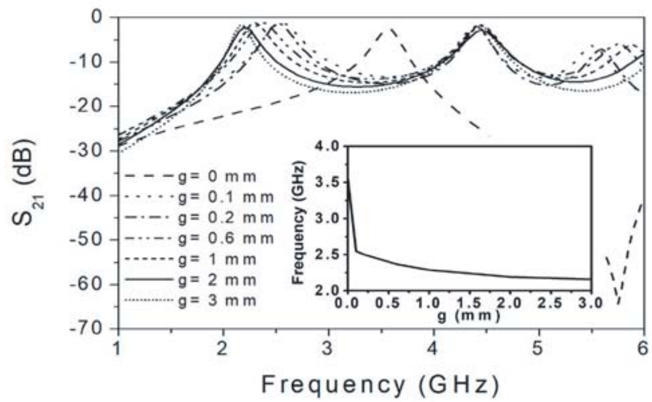

Figure 4. Simulated resonant mode responses of the proposed cross ring resonator with different parallel coupling gaps (g). ($L = 22\,\text{mm}$ and $d = 0\,\text{mm}$)

with different parallel coupling gaps (g) as $L = 22\,\text{mm}$ and $d = 0\,\text{mm}$. As the gap (g) decreases from 3 mm to 0.1 mm, the first resonant mode is shifted to higher frequency from 2.2 GHz to 2.65 GHz, while the second resonant mode is almost kept at 4.4 GHz. Moreover, as the gap (g) is equal to 0, the cross ring resonator becomes a cross resonator in which the side length (L) is the one-half guided wavelength and is not the quarter guided wavelength. The inserted figure shows the frequency of the first resonant mode with different parallel coupling gaps (g). It is thus found that the first resonant mode can be tuned by using the new structural parameter, gap (g), of the proposed cross ring resonator.

To further control the second resonant mode, the length parameter (d) at the four corners is used to modify the impedance of the ring resonator. Fig. 5(a) shows simulated resonant mode responses of the proposed cross ring resonator with different length parameters (d) as $L = 22\,\text{mm}$ and $g = 0.2\,\text{mm}$. It is found when increasing the length parameter (d) from 0.4 mm, 0.8 mm, and 1.2 mm, the second resonant mode is moved to higher frequency from 4.6 GHz, 4.8 GHz, and 5.0 GHz, respectively, while the first resonant mode is almost kept at 2.6 GHz. Fig. 6 shows simulated resonant mode responses of the proposed cross ring resonator with different length parameters (d) as $L = 22\,\text{mm}$ and $g = 2\,\text{mm}$. It is also found that as increasing the line width (d) from 0.4 mm, 0.8 mm, and 1.2 mm, the second resonant mode is moved to higher frequency from 4.8 GHz, 5.0 GHz, and 5.2 GHz, respectively, while the first band is almost kept at 2.4 GHz.

It is thus found that the second resonant mode can be tuned by using another structural parameter, length (d), of the proposed cross ring resonator since the line impedance of the ring resonator is varied. Moreover, it is possible to shift different resonant modes to form a dual-band performance even when

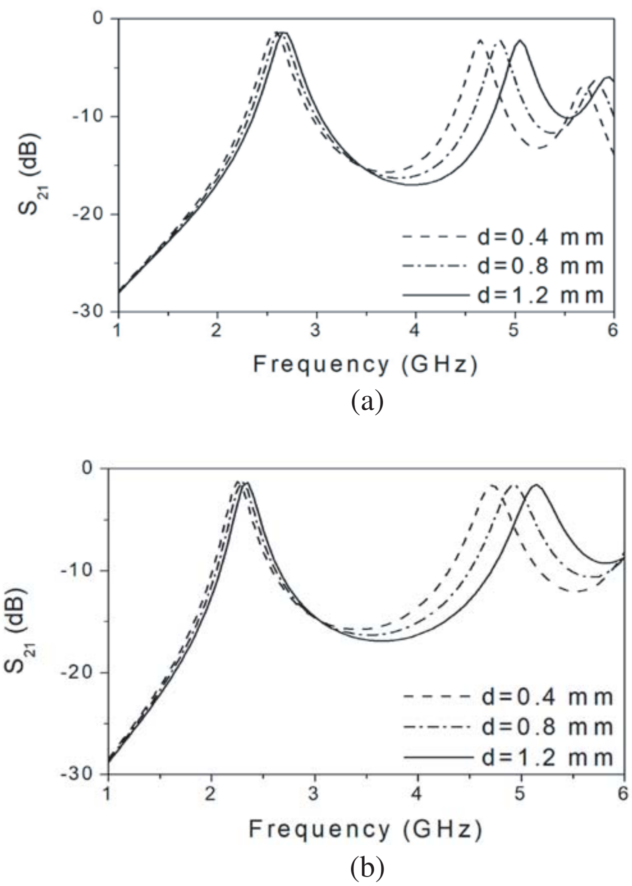

Figure 5. Simulated resonant mode responses of the proposed cross ring resonator with different length parameters (d) as (a) $g = 0.2\,\text{mm}$ and (b) $g = 2\,\text{mm}$. ($L = 22\,\text{mm}$).

these two bands are very close, by using the small gap (g) and small length (d). Thus, the gap ($g = 2\,\text{mm}$) and length ($d = 1.2\,\text{mm}$) can be explicitly determined for obtaining the dual-band response at 2.4/5.2 GHz of WLAN communication.

When forming the filter, I/O ports shall be moved to orthogonal direction, and a perturbation element is needed. By adding an extra section with different lengths (p) to be the perturbation element, two degenerate modes of the proposed cross ring resonator can be coupled, thus to form a filter passband response. The filter performances are obtained by carefully arranging the coupling of the two resonant modes. Typically, the perturbation element is used to tune to obtain the desired bandwidth having suitable coupling coefficients.

Figure 6 shows the filter response of the designed filter using the proposed cross ring resonator with different perturbation lengths (p) from 0.9 mm, 1.8 mm to 2.7 mm as $L = 22\,\text{mm}$, $g = 2\,\text{mm}$, and $d = 0.8\,\text{mm}$. It is found that as length (p) is small as 0.9 mm, the bandwidth of the first band at 2.4 GHz is not enough, and as length (p) is large as 2.7 mm, two resonant modes are slightly split, and the bandwidth and insertion loss of the first band at 2.4 GHz is increased. After optimum EM simulation as length (p) is 1.8 mm, the desired first band at 2.4 GHz and the desired second band at 5.2 GHz are formed. As shown in Fig. 6, the perturbation length (p) mainly affects the bandwidth and insertion loss of the first passband, but does not affect the second passband too much. Moreover, it is obviously observed that the two transmission zeros are provided near the first passband. To explain the cause of the two transmission zeros, the equivalent circuits of the even and odd modes for the proposed cross ring filter shall be used. The even-mode input impedances Z_{even} and the odd-mode input impedances Z_{odd} of the half-circuits corresponding to the A-A′ symmetric line shall be obtained first. Then the S-parameters of transmission (S_{21}) and reflection (S_{11}) for the proposed circuit are obtained based on the even-mode input impedances Z_{even} and the odd-mode input impedances Z_{odd}. It is known that the cause

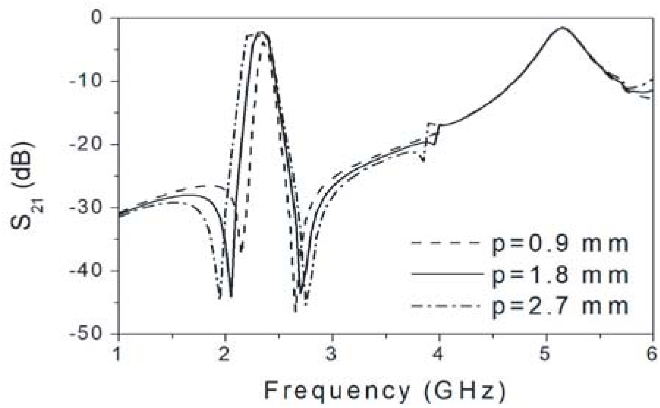

Figure 6. Simulated filter response of the designed filter using the proposed cross ring resonator with different perturbation lengths (p). ($L = 22\,\text{mm}$, $g = 2\,\text{mm}$, $d = 1.2\,\text{mm}$).

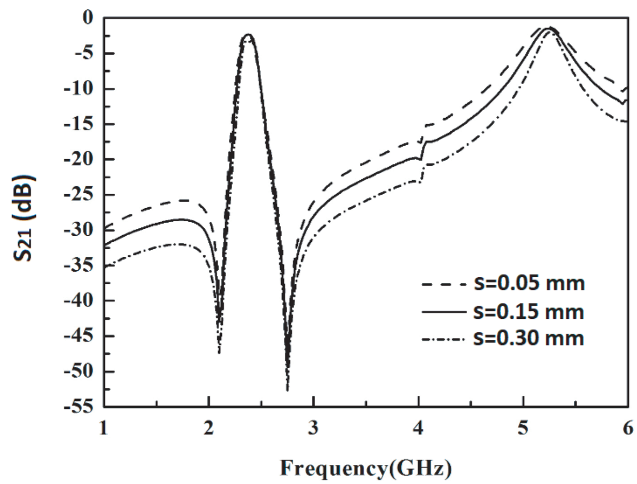

Figure 7. Simulated filter response of the designed filter using the proposed cross ring resonator with different coupling spacings (s). ($L = 22\,\text{mm}$, $g = 2\,\text{mm}$, $d = 1.2\,\text{mm}$, $p = 1.8\,\text{mm}$).

of the transmission zeros can be obtained by setting transmission $S_{21} = 0$ [1]. Therefore, the parameters for obtaining the transmission $S_{21} = 0$ are the parameters to control the appearance of the transmission zero. Since the main difference between Z_{even} and Z_{odd} is the circuit of the perturbation element [1, 5], the parameter for obtaining the transmission $S_{21} = 0$ mainly results from the perturbation length (p). It is clearly observed that the transmission zeros are varied with different perturbation lengths (p). As shown in Fig. 6, the transmission zeros will shift to lower frequencies when increasing the perturbation length (p), and the transmission zeros will shift to higher frequencies when reducing the perturbation length (p).

Theoretically, the bandwidth of the passband is varied by adjusting the coupling strength between the two resonant modes in each band. Moreover, the bandwidths of the two passbands are influenced by the position of the transmission zeros. Therefore, in this study, the coupling between the two resonant modes in each band can be tuned mainly by the perturbation length (p) or the coupling spacing (s) between the cross ring resonator and I/O ports.

Figure 7 shows the simulated filter response of the designed filter using the proposed cross ring resonator with different coupling spacings (s). Typically, increasing the coupling spacing (s) would reduce the external coupling strength, and reducing the coupling spacing (s) would increase the external coupling strength. As shown in Fig. 7, the coupling spacing (s) mainly affects the bandwidth and insertion loss of the second passband, but does not affect the first passband too much. As the coupling spacing (s) is larger than 0.15 mm, the external coupling strength is not enough. The bandwidth of the passband would decrease, and the insertion loss of the passband would increase. As the coupling spacing (s) is smaller than 0.15 mm, the external coupling strength is enough. The bandwidth of the passband would slightly increase, and the insertion loss of the passband would decrease. Since the limitation of width resolution of our fabrication machine is 0.15 mm, the coupling spacing is chosen as 0.15 mm to have the desired passband performances. The simulated results have average insertion losses of 1.9 dB and 1.8 dB, and fractional bandwidth (FBW) ratios of 5% and 7% for 2.4 GHz and 5.2 GHz, respectively.

The design procedure for the dual band BPF using the proposed cross ring resonator is summarized as follows:

1. determining the side length (L) of the proposed cross ring resonator for the frequency of the first resonant mode;
2. determining the coupling gap (g) of the proposed cross ring resonator for slight tuning the frequency of the first resonant mode;
3. determining the parameter length (d) of the proposed cross ring resonator for achieving the frequency of the second resonant mode;
4. moving the I/O ports at the orthogonal direction;
5. determining the perturbation lengths (p) of the added perturbation element for achieving the desired filter response of the first passband; and
6. determining the coupling spacing (s) of the proposed cross ring resonator for achieving the desired filter response of the second passband.

3. FABRICATION AND MEASURE RESULTS

Under the design guide discussed above, the structural parameters of the filter example: $L = 22$ mm, $g = 2$ mm, $d = 1.2$ mm, $p = 1.8$ mm and $s = 0.15$ mm are obtained. Fig. 8 shows (a) a photograph and

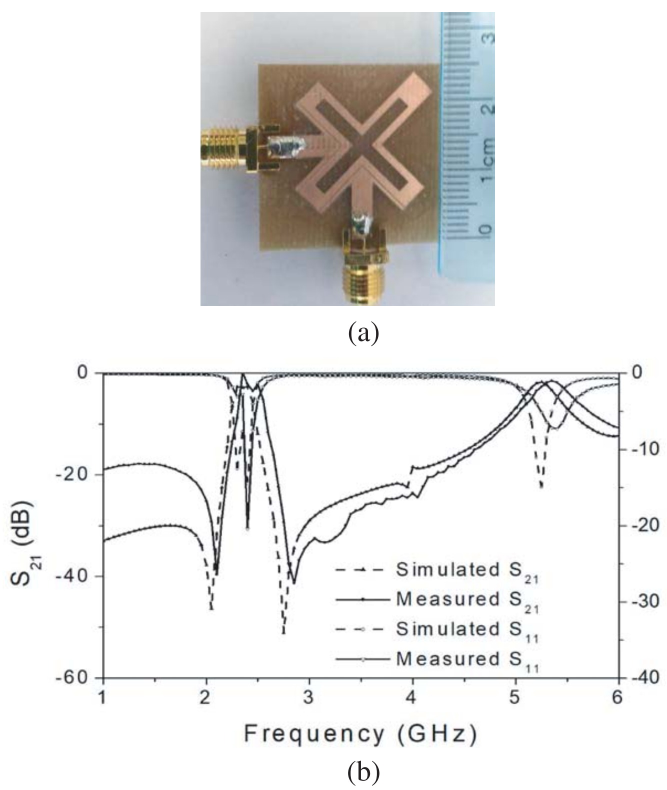

Figure 8. (a) The photograph and (b) the comparison of the simulated and measured frequency responses of the fabricated dual-band BPF.

(b) the comparison of simulated and measured frequency responses of the fabricated dual-band BPF. The filter size is 22 mm × 22 mm, as shown in Fig. 8(a). The fabricated filter is measured by using an HP8722ES Network Analyzer. The measured results show average insertion losses of 2.0 dB and 1.8 dB and return losses larger than 22 dB and 10 dB for 2.4 and 5.2 GHz, respectively. Two transmission zeros near the first passband at 2.2 GHz and 2.7 GHz provide high frequency selectivity of 40 dB and 42 dB, respectively. The slight variances between the simulated and measured results are caused by the fabrication error due to curving machine. However, this filter structure is simple, and the design method still shows a very simple procedure compared to other design methods. Since the proposed cross ring resonator is modified and compressed by a conventional square ring resonator, the device also shows a compact property. The measured results verify the design concept of the proposed structure.

4. CONCLUSIONS

In this paper, we have designed and implemented a compact dual-band BPF at 2.4 and 5.2 GHz using a cross ring resonator. The cross ring resonator is modified from a typical dual-mode ring resonator. It is investigated that the first resonant mode can be tuned by the parallel coupling gap, and the second resonant mode is shifted by the impedance of the ring line. The design procedure is described clearly in this paper. A filter sample at 2.4/5.2 GHz is designed for the WLAN. The designed filter is fabricated and then measured, and the measured results match the simulated ones, thus verify the design concept. The filter design is easy, and the filter structure is simple, since other assisted structures, such as CPW or DGS, are not needed.

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