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A COMPACT DUAL-MODE RESONATOR WITH SQUARE LOOPS AND ITS BANDPASS FILTER APPLICATIONS

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Abstract—In order to realize bandpass filter with Chebyshev and elliptic function responses using a single resonator only, a dual-mode square resonant structure is proposed. Four small square loops are added into a large loop. One of small loops is defined a perturbation element, other small ones are references. By changing the thickness of the perturbation element with respect to that of a reference element, the resonator can produce a capacitive or inductive coupling between two degenerate modes. The capacitive coupling can acquire an elliptic function characteristic since it can create the transmission zeros on both the lower and upper sides of the pass band, while the inductive coupling cancels them which exhibit a Chebyshev characteristic. Therefore, both Chebyshev and elliptic function responses can be obtained for the filter. The proposed device is with a wider stopband and more compact in size. Experiment results have been verified this design.

1. INTRODUCTION

Bandpass filter (BPF) is a circuit element, which plays an important role in wireless communication systems. There are many advantages of high-quality and narrow-band in requiring microwave BPF. Due to good selectivity and flatness in the passband, the BPF with Chebyshev response has been widely used [1]. It can be designed by using a single-mode or dual-mode resonator [2], and microstrip structure is always used [3]. In general, a dual-mode microstrip resonator is more attractive because of very good properties, such as small in size, light weightiness, and lossless energy in transmission. In 1972, a microstrip

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dual-mode resonator is applied to designing the BPF with Chebyshev responses by Wolff [4]. Since then, a triangular ring, circular ring, and hexagonal loop resonators were proposed by other researchers [5–8]. To produce two degenerate modes, some small perturbations are introduced to the resonator which coupled to each other [9]. The nature of the coupling is mainly determined by both shape and size of these perturbation elements added into the corner-cut within the resonator. A perturbation in the corner-cut can produce an inductive effect, which leads to a Chebyshev characteristic. Therefore, a BPF, based on this resonator, can obtain the Chebyshev responses.

On the other hand, the BPF with elliptic function response is also used widely because of advantages of sharp frequency characteristic and good out-of-band performance. The form of BPF can be designed by using dual-mode resonator with different structures. For example, Gorur proposed an open-loop [10] to realize its function. Weng et al. did a Sierpinski fractal-based resonator [11]. Using a dual-mode double-square-ring resonator, Liu et al. developed a quad-band elliptic function BPF [12]. Almost the same time, a dual-mode dual-band ring resonator was used an elliptic function BPF design [13]. Different from the Chebyshev BPFs usually using the corner cuts as perturbations, the elliptic function BPFs discussed above always use the patch as perturbation since they produce a capacitive coupling between the two degenerate modes [14].

However, those dual-mode resonators above can produce only a single type of coupling between degenerate modes, either capacitive or inductive. It would achieve one type of frequency response only, which is either elliptic function or Chebyshev's. When better properties of the BPF are required, both Chebyshev and elliptic function characteristics must be considered together. Nevertheless, it is not convenient to design one BPF with both of these characteristics using a single resonator of the dual-mode above, and the total size of the filter will be increased when some perturbations employed.

In this paper, a more compact dual-mode resonator consisted of square loops is proposed. The perturbation is generated by a small loop at a symmetrical location $135°$ apart from the input/output port. By increasing or decreasing the thickness of the loop, the resonator exhibits two different coupling characteristics between the degenerate modes, and both Chebyshev and elliptic function responses can be achieved simply. At the same time, the size of the filter has not been enlarged. Compared to the conventional dual-mode microstrip BPFs operated around the same frequencies, the proposed BPF has a wider stopband and more compact structure.

2. DUAL-MODE RESONATOR WITH LOADED SQUARE LOOPS

A conventional dual-mode square loop resonator, as shown in Figure 1, can produce only a single type of coupling between degenerate modes. When it is with a patch perturbation, as shown in Figure 1(a), produces a capacitive coupling. While one with a corner-cut perturbation, as shown in Figure 1(b), leads to an inductive coupling. To realize both couplings, four small square loops have been added into the conventional square loop resonator. Figure 2 is shown to us this proposed structure. It is made up of a large square loop and four small square loops named A, B, C and Q, which are connected by identical arms within the loop's corners. All of small loops have the same size of outline, but not the same thicknesses. Loop Q is as the

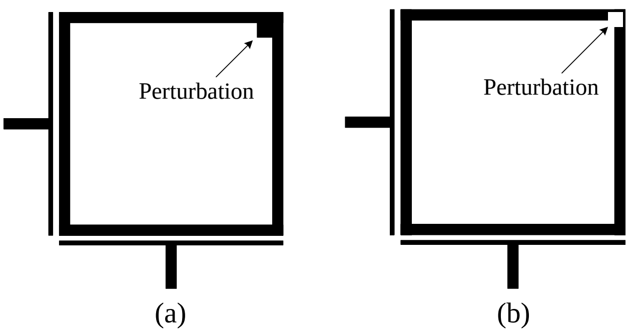

Figure 1. Conventional dual-mode loop resonator with perturbation deficiency at the corner, (a) a patch produces capacitive coupling, and (b) a corner cut does the inductive coupling.

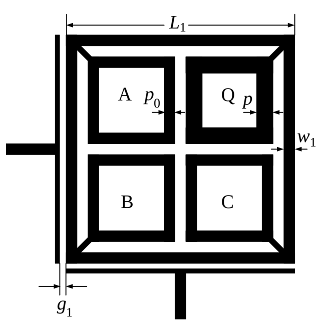

Figure 2. Proposed dual-mode resonator with four small square loops, named A, B, C and Q.

perturbation element, located at the symmetrical location 135° apart from both the input and output ports of the resonator. Three identical square loops A, B and C are called the reference elements with the same thickness of p_0. To distinguish Q from others, perturbation is created by changing the Q's thickness p. Comparing to reference elements, the perturbation occurs to a capacitive and inductive coupling between the degenerate modes for$p > p_0$ and $p < p_0$, respectively.

To excite the proposed dual-mode resonator, the input and output ports are weakly coupled to the resonator and the gap between the feed line and the resonator is chosen to be relatively wide, as shown in Figure 2. By changing the p, the modes splitting can be achieved. The two splitting modes are called even mode and odd mode respectively.

For convenience, $\Delta p = p - p_0$ is defined as the perturbation size. In order to investigate the characteristic of the proposed resonator, a full-wave EM simulator has been used to simulate the resonator with different perturbation size. The resonator is constructed on a substrate with a relative dielectric constant 6.15 and thickness of 0.64 mm. Figure 3 shows the simulated frequency responses of the proposed resonator for different perturbation size Δp. As can be seen, the proposed resonator produces a Chebyshev characteristic for the size $\Delta p < 0$ mm. However, with a size $\Delta p > 0$ mm, the proposed resonator exhibits an elliptic function characteristic since two additional transmission zeros located on either side of the passband are generated. On the other hand, when Δp is increased or decreased from 0 mm, two degenerate modes split. The two resonant peaks shown in Figure 3 correspond to the resonant frequencies of even mode and odd mode. In all the cases, only one mode frequency called even mode is affected, the other one that is called odd mode is almost unchanged. The positive value of Δp results in the even mode being shifted to a lower frequency, while the negative value of Δp shifts the even mode to a higher frequency. And the larger the perturbation size Δp, the lower the resonant frequency of even mode, whether the value of Δp is positive or negative. This is in accordance with that is shown in Figure 4. The coupling coefficient between the two degenerate modes is also plotted in Figure 4. The coupling coefficient k is computed using the relationship between the split in the resonance frequency of the two modes and coupling described by [14].

$$k = \frac{f_o^2 - f_e^2}{f_o^2 + f_e^2}$$

where f_e and f_o are the resonance frequencies of even mode and odd mode, respectively. As the perturbation size Δp increases, the value of coupling coefficient is enlarged, as observed in Figure 4, and the negative value of coupling coefficient means that the perturbation

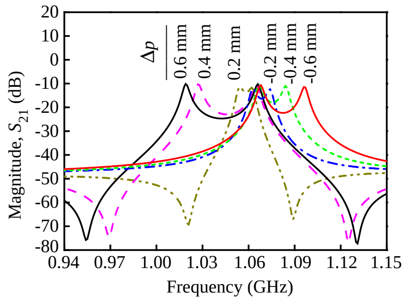

Figure 3. Simulated frequency responses of proposed resonator for different perturbation size Δp, where the resonator dimensions are $L_1 = 21\,\text{mm}$, $w_1 = 1\,\text{mm}$, $g_1 = 0.5\,\text{mm}$, and $p_0 = 1\,\text{mm}$.

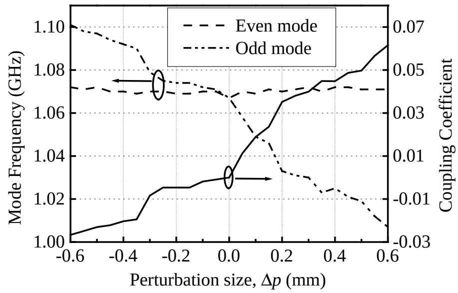

Figure 4. Simulated coupling coefficient and two resonance frequencies of degenerate modes against perturbation size Δp, where the resonator dimensions are the same as those were in Figure 3.

element behaves as an inductive coupling element, while the positive value implies that the perturbation element acts as a capacitive coupling element. This is in agreement with that a dual-mode resonator with an inductive coupling between degenerate modes can produce a Chebyshev characteristic, whereas one with a capacitive coupling exhibits an elliptic function characteristic. Therefore, the proposed dual-mode resonator can acquire both elliptic function and Chebyshev characteristics. Moreover, the guided wavelength of the proposed dual-mode resonator at the fundamental resonance frequency is $\lambda_g = (L_1 + 2 \times L_2) \times 4$, with an increase of $(2 \times L_2) \times 4$ as compared with the conventional dual-mode loop resonators shown in Figure 1. So the proposed resonator has a much lower resonance frequency than the conventional ones with the same circuit size.

3. DUAL-MODE BANDPASS FILTER DESIGN

Based on the two different coupling characteristics between the degenerate modes of the resonator, a dual-mode BPF which can achieve both Chebyshev and elliptic function responses is designed. The configuration of the designed dual-mode BPF is depicted in Figure 5. By changing the thickness of the perturbation element, the BPF can acquire elliptic function or Chebyshev responses. Here the BPF with Chebyshev response ($\Delta p < 0$) is taken as an example to discuss the filter's design. The proposed BPF shown in Figure 5 consists of a dual-mode resonator, presented above, and an interdigital coupling structure which provides a cross coupling between the feed

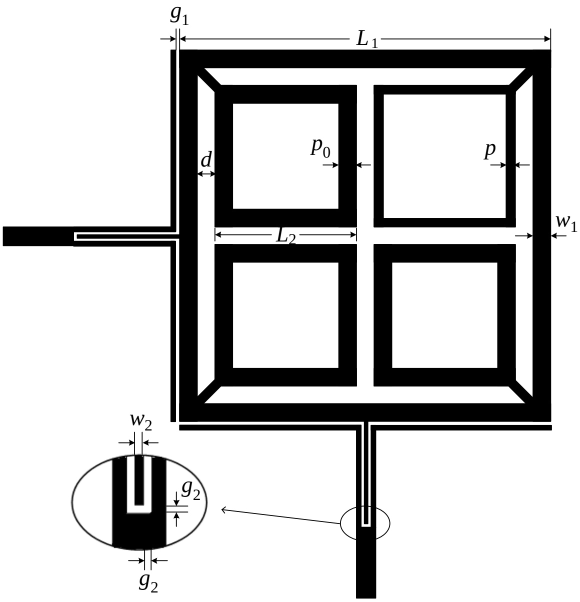

Figure 5. Configuration of the proposed dual-mode microstrip BPF.

line and the resonator. The dimensions w_2 and g_2 of the interdigital coupling structure should be relatively small to provide relatively strong coupling and establish the passband of the filter.

To check this design, some dimensions of the structure have to be discussed. The size of small loops L_2, distance between large loop and small loops, d, and gap width between feeding structure and the resonator, g_1 may influence the properties of the filter.

By using the Ansoft HFSS software, the changing of L_2 is simulated first. As the size of L_2 increases, the center frequency of BPF decreases, and the insertion loss of the passband reduces. But when the value of L_2 is greater than 8 mm, the insertion loss of the stopband is increased. This can be clearly observed in Figure 6.

Figure 7 illustrates that when d is varied from 1 mm to 0.4 mm, the center frequency of BPF can be shifted to a higher one. Nevertheless, it is changed slowly.

Gap width g_1 is related to coupling coefficient between the feeding structure and the circuit. When g_1 is increased from 0.1 mm to 0.4 mm, the insertion loss of the passband become greater, and the passband changed to a narrower one. The simulated results are depicted in Figure 8. It can be viewed clearly that the coupling between the feeding structure and the resonator is deteriorative when g_1 is increased. After simulating with the HFSS software, we obtain optimized dimensions, which are given in Table 1.

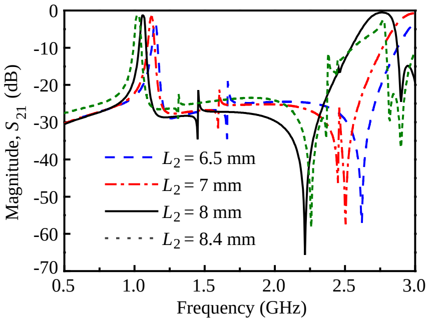

Figure 6. Simulated frequency responses of the proposed dual-mode BPF for different L_2.

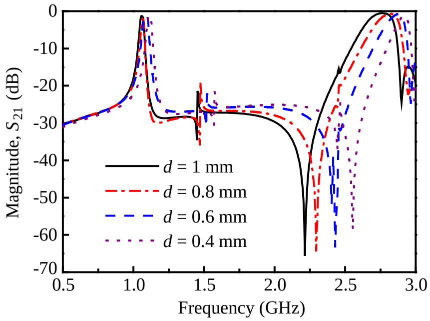

Figure 7. Simulated frequency responses of the proposed dual-mode BPF for different d.

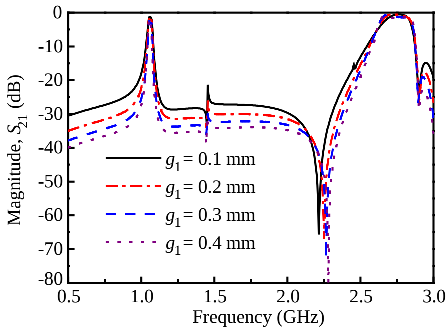

Figure 8. Simulated frequency responses of the proposed dual-mode BPF for different g_1.

Table 1. Dimensions of the designed dual-mode BPF with Chebyshev characteristic (unit: mm).

Element	L_1	L_2	d	g_1	g_2	w_1	w_2	p_0	p
value	21	8	1	0.1	0.1	1	0.2	1	0.6

4. MEASUREMENTS

To verify the design and clearly observe the two different characteristics of the proposed BPF, the dual-mode BPFs with Chebyshev response and elliptic function response are fabricated respectively. Both the two filters are constructed on a TICONIC RF60A substrate with relative dielectric constant $\varepsilon_r = 6.15$ and thickness $t = 0.64$ mm. The dimensions of the two filters are the same as those are shown in Table 1, except that the value of p is changed to 1.4 mm for the filter with elliptic function response. In other words, the two filters have the same dimensions except the perturbation size Δp, which is -0.4 mm for the Chebyshev BPF, and 0.4 mm for the elliptic function BPF, respectively. Photographs of the samples are shown in Figures 9 and 11. To verify the design, we use the AV3620 vector network analyzer in our laboratory to measure the filters. Experiment results are shown in Figures 10 and 12, denoted with dotted lines.

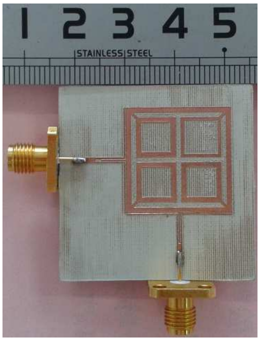

Figure 9. Photograph of the fabricated dual-mode bandpass filter with Chebyshev response.

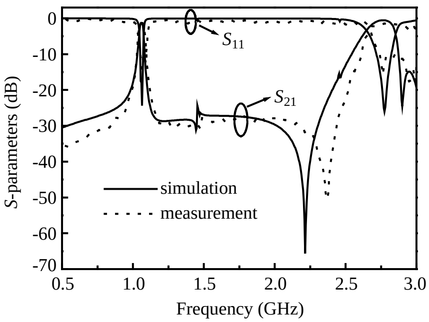

Figure 10. Experiment and simulation results for the S_{11} and S_{21} of the bandpass filter with Chebyshev response.

From Figure 10, the measured passband of the filter with Chebyshev response has a center frequency of 1.06 GHz, and a 3-dB fractional bandwidth of 3.1%. The maximum insertion loss S_{21} and minimum return loss S_{11} are -1.3 dB and -14.1 dB, respectively. The fabricated filter with elliptic response centered at 1.05 GHz, has a maximum S_{21} of -1.1 dB, a minimum S_{11} of -15.4 dB, a 3-dB fractional bandwidth of 3.2%, and a pair of transmission zeros observed near the two-side skirt of pass band at 0.97 GHz and 1.12 GHz, both with attenuations exceeds 45 dB, as shown in Figure 12. It is demonstrated that the transmission zeros can be created or eliminated without sacrificing the passband response by changing the perturbation size. It can also be observed clearly from Figures 10 and 12 that both the two filters have considerably wide stop bands, one is from 1.12 GHz to 2.51 GHz for the Chebyshev BPF, and the other for the elliptic function BPF is from 1.10 GHz to 2.53 GHz. Comparing with measurements, simulated results are given in the same figure, denoted with solid lines. The measurement results are in agreement with

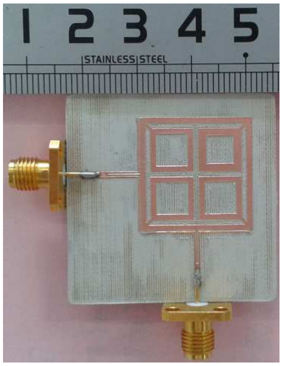

Figure 11. Photograph of the fabricated dual-mode bandpass filter with elliptic function response.

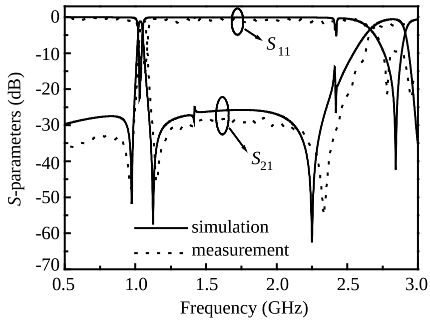

Figure 12. Experiment and simulation results for theS_{11} and S_{21} of the bandpass filter with elliptic function response.

the simulation results on the whole, only slight shift in frequency between measurement and simulation exists due to the tolerances of the fabrication. By the way, the size of the fabricated filters is only $26 \times 26\,\text{mm}^2$, which amounts to about $0.19 \times 0.19\lambda_g^2$. While the size of the filters based on conventional dual-mode loop resonators shown in Figure 1 with the same center frequency is about $0.26 \times 0.26\lambda_g^2$. Compared to the conventional microstrip dual-mode BPF operated around the same frequencies, the proposed filter has a more compact structure with the size reduction of about 27%.

5. CONCLUSION

A dual-mode resonator consisted of one large square loop loaded with four small square loops has been proposed. One of these small square loops which located at 135° from the axes of coupling to the resonator was used as a perturbation element, others were used as reference elements. By changing the thickness of the perturbation element, the resonator can acquire both Chebyshev and elliptic characteristics. BPFs based on the proposed resonator with Chebyshev and elliptic responses are designed and fabricated, and the measurements have been shown in good agreement with the simulation. Compared to the conventional dual-mode microstrip bandpass filter, the proposed filter has a more compact structure and a relatively wide stopband, and facilitates the practical realization of both Chebyshev and elliptic function filters using only a single dual-mode resonator.

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