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Overcoupled Response Improvement with Miniaturizing of Rectangular Dual-Mode Filter by Slow-Wave Modified Resonator

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Abstract: Accompanied with an overcoupled response, a conventional dual-mode rectangular resonator bandpass filter (BPF) inherently has a hump response with a rather wide 3 dB bandwidth and a high insertion loss in the middle of the passband. To improve such a drawback, a miniature dual-mode BPF with a slow-wave modified rectangular resonator is presented in this study. Through a periodic U-shaped inward folding of the resonator, a slow-wave propagation is resulted for two degenerate modes in the guided-wave paths. Having an inter-digital like I/O feed lines for an optimal signal coupling and a perturbation element at the topmost of the slow-wave resonator, the characteristic of fundamental frequency is significantly improved to have sharper rejection skirts with introducing transmission zeros and a single peak response within the bandpass region instead of double peaks response. Due to an utmost use of interior space with an equal amount of 5 inward folding at both sides of the resonator, size reduction could be realized to 41 and 57% against the conventional rectangular ring and square ring, respectively. Besides, the feed lines are also kept along a straight line to favor for a flexible accommodation with the microwave networks.

Key words: Bandpass filter, dual-mode, miniature, overcoupled response, slow-wave resonator

INTRODUCTION

Attractive features of low radiation loss, low fabrication cost and narrow passband bandwidth, the microstrip dual-mode bandpass filters (BPFs) first proposed by Wolff (1972) have been widely used in modern microwave communications. An impressive characteristic of a dual-mode BPF is its compact size because each dual-mode resonator could be used as a doubly tuned resonator circuit, which thus reduces the number of resonators by half required for a given degree of filter (Hong and Lancaster, 2001). On the other hand, a major drawback of using a ring resonator is its curvature, a square loop instead of circular ring had then been proposed for applying in a dual-mode bandpass filter (Hong and Lancaster, 1995a, b). Because of having a 4 fold symmetry property, a square loop resonator provides an easy allocation of orthogonal feed lines at the rim of the resonator. Figure 1 shows such a typical dual-mode BPF with a small perturbation element. When the mean parameters l of this square loop resonator is designed with an integral multiple of a guided wavelength λ_g, the resonance is resulted. Such a relation could be simply expressed as:

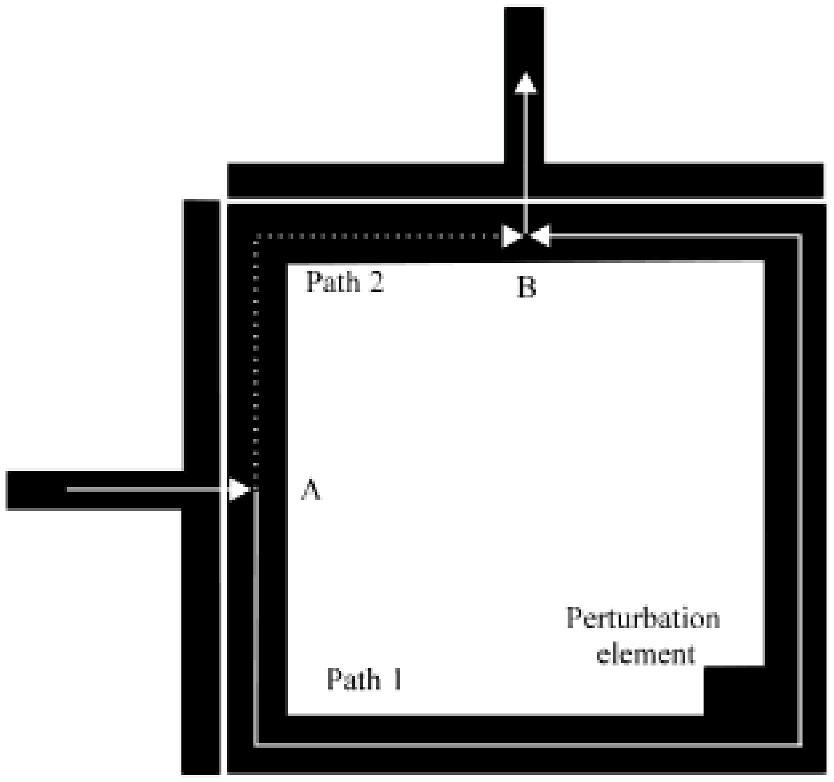

Fig. 1: A conventional dual-mode bandpass filter with a square loop resonator fed by a pair of orthogonal feed lines

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$$l = 4d = n\lambda_g \quad \text{for } n = 1,2,3, ... \qquad (1)$$

where, l is the mean perimeter of the closed loop resonator, d is the mean width of the square resonator, λ_g is the guided wavelength and n is the mode number.

Also, the frequency modes are given as (Chang, 2004):

$$f_0 = \frac{nc}{4d\sqrt{\varepsilon_{eff}}} \quad \text{for } n = 1,2,3, ... \qquad (2)$$

where, c is the light speed and ε_{eff} is the substrate permittivity.

By feeding a microwave signal into the filter, the input signal through resonating mechanism is coupled to the square loop resonator. The coupling signal, simply assumed to be concentrated at position A, is first splitted into two components and then separately transmitted along two different paths (named as path 1 and 2, respectively) to position B. Finally these components are recombined as an output signal of the filter. Therefore, the phase shift of an output signal induced by these guided-wave paths corresponding to the fundamental frequency response is resulted as follows:

$$(270° - 90°) + \Delta\theta = 180° \ \ \Delta\theta \qquad (3)$$

where, $\Delta\theta$ is the nonzero phase shift caused by the perturbation patch. Without a perturbation element involved, $\Delta\theta = 0$, this directly causes the degenerate modes to have an out of phase recombination that greatly depresses the fundamental response.

The above discussion are clearly indicated in Fig. 2. Since, the dual mode is regarded as composing of two degenerate modes or splitting resonant frequencies that may be simply excited by perturbating, two transmission zeros close to the passband are resulted. Therefore, a narrow passband with prominent rejection skirts is a major merit of a dual-mode bandpass filter. Nevertheless, an orthogonal arrangement of input and output (I/O) feed lines increases a certain extent of difficulty in accommodating with the microwave networks.

While evaluating the applications in lower microwave frequency bands, the conventional dual-mode BPF with a microstrip loop resonator still occupies fairly large circuit areas to be integrated in the systems where the size reduction is an important factor, such as satellite and mobile communication systems. Different pattern designs focused on miniaturizing dual-mode BPFs are concerned by folding the resonator (Awida *et al*., 2005; Hong and Lancaster, 1995, 1997), or loading additional elements within the resonator (Gorur, 2002; Hong *et al*., 2007; Lin *et al*., 2007). The main purpose of these miniaturizing techniques is to achieve a maximum use of an interior space of the resonator. Because of having a 4 fold symmetry property, the square loop resonator provides an easy allocation of I/O feed lines at the rim of the resonator in an orthogonal arrangement. Under a fix length of perimeter for a closed loop resonator, although a rectangular loop has a 2 fold symmetry property which is smaller than that of a square loop resonator, it occupies a less area as compared with a square loop. Nevertheless, having been proved in the following part of this study, an overcoupled response (Kuo *et al*., 1999; Hseih and Chang, 2002, 2003) inherently causes a rectangular dual-mode BPF to have a hump response with a rather wide 3 dB bandwidth and a high insertion loss in the middle of the passband. To improve such a drawback, a dual-mode BFP filter with a slow-wave modified resonator is proposed in this study. Besides, the size of the proposed filter could be further reduced as compared with a conventional dual-mode BPF. Also, the I/O ports are kept with a 180° symmetrical separation along a horizontal line to offer a more flexible accommodation with the microwave networks.

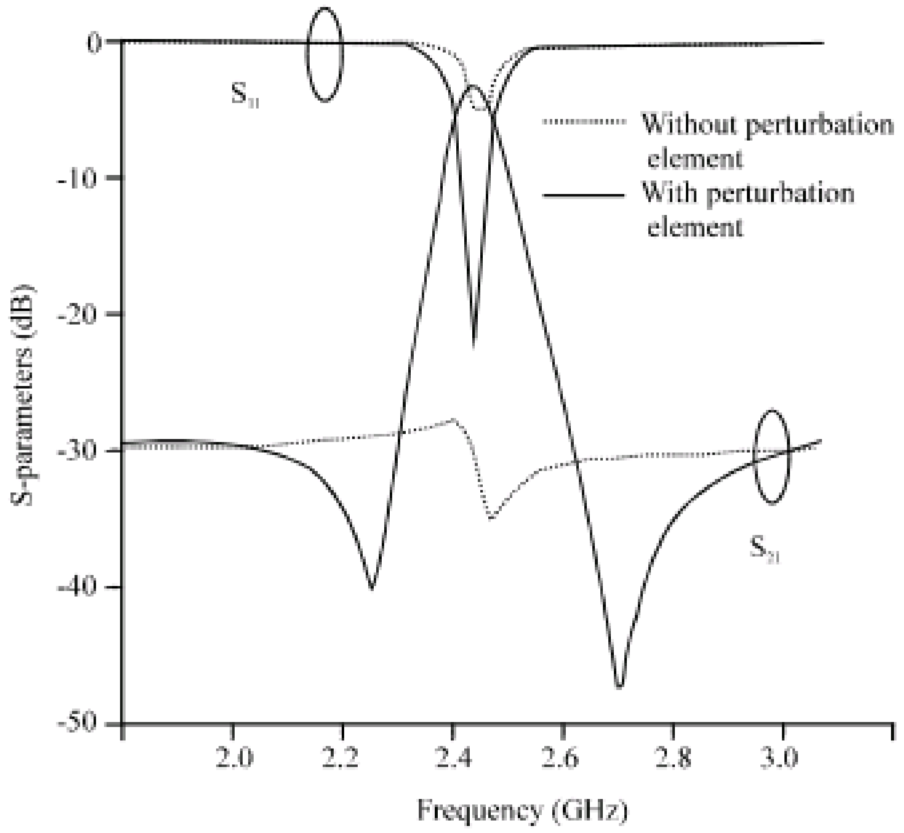

Fig. 2: Comparisons of the frequency responses with and without a perturbation element of the filter shown in Fig. 1

MATERIALS AND METHODS

The filters used in this study were all fabricated on an RT/Duroid substrate having a thickness of 1.27 mm and a relative dielectric constant of 5.15. Additionally, the full-wave simulator IE3D (IE3D User's Manual, Release 11, Feb., 2005) was used to obtain the final physical dimensions of the proposed filter. To fabricate the filter, the substrate was first decreased by acetone and then fully cleaned by alcohol. Then, the substrate was fixed on the PCB holding platform of a programmable engraving machine. By properly adjusting the engraving parameters, the pattern of the filter was finally obtained. The copper scrap left on the substrate's surface was removed by compressed nitrogen gas. After cutting the fabricated filter from the substrate, the device was bonded by SMA male plugs as for directly conducting by an Agilent 8722 ES network analyzer to measure the experimental results.

RESULTS

Drawback of a conventional rectangular loop resonator BPF: Due to the I/O feed lines with an average length approximately equal to, $\lambda_0/4$, λ_0 being the guided wavelength at fundamental response, it is not easy to have an orthogonal arrangement of I/O feed lines for a rectangular resonator because a limit space near the width provided. Figure 3 shows the simulated fundamental frequency response of a conventional rectangular resonator BPF and the corresponding inset shows the filter configuration. The simulated 3 dB fractional bandwidth is approximately 4.62% at the center frequency 2.45 GHz, however, the skirt response is not sharp enough. To analyze the positional effect of I/O feed lines on the fundamental response, they are vertically and symmetrically shifted downwards from the center. For feed lines shifting more away from the center, the filter has sharper rejection skirts with transmission zeros introduced at both sides of the bandpass region. However, no matter where the feed lines are an overcoupled response by showing obvious double peaks within the bandpass region is actually occurred and the results are just similarly depicted in Fig. 4. A conventional rectangular resonator BPF could behave like a dual-mode BPF by shifting the feed lines away from the central position, whereas an overcoupled bandpass response becomes an inherent drawback to make the filter have a rather wide 3 dB bandwidth.

Dual-mode BPF with slow-wave modified rectangular resonator: To overcome such an overcoupled bandpass response, one could use I/O feed lines with one-sided coupling arm (Jenq *et al*., 2009) or double-sided coupling arms having unequal arm lengths and then suitably relocate them along the length side of the rectangular resonator. All these are to adjust a phase shift difference of two degenerate modes for the filter. Conversely, it is inevitably complicated the pattern design of feed lines.

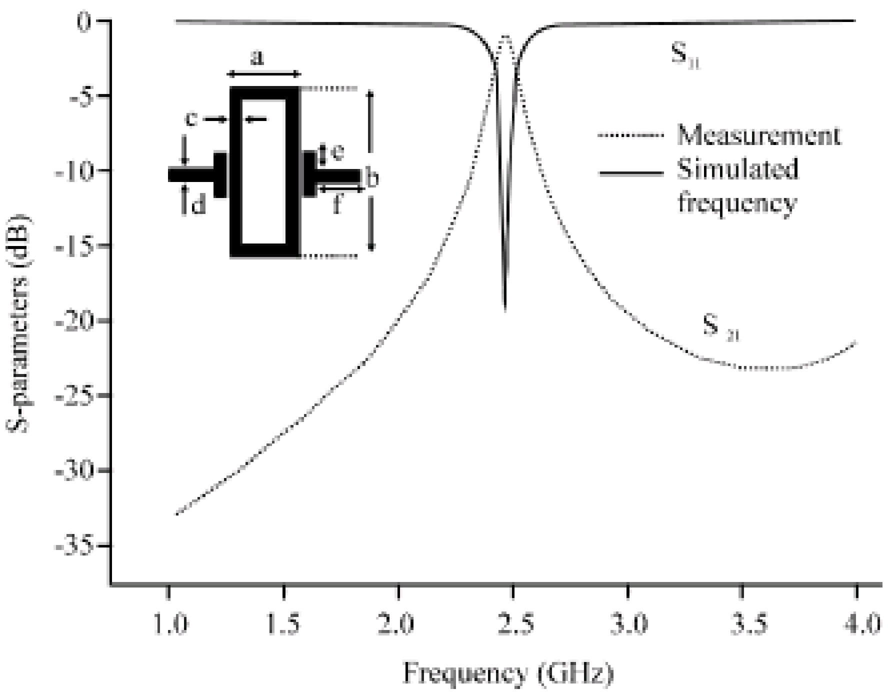

Fig. 3: Simulated frequency response at 2.45 Ghz of a conventional rectangular loop resonator bandpass filter, where the device dimensions are a = 8.07, b = 26.73, c = 1.7, d = 1, e = 3.77 and f = 5 mm

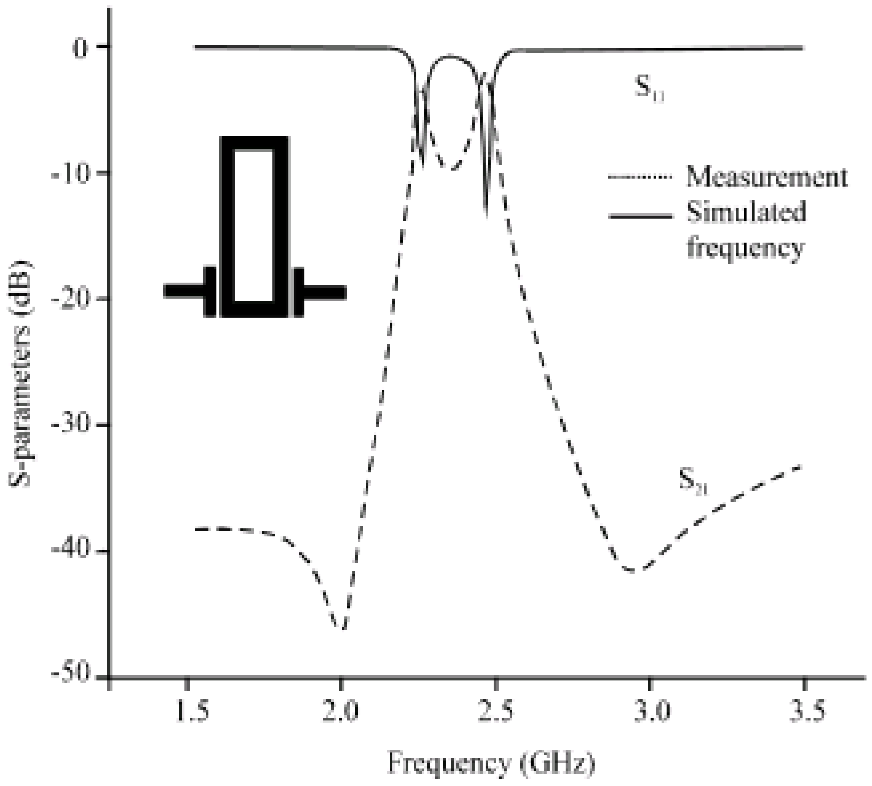

Fig. 4: Simulated frequency response at 2.45 GHz for the same rectangular loop resonator bandpass filter as shown in Fig. 3 but with the feed lines relocated at the bottom sides

Additionally, it might cause the feed lines not to have a 180° symmetrical separation along a horizontal line (Hong and Lancaster, 1996). Importantly, an interior space of the resonator is still left unused. Through a periodic U-shaped inward folding, the modified rectangular resonator as indicated in Fig. 5 induces a slow-wave propagation for two degenerate modes in the guided-wave paths of the resonator. Additionally, the inter-digital like feed lines are designed and inserted into the notches of the resonator to obtain an optimal signal coupling. Referring to Fig. 5, the resultant resonator has a total size of a = 6, b = 21.5 mm. The other filter

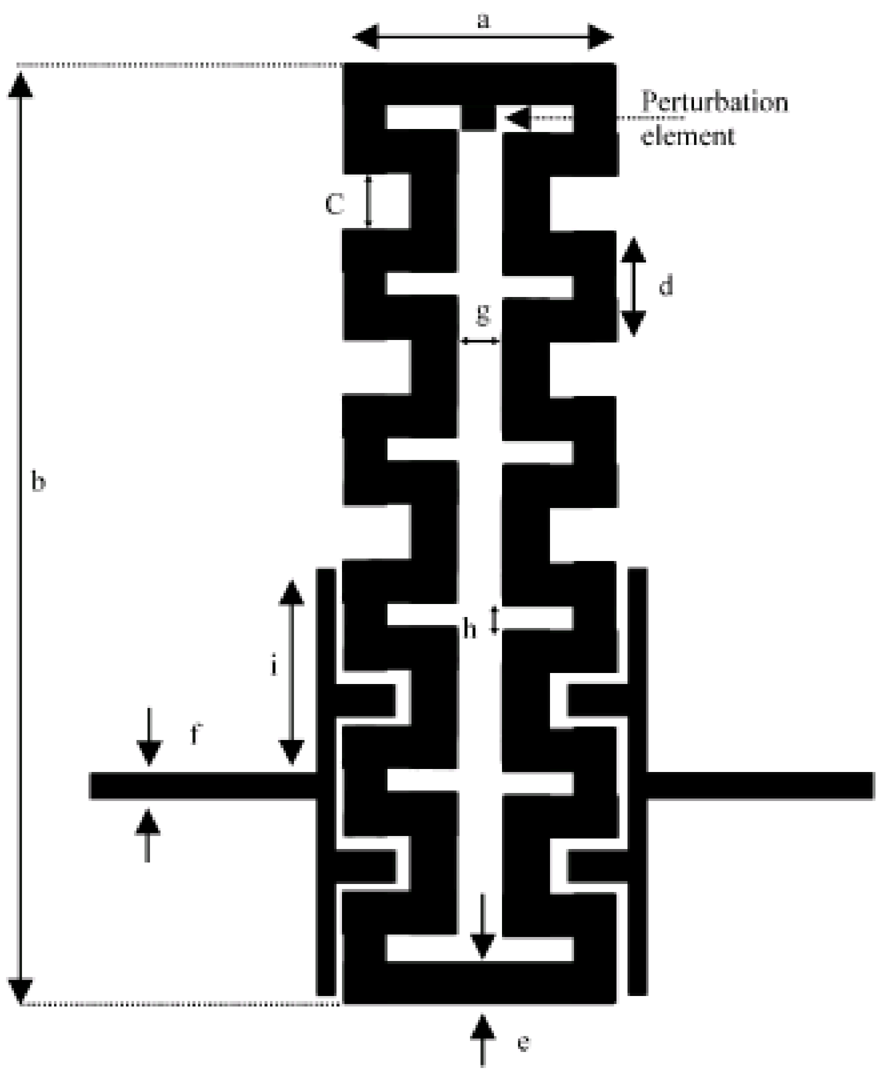

Fig. 5: The proposed dual-mode bandpass filter using slow-wave modified rectangular resonator with the device dimensions as a = 6, b = 21.5, c = 1.3, d = 2.5, e = 1, f = 0.5, g = 0.5, h = 0.5 and I = 4.5 mm

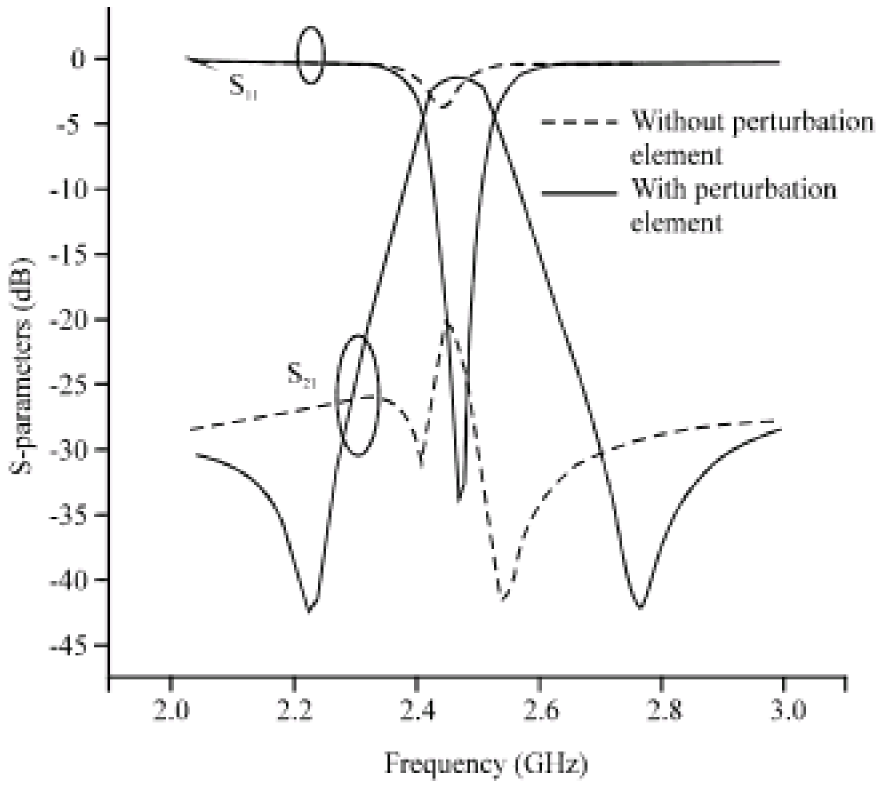

Fig. 6: Comparisons of the frequency responses with and without a perturbation element on the dual-mode bandpass filter with a slow-wave modified rectangular resonator

dimensions are d = 2.5, e = 1, f = 0.5, g = 0.5, h = 0.5 and I = 4.5 mm. Figure 6 describes the frequency responses of this modified filter with and without the perturbation element involved, respectively. Obviously, neither splitting of the resonance frequency nor bandpass response is observed for the filter without a perturbation element involved. With an attachment of a perturbation element at the topmost, the characteristic of fundamental frequency is significantly improved with sharper rejection skirts with introducing transmission zeros and a single peak response within the bandpass region instead of double peaks response.

DISCUSSION

Two resonant peaks can be obtained in an overcoupled condition if the coupling coefficient between two degenerate modes K is larger than 1/Q, with Q being the quality factor of the filter (Kuo *et al*., 1999; Hseih and Chang, 2002, 2003). The parameter of 1/Q could be expressed as (Hseih and Chang, 2003):

$$1/Q = 1/Q_e + 1Q_u$$

where, Q_e is the external quality factor denoting the coupling between the ring resonator and the I/O feed lines and Q_u is the unloaded quality factor of the ring resonator.

In considering an L-shaped coupling arm to enhance the coupling and to generate perturbation for dual-mode excitation, Hseih and Chang (2002) concluded that a single-mode ring resonator should have a low external quality factor Q_e to avoid an overcoupled response. By enhancing the coupling periphery between the feeders and the ring resonator, lower value of Q_e was achieved to increase the value of 1/Q for the filter. In this study, the inter-digital like feeders are adopted to insert into the notches of the slow-wave modified resonator to increase the coupling periphery between the feeders and the resonator. Furthermore, lowering the unloaded quality factor Q_u could also help the filter in eluding an overcoupled response. Therefore, the conventional rectangular resonator of the BPF should be replaced by a resonator with a lower quality factor Q_u. Besides providing a miniature benefit of the filter, U-shaped inward folding design is then used to introduce additional inter-coupling capacitors between meander notches into the modified resonator. Because of these loaded capacitors linked to the modified resonator, a slow-wave propagation is induced for two degenerate modes in the guided-wave paths of the resonator. It then naturally causes a lower value of quality factor Q_u for the resonator. Through the above two mentioned designs, the proposed filter should have the coupling coefficient K to be smaller than 1/Q. Figure 7 exhibits the stimulated and measured fundamental frequency responses of the filter as for an easy comparison. Clearly, the filter has the measurements

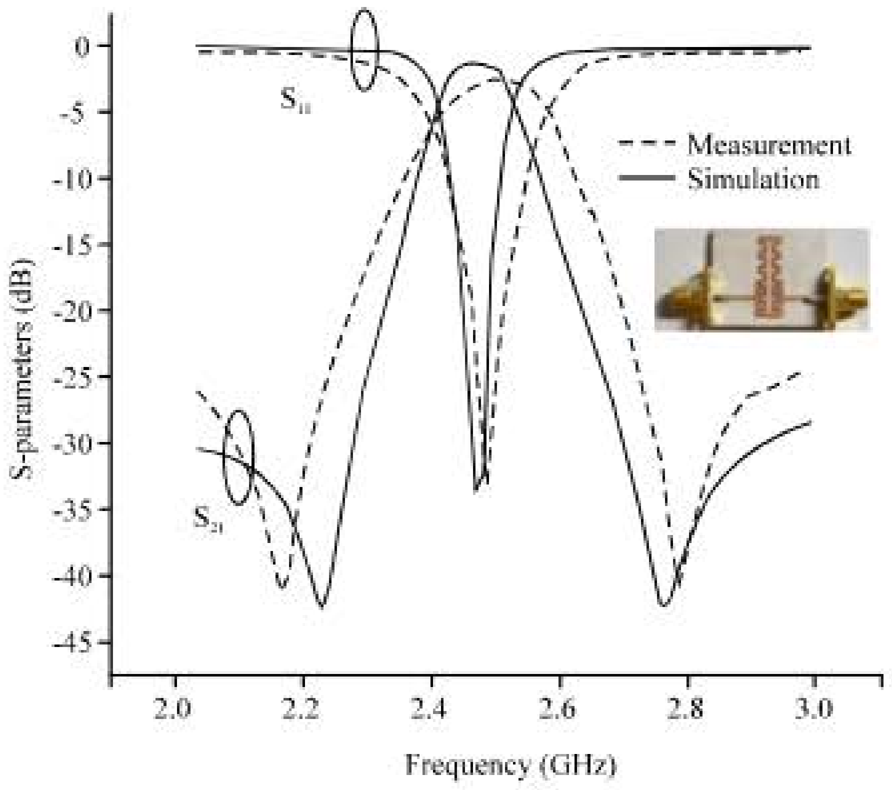

Fig. 7: Comparisons of simulated and measured frequency responses of the dual-mode bandpass filter with a slow-wave modified rectangular resonator

of about 7.1% bandwidth at the center frequency of 2.49 GHz and an insertion loss of -2.51 dB within passband, while the stimulated results of the bandwidth and insertion loss are about 4.5% at the center frequency of 2.45 GHz and -1.37 dB, respectively. The difference between simulated and measured performances is due to fabrication error and unperfected feeding ports soldered in the experiment. On the other hand, instead of directly loading additional elements within the resonator, inward folding of the resonator simply provides an easy and less complexity in miniaturizing a filter. Importantly, this benefit is also reserved in the proposed slow-wave modified rectangular resonator by having a size reduction of 41 and 57% against the conventional rectangular ring and square ring resonators, respectively.

CONCLUSION

To improve an overcoupled bandpass response of a conventional dual-mode rectangular resonator BPF, a novel miniature dual-mode BPF filter with a slow-wave modified rectangular resonator has been investigated. Through a periodic U-shaped inward folding design on the rectangular loop, the modified rectangular resonator induces a slow-wave propagation for two degenerate modes in the guided-wave paths of the resonator. For adapting to the feed lines designed along a straight line to provide a flexible accommodation with the microwave networks, an equal amount of 5 folding are symmetrically assigned at both sides of the slow-wave resonator. With inter-digital like I/O feed lines for an optimal signal coupling and a perturbation element at the topmost of the slow-wave resonator, the characteristic of fundamental frequency is significantly improved with sharper rejection skirts with introducing transmission zeros and a single peak response within the bandpass region instead of double peaks response. Besides, the proposed slow-wave modified rectangular resonator has the size reduction of 41 and 57% against the conventional rectangular ring and square ring resonators, respectively.

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