PAPER *Special Section on Advanced RF Technologies for Compact Wireless Equipment and Mobile Phones*

Dual-Mode Bandpass Filters Using Microstrip Slotted Equilateral Triangular Patch Resonators

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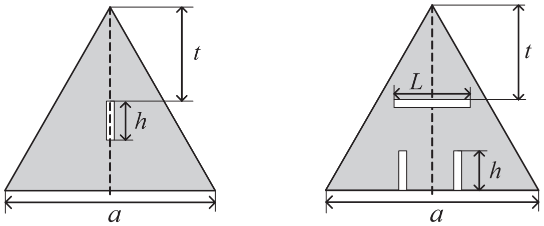
SUMMARY Two compact and low loss dual-mode filters are proposed by using degenerate modes of slotted triangular microstrip patch resonators. The geometrical size and radiation loss of the triangular patch are reduced simultaneously by loading both horizontal and vertical slots. The resonant frequencies of two degenerate modes can be easily controlled by varying the dimensions and positions of the slots. A two-pole dual-mode filter operating at 3.94 GHz with a fractional bandwidth of 4.3% is designed, fabricated, and measured. The measured results verify well the theoretical predictions.

key words: *dual-mode filter, microstrip filter, size-reduction, triangular patch resonator*



(a) (b)

Fig. 1 (a) A microstrip equilateral triangular patch resonator loaded with a single vertical slot. (b) A novel dual-mode triangular patch resonator loaded with one horizontal and two vertical slots.

1. Introduction

High performance narrowband microwave bandpass filters are widely used in various wireless communication systems. Dual-mode microstrip filters have many attractive features, such as low- loss, easy fabrication and compact size [1]. The concept of dual-mode is based on the physical coupling of a pair of degenerate modes in a geometrically symmetrical resonator. A perturbation element is added along the orthogonal plane of two degenerate modes. The coupling of orthogonal modes is achieved as the two degenerate modes are split by the perturbation element.

Many research works based on the circular ring [2], square loop [3], meander loop resonators [4], circular disk [5], and square patch [6] have been reported. Transmission-line resonators have compact size comparing with patch resonators, but generally suffer from higher conductor loss and lower power-handling capability. On the other hand, patch resonators have features like low-loss and easy fabrication. In [7], Hong investigated a novel microstrip triangular patch resonator. He provided innovative explanations of the operation mechanism of the degenerate dual-modes, and developed 2-pole and 4-pole filters based on the dual-mode triangular patch resonators. Recently, Hong [8] reported a dual-mode band reject filter by using a triangular patch resonator with one vertical slot loaded at the middle of the patch, as shown in Fig. 1(a).

In this paper, we propose a novel slotted dual-mode triangular patch resonator as shown in Fig. 1(b). By adding simultaneously one horizontal and two vertical slots to the equilateral triangular patch, we find that the resonant frequencies of the degenerate dual-modes can be reduced significantly, which means an effective size-reduction of the patch compared to the resonators of Hong [7], [8] if the same resonance frequencies are kept. In [7] and [8], Hong used one vertical slot at the middle of the triangular patch to split the degenerate modes. However, only the self-resonant frequency of one (mode 2) of the two degenerate modes is decreased while the self-resonant frequency of the other mode (mode 1) remained unchanged. Therefore, the size of the patch resonator can not be reduced when both the degenerate modes are used in the filter design. Moreover, our computations reveal that the falling of resonant frequency of mode 2 is slow when only one vertical slot is loaded at the middle of the triangular patch. Hence, two vertical slots are suggested in this paper to increase the length of flowing path of horizontal currents of mode 2 so that the resonant frequency of mode 2 can be reduced at a fast rate.

Other distinctive features of the proposed triangular patch resonator include: (1) first, separate control of the degenerate modes of the patch is realized by varying the horizontal and vertical slots respectively, and (2) second, the radiation loss of the slotted triangular patch is reduced simultaneously as the resonance frequencies decreased [9]. These features are described in detail in Sect. 2 with numerical results. Based on the investigation of the slotted triangular patch resonator, two-pole and four-pole microstrip dual-

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Manuscript received August 31, 2005.
Manuscript revised November 25, 2005.

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DOI: 10.1093/ietele/e89–c.4.503

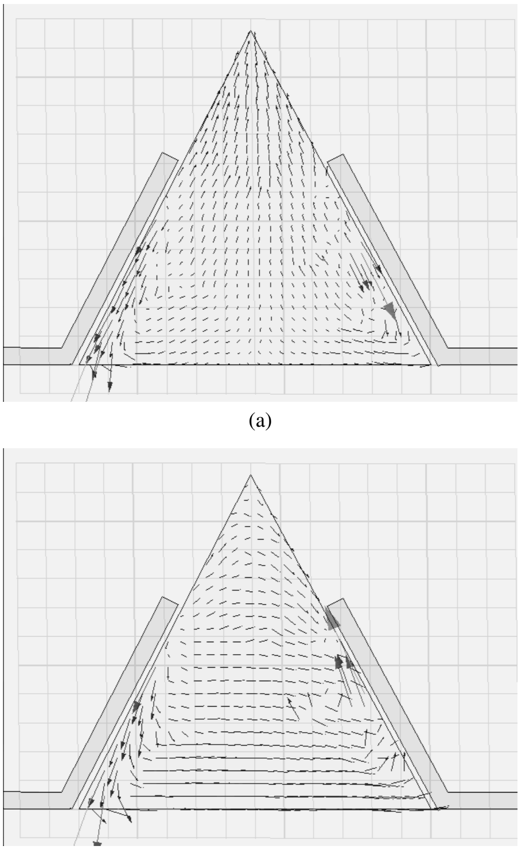
mode bandpass filters are developed in Sect. 3. The two-pole filter is fabricated and measured, and shows a 25% reduction of the side-length of triangular patch compared with the one reported in [7] and [8].

2. Dual-Mode Triangular Patch Resonator

It was shown in [10] that the fundamental mode (mode 1) of the equilateral triangular patch resonator is $TM^z_{1,0,-1}$ mode, and its degenerate mode (mode 2) is obtained through field rotations and superposition [7]. Detailed expressions and discussions of these two modes are referred to [7]. Here in Fig. 2, we provide only the electric current distributions of the degenerate modes, mode 1 and mode 2, of a triangular patch resonator with a hypotenuse of 13.1 mm and a hemline of 12.0 mm. The hypotenuse is chosen a little bit longer than the hemline in order to split the two degenerate modes of the triangular patch resonator since there is no slot in the patch yet. A dielectric substrate with a relative dielectric constant of 10.2 and a thickness of 0.635 mm is used, and the degenerate modes resonate at 4.77 GHz and 5.11 GHz, respectively. In Fig. 2, the directions and lengths of the arrows indicate the flowing directions and intensities of the currents, respectively. The current distributions are computed by using an EM simulator, HFSS of Ansoft Corporation. In the computation, input and output microstrip lines are built on the left and right side of the triangular patch, as shown in Fig. 2. The gaps between the input/output lines and the patch are chosen as 0.2 mm to get a moderate coupling between the resonator and the feed lines.

By observing Fig. 2, we see that the current of mode 1 flows mainly in the upper part of the patch along the vertical direction, while that of mode 2 flows mainly in the lower part of the patch in the horizontal direction. Therefore, if a horizontal slot is added to the patch, as shown in Fig. 1, the current flowing route of mode 1 will become longer. As a consequence, the resonance frequency of mode 1 will be lowered. On the other hand, mode 2 is hardly affected by the horizontal slot in the light of current distribution. Similarly, the resonant frequency of mode 2 will be lowered if a pair of vertical slots is introduced as shown in Fig. 1. Note that the width of the slots is small enough as not to perturb the fields and currents. Therefore, if we introduce both horizontal and vertical slots that are adequately long, the resonant frequencies of the patch will be lowered significantly.

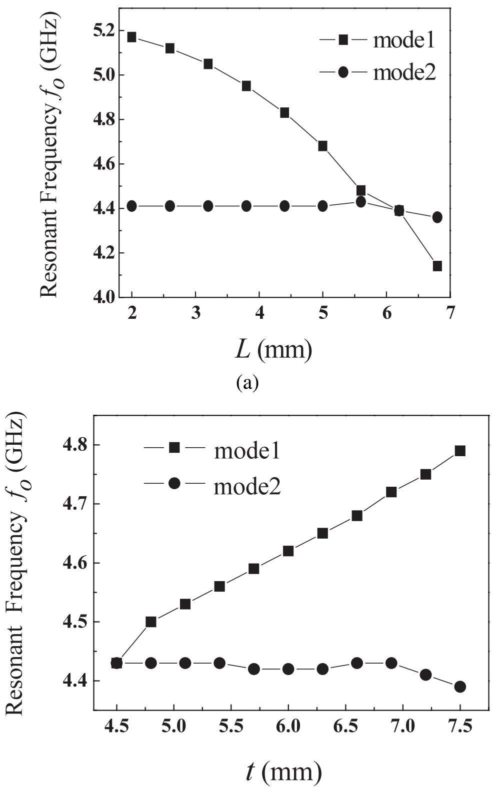
Figures 3(a) and (b) show the variation of resonance frequencies of mode 1 and mode 2 with respect to the horizontal slot length *L* and the distance *t* from the top of the triangular. The curves are simulated by using a full-wave EM



(a)

(b)

Fig. 2 Current distributions of the degenerate modes of a triangular patch resonator with a hypotenuse of 13.1 mm and a hemline of 12.0 mm. (a) mode 1 (4.77 GHz), (b) mode 2 (5.11 GHz).



(a)

(b)

Fig. 3 Resonance frequencies of the degenerate modes versus *L* or *t* of the horizontal slot. (a) Slot length *L* (t=6.6 mm, h=2.5 mm, a=12 mm). (b) The distance *t* from the top of triangular patch. (L=5 mm, h=2.5 mm, a=12 mm)

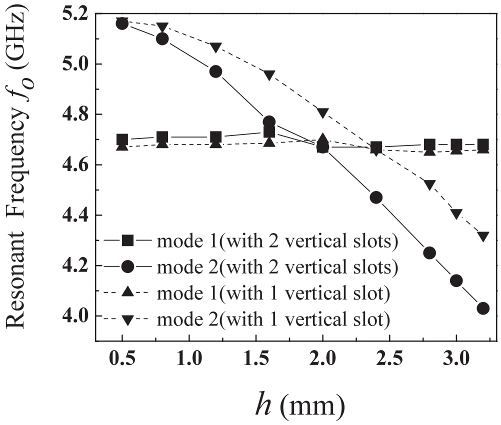


Fig. 4 Resonance frequencies of the degenerate modes versus the length h of the vertical slots. (L=4.6 mm, t=5 mm, a=12 mm)

simulator, Sonnet em [11]. It is found that the frequency of mode1 reduces rapidly as the slot length L increases or the distance t decreases, meanwhile the frequency of mode 2 varies little. Figure 4 depicts the variation of resonance frequencies of the degenerate modes with respect to the length h of the vertical slots. The solid and broken lines are results for the patch resonator with two vertical slots (Fig. 1(b)) and one vertical slot (Fig. 1(b), but both the vertical slots are moved to the central symmetrical line of the patch to merge as one vertical slot), respectively. The frequency of mode 2 decreases quickly as the length h of slots increases. On the other hand, the frequency of mode 1 keeps almost unvaried. From the curves in Figs. 3 and 4, we can conclude that the frequencies of mode 1 and 2 can be controlled separately by varying the lengths and positions of the horizontal and vertical slots respectively.

As described above, the broken lines in Fig. 4 show the variation of resonance frequencies of the two degenerate modes with the length h of the single vertical slot formed by moving the two vertical slots in Fig. 1(b) towards the central symmetrical line of the patch and merging them together as a single vertical slot. By comparing the solid lines with the broken lines, we find that the resonant frequency of mode 2 cannot be reduced from about 5.2 GHz to less than 4 GHz if only one short (h <3.5 mm) slot is loaded at the middle of the triangular patch.

The microstrip open patch resonator can usually be expressed by an equivalent shunt inductance-capacitance - conductance (LCG) circuit, where L indicates the effect of currents flowing on the surface of the patch resonator, C represents the capacitor formed between the patch and the ground plane, and the conductance G is caused by the radiation loss of the patch when conductor and dielectric losses are ignored. As the slots are very small, the electric fields underneath the patch varied little. Therefore, the patch capacitance C remained almost unchanged. On the other hand, since the introduction of slots in the patch makes the current flowing route longer, the effect of slots on the inductance is an increase of shunt L of the resonator, which means a decrease of the resonant frequency. The effect of slots on the conductance G can be observed from the variation of the unloaded quality factor Q_u versus the lengths, L and h, of the horizontal and vertical slots. The unloaded Q-factors, as shown in Fig. 5, of open triangular patch resonators with different slot lengths are computed by using the EM simulator Sonnet em with neglection of the conductor and dielectric losses. The coupling between the resonator and external feed lines is also made negligible in the computation, so the unloaded Q_u is considered as due to the radiation loss of the resonator. From Fig. 5, we see that with the falling of the resonant frequency, the value of unloaded Q_u is increased notably. Therefore, the conductance G is reduced remarkably, and the radiation loss of the slotted triangular patch is also reduced significantly [9].

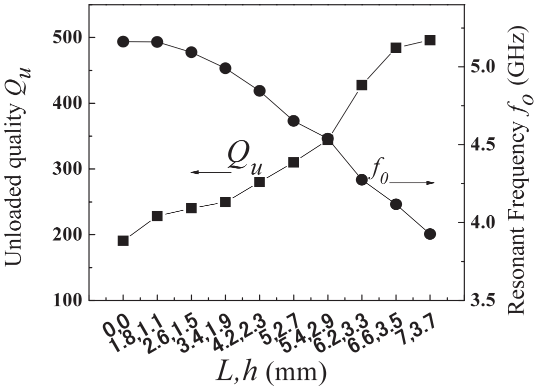
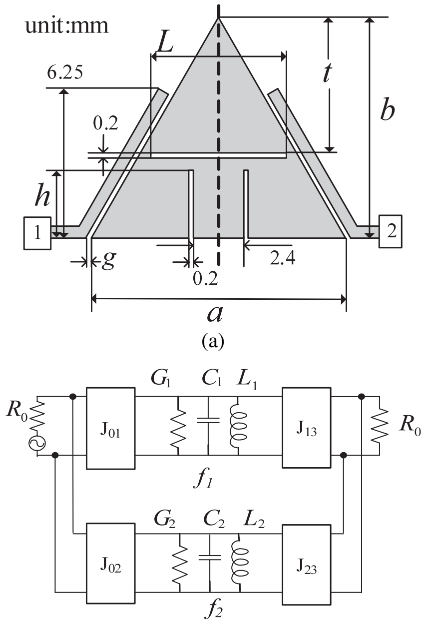


Fig. 5 The unloaded quality factor Q_u and resonance frequency f_0 versus the lengths, L and h, of the slots. (t=6.4 mm, a=12 mm)

3. Dual-Mode Filters

Based on the above investigated properties and EM simulated results of a slotted triangular patch resonator, two-pole and four-pole dual-mode bandpass filters are designed. The two-pole filter, as shown in Fig. 6(a), includes mainly a slotted dual-mode equilateral microstrip triangular patch with a side length of a=12 mm. The patch resonates at 3.94 GHz as opposed to 5.16 GHz of an equilateral triangular patch of the same size but without loading slots. The side-length of the slotted patch is reduced by 25% compared to that of the conventional equilateral triangular patch without slots if the operating frequency is kept the same.

An equivalent circuit of the dual-mode bandpass filter is shown in Fig. 6(b). The resonators with f_1 and f_2 represent mode 1 and mode 2 of the patch resonator, respectively, and are coupled in parallel with external source and load. There is no direct coupling path between these two resonators because, as discussed in detail in [7], there is no coupling between mode 1 and 2 of the patch resonator. Due to the symmetric field distribution of mode 1 and the anti-symmetric field distribution of mode 2 with respect to the input and output lines, we have $J_{01} = J_{13}$ and $J_{02} = J_{23}$, but resonator 2 has an out-phase connection with the load compared with that of resonator 1, as is shown in Fig. 6(b).



(a)

(b)

Fig. 6 (a) Configuration of a new dual-mode bandpass filter using a slotted triangular patch resonator. (b) Equivalent circuit of the dual-mode filter.

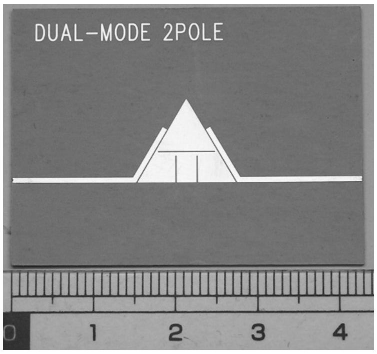


Fig. 7 Photograph of the fabricated two-pole bandpass filter using a slotted dual-mode microstrip triangular patch resonator.

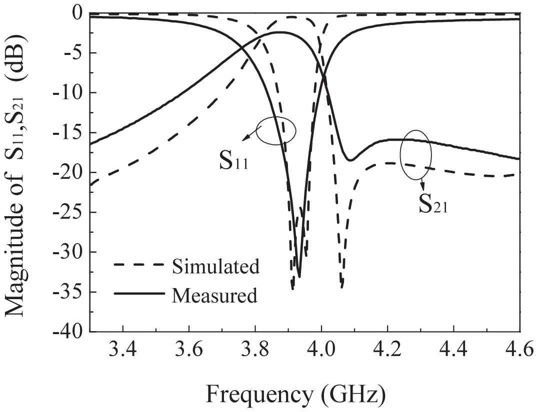


Fig. 8 Simulated (dashed lines) and measured (solid lines) results of the new dual-mode filter.

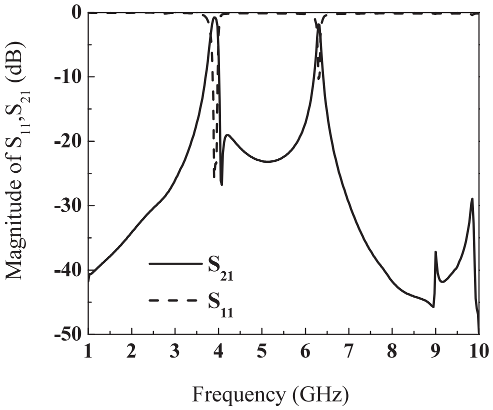


Fig. 9 The simulated wideband frequency response of the 2-pole dual-band filter.

To the authors' knowledge, there is no established design formulas for the parallel coupled resonator filter shown in Fig. 6(b). Therefore, we designed the dual- mode filter shown in Fig. 6(a) by using Sonnet em with appropriate adjustments of the parameters of the horizontal and vertical slots. The final dimensions of the filter in Fig. 6(a) are a=12 mm, b=10.4 mm, L=7 mm, t=6.5 mm, h=3.3 mm, and g=0.2 mm. Figure 7 is a photograph of the filter fabricated using the designed dimensions. The fabricated filter is measured by using an HP 8722ES network analyzer. In Fig. 8, the solid and broken lines indicate the measured and simulated frequency response of the filter, respectively. It is seen that the agreement between the simulated and measured curves is favorable. The midband frequency of the filter is 3.94 GHz, and its fractional 3 dB bandwidth is about 4.3%. The insertion loss over the passband is about 2.3 dB, and it is caused by the conductor and dielectric losses of the substrate, as well as the radiation loss of the patch since no shielding of the filter is implemented in the measurement. A return loss larger than 20 dB is accomplished in the passband.

Figure 9 gives the simulated wideband frequency response of the 2-pole dual-mode filter of Fig. 6(a). It is seen that because the first spurious passband occurs at about 6.3 GHz, which is relatively close to the dominant passband at 3.94 GHz, the attenuations between the dominant and first spurious passband cannot reach large values.

As is seen from Fig. 6(b), since there are two transmission paths (mode 1 and mode 2) between the input and output, a transmission zero will occur in either the lower stopband or the upper stopband of the filter. In Fig. 8, a transmission zero is observed at about 4.06 GHz in the upper stopband of the filter. The transmission zero can also be designed to appear in the lower stopband by adjusting the lengths of the horizontal and vertical slots. We find that if the resonant frequency of mode 1 is adjusted lower than that of mode 2, the transmission zero will appear in the lower stopband. Figure 10 shows the simulated performance of such a two-pole filter with one transmission zero designed in the lower stopband. The easy adjustment of the locations

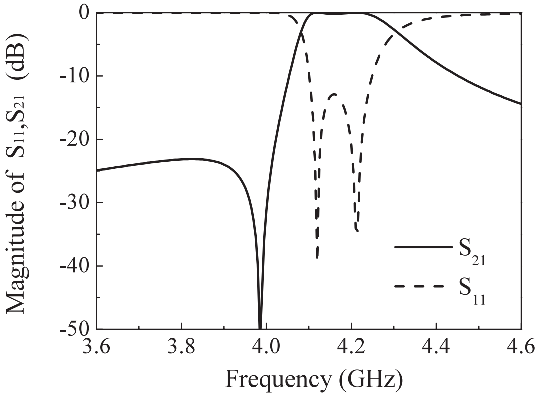


Fig. 10 Simulated performance of a two-pole filter with one transmission zero in its lower stopband.

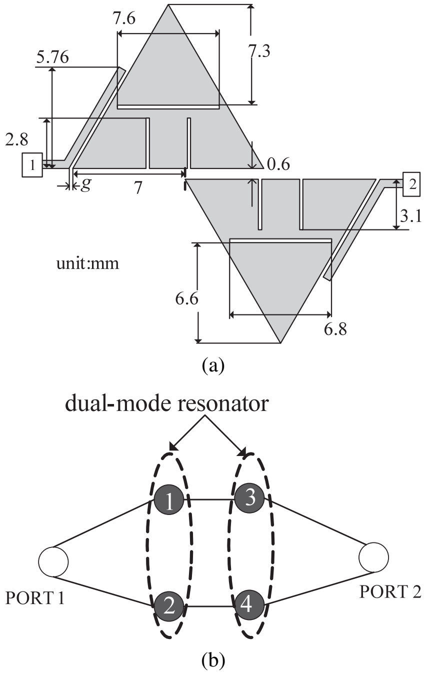


Fig. 11 (a) Configuration of a four-pole bandpass filter using two dual-mode triangular patch resonators. (b) Schematic coupling diagram of the four-pole filter.

of transmission zeros of this type of filer make it suitable for the development of diplexers which always require larger attenuations in one of its two stopbands.

A four-pole dual mode filter is also designed to improve the rejection performance in its stopband. Figure 11(a) shows the configuration of our four-pole bandpass filter using two dual-mode triangular patch resonators, and Fig. 11(b) is a schematic coupling diagram of the filter. The nodes 1, 2 represent the first patch resonator and the nodes 3, 4 represent the second patch resonator, respectively. By combining the above mentioned two types of resonators in Figs. 8 and 10, we can get one transmission zero in both the lower stopband and the upper stopband of the 4-pole filter. As stated above for the 2-pole dual-mode filter, there is up to now no established design formulas to relate the filter specifications with the circuit parameters of the parallel coupled resonator filter shown in Fig. 11(b). Therefore, we designed the 4-pole dual-mode filter shown in Fig. 11(a) by using Sonnet em with appropriate adjustments of the dimensions of the horizontal and vertical slots, coupling lengths and gaps between the resonators. The final dimensions of the 4-pole filter are provided in Fig. 11(a). Figure 12 shows the EM simulated performance of the four-pole filter. The filter exhibits a quasi-elliptic function response and has a better selectivity as compared to the two-pole filter. As for the 2-pole filter, simulated wideband response of the 4-pole filter also shows that the spurious passband occurs at about 6.3 GHz.

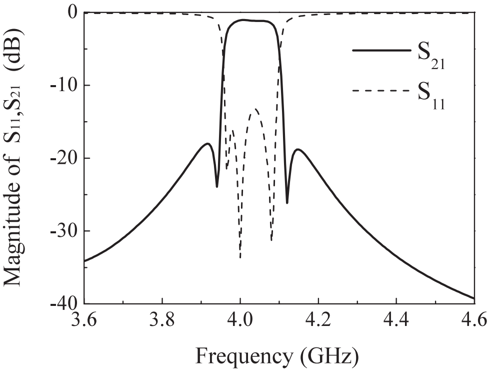


Fig. 12 Simulated frequency response of the four-pole filter.

4. Conclusion

After careful investigation of the resonant properties of a novel triangular patch resonator with one horizontal and two vertical slots, two compact microstrip dual-mode bandpass filters are designed by using the slotted triangular patch resonators. Compared with conventional dual-mode triangular patch filters, the new filters have several remarkable advantages such as size and radiation loss reduction, and easy control of the degenerate modes. The simulated frequency response of the two-pole filter is verified favorably by the measured result.

Acknowledgments

This work is supported in part by the National Natural Science Foundation of China (GP60271029), in part by the High-Tech Research Center Project from the Ministry of Education, Culture, Sports, Science, and Technology, Japan, and in part by the CASIO Science Promotion Foundation.

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