Novel Broadside-Coupled Bandpass Filters Using Both Microstrip and Coplanar-Waveguide Resonators

Pu-Hua Deng, Chi-Hsueh Wang, and Chun Hsiung Chen, *Fellow, IEEE*

***Abstract*—Novel quasi-elliptic coupled-resonator bandpass filters with wider fractional bandwidth are proposed. By using the broadside-coupled mechanism to couple the half-wavelength microstrip resonators and the quarter-wavelength coplanar-waveguide (CPW) resonators together with introducing two CPW shorted stubs, the required mixed and magnetic couplings associated with the resonators may be enhanced so that a wider bandwidth cross-coupled filter may be realized. Specifically, a fourth-order quasi-elliptic broadside-coupled bandpass filter with a center frequency at $f_0 = 1.48$ GHz, a minimum insertion loss of 0.68 dB, and a wider 3-dB fractional bandwidth of 34.6% is implemented, and its stopband is extended up to 6 GHz $(4f_0)$ with a rejection better than 20 dB.**

***Index Terms*—Bandpass filter, bandwidth widening, broadside coupled, coplanar waveguide (CPW), microstrip, stopband extension.**

I. Introduction

IN MICROWAVE communication systems, filters with good selectivity and stopband rejection are required to enhance the system performance. Recently, several cross-coupled filter structures with improved selectivity using half-wavelength $(\lambda/2)$ resonators were reported in [1]–[10]. To reduce the circuit size, the cross-coupled filters using quarter-wavelength $(\lambda/4)$ or quasi-quarter-wave resonators were proposed in [11]–[15]. In order to avoid the via-holes that may degrade the filter performance, the coplanar $\lambda/4$ quasi-elliptic filters without bond-wire bridges were proposed in [14]. These filters are compact in size and possess multiple transmission zeros such that better selectivity may be achieved. However, the fractional bandwidths of these cross-coupled filters using edge couplings are usually limited due to the constraint in the fabrication process. Only a few papers about cross-coupled filters were reported to relax this constraint. For example, two possible configurations to increase the 3-dB fractional bandwidth were proposed in [7] by using similarity transformation of the coupling matrix. However, the increase in 3-dB fractional bandwidth is still limited due to the constraint of edge coupling.

In this paper, a new class of quasi-elliptic coupled-resonator bandpass filters with wider fractional bandwidth will be proposed using both $\lambda/2$ and $\lambda/4$ resonators, as recently suggested by [16]. To enhance the mixed coupling between the resonator structures, the $\lambda/2$ microstrip resonators in the top layer are coupled to the $\lambda/4$ coplanar waveguide (CPW) resonators in the bottom layer through the broadside-coupled mechanism. To increase the magnetic coupling, two shorted stubs are introduced to associate with the $\lambda/4$ CPW resonators so that the required coupling may be adjusted and enhanced. By combining the above two mechanisms to increase both the mixed and magnetic couplings among the resonators, a quasi-elliptic wider bandwidth bandpass filter may be realized using the coupled-resonator configuration. The use of $\lambda/4$ CPW resonators is essential in implementing two shorted CPW stubs, which not only increase the required magnetic coupling for widening the bandwidth, but also avoid the fabrication of bond-wire bridges.

In this study, two fourth-order quasi-elliptic broadside-coupled bandpass filters with wider fractional bandwidth are implemented and carefully examined. To extend the stopband of the proposed broadside-coupled filter, the technique of using dissimilar resonators for spurious suppression [10], [15] is also adopted in the filter design. Specifically, a bandpass filter centered at $f_0 = 1.48$ GHz, a minimum insertion loss of 0.68 dB in the passband, and a wider 3-dB fractional bandwidth of 34.6% is implemented with its stopband extended up to 6 GHz $(4f_0)$.

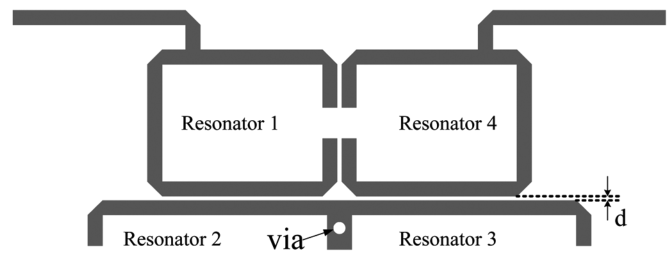

Fig. 1. Layout of the fourth-order cross-coupled filter using both $\lambda/2$ and $\lambda/4$ microstrip resonators.

II. Broadside-Coupled Filter

The bandwidth of the conventional cross-coupled filter using $\lambda/2$ open-loop microstrip resonators is restricted due to the limitation in mixed and magnetic couplings associated with the coupled resonators. A possible way of widening the bandwidth may be achieved by adopting the filter structure composed of both $\lambda/2$ and $\lambda/4$ microstrip resonators, as suggested by [16] and shown in Fig. 1. Here, resonators 1 and 4 are consisted of identical $\lambda/2$ uniform-impedance resonators, and resonators 2 and 3 are made of the identical $\lambda/4$ uniform-impedance resonators

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The authors are with the Department of Electrical Engineering and Graduate Institute of Communication Engineering, National Taiwan University, Taipei 106, Taiwan, R.O.C. (e-mail: chchen@ew.ee.ntu.edu.tw).

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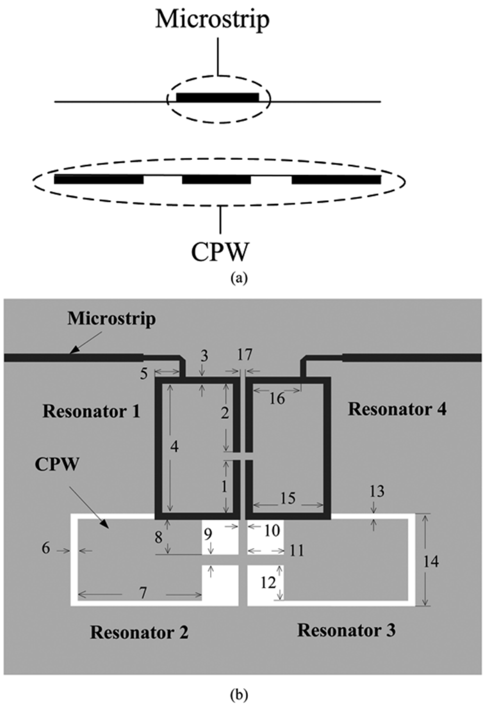

Fig. 2. Proposed fourth-order broadside-coupled filter composed of $\lambda/2$ microstrip and $\lambda/4$ CPW resonators. (a) Side view. (b) Top-/bottom-layer circuit layouts to show the relative location between top microstrip layer and bottom CPW layer.

in which a shorted circuit is introduced and implemented by the grounding via.

In Fig. 1, cross electric coupling is obtained across the gap between the ends of open-loop resonators 1 and 4, while the metallic via connecting to ground shared by resonators 2 and 3 produces the magnetic coupling required between these two resonators. In addition, the coupling between resonators 1 and 2 is of mixed form. Basically, stronger magnetic and mixed couplings are required for widening the 3-dB fractional bandwidth. A stronger magnetic coupling may be achieved by increasing the length of the shorted stub between resonators 2 and 3 (Fig. 1). However, the level of the mixed couplings between resonators 1 and 2, as well as 3 and 4, is limited by the spacing associated with the edge coupling, thereby becoming the bottleneck of the design. For example, the fourth-order quasi-elliptic microstrip filter shown in Fig. 1 and designed on an RO4003C substrate needs a small spacing of 0.05 mm to produce the required mixed coupling for a 3-dB fractional bandwidth of 16% with a center frequency at 1.98 GHz. This spacing is too small to be implemented by the usual fabrication process.

To widen the bandwidth, a novel broadside-coupled bandpass filter structure shown in Fig. 2 is proposed. Here, the $\lambda/2$ microstrip uniform-impedance resonators in the top layer are coupled, in the broadside mechanism, to the $\lambda/4$ CPW stepped-impedance resonators in the bottom layer so that the required mixed couplings between resonators 1 and 2, as well as 3 and 4, may be enhanced. The relative location between the top microstrip layer (two $\lambda/2$ microstrip uniform-impedance resonators) and the bottom CPW layer (two $\lambda/4$ CPW stepped-impedance resonators) is shown in Fig. 2(b). In order to achieve a filter with wider 3-dB fractional bandwidth in the passband, stronger mixed and magnetic couplings should be realized. The bottom CPW layer has two $\lambda/4$ stepped-impedance resonators in which two shorted stubs connecting to the ground planes are implemented to produce the required magnetic coupling. This magnetic coupling may be enhanced by increasing the lengths of two shorted stubs. The via-hole in Fig. 1 is now replaced by the shorted stubs without bond-wire bridges in Fig. 2. In addition, the design also avoids the bond-wire bridges associated with the CPW structures. Note that the effective inductances of the shorted stubs may be extracted by constructing a single CPW resonator made of such stubs and then measuring its loaded quality factor, as detailed in [17].

The design procedures for the proposed filter in Fig. 2 may be described in [1]. To facilitate the design, the three basic coupling structures, associated with the filter in Fig. 2 and shown in the inset of Fig. 3, need to be characterized. Fig. 3(a) shows the electric coupling structure and the corresponding design curve for the coupling coefficient between microstrip resonators 1 and 4.

The magnetic coupling structure, mainly consisting of inductive shorted stubs connected to CPW ground planes between resonators 2 and 3, is shown in the inset of Fig. 3(b). The design curve for this magnetic coupling coefficient is depicted in Fig. 3(b), indicating that the magnetic coupling coefficient ranges from 0.246 to 0.0734 when the distance d_2 changes from 0.05 to 4 mm.

The coupling structure in Fig. 3(c) provides the required mixed coupling. To obtain larger mixed coupling, the broadside-coupled mechanism is introduced between the top $\lambda/2$ microstrip resonator 1 and the bottom $\lambda/4$ CPW resonator 2. The design curve for the mixed-coupling coefficient is also shown in Fig. 3(c), which implies that the strength of the coupling coefficient is enhanced when the overlap area between the microstrip and CPW resonators is increased. All the design curves in Fig. 3 may be obtained by an electromagnetic simulation of the coupling structures shown in the insets of Fig. 3.

In this study, all the circuits are fabricated on a Rogers RO4003C substrate ($\varepsilon_r = 3.38$, $\tan\delta = 0.002$, and thickness $h = 0.508$ mm). The proposed broadside-coupled filter structure (Fig. 2) has a wider 3-dB fractional bandwidth than the one in Fig. 1 with the larger mixed couplings realized by the broadside-coupled structure. The proposed filter is designed according to the fourth-order quasi-elliptic response with a center frequency of 1.5 GHz and a 3-dB bandwidth of 24.6%.

The design parameters associated with the above specifications are given as follows:

$$\begin{aligned} M_{12} &= M_{34} = 0.21416 \\ M_{23} &= 0.1887 \\ M_{14} &= -0.04193 \\ Q_1 &= Q_4 = 3.88. \end{aligned}$$

Here, M's are the coupling coefficients between resonators and Q_1 and Q_4 are the quality factors at the input and output [1]. The dimensions of each part in Fig. 2(b) are given in Table I for further reference. The implemented filter has a size of $0.386\ \lambda \times 0.283\ \lambda$ (47.2 mm $\times$ 34.7 mm), where λ is the guided wavelength of the microstrip structure at the center frequency.

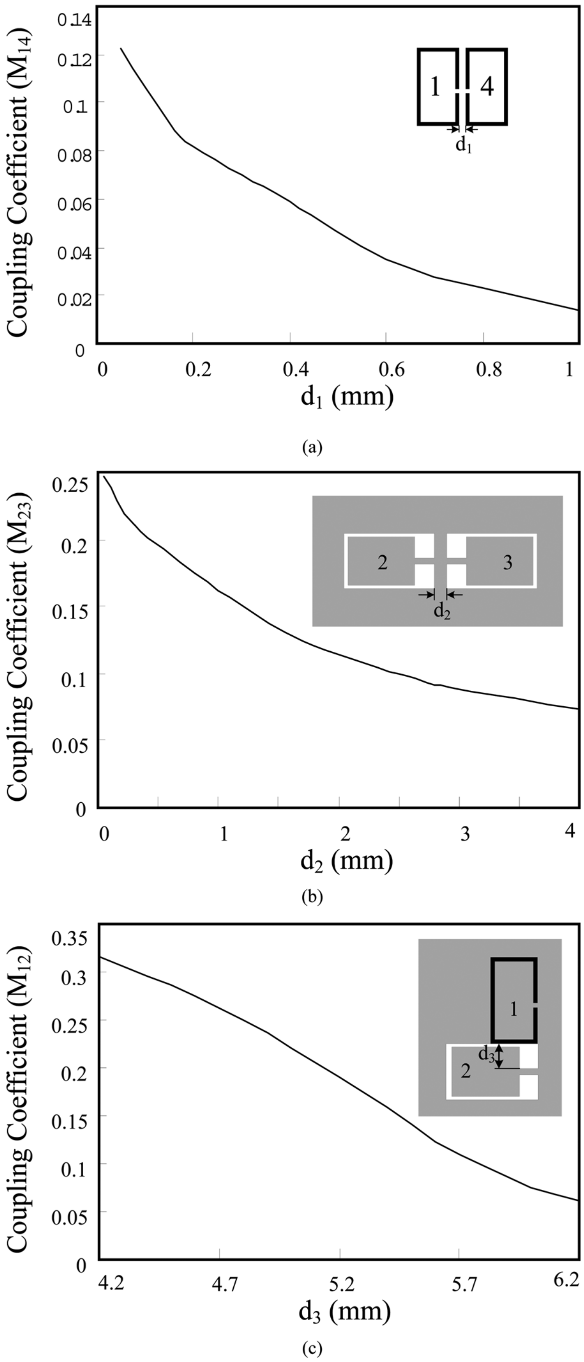

Fig. 3. Coupling structures and design curves for: (a) electric coupling, (b) magnetic coupling, and (c) mixed coupling.

TABLE I
DIMENSIONS (IN MILLIMETERS) OF EACH PART IN FIG. 2(b)

Part number	1	2	3	4	5	6	7	8
Dimension	8	10.4	1	19.6	3.4	1	17	5.3
Part number	9	10	11	12	13	14	15	16
Dimension	1.6	1.2	5	5.4	0.8	14	9.7	7.5
Part number	17							
Dimension	0.7							

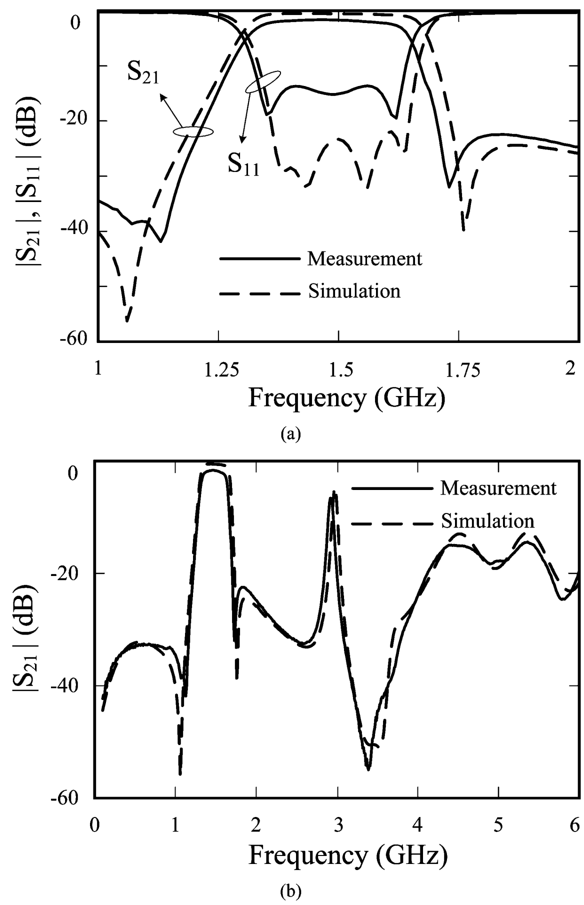

Fig. 4. Measured and simulated results of the proposed fourth-order broadside-coupled filter (Fig. 2) using both $\lambda/2$ microstrip and $\lambda/4$ CPW resonators. (a) Narrowband and (b) wideband frequency responses.

Note that the proposed filter (Fig. 2) is designed based on the formulas in [1], which are suitable for narrowband filters. By designing the proposed filter with a fractional bandwidth of 24.6%, for instance, according to the procedure in [1], it may end up with a developed filter, which, after full-wave simulation, would possess a bandwidth of 22% only, a consequence of using the narrowband formulas. Therefore, after the first design phase, the developed filter should be fine tuned so as to bring the fractional bandwidth back to the specification of 24.6%.

The measured and simulated results of the implemented broadside-coupled filter (Fig. 2) are shown in Fig. 4. The measured center frequency is at 1.47 GHz, the minimum insertion loss is 1.6 dB, and the 3-dB bandwidth is 22.4%. The deviation of the measured bandwidth from the specified value for the design may be resulted from the misalignment between the top microstrip and bottom CPW layers during the filter implementation.

III. STOPBAND-EXTENDED BROADSIDE-COUPLED FILTER

The filter structure shown in Fig. 2 has its bandwidth widened due to the use of a broadside-coupled structure between microstrip and CPW resonators. However, the filter shows several spurious passbands around $2f_0, 2.4f_0, 3f_0, 3.6f_0, \ldots$, which are created by the higher order resonances of the resonators associated with the proposed filter. These spurious passbands

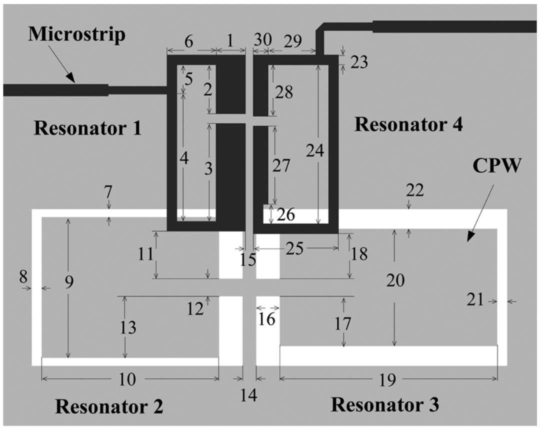

Fig. 5. Top-/bottom-layer circuit layouts of the proposed stopband-extended wider bandwidth broadside-coupled filter composed of $\lambda/2$ microstrip and $\lambda/4$ CPW resonators.

TABLE II
DIMENSIONS (IN MILLIMETERS) OF EACH PART IN FIG. 5

Part number	1	2	3	4	5	6	7	8
Dimension	3	5	10	13	3	4	0.8	1
Part number	9	10	11	12	13	14	15	16
Dimension	14.4	20.1	4.85	1.8	6.3	1	0.6	2.4
Part number	17	18	19	20	21	22	23	24
Dimension	5.1	4.6	24.2	12	1	2	1	16.25
Part number	25	26	27	28	29	30		
Dimension	8.7	2	8	5.25	4.9	1.5		

may be suppressed by properly designing the resonators so as to possess different impedance ratios, as suggested by [10] and [15].

In this study, a stopband-extended bandpass filter (Fig. 5) modified from the wider bandwidth broadside-coupled structure (Fig. 2) is proposed by applying the technique of dissimilar resonators for stopband extension [10], [15]. Specifically, different types of stepped-impedance resonators are adopted for the $\lambda/2$ microstrip and $\lambda/4$ CPW resonators. In this design, four resonators are made completely dissimilar and their higher order resonance frequencies are separated so that the spurious suppression may be achieved for stopband extension.

The proposed fourth-order stopband-extended broadside-coupled filter structure (Fig. 5) has a wider passband bandwidth and better stopband rejection than the one in Fig. 2. The filter is designed according to the fourth-order quasi-elliptic response with a center frequency of 1.5 GHz and a 3-dB bandwidth of 34.6%, and the corresponding parameters are given by

$$\begin{aligned} M_{12} &= M_{34} = 0.301 \\ M_{23} &= 0.2655 \\ M_{14} &= -0.05898 \\ Q_1 &= Q_4 = 2.7586. \end{aligned}$$

The implemented filter has a size of $0.43\,\lambda \times 0.26\,\lambda$ (52.1 mm $\times$ 31.75 mm). The dimensions of each part in Fig. 5 are also given in Table II.

The measured and simulated results of the stopband-extended filter (Fig. 5) are shown in Fig. 6. The measured center frequency is at 1.48 GHz, the minimum insertion loss is 0.68 dB, and the 3-dB bandwidth is 34.6%. The shift in the center frequency is less than 2%.

For the filter in Fig. 5, the spurious passband especially around $2f_0$ is suppressed, and its stopband is extended up to 6 GHz $(4f_0)$ with a rejection better than 20 dB. By using different impedance ratios for the four stepped-impedance resonators, their higher order resonance frequencies are separated and also made different from the frequency $2f_0$. Therefore, the signals go through the main path (from resonators 1 to 2 to 3 to 4) and the cross-coupled path (from resonators 1 to 4) are largely suppressed due to the mutual cancellation effects among the resonators [10], [15]. This explains why the spurious response around $2f_0$ is effectively suppressed.

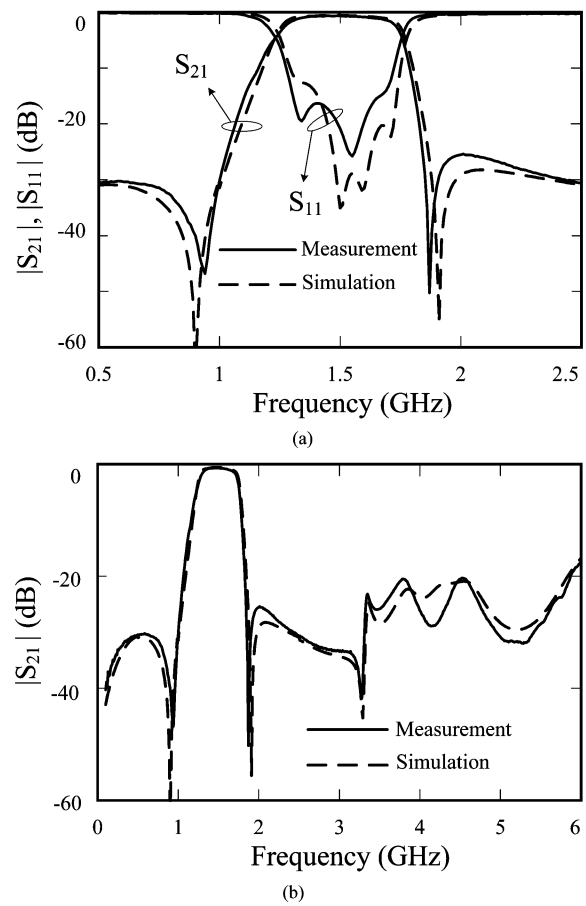

Fig. 6. Measured and simulated results of the stopband-extended wider bandwidth broadside-coupled filter shown in Fig. 5. (a) Narrowband and (b) wideband frequency responses.

The measured frequency response for the filter in Fig. 5 is also compared with that for the filter in Fig. 2, as shown in Fig. 7. With completely different impedance ratios for the four stepped-impedance resonators, the filter in Fig. 5 has much better rejection around $2f_0$ when compared with the one in Fig. 2.

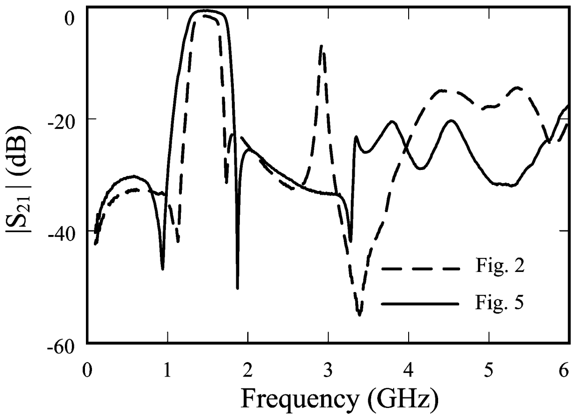

Fig. 7. Comparison of the measured responses for the filters in Figs. 2 and 5.

IV. Conclusion

In this paper, novel quasi-elliptic broadside-coupled bandpass filters with wider fractional bandwidth have been proposed. By using the broadside-coupled mechanism to couple the $\lambda/2$ microstrip resonators and the $\lambda/4$ CPW resonators together with introducing two CPW shorted stubs, the required mixed and magnetic couplings associated with the resonators may be enhanced so that the wider bandwidth cross-coupled filters may be realized. The use of $\lambda/4$ CPW resonators is essential in implementing the two shorted CPW stubs for increasing the magnetic coupling for widening the bandwidth. The technique of using dissimilar resonators for spurious suppression has also been utilized for stopband extension. Specifically, a fourth-order bandpass filter centered at $f_0 = 1.48$ GHz with a wider 3-dB bandwidth of 34.6% has been implemented, and its stopband has been extended up to 6 GHz $(4f_0)$ with a rejection better than 20 dB.

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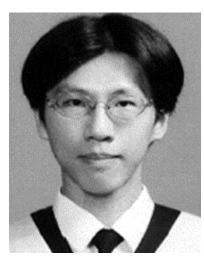
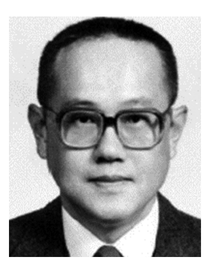
Pu-Hua Deng was born in Kaohsiung, Taiwan, R.O.C., in 1978. He received the B.S. degree in electrical engineering from National Sun Yet-Sen University, Kaohsiung, Taiwan, R.O.C., in 2002, the M.S.E.E. degree from National Taiwan University, Taipei, Taiwan, R.O.C., in 2004, and is currently working toward the Ph.D. degree at National Taiwan University.

His research interests include the design and analysis of microwave filter circuits.



Chi-Hsueh Wang was born in Kaohsiung, Taiwan, R.O.C., in 1976. He received the B.S. degree in electrical engineering from National Cheng Kung University, Tainan, Taiwan, R.O.C., in 1997, and the Ph.D. degree from National Taiwan University, Taipei, Taiwan, R.O.C. in 2003.

He is currently a Post-Doctoral Research Fellow with the Graduate Institute of Communication Engineering, National Taiwan University. His research interests include the design and analysis of microwave and millimeter-wave circuits and computational electromagnetics.



Chun Hsiung Chen (SM'88–F'96) was born in Taipei, Taiwan, R.O.C., on March 7, 1937. He received the B.S.E.E. and Ph.D. degrees in electrical engineering from National Taiwan University, Taipei, Taiwan, R.O.C., in 1960 and 1972, respectively, and the M.S.E.E. degree from National Chiao Tung University, Hsinchu, Taiwan, R.O.C., in 1962.

In 1963, he joined the faculty of the Department of Electrical Engineering, National Taiwan University, where he is currently a Professor. From August 1982 to July 1985, he was Chairman of the Department of Electrical Engineering, National Taiwan University. From August 1992 to July 1996, he was the Director of the University Computer Center, National Taiwan University. In 1974, he was a Visiting Scholar with the Department of Electrical Engineering and Computer Sciences, University of California at Berkeley. From August 1986 to July 1987, he was a Visiting Professor with the Department of Electrical Engineering, University of Houston, Houston, TX. In 1989, 1990, and 1994, he visited the Microwave Department, Technical University of Munich, Munich, Germany, the Laboratoire d'Optique Electromagnetique, Faculte des Sciences et Techniques de Saint-Jerome, Universite d'Aix-Marseille III, Marseille, France, and the Department of Electrical Engineering, Michigan State University, East Lansing, respectively. His areas of interest include microwave circuit analysis and computational electromagnetics.