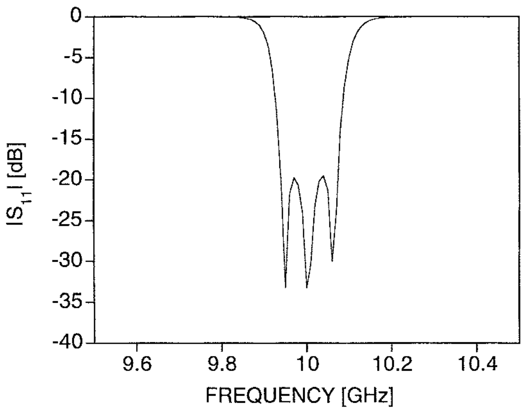


Fig. 5. Full-wave response of the filter after the optimization.

shown in Fig. 5. It can be observed that the original prototype response of the prototype was recovered.

IV. Conclusions

The half-cylinder post geometry is employed in order to realize direct coupled-cavity filters in waveguide.

Such an arrangement permits one to correct the deterioration due to mechanical tolerances by a slight rotation of posts whose main effect is a variation of the adjacent cavities.

References

[1] P. P. Silvester and R. L. Ferrari, *Finite Elements for Electrical Engineers*, 3rd ed. Cambridge, U.K.: Cambridge Univ. Press, 1996.

[2] P. P. Silvester and G. Pelosi, *Finite Elements for Wave Electromagnetics.* Piscataway, NJ: IEEE Press, 1994.

[3] G. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Network and Coupling Structures.* New York: McGraw-Hill, 1965.

[4] N. Marcuvitz, *Waveguide Handbook.* New York: McGraw-Hill, 1951.

[5] R. Coccioli, M. Mongiardo, G. Pelosi, and R. Ravanelli, "Design of matched bends in rectangular waveguides by FEM," *Int. J. Microwave Millimeter-Wave Comput.-Aided Eng.*, vol. 6, no. 6, pp. 391–398, 1996.

[6] J. F. Lee and Z. J. Cendes, "The transfinite element method for modeling MMIC devices," *IEEE Trans. Antennas Propagat.*, vol. 36, pp. 1639–1649, 1988.

[7] J. P. Webb and V. Parihar, "Finite-element analysis of H-plane rectangular waveguide problems," *Proc. Inst. Elect. Eng.*, vol. 133, pt. H, pp. 91–94, 1986.

[8] J. M. Reiter and F. Arndt, "Rigorous analysis of arbitrarily shaped H- and E-plane discontinuities in rectangular waveguides by a full-wave boundary contour mode-matching method," *IEEE Trans Microwave Theory Tech.*, vol. 43, pp. 796–801, Apr. 1995.

[9] D. Rosowsky, "Design of manifold type multiplexers," in *Proc. ESA Workshop Microwave Filters*, Noordwijk, The Netherlands, June 1990, pp. 145–156.

Cross-Coupled Microstrip Hairpin-Resonator Filters

Jia-Sheng Hong and Michael J. Lancaster

***Abstract*—A new class of cross-coupled planar microwave filters using microstrip hairpin resonators is introduced. The realization of both the canonical and the cascaded quadruplet (CQ) filters is feasible. Coupling characteristics of four basic coupling structures encountered in this class of filters are investigated in the light of full-wave electromagnetic (EM) simulations. A four-pole cross-coupled filter of this type is designed and fabricated. Both the theoretical and experimental performance is presented.**

***Index Terms*—Cross coupling, hairpin resonator, microstrip filter.**

I. Introduction

Miniaturized microwave bandpass filters are always in demand for systems requiring small size and light weight. Conventional hairpin line filters, introduced by Cristal and Frankel [1] in the early 1970's, were developed to meet this demand, and have become popular. Further miniaturized hairpin-resonator filters were reported by Sagawa and his colleagues [2] in the late 1980's for application to receiver front-end microwave integrated circuits (MIC's). Recently expanding mobile communications systems, together with advances in MIC's and high-temperature superconducting circuits, have further stimulated the development. Hong and Lancaster reported pseudo-interdigital filters which might be seen as a combination of hairpin and interdigital line resonators [3], while Matthaei and his co-workers developed narrow-band hairpin-comb filters, which use the hairpin resonators in such a way that their filtering properties are similar to those of comb-line filters [4].

In this paper, we present new applications of microstrip hairpin resonators which lead to a new class of cross-coupled microstrip bandpass filters. The cross-coupled filters are so attractive because they exhibit ripples in both passband and stopband, which according to the early work on filter synthesis [5] can improve both frequency selectivity and bandpass loss. For instance, they are able to place transmission zeros near cutoff frequencies of a passband so that higher selectivity with less resonators can be obtained. This property is of much interest in narrow-band filters where the passband insertion loss is strongly related to the number of resonators. The cross-coupled filters, depending on the phasing of cross-coupled signals, may also flatten the group delay. Owing to the difficulty in arranging and controlling the cross couplings in planar transmission-line resonators, only a few types of cross-coupled planar filters have been developed [6]–[8]. The new cross-coupled microstrip hairpin-resonator filters offer alternative designs. They are not only simple and compact in configurations, but also have great flexibility to shape filters into different sizes. The latter is mainly due to the great freedom in choosing hairpin-resonator shapes.

II. Cross-Coupled Filters

Fig. 1 shows two typical microstrip cross-coupled bandpass filters comprised of coupled hairpin resonators. The dielectric substrate with

Manuscript received February 12, 1997; revised October 9, 1997.

The authors are with the School of Electronic and Electrical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, U.K.

Publisher Item Identifier S 0018-9480(98)00620-6.

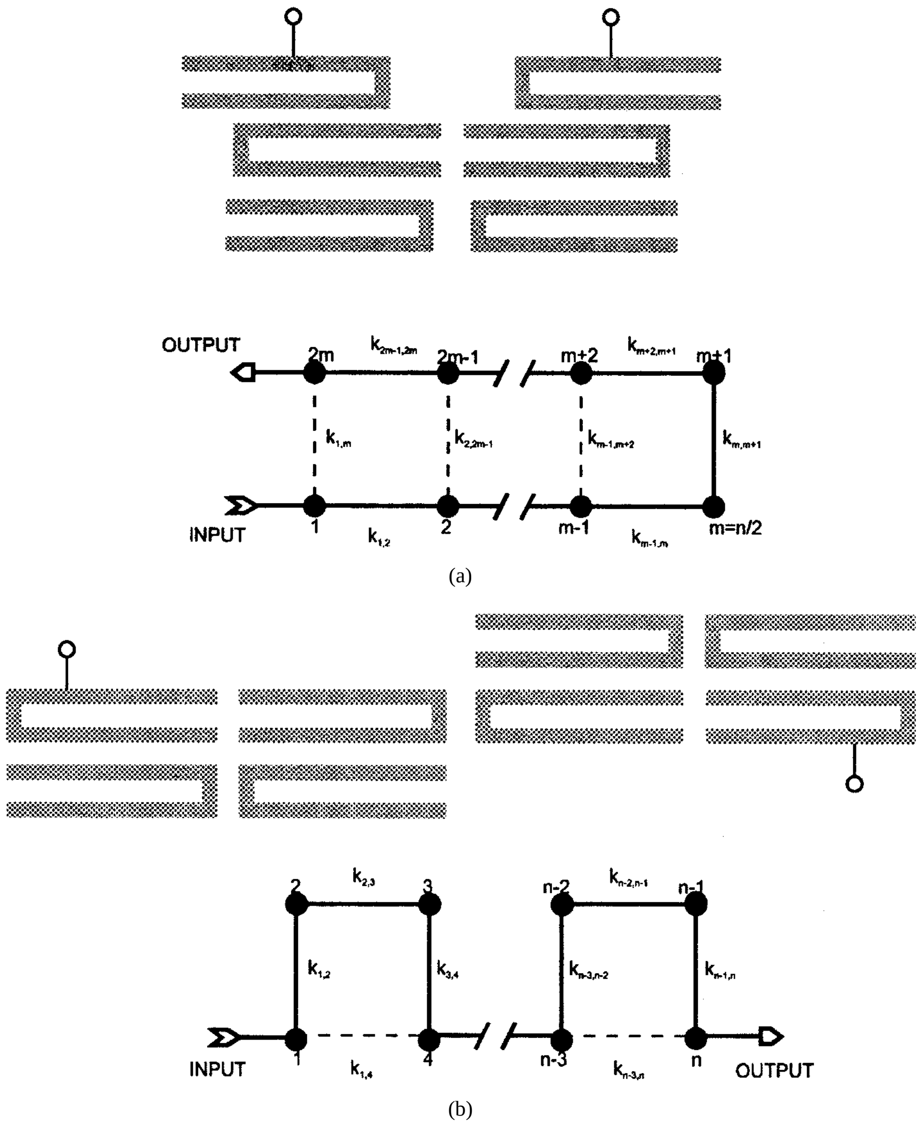


Fig. 1. Typical cross-coupled microstrip bandpass filters comprised of coupled hairpin resonators on substrate (not shown) with a relative dielectric constant λ_r and a thickness h. (a) Six-pole canonical filter with coupling diagram. (b) Eight-pole CQ filter with coupling diagram.

a ground plane is not shown in the diagram. The filter of Fig. 1(a) may be catalogued to the canonical filters [9] with a general coupling structure as depicted, where each node represents a resonator, the full lines indicate the main path couplings, and the broken lines denote the cross couplings. The eight-pole filter, shown in Fig. 1(b), may belong to another type of cross-coupled filters—namely, the so-called cascaded quadruplet (CQ) filters, whose general coupling diagram is also shown in Fig. 1(b). The CQ structure possesses the significant advantage that each CQ section is entirely responsible for producing one pair of transmission zeros. This is not the case for other realizations such as the canonical structure in Fig. 1(a) where each cross coupling affects all the transmission zeros, making the filter more difficult to tune [10].

Although only two types of cross-coupled hairpin-resonator filters have been described, the filters with more poles are easily built up and the building up of filters with other configurations may also be possible. It would seem that a practical method to design this class of filters is to derive a coupling matrix from the transfer function and realize the coupling matrix in terms of inter-resonator couplings. Obviously, this design method requires the knowledge of mutual couplings between coupled microstrip hairpin resonators. In general, four basic coupled structures may be encountered in the cross-coupled hairpin-resonator filters. The characterization of these coupled structures will be discussed in Section III.

III. Coupling Coefficients

It is clear that any coupling encountered in the cross-coupled microstrip hairpin-resonator filters is that of the proximity coupling, which is basically through fringe fields. The nature and the extent of the fringe fields determine the nature and the strength of the coupling. However, the semiopen configuration and inhomogeneous dielectric medium of coupled hairpin resonators make the characterization of couplings even more complicated. On the other hand, it is well known that two resonant peaks in association with the coupling can be observed if the coupled resonators are over-coupled, which occurs when the corresponding coupling coefficient is larger than a critical value amounting to $1/Q_0$, where Q_0 is the quality factor of the resonator circuit [11]. Due to the two split resonant frequencies being quite easily identified in the full-wave EM simulation, the coupling coefficient can be determined from the relationships between the coupling coefficient and the two split resonant frequencies [2], [8].

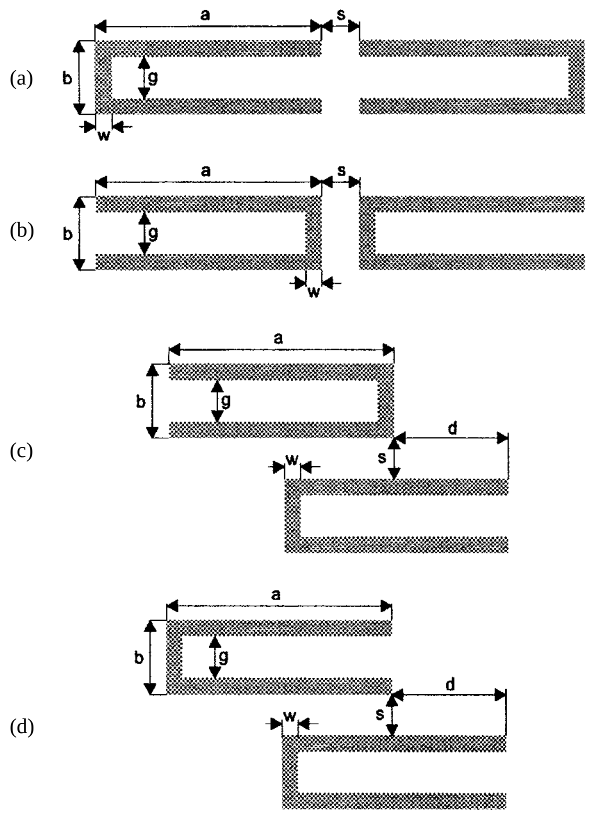


Fig. 2. Basic coupling structures of coupled microstrip hairpin resonators on a substrate (not shown) with a relative dielectric constant λ_r and a thickness h. (a) Electric coupling. (b) Magnetic coupling. (c) The first type of mixed coupling. (d) The second type of mixed coupling.

Thus, we have decided to employ this approach to characterize the four basic coupled structures of microstrip hairpin resonators.

Fig. 2 shows the four basic coupled structures for realization of cross-coupled filters. It is obvious that at resonance the electric fringe field is much stronger near the open ends, while the magnetic fringe field is much stronger near the middle of each resonator. This leads to the electric coupling of Fig. 2(a) and the magnetic coupling of Fig. 2(b). In the coupling structure of Fig. 2(c), the two hairpin resonators in *the opposite orientation* are coupled with each other with a separation s and offset d. In this case, both the electric and magnetic couplings occur, and may be referred to as the first type of mixed coupling. It can be shown that the first type of mixed coupling has resulted from the superposition of the magnetic and electric couplings which are in-phase. The coupling structure of Fig. 2(d) consists of the two coupled hairpin resonators in *the same orientation* with a separation s and offset d. Although both the electric and magnetic couplings occur as the first mixed coupling structure discussed above, this coupling structure exhibits a rather different coupling characteristic. Hence, in this case the coupling may be referred to as the second type of mixed coupling. It can also be shown that the magnetic and electric couplings are out-phase in the second type of mixed coupling.

A full-wave EM simulator, which is based on the method of moments and proven to be quite accurate in its prediction,[1] [14] was used to simulate the frequency responses of the four basic coupling structures. The coupling coefficients would then be extracted from the simulated frequency responses by using

$$k = \frac{f_{p2}^2 - f_{p1}^2}{f_{p2}^2 + f_{p1}^2} \tag{1}$$

where f_{p1} and f_{p2} are the two spilt resonant frequencies [8].

Some typical results are shown in Fig. 3. As can be seen, the electric coupling (indicated by k_E) decays quickly against coupling spacing and also shows a dependence of dielectric constant. It would seem that this dependence is not very significant for the substrate having a higher dielectric constant. On the contrary, to the electric coupling, the magnetic coupling k_M exhibits not only a slower decay against coupling spacing, but also an independence of dielectric constant than what should be expected. The first type of mixed coupling (denoted by k_{x1}) varies with respect to the normalized spacing s/h and normalized offset d/a. It appears that the coupling becomes less dependent on the offset when the coupling spacing is larger. As illustrated, the characteristics of the second type of mixed coupling k_{x2} seems much more complicated than the others. Firstly, its does not monolithically vary against coupling spacing as the others do. Secondly, the coupling can be even smaller for very small coupling spacing. These phenomena are obviously evidences of cancellation of the electric and magnetic couplings. If the cancellation were complete no coupling would exist. In addition to a weaker coupling, it also shows a stronger dependence on the offset than the first type of mixed coupling.

IV. Filter Design Example

As we have emphasized, the characterization of couplings of the basic coupling structures plays an important role in the design of cross-coupled microstrip hairpin-resonator filters, as shown in Section III. Accordingly, a four-pole cross-coupled microstrip hairpin bandpass filter (which can actually be referred to as either the canonical or the CQ filter, so as to be a key element for other higher degree cross-coupled filters) was designed and fabricated for the demonstration. The filter specifications are the center frequency of 965 MHz, the passband bandwidth of 20 MHz (or the fractional bandwidth $\mathrm{FBW} = 2.07\%$), the stopband rejection of 20 dB at ± 15 MHz from the center frequency. This rejection is achieved in the design by replacing a transmission zero at 17.5 MHz from the center frequency. The filter could be synthesized using a method described in [12], from which the lumped-element values of a low-pass prototype were determined as $g_0 = 1.0$, $g_1 = 1.3782$, $g_2 = 1.2693$, $J_1 = -0.2492$, and $J_2 = 0.9771$. The design parameters of the bandpass filter (namely, the elements of coupling matrix and input/output single-loaded external Q_e) could then be calculated as follows:

$$\begin{aligned} M_{12} = M_{34} &= \frac{\mathrm{FBW}}{\sqrt{g_1 g_2}} = 0.0157 \\ M_{23} &= \frac{\mathrm{FBW} \cdot J_2}{g_2} = 0.016 \\ M_{14} &= \frac{\mathrm{FBW} \cdot J_1}{g_1} = -0.0037 \\ Q_e &= \frac{g_0 g_1}{\mathrm{FBW}} = 66.5797. \end{aligned} \tag{2}$$

The positive coupling coefficients $M_{12} = M_{34}$ and M_{23} are realized by the first type of mixed and magnetic couplings, respectively, while the negative coupling coefficient M_{14} is realized by the electric coupling. These coupling coefficients are within the range of coupling coefficients given in Section III so that the design dimensions could be found. The tapped-line feed [13] was used for the loaded external Q_e, though the other means of feed such as the coupled-line feed is feasible.

[1] *EM User's Manual*, Sonnet Software, Inc., New York, version 2.4, 1993.

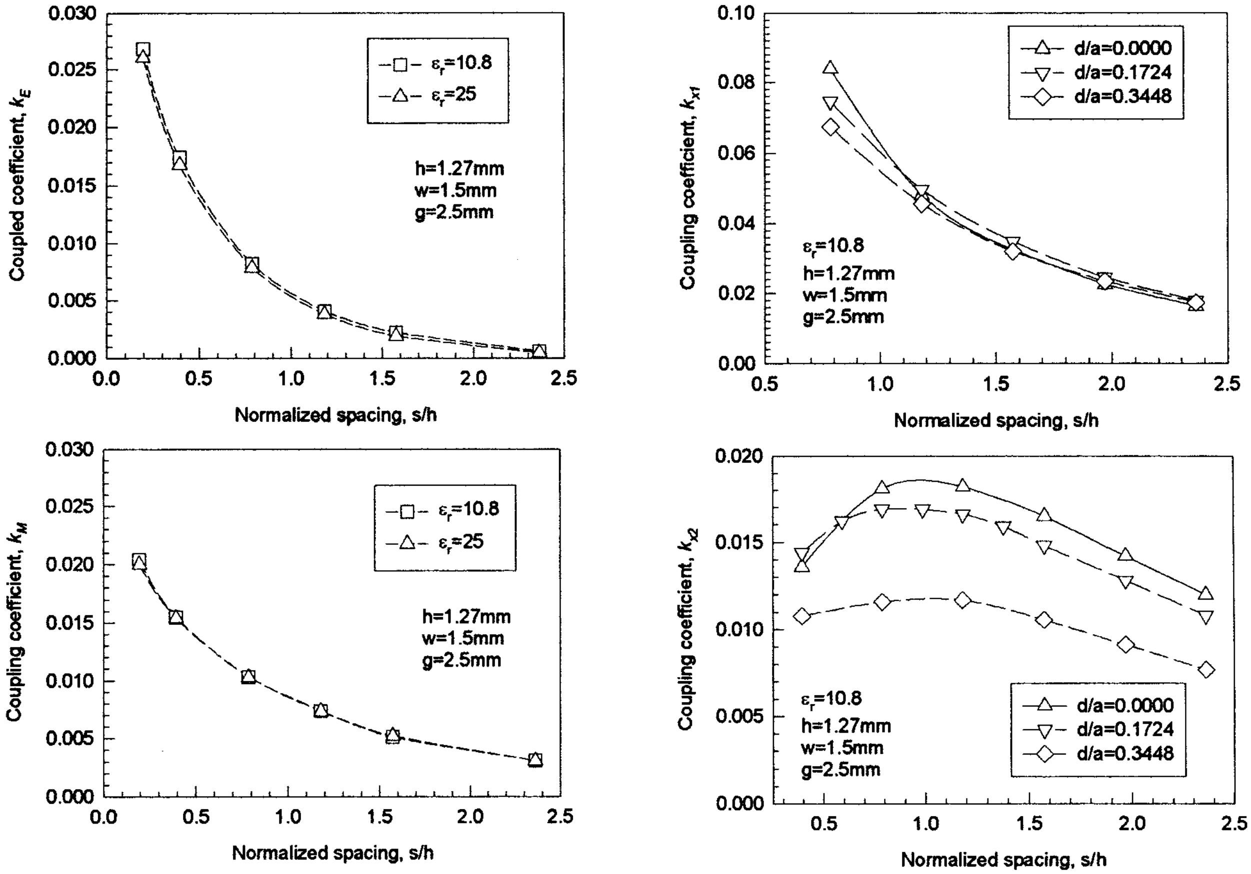
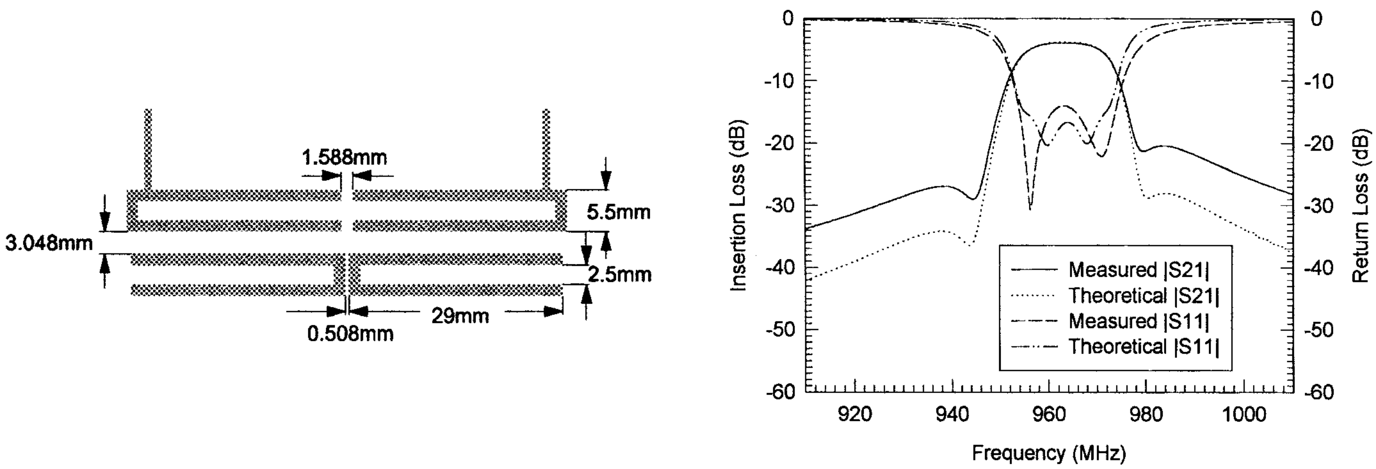


Fig. 3. Typical coupling coefficients of the coupling structures in Fig. 2.



(a) (b)

Fig. 4. (a) Layout of the four-pole cross-coupled hairpin-resonator bandpass filter with 2.07% fractional bandwidth at 965 MHz on an RT/Duroid substrate (not shown) with $\lambda_r = 10.8$ and a thickness $h = 1.27$ mm. The resonators are almost identical for this narrow-band filter. (b) Measured and theoretical responses of the filter.

The filter was fabricated on an RT/Duroid substrate with a relative dielectric constant of 10.8 and a thickness of 1.27 mm. The layout and dimensions of the filter are shown in Fig. 4(a), which is quite compact with an approximate size of $\lambda_{g0}/2$ by $\lambda_{g0}/8$, where λ_{g0} is the guided wavelength on the substrate at the midband frequency. The fabricated filter was measured on an HP 8510 network analyzer, with the measured and theoretical performance shown in Fig. 4(b). The passband insertion loss is approximately 3.8 dB. This is mainly due to the conductor loss for a resonator Q_0 around 250. The two transmission zeros near the cutoff of the passband can clearly be identified, which would result in higher attenuation if the resonator Q_0 were larger. The theoretical model seemed to work well over the passband, but there is higher attenuation in the stopband as predicted. The reason for this may be twofold. Firstly, the theoretical model was based on a complex transfer function of the lumped-element prototype which would only give a more accurate equivalence near the midband of our distributed-parameter filter. Secondly, the coupling beyond the nearest neighbors was ignored in the theoretical mode, and this type of the coupling could have a more significant effect on the stopband than on the passband.

V. Conclusions

We have introduced a new class of planar cross-coupled bandpass filters comprised of microstrip hairpin resonators. The feasibility of realizing the cross-coupled filters such as the canonical and the CQ filters has been described. In order to apply a practical design technique, which is based on the knowledge of coupling coefficients, the typical coupling coefficients of the four basic coupling structures encountered have been extracted from the full-wave simulations. The characteristics of the four types of couplings, namely the electric, magnetic, first type, and second type of mixed couplings have been investigated. For demonstration, we have designed and fabricated a four-pole cross-coupled filter of this type. Both theoretical and experimental performances of the filter have been presented. It has been shown that the capability of implementing transmission zeros, the compactness and flexibility in the size, and the simplicity in both the design and fabrication make the cross-coupled microstrip hairpin-resonator filters attractive for further development toward applications.

References

[1] E. G. Cristal and S. Frankel, "Hairpin-line and hybrid hairpin-line/half-wave parallel-coupled-line filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 719–728, Nov. 1972.

[2] M. Sagawa, K. Takahashi, and M. Makimoto, "Miniaturized hairpin resonator filters and their application to receiver front-end MIC's," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1991–1997, Dec. 1989.

[3] J. S. Hong and M. J. Lancaster, "Development of new microstrip pseudo-interdigital bandpass filters," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 261–263, Aug. 1995.

[4] G. L. Mattaei, N. O. Fenzi, R. Forse, and S. Rohlfing, "Narrow-band hairpin-comb filters for HTS and other applications," in *IEEE MTT-S Dig.*, San Francisco, CA, June 1996, pp. 457–460.

[5] S. Darlington, "Synthesis of reactance four poles which produce prescribed insertion loss characteristics," *J. Math. Phys.*, vol. 18, pp. 257–353, Sept. 1939.

[6] K. Jokela, "Narrow-band stripline or microstrip filters with transmission zeros at real and imaginary frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 542–554, June 1980.

[7] S. J. Yao, R. R. Bonetti, and A. E. Williams, "Generalized dual-plane multicoupled line filters," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 2182–2189, Dec. 1993.

[8] J. S. Hong and M. J. Lancaster, "Couplings of microstrip square open-loop resonators for cross-coupled planar microwave filters," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2099–2109, Nov. 1996.

[9] A. E. Williams and A. E. Atia, "Dual-mode canonical waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1021–1026, Dec. 1977.

[10] R. Levy, "Direct synthesis of cascaded quadruplet (CQ) filters," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2940–2945, Dec. 1995.

[11] B. I. Bleaney and B. Bleaney, *Electricity and Magnetism*, vol. 1, 3rd ed. Oxford, U.K.: Oxford Univ. Press, 1976, ch. 7.

[12] R. Levy, "Filters with single transmission zeros at real or imaginary frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 172–181, Apr. 1976.

[13] J. S. Wong, "Microstrip tapped-line filter design," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 44–50, Jan. 1979.

[14] D. G. Swanson, Jr., Guest Ed., "Engineering applications of electromagnetic field solvers," *Int. J. Microwave Millimeter-Wave Computer-Aided Eng.*, vol. 5, no. 5, Sept. 1995.