Multiple-Coupled Microstrip Hairpin-Resonator Filter

Yingjie Di, Peter Gardner, Peter S. Hall, H. Ghafouri-Shiraz, and Jiafeng Zhou

***Abstract*—This letter presents the design of six-resonator multiple-coupled microstrip filter. A low-pass prototype of six-resonator multiple-coupled filter is developed first based on the conventional Chebyshev filter. The characteristics of attenuation poles located on both sides of the frequency response are described. According to the low-pass prototype, the design of a six-resonator multiple-coupled microstrip hairpin filter at 6 GHz is completed with the aid of EM simulation. The experimental results are demonstrated and discussed.**

***Index Terms*—Cross coupling, multiple-coupled microstrip filter, resonator filter.**

I. INTRODUCTION

THE cross-coupled microstrip filters are attractive for its high selectivity and compact size. There are two classes of the cross-coupled filter: cascaded quadruplet (CQ) filter [1]–[5] and multiple-coupled filter [6], [7]. Although configuration of these two-class filters is different, the extra couplings are used to eliminate direct coupling and to introduce the transmission poles. There are a pair or more of the attenuation poles on the transmission response of filter. Because each cross coupling affects all the transmission poles, the realization of multiple-coupled filter is more difficult than CQ filter.

The designs of CQ microstrip filter working under 2.0 GHz have been fully investigated using different microstrip resonators [1], [3]–[5]. These designs are extremely successful except that of microstrip hairpin filter [5] where the stopband rejection is lower. The successful designs of multiple-coupled waveguide filter were presented in [6] and [7].

Due to the open field configuration of microstrip filter, there are undesirable cross couplings between resonators. Compared with the multiple coupled waveguide filter, multiple coupled microstrip filter are more difficult to realize. So few papers of multiple coupled microstrip filter were published.

In this letter, we introduce a new design of multiple-coupled microstrip hairpin filter. Based on the conventional Chebyshev filter we developed the low-pass prototype of six- resonator multiple-coupled filter which is described in Section II. The design procedure for six-resonator microstrip hairpin filter and measured results are presented in Section III. The discussion about this filter is given in Section IV.

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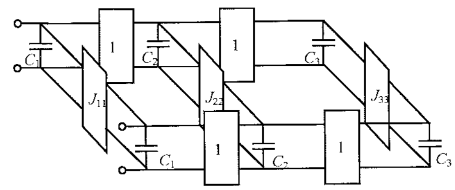

Fig. 1. Low-pass prototype of multiple-coupled filter.

II. THEORY

A. Frequency Responses

Fig. 1 shows the low-pass prototype of six-resonator multiple-coupled filter, where the boxes are the admittance inverters with parameter $J_{\rm ii}$ or 1. Because of weak coupling between C_1s, C_2s, like [2] another appointment we can adopt is C_1, C_2, and C_3 have respectively the same values with that of low-pass prototype Chebyshev filter. But the value of J_{33} is different from J'_{33} of Chebyshev filter in order to match the network. So, if $J_{11} = J_{22} = 0$, it gives the filter design with Chebyshev response by choosing $J_{33} = J'_{33}$.

At $\Omega = 0$, the odd-mode and even-mode input admittances should be equal to those of the Chebyshev filter. So, we can obtain the following relation between J_3, J_1 and J_2:

$$J_3 = \frac{(J'_{33} - C_1 J_1)/C_3}{1 + J_2 C_2 (J'_{33} - C_1 J_1)}$$

where $J_i = J_{ii}/C_i, \quad i = 1, 2, 3.$

B. Attenuation Poles

The cross couplings between $\mathrm{C_1s}, \mathrm{C_2s}$ may arise transmission poles (attenuation poles) rather than transmission zeroes in the filter transmission response. So the frequency response S_{21} at the location $\Omega = \pm\Omega_{\rm a}$ of the attenuation poles satisfies

$$S'_{21}(\pm\Omega_a) = 0$$

where S'_{21} is the derivative of S_{21}.

If cross couplings J_{11} and J_{22} are out of phase to J_{33}, there are a pair of transmission poles. If J_{11} is out of phase to J_{33} and J_{22} has the same phase as J_{33}, there are a pair or two pairs [see [6]] of transmission poles. The frequency response is given in Fig. 2 when $J_1 = J_2 = -0.02$ and with the 0.1 dB ripple level in the passband response. Fig. 3 shows variations of the location $\Omega_{\rm a}$ of attenuation pole and peak magnitude $L_{\rm peak}$ of S_{21} with cross coupling J_1 when $J_1 = J_2$ and with the same ripple as in Fig. 2. From Figs. 2 and 3, we can reckon that the closer the

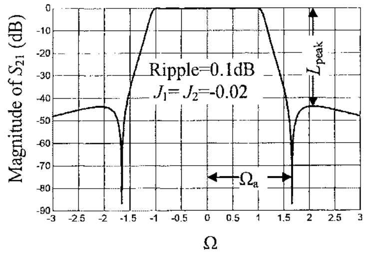

Fig. 2. Frequency response of multicoupled filter.

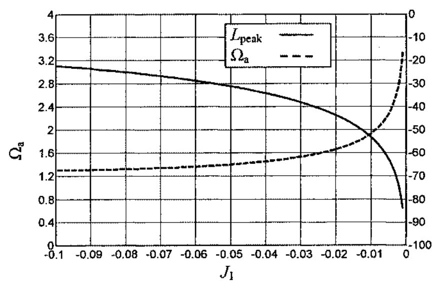

Fig. 3. Location Ω_a of attenuation pole and peak magnitude L_{peak} versus cross coupling J_1.

attenuation poles of the cutoff frequency ($\Omega = 1$), the higher peak magnitude L_{peak} of S_{21}.

III. Six-Resonator Multiple-Coupled Filter

We will complete the design of six-resonator multiple-coupled microstrip hairpin filter according the model described in II. The coupling characteristics between two hairpins are essential for our design. So the discussion about couplings of the microstrip hairpin resonators is presented first.

A. Coupling Between Two Microstrip Hairpins

As stated in [5], there are four basic coupled structures for the coupling of two microstrip hairpins. They respectively correspond to electric coupling, magnetic coupling, the first type of mixed coupling and the second type of mixed coupling.

The full-wave electromagnetic (EM) simulation can give the coupling coefficients between two microstrip resonators [1]. Only three basic structures of coupled microstrip hairpin resonators are used for our filter design. So Fig. 4(b)–(d) shows the coupling coefficients of them for the microstrip hairpin resonator specified in Fig. 4(a) which is fabricated on an RT/Duroid 6010 substrate with a relative dielectric constant of 10.8 and a thickness of 0.625 mm. All results in Fig. 4 are obtained using the HP-ADS design tool.

Fig. 4(c) shows the variation of magnetic coupling coefficient with respect to the resonator spacing for different normalized overlap length l_3/l_1. It is noted that the coupling becomes less dependent on the normalized overlap length l_3/l_1 when the coupling spacing is larger. So, this coupling needs the lower fabricating accuracy in the filter design if coupling spacing is large.

The solid line in Fig. 4(d) shows the coupling coefficients of the second type of mixed coupling between 0.2 mm–8.0 mm range of coupling spacing. We know by the simulation that the coupling characteristics exhibited in the second type of mixed

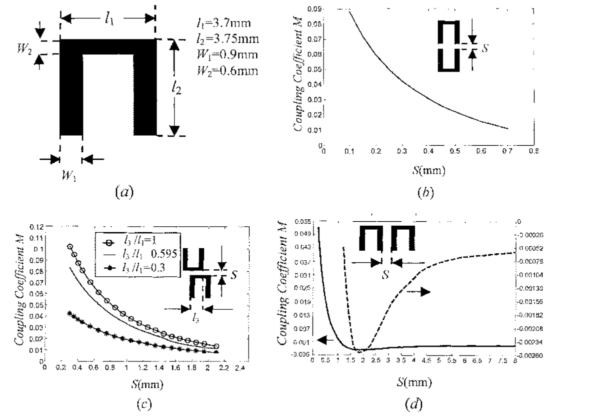

Fig. 4. Coupling coefficients for different coupling structures of coupled microstrip hairpin resonators.

coupling are dependent on the spacing S. When the coupling spacing is less than 1.2 mm, the electronic coupling is stronger than the magnetic coupling. So it exhibits the characteristics of the electronic coupling. When the spacing is greater than 1.2 mm, it exhibits the characteristics of the magnetic coupling. So, for this range of coupling spacing, negative coupling coefficients are illustrated in Fig. 4(d). The dashed line is the magnified curve of coupling coefficient (which can be read out from vertical axe on the right) in 1.2 mm–8.0 mm coupling spacing range. When the coupling spacing is greater than 1.2 mm, the coupling is undercoupling. In this case, the coupling efficient can't be obtained by the method of [1]. Alternative [8] is used for our simulation.

B. Specifications

The filter designed has the following specifications:

$$\text{Passband } (f_1\text{–}f_2)\text{: } 5.81 \text{ GHz–}6.07 \text{ GHz;}$$
$$\text{Stopband } (f_3\text{–}f_4, f_5)\text{: } 5.61 \text{ GHz–}5.69 \text{ GHz}, 6.3 \text{ GHz}$$

so

$$\text{Central frequency: } f_0 = 5.939 \text{ GHz;}$$
$$\text{Fractional bandwidth: FBW} = 4.38\%.$$

With the aid of the low-pass prototype filter of Fig. 1, the bandpass filter with a pair of attenuation poles could be synthesized. The attenuation pole should be located on f_4. That is, $\Omega_a = 1.956$ which corresponds to $J_1 = J_2 = -0.0094$ in Fig. 3.

For the 0.1 dB ripple level in the passband, the elements have the values: $C_1 = 1.1681, C_2 = 1.4040, C_3 = 2.0562$. So, the coupling coefficients [3] between elements are respectively: $M_{12} = 0.0342, M_{23} = 0.0258, M_{11} = M_{22} = -0.0004, M_{33} = 0.0254$. And the external quality factor of input or output resonator is $Q_e = 26.68$.

Fig. 5 shows the filter configuration with above specifications where $1, 2 \ldots 6$ in the hairpins are the numbers of resonator. The coupling coefficients M_{12} and M_{23} are realized, respectively, by the electric coupling in Fig. 4(b) and magnetic coupling in Fig. 4(c). The second type of mixed coupling realizes

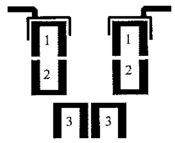

Fig. 5. Layout of six-resonator multiple microstrip filter.

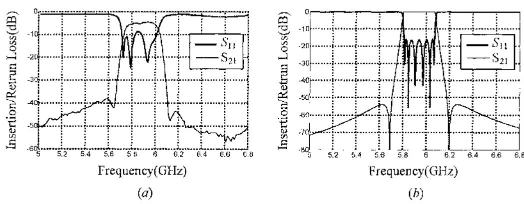

Fig. 6. (a) Measured and (b) theoretical frequency responses of six-resonator multiple-coupled hairpin filter.

M_{33} when coupling spacing is smaller. The weaker coupling coefficients M_{11} and M_{22} opposite to M_{33} are constructed by the second type of mixed coupling with larger coupling spacing. It should be mentioned that there are also weak couplings between resonator 1 on the left and 2 on the right, as well as resonator 2 on the left and 1 on the right. Because those couplings eliminate the couplings M_{11} and M_{22}, in the design we use $M_{11} = M_{22} = -0.0008$ that are larger than the theoretical value -0.0004.

The tapped-line feed or coupled-line feed can be used for the loaded external quality factor Q_e. We found by simulation that coupled-line feed with hairpin construction can present better coupling symmetry with the central frequency f_0 by controlling the length of arms. So our filter design chose the coupled-line feed which length of two arms is different. It can be seen in Fig. 5 that one of them is slightly longer than another.

C. Measured Results

The measured filter response is illustrated in Fig. 6(a). A pair of attenuation poles can clearly be observed. The passband insertion loss is approximately 4.5 dB, which includes the connector loss. The insert loss in passband is mainly due to the conductor loss of the hairpin resonators. Compared with Fig. 6(b) which is obtained by the theoretical model in Fig. 1, the passband and attenuation poles slight shift to the lower frequency. This is caused by the differences in the resonator's length between the theoretical results and fabricated results. By EM simulation, it is confirmed that for a resonator the difference of 0.1 mm in length causes a shift of its resonant frequency up to 0.35 MHz. Also, the frequency-dependent cross coupling M_{11} and M_{22} result to the asymmetric locations of attenuation poles in Fig. 6(a). And measured stopband rejection is lower than theoretical prediction. This discrepancy may be largely due to the low accurate equivalence of hairpin to the lumped resonator.

IV. Conclusion

We have presented the design of the six-resonator multiple-coupled microstrip hairpin filter. We calculated first the coupling coefficients of two resonators and external quality factor based on the low-pass prototype of multiple-coupled filter. In the filter construction of microstrip hairpin resonator, the spacings between two resonators were determined by the corresponding coupling coefficients that were obtained by EM simulation using two methods. The tapped-line feed or coupled-line feed can also meet the external quality factor, but latter has better coupling symmetry for the optimal length of coupled arms. The measured performance of filter designed was also presented. The multiple-coupled microstrip hairpin filter designed due to smaller size and high selectivity is attractive for the communication applications.

The theoretical model used is also suitable for design of other filter structures such as waveguide filter design.

References

[1] 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, 1996.

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

[3] J. S. Hong and M. J. Lancaster, "Theory and experiment of novel microstrip slow-wave open-loop resonator filters," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 2358–2365, 1997.

[4] ——, "Design of highly selective microstrip bandpass filters with a single pair of attenuation poles at finite frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 1098–1107, 2000.

[5] ——, "Cross-coupled microstrip hairpin-resonator filters," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 118–122, 1998.

[6] A. E. Atia, A. E. Williams, and R. W. Newcomb, "Narrow-band multiple-coupled cavity synthesis," *IEEE Trans. Circuits Syst.*, vol. CAS-21, pp. 649–655, 1974.

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

[8] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Couplings Structures*. Dedham, MA: Artech House, 1980, vol. 11, pp. 663–668.