Millimeter-Wave Coplanar-Waveguide Parallel-Coupled Bandpass Filters With Lumped-Element K-Inverters

Yo-Shen Lin, Min-Shun Hsu, Chi-Hsueh Wang, and Chun Hsiung Chen

Department of Electrical Engineering and Graduate Institute of Communication Engineering, National Taiwan University, Taipei 106, Taiwan, +886-2-23635251-209

***Abstract* — Compact coplanar-waveguide (CPW) bandpass filters are proposed, by introducing additional lumped inductor and capacitors to realize K-inverters in the conventional CPW parallel-coupled filter structure for achieving an equivalent to the quarter-wavelength resonator filters. As a result, the filter size may be reduced by about half. In addition, by introducing the cross-coupled effect, two transmission zeros at upper and lower stopbands may be created. Simple equivalent-circuit models are also established as effective design tools. Specifically, two CPW bandpass filters centered at about 40GHz with compact sizes and good selectivity are implemented and carefully examined.**

I. INTRODUCTION

Coplanar waveguide (CPW) structure has gain substantial research interests due to the advantages such as lower dispersion and easier to integrate with solid-stated devices [1]. Various works on CPW bandpass filters were reported in the literature, and the parallel-coupled bandpass filters based on quarter-wavelength (λ/4) coupled-line sections were widely used for their easy realization in planar circuits, wider range of realizable bandwidths, and simple synthesis procedure [2]. The edge-coupled CPW bandpass filter [3] was designed based on the symmetrical CPW coupled-line sections. The ribbon-of-brick-wall type CPW bandpass filter [4] based on the three-line CPW coupled-line structure may achieve larger amount of coupling thus wider bandwidth. Alternatively, shorted CPW coupled-line sections, or coupled-slots, may also be implemented in CPW bandpass filter design [5]. Compared to their microstrip counterpart, the CPW parallel-coupled bandpass filters have the advantage that the coupled-line impedances are mainly determined by the ratio of strip and slot widths. Therefore, the realizable impedance ranges of CPW coupled-line for a given substrate are larger, which is favorable for designing bandpass filters with wider ranges of 3-dB bandwidth.

In modern communication system applications, it is necessary to have filters with very good selectivity for better image or interference rejection. Therefore, improvements on achieving additional transmission zeros to the conventional CPW parallel-coupled bandpass filters were also reported. In [6], the capactively coupled gap and the λ/4 open stubs were adopted for creating two transmission zeros. In [7], the CPW quasi-elliptic bandpass filters based on stepped-impedance resonators may also achieve good selectivity and compact size.

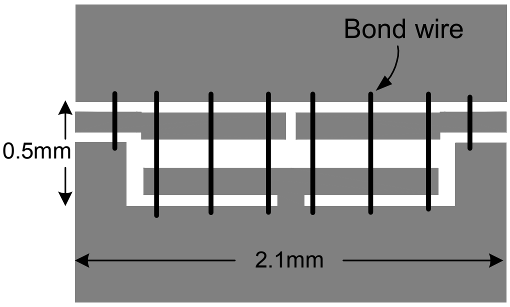
In our previous works [8]-[10], novel parallel-coupled bandpass filters with additional lumped inductor as K-inverter and cross-coupling effect were proposed to achieve compact size and two transmission zeros. In this study, the 2nd-order filter structure in [8] is adopted for the design of a compact CPW bandpass filter at millimeter-wave frequencies. In addition, a novel 4th-order filter structure is also proposed for achieving better performance and more compact circuit size. Simple design formulas for the proposed filters may also be obtained based on the proposed equivalent-circuit models and the conventional filter synthesis technique.

II. FILTER STRUCTURES

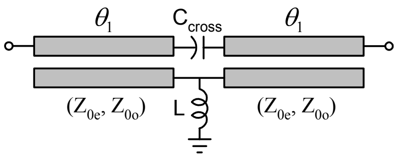
A. 2nd-order Filter

Shown in Fig. 1(a) is the layout of proposed CPW parallel-coupled bandpass filter of 2nd-order, with its equivalent-circuit model in Fig. 1(b). It is based on two cascaded coupled-line sections of electrical length $\theta_1 \approx 90^o$ with an additional shunt inductance L in-between. Here the symmetrical CPW coupled-line structure is adopted in Fig. 1(a). The shunt inductor L is realized by a metal strip connected to the ground plane. The inductance value can be adjusted by varying the length and width of the metal strip. In order to suppress the unwanted odd CPW mode, bond-wires at suitable positions are also included. The capacitor C_{cross} in the circuit model [Fig.1(b)] represents the gap-coupled capacitance between the open-ends of two adjacent coupled-line sections, which is used to provide a cross-coupled path such that two transmission zeros at the upper and lower stopbands may be created [8].

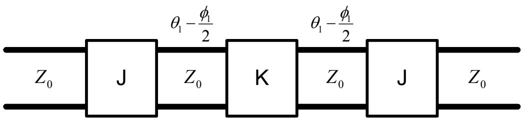
By noting that the signal through the cross-coupled path is substantially less than the one through the main path [8], the design of proposed filter can be simplified by first letting C_{cross} = 0 in Fig. 1(b). The equivalent-circuit model of the filter in Fig. 1(a) can then be obtained as shown in Fig. 1(c). Here the symmetrical CPW coupled-line is modeled by a J-inverter along with two transmission lines of electrical length θ_1. The shunt inductor L along with two transmission lines of length $\phi_1/2$ are modeled by a K-inverter. Therefore, by letting C_{cross} = 0 in Fig. 1(b), the equivalent-circuit model of the filter may be equivalent to that of a 2nd-order λ/4



(a)

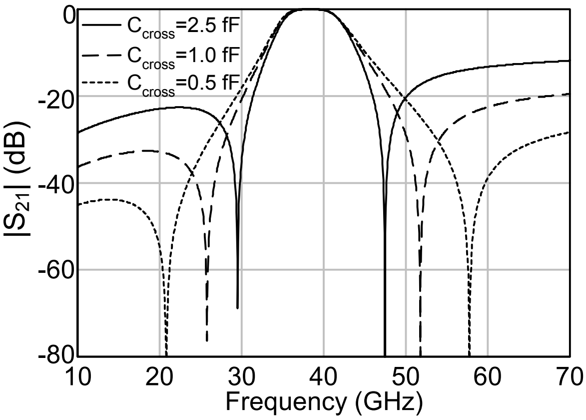


(b)

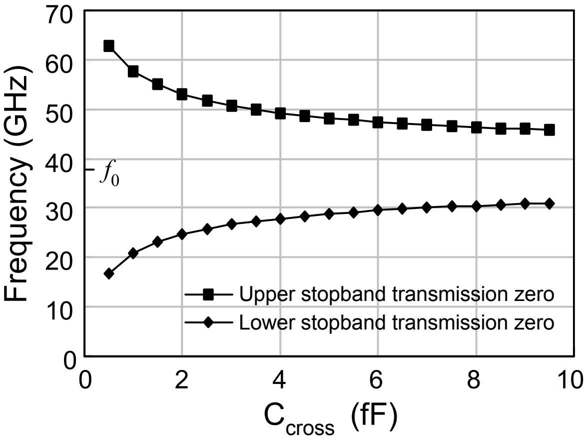


(c)

Fig. 1. 2nd-order CPW parallel-coupled filter with lumped-element K-inverter. (a) Layout, (b) circuit model, and (c) equivalent-circuit model to illustrate the equivalence between Fig. 1(a) and the 2nd-order λ/4 resonator filter when $C_{cross} = 0$ and $\theta_1 - \phi_1/2 = \pi/2$.



(a)



(b)

Fig. 2. (a) Simulated frequency responses of proposed 2nd-order parallel-coupled bandpass filter in Fig. 1(b) for different values of cross-coupled capacitance C_{cross}. (b) Simulated relationship between the locations of transmission zeros and the values of C_{cross}. (f_0=38GHz, Z_{0e}=72.22Ω, Z_{0o}=38.89Ω, θ_1=83.66°, and L=23.55pH.)

resonator bandpass filter as shown in Fig. 1(c). As a result, the filter order is doubled with the additional inductor L compared to the conventional parallel-coupled filter [2]-[6].

As illustrated in [8], the C_{cross} provides a cross-coupled path along which the signal would cancel the one traveling along the main path of the filter at two frequencies, such that the overall filter response has two transmission zeros. Typical simulated responses of the filter structure in Fig. 1(b) are shown in Fig. 2. As C_{cross} increases with reducing gap width, the two transmission zeros move toward the center frequency f_0 at the expense of decreasing insertion loss in the stopband.

B. 4th-order Filter

Shown in Fig. 3(a) is the layout of proposed 4th-order CPW parallel-coupled bandpass filter with lumped-element K-inverters. The corresponding circuit model is shown in Fig. 3(b). It is based on an extension of the 2nd-order filter in Fig. 1(b) with additional shunt capacitors C_1 and transmission line sections introduced at the input and output ports to realize K-inverters [11]. The small cross-coupling capacitance C_{cross} is again introduced for generating two transmission zeros. Compared to the 4th-order parallel-coupled λ/4 resonator filter in [10], the proposed filter has the advantage that the cross-coupled capacitance may now be easily achieved by the gap-coupled capacitance without having to bend the two coupled-line sections.

By first letting $C_{cross} = 0$ in Fig. 3(b), the equivalent-circuit model of the filter in Fig. 3(a) can be obtained as shown in Fig. 3(d), which is equivalent to a 4th-order λ/4 resonator filter when $\theta_1 - \phi_2/2 = \theta_2 - \phi_1/2 = \pi/2$. As a result, the proposed filter may be simply designed based on the conventional filter synthesis techniques for λ/4 resonator filters [12]. Given the desired center frequency, 3dB bandwidth, and reference impedance, one may determine the required values of J- and K-inverters in Fig. 3(d) through the conventional filter synthesis technique. The corresponding circuit parameters in Fig. 3(b) are then obtained from the J- and K-inverter values, with $\theta_1 = \pi/2 + \phi_2/2$ and $\Delta\theta = \phi_1/2 - \phi_2/2$. The cross-coupled element C_{cross} is included later and its value is chosen for the desired locations of transmission zeros.

As shown in Fig. 3(a), an additional ground line is inserted between the parallel-coupled CPW to reduce the amount of coupling. Therefore, the gap between coupled-lines can be made smaller to avoid large power loss for narrowband designs as in [7]. The shunt inductor in the circuit model [Fig. 3(b)] is now realized by two shunt-connected metal strips to ground, which also connect the two ground planes and the center ground strip. As a

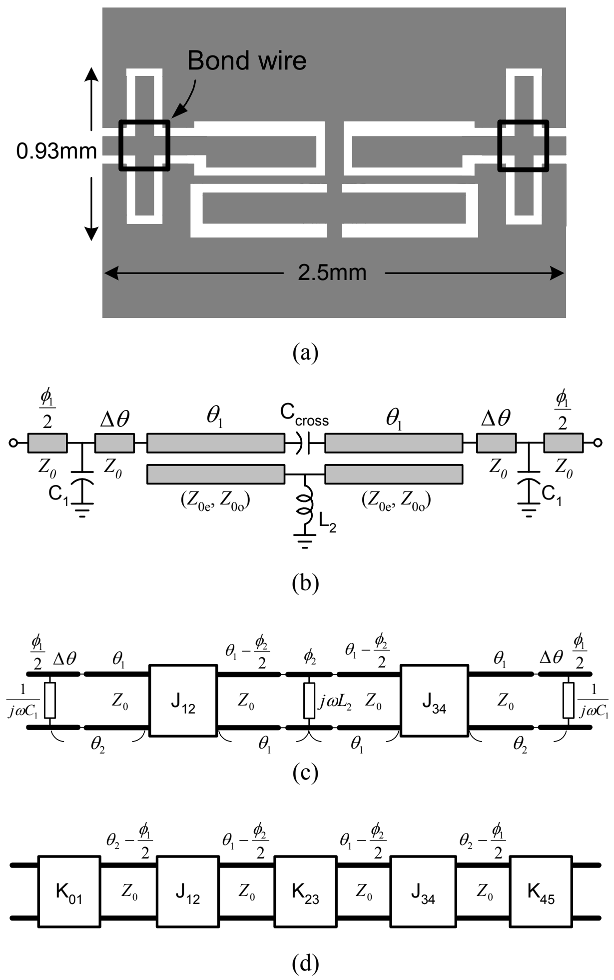


Fig. 3. Proposed 4th-order CPW parallel-coupled bandpass filter with lumped-element K-inverters. (a) Layout. (b) Circuit model. (c)-(d) Equivalent-circuit models to illustrate the equivalence between Fig. 3(a) and the 4th-order λ/4 resonator filter when $C_{cross} = 0$ and $\theta_1 - \phi_2/2 = \theta_2 - \phi_1/2 = \pi/2$.

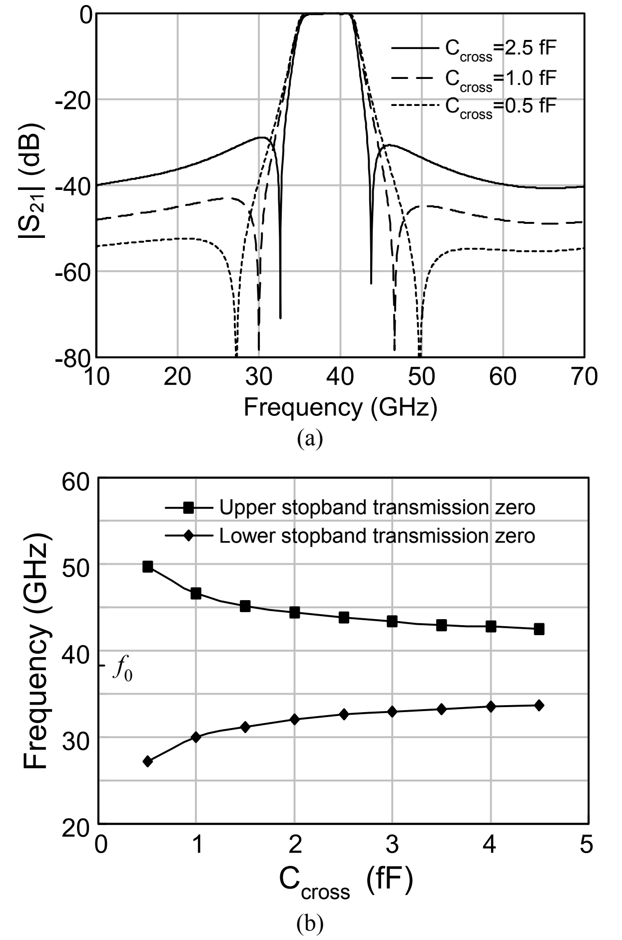


Fig. 4. (a) Simulated frequency responses of proposed 4th-order parallel-coupled bandpass filter in Fig. 3(b) for different values of cross-coupled capacitance C_{cross}. (b) Simulated relationship between the locations of transmission zeros and the values of C_{cross}. (f_0=38GHz, Z_{0e}=57.48Ω, Z_{0o}=44.27Ω, Z_0=50Ω, θ_1=85.14°, $\Delta\theta$=29.23° and L=0.01793nH.)

result, compared to Fig. 1(a), no bond wires across the coupled-lines are required for this filter structure. The shunt capacitors C_1 in Fig. 3(b) are realized by CPW shunt open-stubs. The length and width of each open stub can be properly chosen for creating one additional transmission zero at the upper stopband when its length reaches a λ/4.

Shown in Fig. 4 are the typical simulated frequency responses of proposed 4th-order filter structure in Fig. 3(b). Compared to Fig. 2, the filter selectivity is largely improved due to an increase in filter order. One may suitably choose the value of C_{cross} for the desired level of selectivity and stopband rejection.

For the conventional parallel-coupled filter of 4th-order [2]-[6], five cascaded λ/4 coupled-line sections are required. On the other hand, for the proposed filter in Fig. 3(a), only two parallel-coupled line sections of approximately λ/4 long are needed. Therefore, the size of proposed filter is about half that of the conventional ones of the same order.

III. RESULTS

A CPW bandpass filter for Fig. 1(a) is fabricated on an Al_2O_3 substrate (ε_r = 9.9, thickness h = 0.381mm, tanδ = 0.002). The center frequency f_0 is designed at 38.5 GHz. The simulation is done by the full-wave simulation tool Ansoft Ensemble. The measured and simulated results are shown in Fig. 5. Good agreement between them is obtained except for some frequency shift. The measured f_0 is at 41 GHz, and the passband insertion loss is about 1.85 dB. Two transmission zeros are observed as expected, which greatly improve the filter selectivity.

The 4th-order CPW filter in Fig. 3(a) is also fabricated on the same Al_2O_3 substrate. The measured and simulated results are shown in Fig. 6. The measured insertion loss is less than 2dB from 37 ~ 43 GHz. Two transmission zeros are observed at 32.5GHz and 47GHz. Compared to Fig. 5, better filter selectivity is obtained. Note that the length of the filter in Fig. 3(a) is only a little longer than 2/3λ at f_0, making it much smaller than the conventional CPW parallel-coupled filters of the same order.

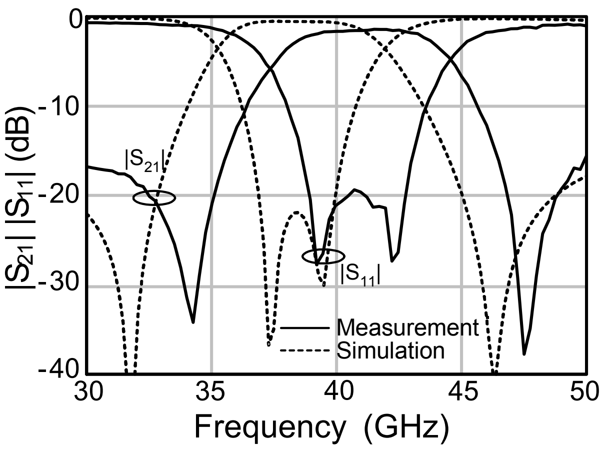


Fig. 5. Measured and simulated results for the CPW filter in Fig. 1(a).

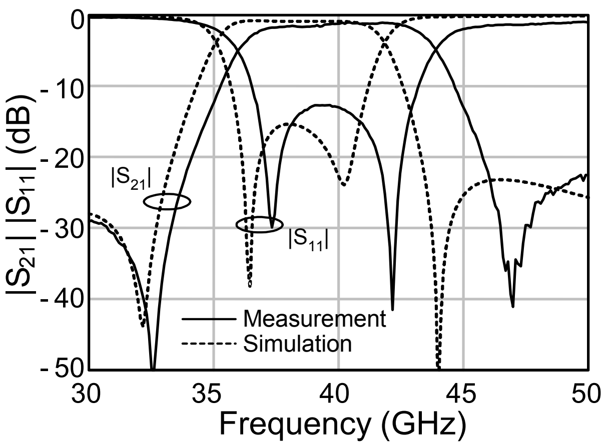


Fig. 6. Measured and simulated results for the CPW filter in Fig. 3(a).

Based on the proposed circuit models, the proposed filter structures may be simply extended to realize higher-order filters for better performance. One may also implement the proposed filters using the stepped-impedance resonators for further size reduction as in [7].

VI. Conclusion

In this study, two compact CPW parallel-coupled bandpass filters have been proposed and carefully examined. By introducing additional lumped-elements to realize K-inverters, along with the cross-coupled effect, the proposed bandpass filters may achieve about half the circuit area of conventional ones and two transmission zeros at upper and lower stopbands. Based on the proposed equivalent-circuit model and the conventional filter synthesis technique for $\lambda/4$ resonator filter, the design equations can be simply obtained. The effectiveness of proposed filters for millimeter-wave applications is also demonstrated by measured results.

Acknowledgement

This work was supported by the National Science Council of Taiwan under Grant NSC 93-2752-E-002-001-PAE and Grant NSC 93-2219-E-002-021.

References

[1] K. C. Gupta, R. Garg, and I. J. Bahl, *Microstirp lines and slotlines*, 2nd ed. Norwood, MA: Artech House, 1996, ch. 7.

[2] C.-Y. Chang and T. Itoh, “A modified parallel-coupled filter structure that improves the upper stopband rejection and response symmetry,” *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 310-314, Feb. 1991.

[3] S. Uysal, “Coplanar waveguide edge-coupled bandpass filters with finite ground planes,” *Electronic Lett.*, vol. 30, no. 22, pp. 1862-1863, Oct. 1994.

[4] F.-L. Lin, C.-W. Chiu, and R.-B. Wu, “Coplanar waveguide bandpass filter – a ribbon-of-brick-wall design,” *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1589-1596, July 1995.

[5] T. M. Weller, “Edge-coupled coplanar waveguide bandpass filter design,” *IEEE Trans. Microwave Theory Tech.,* vol. 48, pp. 2453-2458, Dec. 2000.

[6] J.-S. Chih, C.-H. Wang, Y.-S. Lin, and C. H. Chen, “Coplanar-waveguide coupled-line bandpass filter with attenuation poles in upper and lower rejection bands,” in *2003 Asia-Pacific Microwave Conference,* pp. 1489-1492.

[7] J. Zhou, M. J. Lancaster, and F. Huang, “Coplanar quarter-wavelength quasi-elliptic filters without bond-wire bridges,” *IEEE Trans. Microwave Theory Tech.,* vol. 52, pp. 1150-1156, April 2004.

[8] C.-H. Wang, Y.-S. Lin, and C. H. Chen, “Novel inductance-incorporated microstrip coupled-line bandpass filters with two attenuation poles,” in *IEEE MTT-S Int. Microwave Symposium Dig.,* 2004, pp. 1979-1982.

[9] Y.-S. Lin, M.-S. Hsu, C.-H. Wang, and C. H. Chen, “Compact lumped-distributed parallel-coupled bandpass filters based on conductor-backed coplanar-waveguide,” in *2004 Asia-Pacific Microwave Conf. Abstract* pp. 925.

[10] Y.-S. Lin, C.-H. Wang, C.-H. Wu, and C. H. Chen, “Novel compact parallel-coupled microstrip bandpass filters with lumped-element K-inverters,” to appear in *IEEE Trans. Microwave Theory Tech.*, vol. 53, July 2005.

[11] Y.-S. Lin, H.-M. Yang, and C. H. Chen, “Miniature microstrip parallel-coupled bandpass filters based on lumped-distributed coupled-line sections,” in *IEEE MTT-S Int. Microwave Symposium Dig. CDROM,* 2005.

[12] G. L. Mattaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*. Norwood, MA: Artech House, 1980.