Size Reduction and Harmonic Suppression of Parallel Coupled-Line Bandpass Filters Using Defected Ground Structure

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***Abstract*―** A novel miniaturized parallel coupled-line bandpass filter with suppression of second, third and fourth harmonic frequencies, is demonstrated in this paper. The new filter is based on the slow-wave effect of the Defected Ground Structure (DGS) to achieve size minimization, while the spurious responses are eliminated by the band-rejection property of the DGS unit. These features offer the classical parallel coupled-line bandpass filter simultaneous compactness and wide stopband performance. Using the proposed DGS unit, does not require the filter parameters to be recalculated and, this way, the classical design methodology for microstrip parallel coupled-line filters can still be used. As an example, a 2.0 GHz parallel coupled-line filter has been designed and measured in order to show the validity of the proposed DGS. Compared with the conventional parallel coupled-line bandpass filters, the second, third and fourth measured spurious responses are suppressed to -45, -43 and -34 dB, respectively. In addition, the size of the prototype filter is reduced by 20% compared to that of the conventional parallel coupled-line filter.

***Index Terms*―** Coupled line filter, bandpass filter, Defected Ground Structure.

I. INTRODUCTION

Designing a bandpass filter with wide bandwidth, compact size, low insertion loss and also wideband rejection is still a challenging task. In planar microstrip realization, one of the most common implementation methods is to use a cascade of parallel coupled sections. Although this type of filter is indeed very popular and simple to implement, it does suffer from a fundamental limitation, namely, the presence of spurious responses which are generated at multiples of center frequency f_0, due to the unequal even- and odd-mode phase velocities of the coupled line. To eliminate these unwanted responses, especially for the second and third spurious responses, some methods have been recently proposed. In [1] and [2], an over-coupled resonator is proposed to extend phase length for the odd-mode to compensate difference in phase velocities. The structures in [3] and [4] use capacitors to extend the traveling path of the odd-mode. In [5], the authors used substrate-suspension technology with similar effectiveness. In addition to these structures, sinusoidal perturbation along the coupled-line width has been used [6]. The periodic sinusoidal perturbation offers wave impedance modulation so as to yield Bragg reflection at some frequencies. Besides the sinusoidal etching, indentation of rectangular-wave contour (square grooves) is presented in [7] and [8] and identical even- and odd-mode electrical lengths are achieved. Recently, Ahn [9] have studied parallel coupled-line resonators with defected ground structures (DGS) for suppression of the first spurious harmonic.

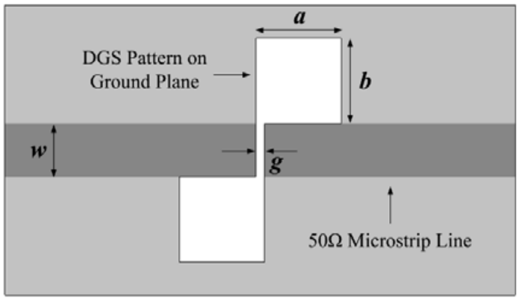


Fig. 1. Schematic top view of a slanted dumb-bell shaped DGS unit (w= 3.09 mm, a=b=5 mm, g=0.5 mm).

In addition to the disadvantage of spurious responses, the conventional parallel coupled-line bandpass filter occupies large circuit size due to long strips of resonant conductors, which render the process inefficient and costly. In order to filter-size diminution, a novel terminated parallel coupled-line was recently proposed by Cheong [10]. This new coupled-line element cascade configuration leads to a new *N*-stage parallel coupled-line bandpass filter. In addition to this structure, Liu [11] introduced modified maximally flat parallel coupled-lines resonators by using enhanced coupling techniques.

Despite the above methodological differences, none have provided simultaneous multispurious suppression and major size reduction. In this paper, a novel DGS structure for microstrip parallel coupled-line filters is proposed to suppress the second, third and fourth harmonics simultaneously. Using the proposed DGS structure, the size of a parallel coupled-line filter is reduced up to 20% compared to that of the conventional parallel coupled-line filter, due to the slow-wave effect. In addition, the design procedure is very simple and does not need a recalculation of the coupled-line dimensions (space between lines and line width). This enhanced performance of the proposed bandpass filter has been verified by simulation and measurement; and a good agreement between these results is obtained.

II. CONFIGURATION AND EQUIVALENT CIRCUIT OF SLANTED DUMB-BELL DGS

Electromagnetic bandgap (EBG) and the defected ground structures (DGS) have recently gained numerous applications in microwave and millimeter-wave frequency bands with various configurations [12]–[16]. The DGS of a microstrip line is implemented by making artificial defect on the ground. Ground defect changes the distribution of shield current in the ground plane and the properties of microstrip changes accordingly.

The configuration of the proposed DGS on the ground plane of a microstrip line is shown in Fig. 1. It has a 50-Ω microstrip line on the top and a slanted dumb-bell shaped pattern which is etched in the ground plane. Slanted dumb-bell shaped DGS consists of two rectangular defects which are positioned in an aslant fashion and a slim vertical gap, wherein defects are coupled through the gap. This DGS was chosen with respect to the structure of the parallel coupled-line filter, since a normal dumb-bell shaped DGS may not be applied to a parallel coupled-line filter properly and it can overlap the adjacent resonators, thereby causing failure during the filter's operation.

As shown in Fig. 1 the microstrip line width is chosen as w=3.09 mm, for the 50Ω characteristic impedance. The substrate used in the simulation has the same parameters as FR4 with a board thickness of 1.5 mm. Simulation results are shown in Fig. 2, which illustrate the characteristic of a one-pole low-pass filter. The simulations are performed using CST Microwave Studio simulator which is based on finite integral technique.

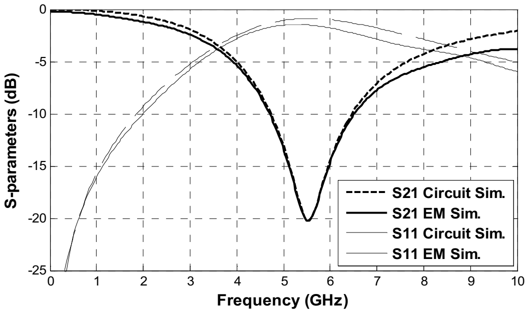


Fig. 2. EM and circuit simulations S-parameters.

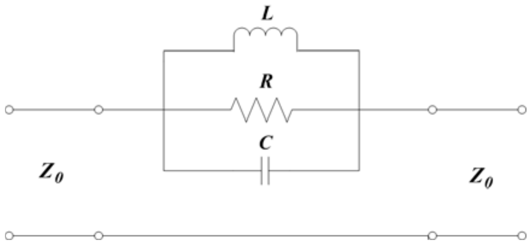


Fig. 3. Equivalent circuit of the microstrip line with one DGS unit.

As shown in Fig. 3, the frequency characteristics of the proposed DGS can be modeled by a simple parallel RLC resonator circuit which blocks the signal as an open at the resonant frequency [17]. The parameters of the equivalent circuit can be extracted from the simulated transfer characteristics. The inductance and the capacitance of the parallel RLC resonant circuit are related to the shape of the defects, as well as the gap width between the two left-hand-side defect and right-hand-side defect. This parallel RLC resonance can be used to reduce the length of the open transmission line resonator and shift the spurious response of an open transmission line resonator to a higher frequency such that interference can be minimized. By the modeling technique in [17], the circuit parameters can be determined from equations (1)-(3).

$$C = \frac{\omega_c}{2Z_0(\omega_0^2 - \omega_c^2)} \tag{1}$$

$$L = \frac{1}{4\pi^2 f_0^2 C} \tag{2}$$

$$R = \frac{2Z_0}{\sqrt{\frac{1}{|S_{11}(\omega_0)|^2} - \left(2Z_0\left(\omega_0 C - \frac{1}{\omega_0 L}\right)\right)^2 - 1}} \tag{3}$$

Here, ω_0 is the angular resonant frequency, ω_c is the lower 3-dB cutoff angular frequency, and Z_0 is the characteristic impedance of the microstrip line. Fig. 2 compares the S-parameters calculated by electromagnetic (EM) simulation for slanted dumb-bell shaped DGS in Fig. 1 and those calculated using the equivalent circuit in Fig. 3. Circuit simulation is performed by employing Advanced Design System (ADS) simulator.

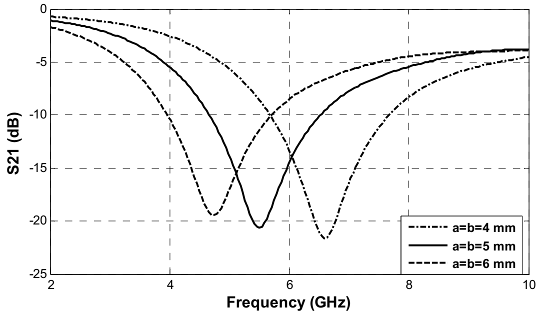


Fig. 4. Simulated insertion loss of slanted dumb-bell shaped DGS unit with different sizes. Here g=0.5 mm, the relative dielectric constant of the substrate is 4.4 and the thickness of the substrate is 1.5 mm.

For the slanted dumb-bell cell shown in Fig. 1, the resonant frequency (f_0) depends on the physical dimensions of the cell. For example f_0 can be reduced by using smaller gap g, larger a, or larger distance between the two squares. In fact, the etched gap and the etched square defect are related with the effective capacitance and inductance of the microstrip line. As the etched area of the square defect is decreased and the gap distance is kept constant to 0.5 mm, the effective series inductance decreases, and decreasing the series inductance gives rise to a higher cutoff frequency, as seen in Fig. 4. Since g is generally limited by PCB fabrication techniques, increasing the size of the cell is the practical approach of reducing the resonant frequency.

III. MICROSTRIP PARALLEL COUPLED-LINE BPF WITH SLANTED DUMB-BELL DGS

In order to demonstrate the effectiveness of the proposed DGS pattern, a parallel coupled-line filter with 2.0 GHz center frequency and 10% fractional bandwidth with slanted dumb-bell DGSs has been designed, and compared with a conventional parallel coupled-line filter. Same procedure can be used for harmonic suppression and size reduction of the parallel coupled-line filters with different response specifications.

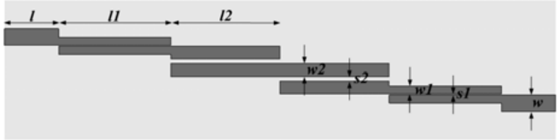


Fig. 5. Schematic top view of a three-order conventional parallel coupled-line filter (l_1=20.70 mm, l_2=20.08 mm, l=10 mm, w_1=1.53 mm, w_2=2.45 mm, w=3.09 mm, s_1=0.15 mm, s_2=0.77 mm, ε_r =4.4).

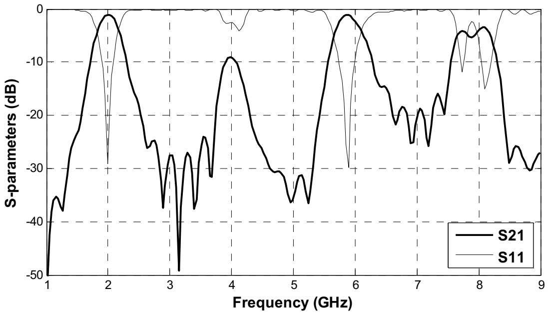
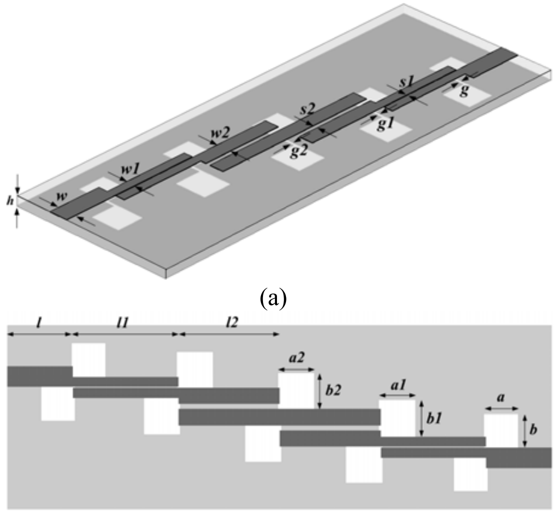


Fig. 6. Simulated S-parameters of the conventional parallel coupled-line filter.

Conventional parallel coupled-line filter exhibiting an N-order filter response comprises of N open transmission line resonators which are designed to have a length of approximately half of the wavelength, $\lambda_g/2$, at the center frequency. Therefore, the physical size of the conventional parallel coupled-line filter is large due to the length of the open transmission line resonators. This is a major disadvantage because it can be inefficient and costly for circuit applications.

Dimensions of a conventional parallel coupled-line filter are calculated for maximally flat response using [18]. Fig. 5 shows the design parameters of the conventional parallel coupled-line filter. A substrate with dielectric constant of 4.4 and a thickness of 1.5 mm is used.



(a)

(b)

Fig. 7. Proposed parallel coupled-line filter (a) 3D view and (b) top view (l_1=15.70 mm, l_2=15.08 mm, l=10 mm, w_1=1.53 mm, w_2=2.45 mm, w=3.09 mm, s_1=0.15 mm, s_2=0.77 mm, ε_r=4.4, h=1.5 mm, a=b=5.1 mm, a_1=b_1=5.5 mm, a_2=b_2=5.5 mm, g=g_1=g_2=0.5 mm).

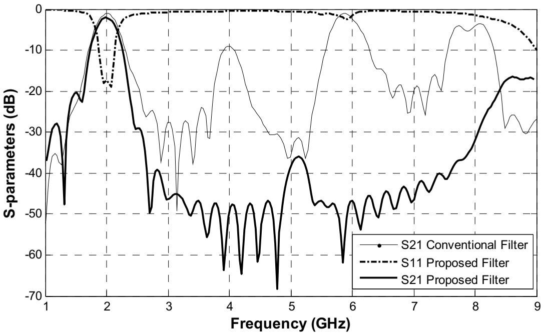


Fig. 8. Comparison between the simulated S-parameters of the proposed and conventional parallel coupled-line filter.

Simulated S-parameters of the conventional filter are shown in Fig. 6. The response curve shows that the spurious harmonics of the parallel coupled-line filter are around 4, 6, 8 GHz, which are multiples of the center frequency. This is another disadvantage of the conventional parallel coupled-line filter, because many other circuits can generate unwanted harmonics at these frequencies.

The configuration of the proposed parallel coupled-line filter with five slanted dumb-bell shaped DGS sections is illustrated in Fig. 7. To simplify the design process and simple fabrication, the etched pattern is symmetrically located under the microstrip line. The lattice dimensions of the 1st and 5th DGS sections and the 2nd, 3rd and 4th DGS sections are similar and are assigned to be 5.1 mm× 5.1 mm and 5.5 mm× 5.5 mm, respectively. The etched gap width is chosen to be 0.5 mm for both types of the DGS units. The length of the narrow gap is the same as the line-width of the corresponding open transmission line resonators.

The increase in effective inductance from insertion of the DGS can provide longer electrical length of transmission line than that of a conventional line, which enables size reduction of resonators. Since, the filter consists of three open transmission line resonators; we use three DGS units for size reduction i.e. 2nd, 3rd and 4th DGS units. Except the length of the resonators, other design parameters of the conventional parallel coupled-line filter remain intact. The 1st and 5th DGS units do not have any impact on the length, center frequency and bandwidth of the filter but are used to suppress the harmonic produced in 5.20 GHz (Fig. 8). As shown in Fig. 5 and Fig. 7, the conventional parallel coupled-line filter has the total length of 101 mm while the size of parallel coupled-line filter with slanted dumb-bell shaped DGS is 81 mm, this results 20% size reduction.

The band-rejection property of the DGS can be utilized in selective suppression of the unwanted harmonics. Since the resonant frequency of the DGS depends on the size of the defect on the ground, we need to adjust the size of defects to suppress the second, third and fourth harmonics simultaneously. Comparison of transmission characteristics between conventional and proposed parallel coupled-line filter described in Fig. 7 is given in Fig. 8. The simulation, exhibits that the proposed filter has successfully improved the spurious harmonics at $2f_0$, $3f_0$ and $4f_0$. The center frequency and bandwidth of the fundamental passband is kept as in the original filter and no significant deviation is observed. Furthermore, the insertion and return losses are -2.45 dB and -18.77 dB at the center frequency, respectively. The insertion loss is slightly larger due to the use of the DGS and high dielectric losses with loss tangent of 0.02.

Fig. 9 shows a general circuit model for modeling a parallel coupled-line filter with slanted dumb-bell shaped DGS. Each one of the DGS units is modeled with a parallel RLC resonant circuit, placed in series along the transmission line. Circuit parameters can be easily found from EM simulations using equations (1)-(3). Fig. 10 shows the S_{21} calculated by electromagnetic (EM) simulation and those calculated by using the equivalent circuit in Fig. 9. The equivalent-circuit simulation is performed by employing ADS. For S_{21} simulation, circuit simulation agrees with EM simulation at the low frequency region below 6 GHz. The difference at high frequencies is due to the radiation at DGS sections. In both simulations, it may be observed that the second, third and fourth harmonics are suppressed simultaneously by using DGS units.

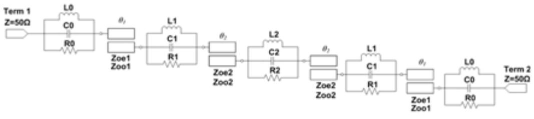


Fig. 9. Equivalent circuit model of the proposed parallel coupled-line bandpass filter.

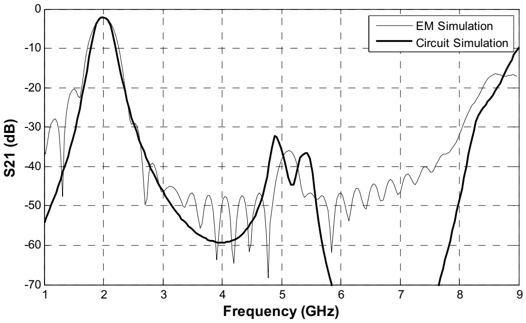
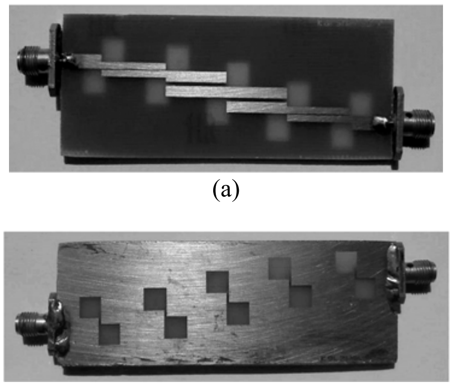


Fig. 10. S-parameters by EM and circuit simulations for the proposed parallel coupled-line filter.

IV. EXPERIMENT AND MEASUREMENT

An experimental parallel coupled-line filter is constructed using the results of the simulation. Fig. 11 shows the top and bottom views of the fabricated parallel coupled-line filter with slanted dumb-bell shaped DGS.

The measurements were performed with a vector network analyzer (Agilent 8722ES). Fig. 12 provides a comparison between simulated and measured transmission characteristics of the proposed parallel coupled-line filter. Good agreement between simulations and experimental data has been obtained. The little differences found can be due to the tolerances in the fabrication process.



(a)

(b)

Fig. 11. Fabricated parallel coupled-line filter with slanted dumb-bell shaped DGS (a) top view and (b) bottom view.

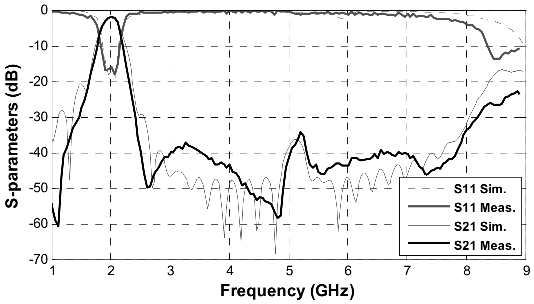


Fig. 12. Measured and simulated S-parameters of the proposed filter.

V. CONCLUSION

In this letter, a compact parallel coupled-line filter having harmonic suppression has been presented. Due to the increased slow wave factor and electrical length of the microstrip line with slanted dumb-bell shaped DGS, the size of the original parallel coupled-line filter has been reduced successfully without any critical deviation in center frequency and bandwidth. In addition, because of the band-rejection property of the slanted dumb-bell shaped DGS, the second, third and fourth harmonic frequencies are rejected. The proposed parallel coupled-line filter has been modeled by an equivalent-circuit and the simulation results of circuit modeling were in good agreement with those of EM simulation. By the simulation and experimental results of a 2.0

GHz prototype filter with 10% fractional bandwidth, 20% size miniaturization and a rejection level of better than 34 dB until $4f_0$ in the stopband can be achieved.

REFERENCES

[1] B. Easter and K. A. Merza, "Parallel-coupled-line filters for inverted-microstrip and suspended-substrate MIC's," *11th European Microwave Conference*, pp. 164-168, 1981.

[2] A. Riddle, "High performance parallel coupled microstrip filters," *IEEE MTT-S International Microwave Symposium Digest*, vol. 1, pp. 427-430, 1988.

[3] S. L. March, "Phase velocity compensation in parallel-coupled microstrip," *IEEE MTT-S International Microwave Symposium Digest*, vol. 82, pp. 410-412, 1982.

[4] J. Bahl, "Capacitively compensated high performance parallel coupled microstrip filters," *IEEE MTT-S International Microwave Symposium Digest*, vol. 2, pp. 679-682, 1989.

[5] T. Kuo, M. Jiang, and H. J. Chang, "Design of parallel-coupled microstrip filters with suppression of spurious resonances using substrate suspension," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, pp. 83-89, 2004.

[6] T. Lopetegi, M. A. G. Laso, J. H. M. Bacaicoa, D. Benito, M. J. Garde, M. Sorolla, and M. Guglielmi, "New microstrip "wiggly-line" filters with spurious passband suppression," *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, pp. 1593-1598, 2001.

[7] T. Kuo, W. H. Hsu, and W. T. Huang, "Parallel coupled microstrip filters with suppression of harmonic response," *IEEE Microwave and Wireless Components Letters*, vol. 12, pp. 383-385, 2002.

[8] B. S. Kim, J. W. Lee, and M. S. Song, "Modified microstrip filters improving the suppression performance of harmonic signals," *IEEE MTT-S International Microwave Symposium Digest*, vol. 1, pp. 539-542, 2003.

[9] J. S. Park, J. S. Yun, and D. Ahn, "A design of the novel coupled-line bandpass filter using defected ground structure with wide stopband performance" *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, no. 1, pp. 2037-2043, January 2001.

[10] P. Cheong and K. W. Tam, "Novel folded-end parallel-coupled-line microstrip filter with 2nd and 3rd harmonic responses suppression," *Mediterranean Microwave Symp.*, p. 115, 2004.

[11] J. C. Liu, B. H. Zeng, J. M. Chang, C. H. Chien, C. C. Chang, and D. C. Chang, "Modified maximally flat parallel-coupled lines for band-pass filter applications and miniaturizations," *Microwave and Optical Technology Letters*, vol. 50, pp. 902-906, 2008.

[12] X. Q. Chen, X. W. Shi, Y. C. Guo, and M. X. Xiao, "A novel dual band transmitter using microstrip defected ground structure," *Progress In Electromagnetics Research (PIER)*, vol. 83, pp. 1-11, 2008.

[13] R. Sharma, T. Chakravarty, S. Bhooshan, and A. B. Bhattacharyya, "Design of a novel 3dB microstrip backward wave coupler using defected ground structure," *Progress In Electromagnetics Research (PIER)*, vol. 65, pp. 261-273, 2006.

[14] H. D. Oskouei, K. Forooraghi, and M. Hakkak "Guided and leaky wave characteristics of periodic defected ground structures," *Progress In Electromagnetics Researc (PIER)*, vol. 73, pp. 15-27, 2007.

[15] J. Chen, Z. B. Weng, Y. C. Jiao, and F. S. Zhang, "Lowpass filter design of hilbert curve ring defected ground structure," *Progress In Electromagnetics Research (PIER)*, vol. 70, pp. 269-280, 2007.

[16] J. S. Lim, H. S. Kim, D. Ahn, and S. Nam, "A power amplifier with efficiency improved using defected ground structure," *IEEE Microwave and Wireless Components Letters*, vol. 11, pp. 170-172, 2001.

[17] D. Ahn, J. Park, C. Kim, J. Kim, Y. Qian, and T. Itoh, "A design of the low-pass filter using the novel microstrip defected ground structure," *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, pp. 86-93, 2001.

[18] S. B. Cohn, "Parallel-coupled transmission-line-resonator filters," *IRE Transactions on Microwave Theory and Techniques*, vol. 6, pp. 223-231, 1958.

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