Design of Compact Multilevel Folded-Line Bandpass Filters

Raghu Kumar Settaluri, *Senior Member, IEEE*, Andreas Weisshaar, *Senior Member, IEEE*, and Vijai K. Tripathi, *Fellow, IEEE*

***Abstract*—A simple design methodology for compact multilevel multiconductor folded-line bandpass filters is presented in this paper. Several new compact folded-line filter topologies in single, as well as multilevel environments are proposed. Simple closed-form design equations are presented for the extraction of an equivalent coupled transmission line representing the folded-line filter section. The folded-line filter designs are validated by full-wave electromagnetic simulation, as well as by measurement for a four-section maximally flat four-coupled-line bandpass filter. The new folded-line filters exhibit a significant reduction in footprint compared to the conventional designs.**

***Index Terms*—Bandpass filters, embedded passives, folded lines, multiconductor transmission lines.**

I. Introduction

BANDPASS filters are extensively used at RF and microwave frequencies for a host of applications including communication, radar, and test and measurement systems. With the emergence of new technologies for wireless communications, compactness and lightweight have been the focus of attention in the realization of new filter geometries. In the early 1970's, Cristal and Frankel [1] introduced the popular hairpin filter, which can be considered as the folded version of the conventional half-wave parallel coupled-line filter. Subsequently, several researchers discussed a number of variations of the hairpin filter configurations [2]–[5].

With an increased interest in three-dimensional components for embedded passive circuits in RF and mixed-signal modules, multiconductor multilayered components have gained prominent importance in recent years. Cho and Gupta [6] reported the design methodology for multilayered coupled-line filters employing an optimization technique.

In this paper, we present several new compact configurations for multiple-coupled folded-line bandpass filters in single and multilevel geometries. A simple design procedure in terms of equivalent coupled-line theory is proposed, which is applicable, in general, to a multilayer multiconductor environment. The procedure retains the advantage of the conventional filter design theory using low-pass filter prototypes [8] and does not require optimization for the realization of physical (structural) parameters. To demonstrate the feasibility of the compact folded-line filters, designs are carried out using single-level folded coupled four- and eight-line geometries, as well as multilevel broadside-edge-coupled geometries. Closed-form design equations are presented for coupled four- and eight-line filter sections for the extraction of equivalent fractional bandwidth and admittance (J) inverter parameters. Several variations of folded-line filter sections in coupled eight-line topology and two- and three-level four-line topologies have been studied. To demonstrate the feasibility of the proposed approach, the design of a four-section maximally flat bandpass filter, using a combination of two types of coupled eight-line sections and a four-section Chebyshev filter in a multilevel configuration are validated with a full-wave electromagnetic simulator. In addition, the design of a compact four-section four-coupled line bandpass filter is validated by comparison with measurement.

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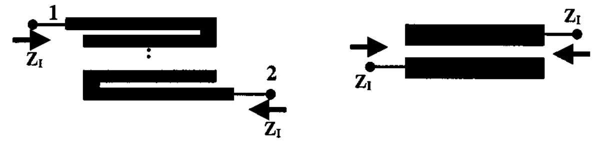


Fig. 1. Schematic representation of a multiple-coupled bandpass filter section and its equivalent coupled-line configuration.

II. Theory

The general design methodology for embedded passive filters is based on the network representation of multilevel multiconductor transmission lines. The procedure is similar to the approach described in [7] for the single and coupled folded-line structures. The circuit parameters of an N-coupled transmission-line system described in terms of the $2N$-port network can be determined using the modeling approaches reported in the literature [9]–[11]. The N-coupled transmission-line network can be reduced to a two-port network exhibiting bandpass filter property by selectively interconnecting the leads, while leaving some open circuited. The choice of interconnection and open-circuit termination can result in diversified filter properties for the reduced two-port network. This procedure enables the designer to take into account the effect of the interconnecting lengths of the transmission-line section during the course of the design.

In this approach, a multiple-coupled line filter section, illustrated in Fig. 1(a), is visualized as an equivalent parallel coupled-line symmetric filter section shown in Fig. 1(b), giving nearly the same filter properties. The aim is to realize the physical parameters, such as the strip width and the separation between conductors of the multiple-coupled section, by matching the image impedance and the image propagation constant with that of the conventional parallel-coupled section at the center frequency. To simplify the procedure, each filter section is assumed to be symmetric so that it offers the same image impedance from either of the two ports. The image impedance and image propagation constant for the symmetric two-port filter section can be expressed in terms of its impedance parameters as [8], [12]

$$Z_i(\omega) = \sqrt{Z_{11}^2(\omega) - Z_{21}^2(\omega)} \tag{1a}$$

and

$$\cos\beta(\omega) = \frac{Z_{11}(\omega)}{Z_{21}(\omega)}. \tag{1b}$$

Generally, in the bandpass-filter design procedure using the conventional parallel coupled-line topology, first the low-pass filter prototype values are obtained from the tables given in [8] after which the admittance inverter (J) parameters are determined for each filter section [12]. This is followed by the extraction of even- and odd-mode characteristic impedances and physical parameters such as the strip width w and the spacing between the conductors s for each section.

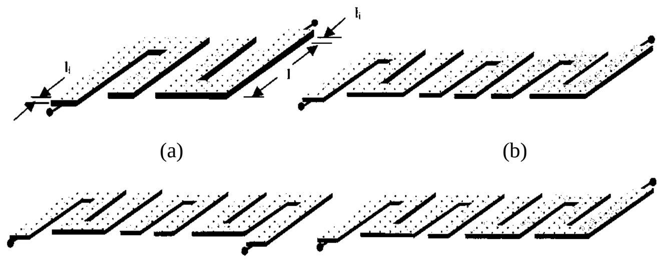
In the proposed design procedure for the multiple coupled-line filters, first the low-pass filter prototype values are obtained for a given number of sections and the type of the filter (maximally flat or Chebyshev). The admittance (J) inverter values for the bandpass filter with $N+1$ filter sections can then be obtained as

$$\begin{aligned} Z_0 J_1 &= \sqrt{\frac{\pi\Delta_e}{2g_1}} \\ Z_0 J_n &= \frac{\pi\Delta_e}{2\sqrt{g_{n-1}g_n}} \\ Z_0 J_{N+1} &= \sqrt{\frac{\pi\Delta_e}{2g_N g_{N+1}}}. \end{aligned} \tag{2}$$

Here, Z_o is the characteristic impedance of ports 1 and 2 and Δ_e is defined as the equivalent fractional bandwidth of the filter. It may be noted that the expressions given in (2) are very similar to those for the conventional parallel coupled-line geometry [12], except that the desired fractional bandwidth Δ is replaced with the equivalent fractional bandwidth Δ_e. As mentioned earlier, the main goal is to match the image impedance and the image propagation constant of the folded-line filter with those of the conventional coupled-line topology at center frequency. Due to the multiple coupling between conductors, this procedure does not necessarily ensure that the response matches at other frequencies in the passband. In fact, it was noticed that multiconductor coupling generally narrows down the bandwidth of the filter. The parameter equivalent bandwidth Δ_e is introduced in (2) in order to compensate this effect so that the designed filter exhibits a 3-dB bandwidth that is same as the desired fractional bandwidth Δ. The desired fractional bandwidth is given by

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0} \tag{3}$$

where ω_1 and ω_2 denote the 3-dB edges of the passband and ω_0 is the center frequency. It has been observed that the equivalent fractional bandwidth Δ_e depends on the filter topology, the desired fractional bandwidth Δ, and the ratio of spacing between the conductors to the strip width (s/w) for the filter section. The procedure for the extraction of the equivalent fractional bandwidth Δ_e may be explained as follows. For a given topology, the initial filter design is carried out by substituting $\Delta_e = \Delta$ in (2) for different cases of s/w and Δ. Due to the multiconductor coupling, the achieved fractional bandwidth will deviate from the desired bandwidth Δ. By evaluating the achieved fractional bandwidth for different cases, it is possible to derive a closed-form expression for Δ_e as a function of Δ and s/w.



(a) (b) (c) (d)

Fig. 2. Various single-level multiple-coupled folded-line filter sections.

Once the J values are determined, the conductor width of each section is found by matching the image impedance at the center frequency. This is achieved by solving for the root of [12]

$$f(w) = Z_i(\omega_0, w) - JZ_0^2 \tag{4}$$

where the equation for image impedance Z_i is given in (1a). Similarly, the length of each section is determined such that, at the center frequency ω_0, $\cos\beta(\omega_0) = 0$ for the obtained conductor width. Calculation of the two-port impedance parameters Z_{11} and Z_{21} includes the effect of the interconnecting lengths, modeled here as curved 180° bends with the same conductor width [7]. It is worth noting that the procedure enables the designer to have a choice of physical dimensions since the filter design can be carried out for different values of s/w.

III. Multiple-Coupled Single-Level Folded-Line Bandpass-Filter Topologies

To demonstrate the feasibility of compact folded-line bandpass-filter structures and to illustrate the proposed approach, several filter topologies are considered. Fig. 2 shows several single-level structures in four- and eight-coupled folded-line configuration. Small lengths of connecting transmission lines l_i are added on either side of the filter section to facilitate convenient layout, as well as to avoid unwanted coupling between various filter sections. The effect of the connecting lines is also included while determining the Z-parameters for the filter sections. For all the design examples, a homogeneous stripline configuration with a dielectric of $\varepsilon_r = 2.2$ is considered and the number of filter sections is assumed to be four. The filter structure is considered to be symmetric in all topologies and the goal is to determine the physical parameters of each section using the design approach explained earlier.

First, the design of a four-section maximally flat bandpass filter using the four-coupled folded-line section shown in Fig. 2(a) is considered. Fig. 3 shows the equivalent bandwidth

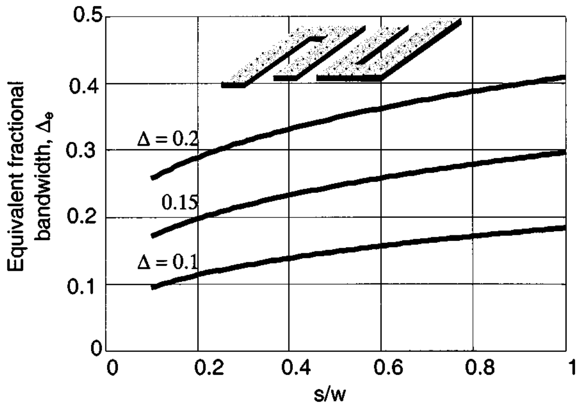


Fig. 3. Variation of equivalent fractional bandwidth Δ_e for a coupled four-line filter as a function of ratio s/w of spacing between conductors and strip width for different values of desired fractional bandwidth Δ.

Δ_e for the four-line design, determined using the procedure explained in Section II. By curve fitting the data, a closed-form expression for the equivalent bandwidth Δ_e for the four-line design is obtained as

$$\Delta_e\left(\frac{s}{w}, \Delta\right) = A(\Delta) \cdot \left[\frac{s}{w}\right]^{0.4017} + B(\Delta) \tag{5}$$

where

$$A(\Delta) = 0.0939 \cos\left[\frac{0.2813}{\Delta}\right] + 0.2367 \tag{6a}$$

$$B(\Delta) = 0.1354 \cos\left[\frac{0.3319}{\Delta}\right] + 0.1695. \tag{6b}$$

The filter design is carried out at a center frequency of 1.5 GHz with a desired fractional bandwidth of $\Delta = 0.1$. For all sections, the ratio of spacing between the conductors s to the strip width w is arbitrarily chosen as 0.5 and the connecting line length on either side of the filter section is assumed to be 1 mm. A ground-plane separation of $b = 62$ mil is considered for the stripline configuration. For a desired fractional bandwidth of $\Delta = 0.1$ and $s/w = 0.5$, the equivalent fractional bandwidth Δ_e for the present four-line design is calculated from (5) and (6) as 0.1481.

Next, a filter design using eight-coupled line sections is considered. The filter specifications are kept the same as in the case with four-coupled lines. As can be seen from Fig. 2, three different single-level topologies can be realized by selectively interconnecting various ports of the eight-coupled line. As in the previous case, closed-form expressions for the equivalent fractional bandwidth Δ_e are obtained for each configuration. For example, for the eight-coupled line section shown in Fig. 2(c), a closed-form expression for Δ_e is found as

$$\Delta_e\left(\frac{s}{w}, \Delta\right) = D(\Delta) \cdot \left[\frac{s}{w}\right]^{0.6} + E(\Delta) \tag{7}$$

where

$$D(\Delta) = 0.0786 \cos\left[\frac{0.2780}{\Delta}\right] + 0.1992 \tag{8a}$$

$$E(\Delta) = -0.1385 \sin\left[\frac{-0.5041}{\Delta}\right] + 0.2844. \tag{8b}$$

Fig. 4 presents the filter response for the four-line filter design shown in Fig. 2(a) and the eight-line section shown in Fig. 2(b).

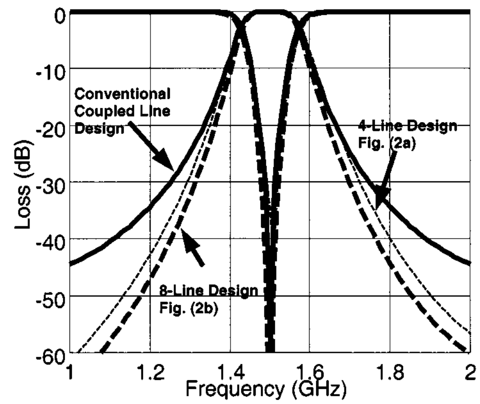


Fig. 4. Response comparison for the four-section single-level multiple coupled maximally flat filters designed at 1.5 GHz and the conventional coupled-line design.

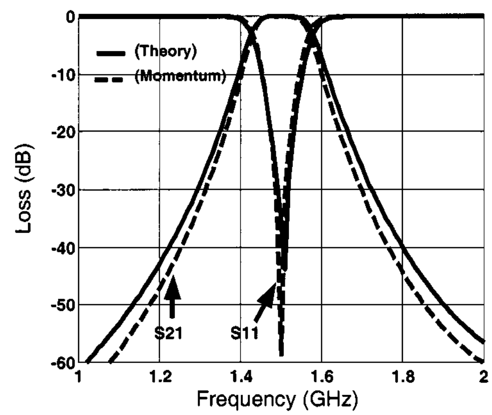


Fig. 5. Response of the four-section maximally flat coupled eight-line filter, designed at 1.5 GHz employing alternate filter sections shown in Fig. 2(c) and (d).

For comparison, the response of the conventional parallel-coupled line design realized in the same stripline geometry is also plotted. It can be seen that, for both cases, the filter response compares well with that of the conventional design. Furthermore, it can be seen that the multiple coupled-line filters give a better stopband performance for the given fractional bandwidth.

To validate the proposed theory, the design of a four-section maximally flat filter using alternate coupled eight-line sections shown in Fig. 2(c) and (d) is considered. This arrangement could give a more compact footprint of the filter by virtue of the combination of two different compact topologies. The substrate specifications and the center frequency are kept the same as for the previous example, except that the s/w ratio is chosen to be unity. The lengths and conductor widths for the two eight-coupled line sections are found to be $l_1 = 16.6$ mm, $l_2 = 15.33$ mm, $w_1 = 0.082$ mm, and $w_2 = 0.151$ mm, respectively. A full-wave electromagnetic simulation using HP Momentum is carried out and a comparison of the response is shown in Fig. 5. The results show very good agreement.

IV. Multiple-Coupled Multilevel Folded-Line Bandpass-Filter Topologies

Fig. 6 shows some of the feasible filter topologies in a multilevel configuration. The design methodology for multilevel fil-

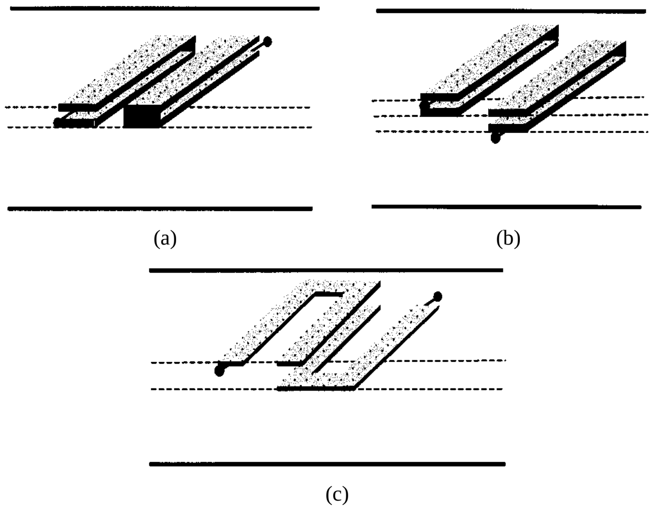


Fig. 6. Various multilevel multiple-coupled folded-line filter sections.

ters is quite similar to that of single-level filters described in Section III. For the design examples, the filter specifications were kept the same as for the single-level topology. In the case of the two-level structure shown in Fig. 6(a), dielectric substrate layers of thicknesses 20, 10, and 20 mil, respectively, and $s/w = 1$ are considered.

For the three-level structure shown in Fig. 6(b), the dielectric substrate layers have thicknesses 31, 10, 10, and 31 mil, respectively, and the s/w ratio is 0.5. Once the equivalent bandwidth Δ_e is determined, the physical line parameters l and w of the filter are determined by solving for the image impedance and $\cos\beta$ at the center frequency. Fig. 7 shows the response for the two- and three-level filter configurations. It can be seen that both designs have a steeper stopband response on the higher frequency side in comparison to the conventional design shown in Fig. 4.

The filter structure shown in Fig. 6(c) has interconnecting transmission-line sections on the same layer as opposed to the filter structures shown in Fig. 6(a) and (b). This can be advantageous from a fabrication point-of-view as the number of interconnecting vias needed will be minimal.

To demonstrate the design feasibility of this geometry, a five-layer structure, with substrate thicknesses of 30, 10, 20, 10, and 30 mil is considered. A four-section Chebyshev type filter with a passband ripple of 0.1 dB at a center frequency of 1.5 GHz and with a desired fractional bandwidth of $\Delta = 0.15$ is designed. The strip widths and lengths of the sections are found to be 0.568 and 15.99 mm for sections 1 and 4 and 0.314 and 18.00 mm for sections 2 and 3, respectively. The layout for one-half of the filter is shown in Fig. 8. It can be seen that, for the complete filter, only three vias are needed to interconnect between the layers. Fig. 9 shows the theoretical response of the designed filter and the full-wave electromagnetic simulation using HP Momentum. The results show a very good agreement. To illustrate the significant reduction in the footprint that can be achieved by the new folded-line filter configurations, Fig. 10 shows a footprint comparison of the HP Momentum layouts for the conventional parallel coupled-line filter design, single-level four-line design [see Fig. 2(a)], eight-line design employing

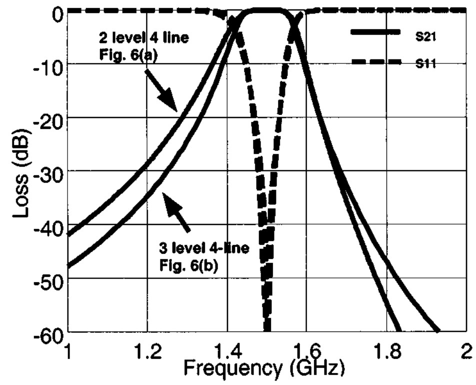


Fig. 7. Response for the four-section maximally flat coupled multilevel four-line filters shown in Fig. 6(a) and (b).

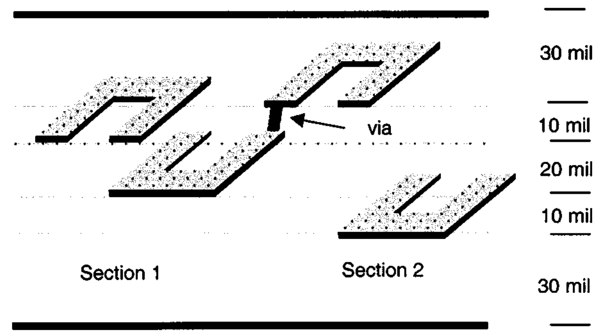


Fig. 8. Layout of one-half of the designed filter structure using the basic configuration shown in Fig. 6(c).

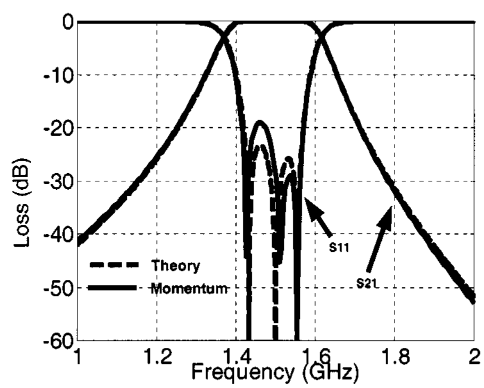


Fig. 9. Response for the four-section 0.1-dB Chebyshev multilevel four-line filter, shown in Fig. 6(c).

alternate sections [see Fig. 2(c) and (d)], and the two-level four-line design [see Fig. 6(a)].

V. Experiment

To validate the theory presented here by measurement, the design of a four-section maximally flat bandpass filter in the coupled four-line configuration shown in Fig. 2(a) is considered. Here, the center frequency is 1.5 GHz and the fractional bandwidth is $\Delta = 0.2$. A homogeneous stripline configuration is chosen with $\varepsilon_r = 2.2$ and a ground-plane separation of 124 mil. For both sections, the s/w ratio has been chosen to be unity. Each section is assumed to have a 3-mm-long connecting transmission line on either side. The effect of the curved sections and

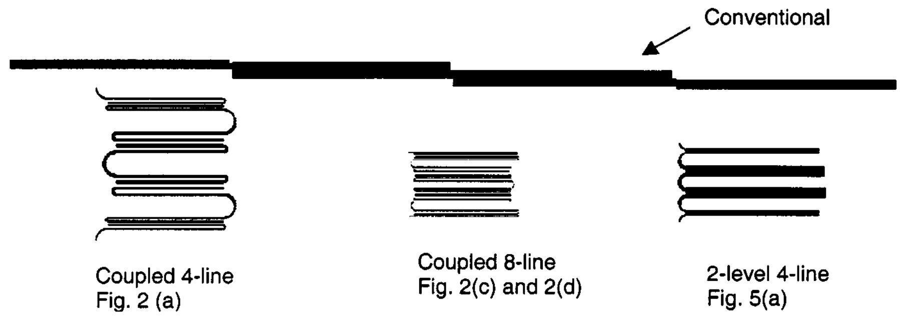


Fig. 10. Momentum layouts for various bandpass filter designs.

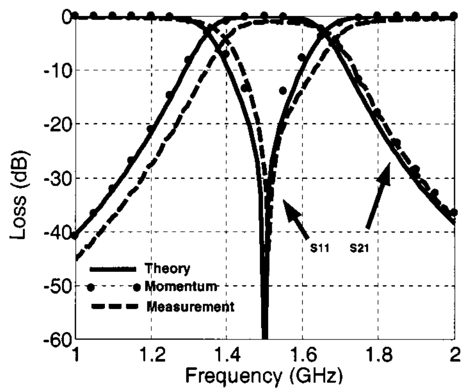


Fig. 11. Computed and measured filter response for the four-section maximally flat coupled four-line filter configuration shown in Fig. 2(a).

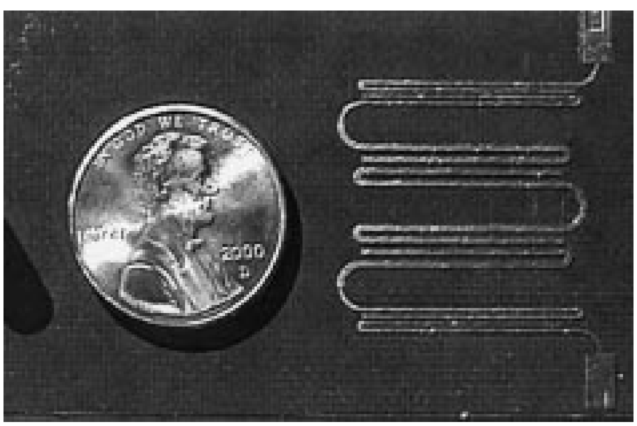


Fig. 12. Fabricated four-section maximally flat coupled four-line filter designed for a center frequency of 1.5 GHz.

the connecting lengths is included in the design, as described earlier. For the specified s/w ratio and the desired bandwidth Δ, the equivalent bandwidth Δ_e is found from the closed-form expression given in (5) to be 0.4096. Using the design procedure described in Section II, the lengths and conductor widths for sections 1 and 2 are found to be $l_1 = 18.55$ mm, $w_1 = 0.295$ mm, $l_2 = 17.25$ mm, and $w_2 = 0.51$ mm, respectively. The design is also analyzed using the full-wave electromagnetic simulator HP Momentum. The filter was fabricated in-house using an RT-5880 62-mil substrate and tested on an HP 8722 network analyzer. The filter layout is found to have a footprint of 23×25 mm^2. Fig. 11 shows the response using the present design and the measured data, as well as results from HP Momentum. All the three results are in good agreement. The measured fractional bandwidth, however, was observed to be slightly less compared to the desired theoretical bandwidth. Upon inspection, it was observed that this deviation was due to fabrication tolerances. This is also supplemented by the fact that the full-wave electromagnetic simulation carried out using HP Momentum closely matches with the theoretical response. A photograph of the fabricated four-section coupled four-line filter is shown in Fig. 12.

VI. Conclusion

A new simple design methodology for a variety of compact folded-line coupled bandpass filters realized in a multilayered environment has been presented in this paper. An equivalent coupled-line theory, which does not require optimization for the realization of the structural parameters, has been proposed to synthesize a variety of compact filter structures. Simple closed-form empirical design equations for determining the equivalent bandwidth have been presented. Several new filter configurations, including the folded-coupled four- and eight-line designs and broadside-edge coupled multilevel topologies, have been reported. To demonstrate the design feasibility, a four-section maximally flat filter design has been carried out using different configurations and a comparison of the responses with that of the conventional coupled line design has been presented. The results are validated with the help of full-wave electromagnetic simulation for selected design examples. The results show very good agreement. A footprint comparison of various multiple-coupled filters with the conventional parallel coupled-line design has been shown to illustrate the compactness of the new geometries. A four-section maximally flat four-coupled line filter has been fabricated and the test results show good agreement with the proposed theory. The new folded-line designs exhibit a considerable reduction in the footprint, opening up a variety of possible applications for embedded passive components for RF and mixed-signal modules.

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