Design of Parallel-Coupled Microstrip Filters With Suppression of Spurious Resonances Using Substrate Suspension

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Abstract—Substrate suspension is used to suppress the spurious response of microstrip bandpass filters at twice the passband frequency $(2f_o)$. It is known that a proper height of substrate suspension can be used to equalize the even- and odd-mode phase velocities for coupled microstrip lines. In this paper, this property is applied to design the coupled stages of a parallel-coupled line filter so that the spurious response at $2f_o$ can be completely suppressed. The individual image impedance for each coupled stage is changed accordingly. Required filter design formulas are derived for a series of coupled stages having different image impedances. Several filters made on a substrate of relative high dielectric constant are designed and fabricated. The measured results show that a rejection level of better than -40 dB to the spurious resonance at $2f_o$ can be obtained.

Index Terms—Image impedance, parallel-coupled microstrip filter, spurious response, suspended substrate.

I. INTRODUCTION

MICROSTRIP bandpass filters made of a cascade of parallel coupled-line sections have been widely used in many microwave and millimeter-wave systems. This type of filter is popular since it has a planar structure, good repetition, and a simple synthesis procedure [1]. The rejection level in the upper stopband of this type of filter, however, is usually degraded by the spurious response at twice the passband frequency $(2f_o)$. This is because that the even and odd modes of each coupled section have different phase velocities [2]. The modal phase velocities, however, are assumed identical for the ease of synthesis. Obviously, if the spurious resonance at $2f_o$ can be eliminated completely, the width and rejection level of the upper stopband and the symmetry of the passband response can be greatly improved simultaneously.

Several techniques have been proposed to tackle this problem [2]–[6]. An over-coupled section is effective in suppressing the spurious response [2]. The stepped-impedance resonator (SIR) filters [3], [4] are capable of pushing the first parasitic harmonic to far beyond $2f_o$. A combination of different SIR structures can be adopted for spurious-free bandpass filters with a wide stopband [3]. An SIR with a large impedance ratio can provide a good rejection level within a wide stopband [4].

In [5], simulation and experiment indicate that the rejection of the filter at $2f_o$ can be improved by decreasing the linewidths of the input/output coupled resonators to less than those of the input/output microstrips, and by reducing the gap size for keeping the strong coupling for input/output resonators. The wiggly coupled microstrip filter in [6] is also successful in suppressing the spurious response. Using a continuous perturbation of the width of the coupled lines following a sinusoidal law, the wave impedance is modulated so that the harmonic passband of the filter is rejected, while the desired passband response is maintained virtually unaltered.

The field-theoretical study in [7] indicates that inserting an appropriate dielectric layer underneath the substrate can eliminate the difference between the even- and odd-mode phase velocities of coupled microstrips. As reported in [7], where the gap size is twice the linewidth, the phase velocities for both the even and odd modes can be made very close to that of the quasi-TEM mode for a single suspended microstrip in a very wide frequency range. In our previous paper [8], this phase velocity equalization technique is used to design the coupled stages for a parallel-coupled microstrip filter. The spurious response of this filter can be suppressed by over 30 dB, as compared with that of a microstrip filter without substrate suspension. It is noted that, in [8], the suspension heights required for each coupled stage, to have equalized modal phase velocities, can be different from one another, and the final uniform suspension height is obtained via an optimization.

In this paper, the concept in [8] is extended to design parallel-coupled microstrip filters on a suspended substrate for a given suspension height. Of the filter, the coupled microstrips of each coupled stage have identical even- and odd-mode phase velocities so that the spurious response at $2f_o$ can be suppressed completely. No optimization for any circuit dimension is required here. It is found that the height, within a certain range, can be a premise for constructing parallel-coupled filters free of spurious responses. Since the image impedance of each coupled stage deviates from 50 Ω, the design parameters for the filter have to be modified accordingly. Detailed design formulas will also be derived. Several parallel-coupled microstrip filters are fabricated on suspended structures with various suspension heights, and the measured results are compared with the simulations.

This paper is organized as follows. Section II explores the eigenmode phase velocity equalization for coupled microstrips using substrate suspension. Section III formulates the design of parallel-coupled microstrip filters, of which each coupled stage
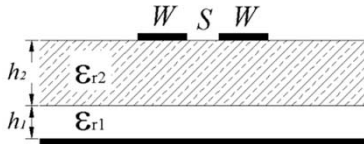
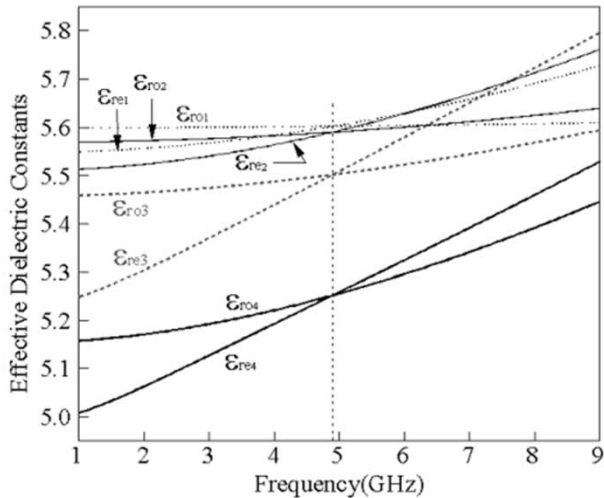Fig. 1.   Cross section of suspended coupled microstrip lines.

Fig. 2.   Dispersive $\varepsilon_{\mathrm{re}}$ and $\varepsilon_{\mathrm{ro}}$ for four suspended coupled microstrip structures. $\varepsilon_{r1} = 1, \varepsilon_{r2} = 10.2$. The circuit dimensions are given is Table I.

TABLE I
CIRCUIT DIMENSIONS OF SUSPENDED COUPLED LINES IN FIG. 2.
$h_2 = 1.27$ mm

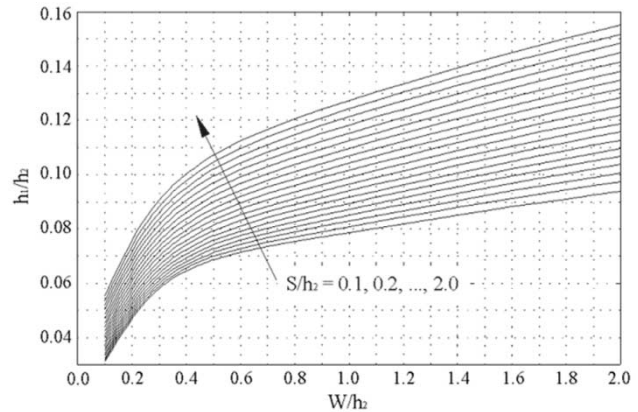| Structure	W/h_2	S/h_2	h_1/h_2
1	0.1	0.1	0.031
2	0.1	1.0	0.040
3	1.0	0.1	0.079
4	1.0	1.0	0.099

Fig. 3.   Required h_1/h_2 ratios to have $\beta_e = \beta_o$ for various S/h_2 and W/h_2 at 4.9 GHz for suspended coupled microstrip lines with $\varepsilon_{r1} = 1, \varepsilon_{r2} = 10.2$, and $h_2 = 1.27$ mm.

has its own image impedance. Section IV presents the simulated and measured results of six fabricated filters, and Section V draws a conclusion.

II. EQUALIZING MODAL PHASE VELOCITIES USING SUBSTRATE SUSPENSION

Suppose that we are designing a bandpass filter with center frequency $f_o = 2.45$ GHz and free of spurious resonance at $2f_o$ using a substrate with $\varepsilon_r = 10.2$ and thickness $h_2 = 1.27$ mm. The reason for choosing this relative high ε_r substrate is to have a circuit of smaller size, compared with those on substrates with lower ε_r. The challenge with this substrate to the filter design is that the deviation between β_e and β_o, the even- and odd-mode phase velocities, respectively, will be relatively large. This will increase the difficulty in suppressing the spurious response at $2f_o$.

For the suspended structure shown in Fig. 1, the height of substrate suspension, i.e., h_1, can be adjusted to equalize β_e and β_o at $2f_o$ [7]. The full-wave spectral-domain approach (SDA) program in [9] is invoked. It is worth mentioning that a full-wave analysis for the inhomogeneous structure is essential since the equalization of β_e and β_o at $2f_o$ can no longer exist at different frequencies. It can be shown that once β_e and β_o for each coupled stage have an intersection at $2f_o$, the filter will be free of spurious response at this frequency, and the width of the upper stopband can be at least doubly extended. Fig. 2 shows the dispersive $\varepsilon_{\mathrm{re}}$ and $\varepsilon_{\mathrm{ro}}$, the even- and odd-mode effective dielectric constants, respectively, for four suspended coupled microstrip lines. The detailed dimensions of the structures are listed in Table I. It is found that the required value of h_1 varies as either W or S changes. As shown in Fig. 2, when operation frequency moves away from $2f_o$, the case with a relatively wide

microstrips and narrow gap (structure 3) has the largest deviation in modal effective dielectric constants.

Not shown here is that the average value of $\varepsilon_{\mathrm{re}}$ and $\varepsilon_{\mathrm{ro}}$ of the coupled lines of the same dimensions, as in Table I, without substrate suspension is 6.2, which is 10% higher than that of the suspended coupled microstrips. It means that the advantage of resulting in a smaller circuit size using a relatively high ε_r substrate still holds for the suspended structures investigated here.

As indicated in Table I, given ratios of W/h_2 and S/h_2, a special ratio h_1/h_2 can be obtained for $\beta_e = \beta_o$. Fig. 3 plots the required h_1/h_2 curves against W/h_2 for S/h_2 varying from 0.1 to 2.0. The lower limits for W/h_2 and S/h_2 are purposely chosen to be 0.1 since $h_2 = 1.27$ mm (or 50 mil) and $0.1 \times 1.27 = 0.127$ mm is the best resolution for a metallic strip width and gap size that can be obtained using a general wet chemical-etching process. As indicated in Fig. 3, when either W/h_2 or S/h_2 is increased, h_1/h_2 is increased. It is noted that the plots are valid only when $f = 4.9$ GHz. If the operation frequency changes, the plots should be recalculated. Also, β_e (or β_o) at any two points on one curve are not necessarily the same, and their values are not indicated in the plots. From Fig. 3, say, $h_1/h_2 = 0.08$, the possible W/h_2 ratios to have $\beta_e = \beta_o$ are between 0.2 and 1.1 if $0.1 \leq S/h_2 \leq 2$. The possible W/h_2 ratios for equalizing β_e and β_o change as the ratio h_1/h_2 is changed.

III. FILTER DESIGN ON A SUSPENDED SUBSTRATE

The modal characteristic impedances Z_{oe} and Z_{oo} of coupled microstrip lines should be calculated to establish a design graph for each coupled stage. The a filter of Chebyshev type or maximally flat response can then be synthesized based on the
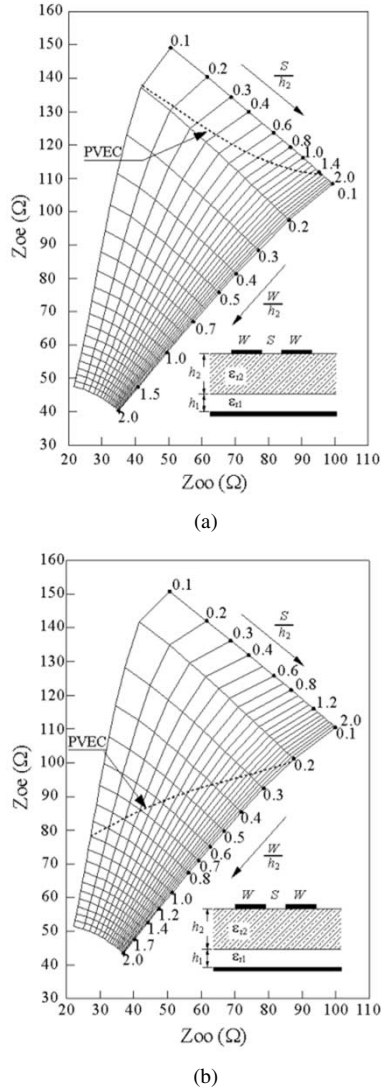
Fig. 4. Even- and odd-mode characteristic impedance design graphs for suspended coupled microstrip lines. (a) $h_1 = 0.06$ mm. (b) $h_1 = 0.10$ mm. The substrate has $h_2 = 1.27$ mm and $\varepsilon_{r2} = 10.2$. PVEC = the phase velocity equalization curve.
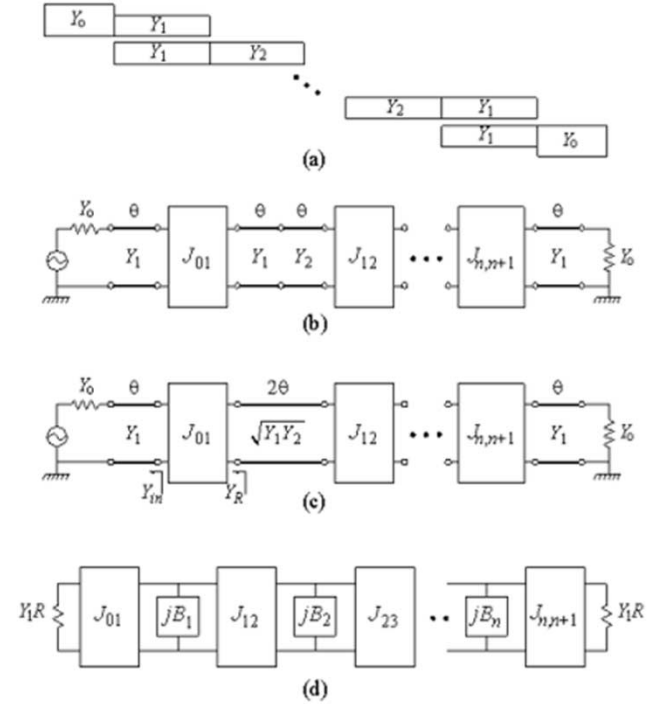

Fig. 5. Development of an equivalent circuit for derivation of design equations for an nth-order parallel-coupled line filter. (a) Circuit layout. (b) Equivalent circuit of admittance inverters. (c) Approximated equivalent circuit. (d) Equivalent circuit of (c).

classical method [1]. Of each coupled section, Z_{oe} and Z_{oo} are determined by the image impedance and the admittance inverter specified by the equivalent circuit of the filter.

The intuitive way for designing filters with suppression of spurious responses using a substrate suspension can be as follows. Apply the classical synthesis method to determine the dimensions of each coupled stage. Insert an air layer of proper height underneath the substrate to make $\beta_e = \beta_o$. Each coupled section, however, has its own h_1 value, and the ground "plane" for the whole filter becomes an uneven surface. For example, in the four-stage or third-order Chebyshev filter in [8], the h_1 values are 0.11 and 0.16 mm for the end and middle stages, respectively.

It is the purpose here to formulate the design of filters on a suspended substrate with a uniform suspension height. Fig. 4(a) and (b) shows the even- and odd-mode characteristic impedance design graphs for suspended coupled microstrips with $h_1 = 0.06$ mm and 0.1 mm, respectively. The substrate has $h_2 = 1.27$ mm and $\varepsilon_{r2} = 10.2$. If a horizontal line for

$h_1/h_2 = 0.10/1.27$ is drawn in Fig. 3, the intersection of this line and each constant S/h_2 curve specifies a W/h_2 ratio that has $\beta_e = \beta_o$. It can be seen that, for this particular substrate, if the ratio h_1/h_2 can be no less than 0.06, the choice of W/h_2 will have a large degree of freedom. The intersection points form a curve, herein called the phase velocity equalization curve (PVEC), which can be plotted with the design graphs, as shown in Fig. 4. It means that when the dimensions of each coupled stage are chosen from the points on the PVEC, then each stage will have $\beta_e = \beta_o$. It is noted that for the PVEC in Fig. 4(a), the widths of the coupled lines are limited to be from $0.1h_2$ to $0.2h_2$, and Z_{oe} is limited to within 110 to 140 Ω, while Z_{oo} can be freely chosen from 40 to 95 Ω.

It is found possible to design filters on a suspension height of within 0.05 and 0.12 mm, including the fabrication limitations to the resolution of linewidths and gap sizes of 0.15 mm for filter fractional bandwidths of up to 25%. A large bandwidth may lead to the linewidth or gap size smaller than the resolution.

Now that only the W/h_2 and S/h_2 on the PVEC can be chosen, more general formulas for filter design should be developed since the two variables Z_{oe} and Z_{oo} locate on a curve, which is of only one dimension. The design method of a filter with arbitrary image impedance [10] can be extended to meet this purpose. Developed in [10] is that all coupled stages have an image impedance different from the reference system impedance (50 Ω). Obviously, if the image impedances of all the coupled stages are allowed to be different from one another, the filter design on a suspended substrate can be completed.

Fig. 5(a) plots the layout of an nth-order parallel-coupled microstrip filter, of which each of the $n + 1$ coupled stages may have its own image admittance. Since a coupled stage can be

approximated by two quarter-wave lines with an admittance inverter J in between [1], the equivalent circuit for Fig. 5(a) can be drawn in Fig. 5(b). The characteristic admittances for the quarter-wave sections are $Y_i = Z_i^{-1}, i = 1, 2, \ldots, n+1$. All Y_i's, including Y_o, the system admittance, can be different from one another. Here, let all the filters be of Chebyshev type of an odd order so that $Y_1 = Y_{n+1}, Y_2 = Y_n$ and so on. Thus, only $(n+1)/2$ pairs of (W, S) need specifying. In Fig. 5(b), there is a cascade of two sections of transmission lines, with different characteristic admittances, between any two adjacent admittance inverters. It has been shown in [11] that a cascade of such two quarter-wave lines of characteristic admittances Y_i and Y_{i+1} can be approximated by a half-wave line of characteristic admittance $\sqrt{Y_iY_{i+1}}$. Thus, the circuit in Fig. 5(b) can be further approximated by the equivalent circuit in Fig. 5(c). The admittance Y_R seen looking toward the J_{01} inverter can be expressed as [10]

$$Y_R = \frac{J_{01}^2}{Y_1 R} + jB_R(\omega) \tag{1}$$

where $R = Y_1/Y_0$ and

$$B_R(\omega) = \frac{J_{01}^2}{Y_1 R} X \left(R - \frac{1}{R} \right) \tag{2}$$

$$X = \frac{\pi}{2} \frac{\omega - \omega_o}{\omega_o} \tag{3}$$

Thus, for the equivalent circuit of a filter of order $n \geq 3$ in Fig. 5(d), the susceptance of the ith resonator $B_i(\omega)$ can be obtained as

$$B_1(\omega) = B_n(\omega) = \frac{J_{01}^2}{Y_1 R} X \left(R - \frac{1}{R} \right) + 2X\sqrt{Y_1Y_2} \tag{4a}$$

$$B_i(\omega) = B_{n+1-i}(\omega) = 2X\sqrt{Y_iY_{i+1}} \tag{4b}$$

for $i = 2, 3, \ldots, n/2 + 1$ for n even and $i = 2, 3, \ldots, (n+1)/2$ for n odd. From (4), the corresponding susceptance slope parameter b_i can be derived using

$$b_i = \frac{\omega_o}{2} \left. \frac{dB_i(\omega)}{d\omega} \right|_{\omega=\omega_o}. \tag{5}$$

The J inverters can be expressed by the following formulas [12]:

$$J_{01} = \sqrt{\frac{Y_1 R b_1 \Delta}{\omega_1' g_0 g_1}} \tag{6a}$$

$$J_{i,i+1}|_{i=1 \text{ to } n-1} = \frac{\Delta}{\omega_1'} \sqrt{\frac{b_i b_{i+1}}{g_i g_{i+1}}} \tag{6b}$$

$$J_{n,n+1} = \sqrt{\frac{Y_1 R b_n \Delta}{\omega_1' g_n g_{n+1}}} \tag{6c}$$

where Δ is the fractional bandwidth and g_i's are the element values of low-pass filter prototype. The even- and odd-mode characteristic impedances for each coupled stage are determined by

$$Z_{oei} = Z_{oe,n+2-i} = Z_i'\left[1 + J_{i-1,i}Z_i' + (J_{i-1,i}Z_i')^2\right] \tag{7a}$$

$$Z_{ooi} = Z_{oo,n+2-i} = Z_i'\left[1 - J_{i-1,i}Z_i' + (J_{i-1,i}Z_i')^2\right] \tag{7b}$$
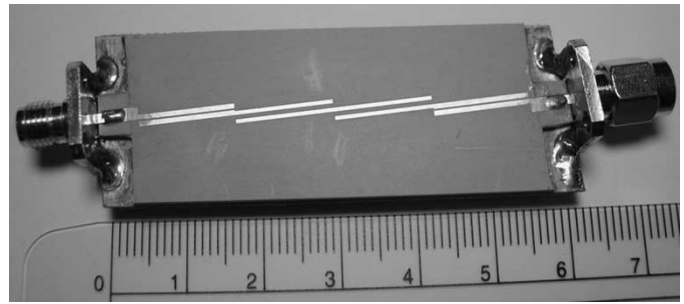

Fig. 6.   Photograph of a tested filter (filter F in Table II).

for $i = 1, 2, \ldots, n/2 + 1$ for n even and for $i = 1, 2, \ldots, (n+1)/2$ for n odd. In (7), $Z_i' = (Y_i')^{-1}$ can be obtained by

$$Y_1' = \sqrt{Y_1\sqrt{Y_1Y_2}} = Y_{n+1}' \tag{8a}$$

$$Y_i' = \sqrt{\sqrt{Y_{i-1}Y_i}\sqrt{Y_iY_{i+1}}} = Y_{n+2-i}', \qquad 2 \leq i \leq n. \tag{8b}$$

IV. SIMULATED AND MEASURED FILTER RESPONSES

Six bandpass filters are made to demonstrate the design of bandpass filters free of spurious response at $2f_o$. The fabrication procedure is as follows. First, the RT/Duroid 6010 microwave laminate ($\varepsilon_r = 10.2$ and $h_2 = 1.27$ mm) and a low-cost FR4 printed circuit board (PCB) are used for the substrate and ground plane, respectively. A plastic film of proper thickness, measured using a digital caliper, is then sandwiched between the circuit substrate and PCB. For example, the thickness of a PP2900 transparency film from 3M Korea is 0.1 mm. Next, the center pins and panel mounts of the subminiature A (SMA) connectors are soldered to the circuit ports and ground plane, respectively. The strength of the soldered portions on both ends of the circuit guarantees a uniform air gap between the flat substrate and ground plane. Finally, the plastic film is removed when the circuit is measured. Fig. 6 is a photo of one of the tested filters (filter F in Table II).

In designing a third-order filter, only two points of the PVEC in Fig. 4 are required. It is noted that when a point on the PVEC is chosen, the second point cannot be chosen freely since Z_1 and Z_2 depend on each other, as indicated in (8). Given a suspension height, Z_1 and Z_2 are determined as follows. First, the PVEC curve in Fig. 4 is expressed in a form as $Z_{oe} = f(Z_{oo})$, e.g., a cubic spline [13]. Next, define a complex error function

$$\Phi(Z_1 + jZ_2) = Z_{oe1} - f(Z_{oo1}) + j\left[Z_{oe2} - f(Z_{oo2})\right]. \tag{9}$$

Then insert (1)–(8) into a program. Finally, use a root-searching algorithm, e.g., the Muller's method or Newton's method [13], to find the solutions. A simple FORTRAN program of less than 50 statements can perform this job well. Only several iterations can complete the design with an initial guess of $Z_1 = Z_2 = 50\,\Omega$. The execution of this program takes less than 0.1 s using a PC of today.

With a center frequency $f_o = 2.45$ GHz and a Chebyshev response with 0.1-dB passband ripple, the six filters have their respective suspension heights. The simulation and measured responses are plotted in Figs. 7–12, and the Z_i value and detailed dimensions of each coupled stage of the filters are listed

TABLE II
SPECIFICATIONS AND DIMENSIONS FOR THE SIX FABRICATED SUSPENDED FILTERS

| Filter	Order (n)	Δ	h_1 mm	$Z_i = Y_i^{-1}$ (Ω), W/h_2 and S/h_2 of coupled stages			Overall length (mm)
				1, $n+1$	2, n	3, $n-1$	
A	3	10%	0.06	82.4 (0.1695, 0.5022)	103 (0.1331, 0.9995)	-	50.3184
B	5	10%	0.08	69.3 (0.5901, 0.2820)	107 (0.1929, 1.3313)	91.7 (0.1718, 1.5194)	76.4020
C	3	10%	0.10	41.4 (0.7566, 0.3445)	103 (0.3230, 1.3293)		51.6089
D	3	25%	0.05	75.5 (0.1375, 0.2335)	92.8 (0.1313, 0.3697)	-	49.674
E	5	25%	0.07	63.0 (0.2489, 0.2759)	93.1 (0.2221, 0.5545)	84.7 (0.2046, 0.7211)	75.1112
F	3	25%	0.09	34.1 (0.5515, 0.1528)	81.3 (0.4396, 0.4477)	-	50.593
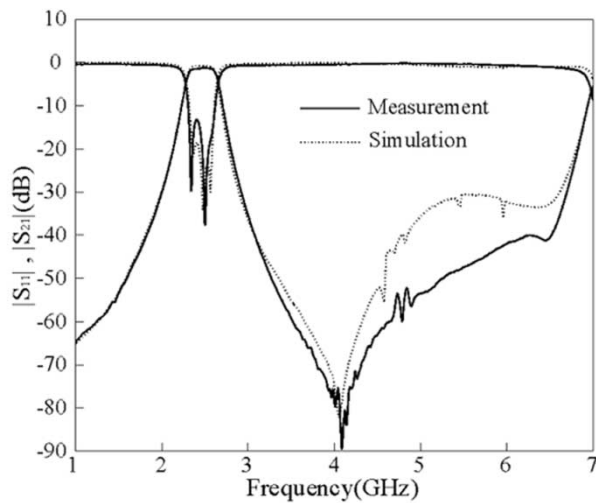
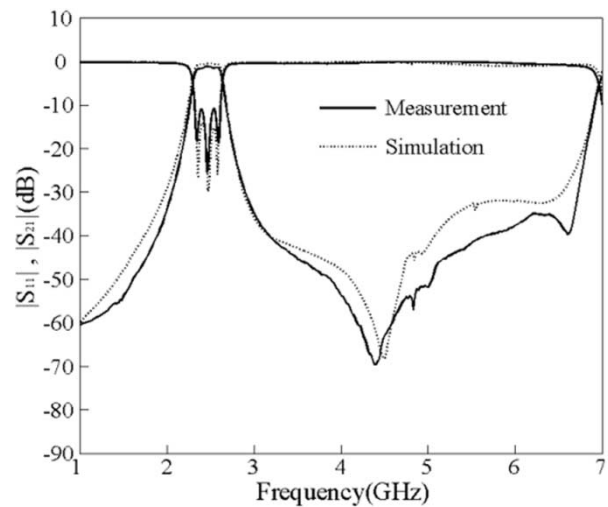Fig. 7. Simulation and measurement responses of filter A. Circuit parameters are in Table II.

Fig. 9. Simulation and measurement responses of filter C. Circuit parameters are in Table II.
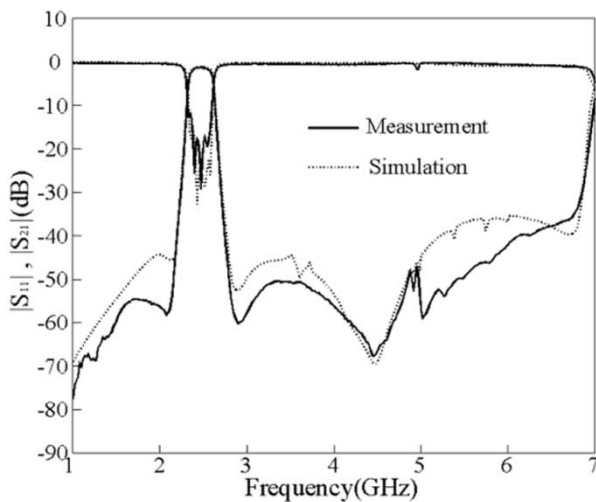

Fig. 8. Simulation and measurement responses of filter B. Circuit parameters are in Table II.
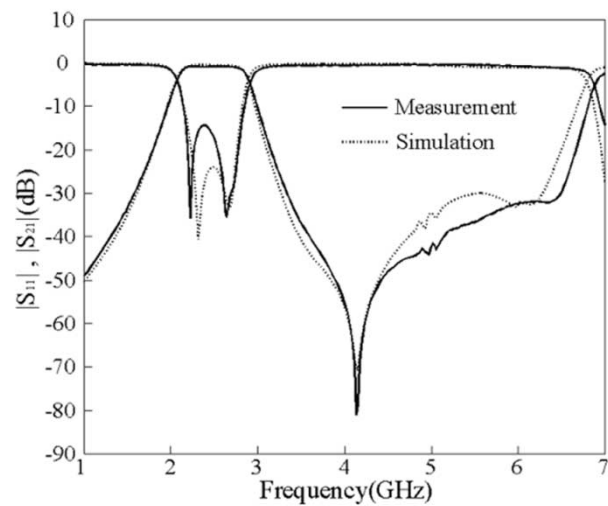

Fig. 10. Simulation and measurement responses of filter D. Circuit parameters are in Table II.

in Table II. It has been verified that the maximal relative deviation of ε_{re} and ε_{ro} for the coupled stages is 0.035%.

The responses of filters A–C are plotted in Figs. 7–9, and their substrate suspension heights are $h_1 = 0.06, 0.08$, and 0.10 mm, respectively. The order of filter B is five, and those of A and C are three. They are designed to have a fractional bandwidth $\Delta = 10\%$. It has been shown in [8] that the spurious responses

at $2f_o$ are higher than -10 dB for the filters with similar specifications on a substrate of $\varepsilon_r = 10.2$ without suspension. It can be observed that the small peaks near $2f_o = 4.9$ GHz are below or close to -50 dB. Thus, the proposed method achieves a suppression of 40 dB to the spurious responses. It can be observes that the dips of the responses of filters A–C are better than -60 dB.

Filters D–F are designed to have $\Delta = 25\%$ given $h_1 = 0.05, 0.07$, and 0.09 mm, and their results are shown in
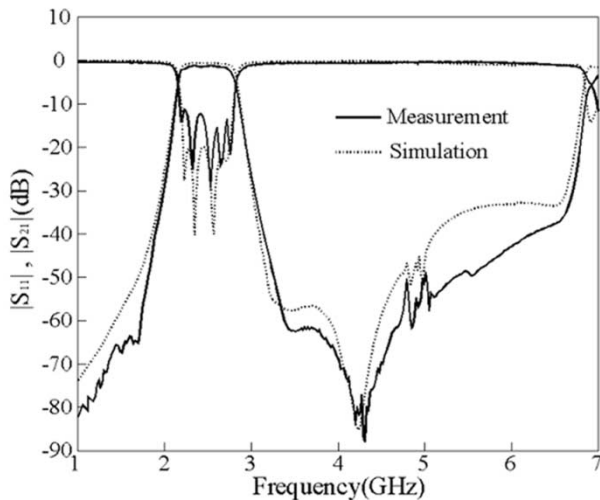
Fig. 11. Simulation and measurement responses of filter E. Circuit parameters are in Table II.
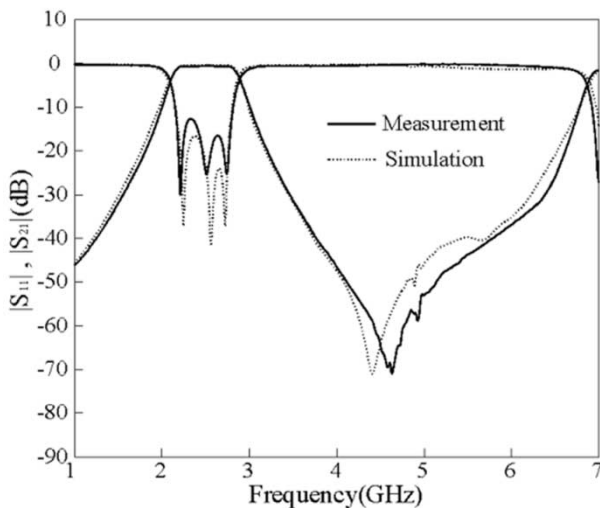

Fig. 12. Simulation and measurement responses of filter F. Circuit parameters are in Table II.

Figs. 10–12, respectively. Filter E is of order five, and filters D and F are of order three. The rejection levels at the response dips are better than -70 dB. The small peaks near $2f_o = 4.9$ GHz for filter D are close to -45 dB. The Ansoft High Frequency Structure Simulator (HFSS) is used for the simulation in this study. It can be observed that all the measured responses have a good agreement with the simulation in both the passband and stopband.

The conditions and parameters of Figs. 7–12 can be further explained as follows. For each h_1, we have to establish a PVEC and even- and odd-mode characteristic impedance design graphs since $\varepsilon_{re}, \varepsilon_{ro}, Z_{oo}$, and Z_{oe} depend on the thickness of the air gap. Once the fractional bandwidth and ripple level are known, the element values of the low-pass filter prototype can be obtained. In designing the third-order filter A, with an initial guess $Z_1 = Z_2 = 50$ Ω, one obtains the image impedances for the first and second coupled stages $Z_1 = 82.41$ Ω and $Z_2 = 103.1$ Ω from the solutions of (9). It is noted that $Z_3 = Z_2$ and $Z_4 = Z_1$. From (7), one

can then obtain the characteristic impedances of the end and middle stages $(Z_{oo1}, Z_{oe1}) = (69.12$ $\Omega, 120.1$ $\Omega)$ and $(Z_{oo2}, Z_{oe2}) = (85.84$ $\Omega, 113.0$ $\Omega)$, which are used to determine the dimensions of the coupled stages, as listed in Table II. Since the two points (Z_{oo1}, Z_{oe1}) and (Z_{oo2}, Z_{oe2}) locate on a PVEC, each coupled stage is guaranteed to have identical even- and odd-mode phase velocities.

It is noted that there are zigzags in all the $|S_{21}|$ responses shown in Figs. 7–12 at $2f_o$. This reflects the fact that the even- and odd-mode phase velocities of the coupled lines of each coupled stage for these filters have very close values.

V. CONCLUSION

This research has combined a field-theoretical study on the propagation characteristics of suspended microstrip lines and a flexible skill for design of parallel-coupled line filters. Substrate suspension is an effective approach in designing microstrip bandpass filters with suppression of the spurious resonance at twice the passband frequency. The design is based on a theory that the even- and odd-mode phase velocities of suspended coupled microstrips can be equalized on a substrate with a proper suspension height. A method has been developed for approximately synthesizing parallel-coupled microstrip filters of which each coupled stage can be of arbitrary image impedance. The simulation and measured results show a good agreement. As compared with the structure without suspension, this design has a suppression of 40 dB to the spurious responses.

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