Simplified Design Technique for High-Performance Microstrip Multisection Couplers

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***Abstract*—A new design technique has been developed which improves the design of a microstrip multisection coupler by a simplified version of the nonuniform coupler method. The technique achieves the performance of a smooth, discontinuity free, nonuniform coupler with a sectional breakdown of the coupling along the structure that can be simply and quickly optimized in a commercial simulator such as Libra. The design is further improved by the use of the "saw-tooth" odd- and even-mode equalization technique, and the effectiveness of this is verified experimentally. The measured results demonstrate an improved performance over the multisection coupler in terms of coupling performance and bandwidth, while the size and the fabrication tolerance are better than the nonuniform line coupler.**

***Index Terms*—Broad-band, coplanar, microstrip, mode equalization, multisecion coupler, nonuniform coupler, saw-tooth.**

I. Introduction

Broad-band couplers are commonly employed for phase shifting, power combining and dividing, and power sampling in microwave circuits. In certain specific applications such as image rejection mixers or signal monitoring in electronic warfare (EW) systems, they demand very broad-band couplers with low amplitude and phase errors. The two natural choices for an extended bandwidth coupler will either be the uniform multisection line coupler or the nonuniform line coupler. The multisection line coupler is simple in its design, but the sharp discontinuities between various sections, together with the even- and odd-mode velocity difference, degrade the accuracy of the coupling response and isolation at high frequencies, as shown by a number of examples in the literature [1]–[4]. The nonuniform line coupler [5]–[7] yields better performance because of the smooth tapering along the structure. This is realized by employing a pair of wavy-shaped coupled microstrip lines to achieve a specified overall coupling response. The design begins with Fourier transform analysis, and the synthesized structure is optimized using iterative techniques [8], [9]. These steps cannot be implemented in standard simulators, and the whole process is rather time consuming. Further, all the examples in the literature [5]–[7] show undesirable ripples and drop-off in coupling as frequency increases. The aim of this work was to develop a design technique which could achieve the better performance of the nonuniform line coupler, by a simplified approximation method, with an optimization procedure which can be carried out quickly on a standard simulator such as Libra.

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II. Design Method

A. Nonuniform Line Coupler

The first step for the nonuniform line coupler design requires the evaluation of the so-called "reflection coefficient distribution function," $p(x)$

$$p(x) = -\frac{2C}{\pi v}\int_0^{2\omega_c} \sin\left(\frac{2\omega x}{v}\right) d\omega \tag{1}$$

where v is the phase velocity of the propagating wave on the line, ω_c is the center frequency, C is the nominal coupling value, and x is the distance along the coupler length. The coupling response $C(\omega)$ is obtained by taking the Fourier transform of (1)

$$C(\omega) = \int_0^{l/2} 2\sin\left(\frac{2\omega x}{v}\right).p(x)\,dx \tag{2}$$

where l is the physical coupler length. The normalized even-mode impedance function Z_{oe} is

$$Z_{oe} = \exp\left(\int_0^{l/2} p(x)\,dx\right) \tag{3}$$

and the continuous coupling distribution function $k(x)$ along the coupler is

$$k(x) = \frac{Z_{oe}^2(x) - 1}{Z_{oe}^2(x) + 1}. \tag{4}$$

The physical structure of the nonuniform line coupler can then be constructed according to (4). A typical $k(x)$ for a three-section nonuniform line coupler is shown in Fig. 1(a).

The major problem of the nonuniform line coupler is that it does not allow one to optimize its coupling response easily even with the aid of existing microwave simulation software.

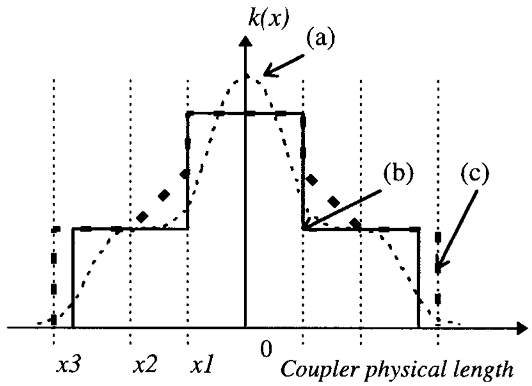


Fig. 1. (a) Coupling distribution for nonuniform line, (b) for multisection line, and (c) for nonuniform line approximation.

For instance, when one wishes to reduce the ripple level for a maximally flat response, it requires several iterations and re-simulation which is very time consuming, and it does not necessarily gives the desired response due to the complication of the continuously varying coupling factors along the nonuniform line structure. Further, as can be seen from Fig. 1(a), the ideal coupling factor required at each end of the coupler needs to be zero, which implies infinite spacing. In practice, the use of finite spacing will modify the whole coupling distribution, which in turn disturbs the accuracy of the overall coupling response. The wide spacing required at each end of the coupled lines can exceed $\lambda/4$ at the highest frequency of interest, resulting in relative time phasing which does not allow coupling to add correctly to the overall coupling response, causing a drop-off in coupling at high frequencies [8]. The higher coupling required at the center section also implies a more stringent fabrication tolerance.

B. Conventional Multisection Coupler

The design of the multisection coupler is similar to the nonuniform line coupler, and the coupling distribution for a three-section coupler is shown in Fig. 1(b). The appropriate coupling values for various sections were derived and expressed conveniently by Cristal and Young [10], and the design is therefore relatively simple for a particular overall coupling and bandwidth. The structure can be simulated easily using standard simulation software. The problem with this type of coupler is that the large step discontinuities and transitions between the different coupling sections degrade the isolation at frequencies above X-band, resulting in large errors in coupling amplitude.

C. The New Technique

A better approximation to the nonuniform line coupling [Fig. 1(a)] than the conventional multisection coupling [Fig. 1(b)] can be achieved by a modified multisection breakdown of the coupling where a tapered section is included between the center and outer sections [Fig. 1(c)]. This approximation allows a very accurate and predictable coupling response to be designed, since all the coupling along the structure is taken into analysis, and the coupler performance can be optimized easily in a standard simulator with relatively straightforward procedure. The coupler design begins with choosing the appropriate coupling values for the various sections, as for the conventional multisection coupler, using the table given by Cristal *et al.* [10], according to the particular desired overall coupling, ripple, and bandwidth. The coupler at the center section sets the overall coupling amplitude and its length determines the center frequency of the design bandwidth, while the spacing of the outer sections can be altered to give a particular ripple level. The taper between the sections can be arbitrarily chosen to be short, but smooth enough for minimal discontinuities, and this section forms a linear tapered coupler. Since (1)–(4) are also applicable to uniform multisection line couplers, evaluating (3) and (4) gives

$$p(x) = \frac{1}{2}\ln\sqrt{\frac{1+k(x)}{1-k(x)}}. \tag{5}$$

Substituting (5) into (2) gives the coupling response

$$C(\omega) = \int_0^{l/2} \sin\left(\frac{2\omega x}{v}\right) . \ln\sqrt{\frac{1+k(x)}{1-k(x)}}\, dx. \tag{6}$$

Referring to Fig. 1(c), (6) can be broken into various couplings

$$\begin{aligned} C(\omega) = &\int_0^{x_1} \sin\left(\frac{2\omega x}{v_1}\right) . \ln\sqrt{\frac{1+k_1}{1-k_1}}\, dx \\ &+ \int_{x_1}^{x_2} \sin\left(\frac{2\omega x}{v_2}\right) . \ln\sqrt{\frac{1+k_2}{1-k_2}}\, dx \\ &+ \int_{x_2}^{x_3} \sin\left(\frac{2\omega x}{v_3}\right) . \ln\sqrt{\frac{1+k_3}{1-k_3}}\, dx \end{aligned} \tag{7}$$

where k_1 and k_3 are the coupling factors along the center and outer sections, respectively, and k_2 represents the varying coupling factor along the arbitrary tapered section. v_1 and v_3 are the phase velocity for the center and outer sections, respectively, and v_2 is the varying phase velocity for the tapered section. The length x_1 sets the center frequency, while x_2 is the arbitrary length of the tapered section. It follows from (7) that there must be a value of x_3 which will satisfy the nominal coupling $C(\omega)$ for the modified coupling distribution along the coupler length. Equation (7) can therefore be repeatedly optimized until the desired coupling response is achieved. This equation also suggests that the coupler structure can be quickly optimized with the aid of commercial simulation software, in a similar manner.

It was found that the overall length of the new structure is always approximately a quarter-wavelength shorter than the nonuniform line coupler, and as one might expect, the design resembles the nonuniform line structure. More sections (over and above three sections) can be cascaded and optimized in the same manner.

D. Coupler Structures Designed

In order to test the approach, two designs were made. Both designs employed planar microstrip coupled lines for the sake of simplicity in fabrication, although other coupler structures

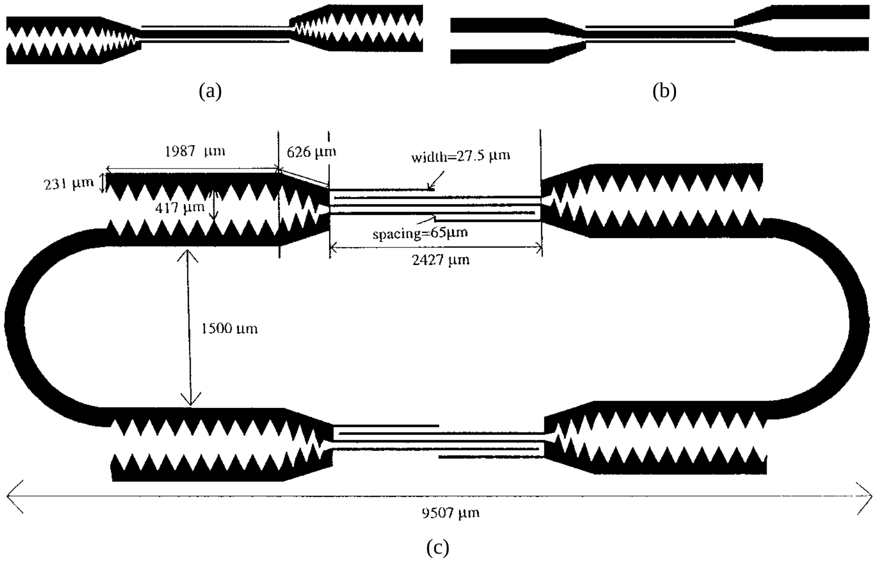


Fig. 2. (a) Three fingers with saw-tooth outer sections, (b) without saw-tooth, and (c) Lange at center with saw-tooth outer sections (tandem connections is shown).

are also feasible. The first design, as shown in Fig. 2(a), were a three-finger interdigitated coupler as the center section.

A tandem connection of two −8.34 dB couplers was used to realize −3 dB coupling because this could reduce sharp change in tapering and also avoided narrow spacing at the center section. The required coupling for the center and outer sections were −6.4 and −20 dB, respectively, for a −8.34 dB overall coupling. The spacing between the two couplers was chosen to be 1.5 mm apart for negligible coupling between the couplers, and circular bends were employed for the interconnections. Comparison with the performance of the same design without saw-tooth compensation [Fig. 2(b)], has also been experimentally investigated.

The second design employs the standard four-finger interdigitated coupler as the center section, with saw-tooth coupled line as the outer sections [Fig. 2(c)]. Both couplers were designed to provide −3 dB equal power splitting over 6–18 GHz, with a maximum of 0.8 dB deviation.

The designs were first carried out in the Libra simulation software. The three- and four-finger couplers and coupled-line models were available from the microstrip component library. The physical dimensions corresponding to the required coupling values for the center and outer sections were obtained from LinCalc. The tapered junction was chosen to be short, but smooth enough for minimal discontinuity. Optimization was then carried out by varying the length and spacing of the outer sections until the desired ripple level was obtained. The coupling amplitude over the desired bandwidth was optimized by controlling the coupling value at the center section. At this stage of simulation, the coupling amplitude was correct but degraded at high frequencies, and the isolation of the coupler was poor. Saw-tooth compensation [11] was then applied to both the tapered and outer saw-tooth sections and each was separately simulated using the Momentum 2.5-D planar electromagnetic simulation package, which was available within Libra. The S-parameters for each section were cascaded together to give the overall response.

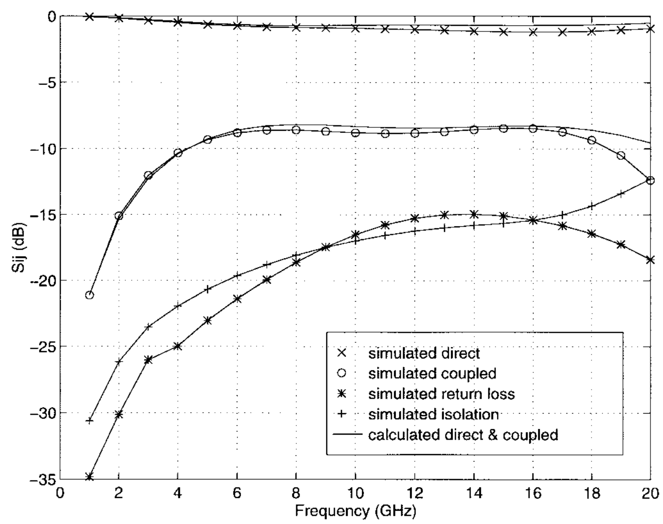
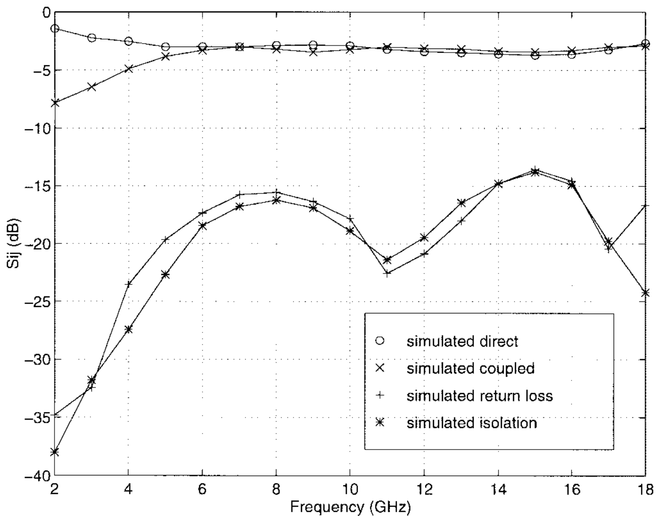


Fig. 3. Libra simulation and calculated response.

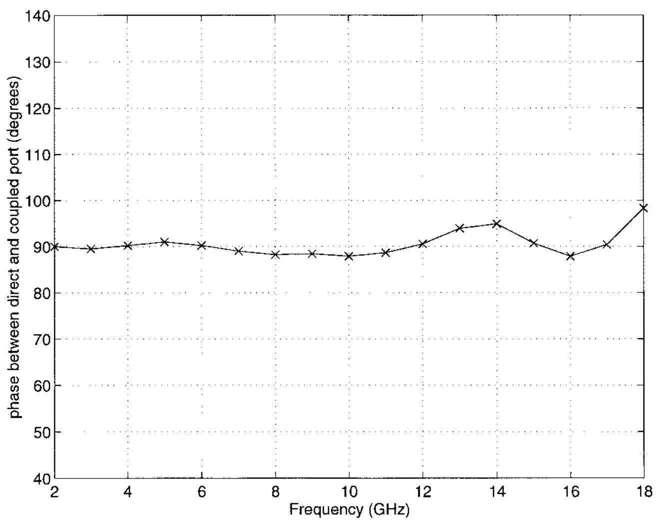
The Libra simulated coupling response for the four-finger model with saw-tooth outer sections (−8.34 dB overall coupling) was compared with (7). The coupling values along the structure (from Libra) were entered into (7). The tapered section was treated as many elemental microstrip coupled lines and the coupling values for each element can be calculated from LinCalc. From the comparison as shown in Fig. 3, it can be seen that (7) predicts a slightly broader bandwidth than the simulated response from Libra. This is because (7) assumes TEM propagation and hence, infinite isolation. A similar response was obtained for the three-finger multisection coupler.

The overall S-parameters (from Libra) and the phase response obtained for the tandem connection of two −8.34 dB couplers are shown in Fig. 4(a) and (b), respectively.

The simulation shows that the coupling is -3 ± 0.8 dB over 6–18 GHz, with a phase difference between the direct and coupled port of better than 8° over 2–18 GHz.



(a)



(b)

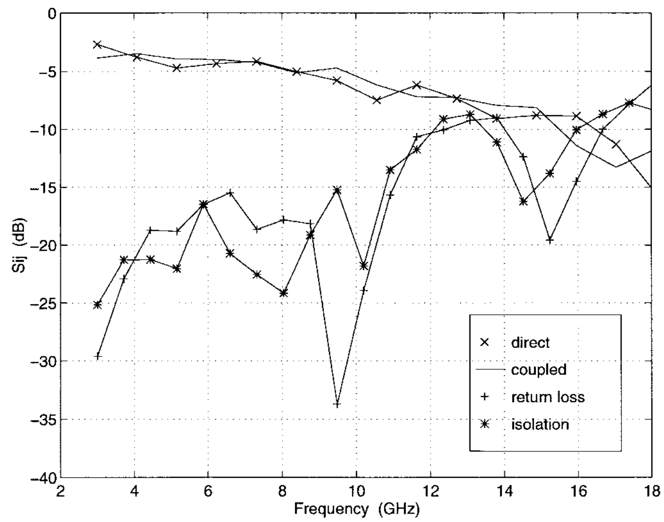
Fig. 4. (a) Simulated S-parameters for four-finger and saw-tooth outer sections -3 dB coupler and (b) simulated phase difference between the direct and coupled port.

TABLE I
DESIRED AND MEASURED PHYSICAL DIMENSIONS OF THE FOUR-FINGER COUPLER

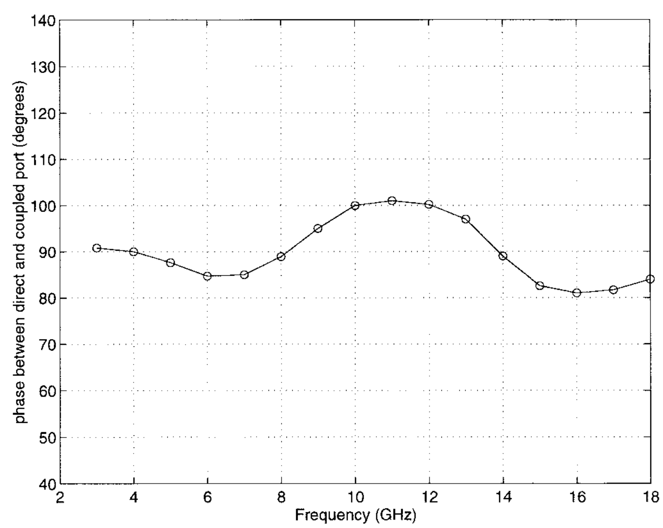
	Desired	Measured (1st run)	Measured (2nd run)
width (μm)	27.5	28	33
spacing (μm)	65	64	60

TABLE II
DESIRED AND MEASURED PHYSICAL DIMENSIONS OF THE THREE-FINGER COUPLER

	Desired	Measured (1st run)	Measured (2nd run)
width1 (μm)	33	34	38
width2 (μm)	139	138	144
spacing (μm)	37	36	32



(a)



(b)

Fig. 5. (a) Three-finger coupler without compensation and (b) phase between direct and coupled port for three-finger coupler without saw-tooth outer section.

III. FABRICATION

The designs shown in Fig. 2 were fabricated on 50.8 mm^2 alumina tile, with thickness 254 μm, using the GMMT thin-film process. The mask was produced by the e-beam technique with a maximum tolerance of less than 0.1 μm. The fabricated circuits were measured under the microscope and the dimensions for the four- and three-finger couplers are compared with the desired dimensions in Tables I and II, respectively, since the coupling amplitude is most sensitive to these center sections.

The circuits fabricated in the first run show very good tolerance. The second run shows oversizing effects in track widths because the gold plate-up time had been increased, since it was thought that this will aid the wire-bonding process. The final gold thickness was measured to be 5 μm. It has been found from the simulator that the deviations of the physical dimensions from the desired values have negligible effects on the performance. Bond wires of 17-μm diameter were used to connect the alternate fingers.

IV. MEASURED RESULTS

The designs were fabricated on 254-μm alumina and measured using GMMT RFOW test facilities. The calibration kit

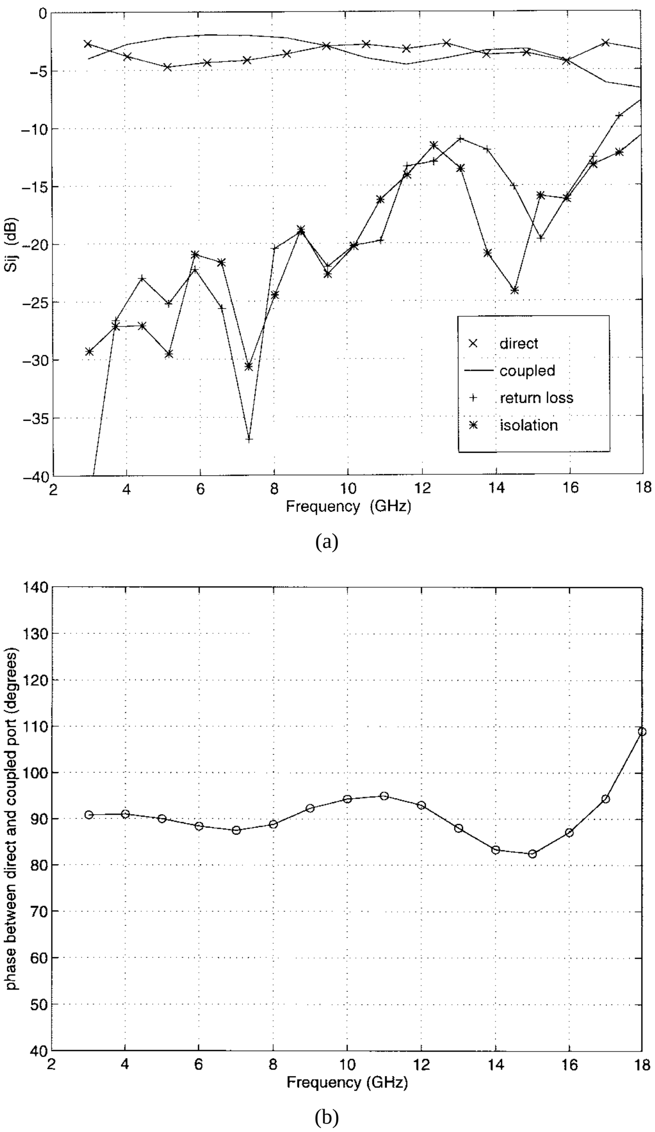


Fig. 6. (a) Three-finger coupler with compensation and (b) phase between direct and coupled port for three-finger coupler with saw-tooth outer sections.

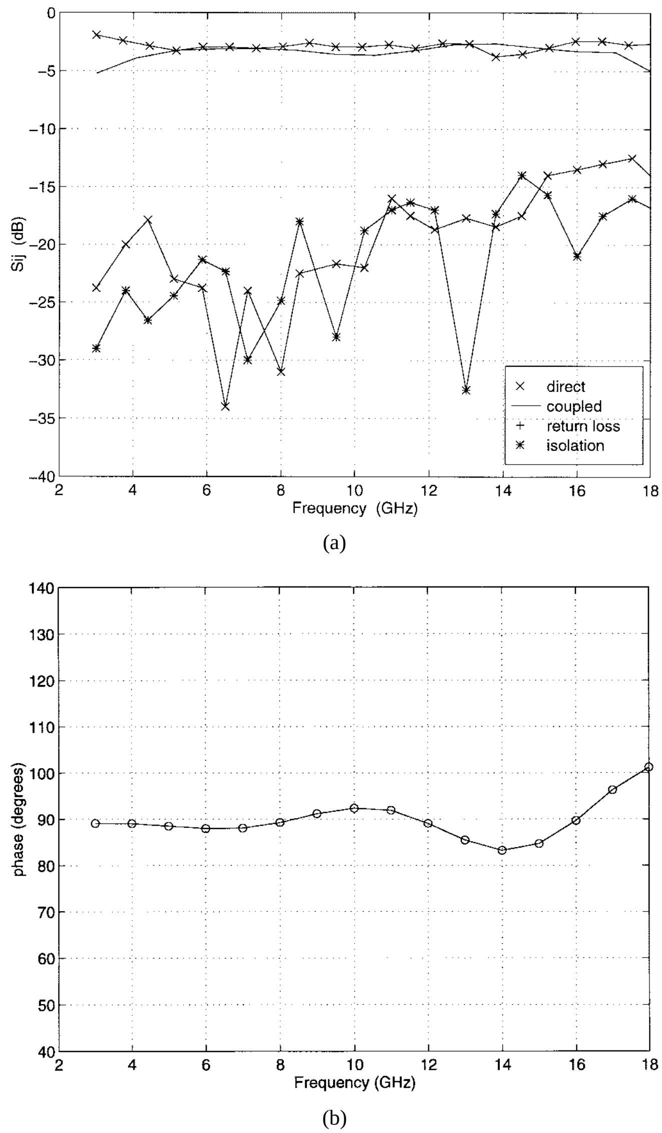


Fig. 7. (a) Four-finger with compensation and (b) phase difference between direct and coupled port for four-finger coupler.

fabricated on the same tile was used to remove reflections at the probe tip and pad transitions. The measured response of the first-run three-finger coupler [Fig. 2(b)] without compensation is shown in Fig. 5(a).

The coupling degrades rapidly with frequency, which is expected, and also occurs in a nonuniform line coupler without compensation. The effects of the even/odd mode phase velocity difference becomes apparent at and above 10 GHz, since the return loss and isolation are both worse than -10 dB, and the phase difference between the direct and coupled port is worse than 10° [Fig. 5(b)].

With saw-tooth compensation, the coupling response shown in Fig. 6(a) is improved significantly, and this performance is similar to the nonuniform line coupler as reported in [5]–[7].

The measured coupling is -3.4 ± 1.3 dB over 3–16 GHz, and the phase between the direct and coupled port is $90 \pm 7^\circ$ [Fig. 6(b)]. The large ripple levels were mainly caused by over-coupling of the outer sections. Because the three-fingers coupler is not compensated, the even- and odd-mode phase velocity difference at high frequencies caused errors in coupling response. From Fig. 5(a), the measured return loss of the coupler without saw-tooth is below -7.5 dB over 3–17 GHz, while the use of saw-tooth compensation suppresses the return loss to below -11.5 dB over the same bandwidth [Fig. 6(a)]. The effectiveness of the saw-tooth compensation could be further optimized for improvement.

The measured coupling and direct ports of the four-finger coupler with optimized saw-tooth compensation are shown in Fig. 7(a). Both direct and coupling are -3 ± 0.7 dB over 4.5–17.4 GHz. The coupling response at high frequency is improved because the even- and odd-mode fields are more evenly distributed in the four-finger center section, as compared with the three-finger coupler. The measured isolation is better than -14 dB over 3–18 GHz, while the return loss is better than -14 dB over the same bandwidth, with worst case of -12 dB at 17.5 GHz. The phase difference between the direct and coupled is less than $90 \pm 6^\circ$ below 17 GHz, as shown in Fig. 7(b). Although the center frequency is 0.5 GHz lower, which might be due to slight variation in effective permittivity caused by fringing fields at microstrip edges and sharp corners at the outer/center sections interface, the measured coupling amplitude has been very flat over the specified bandwidth. These results show significant improvement over those designs reported in the literature which also employ microstrip edge coupling mechanisms. The design procedure can be applied to CPW coupled line to realize an ultra-broad-band coupler, as proposed in [12].

V. Conclusion

A new microstrip multisection coupler design technique has been developed and verified against coupler measurements. The analysis takes all the couplings along the multisection coupler into account, allowing a high-performance, very broad-band coupler to be synthesized with a much simpler procedure than the nonuniform line technique. The inclusion of a linear tapered section provides the following advantages:

- a good approximation of the nonuniform coupling;
- a reduction in discontinuities compared to the convention multisection couplers;
- easy simulation in a standard commercial simulator for a coupler of any number of sections.

The measured results show -3 dB coupling ± 0.7 dB from 4.5 to 17.4 GHz and -14 dB isolation, which exceeds the performance of standard multisection couplers. This technique can be applied to other couplers such as CPW coupled lines or multilayer broadside coupling structures to realize a multioctave band coupler.

Acknowledgment

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