Design of Broad-Band Dielectric Waveguide 3-dB Couplers

PERTTI K. IKÄLÄINEN AND GEORGE L. MATTHAEI, FELLOW, IEEE

Abstract —It is shown how 3-dB couplers with bandwidths on the order of 30 percent can be designed by appropriately taking advantage of the dispersion and the frequency dependence of coupling per unit length between two dielectric waveguides with asymmetrical cross sections. Theoretical methods for computing frequency responses of such couplers are discussed. It is shown how the phase response can be simply compensated to give approximately symmetrical-coupler-type or "magic tee" coupler-type phase-difference responses over comparable bandwidths. Experimental results confirming theoretical calculations are presented.

I. Introduction

VARIOUS RESEARCHERS have treated the problem of designing dielectric waveguide (DW) hybrids (i.e., 3-dB directional couplers) for millimeter-wave applications (see, for example, [1]–[5]). Most designs presented so far have been based on coupling between two identical dielectric waveguides. The bandwidths achieved in such couplers are generally small to moderate, while wider bandwidths may be desirable in many applications of hybrids, such as balanced mixers. Means for achieving broader bandwidths have been demonstrated in [1] and [5]. In [1], a connecting dielectric layer was added between coupled image guides to give wide bandwidth. Very wide bandwidths were also obtained in [5] by using a totally different approach, i.e., a beam-splitter type design. However, the method of [5] may be inconvenient in practice because a layer having a specific dielectric constant different from that of the guides is required. Also, the methods in [1] and [5] tend to give relatively low directivity. Yet another possible approach to wide-band hybrid design would be the tapered velocity coupler principle, [6]–[10]. However, a serious drawback of the tapered velocity couplers is that they have to be very long, several tens to hundreds of wavelengths, which makes them large and lossy.

We have investigated 3-dB directional couplers where coupled guides with unequal cross sections are used to obtain large bandwidths. It was found that the maximum level of coupling between such guides varies so that at lower frequencies more power is allowed to be coupled and the coupling length which is required for this maximum coupling to take place is less than at higher frequencies. Broad-banding is achieved by making use of these effects. The technique was developed by studying coupling between asymmetrical (semi-infinite) slab guides, but because the qualitative behavior of coupling for many types of DW's is similar to that of slab guides, this method should have potential for use with many different types of DW's. Our experiments showed that good results are obtainable at least with image guide. These couplers are relatively easy to fabricate, give large bandwidths, and maintain excellent directivity.

In this paper, we discuss the basic principles of operation of such couplers. We also discuss two different (approximate) theoretical methods for computing frequency responses for such couplers: the conventional coupled-mode approach and a normal-mode analysis (an extended "odd- and even-mode" analysis). Although these two methods are related and give similar results, both are presented as they augment each other in giving additional insight into the coupling process. Finally, experimental results are presented which show good agreement with theoretical calculations.

II. Principle of Operation

It is well known [11] that if two uniformly coupled, lossless DW's have the same propagation constant, all the power propagating in one guide can be transferred to the other if the coupling region is long enough. In a conventional, symmetrical DW coupler (where full power transfer is possible) 3-dB coupling is achieved by choosing the length of the coupler so that half of the power fed into one guide becomes coupled. The bandwidth of such couplers tends to be small because the power is rapidly transferring from one guide to the other as frequency is changed, and this effect is enhanced by dispersion. On the other hand, if the propagation constants of two coupled guides differ, only partial power transfer can occur. In particular, one might design a coupler so that at maximum, exactly half of the power becomes coupled. Then the coupled power versus *coupler length* is flat (has zero first derivative) at the design frequency and it would appear that bandwidth should be improved. We calculated frequency responses for some slab-guide couplers of this sort. The propagation constants were made to differ by making the widths of the

Manuscript received November 11, 1986; revised February 23, 1987. This work was supported in part by the National Science Foundation under Grant ECS83-11987.

P. K. Ikäläinen was with the Department of Electrical and Computer Engineering, University of California, Santa Barbara. He is now with the Technical Research Centre of Finland, Telecommunications Laboratory, Espoo, Finland.

G. L. Matthaei is with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106.

IEEE Log Number 8714792.

0018-9480/87/0700-0621$01.00

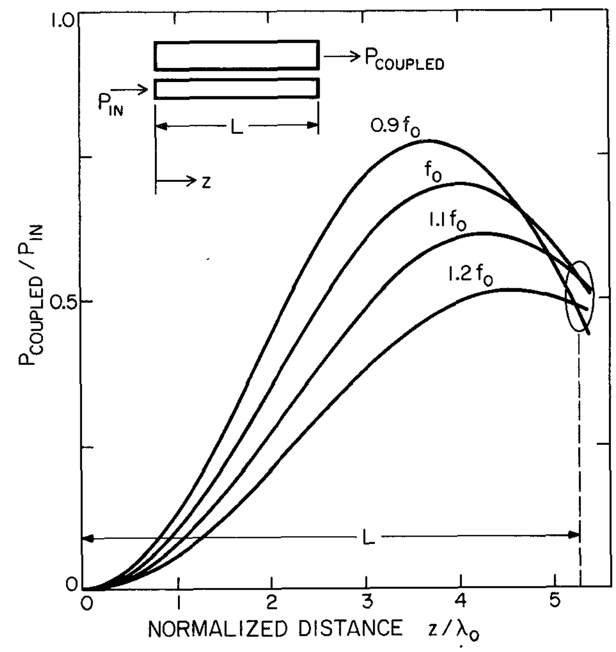


Fig. 1. Coupled power versus distance (normalized to wavelength in air) at various frequencies. For the length L shown, we get close to 3-dB coupling over a wide band of frequencies. The dimensions of the coupled guides are as shown in Fig. 3.

two slabs different from each other, and the spacing between them was chosen so that maximum coupling was 3 dB at the design frequency. We found that, contrary to our expectations, such designs were not significantly more wide-band in terms of *frequency* than the conventional symmetrical coupler although there was slight improvement. This was then attributed to the fact that DW's are dispersive and the coupling strength between two DW's is generally strongly frequency dependent.

Fig. 1 shows curves of coupled power versus distance at various frequencies in an asymmetrical slab-guide coupler (operating in the lowest order TE mode) for one particular case. These curves were obtained using a mode-superposition theory to be discussed in Section III. The characteristic feature of asymmetrical coupling that only partial power transfer can occur is readily apparent from Fig. 1. Note that after the maximum transfer has occurred, the power starts to couple back to the first guide and would all be coupled back if the coupler were long enough, and the cycle would then repeat. Two facts about the appearance of the curves in Fig. 1 are worth noticing. First, the level of maximum coupling is a relatively strong function of frequency. Second, the location of maximum coupling varies in, perhaps, an unexpected way with frequency. As can be seen from Fig. 1, it takes a *longer* length at *higher* frequencies for the maximum coupling to take place, while simple first-order theory ignoring the variation of coupling with frequency would predict exactly the opposite.[1] These observations can be qualitatively explained from the coupled-mode theory point of view (to be discussed briefly in Section III). At low frequencies, the evanescent fields of the modes in the two guides extend out relatively far and strongly interact; thus, the guides are strongly coupled. Conversely, at high frequencies the coupling is weaker because the evanescent fields between the guides decay more rapidly.

[1]An analogous phenomenon can be observed in conventional symmetrical DW couplers where the coupled power typically decreases with increasing frequency (see [2] and [4]).

TABLE I
EXAMPLES OF UNIFORM, ASYMMETRICAL SLAB-GUIDE COUPLERS AND CORRESPONDING THEORETICAL BANDWIDTHS

t_1	t_2	d	L	band
0.45	0.50	0.45	21.5	9.3 to 11.1
0.40	0.50	0.30	10.0	8.9 to 11.6
0.35	0.50	0.20	6.1	8.4 to 12.6
0.30	0.50	0.15	4.4	7.2 to 12.8

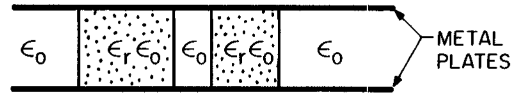
t_1 and t_2 are the widths of the guides, d is the spacing between them, and L is the length of the coupler, all in inches. The dielectric constant is 2.25. The column "band" indicates the theoretical bandwidth (in GHz) for 1-dB unbalance between the outputs.

While the above-mentioned phenomena usually tend to make DW couplers narrow-band, we found that a proper design can benefit from these effects and wider bandwidths are possible. Fig. 1 illustrates this point. The guide dimensions and spacing have been chosen such that at the lower end of the band appreciably more than half of the power is transferred to the second guide, while the coupler length is adjusted so that at the far end of the coupler the excess power has coupled back to the first guide. Then, at the upper end of the band, the maximum coupling drops down closer to 3 dB, while owing to reduced coupling per unit length in this frequency range, the point of maximum power transfer moves approximately to the far end of the coupler. It can be seen from Fig. 1 that curves covering a wide range of frequencies all pass close to the level of one half for the length L shown giving wide-band 3-dB coupling. The required degree of asymmetry and spacing to obtain this kind of coupling do not seem to be critical. Table I shows some results calculated for uniform slab-guide couplers (using the mode-superposition theory). The approximate center frequency of these designs is 10 GHz because our experimental work was performed in that range. The third example of Table I corresponds to the case shown in Fig. 1. The designs in Table I were obtained by first choosing the guide cross-sectional dimensions t_1 and t_2, then choosing the spacing d so that at 10 GHz the maximum coupling was about 65 to 70 percent, and finally choosing the coupler length L so that at the far end of the coupler the excess power coupled at lower frequencies will have coupled back to the other guide. It appears from Table I that the more there is asymmetry, the more bandwidth can be obtained. However, very large asymmetries are not feasible because of considerations such as higher order modes if one guide is very wide, or radiation from curved parts if the other guide is very thin. Also, for large asymmetries, a small spacing between the guides is required. For small spacings, the theory used to calculate the results in Table I becomes less accurate.

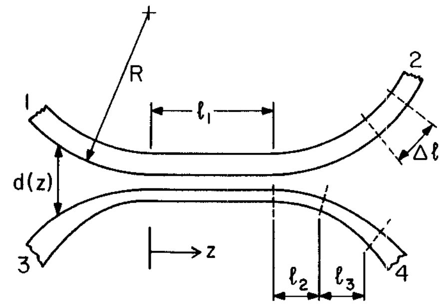
In the foregoing discussion, it has been assumed that the guides are uniformly coupled, while an actual coupler, see Fig. 2(b), for example, must include curved line segments as well. There, the length of the uniformly coupled part has to be adjusted to compensate for the extra coupling in the curved sections, but the basic principles giving the broad bandwidth remain the same. The preceding discussion was also limited to slab guides. In our studies, we have considered the problem of coupled dielectric slab guides because the mode field solutions, which are needed for the coupler analysis, are then easily obtainable in closed form [12]. The appropriate eigenvalue equation can also be written in closed form [12] and can be solved using standard numerical root-finding techniques. In order to check our slab-guide theoretical results experimentally, we have used dielectric waveguide with ground planes on both top and bottom (see Fig. 2(a)) for which the lowest order modes are exactly the same as the TE modes of slab guides. However, while the slab guide or the kind of DW shown in Fig. 2(a) is not very practical for actual millimeter-wave applications, the results for slab waveguides are believed to show qualitative trends of behavior which are applicable for a large class of DW's. This is supported by the widely used effective dielectric constant (EDC) approximation [13], which says that guides such as image guide, for example, behave approximately as slab guide with some effective dielectric constant. It is also supported by our experimental results, which showed that a coupler which was designed entirely on the basis of slab-guide calculations gave good results in image-guide configuration after the spacing between the guides had been experimentally adjusted.

III. Approximate Methods for Computing Frequency Responses

Fig. 2 shows a sketch of an asymmetrical coupler we designed. In order to compute frequency responses for such structures, we needed a method to analyze the sections where the guides are curved and tapered in width. We chose a simple approximation which is often used in similar situations: these curved coupled guides were divided into small segments which were analyzed as being uniformly coupled and parallel. Such segments were then connected in cascade to form the complete structure. Several ways to define the separation between these elemental sections in this kind of an approach have been proposed [3], [4], [14]. We chose to measure the separation simply as the linear distance between the guides, perpendicular to the straight part (see $d(z)$ in Fig. 2(b)). For a coupler such as that shown in Fig. 2(b), where a significant part of the coupling occurs in a straight center portion and where large radii of curvature are used, differences between different ways of measuring the distance are small. For a more accurate treatment of the curved guides, one might consider, e.g., the coupled-mode formulation of [15], which was specifically developed for coupling between curved guides.



(a)



(b)

Fig. 2. (a) Cross section of the type of DW used in our experiments. (b) Top view of a coupler with the top plate removed (not to scale). The dimensions shown are $R = 13.6\lambda_0$, $l_1 = 1.90\lambda_0$, $l_2 = 1.93\lambda_0$, and $l_3 =$ length of taper $= 2.30\lambda_0$, where λ_0 is wavelength in air. The widths and spacing of the guides in the center part are as shown in Fig. 3.

Two different methods for analyzing the uniformly coupled parallel-guide segments were considered: Miller's coupled-mode theory [11] and a normal-mode analysis. Both are approximations that work best in the limit of loose coupling. They also have a close relationship and give similar results. However, their points of departure are very different and they stress different aspects of the coupling process.

A. Coupled-Mode Theory

Coupled-mode theory has been applied to a variety of problems in addition to directional couplers and it has been treated extensively in the literature (see, for example, [11] and [16]–[18]). The coupled-mode equations appear in many different forms in the literature. We used the equations

$$\frac{dE_1}{dz} = -j\beta_1 E_1 + jcE_2 \tag{1a}$$

$$\frac{dE_2}{dz} = -j\beta_2 E_2 + jcE_1 \tag{1b}$$

to describe the coupling. Here, E_i stands for the normalized wave amplitude in guide i, $i = 1, 2$, so that $|E_i|^2$ gives power traveling in guide i; β_1 and β_2 stand for the propagation constants of guides 1 and 2, respectively, in the absence of coupling; c is the coupling coefficient; and $j = \sqrt{-1}$. Solutions to these equations corresponding to different boundary conditions are readily derived. However, finding the coupling coefficient for a given geometry of coupled guides is a difficult problem and has been discussed by several authors (see, for example, [19]–[21]). In this work, we used [21, eq. (14)] to evaluate c in terms of the known fields of the uncoupled modes of the two guides.

B. Analysis by a Superposition of Normal Modes

The other method we have considered for analyzing the parallel-coupled segments of DW's (which form the complete structure when connected in cascade) is an extension of the well-known odd- and even-mode analysis commonly used for symmetrical couplers. The basic idea is to use a superposition of the two lowest-order normal modes of the *coupled waveguide system* (not the modes of the isolated waveguides, as in the coupled-mode theory) to represent a situation where one of the guides is driven and one is not. The coupling arises from interference (beating) between these two modes with differing propagation constants.

It should be realized that the notion of driving only one guide is not well defined. Consider Fig. 2(b). At the far left, the guides are identical and fairly far apart. In this region, if the guide at port 3 is driven while port 1 is not, this excitation is modeled quite well as the sum of an odd mode and an even mode of equal amplitudes whose fields add at port 3 and cancel at port 1. However, near the center of the coupler, where the guides are relatively close to each other and the cross section is quite unsymmetrical, the "odd-like" and "even-like" modes are similar to the solid lines in Fig. 3 (which were computed for the indicated slab-guide example). In this case, it is less clear how a superposition of these two modes can result in all of the power being in one guide and no power in the other. Indeed, since the fields are extensive and unsymmetrical in the region between the guides, it is unclear how power should be attributed to one guide or the other. However, for a simplified theory, a division of power between the two guides is attractive because then we can treat the segments of coupled guides as simple four-port networks. One way to define the relative mode amplitudes in the superposition would be to minimize the power, defined in the usual Poynting vector sense, over the cross section of the nonexcited guide, as was done in [22]. One difficulty in such an approach is that one has to define a "boundary" between the guides, and in the general case of asymmetrical coupled guides it is not at all clear where such a boundary should be located. In [22], the boundary was defined to be midway between the two guides, which may work well for slightly asymmetrical guides but not necessarily for more general cases.

We developed an approximate theory by adopting a simplified definition for "power carried in each guide." (Note that any theory holding on to the idea of "one guide driven" for the case of tightly coupled DW's is an approximation anyhow, as was discussed above.) Consider an uncoupled DW and a guided mode traveling along it. There exists a constant of proportionality G, akin to the characteristic admittance of a transmission line, such that the power carried by the guide is given by

$$P = GE_{\max}^2 \tag{2}$$

where $E_{\max}$ denotes the maximum magnitude of the transverse electric field. Note that in this respect not only the point of maximum electric field but any other point of reference in the guide or even outside it would serve

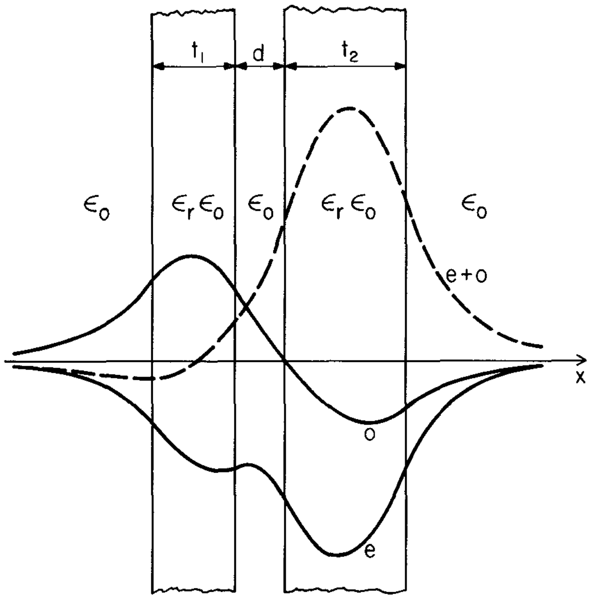


Fig. 3. The solid lines show mode shapes (E_y versus x) for the two lowest order TE modes. The dotted line shows a superposition of these modes which represents driving only the wide guide. The dimensions shown are $t_1 = 0.296\lambda_0$, $t_2 = 0.423\lambda_0$, $d = 0.169\lambda_0$, and $\epsilon_r = 2.25$.

equally well; only the value of G would be different. This idea of defining power in a guide based on a knowledge of the magnitude of the transverse electric field *at one point* was applied to coupled guides. However, now the outcome of the analysis depends on where the point of reference is chosen to be. The point where the electric field of the *uncoupled* mode attains its maximum seems like the most meaningful. We have found that this definition leads to results that are consistent, at least in the case of slab waveguides, with both the coupled-mode theory and experiments, as will be shown. In our slab-guide case (Fig. 3), the formulation is simple. The TE modes have only the y component (i.e., vertical component) of the electric field and the fields have, of course, no y dependence. The electric field of the uncoupled mode (lowest order) attains its maximum at the center of the guide. So let the centers of the two guides be at x_1 and x_2, respectively, and let the transverse mode patterns of the even-like mode and odd-like mode be $E_y^e(x)$ and $E_y^o(x)$, respectively. Power carried by guide i is assumed to be given by the magnitude squared of the total transverse electric field at x_i multiplied by G_i:

$$P_i = G_i \left| E_y^e(x_i) + E_y^o(x_i) \right|^2. \tag{3}$$

Let the two modes be excited with the following amplitudes:

even-like:

$$E_y^e(x_1) = E_0$$

odd-like:

$$E_y^o(x_1) = -E_0.$$

Power fed into guide 1 is then zero, in the sense of (3). The dotted line in Fig. 3 shows an example of such a superposition. Note that the fields add to zero at the center x_1 of the left guide. For a lossless coupler, we can enforce conservation of energy to hold, which allows us to derive an additional relation between the variables. First, define ratios α^e and α^o by

$$\alpha^{e,o} = \frac{E_y^{e,o}(x_2)}{E_y^{e,o}(x_1)}. \tag{4}$$

Then, find the total power (with initial amplitudes at $z=0$ as defined above) and require it to be constant versus z; this leads to

$$P_{\text{tot}}(z) = G_1\left|E_0 e^{-j\beta^e z} + (-E_0)e^{-j\beta^o z}\right|^2 + G_2\left|\alpha^e E_0 e^{-j\beta^e z} + \alpha^o(-E_0)e^{-j\beta^o z}\right|^2$$

$$\frac{dP_{\text{tot}}}{dz} = 0 \rightarrow \frac{G_1}{G_2} = -\alpha^o\alpha^e \tag{5}$$

where β^e and β^o are the propagation constants of the even-like and odd-like modes, respectively. Note that $\alpha^o < 0$.

Let us now write expressions for wave amplitudes E_1 and E_2 at some arbitrary z under the conditions that the power fed into guide 1 at $z=0$ is zero and the power fed into guide 2 at $z=0$ is unity. In addition, let the wave amplitudes be normalized so that the power carried by guide i is given by $|E_i|^2$:

$$E_1(z) = \sqrt{G_1}\left(E_0 e^{-j\beta^e z} - E_0 e^{-j\beta^o z}\right)$$

$$E_2(z) = \sqrt{G_2}\left(\alpha^e E_0 e^{-j\beta^e z} - \alpha^o E_0 e^{-j\beta^o z}\right)$$

where

$$E_0 = \frac{1}{\sqrt{G_2}(\alpha^e - \alpha^o)}.$$

After some manipulation and applying (5), we arrive at

$$E_1(z) = -2j\frac{\sqrt{p^e}}{1+p^e}\sin\left(\frac{\beta^e-\beta^o}{2}z\right)e^{-j(\beta^e+\beta^o)z/2} \tag{6a}$$

$$E_2(z) = \left[\cos\left(\frac{\beta^e-\beta^o}{2}z\right) + j\frac{1-p^e}{1+p^e}\sin\left(\frac{\beta^e-\beta^o}{2}z\right)\right]e^{-j(\beta^e+\beta^o)z/2} \tag{6b}$$

where

$$p^e = -\frac{\alpha^e}{\alpha^o}. \tag{7}$$

Equations (6) allow us to analyze the coupling between asymmetrical slab guides in terms of the propagation constants of the odd- and even-like modes and the ratio p^e, derived from their respective field patterns. The propagation constants and the corresponding field solutions can be obtained as explained in [12].

A well-known result from the coupled-mode theory is that if two waveguides have the same propagation constant they are capable of exchanging 100 percent of their power through coupling. In terms of our theory, p^e of (7) should be one for two waveguides with the same β. We tested this theory for consistency by calculating the maximum coupling for some hypothetical coupled-guide cases. First, two identical coupled slab guides were considered with normalized thicknesses $t_1 = t_2 = 0.3\lambda_0$ and spacing $d = 0.15\lambda_0$ and dielectric constant $\epsilon_r = 2.25$. Then, the thickness of the other guide was reduced but its dielectric constant was also increased at the same time so that its β was kept constant. Using the same spacing d as before, the maximum coupling between the guides was calculated according to (6). Even at considerable asymmetry with t_1 and $\epsilon_{r,1}$ as above but with $t_2 = 0.13\lambda_0$ and $\epsilon_{r,2} = 3.30$ (which kept β unchanged for guide 2), the maximum coupling as found to deviate only 0.01 dB from full power transfer. This shows excellent consistency with the predictions of the coupled-mode theory.

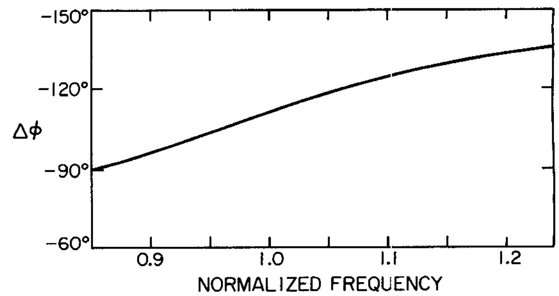


Fig. 4. Calculated phase difference between ports 2 and 4 when driving port 3 for the coupler shown in Fig. 2.

IV. Compensation of the Phase Response

The type of asymmetrical couplers we have been discussing do not possess any inherent constant phase difference properties between their output ports as symmetrical couplers do. However, it turns out that desirable phase properties can be achieved with a very simple phase correction. The theoretical phase difference (calculated using our mode-superposition theory) between the outputs when port 3 of the coupler shown in Fig. 2(b) is driven is shown in Fig. 4. From Fig. 4, we find that in order to make the outputs in phase, the amount of phase correction needed at $f = 0.85f_0$ would be 89.9°, while the required correction increases as the frequency is increased. This suggests that simply a fixed length of line could be used to achieve the required phase shift. In fact, it turns out that when dispersion is taken into account, the phase shift of a fixed length of waveguide ($0.2284\lambda_0$, with the dimensions of the waveguide being those of the terminating guides at the ports of the coupler) tracks the required phase correction so well that the overall theoretical phase balance is held to within a couple of degrees over the band shown in Fig. 4. On the other hand, when port 1 is driven, the phase difference at ports 2 and 4 is then fixed at 180° due to the properties of a lossless, matched, reciprocal four-port with the symmetries present in the configuration of Fig. 2(b). Note that, apart from the added length of waveguide, there is also a

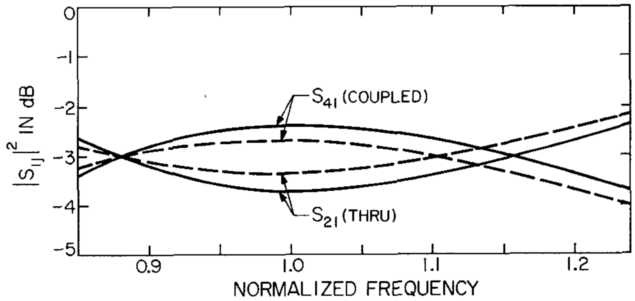


Fig. 5. Frequency response for a coupler as shown in Fig. 2 computed using normal-mode theory (——) and coupled-mode theory (- - -).

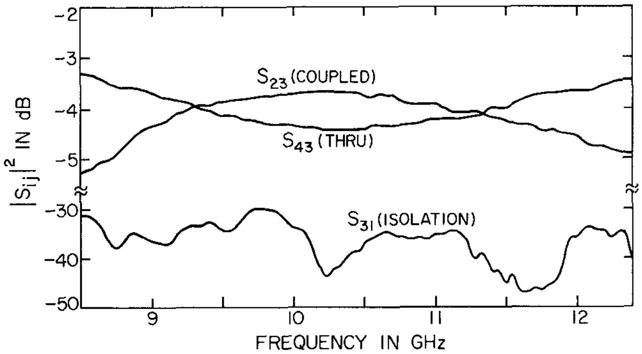


Fig. 6. A measured response for a coupler as shown in Fig. 2 and Fig. 5.

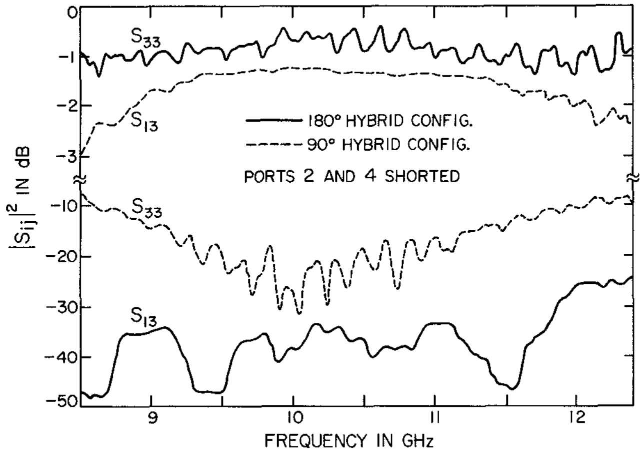


Fig. 7. Measured transmission from the input to the isolated port, and input port return loss, both with ports 2 and 4 shorted. The solid lines show the case where Δl in Fig. 2(b) was adjusted to give 180° phase difference between the output ports, and the dotted lines show the 90° case, respectively.

limited control available over the phase response by varying the location and shape of the tapered section used at both ends of the narrower guide, this can be used to facilitate the phase compensation procedure. A 90° phase difference is also possible by using a waveguide still longer by a quarter of a wavelength, but then the bandwidth for a given phase-difference tolerance is less.

V. Comparison of Theoretical and Experimental Results

We built and tested a coupler of the type shown in Fig. 2. The coupler was designed on the basis of the third example in Table I in that those guide widths and spacing were used in the straight center part. The required length of the coupler, however, is different because Table I was calculated for uniform couplers. The length of the experimental coupler was fixed on the basis of frequency response calculations where the curved, coupled guides were modeled by a cascade of straight, uniform segments. Coupling was taken into account up to the outer end of segment l_3 in Fig. 2(b). Fig. 5 shows the computed frequency responses for the final design. Sixteen segments were used to model the curved guides in these computations. The dotted lines show results computed according to the coupled-mode theory while the solid lines show results from our normal-mode theory. Both methods are seen to give very similar results.

All experiments were carried out at microwave frequencies for ease of fabrication and measurement. The center frequency of the experimental coupler was 10 GHz (i.e., in order to convert the normalized dimensions in Figs. 2 and 3 to actual dimensions, use $\lambda_0 = 30$ mm). The dielectric waveguides used in this experiment were made of paraffin wax ($\epsilon_r = 2.25$). Fig. 6 shows measured frequency responses. The response includes all losses of the test set, including those of the mode launchers. Due to the material being soft, it was difficult to maintain tight tolerances on the mechanical dimensions of the coupler and slight variations were observed from one measurement to another. Nevertheless, comparing the response shown in Fig. 6 with those in Fig. 5, good agreement between theory and experiments is observed. The measured 1-dB amplitude balance bandwidth is 30 percent, and the isolation of the coupler is seen to be better than 30 dB (output ports were terminated in low reflection loads made of absorbing material for this measurement).

Due to the difficulties of absolute phase measurements, we used an indirect method to check the phase characteristics. The extra length Δl was added at port 2, and ports 2 and 4 were terminated with short circuits (see Fig. 2(b)). Transmission from the input to the isolated port (3 to 1) as well as input return loss was then measured. Fig. 7 shows results from such measurements. The solid lines show the case where the length Δl was adjusted to give 180° hybrid behavior, and we see isolation in excess of 30 dB over most of the band and high SWR at the input port. This is as expected for a shorted hybrid having 180° phase difference. The dotted lines show the case where the length of Δl was adjusted to give 90° hybrid behavior, and we see almost total transmission (except for the losses of the waveguides) from the input to the isolated port while the input port SWR remains low. This performance is consistent with a hybrid with 90° phase difference. In both cases, the exact length of Δl required for best results was found experimentally.

We also made tests of this coupler with the top ground plate removed, i.e., in image-guide configuration. By changing the guide separation from 0.20 in ($0.169\lambda_0$ at 10 GHz) to 0.25 in ($0.212\lambda_0$ at 10 GHz), we achieved the

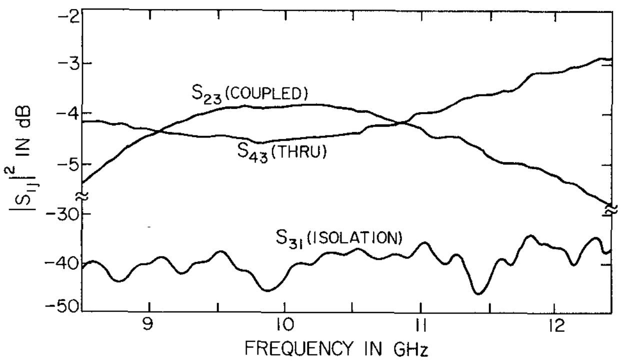


Fig. 8. A measured response for a coupler as shown in Fig. 2 in image-guide configuration. Spacing between the guides was changed to get this response (see text).

response shown in Fig. 8. (Guide height was 0.40 in, or $0.339\lambda_0$ at 10 GHz.) The bandwidth for 1-dB maximum amplitude imbalance is now 28 percent. Note that the directivity is better than for the parallel-plate configuration because a transition between image guide and the DW with ground planes on both top and bottom was now eliminated. Tests similar to those explained above showed that the phase difference response can again be compensated with a fixed length of guide.

We tried analyzing the image-guide structure by using the EDC approximation but the results were poor. Yet, *qualitatively*, the behavior is very similar to coupling between slab waveguides (c.f. Figs. 5 and 6). It is believed that the operating principles and analytical methods presented above would work for image guides, and most other types of DW as well, provided that more accurate methods for finding the propagation constants and field profiles were used.

VI. Conclusions

Broad-band DW 3-dB couplers can be designed by taking advantage of the dispersion and the frequency dependence of coupling between dielectric waveguides with differing dimensions. While giving a bandwidth much broader than that attainable in simple symmetrical couplers, high directivity is maintained and the structure is simple to fabricate. Means for achieving desirable constant phase difference properties between the output ports in asymmetrical DW couplers were also discussed.

A "staircasing" approximation was used to convert the problem of coupling between curved guides to the problem of coupling between parallel segments of uniformly coupled guides. Two approximate methods for calculating the coupling between these segments of asymmetrical DW's were discussed. The well-known coupled-mode theory is one approach while a mode superposition analysis is an alternative approach. Overall agreement between theory and experiments (for the slab-guide case) was good for both theories though there was some error in both cases. However, as there were other approximations involved as well (such as treatment of curved guides), it is difficult to assess the relative accuracies of the two methods.

Experimental results were presented for two kinds of DW's: a (effectively) slab-waveguide-type coupler and an image-guide coupler. No extensive optimization techniques were used in the design of these couplers and dimensions and materials were chosen on the basis of convenience and availability. It may be possible to achieve even broader bandwidths with tighter amplitude balances by optimizing all dimensions of a coupler. While in this work the broadbanding technique and the methods of analysis were applied only to slab waveguides and image guides, the principles should be applicable to the design of wide-band hybrids using many other types of dielectric waveguides as well.

References

[1] D. I. Kim, D. Kawabe, K. Araki, and Y. Naito, "Directly connected image guide 3-dB couplers with very flat couplings," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 621–627, June 1984.

[2] J.-F. Miao and T. Itoh, "Hollow image guide and overlayed image guide coupler," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1826–1831, Nov. 1982.

[3] T. Trinh and R. Mittra, "Coupling characteristics of planar dielectric waveguides of rectangular cross section," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 875–880, Sept. 1981.

[4] M. Abouzahra and L. Lewin, "Theory and application of coupling between curved transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1988–1995, Nov. 1982.

[5] R. J. Collier and G. Hjipieris, "A broad-band directional coupler for both dielectric and image guides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 161–163, Feb. 1985.

[6] J. S. Cook, "Tapered velocity couplers," *Bell Syst. Tech. J.*, vol. 34, pp. 807–822, July 1955.

[7] A. G. Fox, "Wave coupling by warped normal modes," *Bell Syst. Tech. J.*, vol. 34, pp. 823–852, July 1955.

[8] W. H. Louisell, "Analysis of the single tapered mode coupler," *Bell Syst. Tech. J.*, vol. 34, pp. 853–870, July 1955.

[9] M. G. F. Wilson and G. A. Teh, "Tapered optical directional coupler," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 85–92, Jan. 1975.

[10] E. F. Milton and W. K. Burns, "Tapered velocity coupler for integrated optics: Design," *Appl. Opt.*, vol. 14, pp. 1207–1212, May 1975.

[11] S. E. Miller, "Coupled wave theory and waveguide applications," *Bell Syst. Tech. J.*, vol. 33, pp. 661–719, May 1954.

[12] L. O. Wilson and F. K. Reinhart, "Coupling of nearly degenerate modes in parallel asymmetric dielectric waveguides," *Bell Syst Tech. J.*, vol. 53, pp. 717–739, Apr. 1974.

[13] W. V. McLevige, T. Itoh, and R. Mittra, "New waveguide structures for millimeter-wave and optical integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 788–794, Oct. 1975.

[14] M. Matsuhara and W. Watanabe, "Coupling of curved transmission lines and application to optical directional couplers," *J. Opt. Soc. Amer.*, vol. 65, pp. 163–168, Feb. 1975.

[15] M. A. McHenry and D. C. Chang, "Coupled-mode theory of two nonparallel dielectric waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1469–1475, Nov. 1984

[16] A. Yariv, "Coupled-mode theory for guided wave optics," *IEEE J. Quantum Electron.*, vol. QE-9, pp. 919–933, Sept. 1973.

[17] H. A. Haus, *Waves and Fields in Optoelectronics*. Englewood Cliffs, NJ: Prentice-Hall, 1984.

[18] A. W. Snyder, "Coupled-mode theory for optical fibers," *J. Opt. Soc. Amer.*, vol. 62, pp. 1267–1277, Nov. 1972.

[19] D. Marcuse, "The coupling of degenerate modes in two parallel dielectric waveguides," *Bell Syst. Tech. J.*, vol. 50, pp. 1791–1816, July–Aug. 1971.

[20] M. Matsuhara and N. Kumagai, "Theory of coupled open transmission lines and its applications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 378–382, Apr. 1974.

[21] E. F. Kuester and D. C. Chang, "Nondegenerate surface-wave

mode coupling between dielectric waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 877–882, Nov. 1975.
[22] Y. Suematsu and K. Kishino, "Coupling coefficient in strongly coupled dielectric waveguides," *Radio Sci.*, vol. 12, pp. 587–592, July–Aug. 1977.

Pertti K. Ikäläinen received the Diploma Engineer (M.Sc.) degree from the Helsinki University of Technology, Espoo, Finland, in 1981 and the Ph.D. degree from the University of California, Santa Barbara, in 1986.

From 1980 to 1983, he was a Research Engineer at the Technical Research Centre of Finland, Telecommunications Laboratory. From 1983 to 1986, he was a Research Assistant at the University of California, Santa Barbara. Since 1987, he has again been with the Technical Research Centre of Finland, Telecommunications Laboratory. Presently, he is involved in the design of frequency multipliers, amplifiers, and other components for microwave communications receivers and transmitters.

George L. Matthaei (S'49–A'52–M'57–F'65) received the B.S. degree from the University of Washington in 1948, and the Ph.D. degree from Stanford University in 1952.

From 1951 to 1955, he was on the faculty of the University of California, Berkeley, where he was an Assistant Professor, and his specialty was network synthesis. From 1955 to 1958, he was engaged in system analysis and microwave component research at the Ramo-Wooldridge Corporation. From 1958 to 1964, he was at Stanford Research Institute, where he was engaged in microwave device research and became Manager of the Electromagnetic Techniques Laboratory in 1962. In July 1964, he joined the Department of Electrical Engineering at the University of California, Santa Barbara, where he is a Professor. He is the author of numerous papers, coauthor of the book *Microwave Filters, Impedance-Matching Networks and Coupling Structures*, and a contributor to several other books. His current interests are in the areas of microwave and millimeter-wave passive and active circuits.

Dr. Matthaei is a member of Tau Beta Pi, Sigma Xi, and Eta Kappa Nu. He was the winner of the 1961 Microwave Prize of the IEEE MTT Group. In 1984, he received an IEEE Centennial Medal and in 1986 the Microwave Career Award of the IEEE Microwave Theory and Techniques Society.