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BROADBAND DIELECTRIC WAVEGUIDE 3-dB COUPLERS USING ASYMMETRICAL COUPLED LINES

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SUMMARY

It is shown how wideband 3-dB couplers can be designed by appropriately taking advantage of the dispersion and the frequency dependence of the coupling per unit length between two dielectric waveguides with asymmetrical cross sections. Theoretical methods for computing frequency responses of dielectric waveguide couplers composed of asymmetrical coupled guides are discussed. Experimental verifications of theoretical results are presented.

INTRODUCTION

Various researchers have treated the design of dielectric waveguide (DW) hybrids (i.e., 3-dB couplers) for millimeter-wave applications, see references [1] to [5] for example. Most hybrids presented so far have been based on coupling between two identical DWs. The bandwidth of such couplers is generally small to moderate while wider bandwidths may be desirable in many applications of hybrids. Wider bandwidths have been obtained by making the coupling stronger by using a connecting dielectric layer between the coupled lines as in [1]. Very wide bandwidths were also obtained in [5] by using a beam-splitter type approach. However, that design may be inconvenient in practice as 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. We have investigated 3-dB directional couplers where asymmetrical coupled lines are used to obtain large bandwidths. This technique is relatively easy to fabricate, gives wide bandwidth and maintains excellent directivity.

PRINCIPLE OF OPERATION

It is well-known [6] that if two uniformly coupled, lossless DWs have the same propagation constant all the power propagating in one of the guides can be transferred to the other one 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 of the guides 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 increases, 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. We found that the extra degree of freedom in the design that the asymmetry in the guide cross sections brings about allow us to design 3-dB couplers where the dispersion and the variation of the coupling per unit length helps to make the coupler more broadband rather than less. We chose the guide dimensions and spacing such that at the lower end of the band (where the coupling per unit length is relatively large) 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 allowed by the guide cross sections drops down closer to 3 dB, while due 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. In this manner the coupled power at the output end of the coupler stays close to half of the incident power over a wide range of frequencies. Fig. 1 illustrates this by showing coupled power vs. normalized distance at various frequencies for asymmetrical slab waveguides. At the length shown all the curves pass close to the level of one half, i.e., 3-dB coupling. In Fig. 1 the guides are uniformly spaced while an actual coupler, see Fig. 2(b), for example, must include curved line segments as well. In such a situation 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.

In our studies we have considered the problem of coupled dielectric slab waveguides because then exact solutions for the mode patterns are easily obtained. The TE modes of slab waveguides are exactly the same as the lowest order modes of the dielectric waveguide which has ground planes on

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both top and bottom, Fig. 2(a). Also, guides such as image guide can be treated approximately using the EDC method [7] and according to it the more complicated waveguides behave as slab waveguides with some effective dielectric constant. Therefore the results for slab waveguides are believed to show qualitative trends of behaviour which should be applicable for a large class of DWs.

ANALYSIS OF PARALLEL, COUPLED DIELECTRIC WAVEGUIDES

Figure 2(b) 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. Two different methods for analyzing the uniformly coupled parallel-guide segments were considered. 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.

The first one was to use Miller's coupled mode approach [6]. Its application to coupling between DWs is straightforward, apart from the problem of finding the coupling coefficient, and will not be written out in detail here. Several formulas have been proposed in the literature for the coupling coefficient; we have used those in [8].

The other method we have considered for analyzing the parallel-coupled segments of DWs is an extension of the odd- and even-mode analysis commonly used for symmetrical couplers. At the far left in Fig. 2(b) the guides are identical and fairly far apart. In this region if the guide at port 3 in Fig. 2(b) is driven while port 1 is not, this excitation is modelled 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 look like as is shown by the solid lines in Fig. 3 (for slab guides). 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, our simplified theory was constructed so as to include a power division in order to be able to treat the segments of coupled guides as four-port networks.

A simple solution is to assume that the power carried by each guide is given by the amplitude squared of the total transverse electric field at the center of the guide multiplied by a constant of proportionality, g_1 or g_2, akin to the characteristic admittance of a transmission line. The dotted line in Fig. 3 shows a superposition which, in the sense explained above, represents driving only the wide guide (since the total E field is zero at the center of the narrower slab). This simple superposition of odd- and even-like modes, while not a rigorous treatment, does give qualitative insight into the predominant phenomena and appears to give computational accuracy sufficient for many practical applications. Assuming the coupler is lossless, conservation of energy can be enforced and the ratio g_1/g_2 expressed in terms of other variables so that one does not need to know g_1 and g_2 explicitly. Analyzing the case where power fed into guide 1 at z = 0 is zero while the power fed into guide 2 at z = 0 is unity, and then normalizing the waves so that the power carried by guide i is given by $|E_i|^2$, we find

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

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

where

$$p^e = \frac{\alpha^e}{\alpha^o} . \tag{2}$$

Here $\beta^{e,o}$ are the propagation constants of the even- and odd-like-modes, respectively, and $\alpha^{e,o}$ are ratios of the E-field at the center of guide 2 to the E-field at the center of guide 1 in the even- and odd-like-mode, respectively. (Note that in the simple slab-guide case the transverse electric field has just one component.) In Eq. (1a,b) a phase factor $\exp(-j(\beta^e+\beta^o)z/2)$ common to both E_1 and E_2 has been omitted.

EXPERIMENTAL RESULTS

Figure 4 shows frequency responses for a coupler as shown in Fig. 2(b) computed using our extended even- and odd-mode theory (solid line) and the coupled-mode theory (dotted line). The two methods of analysis are seen to give similar results. In analyzing the curved sections of the coupler we measured the separation between the elemental sections in the cascade of parallel-coupled segments simply as the linear distance between the two guides, shown as d(z) in Fig. 2(b).

Figure 5 shows a measured frequency response for a corresponding experimental coupler. The center frequency of the experimental coupler was 10 GHz. The dielectric waveguides used in these experiments were made of paraffin wax ($\varepsilon_r = 2.25$). Agreement between theory and experiments is fairly good. The 1-dB amplitude balance bandwidth is 30%. The isolation of the coupler is seen to be better than 30 dB over the usable bandwidth.

This type of asymmetrical coupler does not possess any inherent constant phase difference properties between its output ports like symmetrical couplers do. However, theoretical calculations showed that the combined phase response of the coupler and a short length of guide (including dispersion effects) connected to one of the ports, shown as $\Delta\ell$ in Fig. 2(b), was such that it is possible to achieve close to 180° phase difference (as in a Magic Tee) over the usable bandwidth. Also, a 90° phase difference is possible by using a guide still longer by a quarter wavelength, but then the bandwidth for a given phase-difference tolerance is reduced. Due to the difficulty of absolute phase measurements we used an indirect method to check the phase characteristics. Figure 6 shows measured transmission from the input port to the isolated port and also the input port return loss, both with the output ports terminated with short circuits. The solid lines show the case where the length $\Delta\ell$ was adjusted to give 180° hybrid behaviour, and we see isolation in excess of 20 dB and high SWR at the input port. This is as is to be expected for a shorted hybrid having 180° phase difference. The dotted lines show the case where the length $\Delta\ell$ was adjusted to give 90° hybrid behaviour, 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 $\Delta\ell$ required for best results was found experimentally.

We also made preliminary tests of this coupler with the top metal plate removed, i.e., in image guide configuration. Similar response performance was obtained after some experimental adjustment in guide spacing. By changing the guide separation from $0.1693\lambda_o$ (0.20" at 10 GHz) to $0.2117\lambda_o$ (0.25" at 10 GHz) we achieved 28% 1-dB amplitude balance bandwidth (which could no-doubt be increased if the image-guide design were optimized).

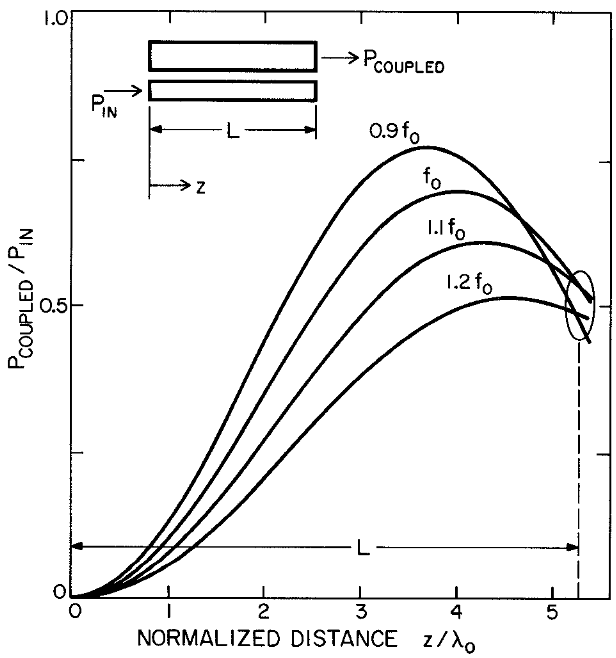

Fig. 1. Coupled power vs. distance (normalized to wavelength in air) at various frequencies. For the length L shown we get close to 3-dB coupling over a wide band of frequencies. The dimensions of the coupled guides are as shown in Fig. 3.

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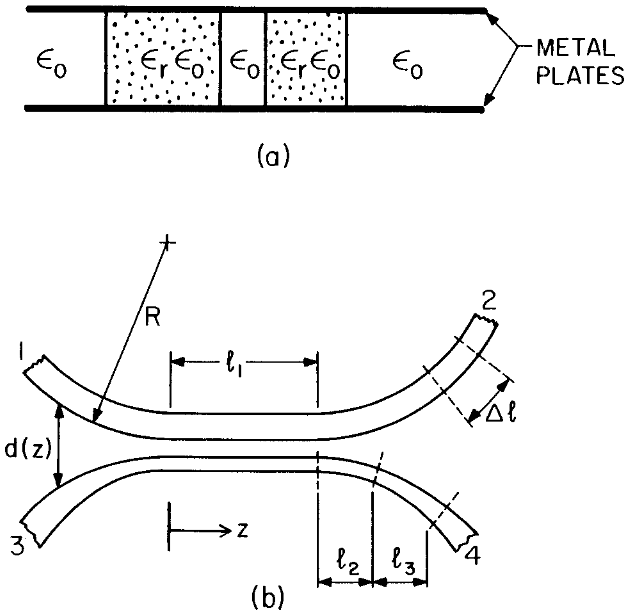

Fig. 2. At (a) is shown the cross-section of the type of DW we used in our experiments. At (b) a top view of a coupler is shown with the top plate removed (not to scale). The dimensions shown are: $R = 13.6\lambda_0$, $\ell_1 = 1.90\lambda_0$, $\ell_2 = 1.93\lambda_0$ and $\ell_3 = 2.30\lambda_0$, where λ_0 is wavelength in air. The widths and spacing of the guides in the center part are as shown in Fig. 3.

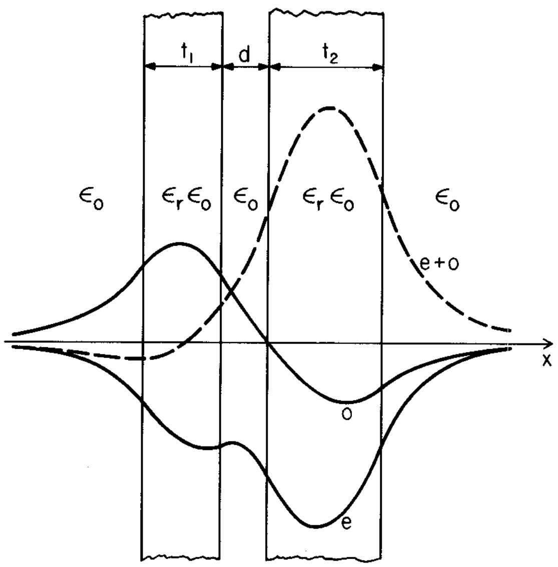

Fig. 3. The solid lines show mode shapes (E_y vs. x) for the two lowest order TE modes. The dotted line shows a superposition of these modes which represents driving only the wide guide. The dimensions shown are: $t_1 = 0.2963\lambda_0$, $t_2 = 0.4233\lambda_0$, $d = 0.1693\lambda_0$ and $\varepsilon_r \doteq 2.25$.

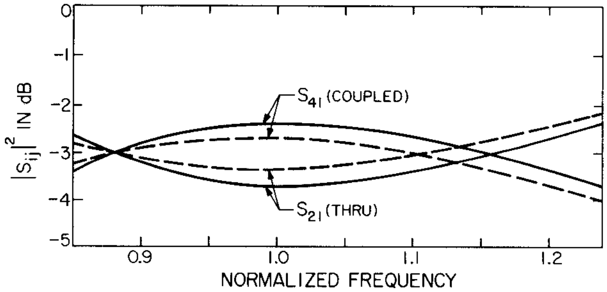

Fig. 4. Frequency response for a coupler as shown in Fig. 2 computed using normal-mode theory (——) and coupled-mode theory (---).

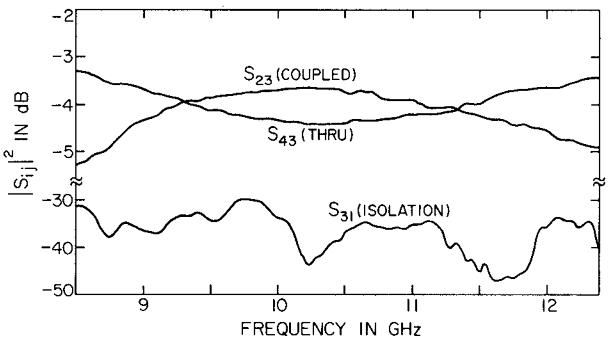

Fig. 5. A measured response for a coupler as shown in Fig. 2 and Fig. 4.

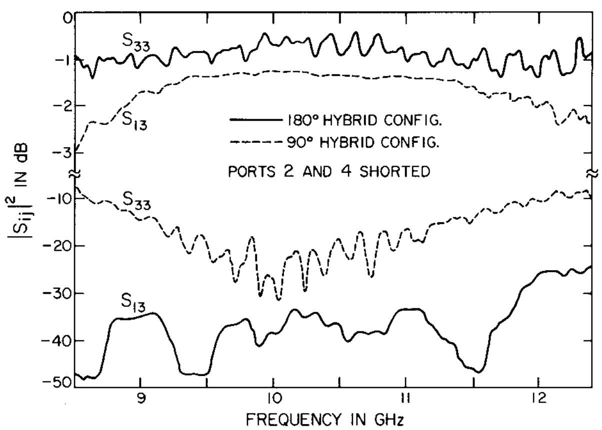

Fig. 6. Measured transmission from the input to the isolated port, and input port return loss, both with ports 2 and 4 shorted. The solid lines show the case where $\Delta\ell$ in Fig. 2(b) was adjusted to give 180° phase difference between the output ports and the dotted lines show the 90° case, respectively.