Wide-Band Directional Couplers in Dielectric Waveguide

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Abstract —In this work, the Π guide is proposed as an alternative in designing proximity directional couplers using dielectric guides in order to obtain coupling factors constant with the frequency, thus increasing the bandwidth of these devices. The propagation constants of the even and odd modes of the coupling zones are determined by means of Schelkunoff's method and the effective dielectric constant method (EDCM).

Two directional couplers, 10 dB and 3 dB, made of polystyrene and Teflon respectively, were designed and measured to work in the millimetric frequency band (32–40 GHz). The inclusion of metallic walls in the curved zones avoids additional couplings and results in flat coupling. Furthermore, the metallic walls reduce the radiation losses and allow the coupling factor to be finely adjusted. The results obtained show a maximum coupling variation of ±0.5 dB for 20-percent bandwidth.

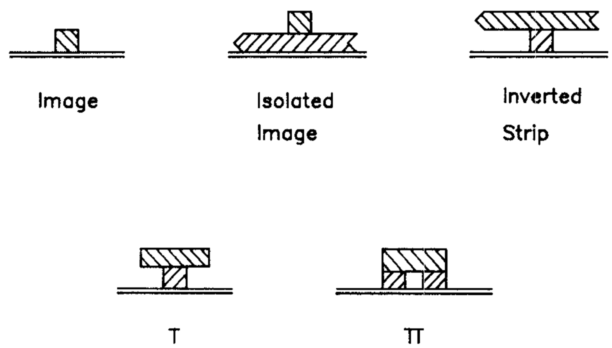

Fig. 1. Cross sections of different dielectric guides.

I. Introduction

DIELECTRIC GUIDES have received considerable attention due to their possible application in integrated microwave circuits within the millimetric and submillimetric bands. Although the first studies of dielectric guides show that these structures propagate only hybrid modes [1], the earliest simplified models were based on the supposition that the guided wave modes could be brought closer by means of two fundamental mode families, E^y_{pq} and E^x_{pq}, where the subscripts p and q refer to the number of extrema of each field component in the x and y directions, respectively, while the superscripts indicate the fundamental component of the electric field [2].

The dielectric guide with the simplest geometry is the image guide; thus, it is the structure which has been studied most. However, in order to reduce the losses which this configuration presents, various modifications of the image guide have been proposed, such as the isolated image guide, the inverted strip guide [3], [4] (Fig. 1), and modifications like the T and Π guides [5], [6] (Fig. 1). They can all reduce the conductive losses of the image guide by separating it from the maximum concentration of electromagnetic energy from the ground plane. Furthermore, the T and Π guides allow a greater concentration of the electromagnetic field around the longitudinal propagation axis. Later, Miao and Itoh [7], [8] placed a dielectric sheet on two image guides, obtaining a structure similar to the Π guide, which they called a hollow image guide.

One of the first components to be made with these kinds of guides (mainly with image guides) was the directional coupler. Three types of directional couplers exist: the proximity directional coupler (with the two guides placed on the same ground plane or on different planes), the multiholed coupler (with the two guides on each side of a common metallic plane), and the beam splitter coupler. The proximity directional coupler with the two guides on the same ground plane is the one with the simplest structure and a planar circuit, and the present work focuses on this configuration. For this type of coupler, the coupling factor turns out to be a function of the difference between the propagation constants K_{ze} and K_{zo} of the even and odd modes respectively.

Most couplers which have been presented use the image guide. A problem common to all these couplers is the reduced bandwidth due to the difference between the propagation constants of the even and odd modes, resulting in frequency-dependent coupling. A recent study [9] suggests modifying the cross section of the image guide to improve the constancy of the coupling coefficient. Nevertheless, the total coupling factor remains frequency-dependent as a consequence of the additional couplings in the curved areas approaching the parallel zone [10].

Various methods exist to determine the propagation constants of the even and odd modes. Some analyze the problem by enclosing the dielectric structure in a conducting box, which allows the continuous spectrum of radiated modes to be discretized. However this also increases the complexity of calculations. Other methods rely on variational techniques [6], whereby modifications of the original dielectric structure can be carried out and analyzed without any additional analytical complexity. Subsequently, approximate analytical methods such as the EDCM can be applied.

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II. Theory

A. Coupled Dielectric Guides

Fig. 2(a) shows a proximity directional coupler consisting of two parallel dielectric guides placed on the same ground plane. The scattering coefficients for the parallel coupling region when the power is introduced at arm 1 are given by [10]

$$|S_{21}| = |\cos(((K_{ze} - K_{zo})/2)\cdot L)| \quad (1)$$

$$|S_{31}| = |\sin(((K_{ze} - K_{zo})/2)\cdot L)| \quad (2)$$

where K_{ze} and K_{zo} are the propagation constants of the even and odd modes, respectively, and L is the length of the coupling zone.

In the curved zones, the distance $2S$ between the two guides varies continuously, as do the values of K_{ze} and K_{zo}. These curved zones introduce additional couplings, whose description requires (1) and (2) to be replaced by their corresponding integral forms, both for the nonparallel symmetrical and asymmetrical coupling structures.

If the nonparallel coupling configuration is symmetrical, the scattering coefficients can be written in the following form [10]:

$$|S_{21}| = |\cos(K\cdot I_s)| \quad (3)$$

$$|S_{31}| = |\sin(K\cdot I_s)| \quad (4)$$

in which K is a function of the transversal and longitudinal propagation constants of each dielectric guide in isolation, as well as its geometry. I_s represents a coupling integral that extends to the nonparallel coupling zone.

When the nonparallel coupling zone is asymmetrical, (3) and (4) must be adequately corrected due to different wavefronts [10]:

$$|S_{21}| = |\cos(\gamma\cdot K\cdot I_n)| \quad (5)$$

$$|S_{31}| = |\sin(\gamma\cdot K\cdot I_n)| \quad (6)$$

where K and I_n are functions similar to those used in (3) and (4), while the parameter γ is a correction factor that takes the asymmetry of the coupling region into account and is determined experimentally [10].

Thus, there are two areas in which the coupling factor has different expressions: one is the curved section, and the other is the zone in which the distance between the guides remains constant. If the ratio between the powers that appear in arms 3 and 2, for a parallel coupling zone of length L, is defined as a coupling factor C, then

$$C = \tan^2(((K_{ze} - K_{zo})/2)\cdot L). \quad (7)$$

From (7), if the length L is fixed, the coupling factor C due to this zone will always remain constant as long as the difference $K_{ze} - K_{zo}$ does not vary with the frequency. In the case of the image guide, this difference has a large frequency dependence. Therefore, other dielectric guides whose cross sections are different from the image guide must be sought so that the coupling factor C given by (7) will remain relatively constant. To determine the propagation constants of the even and odd modes, two theoretical methods will be used, Schelkunoff's method [6], [11] and the EDCM [2]–[5].

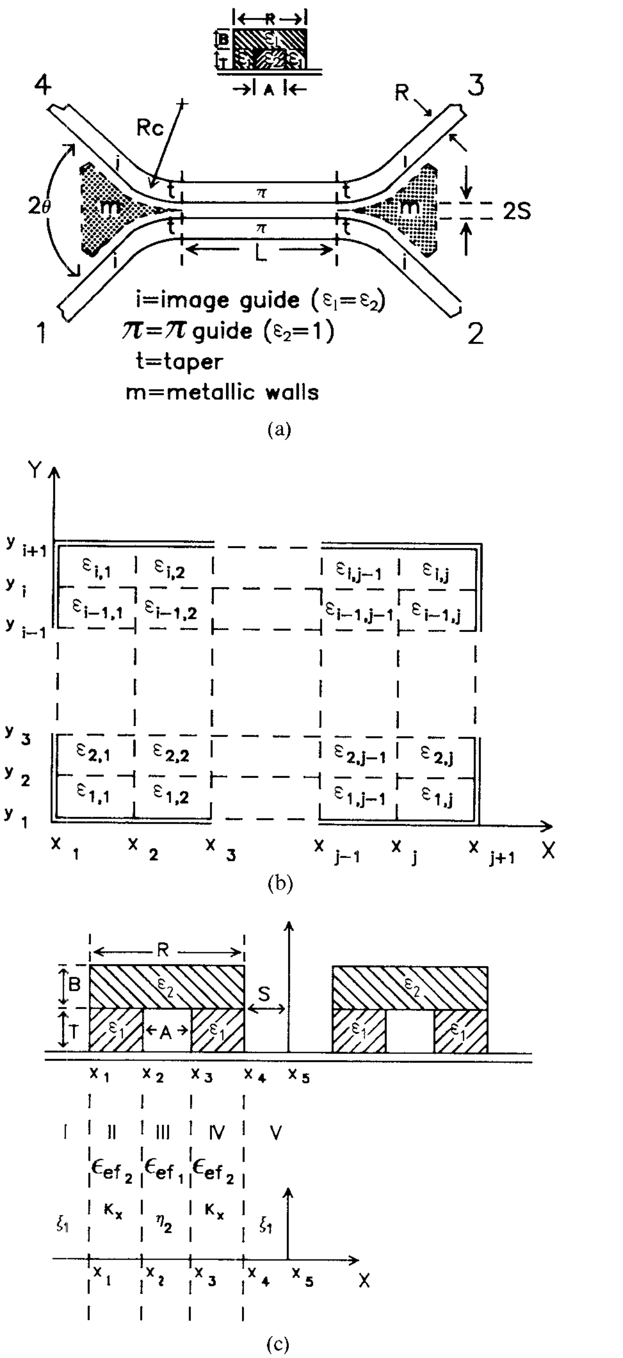

Fig. 2. (a) Top view of a proximity coupler with optional metallic walls. (b) Cross section of a partially filled rectangular waveguide with $i \times j$ different dielectrics. (c) Cross section of two coupled Π guides.

B. Schelkunoff's Method

In dielectric guides with rectangular cross sections, the dielectric interfaces are planes parallel to the yz or xz planes, where z is the propagation direction. When the structure is enclosed by perfectly conducting metallic walls, a modified structure is obtained as shown in Fig. 2(b). Obviously analytic methods are not suitable, and consequently variational methods are preferable.

Schelkunoff's method is variational in nature. The electromagnetic field inside the conducting box can be expanded into an infinite sum of orthogonal functions belonging to a complete set which satisfy the boundary conditions on the walls of the metallic guide. By selecting the solutions of Helmholtz's equation for the empty guide, the transversal electromagnetic field that corresponds to the guide of Fig. 2(b) can be written in the form

$$\vec{E}_t = \sum_i^{\infty} V_{(i)}(z)\cdot\vec{e}_{(i)}(x,y) + \sum_j^{\infty} V_{[j]}(z)\cdot\vec{e}_{[j]}(x,y) \quad (8)$$

$$\vec{H}_t = \sum_i^{\infty} I_{(i)}(z)\cdot\vec{h}_{(i)}(x,y) + \sum_j^{\infty} I_{[j]}(z)\cdot\vec{h}_{[j]}(x,y). \quad (9)$$

Here, $V(z)$ and $I(z)$ are the equivalent voltages and currents of each mode, and $\vec{e}_{(i)}$, $\vec{h}_{(i)}$, $\vec{e}_{[j]}$, and $\vec{h}_{[j]}$ are the expressions of the electric and magnetic fields of the TM and TE modes respectively of the empty guide; the i's and j's are therefore double subscripts.

Assuming that the cross section of the guide is uniform in the z direction, one obtains

$$\left([Z][Y] - K_z^2[i]\right)[V] = 0 \quad (10a)$$

$$\left([Y][Z] - K_z^2[i]\right)[I] = 0 \quad (10b)$$

where K_z is the propagation constant, $[Z]$ and $[Y]$ are doubly infinite matrices, $[i]$ is the identity matrix, and $[V]$ and $[I]$ are infinite matrices formed by the expansion coefficients of $\vec{E}_t$ and $\vec{H}_t$, respectively. The terms of the $[Z]$ and $[Y]$ matrices are given through integrals extended to the cross section of the metallic guide. These integrals depend on the expressions for the fields in the empty guide. When the dielectric interfaces are parallel to the x and y axes, as shown in Fig. 2(b), these integrals offer a simple analytic solution, thus reducing computer calculation time.

The numerical solution of (10) demands the matrix orders to be truncated, indicating the importance of functions (8) and (9). The first step in the selection process involves considering the kind of symmetry of the dielectric configuration under study and the symmetry of the mode to be resolved. Therefore, if solutions which correspond to an even-type mode are sought, we shall select modes whose electric field is an even type, e.g., TE_{10}, TE_{30}, or TM_{11}. Conversely, if the solution corresponds to the odd-type modes, we shall take such modes as TM_{21}, TM_{42}, or TE_{20}. Within the infinite modes thus selected, a subsequent choice can be made by means of increasing cutoff frequencies [11] or transfer admittances [6]. However, the preferred process would be explained as follows: after the propagation constant K_{zn} has been obtained for n modes, a new mode will be selected from among those not yet chosen in order to produce a new $K_{z(n+1)}$ so that the variation over K_{zn} is maximum in absolute value. It is obvious that this latter procedure demands a very high calculation time.

However, it is possible to find a solution which practically coincides with the optimum one by using the following procedure: the fundamental even mode for the family of E_{pq}^y modes is E_{11}^y, and the two modes in the empty guide whose electromagnetic configuration resembles the E_{11}^y mode are the TE_{10} and TM_{11} modes. From these two modes (TE_{10}, TM_{11}), we can obtain an approximate phase constant K_z. Subsequently, we shall form sets of modes made up of TE_{10}, TM_{11}, and a third mode chosen from among the rest of the empty guide modes. After computing the approximate propagation constant K_{zi} for each set, we shall select those modes whose inclusion as a third mode produces the greatest absolute difference between K_z and K_{zi}, i.e., in $|K_z - K_{zi}|$, and they will thus be those which have most influence. As far as the odd mode E_{21}^y is concerned, the two preselected modes are TE_{20} and TM_{21}.

It has been observed that this selection method improves the convergence of the solution in comparison with the two methods mentioned above, allowing the necessary computer calculation time to be reduced by a factor of 4 to obtain a given accuracy.

C. The Effective Dielectric Constant Method (EDCM)

As we shall see later the results obtained by Schelkunoff's method make it possible to deduce that the Π guide and, to a much lesser degree, the isolated image guide can maintain $K_{ze} - K_{zo}$ constant with frequency.

Since EDCM is much faster with respect to computer time than Schelkunoff's method and provides results with sufficient accuracy, the former method has been applied to two identical dielectric Π guides coupled by proximity according to the well-known procedure [2]–[5].

After introducing the first step of the effective dielectric constant method, which replaces each multidielectric region in the y direction (regions I, II, III, IV, and V) by homogeneous and infinite regions in the same direction, with effective dielectric constants 1, ϵ_{ef2}, ϵ_{ef1}, ϵ_{ef2}, and 1, respectively, the dielectric configuration of Fig. 2(c) is obtained.

In the case of two coupled dielectric guides like those of Fig. 2(c) and restricting our study to the E_{pq}^y family of modes, we can take the following solutions for the potential $\Phi(x)$:

$$\Phi(x) = \begin{cases} A\cdot\exp\left(\zeta_1(x-x_1)\right) & x_1 \geqslant x \\ B\cdot\cos\left(K_x(x-x_1)\right) + C\cdot\sin\left(K_x(x-x_1)\right) & x_1 \leqslant x \leqslant x_2 \\ D\cdot\cosh\left(\eta_2(x-x_2)\right) + E\cdot\sinh\left(\eta_2(x-x_2)\right) & x_2 \leqslant x \leqslant x_3 \\ F\cdot\cos\left(K_x(x-x_3)\right) + G\cdot\sin\left(K_x(x-x_3)\right) & x_3 \leqslant x \leqslant x_4 \\ H\cdot\cosh\left(\zeta_1(x-x_4)\right) + I\cdot\sinh\left(\zeta_1(x-x_4)\right) & x_4 \leqslant x \end{cases} \quad (11)$$

in which ζ_1, K_x, and η_2 are the propagation constants in the respective media. The application of adequate boundary conditions leads to the following characteristic equations:

$$H\cdot\cosh(\zeta_1(x_5-x_4))+I\cdot\sinh(\zeta_1(x_5-x_4))=0 \quad (12)$$

for the odd mode and

$$H\cdot\sinh(\zeta_1(x_5-x_4))+I\cdot\cosh(\zeta_1(x_5-x_4))=0 \quad (13)$$

for the even mode.

The propagation constants of the even and odd modes, K_{ze} and K_{zo}, respectively, are expressed by

$$K_{ze,o}=\sqrt{\epsilon_{ef2}\cdot K_0^2-K_{xe,o}^2} \quad (14)$$

where K_0 is the free-space wavenumber, and K_{xe} and K_{xo} are the propagation constants in the x direction and are solutions of (13) and (12), respectively.

III. Theoretical and Experimental Results

In this section, we present theoretical results obtained by the former two methods and experimental results. In all cases, the guides were chosen so that the coupling configuration would operate using the lowest even and odd modes, E_{11}^y and E_{21}^y, respectively. In Fig. 3, the results obtained for K_{ze} and K_{zo} normalized to K_0 are shown. Good agreement between the theoretical values obtained by both methods and the experimental results is clearly demonstrated.

In Fig. 4, the theoretical results obtained for the difference between the phase constants of three Π guide couplers versus frequency are presented. When this quantity is represented for other guides, the slopes of the curves are always negative for increasing values of the frequency, and this slope is very sharp in most cases. When two Π guides are used with dimensions and the separation distance properly chosen, the slope of the curves can always be made positive, negative, or practically zero. This is shown in Fig. 4 for three different Π guides. It can be seen that graph (ii) presents a $K_{ze}-K_{zo}$ value which is relatively constant with the frequency.

In order to check how the dimensions of the Π guide window influence the behavior of the coupler, we studied the variation of the difference between the propagation constants of the even and odd modes as a function of frequency for a pair of Π coupled guides. In Fig. 5(a), this variation is shown when the depth T of the window is increased. It can be seen that the slope of $K_{ze}-K_{zo}$ becomes gradually less negative. There are certain T and B values which produce an almost flat response for the coupler throughout the frequency band. This same behavior is evident when the width of the Π guide window, A, is increased, as shown in Fig. 5(b). Therefore, the Π guide offers two degrees of freedom when searching for the dimensions which lead to a very constant coupling over a given frequency range. Likewise, looking at Fig. 5(a) and (b), it is obvious that for any Π guide there is a frequency for which the coupling would be maximum. This can be used to build a coupler with minimum length for a given coupling factor. In general, any guiding system that reduces the concentration of the electromagnetic field would be of use to improve the constancy of the coupling factor. In this case, the presence of the interior window creates this effect.

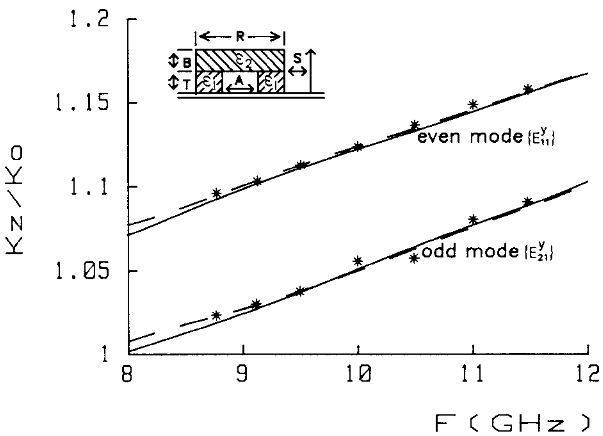

Fig. 3. Normalized propagation constants for two coupled Π guides ($\epsilon_1=\epsilon_2=2.56$). Dimensions (mm): $T=2$, $B=4$, $R=20$, $A=14$, $S=2$. — EDCM. --- Schelkunoff's method. * * * Experimental points.

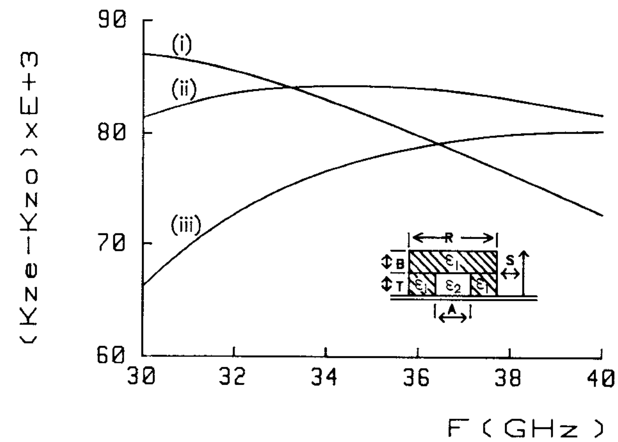

Fig. 4. $K_{ze}-K_{zo}$ versus frequency for three Π guides ($\epsilon_1=2.6$, $\epsilon_2=1$). Dimensions (mm): (i) $T=1$, $B=1.5$, $R=4$, $A=1$, $S=0.5$ (ii) $T=1$, $B=1$, $R=4$, $A=2$, $S=0.5$ (iii) $T=1$, $B=1.5$, $R=4$, $A=2$, $S=0.5$.

We have also studied how the separation $2S$ between the two guides influences the coupling. Fig. 6(a) shows $K_{ze}-K_{zo}$ as a function of frequency for various values of S. As can be seen in this figure, there is an optimum value of S which makes the $K_{ze}-K_{zo}$ value very flat for a broad frequency range, e.g., $S=1$ mm. However, due to the presence of the curved sections at both ends, the coupling factor will be modified significantly. The coupling effect of the curved sections can be minimized by partially shielding this zone with metallic walls (see Fig. 2(b)) [12]. Assuming that the curved effect can be eliminated, the length L necessary to obtain a 3-dB coupling in the 30–40-GHz band for an image guide coupler and Π guide is shown in Fig. 6(b). The necessary length for a Π guide is very constant with the frequency. This explains the flat response of the coupling factor.

IV. Design, Fabrication, and Evaluation

Two proximity couplers in the 34–40-GHz band were designed and measured with theoretical coupling factors of 10 dB and 3 dB in the parallel zone. The 10-dB coupler

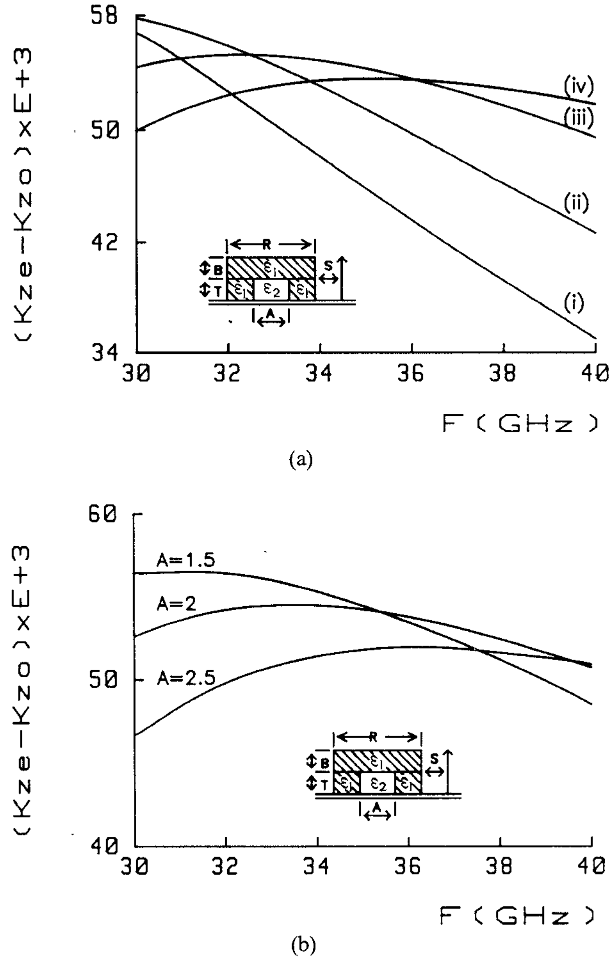

Fig. 5. (a) $K_{ze} - K_{zo}$ versus frequency for one image guide ($\epsilon_1 = \epsilon_2 = 2.1$) and for three Π guides ($\epsilon_1 = 2.1, \epsilon_2 = 1$), using T and B as parameters. Dimensions (mm): $R = 4, A = 2, S = 1$. (i) image guide: $T + B = 3$. (ii) Π guide: $T = 0.4, B = 2.6$. (iii) Π guide: $T = 1.2, B = 1.8$. (iv) Π guide: $T = 2, B = 1$. (b) $K_{ze} - K_{zo}$ versus frequency, using A as parameter, for three Π guides ($\epsilon_1 = 2.1, \epsilon_2 = 1$). Dimensions (mm): $T = 1.5, B = 1.5, R = 4, S = 1$.

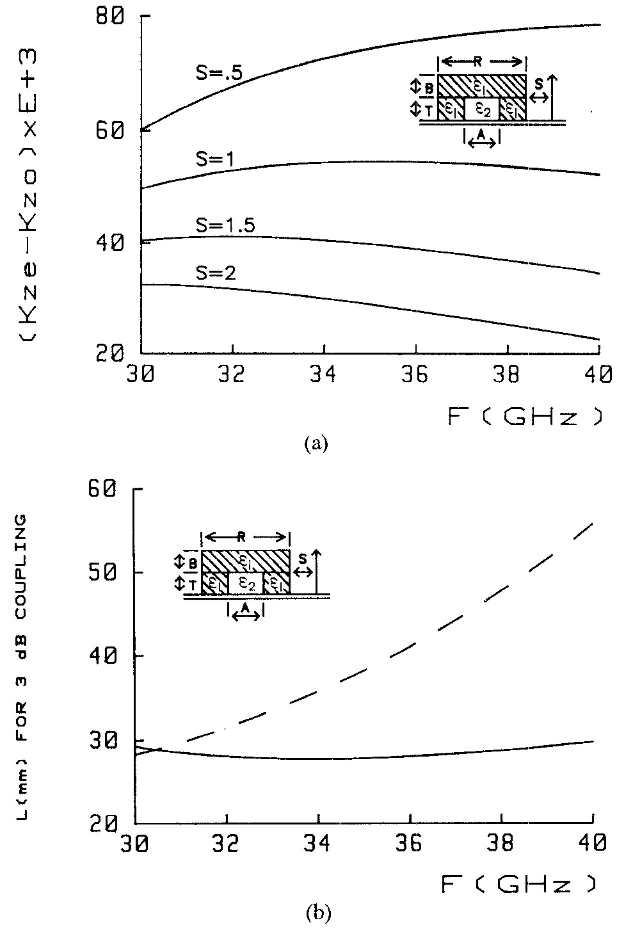

Fig. 6. (a) $K_{ze} - K_{zo}$ versus frequency, using S as parameter, for one Π guide ($\epsilon_1 = 2.55, \epsilon_2 = 1$). Dimensions (mm): $T = 1, B = 1, R = 4, A = 2.2$ (b) Necessary length for a 3-dB coupler using image guide: (---), ($\epsilon_1 = \epsilon_2 = 2.7$) and Π guide: (—) ($\epsilon_1 = 2.7, \epsilon_2 = 1$). Dimensions (mm): $T = 1, B = 1, R = 4, A = 2.2, S = 1$.

was made entirely of polystyrene ($\epsilon_r = 2.6$) and fixed to the ground plane by tetrachloroethylene, while the 3-dB coupler was made of Teflon ($\epsilon_r = 2.1$) and was attached to the metallic plane using adhesive tape. In both cases, the parallel coupling zone was carried out in Π guide, while the rest of the device was made in image guide. In the curved zones, radiation losses are inversely proportional to the curved radius and directly proportional to the distance at which the transverse propagation constant, outside the guides, causes the field to decay by a factor $1/e$ of its maximum value [13]. Since the Π guide presents a field which in the transverse direction is less concentrated than the field due to the image guide, the radiation losses in the curved zones of the latter will be less than those of the corresponding Π guide. The transition betwen the Π guide and the image guide took place gradually, both in the depth of the Π guide window and its width. The return losses of both couplers in the four arms were always less than 25 dB, and their parameters (see Fig. 2(a)) are as follows (all dimensions in mm):

10-dB coupler: image guide: $T + B = 2, R = 4, A = 2.2$, $\epsilon_1 = \epsilon_2 = 2.6$ (polystyrene); Π guide: $T = B = 1$, $R = 4, A = 2.2, L = 10.86, \epsilon_1 = 2.6$ (polystyrene), $\epsilon_2 = 1$; $Rc = 17, S = 1, \theta = 30°$.

3-dB coupler: image guide $T + B = 2.5, R = 4, A = 2.2$, $\epsilon_1 = \epsilon_2 = 2.1$ (Teflon); Π guide: $T = 1.6, B = 0.9, R = 4$, $A = 2.2, L = 31.29, \epsilon_1 = 2.1$ (Teflon), $\epsilon_2 = 1$; $Rc = 19, S = 1, \theta = 15°$.

The band center frequency was 35 GHz in the 10-dB coupler and 37 GHz in the 3-dB coupler. In both cases, the length of the arms of the couplers was $10\lambda_0$ (λ_0 being the free-space wavelength at the central frequency), which is long enough to make the effects of the transitions on the coupling zone negligible [14].

For the 10-dB coupler, the insertion loss in the main arm was measured with the transitions in the absence of the secondary arm. This loss was about 3.5 dB, which corresponds quite well to the theoretical loss of 2.9 dB determined by Schelkunoff's method in the center of the band. The losses due to the dielectrics were calculated by making the permittivity complex, so that matrices $[Z]$ and $[Y]$ of (10) become complex; the losses in the conductors were determined by means of the perturbation method. To determine the radiation loss in the curved regions, we compared the insertion loss of a straight guide with that of an identical curved guide. The loss due to the curves was

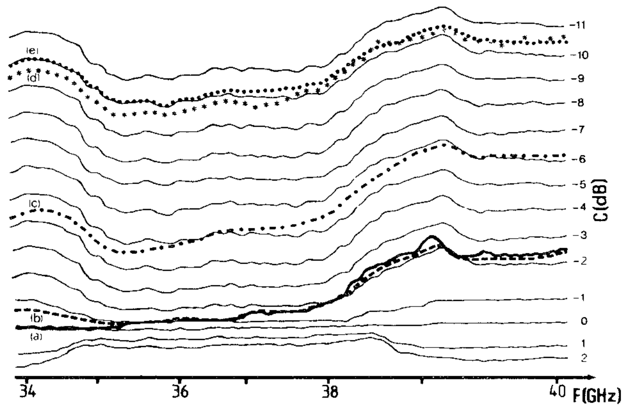

Fig 7. Coupling factor C versus frequency for the 10-dB directional coupler. (e) ($\cdots$) coupling straight zone only (theory); (c) (-·-) coupling straight and curved zones (theory); (b) (---) coupling straight and curved zones with losses (theory); (a) (—) measurement (without metallic walls); (d) (* * *) measurement (with metallic walls).

roughly 1 dB and fairly constant with frequency. When the complete coupler was set up, the coupling factor, shown in curve (a) of Fig. 7, was obtained by measuring the relative power level of arm 3 with respect to that of arm 2. Using the previous experimental data, the losses of the dielectric guide per unit of length can be calculated. Likewise, by means of (3) and (4), we can find the additional couplings in the curved zones. Taking these dielectric losses and the additional couplings into account along with the radiation values in the curved regions, the theoretical coupling was calculated, obtaining curve (b) of Fig. 7, which coincides almost exactly with the previous experimental value. However, if the additional couplings of the curved zones are taken into account, but neither the dielectric losses nor the radiation losses in the curved zones are considered, the theoretical coupling which is shown in curve (c) of Fig. 7 is quite far removed from the experimental result.

In order to eliminate the additional unwanted couplings and to minimize radiation losses, metallic walls [12] were introduced, as is shown by the shaded areas in Fig. 2(a). The shielding had polished lateral walls that were perpendicular to the metallic plane to which it was affixed by pressure. The optimum distance from the metallic edges to the edges of the dielectric curves which minimizes the radiation losses turned out to be about 2.2 mm and 2.5 mm for the 10-dB coupler and 3-dB coupler, respectively. These distances were determined experimentally for the dielectric guides and curvature radii used in the couplers. In curve (d) of Fig. 7, the new coupling factor obtained can be seen to be quite constant throughout the frequency band, with a maximum fluctuation of ± 0.5 dB about the calculated theoretical value, which is shown in graph (e).

Both the theoretical and the experimental results for the 3-dB coupler can be seen in Fig. 8. Along with the theoretical prediction and measurement of the 3-dB coupler with $L = 31.29$ mm, we present the experimental measurements of the coupling factor for two different coupling lengths, $L = 30.15$ mm and $L = 32.22$ mm. These lengths were obtained by slightly modifying the penetration of the metallic shields in the parallel coupling zone. The agreement between the theoretical and experimental results, including slight fluctuation of the coupling factor with the frequency, is very good.

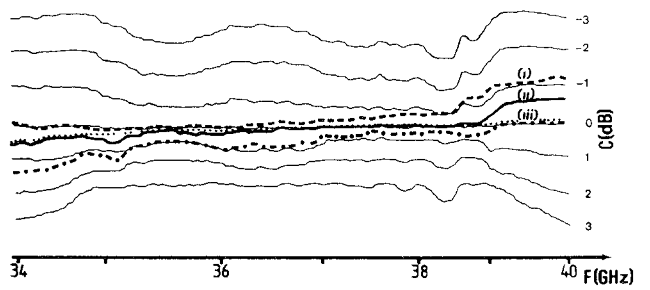

Fig. 8. Experimental coupling factor C versus frequency for three Π different directional couplers using Π guide. (i) $L = 30.15$ mm; (ii) $L = 31.29$ mm; (iii) $L = 32.22$ mm; ($\cdots$) theory for $L = 31.29$ mm.

V. Conclusions

By using Π guides in the construction of directional proximity couplers, the coupling factor can be maintained constant with frequency. However it is necessary to eliminate additional couplings and radiation loss due to the curved zones. The inclusion of metallic walls makes this possible and reduces the total losses of the coupler.

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