COUPLING CHARACTERISTICS OF DIELECTRIC WAVEGUIDES OF RECTANGULAR CROSS-SECTION

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Abstract

An approximate but accurate analytical model has been developed for predicting the coupling characteristics of both symmetrical and nonsymmetrical dielectric couplers of rectangular cross section. The coupling is shown to depend on the field decay coefficient, guide spacing, and cross-sectional dimensions. Comparisons between experimental and theoretical results are presented.

Introduction

Recent interest in the millimeter-wave dielectric integrated circuits, which employ planar dielectrics as guiding structures, has prompted the investigation of the coupling properties of these guides. Coupling characteristics of dielectric waveguides have been studied by several authors [1], [2], [3]. More recently, Itanami and Shindo [4] and Anderson [5] have presented approximate calculations for the coupling between two curved dielectric waveguides. Solbach [6] has computed coupling between two straight dielectric waveguide sections which have curved ends. All of the coupling structures mentioned above are symmetrical in nature. In this paper, we present an approximate but accurate method for calculating the scattering coefficients of nonsymmetrical structures and verify the theoretical results with experimental measurements.

Determination of Scattering Coefficients

Consider the cross-sectional view of the coupled structure at the plane z=0 (Figure 1). The symmetry about the x=0 plane suggests that the fields are either symmetric or antisymmetric with respect to that plane. Consequently, as shown in Reference 2, the propagating modes of the coupled structure are either symmetric (k_{even}) or antisymmetric (k_{odd}). Assuming that the fundamental E_{11}^{y} mode is launched from a conventional metal waveguide, the two wave numbers k_{even} and k_{odd} are given by

$$\left.\begin{matrix} k_{even} \\ \\ k_{odd} \end{matrix}\right\} = k_z \left\{ 1 \pm 2 \frac{k_x^2\, \xi \exp(-d/\xi)}{k_z^2\, a(1+k_x^2\xi^2)} \right\} \tag{1}$$

where k_x and k_z are the transverse and longitudinal propagation constants of a single guide, respectively, and can be derived using the effective dielectric constant method [7]; d is the spacing between the two guides; and ξ is the field decay coefficient, i.e., the distance in which the fields decay by e^{-1}.

$$\xi = \left\{ \begin{matrix} \xi \\ \\ \xi_{re} \end{matrix} \right\} = \left\{ \begin{matrix} 1/\sqrt{(\varepsilon_r - 1)k_0^2 - k_x^2} & \text{(2a)} \\ \\ 1/\sqrt{(\varepsilon_{re} - 1)k_0^2 - k_x^2} & \text{(2b)} \end{matrix} \right.$$

$$\varepsilon_{re} = \varepsilon_r - \left[\frac{k_y}{k_0}\right]^2 \tag{3}$$

The first expression for ξ is applicable to loose coupling, and is given by Marcatili [2], whereas the second expression incorporates the effective dielectric constant approach for tight coupling. The dividing line between the two definitions for ξ is based entirely on experiment.

It is the interaction between the even and odd modes that induces the coupling between the two dielectric waveguides [2]. The scattering coefficients for the coupling section can be expressed as:

$$|s_{31}| = \left|\sin \frac{k_{even} - k_{odd}}{2}\, \ell \right| \tag{4}$$

$$|s_{21}| = \left|\cos \frac{k_{even} - k_{odd}}{2}\, \ell \right| \tag{5}$$

where ℓ is the total coupling length of the coupling section.

Coupling Spacing

Next we consider the nonsymmetric structure shown in Figure 2a. For the radius R sufficiently large, the wave numbers of both the guides can be assumed to be identically equal to that of a straight guide. In a dielectric waveguide, the equiphase fronts of the fundamental E_{11}^{y} mode are normal to the guide axis. We assume that, with the existence of the second dielectric guide, these fronts are cylindrical planes. Consequently, the separation distance between the incremental coupling lengths of the two lines is given by the arc length L. The total coupling of the structures is the summation of the couplings from these incremental coupling lengths. The spacing d in (1) is replaced by L, which for the nonsymmetric structure of Figure 2a, is given by

$$L = r\theta \tag{6}$$

$$r = \frac{d_0 + (R+a/2)\ (1-\cos\theta)}{\sin\theta} \tag{7}$$

The scattering coefficients can be derived by substituting (6), (7), and (1) into (4) and (5) and using $\ell = Rd\theta$.

$$|S_{31}| = |\sin(K\, I_n)| \tag{8}$$

where
$$K = \frac{4k_x^2 \xi R}{k_z a(1+k_x^2\xi^2)} \tag{9}$$

$$I_n = \int_0^{\pi/2} \exp\left[- \frac{\theta\{d_0 + (R+a/2)\ (1-\cos\theta)\}}{\xi \sin\theta}\right] d\theta \tag{10}$$

For this nonsymmetric coupler, the coupling is weak since the phase velocities of the two guides are slightly different. Thus, the presence of one guide does not affect the field distribution of the other. Consequently, the field decay coefficient ξ of the coupled structure is identical to that of a single line structure. For this case, ξ assumes the value given in (2a). The experimental and calculated results of $|s_{21}|$ and $|s_{31}|$ as a function of the spacing d_0 are plotted together (see Figure 3).

For the special case in which two waveguides are symmetric about the z=0 plane (see Figure 2b), the method of calculating the spacing between the two waveguides is the same as that for the nonsymmetric structure. The arc length L for the symmetric structure is given by

$$L = 2r\theta \qquad (11)$$

$$r = \frac{d_0+2(R+a/2)\ (1-\cos\theta)}{2\sin\theta} \qquad (12)$$

The integral term in (8) is replaced by

$$I_s = \int_0^{\pi/2} \exp\left[-\frac{\theta\{d_0+2(R+a/2)\ (1-\cos\theta)\}}{\xi_{re}\sin\theta}\right] d\theta \qquad (13)$$

It is known that appreciable coupling of power from one guide to the other is possible only if the two guides have identical phase velocity [1]. For a symmetric structure, both guides have the same phase velocity. As a result, the coupling is strong, and the field decay coefficient ξ is replaced by ξ_{re} in (12) as defined in (2b). Figure 4 compares the experimental and the calculated results for the scattering coefficients at various frequencies as a function of guide spacing d_0.

The coupling can be greatly improved if a straight dielectric waveguide section of length ℓ_0 is inserted between two curved connecting arms as shown in Figure 5a. The coupling of power takes place largely in the uniform section ℓ_0, whereas the curved connecting arms produce only a slight perturbation compared to that of the uniform section. The scattering coefficients for this hybrid structure become

$$|s_{31}| = \left|\sin \frac{k_{even(s)}-k_{odd(s)}}{2}\ \ell_0 + \frac{k_{even(c)}-k_{odd(c)}}{2}\ \ell\ \right| \qquad (14)$$

$$|s_{21}| = (1-|s_{31}{}^2|)^{1/2} \qquad (15)$$

If k_{even} and k_{odd} are substituted into (14), the scattering coefficients can be rewritten in the form:

$$|s_{31}| = \left|\sin\left(K\left\{\frac{e^{-d_0/\xi_{re}}}{2R}\ \ell_0+I_n\right\}\right)\right| \qquad (16)$$

The experimental and calculated results of $|s_{21}|$ and $|s_{31}|$ as a function of the guide spacing d_0 are plotted together and are shown in Figure 5b.

Experiment Verification

The experiments were carried out in X-band because the component sizes are more manageable and the measurements are more accurate. To reduce the effect of large mismatch caused by reflection and radiation at both receiving and sending ends in normal launching devices, the fundamental E^y_{11} mode was launched from an improved rectangular horn [8]. Mode coupling did not occur since the dielectric waveguides were designed to support the fundamental E^y_{11} mode only.

The guiding media were fabricated from plexiglass ($\varepsilon_r = 2.6$). The curved sections were made sufficiently large to reduce the effect of radiation since the purpose of this investigation is to study the coupling characteristics only. The whole structure is supported by bubble styrofoam ($\varepsilon_r \simeq 1$) and surrounded by absorbers to eliminate stray radiations.

The propagation constant of the single guide was determined by using the effective dielectric constant method. Scattering coefficients of various coupling structures were measured and compared with calculated results as shown in Figures 3-5. If Figures 3 and 4 are compared, it is interesting to note that the coupling is more pronounced in a symmetric coupler than a nonsymmetric coupler even though the symmetric coupler has larger guide spacings. This is caused by the differences between the phase velocities in the coupled waveguides. Experimental results agree well with calculated values throughout. The scattering coefficient $|s_{41}|$ has been ignored in all figures since it is less than 30 dB for all measurements.

Conclusions

Various symmetric and nonsymmetric dielectric coupler structures of rectangular cross section have been investigated experimentally and theoretically. It has been shown experimentally that the theory presented here is useful for calculating the scattering parameters with reasonable accuracy. This method can also be directly applied to other guiding structures such as image lines and inverted strips.

References

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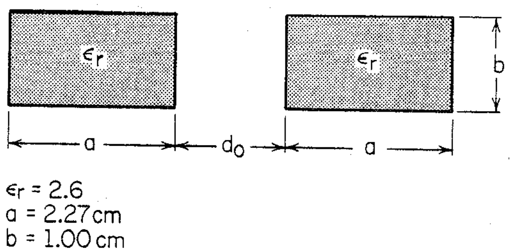

Figure 1. Cross-Sectional View of the Coupled Structure.

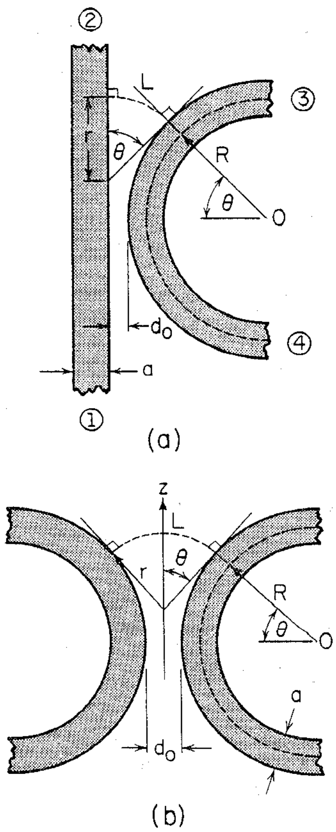

Figure 2. Coupling Structures of Dielectric Waveguide of:
(a) nonsymmetrical, and
(b) symmetrical types.

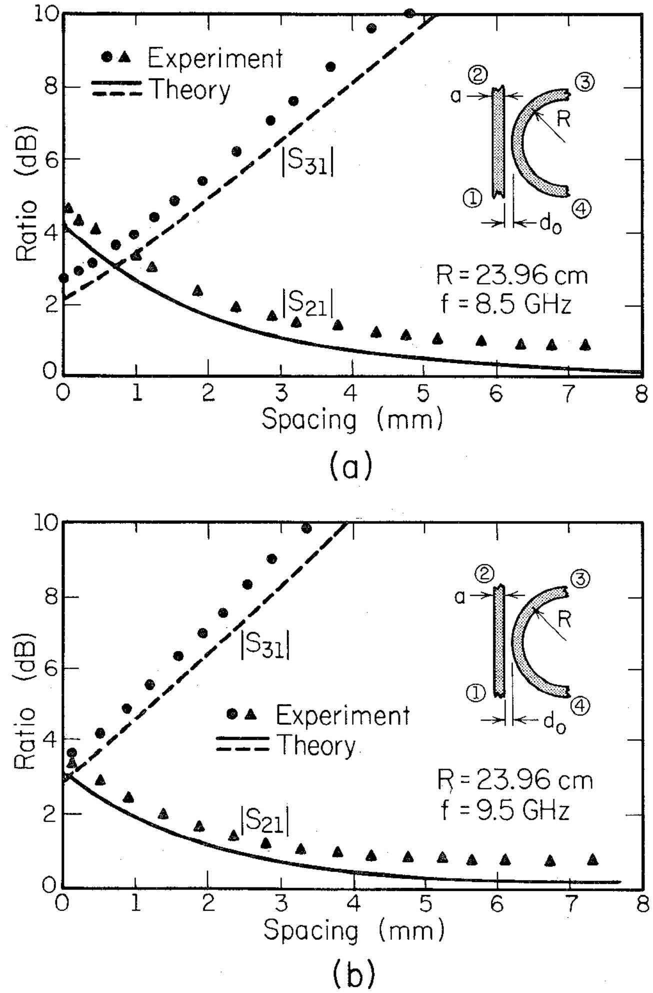

Figure 3. The Scattering Coefficients of a Nonsymmetrical Coupler Versus Guide Spacing d_0 at:
(a) f = 9.5 GHz
(b) f = 8.5 GHz

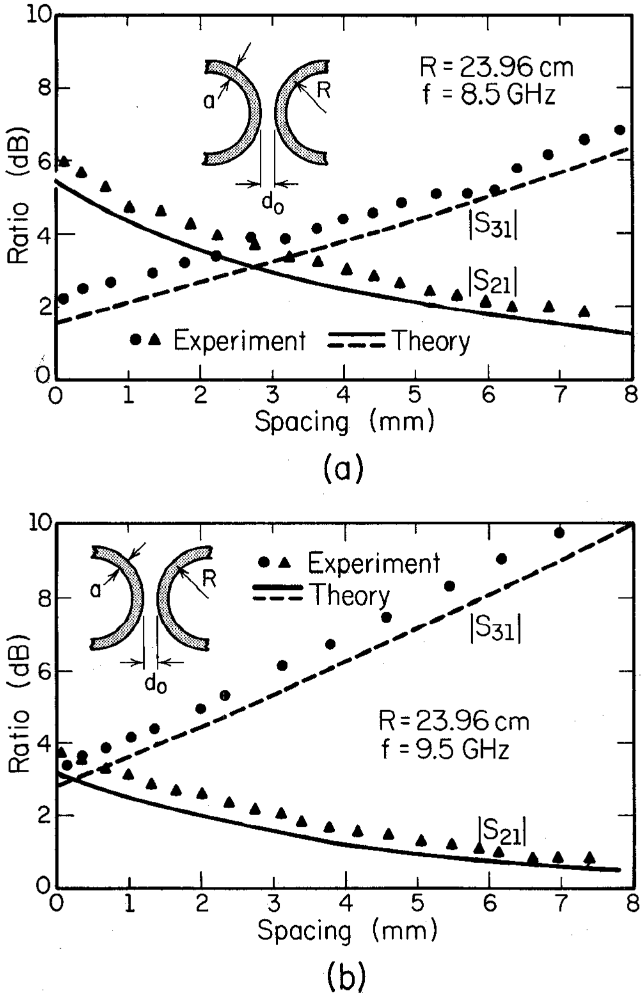

Figure 4. The Scattering Coefficients of a Symmetrical Coupler Versus Guide Spacing d_0 at:
(a) f = 9.5 GHz
(b) f = 8.5 GHz

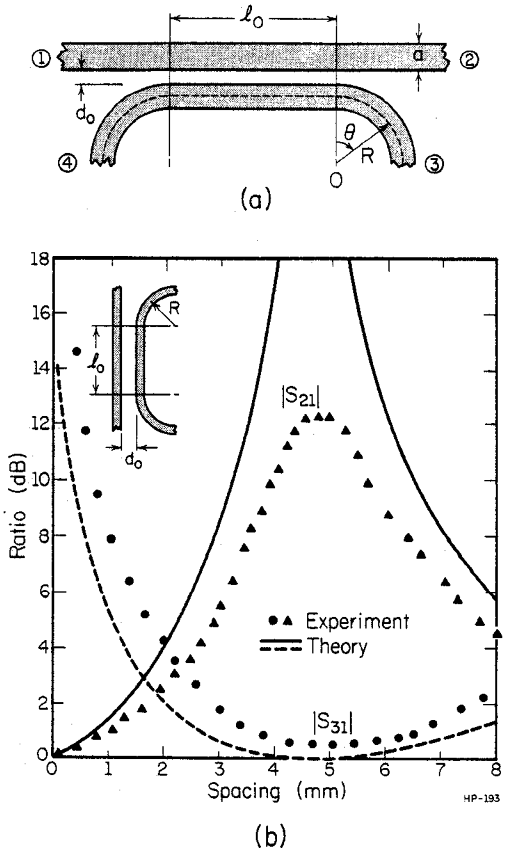

Figure 5. Coupler Structure Incorporating a Straight Section and Curved Connecting Arms:
(a) Hybrid Coupler,
(b) Scattering Coefficients.