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Analysis of Coupling in Image Guide Technology

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***Abstract*—Coupling for symmetrical and asymmetrical structures in image guide technology is described. Starting from Trinh and Mittra's analysis, we propose some improvements for treating strong coupling between an image guide and a ring resonator of any radius of curvature, by taking into account the field displacement effect, and for a nonsymmetric coupler, the difference between the propagation constants of the straight and curved image guides. A comparison between this analysis and Trinh and Mittra's experiments has been made.**

I. Introduction

In recent years, greater interest has been paid to millimeter-wave dielectric propagation media for use both in active and passive devices [1]. Derived from guides widely used in optics, these structures are indeed well suited to high frequency bands. When associated with dielectric ring resonators, dielectric waveguides are especially suitable for the modelling of filters [2]. In order to design filters in image guide technology at millimeter wavelengths, it is necessary to characterize accurately the coupling between basic elements.

This paper presents numerous improvements which can be applied to the analysis proposed by Trinh and Mittra for symmetric and nonsymmetric couplers [3] and which are able to predict both the amplitude and the phase of the scattering parameters without any restrictive assumption. To do this, the analysis takes into account not only the shift of the electromagnetic field due to the curvature of the guide but also, in the case of nonsymmetric couplers, the difference in the propagation constants between curved and straight guides. A slight concordance is observed between our theory and Trinh and Mittra's experimental results.

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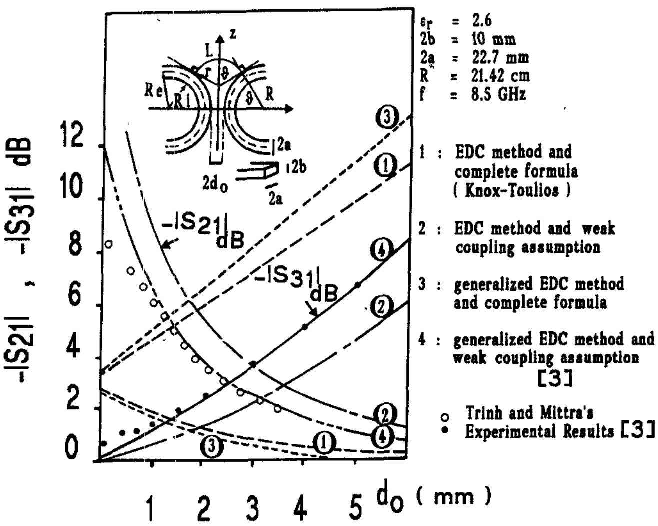


Fig. 1. Scattering coefficients in the case of a symmetric coupler.

II. Trinh and Mittra's Analysis

In the case of a symmetric coupler (Fig. 1), this approach is able to predict scattering coefficients with quite satisfactory accuracy. Their theory is based on three assumptions:

a) The authors assume the radius R to be large enough compared to the wavelength, to neglect the field displacement in the curved structures [4] and approximate the phase constant in this section by the one obtained in a straight section.

b) They use the generalized EDC method (Effective Dielectric Constant) to obtain both the phase constant of the single image guide fundamental mode and the even and odd phase constants of coupled image guides.

c) They suppose that the coupling is weak. From a mathematical point of view, this assumption permits the use of analytical asymptotic equations to derive the even and odd phase constants of the coupler.

To analyze the validity of these hypotheses, we plotted (Fig. 1) the S-parameters versus the spacing between guides for each combination of the techniques available, i.e., for both strong (resolution of Knox and Toulios's transcendental equations [5]) and weak coupling. This figure shows that the results may be very different according to the technique chosen (EDC [5] or generalized EDC method [3]) and that paradoxically Trinh and Mittra's experiments and theoretical results (curve 4, Fig. 1) agree well for strong coupling where the asymptotic equations are not valid.

When applied to a nonsymmetric coupler, the main drawback of Trinh and Mittra's model lies in the necessity of introducing a correction factor into the calculations to model the phase constant difference between straight and curved guides.

Concluding Remark: If the assumption of "weak coupling" in Knox and Toulios's transcendental equations leads to fairly good results concerning symmetric couplers, this may not be significant. Indeed, the excess of coupling obtained when the distance between guides is supposed to be infinite may make up for the omission of the shift of the maximum field amplitude towards the outside of the guide observed in curved structures [4].

Thus, it seems more realistic to take into account this physical phenomenon without assuming a weak coupling approximation and, in the case of nonsymmetric couplers, the difference in propagation constants between a straight and a curved section. This paper presents one way of taking this into account.

III. Improvement of the Coupling Model

A. Use of Transmission Matrix Formalism

Like Trinh and Mittra, we divide the circumference of the guide into an infinity of incremental coupling lengths. To obtain information concerning the phase of the scattering parameters, we define for each of the coupling lengths a partial scattering matrix (S_i) and transmission matrix (C_i). Then the total transmission matrix (C_T) is obtained by chaining the partial transmission matrices (C_i). The scattering coefficients for total coupling are derived by setting:

$$S_{31T} = C_{34T} \quad S_{21T} = C_{33T}. \tag{1}$$

Remark: For the symmetric coupler, the transmission matrix formalism gives the same results as Trinh and Mittra's method for the magnitude of the scattering coefficients (Fig. 1, curve 4). The output (S) parameters are exactly in quadrature as could be expected.

B. Curved Image Guide; Equivalent Model

In order to study strongly curved coupled waveguides, it is necessary to take into account the shift of the maximum field amplitude as well as the "wavelength" (λ_{gc}) of the "E_{11}^y" mode in the curved section.

The analysis of ring dielectric resonators allows such a phenomenon to be described. The resonant frequencies of this structure operating on higher-order azimuthal hybrid modes HE_{m11} are analyzed by means of the "transverse resonance method." This has been the subject of previous papers [6], [7]. This analysis provides the resonant frequency (with an error below 1% in the X-band) as well as the field distribution inside and outside the resonator.

This structure can also be viewed as an annular image guide resonator for which a constructive phenomenon occurs when the "length" of the circumference is equal to a multiple (m) of the wavelength of the fundamental E_{11}^y mode.

By using the equivalence between image guide resonant modes (m; E_{11}^y) and hybrid ring resonator modes HE_{m11} (m being the azimuthal order), we calculate the field displacement and then the phase constant of the curved structure.

For a resonator having the same characteristics as the curved structure used by Trinh and Mittra, we find at 8.5 Ghz a resonant phenomenon corresponding to a high order azimuthal mode HEm11 with $m = 42$. The evolution of $|E_y|$ versus r (Fig. 2) clearly shows an outward shift of the maximum field amplitude.

Measurements of the electric field (E_y) above a ring resonator versus r, for several resonant frequencies (Fig. 3), confirm this evolution, but also show a dissymmetry of the electromagnetic field not taken into account in this approach. This last effect, which is very important at low frequencies as seen in [4], will tend to increase the coupling between structures.

As, from a mathematical point of view, the coupling is a recovering integral, from an energetical point of view the two coupled guides seem to be closer. Once the shift is determined, it is possible to operate on a fictitious structure having the same cross section but a greater mean radius of curvature:

$$R'_m = R_m + s. \tag{2}$$

Given m and R'_m we can define the wavelength (λ_{gc}) in the curved structure as

$$\lambda_{gc} = 2\pi R'_m / m. \tag{3}$$

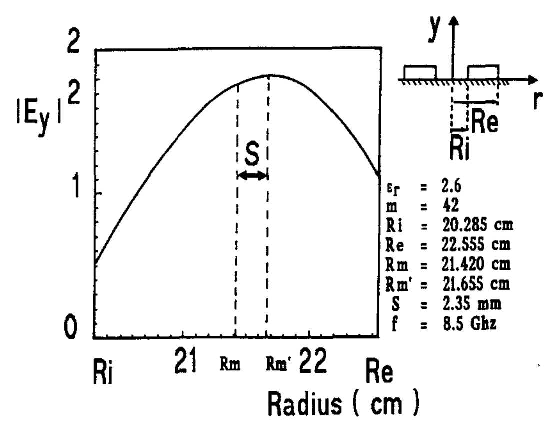


Fig. 2. Field amplitude as a function of the transverse position of the guide.

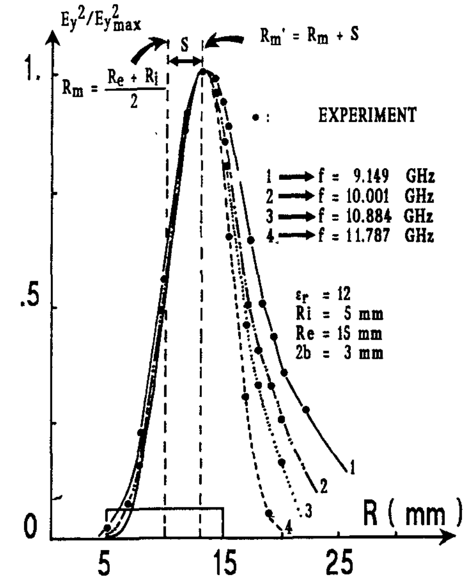


Fig. 3. Plot of the field amplitude as a function of the transverse position in the guide for various frequencies.

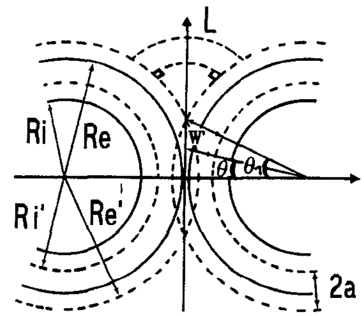


Fig. 4. Equivalent model of the symmetric coupler.

Fig. 4 outlines both the real and fictitious structure and shows that for small spacings, the fictive guides superimpose. It is obvious that we must now consider two different areas:

a) a covering area where the coupled guides can be considered as a single guide of width $2W'$ where

$$W' = \frac{R'_e \cos \vartheta_1 - R'_i \cos \vartheta}{\cos \vartheta} \tag{4}$$

and

$$\vartheta_1 = \text{arcos}\,((R_e + d_0)/R_e'). \quad (5)$$

The propagating (symmetric and antisymmetric) modes are respectively the fundamental mode E_{11}^y and the higher order mode E_{21}^y of this structure.

b) a non covering area where the coupled lines split. In this zone, processing is the same as in Section III-A with

$$L = 2 \cdot \vartheta \cdot R_e' \cdot (\cos \vartheta_1 - \cos \vartheta)/\sin \vartheta \quad (6)$$

C. Straight Guides

In order to be coherent with respect to the basic analysis of curved and straight guides, the transverse resonance (TR) method (already used for the curved guide) is applied to analyze straight single or coupled image guides [8].

IV. Results

A. Case of a Symmetric Coupler

Using the TR method, the transmission matrix formalism, and taking into account the field displacement, we have reported on Fig. 5 the results on the modula of the scattering coefficients. As only a small discrepancy is observed between Trinh and Mittra's experimental points, we may say that our model represents the physical reality rather accurately. The output ports of the coupler are in quadrature.

B. Case of a Nonsymmetric Coupler

The dissymmetry of the coupler can be conveyed by adding a phase difference matrix (D_i) to the partial scattering matrix (S_i) for each coupling segment. It is necessary to take into account the geometrical difference in lengths between the curved guide (ds) and the straight guide (dz) (Fig. 6) and also the different propagation velocities between a curved and a straight section. The guided wavelength in a curved section can be approximated by using the relation $2\pi R_m' = m\lambda_{gc}$ as m (azimuthal order) and R_m' (new mean radius) have already been determined. Hence, the correct phase difference can be restored for each coupling segment. This leads to a partial transmission matrix (C_i') (see appendix for details).

Using this phase correction and the improvements mentioned above we present on Fig. 7(a)–(b) the simulated scattering coefficients versus the spacing between guides. Unlike in the case of a symmetric coupler for which the phase difference equals 90 degrees, we can notice a variable phase difference between the output ports of the coupler.

Concerning the magnitude of the (S) parameters, our theory and Trinh and Mittra's experimental results do not coincide very well. Nevertheless, no correction factor has been introduced here.

Contrarily to the Trinh and Mittra's model without correction factor which allows a complete transfer of power on the output ports (see Fig. 7(a)) our analysis forbid this phenomenon between two different waveguides. This is in accordance with the Miller's theory [9]. Although this model seems more accurate, we did not have the opportunity to verify the coupling between a straight and a curved section directly.

V. Conclusion

An improvement of Trinh and Mittra's model has been developed in order to derive the coupling characteristics of symmetric and nonsymmetric couplers in image guide technology. Although our theory agrees well with experimental results, the model is not perfect. To describe the physical mechanism of coupling more accurately, it is necessary to improve the characterization of the basic elements and especially to convey the dissymmetry of the electromagnetic field outside a curved section rigorously.

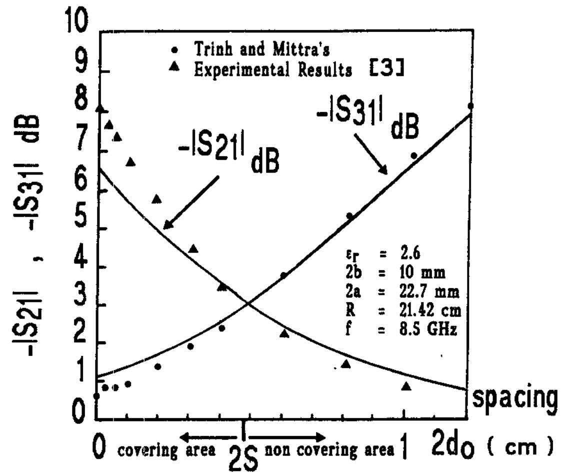


Fig. 5. Scattering coefficients in the case of a symmetric coupler (use of the transverse resonance method).

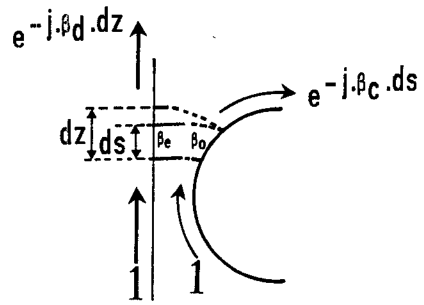


Fig. 6. Phase shift associated to a curved incremental coupling length.

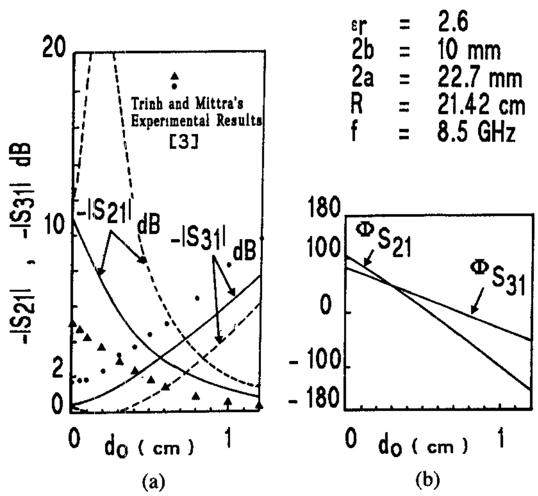
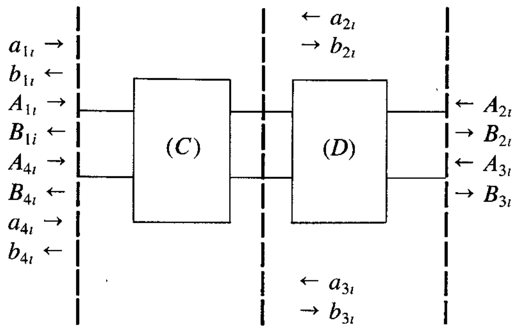


Fig. 7. Scattering coefficients in the case of a nonsymmetric coupler as a function of the spacing between guides (use of the TR method). (a) amplitude; (b) phase.———: TR method.-----: Trinh and Mittra's method without correction.

Appendix

A coupling segment of length ds can be represented by



where

$$a_{1t} = A_{1t} \quad B_{2t} = e^{-j\beta_d(dz-ds)} b_{2t}$$

$$b_{1i} = B_{1i} \quad A_{2i} = e^{j\beta_d(dz-ds)} a_{2t}$$

$$a_{4t} = A_{4i} \quad B_{3i} = e^{j(\beta_d-\beta_c)ds} b_{3t}$$

$$b_{4t} = B_{4t} \quad A_{3t} = e^{-j(\beta_d-\beta_c)ds} a_{3i}$$

with

$$ds = R_e\, d\vartheta$$

$$dz(\vartheta) = r(\vartheta + d\vartheta)(1 - \cos(\vartheta + d\vartheta)) + R_e(\sin(\vartheta + d\vartheta) - \sin\vartheta) - r(\vartheta)(1 - \cos\vartheta)$$

β_d: phase constant of the straight guide

β_c: phase constant of the curved guide

By setting:

$$(B)_t = (S')_t (A)_i$$

$(S')_t$ can be derived:

$$(S)'_t = \begin{pmatrix} 0 & S_{21t} e^{-j\beta d(dz-ds)} & S_{31t} e^{j(\beta_d-\beta_c)ds} & 0 \\ S_{21t} e^{-j\beta d(dz-ds)} & 0 & 0 & S_{31t} e^{-j\beta_d(dz-ds)} \\ S_{31t} e^{j(\beta_d-\beta_c)ds} & 0 & 0 & S_{21i} e^{j(\beta_d-\beta_c)ds} \\ 0 & S_{31t} e^{-j\beta_d(dz-ds)} & S_{21t} e^{j(\beta_d-\beta_c)ds} & 0 \end{pmatrix}.$$

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Microwave Reflection at an Active Surface Imbedded with Fast-ion Conductors

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***Abstract*—The microwave reflection characteristics at a surface of a composite medium comprised of thermally controllable, solid-electrolyte based active-zones are studied. These zones are energized (heated) reconfigurably so as to alter their electric conductivity, and hence their reflection/transmission characteristics. Experimental studies at *X*-band frequencies on a test active surface formed by a two dimensional array of AgI pellets (fast-ion conductors) imbedded in a dielectric medium are presented. Suitability of the proposed composite-medium for broadband applications is indicated.**

I. Introduction

Controllable electromagnetic absorption and/or reflection by materials are of importance in the development of radar absorbing surfaces and in certain EMI/EMC problems. Conventionally, microwave materials composed by a combination of metallic and/or nonmetallic (dielectric) absorbing constitutents are used for this purpose. For discrete-tuned frequency applications magnetically and dielectrically lossy materials could be blended to obtain moderate performance on absorption/reflection characteristics. The base materials for such applications include: graphite/iron/aluminum particles (spherical/fibrous/flaky) dispersed in a host medium such as natural rubber-latex, polyisoprene, neoprene, silicone, urethene, etc. However, for better absorption the frequency-tuning is done by the principle of quarter-wave window(s) via multiple layers of lossy dielectrics.

An alternative approach suggested by Meyer *et al.* [1] consists of distributing a large number of magnetic dipoles on a conducting surface to achieve pronounced reflection/absorption characteristics depending on the orientation and distribution of the dipoles. A successful application of this principle has been reported by Chatterjee *et al.* [2]. Typically, a reflectivity reduction in the order of −20 to −30 dB could be accomplished at selective resonance frequencies

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