A NEW CLASS OF LEAKY MODES ON OPEN DIELECTRIC WAVEGUIDES

A. A. Oliner and S. T. Peng
Microwave Research Institute
Polytechnic Institute of New York
333 Jay Street
Brooklyn, New York 11201

ABSTRACT

It is not generally known that most guided modes on many open dielectric waveguides for integrated optics and millimeter waves can be leaky, rather than purely bound, as is customarily assumed. The previously-unrecognized leakage on this new class of modes is the result of coupling between constituent TE and TM waves produced at the sides of the waveguide when these waves bounce back and forth inside the dielectric waveguide, as part of the guiding process. A generally-applicable simple criterion will be presented which predicts when such leakage can occur.

Open dielectric waveguides have become increasingly important within the past few years, particularly in connection with the areas of integrated optics and millimeter wave integrated circuits. The major types of waveguides being investigated in these two areas are presented in Figs. 1 and 2. As seen, these waveguides are associated with either a substrate or a ground plane; we are not concerned here with fiber waveguides of circular cross section.

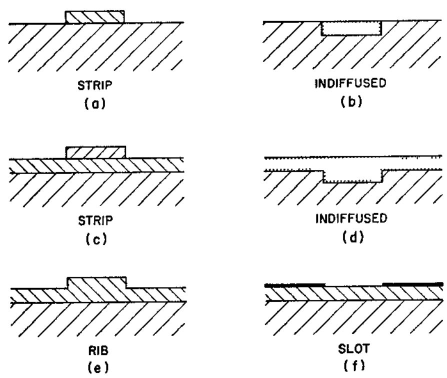

Fig. 1. Examples of open dielectric waveguides for integrated optics. Waveguides (a) and (b) fall into the class for which no leakage is possible; the rest are members of the class for which some modes may leak.

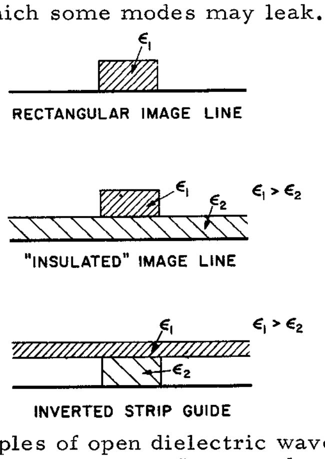

Fig. 2. Examples of open dielectric waveguides for millimeter waves. Some modes on the "insulated" image line and the inverted strip guide may leak, whereas all modes on the rectangular image line are purely bound.

It is not generally known that most modes on most of these waveguides can be leaky, instead of being purely bound, as is customarily assumed. The tacit assumption that these modes are completely bound is based largely on published theoretical propagation characteristics, which are obtained from approximate analyses[1-5] that neglect those features which lead to the leakage effects. More careful analyses[6,7] reveal that under appropriate conditions leakage is indeed possible. Here, we present a simple criterion, based on the pertinent physical interaction, that is systematic and generally applicable and which permits one to determine when leakage will be present without having to first solve the specific problem. From this criterion we can make predictions relating to various classes of waveguides; we can determine which classes may leak and which will never leak, which modes will do the leaking and which will not, and we can prescribe how to modify the waveguiding structure to avoid leakage, or alternatively to produce leakage when we wish to.

It is important for two reasons to know whether or not leakage is present. Since these open dielectric waveguides are intended for use in an integrated circuit fashion, the first reason is that unwanted leakage can cause cross talk between neighboring components and thus deteriorate the performance of the circuit. The second reason is that novel components could be designed to make deliberate use of the leakage present. An example of such a component for integrated optics is a novel leaky-wave directional coupler, which has potential use as a mode stripper or purifier.

Open dielectric waveguides can be broadly divided into two classes: those which are essentially modifications of dielectric rods, and those which are formed by a dielectric strip that perturbs a planar dielectric waveguide. Examples of the first class are the dielectric image line (Fig. 2(top)) for millimeter waves, the dielectric strip placed directly on a dielectric substrate (Fig. 1(a)) and the channel diffused into the surface of a dielectric substrate (Fig. 1(b)), the latter two arising in integrated optics. Examples of the second class are the "insular" guide (Fig. 2(middle)) and the inverted strip guide (Fig. 2(bottom)) for millimeter waves, and the waveguides for integrated optics shown as Figs. 1(c) through 1(f). In all examples of the second class, a wide planar dielectric layer is present which could guide a surface wave in the absence of the central strip which concentrates the field laterally.

The modes which we discuss here are all above cutoff, in contrast to certain high-loss below-cutoff leaky wave solutions appearing in some treatments of optical fibers (dielectric waveguides) of circular cross section. Furthermore, we do not consider the mechanisms which give rise to certain above-cutoff "tunneling" modes which occur in such optical fibers. The class of leaky modes we treat here do not occur in dielectric open waveguides of circular cross section, and they involve a coupling mechanism which is not applicable there.

It can be shown, using the criterion discussed below, that all waveguides falling into the first class possess only purely bound modes; none of the modes are ever leaky (assuming that the waveguide is longitudinally uniform, of course; a taper or appropriate periodic loading will produce leakage). On the other hand, leaky modes can be present on waveguides of the second class. On such structures, the lowest mode never leaks, the next mode (which is usually present simultaneously) may or may not leak depending on the geometrical conditions, and modes formed from the higher modes in the planar dielectric layer almost always leak. In predictions, care must be taken to determine which mode, in fact, is the lowest mode. For example, in the inverted strip guide (Fig. 2(bottom)) it has been assumed that the TM mode, which is the incident mode, is the lowest one under customary operating conditions; in fact, a cross-over occurs in the dispersion plots, and the lowest mode is really the TE mode, with the result that the TM mode leaks, contrary to expectations.

As a typical waveguide belonging to the second class, let us consider the strip guide of Fig. 1(c), which is also reproduced as the upper part of Fig. 3.

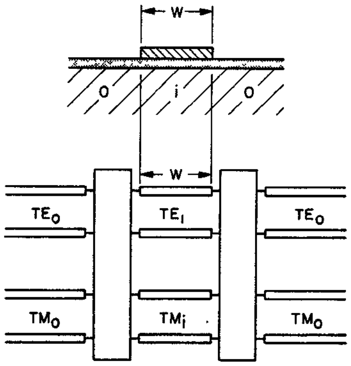

Fig. 3. Transverse equivalent network for an open dielectric waveguide which takes into account the TE-TM mode coupling produced at the strip sides. The symbols i and o signify respectively the inner (strip) and outer (layer) constituent portions of the waveguide cross section.

We may divide the cross section into the strip, or inner, region and the outer regions, designated respectively as i and o. The guiding process is usually viewed simply as a TE or a TM surface wave (depending on the incident polarization) bouncing back and forth in the inner region at an angle to the strip sides, undergoing total reflection at each bounce. However, the layer thickness is usually such that both a TE and a TM surface wave can be supported simultaneously in each region. An examination of the field components associated with the TE and TM surface waves obliquely incident on the strip sides shows that they have field components in common and that they therefore must necessarily couple to each other at each of the bounces mentioned above. As a result, a transverse equivalent network characterizing this behavior takes the form shown in Fig. 3, where the coupling between these modes is represented by the boxes between the transmission lines.

In the approximate analyses mentioned earlier,[1-5] the TE-TM coupling is neglected and only one transmission line, either the TE or the TM, is treated. Suppose TM wave incidence is considered; consistent with the total reflection viewpoint, the TM_i transmission line is above cutoff whereas the TM_o ones are below cutoff, and the guided wave is purely bound in these approximate analyses. Since the TE mode is the lowest mode in this structure, it can be shown that when TE-TM mode coupling is included, and the complete network in Fig. 3 is used, the TE transmission lines can be above cutoff both in the inner and outer regions. If the TE_o transmission line in Fig. 3 is above cutoff, then leakage of energy from the TM_i wave into the TE_o wave will occur at each bounce at the strip sides and a leaky mode will result. This situation is pictorially summarized in Fig. 4.

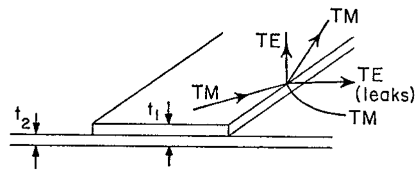

Fig. 4. Pictorial representation of the TE-TM mode coupling at the strip side, which produces leakage when the TM surface wave is incident on the strip side.

The leakage, when it occurs, is thus due to the coupling between the constituent TE and TM waves produced at the strip sides when these waves bounce back and forth in the strip region, as part of the guiding process. Consistent with this viewpoint, the simple quantitative criterion for leakage presented below requires one to investigate the dispersion behavior for the independent TE and TM waves in each of the constituent regions, i and o, in the waveguide cross section, assuming each region to be infinitely wide.

In Fig. 4, let us take the waveguide axial direction to be the z direction, and the horizontal direction in the cross section to the x direction. Let us also choose the TM wave to be the incident one, so that leakage occurs in the TE wave outside, if it occurs at all. These considerations are consistent with the qualitative discussion above. The explicit condition for leakage is then

$$(k_x^{TE})^2_{out} > 0 \quad . \tag{1}$$

The quantity $(k_x^{TE})_{out}$ is the transverse wavenumber of the TE wave in the outside region, and relation (1) states that the outer TE transmission line in the transverse equivalent network in Fig. 3 is above cutoff.

The actual TE surface wave outside, with wavenumber $(k_s^{TE})_{out}$, where s represents "surface wave," will be propagating away from the strip at some angle, and it will possess components k_z along the waveguide direction and $(k_x^{TE})_{out}$ perpendicular to it in the plane of the thin dielectric film. Quantity k_z needs no other qualifying indices because all constituents of the net guided mode along the waveguide must possess the same k_z value. We may thus write

$$(k_s^{TE})^2_{out} = k_z^2 + (k_x^{TE})^2_{out} \tag{2}$$

so that

$$(k_s^{TE})_{out} > k_z \tag{3}$$

or, dividing by k,

$$(n_{eff}^{TE})_{out} > (n_{eff})_{guide} \tag{4}$$

in the light of relation (1).

The quantity $(n_{eff}^{TE})_{out}$ is obtained directly from the dispersion curve (since $n_{eff} = \beta/k_o = \lambda_o/\lambda_g$) for the constituent TE surface wave in the outside region.

However, $(n_{eff})_{guide}$ corresponds to the net guided wave along the z direction, and is known only after the complete problem is solved. On the other hand, simple approximations to $(n_{eff})_{guide}$ can be used which are quite accurate for the present need. The so-called equivalent index method,[2,3] which is a modification of the Marcatili approach,[1] or the equivalent dielectric constant method,[4,5] which is the first step of a transverse resonance procedure, can supply us with an approximation which is reasonably accurate and yet simple. In both of these approximate procedures, the TE-TM coupling is neglected entirely; as a result, neither method can predict any leakage, but the k_z values obtained are reasonably reliable under most conditions.

As an approximation, therefore, we take

$$k_z \approx (k_z^{TM})_{approx.} \tag{5}$$

where the k_z found will be purely real and corresponds to the case of TM waves alone. Then, using Eqs. (3) or (4) we write

$$(k_s^{TE})_{out} > (k_z)^{TM}_{approx.} \tag{6}$$

or

$$\boxed{(n_{eff}^{TE})_{out} > (n_{eff}^{TM})_{\substack{guide\\approx.}}} \tag{7}$$

Now, a plot of $(n_{eff}^{TM})_{\substack{guide\\approx.}}$ as a function of strip width W can be obtained relatively easily, avoiding the complications introduced by TE-TM coupling and the continuous spectrum contributions.

With the simple criterion given in (7), which is applicable generally, one can determine in any specific case whether or not leakage will occur, or for what strip width it will occur. In many cases, it is not even necessary to solve for the quantity on the right hand side of (7). One can observe directly from the dispersion curves of the constituent TM waves, both inside and outside, the range of possible values that $(n_{eff}^{TM})_{guide}$ can have, for a given frequency, as the strip width is varied. The inequality in (7) may then be satisfied for <u>all</u> values of strip width. In that case, it is unnecessary to evaluate $(n_{eff}^{TM})_{\substack{guide\\approx.}}$. When the inequality is seen to be satisfied for only a certain range of strip widths, such an evaluation is required. Under those circumstances, we recommend that the equivalent dielectric constant method be used for the simple first-order approximation.

References

1. E.A.J. Marcatili, "Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics," Bell System Tech J., <u>48</u>, pp. 2071-2102 (September 1969).
2. H. Furuta, H. Noda and A. Ihaya, "Novel Optical Waveguide for Integrated Cptics," Appl. Opt., <u>13</u>, pp. 322-326 (February 1974).
3. N. Uchida, "Optical Waveguide Loaded with High Refractive-Index Strip Film," Appl. Opt., <u>15</u>, pp. 179-182 (January 1976).
4. W.V. McLevige, T. Itoh and R. Mittra, "New Waveguide Structures for Millimeter-Wave and Optical Integrated Circuits," IEEE Trans. on MTT, <u>MTT-23</u>, pp. 788-794 (October 1975).
5. T. Itoh, "Inverted Strip Dielectric Waveguide for Millimeter-Wave Integrated Circuits," IEEE Trans. on MTT, MTT-24, pp. 821-827 (November 1976).
6. S.T. Peng and A.A. Oliner, "Leakage and Resonance Effects on Strip Waveguides for Integrated Optics," Trans. IECE of Japan, <u>E61</u>, pp. 151-154 (March 1978).
7. A.A. Oliner, S.T. Peng and J.P. Hsu, "New Propagation Effects for the Inverted Strip Dielectric Waveguide for Millimeter Waves," International Microwave Symp. Digest, pp. 408-410, Ottawa, Canada (June 1978).
8. E.W. Hu, S.T. Peng and A.A. Oliner, "A Novel Leaky-Wave Strip Waveguide Directional Coupler," Topical Meeting on Integrated and Guided Wave Optics, Paper No. WD2, Salt Lake City, Utah (January 1978).

Acknowledgment

This work was supported by the Joint Services Technical Advisory Committee under Contract No. F49620-74-C-0056.