SCATTERING OF SURFACE WAVES BY NONUNIFORM WAVEGUIDES

S. T. Peng*, S. J. Xu*, and Felix K. Schwering**

* New York Institute of Technology
Old Westbury, NY 11568
**U.S. Army CECOM
Ft. Monmouth, NJ 07703

Summary

We present here an analysis of a class of nonuniform dielectric waveguides by the method of staircase approximation. Numerical data are obtained to develop guidelines for the design of transition dielectric waveguides for integrated optical or millimeter-wave applications

Introduction

An electromagnetic system generally consists of various electronic devices, waveguiding components and antennas, which are usually interconnected by gradual transition waveguides, in order to reduce the scattering losses due to junction discontinuities. While a thorough understanding of the characteristics of individual components is the first important step towards the development of integrated optical or millimeter-wave systems, it is equally important to understand thoroughly the characteristics and performance of an aggregation of interconnected components and devices, so that the electromagnetic system can then be optimally designed. Generally speaking, a transition region between two uniform waveguides, such as a bend or curved waveguide, a taper, or a step-junction discontinuity, may be regarded as a nonuniform waveguide. The demand for better system performance will require versatile circuit design, and a large class of nonuniform waveguiding structures will be needed. In this paper, we present an analysis of a class of nonuniform dielectric waveguides for integrated optical or millimeter-wave applications.

Some typical nonuniform dielectric waveguides of practical interest are shown in Fig. 1. The structure in Fig. 1(a) shows a taper transition that is intended to optimize the transmission of energy between two uniform waveguides of different sizes. In the limit that the smaller waveguide is absent, as shown in Fig. 1(b), we have a taper that will radiate the guided energy into an open region, and such a structure is commonly known as a taper radiator. The structure in Fig. 1(c) shows a curved waveguide that connects two nonaligned identical waveguides. More generally, curved waveguides may be assembled together to form a branching circuit, as shown in Fig. 1(d), so that the guided energy may be directed to various parts of a circuit in a desired proportion.

The scattering of surface waves by the types of structure mentioned above is not amenable to an exact analysis even for simple geometrical profiles and one must resort to approximate anaylses. Here, we shall employ the method of staircase approximation which is applicable to a large class of structures so that the effects of transition profile can be identified and their magnitudes assessed.

Method of Staircase Approximation

Fig. 2 shows the approximation of a continuous profile (solid line) by a piecewise-constant one (dashed line), and this is known as the staircase approximation. Evidently, in the limit of vanishing step size, the piecewise-constant profile will approach the continuous one. In addition, since we are concerned with the scattering of guided waves which are confined to the vicinity of the dielectric structure, we shall employ the technique of dicretizing the continuous spectrum into a complete set of discrete modes by introducing an oversize metallic waveguide, as is customarily done in the literature [1-3]. With such an approximation, the mathematical analysis and the physical interpretation of wave phenomena associated with nonuniform dielectric waveguides can be kept simple and clear. It should be stressed that although the discretization of modes does introduce some degree of approximation as far as the surface waves are concerned, the presence of an oversize metallic waveguide does not change the physics of the problem.

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With the piecewise-constant profile, the structure consists of a cascade of uniform constituent regions separated by step discontinuities. Each constituent region can be considered as a portion of a uniform partially-filled parallel-plate waveguide for which a complete set of discrete eigenvalues and their corresponding mode functions are well known. The electromagnetic fields in each constituent region may then be represented in terms of the complete set of mode funcitons of the region, and they are required to satisfy the boundary conditions at each step discontinuity. To simplify the formulation, the staircase structure may be viewed as a cascade of basic units, each consisting of a step discontinuity and a uniform waveguide of finite length, and the scattering of surface waves by the staircase structure can then be analyzed in terms of the scattering by each basic unit. We have carried out a rigorous formulation, in terms of transfer matrices, of such a constituent problem which is then used as a building block for the analysis of the whole staircase structure with relative ease.

The method of staircase approximaiton is seen to be very simple and straightforward. It applies to structures with any geometrical profile and any material composition. In addition, the building-block approach with the help of the transfer-matrix technique is paricularly useful for the development of computer programs for numerical analysis, which had been employed for the study of the performance of taper dielectric antennas, with many interesting results obtained [3]. Therefore, this method is paricularly suitable for a comparative study of a large class of nonuniform dielectric waveguides, as shown below.

Numerical Results

Consider first the case of transition between two nonaligned identical waveguides, as shown in the insets in Fig.3. The profile of the transition region is characterized, for the center line, by

$$y = \tanh(x/a) \qquad (1)$$

where a is called the aspect ratio that is proportional to the transition length. It is noted that the local thickness of the waveguide is kept at a fixed value throughout the entire structure. For such a structure, it is intuitively expected that when the transition length is sufficiently large, an incident mode will pass through the nonuniform portion without appreciable perturbation. In an integrated circuit where the space is often limited, it is important to know how small a transition length is acceptable for a particular application, and this is what we intend to illustrate. In the examples given below, we consider only the case of fundamental-mode incidence, and the results are given explicitly only for the reflected and transmitted fundamental modes. It should be pointed out that in our numerical analysis, we always require the conservation of power as a measure of accuracy. Therefore, the deviation of the scattered power of the fundamental mode, including the reflected and transmitted powers, means the power conversions into the higher modes, and this is interpretted as the radiation due to the continuous spectrum.

Figs.3(a) and (b) show the variations of the reflected and transmitted powers of the fundamental mode for two different thicknesses of the waveguide. It is found that for $a > 3\lambda$, over 95% of power is transmitted. For a small aspect ratio, the reflected power of the fundamental mode is quite substantial. Also, the conversion of power into the higher modes is very large. Furthermore, it is observed that between the two sets of curves, the transmission is better for the case of smaller thickness. It is generally true that the discontinuity effect of the transition region decreases with decreasing thickness of the waveguide. A physical interpretation of such a phenomenon is that as the thickness of the waveguide is decreased, the guided energy is distributed more and more outside the dielectric region and, hence, less perturbed.

Fig.4(a) and (b) show the transmission characteristics of a bend, for two different thicknesses of the waveguide. The profile is symmetric with respect to x=0 and the left half is characterized by (1), as indicated in the insets. In contrast to the transition case in Fig.3, we have a total transmission in the limit of zero aspect ratio as well as in the limit of large aspect ratio. In the intermediate range, we have a substantial reflection of the fundamental modes and the radiation loss can be as high as 80% of the incident power. Also, between the two sets of curves, we observe that the transmission is better for the case of smaller thickness than the case of larger one, and the same physical interpretation for the transition case shown in Fig.3 also applies here.

Based on the numerical data we have obtained, we may state that a loosely guided mode can pass through nonuniform waveguide with less perturbation than a well guided mode. A loosely guided mode can be achieved by using either a small dielectric constant or a small thickness of the waveguide. In all the cases analyzed, we observe that a transition length of over 5 wavelengths will assure a transmission of over 95% of the incident power.

Conclusion

We have formulated rigorously a class of nonuniform dielectric waveguides by the method of staircase approximation. Extensive numerical data have been obtained to quantify the sacttering characteristics of various types of nonuniform waveguides. Some useful guidelines for the design of nonuniform dielectric waveguides are thereby suggested.

References

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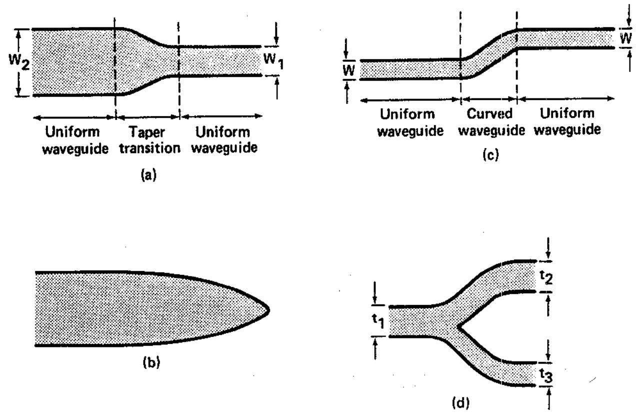


Fig. 1. Typical profiles of nonuniform waveguide

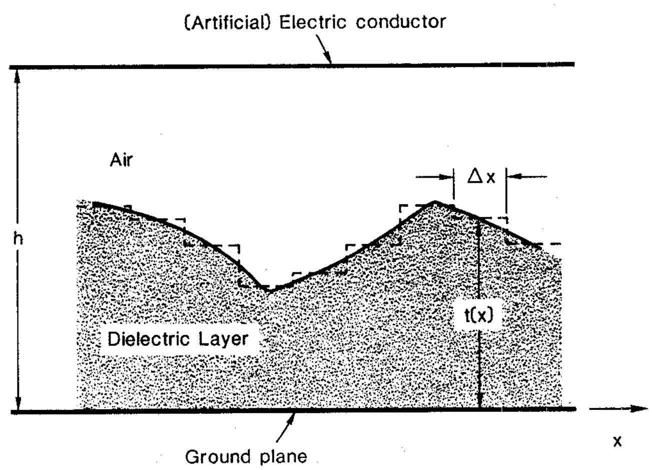
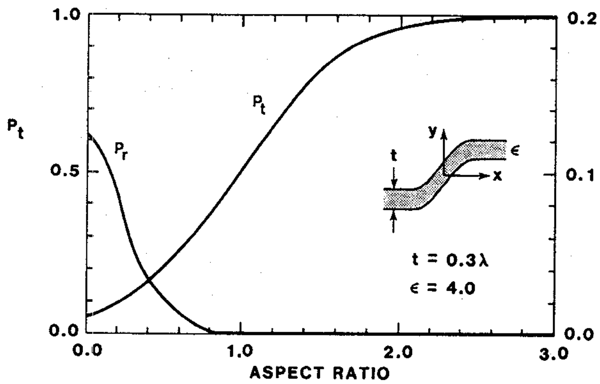
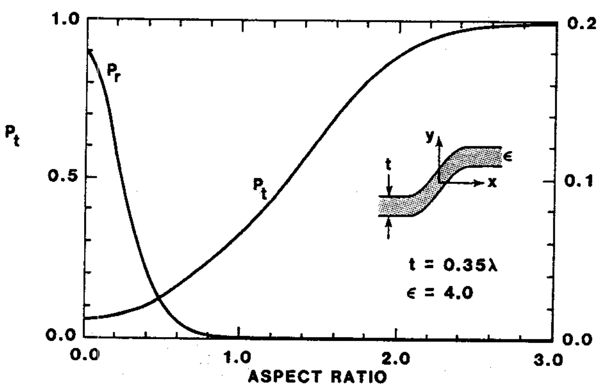


Fig. 2. Staircase approximation of continuous profile of dielectric waveguide placed in over-size parallel-plate waveguide

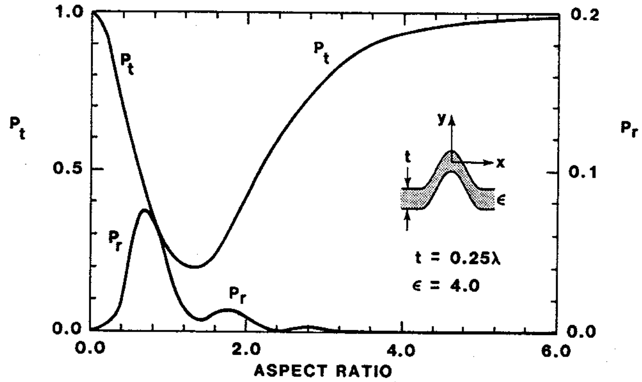


(a)

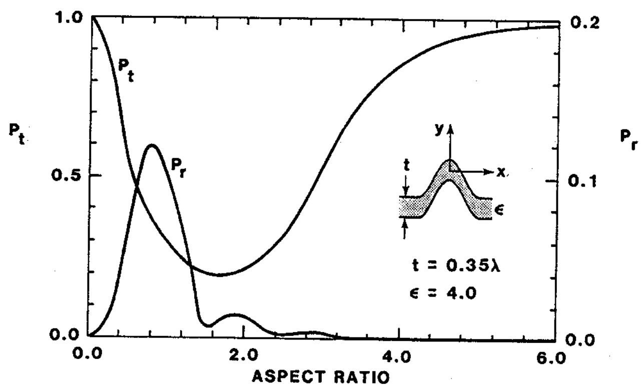


(b)

Fig. 3. Scattered powers of transition waveguide. (a) $t = 0.3\lambda$ and (b) $t = 0.35\lambda$



(a)



(b)

Fig. 4. Scattered powers of waveguide bend. (a) $t = 0.25\lambda$ and (b) $t = 0.35\lambda$