ANALYSIS OF DISCONTINUITIES IN OPTICAL WAVEGUIDES

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ABSTRACT

In this paper we illustrate the solution of diffused channel waveguides, the effect of electrodes for rib waveguides, and calculation of coupling length for a directional coupler problem using the vector H-field finite element method along with infinite elements and a penalty method. We also present solutions of discontinuities for optical waveguides by combining vector finite element method and least square boundary residual methods. Some basic discontinuity steps, such as vertical misalignment, change of width, and change of rib height for rib waveguides are illustrated here.

INTRODUCTION

The finite element method is one of the most powerful and versatile methods for the accurate solution of a wide variety of optical waveguide problems [1-3]. This method is capable of considering waveguide with arbitrary cross-section and material distribution in the transverse plane, where most of the alternative methods are unable to handle such a general problem. A vector H-field formulation considers truly hybrid mode without any fundamental approximation and can tackle general anisotropic materials like $LiNbO_3$, only limited in being lossless. Earlier we have introduced infinite elements [4] to extend the problem domain up to infinity without introducing artificial boundary walls, which is very useful for open type optical waveguides. We have also used a penalty method [5] to force divergence free field conditions to eliminate spurious solutions and improve eigenvectors quality. We are here presenting a novel technique to solve such a wide variety of discontinuity problems - by combining the vector H-field finite element method to solve for eigenvalues and eigenvectors of many modes with field matching at the discontinuity plane, which is done by accurate least square boundary residual method. In this paper we are also presenting the analyses of a few types of the basic discontinuities involving rib waveguides.

FINITE ELEMENT METHOD

In the finite element method we first discretise the entire problem domain into a finite number of triangular subregions, called elements [4]. For our H-field formulation the field functions H_x, H_y, and H_z are defined by a set of polynomials over each element in the transverse plane. In the original variational form [4] it finds the stationary solution for the frequency for a given propagation constant. The vector program can also be switched to the approximate scalar TE or TM mode solution for the convenience of faster and more automatic solution.

Infinite Elements

We have used infinite elements around the orthodox finite domain boundary. Inside these infinite elements we consider exponential decay in outward directions to represent field components that are continuous functions over the whole unbounded cross-section. This allows us to use the orthodox (finite) mesh divisions most efficiently. The decay parameters are automatically calculated in the first run of the program and can be used for subsequent refined solutions.

Penalty Method

We have imposed a divergence free constraint on the H-field by using a penalty technique [5,6]. A variable penalty parameter imposes the divergence free constraint in a least-squares sense. This technique does not take any additional computer space, but removes non-physical spurious solutions and improves the eigenvector quality appreciably [5].

Computer Solution

When the extremum functional is minimised with respect to the nodal field components, it generates a set of linear algebraic eigenvalue equations. We have taken advantage of the extreme sparsity of the matrices by storing only the nonzeros of the matrices. We used the efficient subspace iteration technique for sparse matrices, taking advantage of the symmetry of the transformed real matrices.

LEAST SQUARE BOUNDARY RESIDUAL METHOD

For the calculation of scattering coefficients from a junction of dissimilar waveguides we have used the least square boundary residual method [7,8] which matches field continuity conditions over the junction plane in a least square sense. This powerful method provides guaranteed convergence and minimises the error in a global sense. We can consider as many modes as we wish in both sides of the discontinuity plane. Then this method provides the amplitudes of all the modes propagated or radiated, transmitted or reflected, so as to have the least error in matching the continuity conditions of the fields over the junction plane.

Discontinuity Solution

The vector finite element method is used to calculate as many modal eigenvectors as we wish to consider on both sides of the discontinuity plane. Here the modal eigenvectors are the three components of the H-field at all the nodal points of each "element". We calculate for E and H the field cross products [8] between different modes by integrating over all elements numerically. Finally a Singular Value Decomposition subroutine calculates the stationary solution of the modal coefficients to have the least error in matching the field continuity conditions over the junction plane.

RESULTS

Waveguide Solutions

In this part we have shown the capabilities of the finite element method by presenting solutions for different types of optical waveguides and devices.

a) Diffused channel waveguide: In this we illustrated the solution of diffused channel waveguide. For this example we considered the Gaussian y-dependence of refractive index, although different types of diffusion in both the transverse directions is possible. The refractive indices at the guide top, bulk substrate, and cladding are 2.2913, 2.2853, and 1.0 respectively. Fig.1 shows the variation of normalised propagation constant, b (or V of ref. 1), for the H^y_{11} and H^y_{21} modes for different guide width, when the diffusion depth was 2.47 μm. It shows that for W= 3μm, single mode operation was for wavelength between 0.52 to 0.86 μm. When the guide width increased to 6 μm this range changed 0.75 μm to 1.0 μm. Similarly when the guide width was decreased to 2 μm then single mode operation was for λ from 0.40 μm to 0.76 μm. It is not shown here, but when we have changed the diffusion depth to 3 μm then single mode operation was between λ=0.555μm to 0.95 μm for W= 3μm.

b) Effect of electrode: In this section we have illustrated the effect of an electrode above or below a rib waveguide. In this example we have considered that the bottom electrode extends under the whole substrate but the top electrode is only above the rib and supported on a buffer material. For this example we have considered the guide, substrate, and cladding refractive indices were 3.44, 3.434, and 1.0 respectively, where the buffer refractive index was varied. The rib was 5 μm wide and 1 μm high, the guide slab was 2.0 μm thick and the operating wavelength was 1.15 μm. Fig. 2 illustrates the effect of the position of the two electrodes on the normalised propagation constant, b, for both H^x_{11} and H^y_{11} modes. As the electrodes are placed close to the rib top or bottom of the guide slab, b for the H^x_{11} mode increases, whereas for H^y_{11} mode b decreases. The effect of the electrode is also to increase the magnitude of the H_x field at the electrode location for H^x_{11} mode but forces the H_y field to zero for the H^y_{11} mode. In the above example the buffer refractive index was 3.434. Fig. 3 illustrates the effect of the top electrode position for the H^x_{11} mode for different buffer materials. As the buffer refractive index decreases, magnetic field above the guide also decreases, thus reducing the effect of electrode placement.

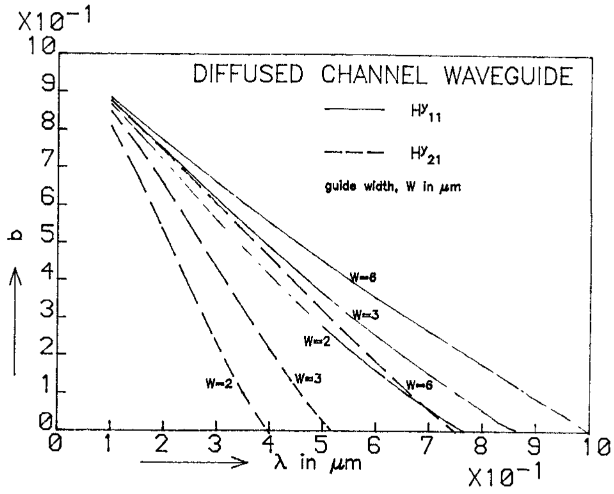

Fig.1 Single mode operation of diffused channel waveguides.

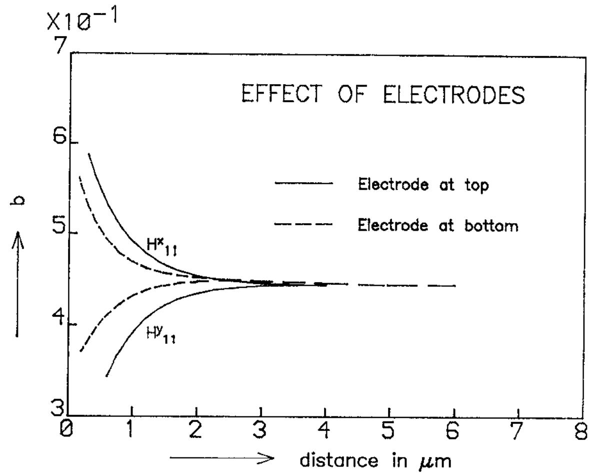

Fig.2 Effect of top and bottom electrodes for a rib waveguide for H^x_{11} and H^y_{11} modes.

c) Directional coupler: In this section we have presented the analysis of a directional coupler problem. Here the separation distance, s, between two identical rib waveguides are varied. In this example the guide, substrate and cladding refractive indices were 3.41, 3.3, and 1.0 respectively. The rib was 4 μm wide and 0.1 μm high and the guide slab was 0.6 μm thick. Fig. 4 shows the variation of the coupling length between the guides with the separation distance, s, for two different wavelengths 1.15 μm and 1.3 μm.

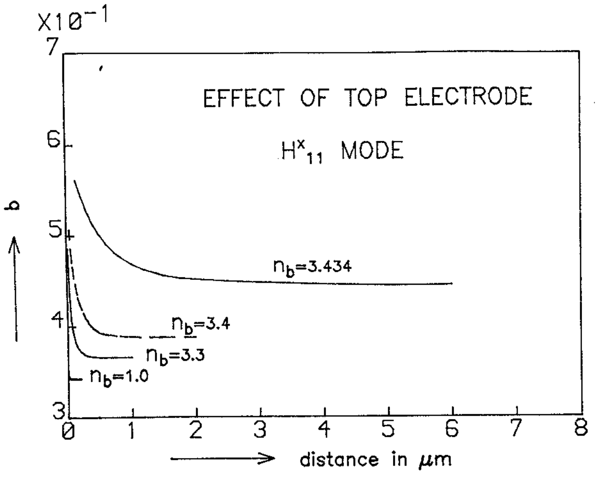

Fig.3 Effect of top electrode for different buffer refractive indices for H^{x}_{11} mode.

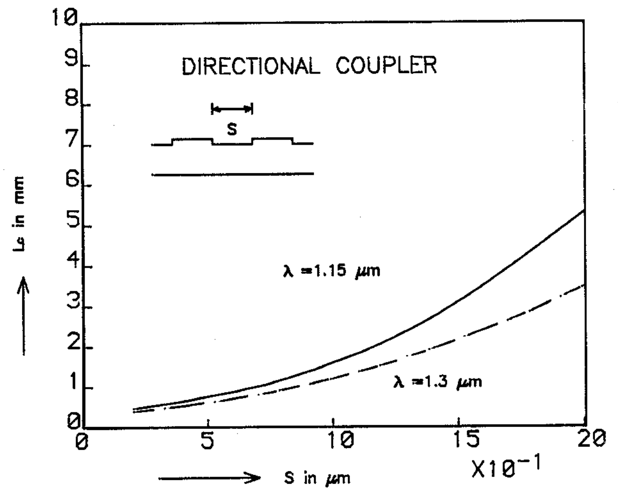

Fig.4 Variation of Coupling Length, Lc with guide separation, s, for a rib directional coupler.

Discontinuity Solutions

a) Vertical misalignment: In this section we have considered two identical rib waveguide joined together with a vertical misalignment. For this example, guide, substrate, and cladding refractive indices were 3.4406, 3.4145 and 1.0 respectively. The ribs were 20 μm wide and 5.0 μm high, the guiding slabs were 0.5 μm thick and the operating wavelength was 1.55 μm. These multimode guides can support about 44 in total of quasi TE and quasi TM modes with different x and y dependences. In this example we have considered that H^{y}_{11} mode of unit power amplitude is incident from side 1. At the discontinuity plane many modes are generated to satisfy the boundary conditions and they are propagated or radiated away from the junction. Fig. 5 illustrates the variation of amplitudes of the transmitted H^{y}_{11} mode, and generated and transmitted H^{y}_{12} and H^{y}_{13} modes with the vertical misalignment.

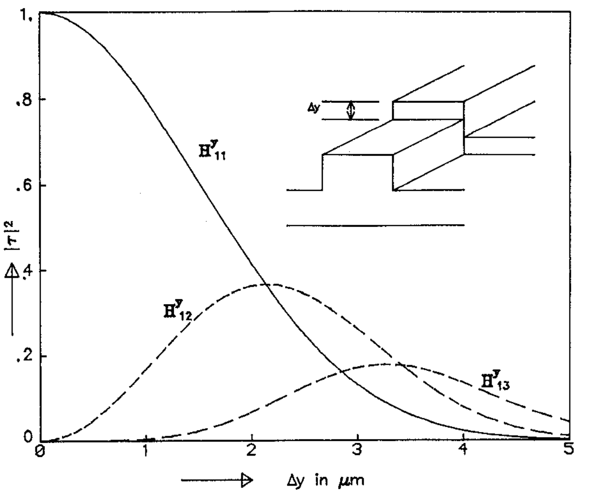

Fig.5 Vertical misalignment between two identical rib waveguides.

b) Change in width: In this section we have considered two guides differing in width which are joined together. In this example we have considered guide, substrate, and cladding refractive indices were 3.4406, 3.4145, and 1.0 respectively. Rib heights were 1.0 μm, guiding slab thicknesses were 0.5 μm and the wavelength was 1.55 μm. An H^{y}_{11} mode of unit power was incident from side 1, its width kept fixed (in this example either 20 μm or 12 μm). Fig. 6 illustrates the variation of the power transmitted in side 2 by the H^{y}_{11} mode with the change in width of side 2. Extension of this type of problem by considering many successive changes in width, we can analyse taper optical waveguide or a bend section.

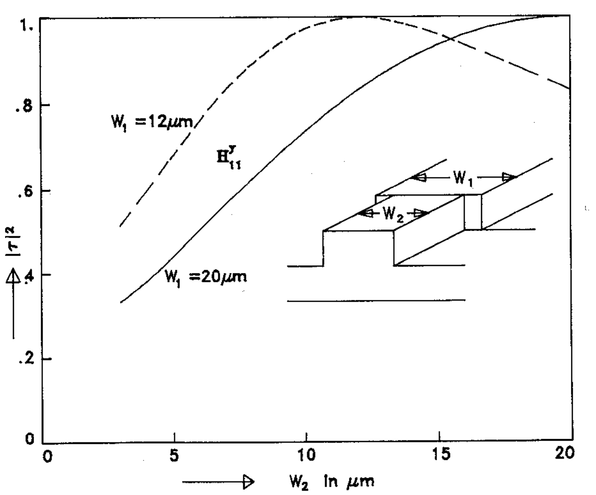

Fig.6 Change in width between two rib waveguides.

c) Change in rib height: In this section we have considered junction between two rib waveguides where rib heights were not the same. Here the guide, substrate and cladding refractive indices were 3.44, 3.434 and 1.0 respectively. The rib widths were 5.0 μm, guide slab thicknesses were 2.0 μm and wavelength considered was 1.15 μm. In this example we have considered the H^x_{11} mode of unit power incident on the discontinuity plane from side 1 where rib height was fixed as 1.0 μm. Fig. 7 illustrates the variation of power transmitted by the H^x_{11} mode in side 2 with the change of rib height in side 2. Extension of this type of problem by considering a periodic change of rib height may represent gratings or optical filters.

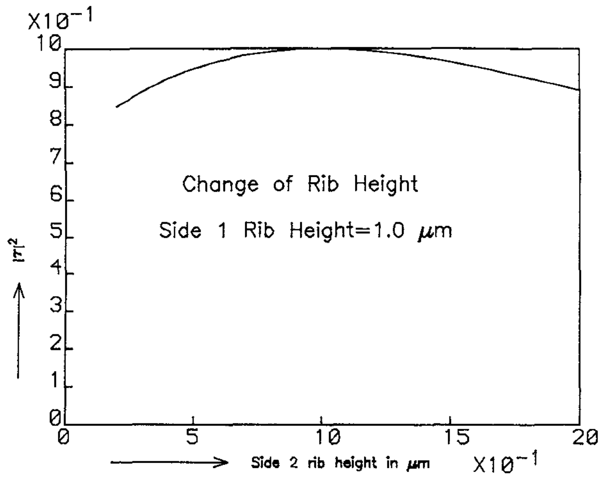

Fig.7 Change of rib height between two rib waveguides.

CONCLUSION

In this paper first we have illustrated vector H-field finite element solutions for a few optical waveguides. This method, taken along with infinite elements and the penalty method is suitable for a wide varieties of optical waveguides [1,3]. Previously we have also considered [1] waveguides where the guide axes were not the same as the optical axes. For the directional coupler problems the guides may not be symmetric or identical. It is possible to extend this method to analyse electro-optic devices. Guides with small loss can be analysed by a perturbation technique or for guides with considerable loss (or gain) by changing the variational formulation to a suitable one. Combining all these techniques with finite element method we may be able to analyse more complicated optical devices such as lasers or electro-optic switches and modulators.

In this paper we have also illustrated the analyses of different types of discontinuities between two rib waveguides, but this technique can be equally applied to all types of optical waveguides such as diffused channel waveguide or optical fibres. Also the discontinuity may not be a single type such as vertical or horizontal or longitudinal misalignment but any combination of them or two totally different types of guides or devices. Similarly there may not be a single discontinuity step but multiple steps, irregular or periodic. Combining all these capabilities, it may be possible to analyse a wide varieties of structures from the simple design of an optimum guide coupler to devices such as tapers, bends, y-junctions, gratings or filters.

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