THEORY AND APPLICATIONS OF THE BEAM PROPAGATION METHOD

Lars Thylén
Ericsson Telecom, S126 25 Stockholm, Sweden

INTRODUCTION

The beam propagation method [1,2] has been extensively employed in recent years to model various guided wave structures. This method involves an operator solution of the Hemholtz equation (or of this equation in the Fresnel approximation) which has the advantageous property that it gives a unified treatment of guided and radiation modes in complex waveguide structures, where the index is also allowed to vary in the propagation direction . Hence, an incident exciting field can be traced through the structure, and important waveguide and device properties can be calculated. These include propagation constants and modal fields[3,4], loss (e g due to bends) [5], crosstalk in switches[6], switching voltage in electrooptic devices[7], coupling efficiences as well as gain and attenuation in media with gain or loss[8]. This makes the method ideally suited for simulation of integrated optics devices[9,10]. However, the method is only applicable in cases with limited transverse spatial frequency bandwidth of index profiles and field (paraxiality requirements) as well as limited index steps [11,12].
This paper reviews the theory of the beam propagation method (BPM), its limitations and some typical applications. Possible extensions are mentioned.

THE BEAM PROPAGATION METHOD: THEORY AND LIMITATIONS

The beam propagation method implements an operator solution of the Helmholtz equation; the most convenient derivation relies on the Fresnel approximation of this equation:

$$2ik_0n_0 \cdot \frac{\partial E}{\partial x} + \nabla\perp^2 E + (n^2k_0^2 - n_o^2k_0^2) \cdot E = 0 \tag{1}$$

The formal operator solution expresses the field E at $z = z_0 + \Delta z$ in terms of that at $z = z_0$, hence no reflections can be taken into account in this formulation.

$$E(z + \Delta z) = P \cdot Q \cdot P \cdot E(z) \tag{2}$$

where E is a slowly varying field envelope in the total field expression: $E(z) \cdot exp(ik_0n_0z)$, n_0 being an average index in the structure. Further:
$P = exp[-i\nabla\perp^2\Delta z/(4k_0n_0)]$, $Q = -i \cdot \Delta z k_0 \delta n$, $\nabla\perp^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$, $n(x,y)$ is the index profile as a function of the transverse coordinates and possibly z and $\delta n = n(x,y) - n_0$.
P can be viewed as a propagator operator in homogeneous medium, Q as a phase transformer ('thin lens'). In this derivation, the Fresnel formalism implies that we are limited to situations where paraxial conditions prevail, one can furthermore[11] show that the spatial frequency contents of the index profile and the field give conditions on the step size Δz in the sense that higher transverse spatial frequencies imply shorter steps and more timeconsuming calculations. No conditions on index steps are given in the Fresnel approximation (cf ref 11). Since the BPM as derived here rests on the scalar wave equation the polarization properties of large index steps cannot be taken into account. This feature, together with the inability to treat nonparaxial situations are the main limiting factors of the BPM. (Different polarizations can be handled by a modification of the above the formalism, at the expense of introducing high spatial frequency components). Indeed, for an important case such as a channel waveguide in $LiNbO_3$, the TM-modes are not accurately modeled by the above formalism; the TE-modes are better approximated

due to the smallness of the crossterm $\nabla n \cdot E$ for this polarization.Various techniques to treat the large index step at the waveguide/air interface have been proposed: Waveguide symmetrization [10], effective index method [9]. The former method, however, neglects the polarization dependence, whereas the effective index method yields different profiles for the different polarizations. Indeed, the combination of the BPM with the effective index metod has the desirable properties that it combines a reduction of the dimensionality (giving increased computational efficiency) with a polarization dependence, this combination has been extensively used in the litterature, and fig 1 shows a flowchart for a typical procedure for device simulation. This type of simulation was used in develpoing the switch matrix of ref 13. It should also be mentioned that an extension of the BPM to accurately treat large index steps has been given in ref 12, however, with large increase in the computational requirements.
The BPM has also been extended to media exhibiting linear [14,15] as well as circular birefringence [16], enabling modelling of polarization conversion in e g $LiNbO_3$ and GaAs devices.

SIMULATION RESULTS

The formalism outlined above can be employed to a number of integrated optics devices , eg directional couplers, interferometers, 'BOA'-type structures, x-switches, gratings, polarization converters, waveguide branches etc. As mentioned, the great advantage of the BPM is that it allows one single tool to be used for the analysis of all these structures, rather than employing the variety of different methods that have been developed. A few representative examples are shown here. Fig 2 depicts the field evolution in an x-switch [6,7], with and without applied voltage, the figure shows how the applied voltage brings about a variation of the period of inteference between the "supermodes" of the switch, resulting in switching. Another example is shown in fig 3, where the loss in an X-switch is calculated, evaluating the effective index profile at each step. Since radiation modes are included (both their excitation and recapture by the wavegudie) this calculation should be more accurate than other methods, such as those relying on local normal modes. Note the difference to ref 6, due to different modelling of the index of the crossover region. Also shown is the spatially varying effective index profile.
Fig 4 shows a BPM calculation on the "digital switch"[17], in an X-cut $LiNbO_3$ structure with equal input and output angles of 1.25 mrad. The field evolution is shown for 0 applied volts and for the switched state. The deviation from digital behaviour is easily determined, as are the losses as well as the switching voltage in relation to other switch types.

SUMMARY

The beam propagation method constitutes a versatile instrument for the simulation of guided vawe devices, provided its limits in applicability are observed. The method as presented above is scalar and limited to paraxial situations. Hence, it cannot handle important cases such as the polarization properties of interfaces with large index steps. One solution to this problem is to use the BPM with the effective index method. Thus, it would be interesting to compare the BPM+effective index method with eg FEM-based solutions to assess the accuracy of the BPM. Another problem with the effective index method in this case (which is not per se associated with large index steps), is that the effective index method is not likely to accurately model depth variations in channel waveguides, hence the loss calculations for e g Y-junctions as well as for the X-switches given above are somewhat uncertain. In principle, these cases can of course be treated by using the full 3D BPM, however, with a siginificant increase in cumputer time. A simple BPM type formalism for solving the vector wave equation is a very interesting research

topic.
The talk will further discuss the BPM applied to TM modes and to anisotropic media.

REFERENCES

1. J A Fleck, J R Morris, M D Feit, Appl Phys, vol 10, (1976), 129

2. M D Feit, J A Fleck: "Light propagation in graded-index optical fibers", Appl Opt, vol 17, (1978), p 3990

3. M D Feit, J A Fleck, "Computation of mode eigenfunctions in graded index optical fibers by the propagating beam method", Appl. Opt, vol 19, (1980), p 2240

4. D Yevick, B Hermansson, "New approach to lossy waveguides", Electron. Lett., vol 21, (1985), p 1029

5. J Saijonmaa, D Yevick, "Beam propagation analysis of loss in bent optical waveguides and fbers", J Opt Soc Amer., vol 73, (1983), p 1785

6. A Neyer, W Mevenkamp, L Thylén, B Lagerström, "A Beam Propagation Method Analysis of Active and Passive Waveguide Crossings", IEEE J Lightwave Techn., vol LT-3, (1985), p 635

7. A Neyer, "Electro-optic x-switch using single mode $Ti : LiNbO_3$ channel waveguides", Electron. Lett., vol 19 (1983), p 553

8. C J Setterlind, L Thylén, "Directional Couplers with Optical gain", IEEE J Quantum Electron., QE-22, (1986) p 595

9. L Thylén, B Lagerström, P Svensson, A Djupsjöbacka, G Arvidsson, "Computer analysis and design of $Ti : LiNbO_3$ integrated optics devices and comparison with experiments", Proc 9th ECOC , (1983), pp 425-428

10. M D Feit, J A Fleck, L McCaughan, "Comparison of calculated and measured performance of diffused channel-waveguide couplers", J Opt Soc Amer., vol 73, (1983), p 1296

11. L Thylén, "The Beam Propagation Method: An analysis of its Applicability", Opt Quant Electr. 15 (1983) , p 433

12. J Van Roey, J van der Donk, P E Lagasse, "Beam propagation method: Analysis and assessment", J Opt Soc America, vol 71, (1981), p 803

13. P Granestrand et al, "Strictly non-blocking 8x8 integrated optical switch matrix", Electron. Lett., vol 22, (1986), p 816

14. L Thylén, D Yevick, "Beam propagation method in anisotropic media", Appl. Opt., vol 21, (1982), p 2751

15. J A Fleck, M D Feit, "Beam propagation in uniaxial anisotropic media", J Opt Soc Amer., vol 73, (1983), p 920

16. L Thylén, L Swahn, to be published.

17. Y Silberberg, P Perlmutter, J E Baran, "Digital optical switch", Appl. Phys. Lett., vol 51, (1987), p 1230

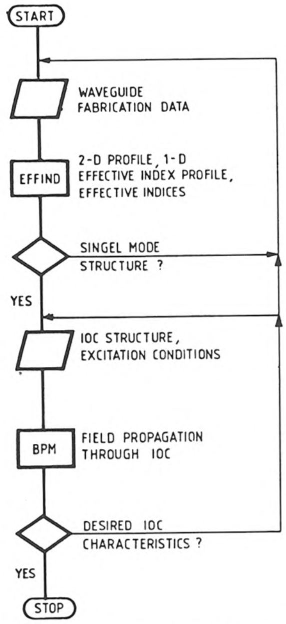

Fig 1: Flow chart for integrated optics circuit simulation and optimization, for analyzing loss, crosstalk, coupling lengths etc. This software could also be interfaced to CAD software.

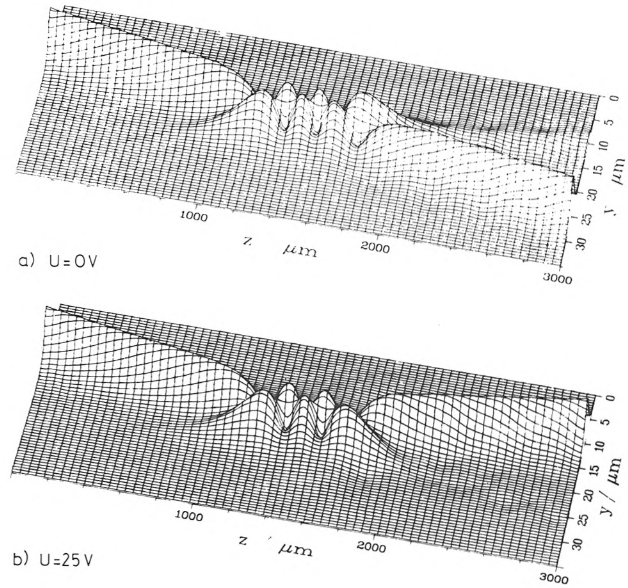

Fig 2: Beam propagation method analysis of the field evolution in an X-switch with no applied voltage (above) and 25 Volts applied (below). Note the change in beat pattern in the waveguide crossover region, effecting the electrooptic switching. Also note some residual radiation in the lower guide in the lower figure.

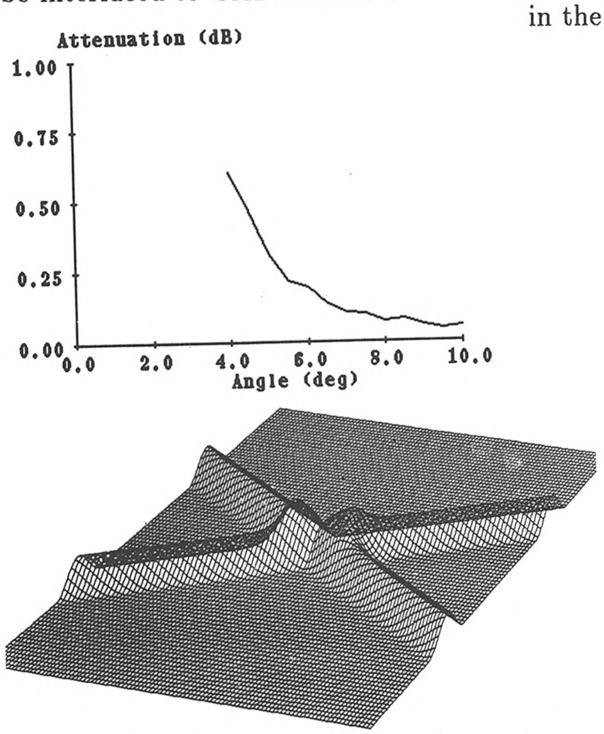

Fig 3: Loss vs intersection angle as well as effective index profile, varying in the propagation direction for an X-crossing; waveguide parameters: diffusion depth: 4.0 μm, max planar index increase: 0.01, titanium stripe width: 6.0 μm.

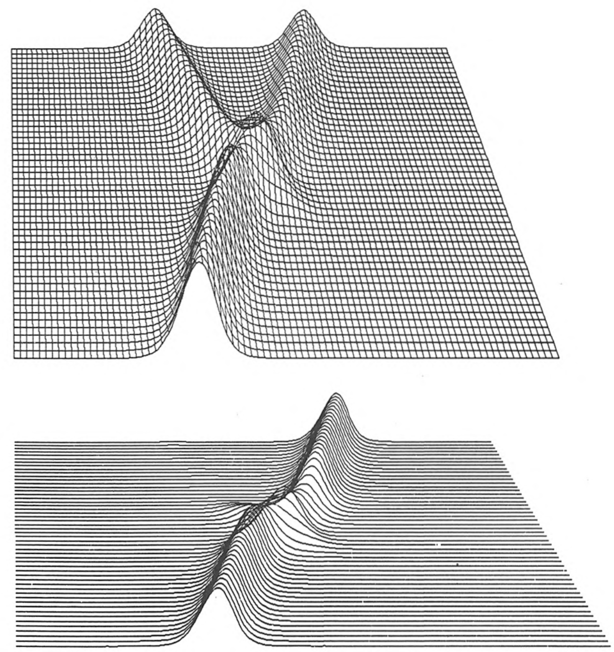

Fig 4: Field evolution in a "digital switch" in X-cut $LiNbO_3$ for an intersection angle of 1.25 mrad, 0 applied volts (above) splits the incident light equally between the output ports whereas 12 volts effects switching.