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THE BEAM PROPAGATION METHOD USED FOR THE DESIGN OF AN INTEGRATED OPTICAL COUPLER

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ABSTRACT

The beam propagation method (BPM) used for the design of an integrated optical (IO) coupler was proposed in this paper. A modal of the IO coupler was set up in BeamPROP software that is based on the BPM, and then the modes and the bi-directional propagation in the proposed coupler were investigated. Finally, the structure and dimension of the coupler was determined.

Keywords: IO coupler, BPM, BeamPROP

1 INTRODUCTION

The techniques for handling both uniform and nonuniform structures include beam propagation method (BPM), the method of lines (MoL) and the coupled mode theory etc [1]. In these techniques, the BPM is the most widely used propagation technique for modelling integrated and fibre optic photonic devices, and most commercial software for such modelling is based on it. This method is conceptually straightforward, efficient, flexible and extensible.

There are already many applications of the BPM to modelling different aspects of photonic devices or circuits, such as passive waveguiding devices [2], channel-dropping filters [3], electro-optic modulators [4], multimode waveguide devices [5,6], ring lasers [7], optical delay line circuits [8,9], novel y-branches [10], optical interconnects [11], polarization splitters [12], multimode interference devices [13,14], abiabatic couplers [15], waveguide polarizers [16], poarization rotators [17] etc. In this paper, the BPM will be used for the design of an integrated optical (IO) coupler.

2 METHODOLOGY

The BPM is a particular approach for approximating the exact wave equation for monochromatic waves and solving the resulting equations numerically. The wave equation can be written in the form of the well-known Helmholtz equation based on the scalar field assumption

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}+k(x,y,z)^2\phi=0 \tag{1}$$

where $\phi(x,y,z)$ is the phase field and it can be obtained by $E(x,y,z,t)=\phi(x,y,z)e^{-i\omega t}$; $E(x,y,z,t)$ is the scalar electric field. The notation $k(x,y,z)=k_0 n(x,y,z)$ has been introduced for the spatially dependent wavenumber, where $k_0 = 2\pi/\lambda$.

Considering that in typical guided-wave problems the most rapid variation in the field ϕ is the phase variation due to propagation along the guiding axis, and assume that axis is predominantly along the z direction, it is beneficial to factor this rapid variation out of the problem by introducing a so-called slowly varying field u via the ansatz

$$\phi(x,y,z)=u(x,y,z)e^{i\bar{k}z} \tag{2}$$

where $\bar{k}$ is a constant number to be chosen to represent the average phase variation of the field ϕ. It is also referred to the reference wavenumber, $\bar{k}=k_0\bar{n}$ ($\bar{n}$ is the reference refractive index). Introducing the above expression into the Helmholtz equation yields the following equation for the slowly varying field

$$\frac{\partial^2 u}{\partial z^2}+2i\bar{k}\frac{\partial u}{\partial z}+\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+(k^2-\bar{k}^2)u=0 \tag{3}$$

At this point the above equation is completely equivalent to the exact Helmholtz equation, except that it is expressed in terms of u. It is now assumed that the variation of u with z is sufficiently slow so that the first term above can be neglected with respect to the second; this is the familiar slowly varying envelope approximation and in this context it is also referred to as the paraxial or parabolic approximation. With this assumption and after slight rearrangement, the above equation reduces to

$$\frac{\partial u}{\partial z} = \frac{i}{2\bar{k}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \left(k^2 - \bar{k}^2\right)u\right) \tag{4}$$

This is the basic BPM equation in three dimensions (3D); simplification to two dimensions (2D) is obtained by omitting any dependence on y. Given an input field, $u(x, y, z = 0)$, the above equation determines the evolution of the field in the space z>0.

3 SIMULATION AND RESULTS

For the proposed IO coupler, single mode and low propagation loss are basic requirements. In order to determine the structure and dimensions of the IO coupler, a modal is set up in BeamPROP software as shown in Figure 1, and then the mode and bi-directional propagation in the IO coupler modal are investigated. In this modal, the proposed IO coupler is designed to be composed of two identical square-cross-section channel waveguides. It is supposed that the coupler divides the light entering one of the input ports about equally over both output ports. The free space wavelength is 1.55μm; the background index is 1.46; the index difference between the core and the claddings is 0.75%; waveguide width is 6μm; the output waveguide pitch is approximately 0.25mm, which is dependent on the chip packaging; the bend radii of waveguide are 5mm, which can ensure that bending loss is very low [18]; the coupling length is 1mm. The size of the whole coupler is proposed to be 12mm×16mm.

3.1 MODE SOLVING

There are several mode-solving techniques based on BPM have been developed. The earliest one is the correlation method, and it was used to calculate modes and dispersion characteristics of multimode fibres [19]. Recently, a technique referred to as the imaginary distance BPM has been developed which is generally significantly faster [20]. In both BPM-based mode-solving techniques a given incident field is launched into a geometry with z-invariant. Since the structure is uniform along z, the propagation can be equivalently described in terms of the modes and propagation constants of the structure. Considering 2D propagation of a scalar field for simplicity, the incident field, $\phi_{in}(x)$, can be expanded in the mode of the structure as

$$\phi_{in}(x) = \sum_m c_m \phi_m(x) \tag{5}$$

Then the propagation through the structure can be expressed as

$$\phi(x, z) = \sum_m c_m \phi_m(x) e^{i\beta_m z} \tag{6}$$

In this paper, the imaginary distance BPM is used. As the name implies, in the imaginary distance BPM the longitudinal coordinate z is replaced by $z' = iz$, so that propagation along this imaginary axis should follow

$$\phi(x, z') = \sum_m c_m \phi_m(x) e^{\beta_m z'} \tag{7}$$

The essential idea of the method is to launch an arbitrary field and propagate the field through the structure along the imaginary axis.

At the input side, a Gaussian pulse of the form $\exp(-x^2 / a^2)$ is used, where $a = w/2$ and w is the width of the input waveguide. The full transparent boundary condition (TBC) is applied to determine the boundary conditions because it effectively lets radiation pass through the boundary and leave the computational domain. Figure 2 shows the mode profile. In Figure 2, the fundamental mode (m=0) has the highest propagation constant, and its contribution to the field has the highest growth rate and dominates all other modes after a certain distance, leaving only the field pattern $\phi_0(x)$. Higher order modes can be obtained by using an orthogonalization procedure to subtract contributions from lower order modes while performing the propagation [21]. Figure 3 shows the mode spectrum. The mode spectrum represents the fast Fourier transform (FFT) of the correlation function. The frequency axis in these graphs is defined by the mode effective index minus the reference index.

3.2 BI-DIRECTIONAL PROPAGATION

If the coupler waveguides have a good uniformity, the loss caused by bi-directional propagation will be small and the guided wave propagation in the proposed waveguides will be very smooth. Various bi-directional BPM techniques have been considered to address backward travelling waves as a separate, though coupled, part of the problem [22], with most focusing on the coupling that occurs through reflection of a wave incident on an interface along z. The guided wave propagation is divided into regions that are uniform along z, and the interfaces between these regions. At any point along the structure it is considered that both forward and backward waves can exist, which are denoted by $u^+(x,y,z)$ and $u^-(x,y,z)$, respectively. In the uniform regions the forward and backward waves are decoupled, while the interfaces between these regions couple the forward and backward waves due to reflection. The essential idea is to employ a transfer matrix approach in which the individual matrices are differential operators [23]. The physical problem generally has the incident (forward) field given at the input of the structure, and the goal is to determine the reflected (backward) field at the beginning and the transmitted (forward) field at the output. The transfer matrix problem, however, is formulated by assuming that both the forward and backward fields are known at the input of the structure, and an overall transfer matrix, M, then describes the system as follows

$$\begin{pmatrix} u_{out}^+ \\ u_{out}^- \end{pmatrix} = M \begin{pmatrix} u_{in}^+ \\ u_{in}^- \end{pmatrix} \tag{8}$$

Given incident field (u_{in}^+), the above is solved iteratively for reflected field (u_{in}^-) such that the backward field at the output is zero (u_{out}^-=0). The transfer matrix M describing the entire structure is composed of successive applications of propagation and interface matrices.

The simulation results of the single and bi-directional propagations are shown in Figures 4 and 5 respectively. It is obvious that the propagation in Figure 5 is not as smooth as the one in Figure 4; there are some drift produced during the bi-directional propagation that is mainly caused by the nonuniform waveguide geometry. Therefore, In order to reduce the influence caused by bi-directional propagation, the waveguides should have a good uniformity.

4 CONCUSIONS

The BeamPROP software based on BPM was used for the proposed IO coupler design. A modal of the IO coupler was built up, and then the modes in the coupler waveguides and the bi-directional propagation were investigated. It was found that only one mode existed in the proposed IO coupler and the bi-directional propagation produced some loss; however, the influence of bi-directional propagation can be reduced if the uniformity of the coupler waveguides is good enough. After carefully considering the application requirements and the simulation results, the dimension and structure of the proposed IO coupler was determined. They were shown in Figures 6 and 7 respectively. The size of the whole coupler was 12mm×16mm; the output waveguide pitch was approximately 0.25mm; the bend radii of waveguide were 5mm; the coupling length was 1mm. The proposed IO coupler was designed to be composed of two identical square-cross-section channel waveguides. The core was doped with Germanium (Ge) while the lower and upper cladding layers were both co-doped with boron (B) so as to realise a low refractive index contrast of 0.75% between the core and cladding layers; the core width and height were both 6μm; the heights of the upper and lower cladding layers were both 15μm.

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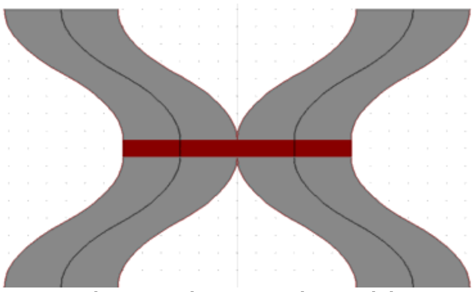

Figure 1: The IO coupler modal

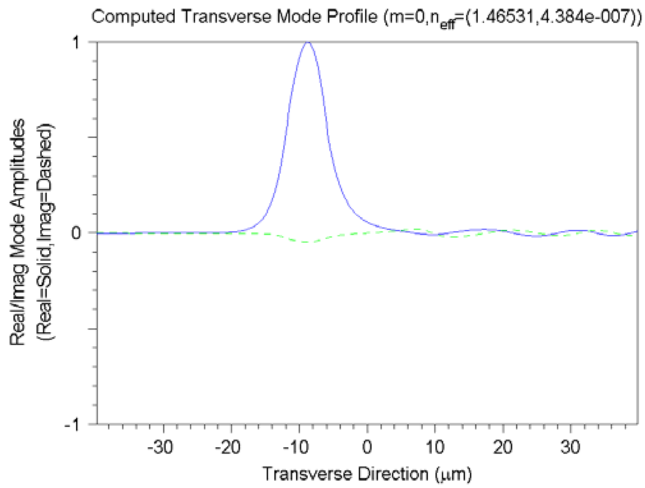

Figure 2: The mode profile

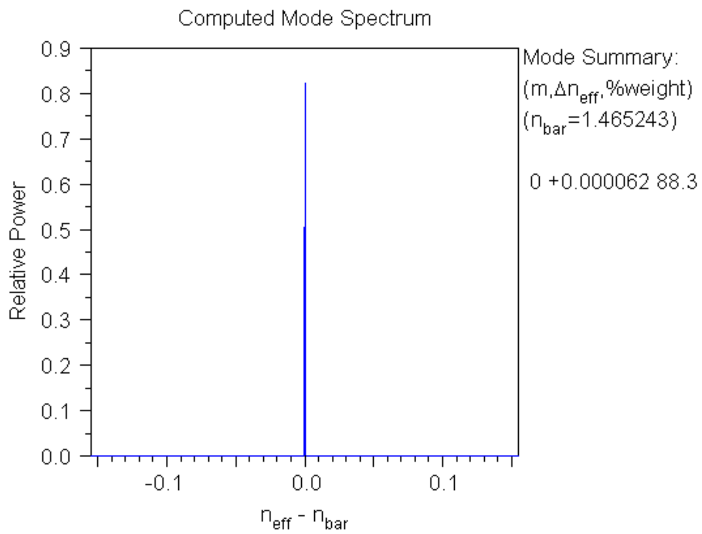

Figure 3: The mode spectrum

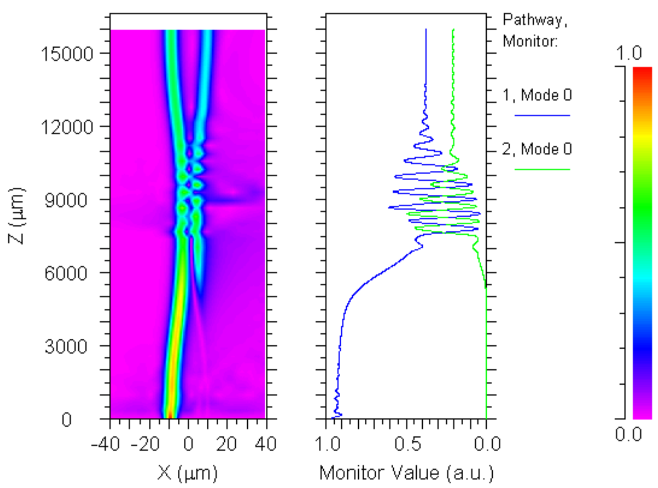

Figure 4: The single direction simulation results

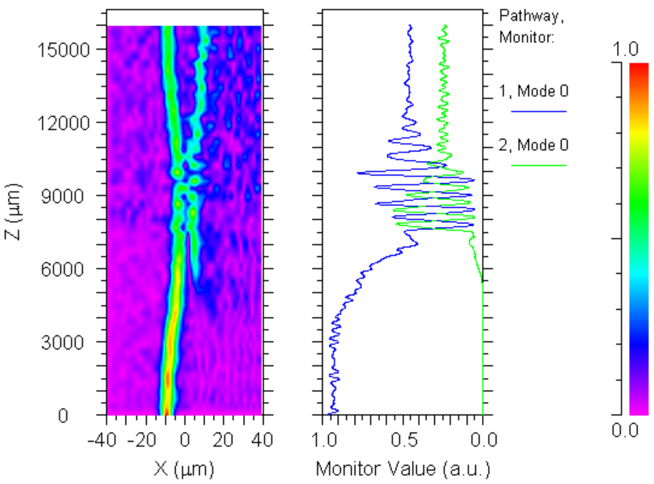

Figure 5: The bi-directional simulation results

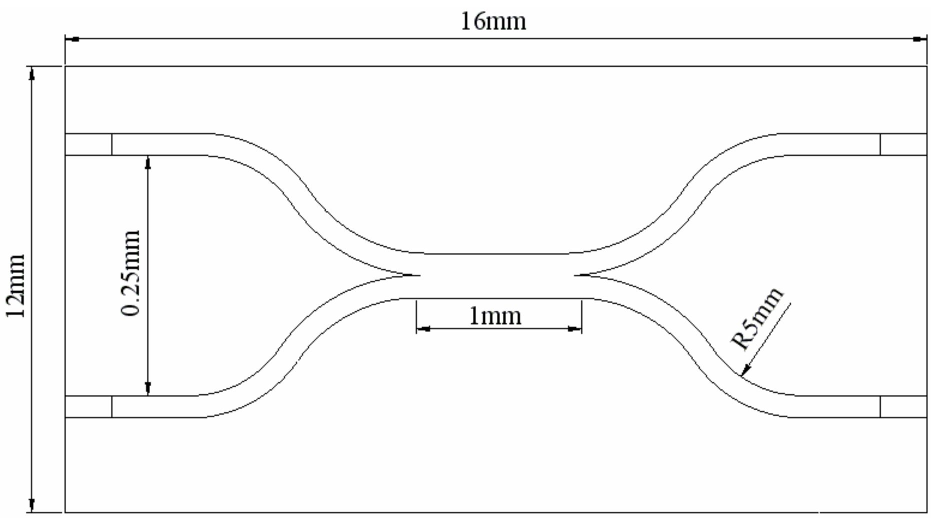

Figure 6: The dimension of the IO coupler

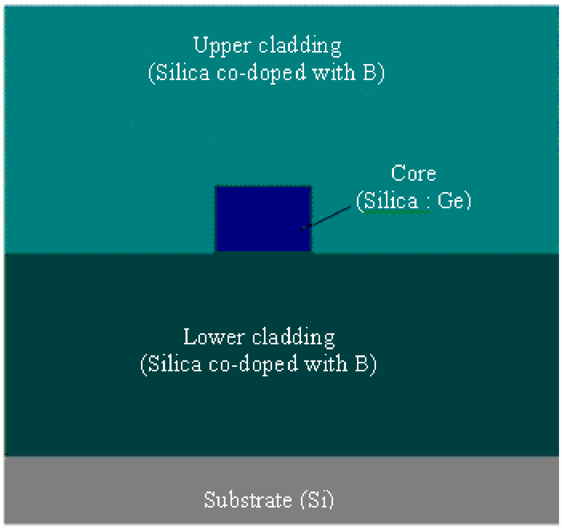

Figure 7: The structure of the coupler waveguide