The Method of Lines Analysis of TE Mode Propagation in Silica based Optical Directional Couplers

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The Method of Lines Analysis of TE Mode Propagation in Silica based Optical Directional Couplers

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Highlights:

- The method of lines was applied to analyze the wavelength dependence characteristics of directional couplers.
- This forward semi numerical and analytical scheme was proven to be a versatile method to simulate simple optical directional couplers.
- To prevent mode back reflection propagating near the computational edge, a special absorbing boundary condition was applied to increase the calculation accuracy.
- The switching characteristics of optical directional couplers were analyzed to show the versatility of the method of lines.

Abstract. Optical directional couplers fabricated using planar light wave circuit (PLC) technology are versatile tools in integrated photonics devices. They have the advantages of small size, high consistency, ability for high volume production, and excellent possibility to be integrated with electronics circuits. Optical waveguide couplers are mainly utilized as power dividers, optical switches, and wavelength division multiplexers/de-multiplexers (WDM). A number of methods have been used to analyze directional couplers, such as coupled mode theory (CMT), the beam propagation method (BPM), the method of lines (MoL), finite-difference methods (FDM) and finite element methods (FEM). Among these numerical approaches, MoL is the simplest method to analyze mode propagation inside directional couplers because it has the advantages of very fast convergence and accurate solutions for one-dimensional structures. The objective of this study was to analyze the propagation of TE modes in optical directional couplers by using MoL. The parameters used, i.e. waveguide width, refractive index and wavelength, were taken from the characteristics of silica-on-silicon directional couplers that were used in fabrication. MoL is considered a special finite-difference method, which discretizes a one- or two-dimensional wave equation in the transverse direction and uses an analytical solution for the propagation directions. Basically, MoL is a semi analytical numerical method with the advantages of numerical stability, computational efficiency and calculation time

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reduction. Further, we explored the possibility of using directional couplers as optical switching devices.

Keywords: *method of lines; absorbing boundary condition, optical directional couplers; optical switch; planar light wave circuits.*

1 Introduction

Optical directional couplers are versatile devices that play a pivotal role in the construction of advanced optical communication networks. They are widely used in a number of passive and active devices in fiber and integrated optics structures, including in modulators, switches, wavelength filters, ring resonators, interferometers, and wavelength division multiplexers/ demultiplexers [1-6]. They consist of two parallel waveguides that are put closely together with a separation distance small enough to let power transfer occur between two modes in two different waveguides through the evanescent field [7]. The light initially launches into the first waveguide. The presence of the second waveguide in close proximity to the first waveguide perturbs the mode inside the first waveguide. This perturbation creates a transfer, or coupling, of energy from the first to the second waveguide, as the light propagates in the z direction. The total power transfer may be obtained if both waveguides are identical [7-12].

So far, a number of effective numerical techniques have been suggested for the analysis of directional couplers. These include finite-difference methods (FDM), finite-element methods (FEM), the beam propagation method (BPM), and the method of lines (MoL). FDM is the oldest numerical method for solving partial differential equations. It is easy to program and to apply to non-homogenous refractive index profiles. This method subdivides the domain into many sub regions, in which the partial derivatives are replaced by finite-difference operators. The set of equations is then solved to obtain the eigenvalues. A drawback of FDM is that it offers less flexibility in the modeling of the domain since the sub regions are normally rectangular in shape. FEM can model intricate domain geometries, where the waveguide cross section is split into surface or volume elements and a polynomial is used to approximate the field in each element interface. Boundary conditions for field continuity are applied on all interfaces between the different elements. Various representations of Maxwell's equations are then employed to obtain an eigenvalue equation matrix form, which is then solved by common methods. This method requires a more complex programming structure and is more demanding in terms of both computer time and memory [13-16].

BPM has been used to analyze various two- and three-dimensional optical devices. The original BPM used a fast Fourier transfer (FFT) algorithm and solved a paraxial scalar wave equation. The fundamental concept of BPM is to signify the field by the plane wave's superposition in homogenous media. The advantages of BPM are that it can be used on an arbitrary cross-section structure and that both guided and radiative waves are included in the analysis. However, since the formulation is derived with the assumption that the variation of the refractive index is negligible in the transverse direction, FFT-BPM cannot be used on structures with large index discontinuities [17-19].

To analyze a general waveguide structure, MoL has been proved to be a versatile tool because it has advantages in terms of convergence rate and the accuracy of the solution for one-dimensional structures. It is a special numerical method combined with an analytical method, where the wave equations are divided into a small area in the transverse direction. The analytical solution is employed in the propagation direction, which results in efficient computer calculation. An exact solution may be achieved because MoL behaves in a stationary way and convergence is monotonic. The discontinuity of the fields may be matched exactly since boundary conditions are inserted at the edges of the calculation window [16]. Additionally, as a numerical scheme MoL can easily be applied in computer calculations. In this study, MoL was used to analyze TE mode propagation in a simple optical directional coupler based on silica-on-silicon structures [16,20]. Further, we give an example of the directional coupler's application as an optical switching device.

2 Research Method

The approach used was to employ MoL to analyze silica waveguide based optical directional couplers that were fabricated using electron beam irradiation [26]. This fabrication method results in a weakly guiding structure, hence the refractive index differences between core and cladding are not very high. The basic data, i.e. waveguide width, waveguide separation, refractive index of core and cladding, were taken from real measurements of the power exchange in the silica based optical directional couplers.

2.1 The Method of Lines

To analyze the silica based directional coupler arrangement, we built an appropriate numerical model considering a coupler constructed by two parallel waveguides with constant thickness and gap, as shown in Figure 1. It was assumed that both guides were weakly guiding and single moded; the width and separation of the two guides were constant so that the amplitudes changed slowly with propagation distance. For the TE mode case, E_y is the only available electric field component. For the analysis we therefore started with the following scalar equation [20-22]:

$$\nabla^2 E_y(x,z) + k_o^{\,2} n^2 E_y(x,z) = 0 \qquad (1)$$

here n is the refractive index distribution forming the waveguide and k_o is the wave number, i.e. $2\pi/\lambda$, where λ is the optical wavelength. To solve Eq. (1) by using MoL, the structure to be analyzed is divided into small elements of Δx in the transverse x direction, as shown in Figure 1.

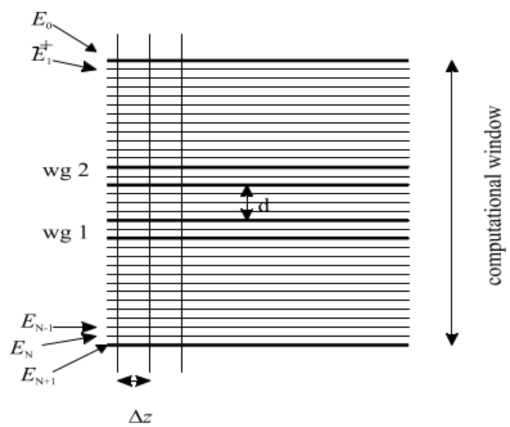

Figure 1 MoL discretization scheme used for the example of a directional coupler.

For the second derivative term, d^2E/dx^2, the following approximation was used [14,16]:

$$\frac{d^2E}{dx^2} \cong \frac{E_{i+1} - 2E_i + E_{i-1}}{\Delta x^2} \qquad (2)$$

Then Eq. (1) decreases to a set of differential equation in matrix form:

$$\frac{d^2\vec{E}}{dz^2} + \vec{Q}^2\vec{E} = 0 \qquad (3)$$

where $\vec{E} = [E_1, E_2, E_3, \ldots\ldots, E_N]^t$ is a transpose column vector consisting of discretized quantities of the $E(x)$ field at points $x_1, x_2, \ldots. x_N$.. Q is a matrix consisting of diagonal elements $n_1^2, n_2^2, \ldots.n_N^2$ representing the dielectric constant distribution of the waveguide at points $x_1, x_2, \ldots. x_N$.. In Eq. (3) there appears the tridiagonal structure of matrix $\vec{Q}$, which consists of three components that are coupled with each other so a simple analytical solution cannot be achieved. Therefore, the $\vec{Q}$ matrix needs to be transformed so that:

$$\vec{\beta} = \vec{T}\vec{Q}\vec{T}^{-1} \tag{4}$$

and

$$\overline{E} = \vec{T}^{-1}\vec{E} \tag{5}$$

where $\overline{E}$ is the transformed field vector, $\vec{T}$ are the eigenvectors of matrix $\vec{Q}$ arranged in columns, and $\vec{\beta}$ are the eigenvalues of $\vec{Q}$ in diagonal matrix form. If this is done, the wave Eq. (3) can be written as a diagonalized equation of the form [21]:

$$\frac{d^2\overline{E}}{dz^2} + \overline{\beta}^2\overline{E} = 0 \tag{6}$$

If $\vec{\beta}$ is a constant matrix, i.e. if the structure is invariant in the z direction, a solution to Eq. (6) may be obtained in the following form [20-22]:

$$\overline{E} = e^{-j\overline{\beta}z}\overline{a} + e^{j\overline{\beta}z}\overline{b} \tag{7}$$

Here, the two terms describe forward and backward going waves, whose amplitudes are described by the vectors $\overline{a}$ and $\overline{b}$, respectively. If no back-reflected waves occur (such as in a straight lossless waveguide), Equation (7) may be written as:

$$\overline{E} = e^{-j\overline{\beta}z}\overline{a} \tag{8}$$

To obtain the field in the original domain, we use Eq. (5) to invert Eq. (8). For an input field $\vec{E}_{inp}$ the result is:

$$\vec{E} = \vec{T}e^{-j\vec{\beta}z}\vec{T}^{-1}\vec{E}_{inp} \tag{9}$$

Eq. (9) represents the solution for a mode transmitting in the $+z$ direction. Finally, the mode powers remaining in the optical core at a certain point z can be computed by using the overlap integral as [24]:

$$P(z) = \left| \int_{-\infty}^{\infty} E(x,0)E(x,z)dx \right|^2 \tag{10}$$

Here $E(x,0)$ and $E(x,z)$ are the initial and the output fields at point z respectively.

2.2 Boundary Condition

In computational calculations using a numerical method, the computational window needs to be restricted; therefore the field values near the boundaries have to be altered as if the computational window appears to extend infinitely. If there are no truncation conditions, the radiation fields will bounce back from the calculation border and enter the computational window, leading to a standing wave pattern that interferes with the final result. To overcome this, a slightly different absorbing boundary condition (ABC) is introduced [22,23]. The most common method of defining an ABC is based on the factorization of the wave equation. To begin with Eq. (1) is rewritten as:

$$LE = (D_z^2 + D_x^2 + k_0^2 n^2)E = 0 \quad (11)$$

where :

$$D_x^2 \equiv \frac{\partial^2}{\partial x^2}, \quad D_z^2 \equiv \frac{\partial^2}{\partial z^2}$$

The operator L is then divided into part L^+ and L^- as inbound and outbound mode respectively, as described in [22], so that:

$$LE = L^+ L^- E = 0 \quad (12)$$

Here the terms L^+ and L^- are given by :

$$L^{\pm} = D_x \pm j\sqrt{\varepsilon}\sqrt{1+S^2}\ \text{, here}\ S^2 = \frac{D_z^2}{\varepsilon} \quad (13)$$

and:

$$\varepsilon = k_0^2 n^2$$

If we want to prevent wave reflection at both edges of the computational window, only outbound waves are allowed at that point. It can be shown that the field must then described by [23]:

$$L^- E = 0 \quad (14)$$

for the mode propagating in the $-x$ direction, and

$$L^+ E = 0 \quad (15)$$

for the mode transmitting in the $+x$ direction. Suitable absorbing boundary conditions will be obtained from these two equations. However, the existence of a radical in Eq. (13) prevents direct calculation of Eq. (12). Therefore, to implement ABC an approach to simplify the radical using algebraic approximation is needed. The radical may be approximated as [22,23]:

$$\sqrt{1+S^2} \approx p_0 + p_2 S^2 \tag{16}$$

where, the coefficients p_0 and p_2 need to be chosen according to the method of interpolation [23]. However, the values $p_0 = 1$ and $p_2 = 0.5$ are usually utilized. Eqs. (12), (13) and (16) are employed to find the field factors E_0 and E_{N+1} at the computational border of the discretized field at the computational edge in the upper and the lower sections, as shown in Figure 1. By using some algebraic operation it can be shown as follows [23]:

$$E_0 = -a_u E_1 + b_u E_2$$

$$E_{N+1} = b_l E_{N-1} - a_l E_N \tag{17}$$

where the coefficients a_p and b_p are given by:

$$a_p = \frac{2+n_d^2}{1+jn_d},$$

$$b_p = -\frac{1-jn_d}{1+jn_d} \quad (18)$$

with $n_d = \Delta x \varepsilon_p^{1/2}$ and $p = u,l$, where u and l represent the computational edges in the upper and lower sections, respectively.

2.3 Optical Switching Mechanism

One interesting application of optical directional couplers is as switching devices, which is a key component in optical communication systems. Currently, many switching technologies are available with very reliable operational mechanisms, such as electro-optic effects [1,2], thermo-optic (TO) effects [3,4], and mechanical means [6]. One reliable technology for optical switching waveguides is Ti-diffusion in $LiNbO_3$, where electro-optic effects are used. Today, switched directional couplers based on $LiNbO_3$ devices are commercially available. However, they are polarization sensitive and expensive, while the main benefit of such devices is that they can operate very fast, in the sub-nanosecond regime.

3 Numerical Results

The propagation of modes inside the coupling area is highly governed by the waveguide parameters, i.e. effective refractive index of waveguides structures, wavelength and separation distance between the two cores. However, the condition where two waveguides are initially isolated will be disturbed by the presence of a second adjacent waveguide. If both waveguides are closely separated, then the evanescent field starts to transfer to the second waveguide, which leads to power exchange from waveguide core 1 to waveguide core 2.

The parameters used in the simulation are typical of silica-on-silicon slab waveguide devices and were taken from experiments. Following [20], we used a substrate refractive index of $n_s = 1.460$ and an index different of 5×10^{-3}. A core guide width of $h = 4.5\ \mu m$ and a wavelength of $\lambda = 1.55\ \mu m$ were also used. To implement the method, the eigenvalues and eigenvectors of matrix Q were first calculated numerically using Eq. (4). For the eigenvalues, the result was in the range of discretised values of β, as shown schematically in Figure 2. The single-mode guided propagation constant is then the maximum value of β, which lies between the values $k_o n_2$ and $k_o n_1$.

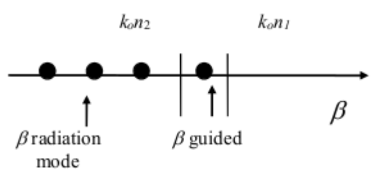

Figure 2 Discretized values of β obtained by the method of lines, including radiation propagation constants.

Figure 3 demonstrates the effective refractive index as a function of wavelength for a straight dielectric waveguide. The solid line signifies solutions of the eigenvalue equation, while the circle points were obtained from the MoL calculation. In this calculation, parameter values typical of the silica-on-silicon waveguide as mentioned above were used again. Both solutions had excellent similarity between the MoL numerical and the exact analytical results. This shows that the MoL theory can be used as an excellent tool to calculate planar waveguide geometry [4].

Figure 4 demonstrates the power transfer propagating between modes inside two waveguides along the coupling length directional coupler for three different refractive index values. It shows the power transfer between the modes in the two waveguides as an oscillatory function of propagation distance. As the refractive index difference increases, coupling occurs at longer length; this is because the modes are strongly confined inside the waveguides and the evanescent field inside the core tends to be very small, and therefore longer coupling lengths are needed to exchange power between the two waveguides.

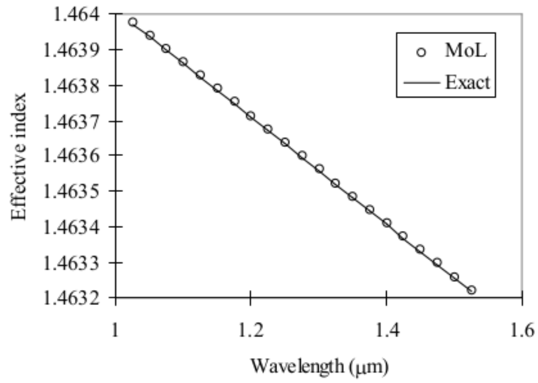

Figure 3 Effective index refraction of a planar waveguide computed by MoL and by solution of the analytical equation.

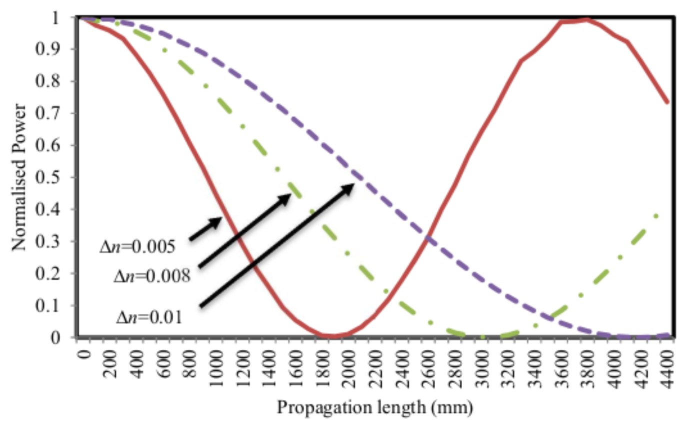

Figure 4 Power transfer as a function of propagation distance with different refractive index changes.

Figure 5 demonstrates the variation of normalized power with propagation distance for three different wavelengths; again, the output is transferred between the two guides in an oscillatory manner. The same as in Figure 4, as the wavelength becomes longer, the coupling length gets shorter. This is because for a longer wavelength the mode tends to spread further into the cladding, creating larger evanescent fields and shorter coupling lengths. Similar power transfer characteristics can also be obtained by using CMT. A comparison of the power transfer results obtained using CMT and MoL was done in [8] with slightly different structures, however both theories agree very well.

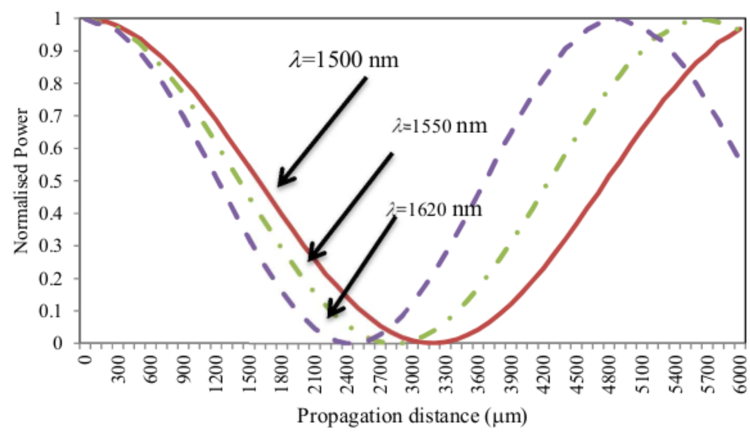

Figure 5 Power transfer as a function of propagation distance with different wavelengths.

Figure 6 demonstrates the power exchange along the propagation distance; power is plotted in a three-dimensional representation. In this case, different parameters were used, with a substrate refractive index of $n_s = 1.460$ and an index different of 1x 10^{-2}. A core guide width of $h = 4.0$ μm and a wavelength of $\lambda = 1.55$ μm were also used. The input power was inserted into the left-hand waveguide and was gradually coupled into the right-hand guide. In this example, full power transfer was obtained after propagation over a distance of 8445 μm.

An important application of a directional coupler is in optical switches. In this case, as shown in Figure 6, energy launched into one waveguide will totally transfer to the other guide. This condition is referred to as the coupled state. If by some means we can now introduce a finite difference between the two guides, the power will instead emerge from the first guide. This condition is referred to as the straight-through state. By varying the refractive index electrically we can switch the light energy from one waveguide to the other. This phenomenon is the basic principle behind the optical directional coupler switch [9-12].

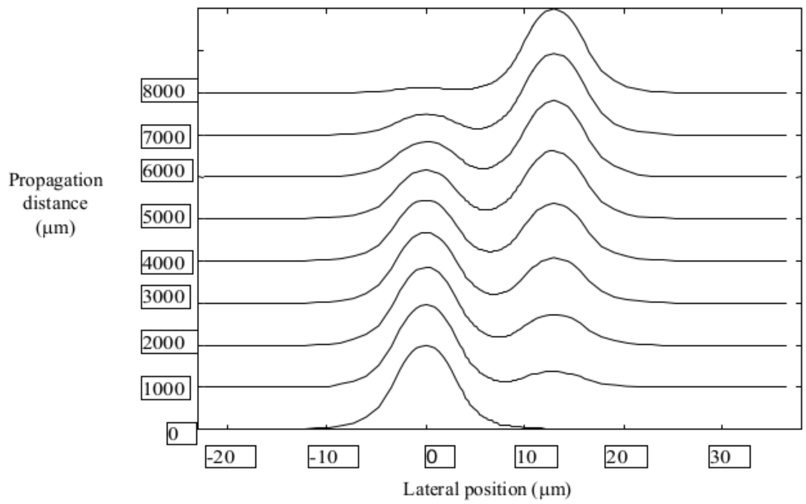

Figure 6 Power exchange of a planar waveguide directional coupler computed with MoL. The modal power launched into the left guide is seen to couple to the right guide.

We now consider the physical mechanisms that allow electrical operation of a switch. There are two common mechanisms, namely the electro-optic effect and the thermo-optic effect. The former refers to the modification of the material index of refraction caused by an electric field. The effect is strong in non-centro symmetric crystals such as $LiNbO_3$. In case of a directional coupler switch, the index change is obtained by utilizing an electric field on the two guides via metal electrodes deposited above the waveguides so that the effective index of one guide increases while the other decreases [10,25]. As a result, light can be made to switch back and forth between the two guides. Two assumptions are made: first, the change in propagation constant of each guide is assumed to be directly proportional to the electric field, and second, any variation of coupling coefficient due to the electric field is assumed to be negligible.

On the other hand, directional couplers based on silica-on-silicon waveguides cannot easily be used as switching devices. Unlike the electro-optic effect (where the index changes directly proportional to the voltage), the refractive index changes in silica-on-silicon devices are caused by the thermo-optic effect induced by a thin film heater above the silica guide. The driving power and response time depend on the waveguide and the thermal conductivity of the materials. The main problem is that it is almost impossible to heat one waveguide without affecting another nearby guide so that switching cannot be performed in a directional coupler geometry. One possible solution is to introduce a groove between the waveguides; however, this will attenuate or even eliminate the light to be switched. The usual method is to use another design, such as a Mach-Zehnder interferometer, as switching device [26,27].

4 Conclusion

In this study, we have demonstrated the use of a semi analytical numerical solution using the method of lines for optical directional couplers with different refractive index and wavelength variations. The examples demonstrated that MoL is an excellent semi analytical numerical method that can be applied to simulate optical waveguide devices with accurate calculation results. Unfortunately, a shortcoming of MoL lies in the fact that the computing time depends highly on the number of lines used and the computation time increases dramatically for wider and more complex structures. Additionally, for complex structures such as S-bend waveguides based on a sinusoidal function, the guide edge tends to approach the boundary of the computational window at both ends. Another possible solution is to use coordinate transformation or cascading curve waveguides to model the S bend structures so that the computational window and hence the matrix size can be minimized to decrease the computational time.

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