Intermediate Value Wavefront Matching Method for InP Waveguide Design

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***Abstract*—An adapted wavefront matching (WFM) method for the optimization of high-index contrast waveguides is presented. Amending the WFM method by introducing intermediate refractive index values enables the method to be used for the design of waveguide structures in indium phosphide. As an example, the design of a TE_0 to TE_1 mode converter is presented.**

Keywords—Wavefront Matching Method, Inverse Design, Beam Propgation Method, Indium Phosphide, Mode converter

I. Introduction

In the design of optical waveguide structures, optimization techniques offer significant benefits. Especially inverse design techniques are gaining popularity. These techniques fundamentally involve defining an input and a desired output field and transforming an initial structure to effectively convert the input field into the output field. The wavefront matching (WFM) method, as presented in [1], is a beam propagation method (BPM)-based inverse design approach originally suited for low index contrast platforms, such as silica. Table 1 summarizes the WFM methods applied to different material platforms. In [2], the full vector BPM-based WFM method was introduced. However, on high index contrast platforms, this approach becomes ineffective. To address this, a finite element method (FEM)-based WFM method was developed for silicon [3, 4], but its high computation time restricts its use to small-scale structures. Applying both methods to the indium phosphide (InP) platform is problematic due to its large-scale structures and high index contrast, leading to inefficiencies: the FEM-based WFM incurs high computation times, while the BPM-based method becomes ineffective. Although in [6] the BPM-based WFM method incorporating the effective index method has been successfully applied to the InP platform, this is not a general approach due to its limited accuracy [5, 6].

TABLE I. List of Published WFM Methods

Reference	Material system	Index Contrast	Simulation Method
[1]	Silica	0.01	2D BPM
[2]	Si + SiNx	1.4	3D FV-BPM
[3]	Si	2.0	3D FEM
[4]	Si	2.0	3D FEM + stabilization
[5]	Si	0.4 – 2.0	Scalar-/FV-BPM
[6]	InP	2.2	2D BPM + Effective Index
This work	InP	2.2	3D BPM + intermediate values

To address this gap and generally enable the WFM method for the InP platform, we present an adapted WFM method based on the full vector finite difference BPM.

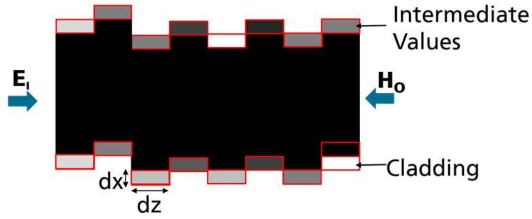

Fig. 1 IWFM method. Only red-boxed pixels are allowed to change.

II. The Intermediate Value WFM Method

The originally proposed WFM method is based on the beam propagation method [1, 2]. An input field $\mathbf{E_I}$ is launched and propagated through an initial structure. At the end position the desired output Field $\mathbf{H_O}$ is launched and is propagated backward through the structure (Fig. 1). The simulation domain is discretized into an optimization grid with pixel size $dx \times dz$. To enhance the coupling factor

$$\eta = |\int\int (\boldsymbol{E_I} \times \boldsymbol{H_O^*}) \cdot \boldsymbol{i_z}\, dxdy|^2$$

of input and output field, for each pixel at the border of the structure,

$$D = Im\{\boldsymbol{E_I} \times \boldsymbol{H_O^*}\} \cdot \boldsymbol{i_z}$$

is computed. Based on the sign of D, a pixel will be changed. For $D < 0$, the pixel changes from n_{wg} (waveguide material) to n_{clad} (cladding material) and for $D > 0$ from n_{clad} to n_{wg}. For low index contrast platforms, this method generates an optimized waveguide shape. However, for high index contrast platforms, this optimization progress is limited as shown in [4]. To overcome this issue, we propose an intermediate value wavefront matching (IWFM) method that allows the refractive index of a border pixel to change by a factor of

$$\Delta n = \frac{n_{wg} - n_{clad}}{m}, m \geq 1.$$

For $m = 1$, we have the standard WFM method. For $m \geq 2$ the method generates an intermediate structure with a lower refractive index contrast between waveguide and cladding. When $D < 0$, the refractive index n_b of a border pixel is

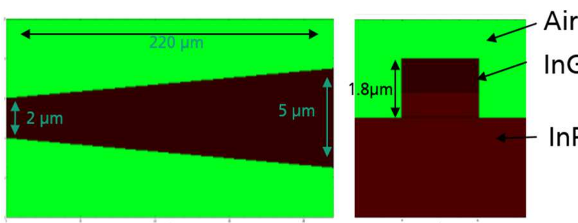

Fig. 2 Initial structure and material stack for the design to the TE_0 to TE_1 mode converter

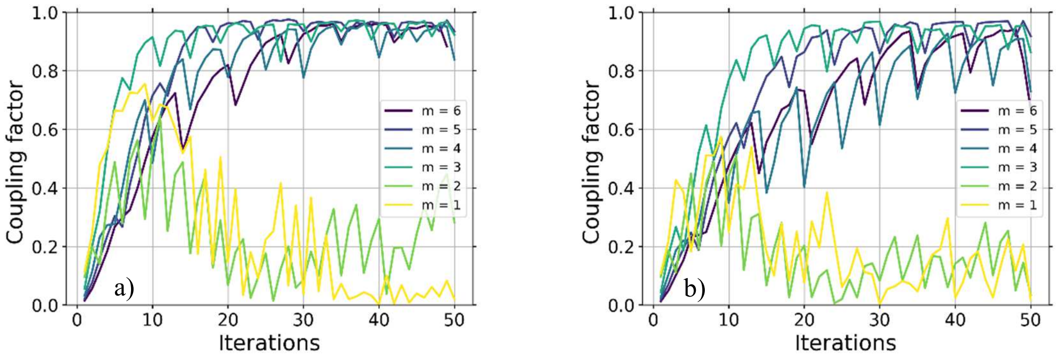

Fig. 3 Coupling factor for different settings of m and a) dz = 1 µm and b) dz = 0.5 µm

reduced by Δn and for $D > 0$, it increases by Δn, with the restriction that $n_{clad} \leq n_b \leq n_{wg}$. Furthermore, only one layer of pixels with intermediate values is permitted between pixels with n_{wg} and n_{clad} (Fig. 1). After $M \geq m$ iterations (cycle length), the intermediate refractive indices are converted back to the original materials. This is followed by a linearization step. For this step, the structure is divided in sections of length L_{Lin} (linearization length), where, the border of the structure is linearized. This process removes small ripples, enhancing the accuracy of the BPM simulation, and facilitating the subsequent fabrication of the optimized waveguide structure. Thanks to its efficiency, the BPM-based method can simultaneously optimize multiple wavelengths or polarizations.

III. Example Design

As in [3, 4], the capabilities of the IWFM method are demonstrated by designing a TE_0 to TE_1 mode converter. Fig. 2 illustrates the 220 µm long tapered initial structure with 1.8 µm deep etched rib waveguide structure based on an InP platform. Optimization is performed for the wavelengths 1.55, 1.61 and 1.6 µm, with a linearization length of 2 µm. The pixel size ($dx \times dz$) of the optimization grid is $0.05\,\mu m \times 1.0\,\mu m$ or $0.05\,\mu m \times 0.5\,\mu m$. For the intermediate values the cycle length is set to $M = m + 1$. Fig. 3 presents a study of the number of intermediate values used in the IWFM method for the design of the TE_0 to TE_1 mode converter. For both pixel sizes, the classical WFM method with $m = 1$ fails to converge to a solution. For $m \geq 3$, the IWFM method converges to a viable solution, with the setting $m = 5$ delivering the highest field conversion. The conversion factors for $dz = 1$ µm are generally higher as for $dz = 0.5\,\mu m$, due to less scattering. The dips in the curves are due to the refractive index conversion and linearization step, altering the computed structure and typically worsen field conversion. Given that the IWFM method is based on the approximate BPM, the result for $m = 5,\ dz = 1\,\mu m$ is verified through a finite difference time domain (FDTD) simulation. For the wavelength of 1.55 µm the FDTD coupling efficiency for the TE_0 to TE_1 mode coupler is -0.29 dB, being in excellent agreement with the -0.30 dB of the IWFM method after 50 iterations. Fig. 4 shows the intensity distribution of the designed converter waveguide. The 50 iterations for generating the optimized result for $m = 5,\ dz = 1$ took approximately 2 hours on a 64-core simulation server, whereas the validation via the FDTD method took about 10 hours. The example shows, that introducing intermediate values with $m > 2$ generally enhances the performance of the optimization, making the IWFM method superior to the standard WFM method. However, determining the optimal settings for m, M, and dz requires conducting a series of optimizations.

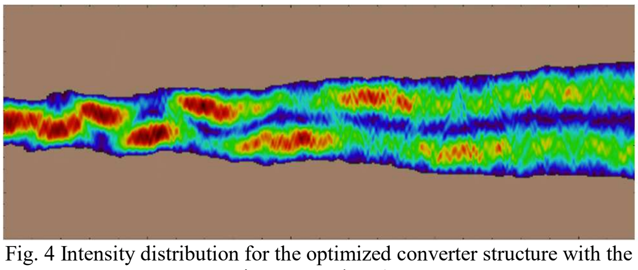

Fig. 4 Intensity distribution for the optimized converter structure with the setting m = 5, dz = 1 µm

IV. Conclusion

We have presented the IWFM method, an enhanced WFM method, by allowing the use of intermediate values for the refractive index during optimization. This adaptation enables the WFM method to be effectively employed in the design of high index contrast InP waveguide structures. A robust FDTD simulation confirmed the efficiency of the results produced by this adapted WFM method.

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