Fourier Series Based 3D Bi-directional Propagation Algorithm for Integrated Photonics

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***Abstract* — A 3D bi-directional mode expansion propagation algorithm based on Fourier series using trigonometric functions is briefly described. Nonlinear complex coordinate transformations are used as boundary conditions in transversal coordinates. In vertical direction, the adaptive spatial resolution algorithm can be alternatively applied, too. Mirror symmetries can be fully utilized to reduce numerical effort. Applications to a subwavelength-grating waveguide SOI mode transformer and a novel planar metal-dielectric slot waveguide are shown.**

Keywords-numerical modeling; bi-directional mode expansion; Fourier modal methods; plasmonic slot waveguide; subwavelength-grating waveguide

I. Introduction

Numerical modelling is an ever more important part of analysis and design of novel integrated photonic structures and devices. Despite the tremendous progress in computing power and memory of modern computers, realistic 3D modelling still remains rather challenging. Perhaps the most frequently used method for modelling 3D structures is the well-known finite-difference time domain (FDTD) method. Modelling of structures larger than just a few wavelengths in each direction is, however, still rather demanding. Frequency-domain modal methods are generally less flexible but bring deeper physical insight into the wave effects in photonic structures, and are especially well suited for modelling structures consisting of longitudinally uniform segments. In this contribution, a fully vectorial 3D bi-directional mode expansion propagation algorithm based on trigonometric Fourier series is presented. It represents an extension of a 2D method [1] into 3D. Similar as in [1], nonlinear complex coordination transformations [2] are used in both transversal coordinates as efficient perfectly matched layers (PML). The application of trigonometric (sin and cos) expansion functions instead of complex exponentials typically used in Fourier modal methods enables to fully utilize mirror symmetries of the problem to reduce the problem size without any additional effort. It is known that adaptive spatial resolution algorithm (ASR) [3, 4] helps significantly reduce the numerical effort, but it makes modelling of complex devices difficult. For this reason it can be alternatively applied only to one – vertical – direction. Fourier factorization rules [4,5] are correctly applied in both transversal directions using the approach described in [6]. The full-vector mode solver is based on transversal components of magnetic field intensity.

II. The Algorithm

The structure to be modelled is considered as a concatenation of a finite number of longitudinally uniform sections. In each section, the piecewise-constant transversal permitivity distribution is supposed. Infinite transversal cross-section of a real structure is mapped into a finite calculation window (shown in Fig. 1) using nonlinear complex coordination transformations $x \to x'$, $y \to y'$ described in [2]. Coloured (shadowed) part of the cross-section represents the transformed (PML) region, the white central part of the cross-section is not modified by the transformation.

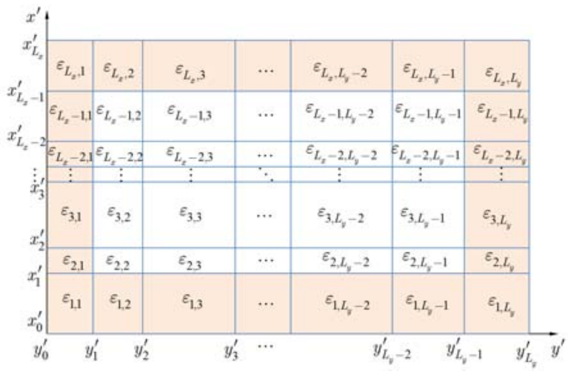


Figure 1. Transversal computation window with schematic representation of a piecewise-constant permittivity distribution after the complex nonlinear transformation.

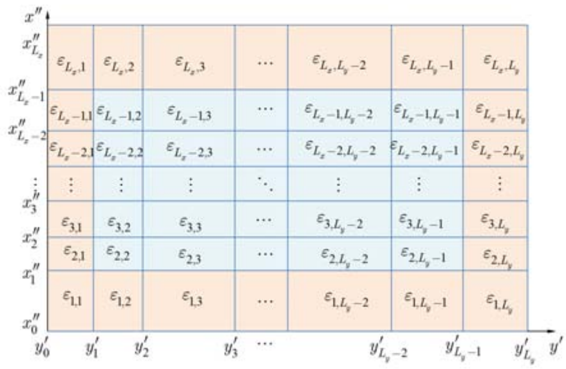


Figure 2. Transversal computation window after the application of the ASR transformation in vertical (x) direction.

Another transformation – the ASR transformation [3, 4] – can be alternatively applied to the vertical (x) coordinate at the inner part of the cross-section. After the transformation, the thicknesses of all inner horizontal layers become identical (see Fig. 2), the transformed vertical permittivity distribution becomes almost smooth, and thus the number of Fourier expansion terms required for sufficient accuracy is significantly reduced. This algorithm is thus well suited not only for modelling integrated photonic components fabricated by 2D patterning of a layered planar structure as SOI, InP, silica-on-silicon and similar devices, but also for 3D structures with metallic (plasmonic) components.

III. Examples

As a convergence test of the basic algorithm, the effective refractive index of the quasi-TE_{00} mode of a silicon nanowire embedded in SiO_2 versus the number of expansion terms is shown in Fig. 1. The results of the film mode matching method [10] were used as a reference.

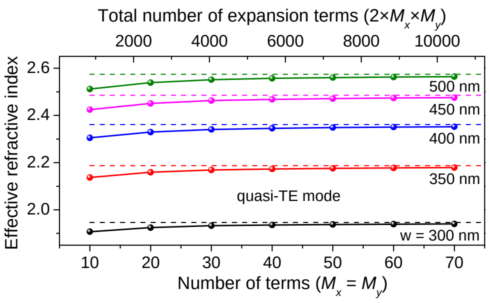


Figure 3. Effective refractive index of the fundamental quasi-TE mode of a silicon nanowire embedded in SiO_2 versus the number of Fourier expansion terms. The wire height is 260 nm, the width varies from 300 to 500 nm. The wavelength is 1550 nm.

As a next example, calculated optical field distribution in the SOI subwavelength grating waveguide mode transformer [8] embedded in SU8 resist with 60 subwavelength sections is shown in Fig. 4. The calculated coupling losses at the wavelength of 1550 nm are 0.61 dB and 0.45 dB for TE_{00} and TM_{00} mode, respectively. 60×70 Fourier terms were used in the calculation.

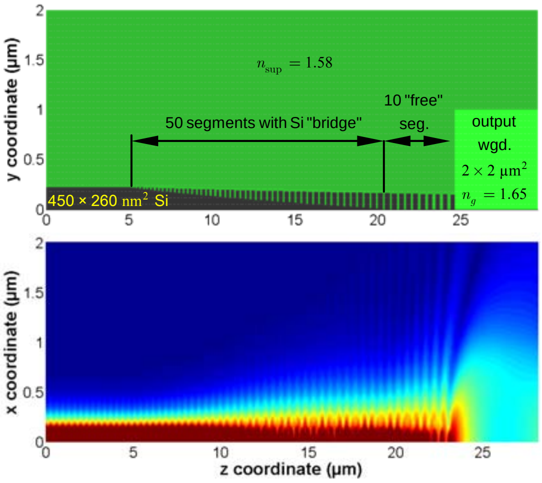
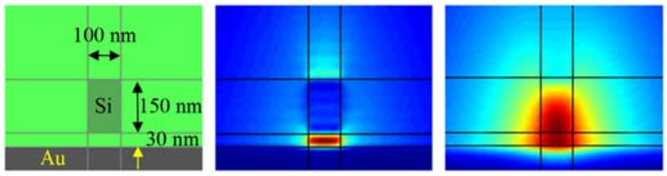


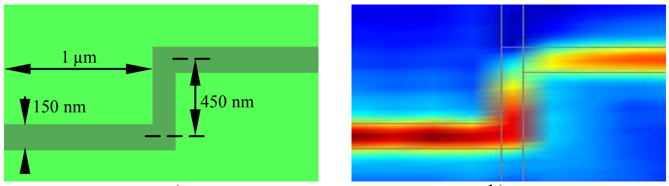
Figure 4. a) Top view of the mode transformer; because of symmetry, only one half of the structure is considered.
b) calculated optical field distribution, TE_{00} excitation. Perfectly conducting magnetic wall was placed at the symmetry plane.

In Fig. 5, the cross-section and the calculated mode field distribution of a metal-dielectric slot waveguide [9] is plotted. The waveguide is formed by a very thin Si nanowire embedded in SiO_2 and separated from an Au layer by a 30 nm slot. 80×60 Fourier terms were used. Fig. 6 shows the geometry and the field distribution of a very sharp S-bend in this waveguide. All these results have been, in fact, checked with another our modal method, namely aperiodic rigorous coupled wave analysis (aRCWA) technique, their comparison will be shown.



a) b) c)

Figure 5. a) Cross-section of the metal-dielectric slot waveguide,
b) vertical electric field component,
c) horizontal magnetic field component of the plasmonic mode.



a) b)

Figure 6. a) Geometry of the sharp S-bend in the metal-dielectric slot waveguide, b) distribution of a vertical electric field component.

IV. Acknowledgments

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[1] J. Čtyroký, "Improved bidirectional-mode expansion propagation algorithm based on Fourier series," J. Lightwave Technol., Vol. 25, pp. 2321-2330, 2007.

[2] J. P. Hugonin and P. Lalanne, "Perfectly matched layers as nonlinear coordinate transforms: a generalized formalization," J. Opt. Soc. Amer. A, Vol. 22, pp. 1844-1849, 2005.

[3] T. Vallius and M. Honkanen, "Reformulation of the Fourier modal method with adaptive spatial resolution: application to multilevel profiles," Optics Express, Vol. 10, pp. 24-34, 2002.

[4] J. Čtyroký, P. Kwiecien, and I. Richter, "Fourier Series-Based Bidirectional Propagation Algorithm with Adaptive Spatial Resolution," J. Lightwave Technol. Vol. 28, pp. 2969-2976, 2010.

[5] P. Lalanne and G. M. Morris, "Highly improved convergence of the coupled-wave method for TM polarization," J. Opt. Soc. Amer. A, Vol. 13, pp. 779-784, 1996.

[6] L. Li, "Use of Fourier series in the analysis of discontinuous periodic structures," J. Opt. Soc. Amer. A, Vol. 13, pp. 1870-1876, 1996.

[7] L. Li, "Fourier modal method for crossed anisotropic gratings with arbitrary permittivity and permeability tensors," J. of Optics A: Pure and Applied Optics, Vol. 5, pp. 345-355, 2003.

[8] P. Cheben, P. J. Bock, J. H. Schmid, et al., "Refractive index engineering with subwavelength gratings for efficient microphotonic couplers and planar waveguide multiplexers," Optics Letters, vol. 35, pp. 2526-2528, 2010.

[9] M. Fujii, J. Leuthold, and W. Freude, "Dispersion Relation and Loss of Subwavelength Confined Mode of Metal-Dielectric-Gap Optical Waveguides," IEEE Phot. Technol. Letters, vol. 21, pp. 362-364, 2009.

[10] L. Prkna, M. Hubálek, and J. Čtyroký, "Field modeling of circular microresonators by film mode matching," IEEE Journal of Selected Topics in Quantum Electronics, vol. 11, pp. 217-223, 2005.