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# An Efficient Method for Estimating the Electromagnetic Wave Propagation in Three Dimensional Optical Waveguide Structures

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**Abstract.** In this work, the full vectorial beam propagation methods (BPMs) are adopted for the calculations of the electromagnetic wave propagation from the two dimensional and three dimensional optical waveguide structures. First, the full vectorial BPM for the three dimensional optical waveguide structures is introduced. Next, in the transverse directions of the considered waveguide structures, we adopt the second order finite difference method to discretize the electromagnetic components. Then, the Lanczos/Arnoldi fast solvers are adopted to find the leading eigenvalues and eigenvectors of the square root operator in the BPM process of the optical waveguide structures. Furthermore, we propose the rational $[(p-1)/p]$ Padé approximation to approximate the exponential operator in the BPM process. To demonstrate the efficiency of the numerical solvers, the two dimensional symmetric and unsymmetric problems are considered, and good convergence results are obtained. Furthermore, the resulting full-vectorial BPM is adopted to simulate the wave propagation among the three dimensional rib and taper waveguide structures. Numerical results demonstrate the efficiency of the proposed method with respect to both the accuracies and convergence results.

**AMS subject classifications**: 78M25, 78M16, 78A45

**Key words**: Wave propagation, fast solver, Lanczos method, perfectly matched layer.

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# 1 Introduction

The beam propagation method (BPM) [1–6] is widely used in the numerical simulation of the wave propagation among the optical waveguides and optical fiber waveguide structures [7–10]. The simplest BPM is derived from the slowly varying envelope approximation [11], and more advanced variants are based on rational approximants of the square root operators [3] or the exponential of the square root operators [12, 13]. The limitation of the slowly varying envelope approximation is that it is only accurate for wave fields propagating in a small angle around the waveguide axis. For the planar waveguide structures, it is widely accepted that the scalar wide-angle BPM [3] is more accurate than the slowly varying envelope approximation BPM. Importantly, BPM is an efficient method for modeling wave propagation in slowly varying waveguides, including waveguide bends, branches, tapers, etc.

For two dimensional waveguide structures with the TE or TM polarized waves, the governing equation for the electromagnetic wave propagation is a scalar Helmholtz equation [14]. For the three dimensional guided-wave structures, the scalar and semi-vectorial formulations of the BPM are often not sufficient. A full vectorial formulation [15] is necessary for polarization-dependent optical waveguide structures. Most full vectorial BPMs [15–17, 19, 20, 34] could use the slowly varying envelope approximation. A wide-angle full vectorial BPM has already been formulated [12]. Recently, the full vectorical BPMs have been widely studied by the researchers from engineers, physicists and mathematicians. For instance, in [15], the simulations of three dimensional optical waveguides were described. The polarizations dependence and their coupling for the vectorial electromagnetic fields in nature were formulated in detail. The guided modes from the rib optical waveguide were investigated [18]. Specifically, the comparisons results of the simulation results via the scalar, semi-vectorial and full vectorial from the rib optical waveguide were made in detail. In [20], a novel full-vectorial beam-propagation method based on the McKee–Mitchell scheme was proposed. Compared to the Peaceman–Rachford scheme, the proposed McKee–Mitchell scheme demonstrates its better accuracy while maintaining the high computational accuracy. Moreover, the finite difference formulas with the consideration of the discontinuities of refractive index was developed. The three dimensional rib optical waveguide was considered with the eigenmode analysis with the aid of the proposed method in [20]. In [21], a numerical analysis of wave propagation through optical rib waveguide using Lanczos versions of the Fresnel, wide-angle, and Helmholtz propagation processes. Furthermore, the Lanczos algorithms combined with the finite-difference as opposed to the fast Fourier transform formulations of the transverse derivative operators from the Helmholtz propagation process were adopted. In [23], the typical beam propagation methods for the approximations to the one-way Helmholtz equation were considered first. Then, the efficient implementation of the beam propagation method based on the rational approximations of the propagator was developed successfully. Numerical results on the mode distribution from the taper optical waveguide were demonstrated.