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PCFDT: An accurate and friendly photonic crystal fiber design tool

Arismar Cerqueira S. Jr. [a,b,c,*], K.Z. Nobrega[d], H.E. Hernandez-Figueroa[c], F. Di Pasquale[b]

[a]*Department of Physics, University of Bath, UK*
[b]*Scuola Superiore Sant'Anna di Studi Universitari e di Perfezionamento, Italy*
[c]*DMO, FEEC, State University of Campinas (UNICAMP), Brazil*
[d]*CEFET-MA, Brazil*

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Abstract

This paper presents PCFDT, which is an accurate and friendly photonic crystal fiber design tool based on full-vectorial finite element method. Photonic crystal fibers based on circular and non-circular microstructured holes, and on different propagation mechanisms have been analyzed. Comparisons with other numerical methods and experimental results have shown excellent agreement. The design tool validation includes experimental results of hybrid photonic crystal fibers, proposed by us, which made possible for the first time light be simultaneously confined and manipulated by two propagation mechanism, total internal reflection and photonic bandgap effect.

Keywords: Photonic crystal fiber; Design tool; Finite element method; Index-guiding and photonic bandgap

1. Introduction

Photonic crystal fibers (PCFs), also known as Holey Fibers, have wavelength morphological microstructure running down their length. They were proposed by Russell and his team, from University of Bath, in 1992. The first prototype was produced in 1995 and reported in 1996 [1]. Since then, this new kind of fiber has been extensively studied and investigated. They enable light to be controlled within the fiber in ways not previously possible or even imaginable. Therefore, their unusual properties allows to deliver significant improved performance compared to the traditional technology in several aspects [2]. Between them, it is worth to highlight guidance due to 02 propagation mechanism simultaneously [3], endlessly single-mode behavior [4], highly birefringent [5], ultrahigh nonlinear [6], large mode-area [7], ultra-flattened, and anomalous dispersion [8,9] and light propagation in air-cores [10]. Hollow-core PCFs have made possible light propagation in the air and even in gases [11]. On the other hand, hybrid photonic crystal fibers enable light be simultaneously guided by total internal reflection and photonic bandgap effect. Moreover, it was experimentally demonstrated, for the first time, phase matching and wavelength conversion in 02 different photonic bandgaps by launching 200 fs pulse at 78 MHz, from a Ti:Sapphire system, near one of zero-dispersion wavelengths of a hybrid photonic crystal fiber [12].

PCFs have multiple rods periodically arranged around their core. This periodic structure is called

*Corresponding author.
E-mail address: arismarjunior@yahoo.com.br (Arismar Cerqueira S. Jr.).

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photonic crystal and it is similar to normal crystals present in semiconductor materials. In other words, photons in a PCF have similar behavior as electrons have in a semiconductor crystal.

The huge possibilities of hole shapes and arrangements demand the use of numerical methods that are able to handle arbitrary cross-sections in order to analyze this kind of structures. Moreover, the existence of high index contrast in the interfaces of the host material and rods requires a vectorial method to accurately model it. Many modelling techniques have been applied in their characterization, including plane-wave expansion methods [13], localized function methods [14], finite element methods [15], finite difference time domain methods [16], Fourier decomposition method [17], multipole methods [18] and multiple reciprocity boundary element method [19].

A full-vector model is crucial for accurately predicting the modal properties, owing to the large refractive index difference between silica materials and air holes. In this work, we use full-vector finite element method (VFEM) various kinds of photonic crystal fibers. In order to demonstrate the potentiality and accuracy of PCFDT, structures with either solid material and air core, as well as with circular and non-circular microstructured rods have been considered. The comparisons with other numerical methods [16–20] and experimental results [3,5] have been done in terms of effective index, dispersion, birefringence, beat length, magnetic field and intensity patterns. The outstanding feature of the proposed tool is that it provides very accurate analysis and, at the same time, friendly pre- and post-processing due to its interfaces written in Matlab. Additionally, it gives an opportunity to refine the mesh in the regions of large refractive index step (extremely important features in the PCF design) and where magnetic field is concentrated.

2. Finite element analysis

The large index contrast and complex structure in PCFs make them difficult to treat mathematically. Standard optical fiber analysis do not help and, in addition, in the majority of PCF cases it is practically impossible to perform modal analysis analytically, so Maxwell's equations must be solved numerically. The main idea consists of transforming this complicated problem, which can be described by the curl–curl equation:

$$\nabla \times (\varepsilon_r^{-1} \nabla \times H) - k_0^2 \mu_r H = 0 \tag{1}$$

into an eigensystem, in which its eigenvalues are β/k_0, the effective indexes, and its eigenvectors are the magnetic field components (H_x, H_y, and H_z). In (1) H is the magnetic field, ε_r and μ_r are the dielectric permittivity and magnetic permeability tensors, respectively, and k_0 is the wave number in vacuum.

The finite element method is basically divided in four steps [21]. The domain discretization is the first and perhaps the most important step in any finite element analysis. It consists of dividing the solution domain Ω into a finite number of subdomains, which form a patchwork of basic elements that can have different sizes, shapes and physical properties. The second step is selecting interpolation functions, which provide an approximation of the unknown solution within each element. In this specific case, the solution domain is the transverse cross-section of the optical waveguide which is divided in triangular finite elements; the nodal approach is followed using second-order polynomials as interpolating functions in each finite element (each triangle is characterized by 6 nodes and the unknowns are the magnetic field components). In the next step the curl–curl equation is transformed into a generalized eigenvalue problem by applying a variational formulation. The formulation we are considering is based on a penalty function to suppress spurious modes, as shown in (2) [21].

$$F(H) = \frac{1}{2} \int \int_{\Omega} \left[\frac{1}{\varepsilon_r} (\nabla \times H)(\nabla \times H)^* + \frac{s}{\mu_r^2 \varepsilon_r} |\nabla(\mu_r H)|^2 - k_0^2 \mu_r H H^* \right] \mathrm{d}\Omega, \tag{2}$$

where s is the penalty function. By finding the stationary solutions of functional $F(H)$, it is possible to obtain the following generalized eigenvalue system:

$$[A]\{\phi\} - \lambda[B]\{\phi\} = \{0\}, \tag{3}$$

where the eigenvalue λ is the mode effective refractive index (n_{eff}) and the eigenvector ϕ is the full vectorial magnetic distribution (H_x, H_y, and H_z) in the nodal points.

Finally, solving the eigenvalue system is the fourth and final step in a finite element analysis. The matrices $[A]$ and $[B]$ are sparse and symmetric, so the computational time is effectively minimized using a sparse matrix solver. The frequency-dependent refractive index $n(w)$, which allows one to take into account the material dispersion, has been described by using the Sellmeir equation:

$$n^2(w) = 1 + \sum_{j=1}^{M} \frac{B_j w_j^2}{w_j^2 - w^2}, \tag{4}$$

where w_j is the resonance frequency and B_j is the oscillator strength, found empirically for each material. The dispersion parameter $D(\lambda)$ can be directly calculated from the modal effective index $n_{\mathrm{eff}}(\lambda)$:

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2 n_{\mathrm{eff}}(\lambda)}{d\lambda^2}, \tag{5}$$