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Analysis of amplification properties of a photonic crystal fiber

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ABSTRACT

In this work, effects of geometrical parameters and dopant concentration on amplification performance of Yb doped photonic crystal fiber amplifiers (YDPCFAs) are investigated. To this end, numerical results obtained from fully vectorial effective index method, are combined with conventional rate equations. The variation of the normalized frequency of the photonic crystal fiber with respect to air filling factor for different air hole spacing are depicted. Using obtained results, the single-mode region at signal and pump wavelengths are determined. In addition, the influence of dopant concentration on the maximum gain and optimum length are investigated. It is shown that by changing photonic crystal fiber cross-section parameters such as pitch and air filling factor, rather than increasing dopant concentration, one can obtain a higher gain at shorter optimum length. These results are useful for the design of YDPCFAs with less nonlinearity effects such as cooperative up conversion and Yb^{3+} ion quenching.

1. Introduction

Photonic crystal fibers (PCFs), as the waveguiding optical fibers have been under intensive study for the past several years [1]. These fibers consist of a central defect region surrounded by a regular array of wavelength-scale air holes running along the fiber length. The waveguiding is due to the complex microstructuring of the fiber cross-section. According to light guidance there are two basic categories of PCFs, namely the solid core PCFs which guide light by total internal reflection similar to the standard fibers [2] and the photonic band gap fibers (PBGF) which confine the light in the band gap and guide the light in a low index core region [3].

Numerical simulations are crucial for the design and modeling of PCFs [1]. So far, various modeling techniques have been developed such as effective index [4–6], plane wave expansion [7], localized function [8], multipole [9], beam propagation [10], finite deference [11], finite difference time-domain [12], boundary element [13], and finite element methods [14].

The full vector finite element method (FEM) has been successfully applied to study the amplification properties of honeycomb and triangular PCFs [15,16]. The effects of the dopant radius and the size of the first hole ring on the amplifier performance have been investigated. It has been shown that the optimum length of doped fiber, strongly decreases by enlarging the dopant radius. Also, enlarged first air-hole sizes can be usefully exploited in order to achieve higher gain at a fixed length of the doped PCF [15]. In addition, results have been demonstrated that the splice losses are decreased by increasing pitch, Λ, and by reducing air filling factor, d/Λ [17].Hence, it is important to investigate the influence of PCF cross section parameters on the amplification performance of doped PCF amplifiers. Although FEM is known to be more powerful and accurate method to analyze PCF-based devices [18]. However it is also a time consuming method respect to the other simple ones such as effective index method (EIM) [19].

Combining EIM with the rate equations offers a simple and fast method to analyze PCF amplifiers [19,20]. The simulation for the Er doped holey fiber amplifiers (EDHFA) exhibits to be in good agreement with the experimental results [20,21].

There are two effective index methods i.e. the scalar [4] and vectorial [22]. The scalar approach in EIM is applicable for weekly guiding regime. It has been applied to study the amplification properties of Er doped Photonic crystal fibers [19]. In the case of PCFs, where a large contrast exists between air and silica, the applicability of scalar effective index method (SEIM) [23] reduces and the fully vectorial effective index method (FVEIM) is successfully used as an alternative.

Here, a triangular lattice Yb doped PCF is analyzed to understand how its hole geometry and dopant concentration can be designed in order to improve the amplification properties. The study is performed by the combined use of FVEIM method with the Runge-kutta algorithm. The former provides variation of the effective index, normalized frequency V_{eff}, and mode field diameter (MFD) by changing hole geometry of PCF. The latter is applied for solving conventional rate equations to describe the amplification mechanism.

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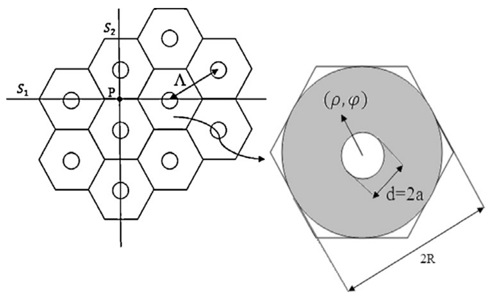

Fig. 1. The photonic crystal fiber cladding structure, corresponding hexagonal and circular unit cells. The straight lines S_1 and S_2 represent planes of symmetry of the structure.

2. Fully vectorial effective index method

2.1. The fundamental space filling mode

In the EIM photonic crystal fiber is replaced by a step index fiber with effective cladding index [4–6]. The hexagonal unit cell of the cladding also is approximated by a circular one of radius R. Fundamental parameters of PCF structure, corresponding hexagonal unit cell and circular unit cell are demonstrated in Fig. 1.

The exact solution of Maxwell's equations in a hexagonal lattice can be obtained considering simple symmetry properties for the lattice [5]. In Fig. 1, two planes, marked with S_1 and S_2 solid lines, represent symmetry planes of the structure. Applying the continuity conditions on the air-silica border with the boundary conditions for $\rho = R$, we finally get the characteristic equation that a mode of the cladding should satisfy as Eq. (1) [22]:

$$\left[\frac{P_l'(ua)}{uaP_l(ua)} + \frac{I_l'(wa)}{waI_l(wa)}\right]\left[n_{si}^2\frac{P_l'(ua)}{uaP_l(ua)} + n_{air}^2\frac{I_l'(wa)}{waI_l(wa)}\right] = l^2\left[\frac{1}{(ua)^2} + \frac{1}{(wa)^2}\right]\left(\frac{\beta}{k_0}\right)^2, \tag{1}$$

where $u^2 = n_{si}^2k_0^2 - \beta^2$, $w^2 = \beta^2 - n_{air}^2k_0^2$ and $\beta = k_0n_{FSM}$ is the propagation constant of the mode. I_l is the modified Bessel function of the first kind of order l and $P_l(u\rho)$, $Q_l(ua)$ are expressed as Eq. (2):

$$P_l(ua) = Q_l(ua) = J_l(ua)Y_l(uR) - Y_l(ua)J_l(uR), \tag{2}$$

in which J_l and Y_l are the Bessel functions of the first and second kind, respectively. Putting $l = 1$ in Eq. (1), one can get the effective index of fundamental space filling mode, $n_{FSM} = \beta/k_0$. This is the value of cladding effective index in EIM.

2.2. Index guiding mode

For finding effective index of the guiding LP_{01}, photonic crystal fiber is replaced with an equivalent step index fiber with core refractive index of n_{co} and cladding index of n_{FSM} obtained from Eq. (1). Applying boundary conditions, the characteristic equation of the fundamental mode is given by Eq. (3) [22]:

$$\left[\frac{J_l'(U_{eff})}{U_{eff}J_l(U_{eff})} + \frac{K_l'(W_{eff})}{W_{eff}K_l(W_{eff})}\right]\left[n_{cl}^2\frac{J_l'(U_{eff})}{U_{eff}J_l(U_{eff})} + n_{eff}^2\frac{K_l'(W_{eff})}{W_{eff}K_l(W_{eff})}\right] = \left[\left(\frac{1}{(U_{eff})^2}\right)^2 + \left(\frac{1}{(W_{eff})^2}\right)^2\right]\left(\frac{\beta}{k_0}\right)^2, \tag{3}$$

in which n_{eff} and n_{cl} are the fundamental mode and cladding effective index, respectively. U_{eff}, W_{eff} and V_{eff} parameters are defined as follows:

$$U_{eff} = k_0\rho_{co}\sqrt{n_{co}^2 - n_{eff}^2} \tag{4}$$

$$W_{eff} = k_0\rho_{co}\sqrt{n_{eff}^2 - n_{cl}^2} \tag{5}$$

$$V_{eff} = k_0\rho_{co}\sqrt{n_{co}^2 - n_{cl}^2} \tag{6}$$

where, the core refractive index, n_{co} is equal to refractive index of GeO_2/SiO_2 doped silicate. The corresponding value is calculated from the Sellemier equation [24] such that:

$$n_{Si}^2 = 1 + \sum_1^3 \frac{[SA_i + x(GA_i - SA_i)]\lambda_0^2}{\lambda_0^2 - [SL_i + x(GL_i - SL_i)]^2} \tag{7}$$

where x is molar fraction of GeO_2 and SA_i, SL_i, GA_i, and GL_i are the coefficients of Sellemier equation for SiO_2 and GeO_2, respectively [24], and λ_0 ascertains the free space wavelength.

The single mode region in conventional fibers is determined by the criteria $V = \frac{2\pi a}{\lambda}\sqrt{(n_{co}^2 - n_{cl}^2)} < 2.4045$, where V is the normalized frequency of fiber [25]. For PCFs, the effective normalized frequency is given by $V_{eff} = \frac{2\pi\rho_{co}}{\lambda}\sqrt{(n_{co}^2 - n_{cl}^2)}$ [26] but by two correct definition. The study in [27] assumes that in Eq. (6), n_{co} is the effective index of the guided principle mode, while in studies in [28,29], defines n_{co} as the refractive index of glass in the core of PCF which can be doped. Although all these definitions are shown to be capable of properly describing the modal behavior of PCFs, they result in different values of single mode cutoff for V_{eff}. For example V_{eff} holds the value of π in [27], while in [29], the classical value of 2.405 is obtained [30].

Solving Eqs. (1) and (3), we can get n_{cl}, n_{eff} also U_{eff}, W_{eff} and V_{eff} parameters. Although the intensity distribution of the fundamental mode in a PCF is not rotational symmetric but rather has the 6-fold symmetry of the triangular cladding structure, a Gaussian approximation is in fact very good and has previously been employed in the description of various PCF properties [31–34]. Therefore, mode field intensity distribution is taken with a Gaussian approximation:

$$\psi(r, \Omega) = \frac{\exp(-r^2/\Omega^2)}{\pi\Omega^2} \tag{8}$$

where the MFD of fundamental mode is theoretically defined as [19,35]:

$$\Omega = \rho_{co}J_0(U_{eff})\frac{V_{eff}K_1(W_{eff})}{U_{eff}K_0(W_{eff})} \tag{9}$$

Obtained results must be in agreement with Marcuse formula Eq. (10) [36]. In fact, applicability of this formula for case of PCFs has been clarified in Fig. 8 of Ref [1], where the MFD values obtained by Marcuse formula are in good agreement with measured experimental results.

$$\Omega = 2\rho_{co}\left(0.65 + \frac{1.619}{V_{eff}^{3/2}} + \frac{2.879}{V_{eff}^6}\right) \tag{10}$$

3. Modeling Yb doped photonic crystal fiber amplifier

For modeling YDPCFA, the results obtained from FVEIM are combined with the rate equations. The cross-section is manipulated to improve the amplification properties of PCF.

Ytterbium is an important rare earth element which is frequently used as dopant in the optical materials, usually in the