Optical Fiber Technology 20 (2014) 374–379

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Analysis of modal characteristics and thermal effects on photonic crystal fiber laser

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ARTICLE INFO

Article history:
Received 26 October 2013
Revised 11 March 2014
Available online 27 May 2014

Keywords:
Index-guiding photonic crystal fiber
Double clad fiber lasers
Plane wave expansion method
Thermo optic effects

ABSTRACT

In this paper, thermo-optics effects on fiber lasers based on index-guiding photonic crystal fibers (PCFs) are studied. The modal characteristics of the PCF lasers are discussed in terms of the thermal effects. Modal analysis of PCF has been done with help of plane wave expansion and supercell lattice methods. The thermal analysis is performed by obtaining the effective index of fundamental mode and core confinement factor (CCF) when the fiber laser was pumped. The results show that PCF laser structure has negligible modal sensitivity to thermal load in comparison to conventional fiber laser. Analyzing the mode performance of the fiber laser under thermal load shows that the assumed PCF laser at 80 W/m pump power show ∼500° rise in temperature and 0.34% propagation constant variation in fundamental mode index and 0.04% CCF variation in fundamental mode.

1. Introduction

In recent years, high power fiber lasers have found in large industrial and scientific applications. Continuous-wave output powers well above the kilowatt range with excellent beam quality have been achieved [1]. In conventional photonic crystal fibers, the cladding structure is formed by embedding a number of air channels which form square-lattice or triangular-lattice structures around the core and run along the fiber. Beside the triangular-lattice structures as a common PCF, the propagation characteristics of the PCFs with square-lattice structures have been recently studied and reported [2,3]. The first simple PCF laser was reported in 2000 [4]. Fiber lasers based on index-guiding PCF offer the laser designer novel degrees of freedom not available in the conventional fiber lasers. For instance, they can operate in single-mode, they reach high numerical aperture values for the pump core up to ∼0.9, they have high power-scaling factor and finally their all-glass structure make the high-power operation possible [5,6]. The air-cladding in the PCF lasers is used to achieve high numerical aperture for the pump and also it prevents the contact between radiation and coating materials. The main disadvantage of these structures seems to be that the air-cladding acts as a thermal insulation layer and it interrupts the heat dissipation from the inner to the outer cladding [6]. Since thermal effects are crucial for efficient operation of fiber lasers, extensive studies have been done so far [6–11].

Limpert et al., modeled the thermo-optical behavior of air-clad ytterbium-doped large-mode-area PCF lasers. The authors drew the conclusion that the air-clad PCF lasers are likely to be scalable to power levels of several kWs [6]. Cheng et al. studied the temperature distribution and thermo-optical properties of PCF lasers [7]. They reported that the air-filling factor of PCF is a key parameter to the thermal performance of the PCF lasers and the fiber core temperature is a critical limitation to the power scaling [7].

In this work, the heat generated in the index-guiding PCF laser as well as thermo-optical effect on some modal properties of laser is studied. To the best of our knowledge, the modal characteristics of laser signal in PCF lasers at different pump power resulting heat power were not investigated. We consider a square lattice based structure due to simplicity of analyzing, simulating and also the result will be clearly applicable to other common structure like. Here, as a main objective we try to analyze some modal characteristics of the PCF laser under thermal load. Therefore, in this paper, as a result of PCF laser and thermal analysis, the variation of the effective index of fundamental laser modes, core confinement factor (CCF) of fundamental mode are investigated. The plane wave expansion and supercell lattice method are used to calculate the modal characteristics of the assumed PCF structure.

2. Radial temperature distribution and PCF laser principle

The porous cladding of PCFs which containing a regular arrangement of air holes leads to a special heat conduction properties, which commonly used step index fibers do not posses.

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http://dx.doi.org/10.1016/j.yofte.2014.04.010
1068-5200/

An assumed PCF cross section used in fiber lasers has been shown in Fig. 1. The figure schematically shows the core, photonic crystal cladding as an inner cladding (first cladding), air-cladding, outer cladding (second cladding) and coating region. The figure also shows the PCF structure as a square lattice and also the unit cell used in the calculation and their geometrical parameters. The gain medium of a PCF laser can be fabricated by introducing a rare-earth ion doping into the core of PCF.

2.1. Radial temperature distribution

In the PCF core, heat is mainly generated due to the quantum defects between the pump and laser photons. The heat is transferred to the surface of the fiber by thermal conduction through the core, the photonic crystal cladding, the air-cladding, the outer cladding, and the coating material. Heat dissipation from the coating to the ambient air also involves convection and conduction mechanisms. In a cylindrical coordinate system the heat transfer equation in the core and the outer layers can be expressed as the following [12]

$$\begin{aligned} &\frac{1}{r}\frac{\partial}{\partial r}\left[rk_\circ \frac{\partial T_\circ}{\partial r}\right] = Q_\circ \quad 0 \leqslant r \leqslant a_\circ \\ &\frac{1}{r}\frac{\partial}{\partial r}\left[rk_i \frac{\partial T}{\partial r}\right] = 0 \quad a_\circ \leqslant r \leqslant a_4 \end{aligned} \tag{1}$$

where $k_\circ$ is the thermal conductivity of the core and $Q_\circ$ is the heat flow density given by $Q_\circ = \frac{\eta P_p}{\pi a_\circ^2}$ with P_p as the pump power per unit length and η as the heat fraction. In Eq. (1) the heat flow density is equal to zero and k_i ($i = 1,\ldots,4$) are the thermal conductivity factors of the cladding a_i (as shown in Fig. 1). Considering appropriate boundary conditions, one can solve the differential equations of Eq. (1) to obtain a relation describing temperature distribution in the core and claddings as

$$\begin{aligned} T_\circ(r) = T_c - \frac{Q_\circ r^2}{4k_\circ} + \frac{Q_\circ a_\circ^2}{2}\left[\frac{1}{a_4 h} + \frac{\ln a_4}{k_4} + \left(\frac{1}{k_3} - \frac{1}{k_4}\right)\ln a_3 + \left(\frac{1}{k_2} - \frac{1}{k_3}\right)\ln a_2 \right. \\ \left. + \left(\frac{1}{k_1} - \frac{1}{k_2}\right)\ln a_1 - \frac{\ln a_\circ}{k_1} + \frac{1}{2k_\circ}\right] \quad 0 \leqslant r \leqslant a_\circ \\ T_i(r) = T_c - \frac{Q_\circ a_\circ^2}{4k_i}\ln\frac{r}{a_{i-1}} + \frac{Q_\circ a_\circ^2}{2a_4 h}\sum_{n=1}^{4}\frac{Q_\circ a_\circ^2}{2k_n}\ln\frac{a_n}{a_{n-1}} \quad a_{i-1} \leqslant r \leqslant a_i;\ 1 \leqslant i \leqslant 4 \end{aligned} \tag{2}$$

where T_c and h are coolant temperature and heat transfer coefficient of air, respectively. To determine the effective thermal conductivity of each unit cell (as shown in Fig. 1), we employ the series–parallel connection concept which is well known in the analysis of electric resistance [7]. The unit cell is divided into three layers, and the effective thermal conductivity is estimated by the weighted summation of these layers

$$k_{eff} = \frac{S_A}{S_A + S_B + S_C}k_A + \frac{S_B}{S_A + S_B + S_C}k_B + \frac{S_C}{S_A + S_B + S_C}k_C \tag{3}$$

here $S_{(A,B,C)}$ is the area occupied by the fused silica and $k_{(A,B,C)}$ are thermal conductivities corresponding to layers A, B, C, respectively. The effective thermal conductivity of photonic crystal cladding is given by

$$k_{eff} = (1-\alpha)k_{si} + \frac{4\alpha k_{air} k_{si}}{\pi\alpha k_{si} + (4 - \pi\alpha)k_{air}} \tag{4}$$

where k_{si}, k_{air}, and α represent the thermal conductivities of the silica and air and air-filling factor ($\alpha = d/D$; d is hole diameter and D is pitch), respectively. Also based on the series–parallel model, the thermal conductivity of the air-cladding, k_2, is given by [7]

$$k_2 = \frac{w_b}{w_b + w_{air}}k_{si} + \frac{w_{air}}{w_b + w_{air}}k_{air} \tag{5}$$

where w_b and w_{air} are the thicknesses of silica bridges and air gaps, respectively. Since, the Δn_{stress} is usually smaller than Δn_{temp} by three orders of magnitude, it could be ignored in our calculations [7]. Thus the index change in the core is obtained as

$$\Delta n_{core} = \frac{dn}{dT}\frac{Q_\circ a^2}{4k_\circ} \tag{6}$$

where $dn/dT = 1 \times 10^{-5}/°\mathrm{C}$ is the thermal coefficient of refractive index change [7].

2.2. PCF laser principle

A quasi analytical model based on a set of rate equations for strongly pumped fiber lasers was developed by Kelson et al. [13] and Hardy et al. [14]. Here we use their model at steady state for a Yb^{+3}-doped PCF laser which is regarded as a quasi-three-level system emitting at 1090 nm. A typical PCF laser consists of a doped index-guiding PCF section of length L, with a Bragg reflector on either side, as shown in Fig. 2.

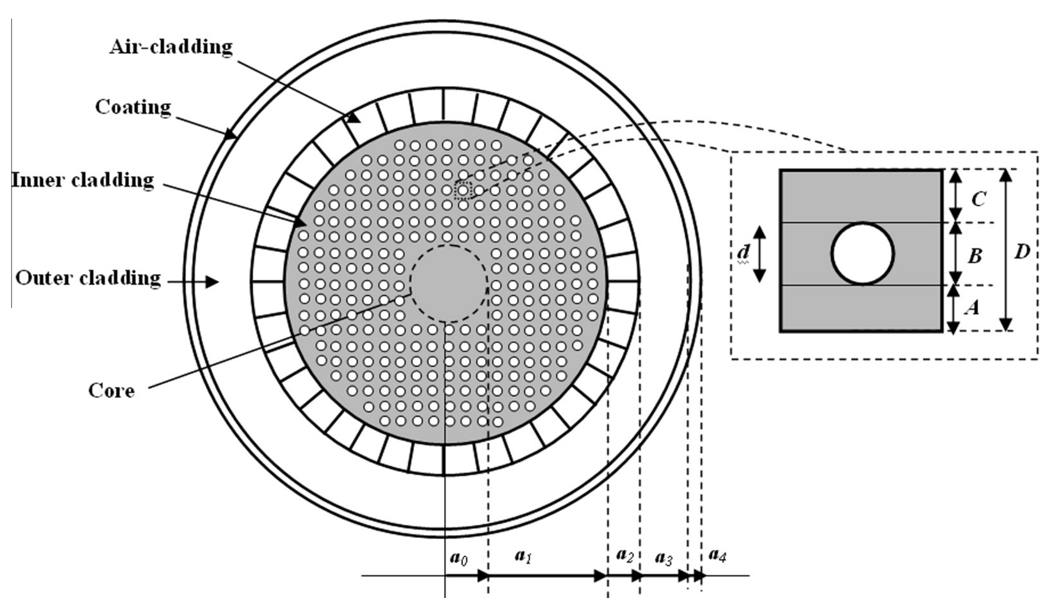

Fig. 1. An assumed PCF cross section, the square lattice photonic crystal, and the unit cell used in the calculation and their geometrical parameters.