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Long-period gratings for the optimization of cladding-pumped microstructured optical fiber laser

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ABSTRACT

The design of a laser constituted by an ytterbium doped, double-cladding microstructured optical fiber (DCMOF) with an optimized optical coupler inscribed in the doped core region is illustrated. The coupler is constituted by a long-period grating (LPG) which increases the pump power transfer from the inner cladding modes towards the fundamental core mode. A home-made numerical code solving the coupled-mode equations and the rate equations is ad hoc developed to investigate the dependence of the fiber laser performance on the LPG parameters such as the grating period and the length. The simulations highlight that it is possible to transfer a lot of the total input pump power from the inner cladding modes towards the fundamental mode guided into the core, leading to a significant improvement of both the pump power absorption and the output signal power. Moreover, a reduction of the total length of the laser and a minimization of the length-dependent nonlinear effects can be obtained.

1. Introduction

In the near future, the employment of fiber lasers will be extended to high-power applications including material processing and directed energy delivering. In particular, the cladding pumping technique has enabled power scaling of continuous-wave and pulsed fiber lasers, bringing the fiber technology advantages in a number of areas typically dominated by traditional CO_2 and Nd-YAG lasers, e.g. laser welding, marking and cutting, optical parametric oscillators, LIDAR, targeting, illumination and isotope separation [1–3].

Double cladding fibers (DCFs) allow: the exploitation of the cladding pumping technique, the employment of low-cost and multimode pump sources, the reduction of the thermal load density [4–6]. In this kind of fibers, a single-mode core is surrounded by a large inner cladding having high numerical aperture. An outer cladding layer, having lower refractive index, surrounds the inner cladding. The multimode high-power beam, at the pump wavelength, is launched into the inner cladding and it is gradually absorbed by the doped core.

The use of microstructured optical fibers (MOFs) permits to overcome some limitations occurring in the conventional optical fibers employed in high-power applications. In fact, the standard DCFs do not permit an easy handling of the heat capacity, inner cladding numerical aperture, and single-mode core size. It is well known that MOF optical features strongly depend on the cladding configuration. In fact, the number of holes, their size, shape, orientation, transversal distribution and the nature of dielectric material can provide useful modal and dispersive properties [7–10]. Therefore, large mode area, high numerical aperture, core design flexibility, low transmission and bending losses [7,8] are easily attainable via MOF technology.

Long-period gratings have been exploited in many applications as filters, gain flatteners for erbium-doped fiber amplifiers, dispersion compensators, sensors, etc. [11–16].

In this paper, an LPG is accurately designed to enhance the coupling of the pump power into the ytterbium-doped core of a DCMOF. The proposed LPG could be an important and strategic element in actual high-power DCMOF amplifiers and lasers in order to improve the pump power absorption.

The electromagnetic field is accurately calculated via a finite element method (FEM) while the power coupling in the rare-earth doped fiber is investigated via a home-made computer code based on multimode coupled-mode theory. In the design, the inner cladding section, the length and period of the grating and the geometrical parameters of the air holes are identified in order to optimize the coupling among the inner cladding modes and the core mode and to enhance the power absorption at wavelength $\lambda = 976$ nm.

2. Theory

In order to design the coupler, a suitable model and a home-made computer code have been ad hoc developed. The

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model takes into account the interaction among the twofold degenerate fundamental mode guided in the ytterbium-doped core (HE_{11}) and the inner cladding modes, at the pump wavelength. In particular, the design of this device requires: (i) the electromagnetic investigation based on the eigenvalue analysis and (ii) the solution of coupled-mode equations and of the rate equations describing the changes of rare-earth ion populations. The modal electromagnetic field distribution and the propagation constant of the guided modes are computed by solving the transversal wave equation for the magnetic field via an efficient full-vectorial finite element method. The wavelength dispersion of silica has been taken into account in the calculation via the Sellmeier equation [17]. An accurate MOF section design allows to neglect the nonlinear effects because a large effective area of both inner cladding and core modes can be obtained.

The coupling of the core mode with the cladding pump modes in the LPG has been accurately modelled by using the well known coupled-mode theory derived in slowly varying envelope approximation SVEA [15,18]. In particular, the grating region is obtained by means of a refractive index perturbation, $\Delta n(z)$, uniform in the fiber transverse plane and expressed by [18]:

$$\Delta n(z) = n_1(z) - n_1 = n_1\sigma(z)[1 + m\cos(2\pi z/\Lambda_1)] \quad (1)$$

where n_1 is the core refractive index, Λ_1 is the grating period, m is the induced-index fringe modulation, and $\sigma(z)$ is the slowly varying envelope of the grating. The fabrication technology to obtain an LPG in the core of a MOF is reported in literature [16].

Because the core is rare-earth doped, the multimode coupled-mode theory is suitably modified/completed, by considering the light-matter interaction phenomena occurring in the active medium. A quasi-two level scheme is employed to describe the ytterbium activated glass-system. The pump and the signal wavelengths being $\lambda_p = 976$ nm and $\lambda_s = 1060$ nm, respectively. Therefore, the modified coupled-mode equations are:

$$\frac{dA_\mu^{pump}}{dz} = i\sum_{\nu=1}^{N}\left\{A_\nu^{pump}K_{\nu\mu}\exp[i(\beta_\nu - \beta_\mu)z]\right\} + \frac{1}{2}\alpha(z,\lambda_p)A_\mu^{pump}$$
$$\mu = 1, 2, \ldots, N \quad (2)$$

$$\frac{dA_{signal}^{\pm}}{dz} = \pm\frac{\alpha(z,\lambda_s)}{2}A_{signal}^{\pm} \quad (3)$$

where N is the number of the considered pump modes, A_μ^{pump} (A_ν^{pump}) is the amplitude of the transverse field profile of the forward propagation μth (νth) mode at the pump wavelength λ_p, β_ν and β_μ are the propagation constants of the modes ν and μ, $K_{\nu\mu}$ is the transverse coupling coefficient between the modes ν and μ [18]. A_{signal}^{+} and A_{signal}^{-} are the amplitudes of the forward and backward propagating signals at the laser wavelength λ_s, respectively. The expression for the gain coefficient α is:

$$\alpha = [\sigma_{21}(\lambda)N_2(z) - \sigma_{12}(\lambda)N_1(z)]\Gamma(\lambda) - loss(\lambda) \quad (4)$$

where σ_{21} and σ_{12} are the emission and absorption ytterbium cross-sections, respectively, N_1 and N_2 are the concentrations of the ytterbium ions Yb^{3+} at the ground state $^2F_{7/2}$ and at the upper laser energy level $^2F_{5/2}$, respectively. In the steady state condition the expressions of rate equations are:

$$N_2 = \frac{W_P^{GSA} + W_S^{GSA}}{W_P^{GSA} + W_S^{GSA} + 1/\tau_{21} + W_P^E + W_S^E}N_T \quad (5)$$

$$N_1 = N_T - N_2 \quad (6)$$

where N_T is the total ytterbium ion concentration in the core of the fiber, $1/\tau_{21}$ is the spontaneous emission rate, W_P^{GSA}, W_S^{GSA} are the ground state absorption (GSA) rates at pump and laser wavelength; W_P^E, W_S^E are the emission (E) rates at pump and laser wavelength [19]. $\Gamma(\lambda)$ is the overlap factor, defined as the overlapping integral between the normalized light intensity distribution and the fiber core.

In the system (2) the longitudinal coupling coefficients are neglected because they are generally 2–4 orders of magnitude smaller than the transverse coupling coefficients $K_{\nu\mu}$ (z) [18], and a small index perturbation ($\sigma(z) \ll 1$) has been considered [18]. Moreover, the aforesaid formalism, based on SVEA, can be still derived because (i) the refractive index variation constituting the grating induces a weak perturbation on the propagation modes and (ii) the field amplitudes of the forward and backward lasing modes $A_{signal}^{\pm}$ are amplified by the rare-earth without strong/discontinuous changes.

3. Numerical results and discussion

In order to illustrate the LPG behavior, we consider, as an example, a DCMOF having a transversal section useful for an ytterbium laser fabrication as that reported in Fig. 1 [20]. At first, this fiber section has been identified via a preliminary design. It consists of a Ge-doped single-mode core, having diameter d_c = 7.6 μm, surrounded by five rings of air holes (inner cladding) having diameter d_h = 2.5 μm and arranged in a triangular lattice with hole-to-hole spacing (pitch) Λ=7 μm. The inner cladding is surrounded by three rings of hexagonally arranged air holes with hole diameter D_h = 6 μm and pitch Λ=7 μm. The fiber radius is R_{out} = 53.6 μm and the refractive index change between the Ge-doped core and the pure silica cladding is 0.001 [20]. The model/software can be employed to other more complex MOF transversal sections.

In the LPG design, the computation of the coupling coefficients between the core and cladding modes requires an accurate evaluation of both the propagation constant and the transversal electromagnetic field profile of the propagation modes. To this aim a FEM-based commercial software has been employed. The computational domain has been divided in about 900,000 elements. The electromagnetic field profile and the propagation constant of the fundamental core modes (HE_{11}^x and HE_{11}^y) and a large number of inner cladding modes have been found by solving the eigenvalue equation for the magnetic field. Among this large number of calculated cladding modes, only the modes effectively involved in the energy

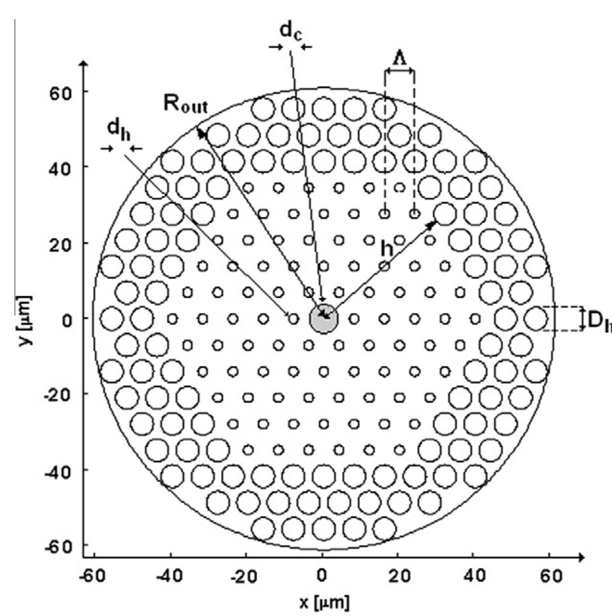

Fig. 1. Transversal section of the double-cladding microstructured optical fiber.