



Design of Er³⁺-doped chalcogenide glass laser for MID-IR application

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ABSTRACT

The feasibility of a photonic crystal fiber laser (PCF laser), made of a novel Er³⁺-doped chalcogenide glass and operating at the wavelength $\lambda_s = 4.5 \mu\text{m}$ is investigated. The design is performed on the basis of spectroscopic and optical parameters measured on a fabricated Er³⁺-doped Ga₅Ge₂₀Sb₁₀S₆₅ chalcogenide bulk sample. The simulations have been performed by employing a home made numerical code that solves the multilevel rate equations and the power propagation equations via a Runge-Kutta iterative method. The numerical results indicate that a laser exhibiting slope efficiency close to the maximum theoretical one and a wide tunability in the wavelengths range where the atmosphere is transparent can be obtained.

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1. Introduction

The increasing interest in fiber lasers originates from the large number of their conventional and novel applications. As an example, fiber lasers are used in the field of infrared-guided missile countermeasures [1] due to their spectral overlap with the thermal signature of aircrafts and the atmospheric transmission window in the medium infrared (MID-IR) wavelength range. Moreover, photonic crystal fibers (PCFs) are suitable for laser applications because of their peculiar optical properties, such as light polarization, high non-linearity, endlessly single mode operation and so on [2–6]. PCFs generally include a number of air holes, running along the longitudinal direction, which can be arranged in different kinds of lattices.

In recent years, chalcogenide glasses have induced a particular interest as host materials for PCFs employed in a wide wavelength range, in both passive and active device applications: this kind of glasses is based on chalcogenide elements with the addition of other elements such as Ga, Ge and Sb. Chalcogenide glasses show many interesting properties such as low phonon energy and high

refractive index, allowing the possibility of novel transitions among the Er³⁺ energy levels as well as larger pumping efficiency [7]. They present also a transparency from the end of the visible region to the medium infrared wavelength range, useful for chemical sensing applications since many molecules vibrate in the IR region [8]. They also exhibit high non-linearity, useful for ultrafast switching in time division multiplexing communication systems [9], and capability to host high dopant concentration without suffering from ion-clustering or concentration quenching effects. Moreover, because of their transparency in the IR wavelength range, chalcogenide glasses are useful in active applications such as amplifiers [2,3] and IR fiber lasers.

In this work, a novel Er³⁺-doped Ga₅Ge₂₀Sb₁₀S₆₅ chalcogenide fiber laser, pumped at the wavelength $\lambda_p = 806 \text{ nm}$ is designed in order to obtain high performance at the wavelength $\lambda_s = 4.5 \mu\text{m}$. More particularly, the design is performed with the aim to enhance the effective mode area by preserving the mono mode operation.

2. Theory

In order to investigate the feasibility of the Er³⁺: Ga₅Ge₂₀Sb₁₀S₆₅ fiber laser operating at the wavelength $\lambda_s = 4.5 \mu\text{m}$, a numerical code has been *ad hoc* developed. The code takes into account the measured erbium energy levels lifetimes τ and the emission/

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absorption cross sections $\sigma_{e,a}$ of erbium ions in the investigated chalcogenide glass, both measured on the novel $\text{Ga}_5\text{Ge}_{20}\text{Sb}_{10}\text{S}_{65}$ preliminary sample [10]. Especially, absorption and emission spectra have been recorded from visible to MID-IR for different dopant levels and the radiative lifetimes of the excited levels $^4\text{I}_{9/2}$, $^4\text{I}_{11/2}$ and $^4\text{I}_{13/2}$ have been determined, as well as the emission cross section at $4.5 \mu\text{m}$. As Fig. 1 shows, the pump signal, at the wavelength $\lambda_p = 806 \text{ nm}$, assists the transition from the $^4\text{I}_{15/2}$ ground level to the $^4\text{I}_{9/2}$ excited level. The emission at the wavelength $\lambda_s = 4.5 \mu\text{m}$ occurs when the excited ions decay from the $^4\text{I}_{9/2}$ level to the $^4\text{I}_{11/2}$ level. A uniform up-conversion (C_{up}) occurs when two erbium ions in the $^4\text{I}_{13/2}$ level exchange energy between them. After the energy exchange, one ion transits to the higher $^4\text{I}_{9/2}$ level and the other to the lower $^4\text{I}_{15/2}$ level. A similar uniform up-conversion (C_3) occurs between two erbium ions in the $^4\text{I}_{11/2}$ energy level: one ion leaves to the higher $^4\text{F}_{7/2}$ level and rapidly decays to $^4\text{S}_{3/2}$ level and the other leaves to the ground $^4\text{I}_{15/2}$ level. In the cross-relaxation phenomenon (C_{14}), an ion of the $^4\text{I}_{9/2}$ level transfers part of its energy to a ion of the $^4\text{I}_{15/2}$ level, both moving to the intermediate $^4\text{I}_{13/2}$ level. These transitions are taken into account by the multilevel rate equations modeling the Er^{3+} system at wavelength $\lambda_s = 4.5 \mu\text{m}$. In addition, the model takes into account the cross relaxation processes (C_{16}) and the other two up-conversion phenomena (C_4) and (C_{24}) since in the considered chalcogenide glass the involved ground state and excited levels are quite populated.

In the laser design, the optimization of the fiber transversal section constitutes an item of critical importance because it allows the reduction of fiber length and residual pump power as well as the improvement of the core mode area. To this aim, a fine control of the refractive index is needed. Unfortunately, the conventional optical fiber technology does not permit a full solution to this problem. On the contrary, the PCF technology allows the fabrication of single propagation mode fibers having large mode area, high numerical aperture, core design flexibility, and low transmission and bending losses.

A numerical code based on a full-vectorial finite element method (FEM) has been used in order to perform the electromagnetic investigation by varying the wavelength and PCF transversal geometry. In order to reduce the computational time and memory resources, the structure symmetries have been considered. To this aim a quarter of the solution domain has been considered by applying the suitable perfect electric conductor (PEC) and perfect magnetic conductor (PMC) boundary conditions on the symmetry planes. Moreover, in order to simulate the free space condition, the perfectly matched layer (PML) boundary conditions have been considered in the electromagnetic analysis.

The home made numerical code uses the calculated electromagnetic field profile and the modal propagation constant as input data in order to evaluate the ion population of each involved erbium energy level, and the evolution of both pump and signal

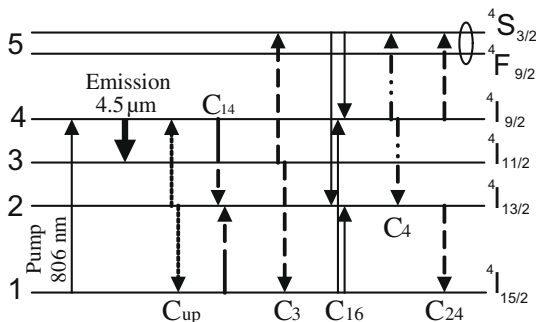


Fig. 1. Er^{3+} energy levels diagram: pump and signal wavelength are $\lambda_p = 806 \text{ nm}$ and $\lambda_s = 4.5 \mu\text{m}$.

power along the fiber propagation direction. In particular, in order to solve the nonlinear system constituted by the multilevel rate equations a numerical code based on Newton's method has been implemented with a globally convergent strategy. The nonlinear differential system constituted by the propagation equations has been solved via a home made numerical code based on a Runge-Kutta iterative method with adaptive stepsize.

3. Results

Fig. 2 illustrates the transversal section of the designed (and optimized) chalcogenide PCF. A number of simulations have been performed in order to optimize the geometrical parameters of the fiber section by following the approach reported in [11]. The obtained results show that the chalcogenide PCF of Fig. 2 is a good candidate for MID-IR laser applications, in a wide range of wavelengths. In particular, it consists of three rings of air holes arranged in a triangular lattice having hole-to-hole distance $\Lambda = 8 \mu\text{m}$, hole diameter $d = 3.2 \mu\text{m}$ and a fiber diameter $D = 125 \mu\text{m}$. In the same figure, the electric field distribution of the x-polarized HE_{11} fundamental mode at the wavelength $\lambda_s = 4.5 \mu\text{m}$ is also reported.

The numerical code that solves the rate equations and the power propagating equations, takes into account the ion-ion interactions coefficients according to the literature data: $C_{\text{up}} = 3 \times 10^{-23}$, $C_3 = 2 \times 10^{-23}$, $C_{14} = 5 \times 10^{-23}$, $C_{16} = 5 \times 10^{-24}$, $C_4 = 2 \times 10^{-24}$ and $C_{24} = 2 \times 10^{-24} \text{ m}^3/\text{s}$ [12].

Fig. 3 shows the contour plot of the optimal output power P_{out} , i.e. the output power calculated for the fiber length maximizing the laser performance, with respect to the output mirror reflectivity R_2 and to the wavelength λ for the following conditions: input pump power $P_p = 250 \text{ mW}$, Er^{3+} concentration $N_{\text{er}} = 11.53 \times 10^{25} \text{ ions/m}^3$ (10 000 ppm), input mirror reflectivity $R_1 = 99\%$, pump losses $\alpha_p = 0.03 \text{ dB/cm}$ and signal losses $\alpha_s = 0.02 \text{ dB/cm}$.

Fig. 4 depicts the simulated laser output power P_{out} versus the wavelength λ for different input pump powers $P_p(0) = 100 \text{ mW}$ (full line), $P_p(0) = 200 \text{ mW}$ (dash line), $P_p(0) = 300 \text{ mW}$ (dot line). The other parameters considered in the computation are: fiber length $L = 50 \text{ cm}$, Er^{3+} concentration $N_{\text{er}} = 11.53 \times 10^{25} \text{ ions/m}^3$, input mirror reflectivity $R_1 = 99\%$, output mirror reflectivity $R_2 = 50\%$, pump losses $\alpha_p = 0.03 \text{ dB/cm}$ and signal losses $\alpha_s = 0.02 \text{ dB/cm}$.

Fig. 5 shows the slope efficiency η , i.e. the slope of the curve obtained by plotting the laser output power with respect to input pump power, versus the fiber length L for different output reflectivity: $R_2 = 5\%$ (full line), $R_2 = 10\%$ (dash line), $R_2 = 15\%$ (dot line).

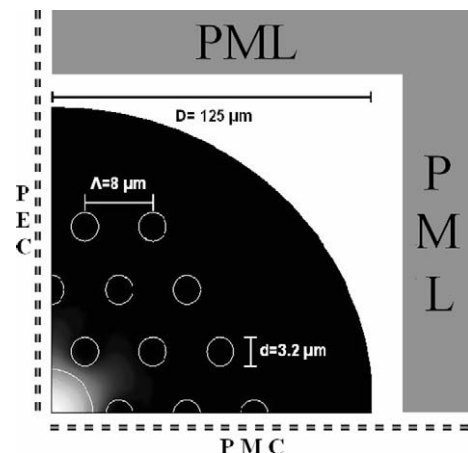


Fig. 2. Distribution of electromagnetic field, calculated at the wavelength $\lambda_s = 4.5 \mu\text{m}$ over a quarter of fiber section.

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