

Pump induced refractive index changes in commercial single-mode Yb-doped optical fibers

Andrei A. Fotiadi ^(1,3), Oleg L. Antipov ⁽²⁾, Patrice Mégret ⁽¹⁾

¹Service d'Electromagnétisme et de Télécommunications, Faculté Polytechnique de Mons, 31 boulevard Dolez, B-7000 Mons, Belgium

² Institute of Applied Physics of Russian Academy of Science, 603950, 46 Uljanov St., Nizhny Novgorod, Russia

³Also with Ioffe Physico-Technical Institute of RAS, St.Petersburg, Russia

We have explored the refractive index changes (RIC) in single-mode aluminum silicate ytterbium-doped optical fibers induced by optical pulses at 980 nm and report dynamical fundamentals of the process. The RIC dynamics is shown to follow the population dynamics of the excited and unexcited ions with a factor proportional to their polarizability difference (PD). The PD dispersion profile indicates to a predominant contribution to the RIC of far-resonance UV rather than near-resonant IR transitions. The absolute PD value is established in the range of 1460-1620 nm and found to be independent on fiber geometry and ion concentration.

Introduction

The refractive index change (RIC) of pumped rare-earth-doped optical fibers is caused by a change of the population of levels with different polarizabilities [1-3]. The origin of the polarizability difference (PD) is widely discussed during recent years. Some authors believe that the main contribution to the PD comes from near-resonance IR transitions, rather than far-from-resonance strong UV transitions [1, 3]. The understanding of the phenomenon appears to be very important because the pump-induced index change could be used for optical switching and coherent beam combining [2]. Obviously, the RIC may contribute to the dynamics of the fiber lasers and amplifiers.

Here we present our recent results [5] on the study of the RICs in commercial single-mode Yb-doped fibers (YDF) under diode pumping by use of a Mach-Zehnder interferometer operating in a spectral range far from Yb-ion transitions both in the near-IR and UV. The main objective is to investigate the mechanisms of the RIC and to determine the value of the PD in the YDF in a spectrum range from 1460 to 1620 nm.

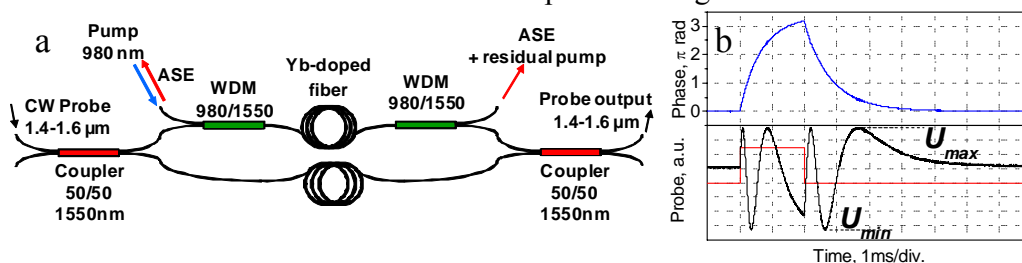


Fig.1 Experimental setup for Yb-doped fiber test (a) and a reconstruction of the induced phase shift from an experimental trace (b).

Experimental setup

The experimental setup is shown in Fig.1(a). The all-fiber spliced Mach-Zehnder interferometer comprises the tested Yb-doped fiber in one of the arms. The CW-radiation emitted by a diode laser “Tunics” with a coherence length of about 10 m is used as a testing signal. The signal was detected at the interferometer output by a fast photodiode. The test signal wavelength λ_T could be continuously tuned from 1460 to 1620 nm. The tested fiber was pumped by a standard pump laser diode operating pulses at $\lambda_p \approx 980 \text{ nm}$ with the pulse amplitude up to $\sim 150 \text{ mW}$.

The RIC is evaluated as a response on the fiber excitation by a rectangular pulse ($10 \mu\text{s}$ - 10ms). A typical oscilloscope trace recorded in the experiment is shown in Fig.1(b). The induced phase shift $\delta\varphi(t)$ is recalculated from the oscilloscope trace $U(t)$ as

$$\delta\varphi(t) = \varphi(t) - \varphi(0), \quad \text{where} \quad \varphi(t) = (-1)^k \arcsin\left(\frac{2U(t) - U_{\max} - U_{\min}}{U_{\max} - U_{\min}}\right) + \pi k \quad \text{and}$$

$k = 0, 1, 2, \dots$ is fitting for continuity of $\delta\varphi(t)$, see the Fig.1(b). Several aluminum silicate Yb-doped fiber samples manufactured by CorActive Inc. (Canada) of a different length, mode field diameter and Yb^{3+} -ion concentration have been examined.

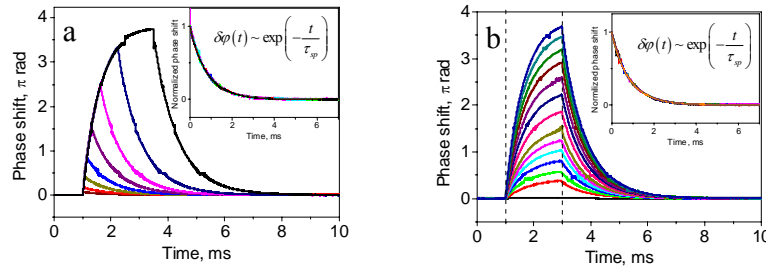


Fig. 2. Phase shifts at 1550 nm induced in by pulses of different (0.02 – 2.5 ms) pulse duration (a) and of different (2 - 145 mW) pulse amplitude (b). Inserts show the same phase shifts normalized to their maximal levels (only decaying parts are presented)

Results and discussion

A strong phase shift (up to several π) indicating to the RIC in the Yb-doped fiber has been observed under diode pumping. Fig. 2 presents the phase shift as dependences on the pulse duration (a) and pulse amplitude (b). The RIC possesses strong saturation effect attributed to the saturation of the pump absorption and generation of the amplified spontaneous emission (ASE). For all the fiber samples the decay time of the RIC was found to correspond to the lifetime of the excited Yb-ions in the used glasses $\tau_{sp} \sim 800 \mu\text{s}$ independent on the pump pulse duration and amplitude. Such relaxation behavior indicates to the electronic mechanism of RIC associated with population redistribution between the Yb-ion levels. In simplified two-level approximation, the electronic RIC δn caused by the excited state population (${}^2F_{7/2}$) change δN_2 can be expressed as [4]:

$$\delta n = \frac{2\pi F_L^2}{n_0} PD\delta N_2 \quad (1)$$

where n_0 is the unperturbed refractive index; $F_L = (n_0^2 + 2)/3$ is the Lorentz factor; $PD = p_2 - p_1$, p_1 and p_2 are the polarizabilities of Yb^{3+} ions in the ground ($^2F^{7/2}$) and excited state ($^2F^{5/2}$), respectively.

The corresponding phase shift detected in the probe wave at λ_T in the fiber length L can be evaluated from Eq. (1) by integration with $\rho_T(r)$ as a weight function:

$$\delta\varphi = \frac{4\pi^2}{\lambda_T} \int_0^L \int_0^\infty \delta n(z, r) \rho_T(r) r dr dz \approx \frac{\bar{\eta} \rho_T(0)}{\lambda_T} \left[4\pi^2 \frac{F_L^2}{n_0} PD \right] \delta N_2^\Sigma \quad (2)$$

where $\delta N_2^\Sigma = 2\pi \int_0^L \int_0^\infty N_2(z, r) r dr dz$ is the pump-induced change in the number of the excited Yb^{3+} ions in the whole fiber volume, $\rho_T(r)$ is the normalized power radial distribution of the probe light. Parameter $\bar{\eta} \rho_T(0)$ approximates the efficiency of the probe mode interaction with the population changes $\delta N_2(r)$ induced in the fiber core. Note that the factor $\rho_T(0)/\lambda_T$ includes the major part of the dependence on λ_T , while the correction factor $\bar{\eta}$ accounts for a distributed character of the population changes $\delta N_2(r)$ within the doped area core. If all changes are considered to occur near the fiber axis $\bar{\eta} \rightarrow 1$ and for uniform Yb-ion distribution on the fiber core $\bar{\eta} \approx 0.7$. Importantly, the factor $\bar{\eta} \rho_T(0) \sim \bar{a}^{-2}$, where \bar{a} is a core radius accounted in step-index fiber model.

Equation (2) predicts that the phase shift is proportional to the pump-induced change in the whole number of the excited ions. Therefore, the dynamics of both of them is governed by the same rate equation:

$$\frac{d\delta\varphi}{dt} = K \left(P_{P_{in}} - P_{P_{out}} - \frac{\lambda_s}{\lambda_p} P_{ASE} \right) - \frac{\delta\varphi}{\tau_{sp}} \quad (3)$$

where $K = \frac{\bar{\eta} \rho_T(0) \lambda_p}{\lambda_T h c} [2\pi F_L^2 PD]$, h is the Plank constant, ν_p , ν_{ASE} are the average frequencies of the pump and the amplified spontaneous emission (ASE), P_{in} , P_{out} are the input and output (residual) powers at ν_p , and P_{ASE} is the emitted power at ν_{ASE} .

In case of total pump absorption and low spontaneous emission, Eqs. (2,3) reduce to the following simple expression that is in good agreement with the experimental data (Fig.2):

$$\delta\varphi(t) = K \tau_{sp} \left[1 - \exp\left(-\frac{t}{\tau_{sp}}\right) \right] P_{in} \quad (4)$$

To determinate the PD dispersion the linear phase shifts $\delta\varphi$ induced by $200\mu s$ pump pulses with varied amplitudes $\delta P_{P_{in}}$ have been recorded at different test wavelengths λ_T (Fig.3(a)). The reconstructed PD values are shown in Fig.3(b) for the

spectrum range 1450-1620 nm. The dependence should be compared with the Lorentz-line PD profiles related to the resonance and non-resonance Yb-ion transitions at $\sim 1\mu\text{m}$ and $\sim 0.4\mu\text{m}$, respectively. One can see that the reconstructed PD well matches the second profile and has the value of $PD \approx 7.5 \cdot 10^{-26} \text{ cm}^3$ nearly the same for all range. Importantly, this value is found to be the same for all tested fibers and comparable with the PD values measured for several Yb-doped laser crystals [4].

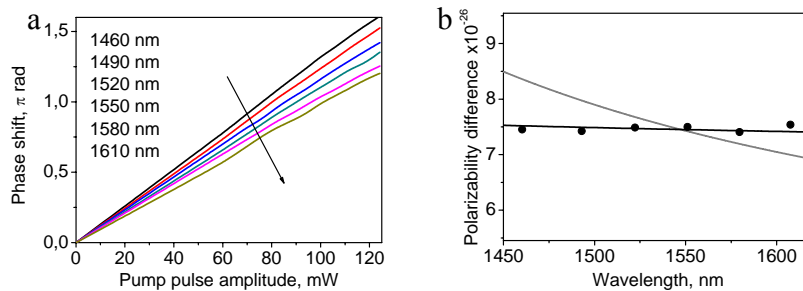


Fig.3. The phase shifts induced by 200 μs pulses of different pulse amplitude at different tested wavelengths (a) and the restored values of the PD (points) in comparison with resonance and non-resonance PD contributions at $\sim 1\mu\text{m}$ (gray) and $\sim 0.4\mu\text{m}$ (black), respectively.

Conclusion and acknowledgements

In conclusion, we have observed a strong RIC at wavelengths 1460-1620 nm when pumped at the absorption or gain lines of Yb-ions. The RIC exhibits a typical excited population dynamics. These facts clearly indicate to the electronic mechanism by PD of the excited and unexcited Yb-ions. The value of PD is determined for Yb-doped fibers. The PD dispersion curve makes evidence of the nonresonant contribution of the UV transitions to the PD, explicating some resent observations [6]. The results obtained are of great interest for fiber lasers, beam combining, laser synchronization and so on.

This work was supported by “Interuniversity Attraction Pole program VI/10” of the Belgian Science Policy program and by “Nonlinear optics of unique laser system” program of Russian Academy of Science and Russian Foundation of Basic Research (grant № 07-02-92184).

References:

- [1] E. Desurvire, Erbium-doped fiber amplifiers: Principles and Applications (Wiley, New York, 1994).
- [2] M. J. F. Digonnet, R. W. Sadowski, H. J. Shaw, and R. H. Pantell, “Resonantly Enhanced Nonlinearity in Doped Fibers for Low-Power All-Optical Switching: A Review,” *Opt. Fiber Technol.* 3, 44-64 (1997).
- [3] H. Garcia, A. M. Johnson, F. A. Oguama, and S. Trivedi, "Pump-induced nonlinear refractive-index change in erbium- and ytterbium-doped fibers: theory and experiment," *Opt. Lett.* 30, 1261-1263 (2005).
- [4] O. L. Antipov, D. V. Bredikhin, O. N. Eremeykin, A. P. Savikin, E. V. Ivakin, and A. V. Sukhadolau, "Electronic mechanism for refractive-index changes in intensively pumped Yb:YAG laser crystals," *Opt. Lett.* 31, 763-765 (2006)
- [5] A.A. Fotiadi, O. L. Antipov and P. Mégret, “Dynamics of pump-induced refractive index changes in single-mode Yb-doped optical fibers,” *Opt. Express* 16, 12658-12663 (2008).
- [6] S. I. Stepanov, A. A. Fotiadi, P. Mégret, “Effective recording of dynamic phase gratings in Yb-doped fibers with saturable absorption at 1064nm,” *Opt. Express* 15, 8832-8837 (2007).