PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Novel Y₂O₃-codoped Yb/Tm-doped picosecond fiber laser

Vladislav V. Dvoyrin, Dmitry Klimentov, Arindam Halder, Mukul C. Paul, Mrinmay Pal, et al.

SPIE.

Novel Y_2O_3-codoped Yb/Tm-doped picosecond fiber laser

Vladislav V. Dvoyrin*[a], Dmitry Klimentov[a], Arindam Halder[b], Mukul C. Paul[b], Mrinmay Pal[b], Shyamal K. Bhadra[b], Alexander V. Kir'yanov[c], and Irina T. Sorokina[a]
[a] Department of Physics, The Norwegian University of Science and Technology, Trondheim, Norway; [b] Central Glass & Ceramic Research Institute, Kolkata, India; [c] Centro de Investigaciones en Optica, Leon, Mexico

ABSTRACT

We demonstrate the novel picosecond mode-locked Y_2O_3-codoped Yb/Tm-doped fiber lasers, operating at 1950 nm and producing pulses of up to 1 nJ energy, using a SESAM and an Er-doped pump fiber laser operating at the wavelength 1590 nm or a semiconductor pump laser operating at the wavelength of 1560 nm. We also report on the spectroscopic characterization of these new fibers with various compositions, identifying the optimum one for the maximum Yb/Tm energy transfer, the latter increasing with the increase of the Y concentration. The observed energy transfer between Yb and Tm makes this laser promising also for direct diode-pumping with most advanced and low cost 975 nm diodes, making this laser attractive for compact low cost picosecond Tm-doped fiber laser systems.

Keywords: Yb/Tm codoping, energy transfer, picosecond fiber lasers

1. INTRODUCTION

The advantage of Yb/Tm-doped fibers is the possibility of their direct pumping by diode lasers operating at 975 nm[1,2]. In this connection the efficiency of the energy transfer from Yb^{3+} to Tm^{3+} is of great importance[3,4]. This efficiency is known to be dependent on the fiber composition. Thus, investigation of new compositions of core glass of Yb/Tm-doped fibers is also of great importance which is the subject of this work.

2. EXPERIMENTAL

We report here on the fabrication by MCVD method and spectroscopic characterization of a set of double-clad Yb-Tm-doped silica-based fibers. Yb, Tm, Y and Al oxides were incorporated by solution-doping technique whereas P and Ge oxide were deposited from the vapor phase. The fibers' cores also contained Y, Al, Ge and P. The total doping level was varied from 4 to 20 wt% with up to 3, 3.5, 2 and 0.9 wt% of Y_2O_3, Al_2O_3, Yb_2O_3 and Tm_2O_3, respectively (see the Table 1). The core sizes of the fibers varied from 15 to 25 μm approximately.

The emission and absorption spectra of the fibers, as well as the laser emission were recorded with an optical spectrum analyzer (Yokogawa) allowing optical spectra measurement up to 2400 nm. The absorption spectra were measured by cut-back technique. The efficiency of the energy transfer from Yb^{3+} to Tm^{3+} was estimated from the fluorescence spectra and analysing the time decays recorded under the optical excitation at 970 nm wavelength. Si and InGaAs semiconductor detectors were used for the fluorescence decay detection. The first detector, sensitive up to 1.1 μm, allowed us to measure the decay of Yb^{3+} fluorescence only, whereas the other one, sensitive up to 2.6 μm, permitted measurements of fluorescence signal from both Yb^{3+} and Tm^{3+} ions. The emission spectra and decays were recorded from outer fiber surface.

Fiber Lasers X: Technology, Systems, and Applications, edited by Sami T. Hendow, Proc. of SPIE
Vol. 8601, 86012X · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2004420

Table 1. Composition list of the investigated fibers.

Fiber	Yb_2O_3, wt%	Tm_2O_3, wt%	Al_2O_3, wt%	Y_2O_3, wt%	P_2O_5, wt%	GeO_2, wt%
LCTP-1	0.6	0.4	0.8	0.2	2	–
LCTP-2	0.7	0.5	3.5	0.3	3.6	10
LCTP-3	1	0.9	3	0.3	3.6	12
LCT-2	0.8	0.7	1	0.8	–	–
LCT-3	0.6	0.5	2	0.6	–	–
LCT-6	2	0.8	2	1.9	–	–
LCT-8	2	0.5	1	3	–	–

The simplified scheme of the linear-cavity mode-locked fiber lasers is shown in Fig. 1. The output coupler in the form of a Sagnac mirror was used, the highly reflective mirror was SESAM semiconductor structure. The Sagnac mirror was made from a fiber coupler based on the standard SMF-28 fiber type. The laser cavity length was controlled by inserting in the cavity a piece of SMF-28 fiber of a desired length. The lasers were pumped at 1590 nm by an Er-doped fiber laser as well, as by a semiconductor fiber-coupled pump diode operating at the wavelength of 1560 nm. The fibers were spliced by a commercial electrical fusion splicer.

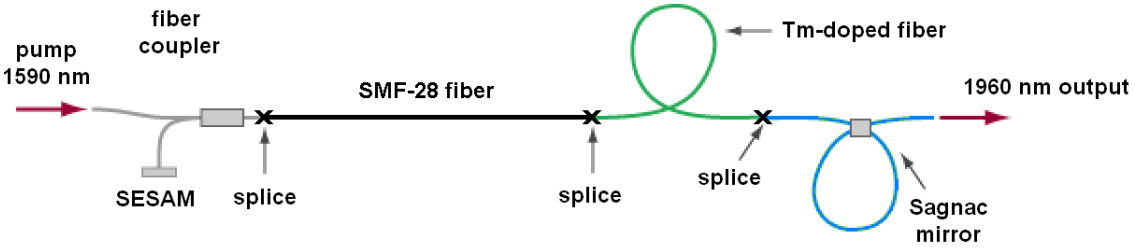

Figure 1. Schematic of the mode-locked fiber lasers.

For the measurements of the pulse duration a custom-made interferometric autocorrelator was built with a detection system based on a two-photon absorption in a Si photodetector. The pulse repetition rate was controlled by a GaAs photodetector.

3. RESULTS AND DISCUSSION

3.1 Spectroscopy

The typical absorption and emission spectra are shown in Fig. 2. The absorption level at the 1600 nm wavelength varied among the set of the fibers from 10 to 30 dB/m.

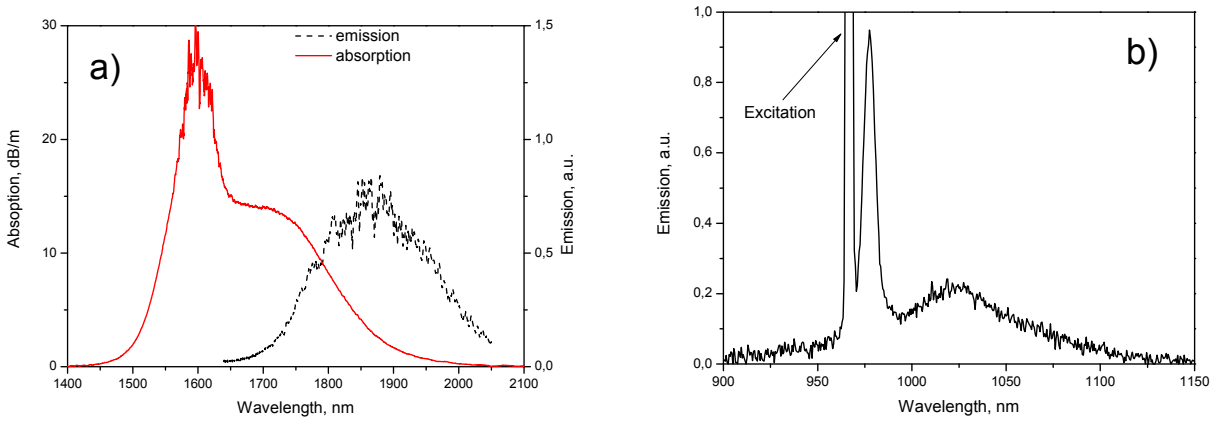

Figure 2. Typical absorption and emission spectra. In the emission spectra (b) the excitation radiation (970 nm) is also observed.

The fluorescence decays recorded with both detectors for the fibers with the worst energy transfer were exponential and nearly the same in magnitude for each fiber, varying among such fibers from 550 to 750 μs. In some of them no Tm^{3+} emission was observed at all. Other fibers were characterized by non-exponential decays; the Yb^{3+} decay time was shorter than the decay comprised of the fluorescence contributions from both Yb^{3+} and Tm^{3+} ions. The time constant of the Yb^{3+} decay amounted to 540 μs as compared to approximately 650 μs of the decay of the gathered fluorescence from Yb^{3+} and Tm^{3+}. It is worth noticing that such fibers showed the most intensive Tm^{3+} fluorescence relatively to the Yb^{3+} fluorescence among the fibers' set. Typical snapshots of the decays are shown in Fig. 3.

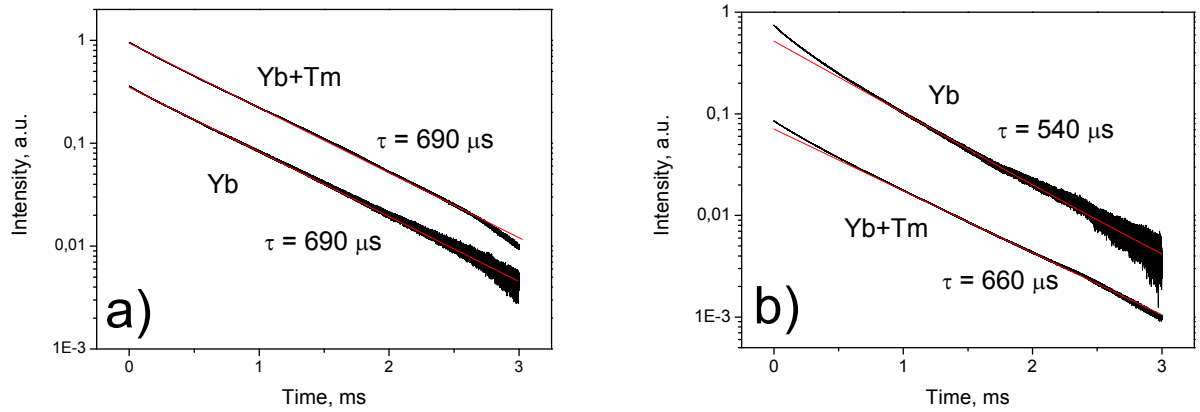

Figure 3. Typical decays of fluorescence from Yb^{3+} and Tm^{3+} ions, and from solely Yb^{3+} ions: a) exponential decays in the absence of the energy transfer; b) non-exponential decays corresponding to the energy transfer between the ions. The decays' constants as well as exponential curves are shown for convenience.

The non-exponential decays were further decomposed in a sum of two exponential decays. Also, the ratio of the integrals under the emission curves of Tm^{3+} and Yb^{3+} was calculated to compare the relative emission intensity of these ions among the set of the fibers. These results are presented in the Table 2.

Table 2. Ratio K of the integrals under the emission curves of Tm^{3+} and Yb^{3+}, and decay constants τ and τ_{yb} corresponding to the emission from both ions and from Yb^{3+}, respectively. The decay constants obtained from the decomposition of the experimental non-exponential decays in the sum of two exponential decays are presented in brackets.

Fiber	K	τ, μs	τ_{yb}, μs
LCTP-1	<0.1	730	740
LCTP-2	<0.1	690	690
LCTP-3	0.32	540	560
LCT-2	0.4	620	600
LCT-3	0.56	560	560
LCT-6	0.79	650 (250/690)	540 (150/580)
LCT-8	0.88	660 (240/710)	540 (210/610)

It is seen that there is practically no thulium emission in the fibers doped with germanium oxide. In contrast, the fibers codoped with Y oxide show the strongest thulium emission. These fibers are also characterized by a non-exponential emission decay which is an indication of an efficient energy transfer between the ions. The decay constants for these fibers, τ and τ_{yb}, are also noticeably different in contrast to other fibers. At the same time, the longest components of the non-exponential decays correspond to the decay constants of the other fibers. We suppose that these components corresponding to the decay tail describe the decays of Tm and Yb ions in the absence of the energy transfer. We assume that these results indicate that Y oxide improves the energy transfer between Yb and Tm ions.

3.2 Mode-locked lasers

For the laser experiments the fibers LCT-6 and LCT-8 were chosen because these fibers showed the most intense Tm emission and the energy transfer between Yb and Tm was mostly pronounced for them. The absorption coefficient at the wavelength of 1600 nm was about 30 dB/m for both these fibers. The lengths of 30 cm were used in the lasers. The core diameters of the fibers were about 20 μm and the fibers were not single-mode. Nevertheless, the short fiber length allowed us to expect a low efficiency of the conversion of the fundamental mode into the modes of higher orders. We used a piece of the standard SMF-28 fiber (Fig. 1) to increase the cavity length in order to increase the pulse energy at a fixed pump power. The resulted cavity length amounted to 25 m. We used for pumping the Er-doped fiber laser (1590 nm) or the fiber-coupled laser diode (1560 nm) and no noticeable difference was observed between these pump sources.

Both lasers showed the pretty similar behavior. At the threshold of about 40 mW they started to generate laser radiation at approximately 1954 nm wavelength in the mode-locked regime. The corresponding pulse train is shown in Fig. 4. The repetition rate amounted to 4 MHz. The output power reached 4 mW which corresponded to 1 nJ of pulse energy. Further energy increase was prevented by the by the pulse breakup. Increasing the output power resulted in the either double-pulsing or harmonic mode-locking. The slope efficiency of the laser action relatively to the launched pump power amounted to 12%.

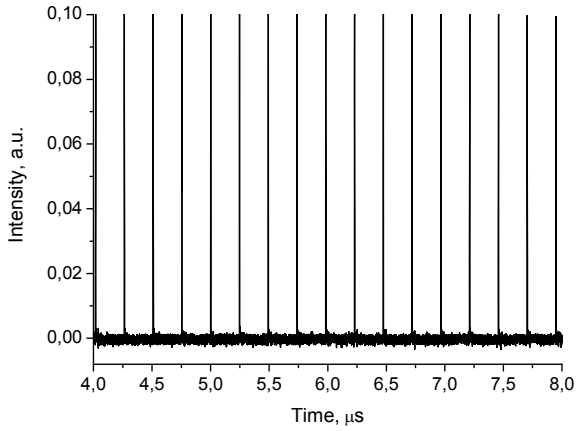

Figure 4. Typical pulse train of the mode-locked fiber lasers.

The full width at half maximum (FWHM) of the output spectrum showed in Fig. 5. amounted to the 0.8 nm. It was not possible to accurately measure the autocorrelation function with our autocorellator due to a relatively long duration of the laser pulse. The estimation from the spectrum width gives the temporal pulse width of more than 5 ps.

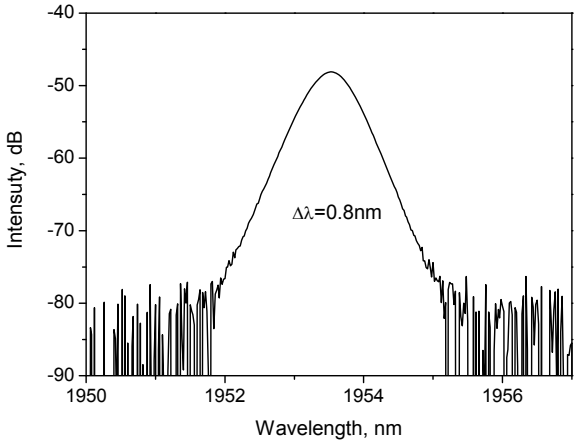

Figure 5. Output spectrum of the mode-locked fiber lasers.

The decrease of the cavity length up to 6 m by reducing the length of the SMF-28 fiber piece did not allow us neither to reduce the pulse duration, nor to increase the spectrum width. To compare these results with standard fibers, the laser based on a piece of a standard Tm-doped fiber of 2 m length produced by Nufern company was constructed according to the same laser scheme with the total cavity length of 6 m approximately. The absorption in the fiber piece was just the same as in the previous cases. The fiber core diameter amounted to approximately 10 μm thus matching well the SMF-28 fiber. In this case the repetition rate increased up to 15 MHz but the pulse breakup limited the pulse energy to 0.25 nJ. The corresponding pulse width measured with our autocorrelator amounted to 1.2 ps, and the output power before the pulse breakup amounted to 3.75 mW. The FWHM of the output radiation amounted to ~ 6 nm. The difference between the results at the moment is attributed to the difference in the active fibers' core diameters. It is supposed that the perturbation in the cavity strongly affects the soliton evolution. This conclusion also shows that the first reported here results with new fibers can be further improved with a proper optimization of the laser system. At the same time, the optical efficiency was nearly the same, about 15%, indicating that the newly developed Yb/Tm-doped fibers effeciency is comparable to the commercial fibers with direct thulium pumping.

In the conclusion, it was found that for the Yb/Tm-doped fibers codoped with Y the energy transfer was the most prominent in the fibers without Ge and P codoping whilst it was dependent on the total concentration of Al and Y oxides in their cores. Moreover, for the fibers with the same total content of Y and Al oxides in core the energy transfer was better in the ones with higher Y content. We could obtain the mode-locking regime at 1954 nm with one of such fibers of 30 cm length in a linear cavity with one of the couplers in the form of InGaAs SESAM semiconductor structure. Train of subnanosecond optical pulses with the repetition rate of 4 MHz and average power of 4 mW was observed. The corresponding pulse energy amounted to 1 nJ.

The laser experiments with direct diode pumping of the existing fibers using 975-nm diode lasers as well as fabrication and spectroscopic characterization of new Yb-Tm-doped fibers with improved parameters are in progress now. The main aim of the latter is the clarification of the role of Y codoping in enhancing the energy transfer between Yb^{3+} and Tm^{3+} ions.

The work is supported by the NFR projects FRITEK/191614 and MARTEC project MLR.

REFERENCES

[1] S. D. Jackson, “Power scaling method for 2 μm diode cladding-pumped Tm-doped silica fiber lasers that uses Yb codoping,” Opt. Lett. 28, 2192–2194 (2003).

[2] R.A. Hayward, W.A. Clarkson, P.W. Turner, J. Nilsson, A.B. Grudinin, D.C. Hanna, "Efficient cladding pumped Tm-doped silica fibre laser with high power single-mode output at 2 μm," Electron. Lett. 36, 711-712 (2000).

[3] A. Pal, A. Dhar, S. Das, K. Annapurna, A. Schwuchow, T. Sun, K. Grattan, and R. Sen, “Energy-transfer parameters in a Tm/Yb doped single mode silica fiber,” JOSA B 27, 2714-2720 (2010)

[4] D. Ghosh, H.T. Bookey, M.Pal, M.C. Paul, S.K. Bhadra and A.K. Kar, “Characterisation of Yb-Tm co-doped air-clad fibers for 2 μm laser applications,” in proc. of 23rd Annual Meeting of the IEEE Photonics Society, pp. 510-511 (2010).