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Abstract

We present preparation and spectroscopic characterization of the Tm-doped fibers with enhanced $^3H_4$ fluorescence lifetime thanks to codoping with alumina. With the alumina content of 10 mol %, the fluorescence lifetime of 58 μs was achieved. Using experimentally obtained fiber characteristics, we used numerical simulations to study and optimize for the first time the thulium-doped fiber amplifier (TDFA) with dual wavelength (800 + 1400 nm) pumping scheme where the pump at 800 nm propagates in the cladding and the other pump propagates in the core. The results are compared with numerical simulations of TDFA pumped at single-wavelength in the 1050 nm band.

Keywords: fiber lasers; fiber amplifiers; thulium PACS: 42.81 Fiber optics, 42.55.Wd Fiber lasers, 42.70.Hj Laser materials

1. Introduction

The thulium doped fibers are promising candidates for optical amplification in the optical telecommunication S-band (1460-1530 nm). Since the nonradiative decay of the lasing transition of thulium in conventional silica based fibers is high, the lower phonon energy, fluoride-based fiber host are often used. However, excellent environmental stability of silica fibers and their inherent compatibility with standard telecommunication fibers makes the preparation of an efficient silica based thulium doped fiber a technological challenge. Several codopants that locally modify the silica environment of Thulium ions were investigated in order to decrease the local phonon energy and thus minimize the nonradiative decay. The S-band signal gain of 10 dB in bismuth codoped core [1] and 12 dB in gallium and yttrium codoped core [2, 3] was demonstrated. Gain of more than 20 dB was demonstrated in highly antimony codoped silicate fiber [4], but the complicated triple crucible method was used for fiber preparation and the fiber still was not compatible with standard telecommunication fibers. In our preliminary report [5] we have demonstrated that incorporation of alumina can increase the 1470 nm luminescence quantum efficiency. Another issue to be addressed in the TDFA design is the pumping scheme. Since the lifetime of the upper laser level is shorter than the lifetime of the lower level, population inversion can be hardly achieved with a direct pumping of the upper laser level. To overcome the problem, upconversion pumping at single wavelength of about 1050 nm, see Fig. 1a, or two pumps at different

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wavelengths can be used. The pumping methods are reviewed e.g. in [6].

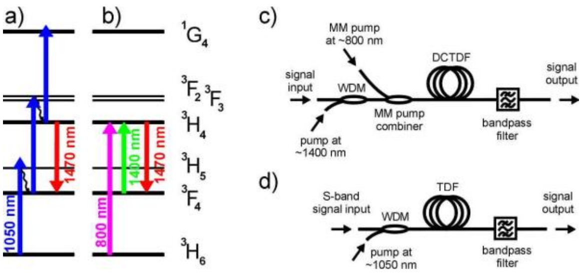

Fig. 1. (a, b) TDFA upconversion pumping schemes. Dual-wavelength (c) and single-wavelength (d) TDFA setup.

In this paper we report preparation and spectroscopic characterization of the Tm-doped fibers with enhanced $^3H_4$ fluorescence lifetime thanks to codoping with alumina. With the experimentally obtained fiber characteristics, we present numerical modeling of Tm-doped fiber amplifier at telecommunication S-band. For the first time we study the dual wavelength scheme using combination of cladding pumping at the wavelength λ_{p1} in the 800 nm band, and pumping in the fiber core at λ_{p2} in the 1400 band, see Fig. 1b. The method was proposed in [3] but to our knowledge it was studied neither experimentally nor theoretically. Since the effective absorption cross section can be varied by proper ratio of the core and cladding cross section areas, this method offers one more degree of freedom in the TDF design. In addition, relatively inexpensive, multimode and high power pump diodes at 800 nm can be used. The TDF amplifier performance under this pumping scheme is compared with the upconversion pumping at single wavelength λ_{p3} in the 1050 nm band.

2. Fiber preparation and characterization

The fiber preforms were fabricated by using the MCVD (Modified Chemical Vapor Deposition) method. Thulium and aluminum ions were incorporated by solution doping technique. Germanium was also added to increase the refractive index. It was incorporated during the core layer deposition and collapsing passes. Electron Microprobe Analysis was made and GeO_2 and Al_2O_3 typical concentrations of 4 and up to 10 mol %, respectively. Thulium ions concentration was estimated from the $^3H_4$ absorption peak and it varied typically between 40-300 ppm.

The fluorescence lifetime of the $^3H_4$ level in the fiber of the highest (10 mol %) alumina content was measured to be 58 µs (under direct excitation at 786 nm). The $^3H_4$ lifetime in high alumina codoped fiber represents an improvement compared to pure or weakly modified silica glass where the respective lifetime is about 14 µs [7]. The fluorescence lifetimes of the $^3H_4$ and $^1G_4$ levels were measured to be about 430 µs (using direct excitation at 1586 nm) and 540 µs (using upconversion excitation at 980 nm), respectively. In the case of the $^1G_4$ level lifetime measurement, a fiber codoped with ytterbium was used. Luminescence decay waveforms were non exponential. Therefore the lifetime of the levels were taken as the time where the fluorescence intensity decreases to 1/e of its initial value. This non-exponential behavior has been observed in many other thulium-doped glasses. The luminescence detected is the sum of the emission from all the emitting centers. In a glass, such as silica, there are many sites with different environment for thulium. This site to site variation yields to distribution of crystal fields and then to various lifetimes for thulium which implies the non-exponential shape of the decay curves.

3. Modeling of Tm^{3+} doped fiber amplifier

The setup of the TDFA under investigation is shown in Fig. 1c. The S-band input signal is combined with the 1400 nm pump in the wavelength division multiplexer (WDM) and then coupled together with 810 nm multi-mode (MM) pump to the double-clad (DC) TDF. Several methods can be used to combine the pump and signal into the DCTDF, reviewed e.g. in [8]. The DCTDF is of a narrow core for single-mode propagation of the signal and 1400 nm pump; and of a wide inner cladding for propagation of the multi-mode pump. The inner cladding is surrounded by the lower index material. For predicting the amplifier performance and its optimization we developed a comprehensive, spectrally and spatially resolved numerical model described in detail elsewhere [6]. In the numerical simulations we use spectroscopic parameters listed in the previous section and in [6]. The optimized core refractive index profile of numerical aperture NA=0.4 and core diameter of 2 µm is considered [5]. For the numerical simulation we set the thulium concentration to 1000 ppm. The pair induced quenching processes among neighbouring thulium ions can be still assumed negligible at this level of concentration [7]. Unless otherwise stated, the total pump power is set to 1 W. The peak gain and optimum TDF length dependence on the pump wavelength λ_{p1} is shown in Fig. 2a for several ratios of the core to cladding areas Γ_{p1}. The ratio Γ_{p1} corresponds approximately to the pump overlap with the thulium ions. The second pump of power 700 mW and λ_{p2}=1395 nm is used. The gain characteristics are found rather flat with respect to the second pump in the 1390-1410 nm range and the pump power between 500-800 mW. For small overlap Γ_{p1} corresponding to a typical cladding pumping case the maximum gain of about 26 dB is achieved for the wavelength λ_{p1}=790 nm. With increasing overlap, i.e. with smaller inner cladding cross section area, the optimum pump shifts towards longer pump wavelength. For λ_{p1}=805 nm and Γ_{p1}=0.2 the gain of 28 dB is achieved.

The single-wavelength upconversion scheme using the pump wavelength λ_{p3} from the 1050 nm band, see Fig. 1a and 1d, is also studied. The peak gain and optimum TDF length are shown Fig. 2b. Commonly used pump wavelengths of 1050 and 1064 provide gain of 17 and 14 dB, respectively, considerably lower than the optimized dual-wavelength scheme, at the same total pump power level of 1 W. For higher pump power at λ_{p3}, the optimal pump wavelengths shifts towards 1020 nm, where the gain of 24 dB is achieved, only slightly lower than the optimized dual wavelength gain. However, it might be a problem to find suitable high power pump source at this wavelength as the highly efficient Yb-fiber laser source are more difficult to build at wavelength below 1030 nm [9].

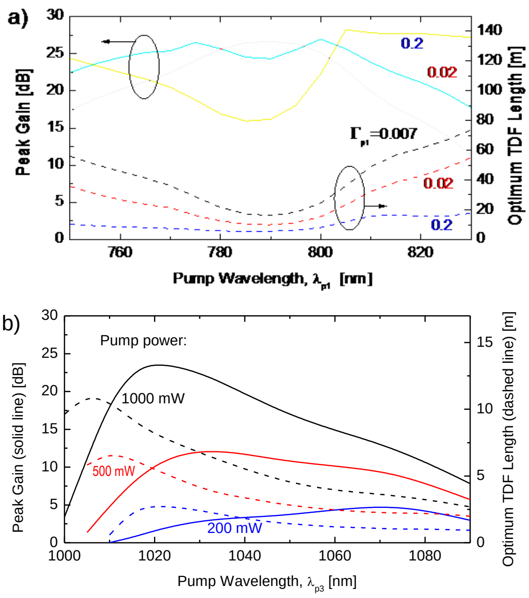

Fig. 2. Maximum gain and optimum TDF length for (a) dual wavelength scheme using 800 nm + 1400 nm pump band and (b) upconversion pumping at single wavelength.

4. Conclusions

We presented preparation and spectroscopic characterisation of the Tm-doped fibres with enhanced $^3H_4$ fluorescence lifetime thanks to codoping with alumina using MCVD and solution doping methods. With the alumina content of 10 mol %, the fluorescence of 58 μs was achieved. Using the experimentally obtained fibre characteristics, we studied and optimized for the first time TDFA with dual wavelength pumping scheme where one of the pumps propagates in the cladding while the other pump propagates in the core. Although higher gain was predicted for the dual wavelength scheme, the optimized single wavelength scheme might be preferable thanks to its less complexity.

In this work we limited the study only to the pumping scheme at the wavelength of 800 nm band (cladding) and the 1400 nm. Next step would be modeling of the cladding pumped Tm/Yb fiber devices. The in-core pumping of Tm/Yb fiber S-band amplifiers has been already proposed [3] and also studied theoretically [10].

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