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Enhanced broadband upconversion emission and 23 dB optical gain at 780 nm in Tm^{3+}/Nd^{3+} codoped optical fiber

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ABSTRACT

Maximum gain of 23 dB at 780 nm and a broadband optical gain with full width at half maximum (FWHM) of 88 nm (761–849 nm) were obtained from the Tm^{3+}/Nd^{3+} codoped fiber upon pumping at 1550 nm. The enhancement of the upconversion emission stretching from 730 to 970 nm was observed in the Tm^{3+}/Nd^{3+} codoped fiber due to the energy transfer from Tm^{3+} to Nd^{3+} ions.

1. Introduction

Significant progress has been made in optical amplifier technology especially for the amplifiers operating in the 1550 nm telecommunication window, so-called the third window wavelength band. Due to the combination of high gain with wideband optical amplification available in the low-loss window of optical fiber, amplifiers operating in the 1550 nm band have become the most widely used amplifiers in optical communications [1]. However, there is no suitable amplifier for the old first window wavelength band (FWWB, ~800 nm), which was commonly used for the multi-mode fiber communication. The FWWB is not popular in telecommunication system because of high loss and dispersion of the fiber presented in this wavelength band. Recently, as a result of the rapid increase in information traffic and for need of wavelength division multiplexing optical communication, the FWWB has come into focus [2].

Emission of Tm around 800 nm has attracted significant interest in developing an efficient laser source and amplifier operating in the FWWB. However, lasing around 800 nm is hard to achieve in Tm-doped materials especially in silica based materials due to their relatively low quantum conversion efficiency [3]. Fortunately, the emission efficiency of Tm^{3+} can be enhanced by using upconversion pumping scheme and by codoping Tm^{3+} with other rare earth ions [4–8]. Theoretical and experimental studies have been reported for upconversion pumping of Tm around 800 nm [9–11]. In addition, the enhancement of upconversion emission efficiency of Tm^{3+} ions has also been reported by effectively using Nd^{3+} ions as a sensitizer [12,13]. By modification of local environment of Tm^{3+} ions with Nd^{3+} ions, the quantum conversion efficiency is raised and the lasing is possible even for silica based optical fiber.

The current study aimed at the quantitative analysis of the energy transfer between Tm^{3+} and Nd^{3+} as a contribution to the growing interest in high power operation of the fiber lasers. Our experiment can reduce the laser threshold by using an efficient and low-cost pumping scheme. The emission was drastically increased in the codoped samples because Tm has strong energy absorption at 1550 nm and can effectively transfer energy to Nd^{3+} ions. A peak gain of about 23 dB at 780 nm has been achieved in single mode fiber with FWHM of 88 nm upon pumping with a 1550 nm laser source.

2. Experiment

The optical fiber preform doped with 0.1 M% of Tm^{3+} ions and 0.05 M% of Nd^{3+} ions was fabricated by the modified chemical vapor deposition process. The core, outer and total diameters of the fiber were 7.52, 125 and 270 m, respectively. The estimated

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concentrations of Tm^{3+} and Nd^{3+} in the Tm^{3+}/Nd^{3+} codoped optical fiber were 1.76×10^{25} and $0.91 \times 10^{25}\ m^{-3}$, respectively. The index difference between the core and cladding was 0.0039 and the cutoff wavelength was 1250 nm. The absorption spectrum was measured by the cutback method using a broadband white light source emitting from 350 to 1750 nm. Gain measurements were conducted by using light source operating at 1550 nm as a pump source and 980 nm LD as a signal source. The pump light source and the input signal source were coupled into the single mode optical fiber (SMF) by using a 3 dB coupler. The resulting absorption, emission and gain spectra were observed using an optical spectrum analyzer (OSA, Ando AQ-6315B).

3. Results and discussion

Fig. 1 shows the absorption spectrum and corresponding energy levels of Tm^{3+}/Nd^{3+} codoped fiber. The figure showed nine prominent absorption peaks within the wavelength range of 400–1750 nm. The absorption peaks at 525, 588, 739 and 861 nm were attributed to Nd^{3+} ions and the peak at 1212 nm was related to Tm^{3+} ions. Nd^{3+}: ${}^4I_{9/2} \rightarrow {}^4G_{7/2} + {}^4G_{5/2} + {}^2G_{7/2}$ transition showed the highest absorption peak at 588 nm. The other four absorption bands of Tm^{3+} and Nd^{3+} overlapped at 459, 679, 785 and 1579 nm. The sharp absorption peak at 785 nm and wide absorption peak at 1579 nm were due to the transition of Tm^{3+}: ${}^3H_6 \rightarrow {}^3H_4$, Nd^{3+}: ${}^4I_{9/2} \rightarrow {}^4F_{5/2}$ and Tm^{3+}: ${}^3H_6 \rightarrow {}^3F_4$, Nd^{3+}: ${}^4I_{9/2} \rightarrow {}^4I_{15/2}$, respectively.

Upconversion emission spectrum recorded from the Tm^{3+}/Nd^{3+} codoped fiber was investigated at room temperature using a fiber light source operating at 1550 nm with pump power of 120 mW, as shown in Fig. 2. The broadband upconversion emission extending from 728 to 997 nm with FWHM of ~200 nm was observed in the Tm^{3+}/Nd^{3+} codoped fiber with 1550 nm pumping. The emissions peaking at 780 and 905 nm were related to Tm^{3+}: ${}^3H_4 \rightarrow {}^3H_6$ and Nd^{3+}: ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transitions, respectively. Cooperative upconversion is normally obscure at low pumping levels since it requires two interacting ions in the excited state. At high pump powers it appears as accelerated and nonexponential decay due to interaction of strength between excited ions [14].

The Judd–Ofelt (JO) analysis was applied using the absorption bands of Nd^{3+} in the Tm^{3+}/Nd^{3+} codoped optical fiber to characterize its spectroscopic properties. The JO parameters for current fiber are calculated in [15] and listed in Table 1, following the trend $\Omega_2 > \Omega_4 > \Omega_6$. The large value of the intensity parameter Ω_2 in the present work is indicative of the amount of covalent bonding between rare earth ions (Tm^{3+} and Nd^{3+}) and ligand anions. High covalency provides greater Ω_2 values, which indicates lower symmetry around the rare earth ion in the host. The parameter Ω_4 and Ω_6 are associated with the rigidity of the medium in which the ions are situated. The ratio Ω_4/Ω_6 (1.2 in the present work) determines the spectroscopic quality of material and implies that the Tm^{3+}/Nd^{3+} codoped fiber possessed a good spectroscopic quality. The fluorescence lifetime of Nd: ${}^4F_{3/2}$ transition at 1074 nm was measured to be 0.55 ms. The quantum efficiency at 780 nm was 1.3×10^{-7} when the pump power of 120 mW at 1550 nm was applied.

The energy transfer mechanism involved in the upconversion process is presented in Fig. 3. The mechanism of the upconversion

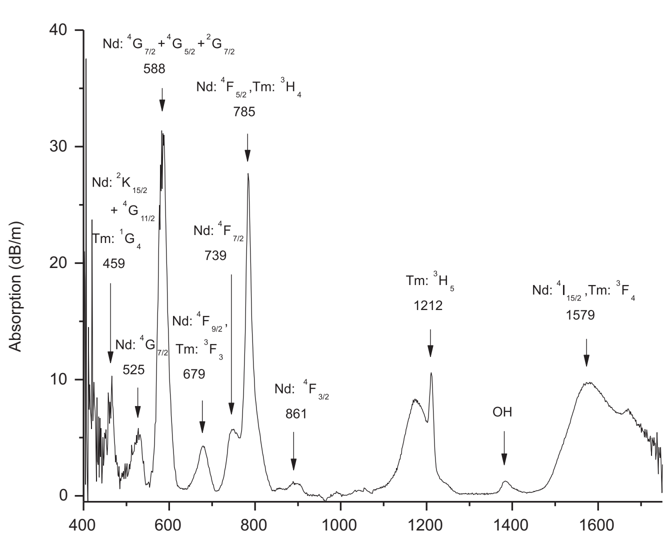

Fig. 1. Absorption of the Tm^{3+}/Nd^{3+} codoped optical fiber at room temperature.

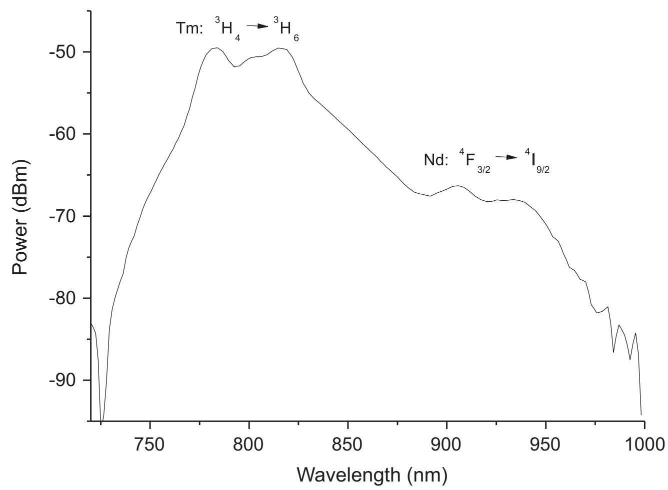

Fig. 2. Upconversion emission of the Tm^{3+}/Nd^{3+} codoped fiber with the excitation of 1550 nm laser.

Table 1
Calculated optical parameters of the Tm^{3+}/Nd^{3+} codoped optical fiber.

JO intensity parameter ($10^{-24}\ m^2$)	Tm^{3+}/Nd^{3+} doped fiber
Ω_2	8.16 ± 0.30
Ω_4	3.2 ± 0.13
Ω_6	2.67 ± 0.23

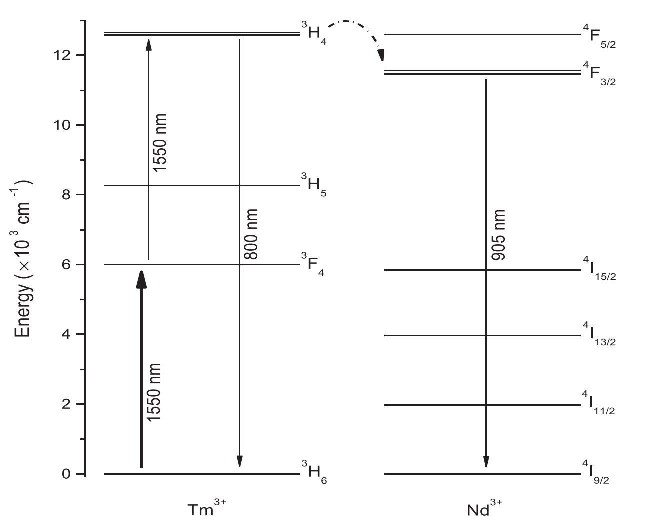

Fig. 3. The energy level diagrams representing the cooperative upconversion of Tm^{3+} and Nd^{3+} ions.