Optics Communications 410 (2018) 632–636

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Sensitivity-enhanced Tm^{3+}/Yb^{3+} co-doped YAG single crystal optical fiber thermometry based on upconversion emissions

Lu Yu, Linhua Ye *, Renjie Bao, Xianwei Zhang, Li-Gang Wang

Department of Physics, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Keywords:
Optical thermometry
Upconversion luminescence
FIR
YAG single crystal fiber
Tm^{3+}/Yb^{3+} co-doped YAG crystal

ABSTRACT

Optical thermometry based on $Y_3Al_5O_{12}$ (YAG) single crystal optical fiber with end Tm^{3+}/Yb^{3+} co-doped is presented. The YAG crystal fiber with end Tm^{3+}/Yb^{3+} co-doped was grown by laser heated pedestal growth (LHPG) method. Under a 976 nm laser diode excitation, the upconversion (UC) emissions, originating from $^3F_{2,3}\rightarrow{}^3H_6$ and $^3H_4\rightarrow{}^3H_6$ transitions of Tm^{3+} ions, were investigated in the temperature range from 333 K to 733 K. Interestingly, the UC emission intensity of $^3F_{2,3}\rightarrow{}^3H_6$ transition was significantly enhanced with increase of temperature, as compared with the other Tm^{3+}/Yb^{3+} co-doped materials. The temperature dependence of fluorescence intensity ratio (FIR) of these two emission bands ($^3F_{2,3}/{}^3H_4\rightarrow{}^3H_6$) suggests that this doped YAG crystal fiber can be used as a highly sensitive optical thermal probe, which demonstrates a high absolute sensitivity with the maximum value of 0.021 K^{-1} at 733 K. In addition, due to the compact structure, strong mechanical strength and high thermal stability, such thermal probe may be a more promising candidate for temperature sensor with a high spatial resolution.

1. Introduction

In recent decades, optical fiber temperature sensors are widely applied in harsh conditions, such as electromagnetic interference and high temperature environments. Optical fiber temperature sensors offer some unique advantages, including superior stability, high sensitivity, high resolution and fast response [1]. Among optical thermometry techniques, fluorescence intensity ratio (FIR) technique by comparing fluorescence intensities of two thermally coupled levels (TCL) has attracted much attention because of its high sensitivity and the simple working principle [2,3].

Rare earth (RE) ions which can emit visible light via upconversion (UC) mechanism have been studied widely under the proper excitation [4]. Especially, the UC emissions from TCL transitions of RE ions can be used for optical thermometry based on FIR technique. The TCL ($^2H_{11/2}$ and $^4S_{3/2}$) of Er^{3+} in Er^{3+}/Yb^{3+} co-doped materials were utilized for optical thermometry [5–10]. Blue UC luminescence of Tm^{3+} from $^1G_4\rightarrow{}^3H_6$ transition in Tm^{3+}/Yb^{3+} co-doped Y_2O_3 was studied for optical temperature sensor [11]. The temperature dependence of UC emissions from Tm^{3+} ions in Tm^{3+}/Yb^{3+} co-doped oxyfluoride glass ceramic was also analyzed [12], and the results show that the FIR of 700 nm ($^3F_{2,3}\rightarrow{}^3H_6$) and 800 nm ($^3H_4\rightarrow{}^3H_6$) is temperature dependent and the $^3F_{2,3}$ and $^3H_4$ levels are the TCL. As mentioned previously, the host materials are mainly glass, powder or ceramic. After that, Xing et al. evaluated the Tm^{3+}/Yb^{3+} co-doped $LiNbO_3$ single crystal for optical thermometry [13]. However, in $LiNbO_3$ single crystal, the intensity of 700 nm ($^3F_{2,3}\rightarrow{}^3H_6$) luminescence is weak, which causes the deviation and influences the temperature measurement accuracy in reality.

$Y_3Al_5O_{12}$(YAG) crystal is widely used as UC host materials due to its favorable chemical, optical, thermal, and mechanical properties [14,15]. In fact, the Tm^{3+}/Yb^{3+}: YAG crystals have been studied for a long time, but the research work mainly focus on growth, spectral properties and the enhancement of the blue UC emissions [16,17]. To our best knowledge, no reports have discussed the possibility of using the temperature dependence of red and near-infrared emissions of Tm^{3+}/Yb^{3+}: YAG crystal for optical thermometry.

In this paper, YAG single crystal fiber with end Tm^{3+}/Yb^{3+} ions co-doped was grown by laser heated pedestal growth (LHPG) method [18]. The YAG crystal fiber was directly connected with the Tm^{3+}/Yb^{3+} ions co-doped YAG crystal fiber, and this structure may reduce the optical connection losses and improve fluorescence collecting efficiency. The temperature dependence of red and near-infrared of UC luminescence

* Corresponding author.
E-mail address: lhye@zju.edu.cn (L. Ye).

https://doi.org/10.1016/j.optcom.2017.10.075
Received 8 August 2017; Received in revised form 24 October 2017; Accepted 27 October 2017
0030-4018/

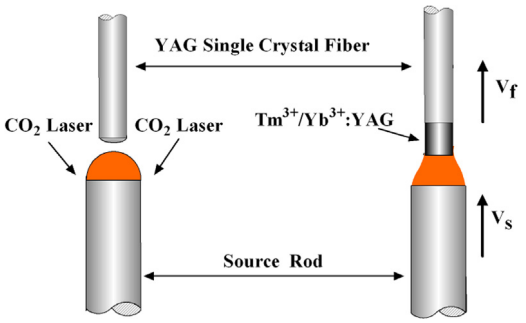

Fig. 1. Growth schematic of the YAG crystal fiber with end Tm^{3+}/Yb^{3+} co-doped.

was investigated under a 976 nm laser diode excitation. The UC mechanism of the luminescence and the sensitivity of the optical thermometry are discussed.

2. Experiments

The co-doped YAG single crystal fiber was grown from the sintered Tm^{3+}/Yb^{3+} co-doped powder rod, which was prepared from oxide mixtures with a following composition of $(Y_{0.945}Yb_{0.05}Tm_{0.005})_3Al_5O_{12}$. The doped concentrations are 5 mol% for Yb^{3+} and 0.5 mol% for Tm^{3+}, respectively. A relatively low concentration of Tm^{3+} was chosen to avoid the energy transfer (ET) of Tm^{3+}-Tm^{3+} to optimize efficiency [12]. The original powders were mixed in agate mortar using Y_2O_3 (4N), Al_2O_3 (4N), Tm_2O_3 (4N), Yb_2O_3 (4N) high purity powders. Then the mixed powders were compressed into rods which were then heat treated at 1200 °C for 4 h. Finally, the sintered source rods were formed.

Fig. 1 shows the growth schematic of the Tm^{3+}/Yb^{3+} co-doped YAG single crystal fiber by LHPG. Firstly, a pure YAG crystal fiber was grown from a source rod which was prepared from bulk YAG crystal discussed in our previous work [19]. YAG crystal fibers with length up to 400 mm and diameter up to 1 mm have been successfully prepared. Then, the grown YAG crystal fiber was used as a seed. The previously sintered powder rod was used as the source rod. Two symmetric CO_2 laser beams were focused on the top of the source powder rod to form a small molten zone. The seed, pure YAG single crystal fiber, was inserted into the molten zone. The seed was pulled upward at the speed of v_f and the sintered source rod was fed upward together at the speed of v_s. In stable growth process, due to the conservation of the mass in the melting zone, the diameter of the co-doped YAG crystal fiber can be described by an equation:

$$d_f = d_s\sqrt{\frac{\rho_s v_s}{\rho_f v_f}}. \quad (1)$$

where d_f and d_s are the diameters of the co-doped YAG crystal fiber and the source rod, respectively; ρ_s and ρ_f represent the densities of the source rod and the grown YAG crystal fiber, respectively. Hence, the diameter of the Tm^{3+}/Yb^{3+}co-doped YAG single crystal fiber can be controlled by changing the speed ratio of v_s to v_f.

Fig. 2 shows a YAG single crystal fiber with end Tm^{3+}/Yb^{3+}co-doped, where the pure YAG single crystal fiber is about 40 mm in length and 0.8 mm in diameter and the fluorescence tip (Tm^{3+}/Yb^{3+} co-doped YAG) is about 3 mm in length. The Tm^{3+}/Yb^{3+}co-doped YAG fiber grown by this method has good optical quality and high mechanical strength. Under a 976 nm laser diode excitation, strong purple colored emissions can be seen by the naked eye, as shown in the inset of Fig. 2.

3. Results and discussion

3.1. Concentration distribution

The concentrations of Yb^{3+} and Tm^{3+} ions affect the UC luminescence properties. In crystal growth process, segregation coefficient of

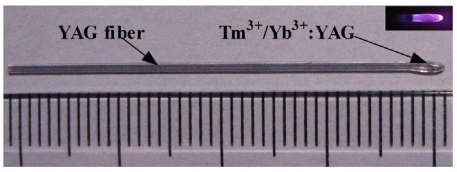

Fig. 2. (Color online) YAG single crystal fiber with end Tm^{3+}/Yb^{3+} co-doped. Inset photo shows the strong purple UC emissions.

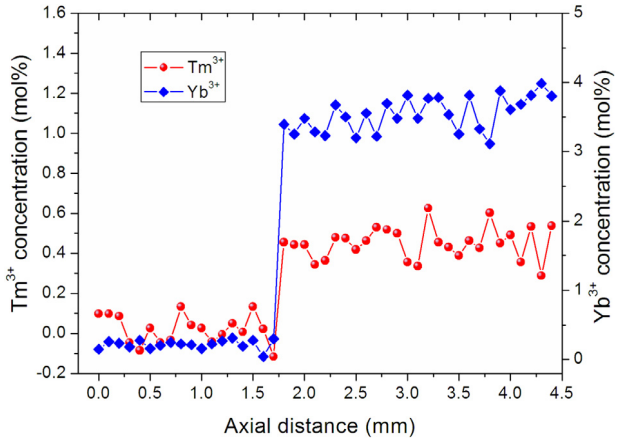

Fig. 3. Concentration distribution of Yb^{3+} and Tm^{3+} ions along the fiber.

the doped ions determines the final repartition in the host material. The concentration distribution of Yb^{3+} and Tm^{3+} ions along the fiber was analyzed by electron probe microanalyzer (EPMA) using the JEOL JXA-8100 as shown in Fig. 3. The connected position locates near 1.75 mm. The average concentrations of Yb^{3+} and Tm^{3+} ions are about 3.7 mol% and 0.42 mol%, respectively, which is lower than the starting concentration of source rod.

3.2. Temperature dependence of UC luminescence

The UC emission spectra were recorded by an optical fiber spectrometer (Seeman Tech. S3000) with a resolution of 1.5 nm under the excitation of a 976 nm laser diode (Lasever Inc. LSR980H). An infrared cut-off filter (>900 nm) was placed in front of the spectrometer to filter out the reflected 976 nm excitation laser. To improve the accuracy of measurement, a Y-shaped silica optical fiber bundle was employed to transmit the pumping light and collect the UC luminescence. The fluorescence tip was inserted in a heating stage which was controlled by a temperature control system with a type-K thermocouple in the temperature range from 333 K to 733 K.

The UC emission spectra at different temperatures were investigated under a 976 nm laser diode excitation, in which the pump power was set at 350 mW to avoid the laser induced heating [20]. Fig. 4 shows the UC emission spectra in the wavelength range from 650 to 850 nm. The spectra show two emission bands which do not overlap with each other. There is no shift of the UC emission peaks as temperature increases. One band centered at 683 nm from 660 to 740 nm is attributed to $^3F_{2,3}\rightarrow{}^3H_6$ transitions of Tm^{3+}, and the other band from 740 to 820 nm is originated from $^3H_4\rightarrow{}^3H_6$ transitions of Tm^{3+}. However, the central wavelengths of emissions from $^3F_{2,3}$ and $^3H_4$ levels are slightly different from that of previous Tm^{3+} emissions in oxyfluoride glass ceramic and $LiNbO_3$ single crystal [12,13]. Because the optical properties of RE ions are slightly influenced by the crystal field and the lattice vibration in different host materials, the two emission peaks centered at 782 nm and 786 nm show characteristic Stark splitting, ascribing to the spin–orbit splitting of the $^3H_4$ energy level in YAG single crystal. It can be