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Optimization of doping concentration in Er:tellurite glass based on heat analysis

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ABSTRACT

The comprehensive analysis about heat-generating processes is presented in Er:tellutire glass. The heat fraction of each process and total heat fraction during pumping are investigated. The results show that upconversion is an important heat-generation process and heat problem is serious especially at high Er^{3+} doping level. The influence of pump power on heat fraction is also discussed. Based on the heat analysis, the optimized doping concentration range of Erbium ions is about 0.5 mol% to 1.0 mol%.

1. Introduction

Er^{3+} ions doped materials have been used in many fields due to infrared emission. Er:tellurite glass has large and broad stimulated emission cross-sections at communication band and high fluorescence efficiency due to low phonon energy [1–3]. Therefore, Er:tellurite glass has been studied as a candidate of fiber amplifiers for many years [4–6].

In Er^{3+} ions doped solid-state laser materials, heat generated is a serious problem especially at high doping concentration [7,8]. Hence, accurate predictions of each heat-generating process and the amount of heat generated by each process in laser materials are so important, and that is also particularly useful for laser material optimization and laser design.

In this paper, a comprehensive analysis about heat composition in Er:tellurite glass is presented. By studying the relationship between heat fraction and doping concentration of Er^{3+} ions, an optimized doping concentration of Er^{3+} ions is obtained. This work is essential for material optimization and amplifier design.

2. Experimental procedure

Er:tellurite glass are prepared by common melting techniques, and the detailed procedures are listed elsewhere [9]. The batch compositions are $75TeO_2$–$20ZnO$–$(5-x)La_2O_3$–xEr_2O_3. The glass samples prepared for measurement are polished with 1.5 mm thickness. The absorption spectra are measured with Perkin-Elmer Lambda 900UV/VIS/NIR spectrophotometer and luminescence spectra and lifetimes are measured with TRIAX500 spectrophotometer with 980 nm LD as a pump source. The IR spectra are measured with HITACHI270-50 spectrophotometer. All measurements are carried at room temperature.

3. Experimental results

The absorption and photoluminescence spectrum are shown in Fig. 1. From the absorption spectrum, we can see that Er^{3+} ions have complicated energy levels, and hence there are many energy transfer channels. Except for the emission of Er^{3+} $^4I_{13/2} \rightarrow {}^4I_{15/2}$ centered at 1.5 μm, there are also upconversion emissions. The emission located at 1.5 μm is safe for eyes and the peak emission cross section σ_{em} is about 0.9×10^{-20} cm^2 and the FWHM is about 47 nm. The dependence of fluorescence intensity and OH^- absorption coefficient on Er^{3+} (mol%) concentration is shown in Fig. 2. At 1.0 mol% Er^{3+} doping concentration, the fluorescence intensity is the largest. This means the optimized Er^{3+} ions doping concentration is near 1.0 mol%. The absorption coefficients of OH^- at 3000 cm^{-1} shown in Fig. 2 are about 2.0 cm^{-1} for all samples and the effect of OH^- will be analyzed in the next section.

Although the spectral properties of Er:tellurite glass show that it is a promising candidate for the amplifier, heat is a serious problem for Er^{3+} ion doped materials [7,8]. Thus, we will discuss the heat-generation processes and investigate the heat fraction of each process in this glass.

4. Heat-generation process analysis

The simplified energy level diagram for Er^{3+} ions is shown in Fig. 3. Under 980 nm pump, an Er^{3+} ion at $^4I_{15/2}$ ground level jumps to $^4I_{11/2}$ level, then non-radiatively relaxes to $^4I_{13/2}$ level. The $^4I_{13/2}$ Er^{3+} ions radiate to ground level and emit 1.53 μm light. The major pathway for upconversion is that, two Er^{3+} ions at $^4I_{13/2}$ level interact, with one elevates to higher $^4I_{9/2}$ level, and the other jumps to ground level. Most of Er^{3+} ions on higher level drop down owning to multiphonon relaxation and generate extra heat in glass. Besides the interaction process of Er^{3+}, the interaction of Excited Er^{3+} and OH^-, the non-unity quantum efficient of Er^{3+} and the energy difference between bump photon and emission photon will induce extra heat in glass.

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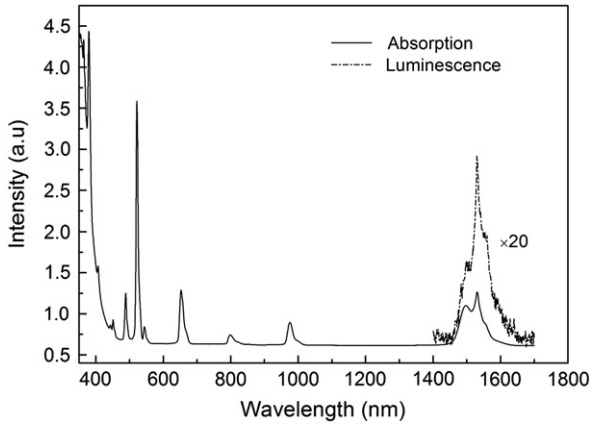

Fig. 1. The absorption and fluorescence spectrum of Er:tellurite glass.

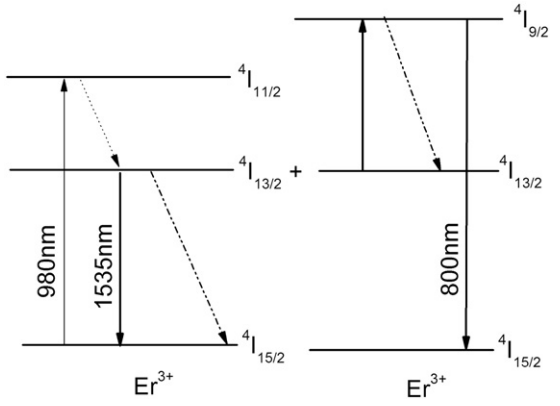

Fig. 3. The energy level diagram scheme of Er^{3+} and corresponding upconversion process.

Now, we discuss these processes and investigated heat fractions generated by these processes.

The ion density $n_m(\rho)$ evolution with time could be described by rate equation. As a function of ion concentration ρ (mol%), the ions density of $^4I_{13/2}$ level under 980 nm pump could be written as

$$\frac{dn_{4I13/2}(\rho)}{dt} = \eta_e(\rho)R_e(t) - k_R n_{4I13/2} - k_Q(\rho)n_{4I13/2} - k_{QE}(\rho)n_{4I13/2} - 2C_{UP}(\rho)n^2_{4I13/2} \quad (1)$$

Where $R_e(t)$ is the excitation density and can be time dependent, $\eta_e(\rho)R_e$ is used to account for non-unity transfer efficiency form $^4I_{11/2}$ to $^4I_{13/2}$ level.

k_R is the radiative rate constant of $^4I_{13/2}$ level. We can use the lifetime for zero Er^{3+} ion density to describe it: $k_R = 1/\tau_R$. The value of τ_R used in this paper is 3.6 ms, available from the calculation according to the Judde–Ofelt theory.

$k_Q(\rho)$ is the concentration quenching variable which is dependent on Er^{3+} ions and OH^- concentration. The lifetime of Er^{3+} ions in metastable $^4I_{13/2}$ level would decrease because of quenching. With low OH^- concentration, concentration quenching happens for the interaction of Er^{3+} ions and cannot be avoided. With high OH^- concentration, the quenching will be exacerbated because of the formation of OH^-–Er^{3+} pair. According to the theory of Dexter [10], the resonant energy transfer rate among Er^{3+} ions for the dipole–dipole interaction can be calculated from the spectral date using the following equation:

$$W_{Er-Er} = \frac{3h^4c^4}{64\pi^5 n^4 R^6}\frac{Q_a}{\tau_R}\int\frac{f_a(E)f_e(E)}{E^4}dE = \left(\frac{R_0}{R}\right)^6\frac{1}{\tau_R} \quad (2)$$

Where h is the Planck's constant, c is the speed of light, n is the refractive index of the host, E is the energy of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission, the factor of f_a and f_e are the normalized lineshape functions for the absorption and emission of the 'acceptor' and 'donor' transitions, respectively. R is the distance between donor and acceptor determined by the Er^{3+} density N_{er} according to $R = (4\pi N_{er}/3)^{-1/3}$, and $Q_a = \int \sigma_a(E)dE$ is the integrated absorption cross-section of the energy-accepting level. R_0 is the critical distance at which $W_{er-er} = 1/\tau_R$. This equation shows that the relation between W_{Er-Er} and Er^{3+} ion concentration is quadratic. Based on the assumption proposed by Yan et al. [11], the energy transfer rate W_{OH} between Er^{3+} and OH^- groups is proportional to the acceptor and donor concentrations, $W_{OH} = 8\pi C_{er-er}N_{er}N_q$. Where C_{er-er} is the interaction microparameter for the migration rate of $^4I_{13/2} \rightarrow {}^4I_{15/2}$, and can be calculated by the following equation $\frac{C_{er-er}}{R^6} = W_r\left(\frac{R_0}{R}\right)^6$. W_r is the radiative transition rate of the level calculated from the Judde–Ofelt theory. For our glass C_{er-er} is about $44\times10^{-40}cm^6s^{-1}$. N_q is the density of quenching sites which directly couple to the OH^- group. The relation between W_{OH} and Er^{3+} ion concentration is linear. In Ref. [9] the effect of OH^- is studied for our glass, and indicates that about 14% of OH^- forms the quenching center. According to the absorption coefficient shown in Fig. 2, the concentration of OH^- is about $2.7\times10^{19}/cm^3$. The quenching concentration of OH^- N_q is about $0.38\times10^{19}/cm^3$.

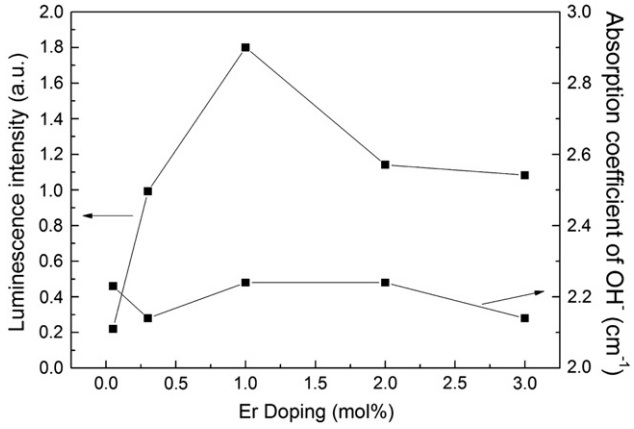

Fig. 2. The dependence of fluorescence intensity and absorption coefficient of OH^- on Er^{3+} concentration.

The dependence of decay rate $1/\tau$ on Er^{3+} concentration is shown in Fig. 4. We can see that the relation between $1/\tau$ and Er^{3+} ion concentration is approximately linear when Er^{3+} ions' doping level is below 1.0 mol%. This means the decay rate is mainly affected by the interaction of Er^{3+}–OH^- when Er^{3+} ions' doping level is below 1.0 mol%. When Er^{3+} ions' doping level is above 1.0 mol%, the relation between $1/\tau$ and Er^{3+} concentration is not linear. The decay rate is affected by the interaction of Er^{3+}–Er^{3+} and Er^{3+}–OH^- simultaneously. Therefore, $k_Q(\rho) = (W_{OH} + \delta W_{er-er})/N_{er} - 1$, Where $\delta = 0$ when Er^{3+} ions' doping level is below 1.0 mol%, and $\delta = 1$ when Er^{3+} ions' doping level is above 1.0 mol%.

$\eta_{QE}(\rho)$ is the rate constant associated with the quantum efficiency of the Er^{3+} ion laser upper level $^4I_{13/2}$ level, which is close to 1 at low Er^{3+} doping concentration. With the increase of Er^{3+} ion concentration, the quantum efficiency decreases. Therefore, we define the quantum efficiency by $\eta_{QE} = \tau/\tau_R$, where τ is the measured lifetime of