Vol 13 No 10, October 2004
1009-1963/2004/13(10)/1728-05

Chinese Physics

© 2004 Chin. Phys. Soc.
and IOP Publishing Ltd

Analysis of the laser performance of Tm^{3+}: ZBLAN glass at 1.47μm wavelength*

Huang Li-Lei(黄莉蕾)[a)†], Cao Guo-Xi(曹国熹)[b)],
Zhang Lun(张 伦)[a)], and Luo Hong-Lei(罗宏雷)[a)]

[a)] *Optoelectronic Division, China Institute of Metrology, Hangzhou* 310034, *China*

[b)] *Shanghai Institute of Optics & Fine Mechanics, Chinese Academia of Sciences, Shanghai* 201800, *China*

(Received 9 December 2003; revised manuscript received 19 May 2004)

A formula for the threshold energy of a four-level-system laser in Tm^{3+} doped fluoride glass is derived. The formula contains the parameters of the interaction between the ions and the up-conversion rate of the pump-light. It is discussed that the Tb^{3+} ions and the up-conversion pump-light have an influence on the laser performance of Tm^{3+} ions around 1.47μm wavelength. We draw the following two conclusions. (1) The laser threshold descends obviously due to the doping of Tb^{3+} ions, but the descending gradually flattens out with the increase of the content of Tb^{3+} ions. Its suitable content is (1–2)$\times 10^{20}$cm^{-3}. (2) When pump-lights both from the up-conversion and from the ground state excite simultaneously the single-doped Tm^{3+} ions, the threshold energy can reduce and the output energy can increase. In this paper, the energy conversion efficiency from the up-conversion pump-light to the output energy of laser is estimated.

Keywords: Tb^{3+} and Tm^{3+} ions, threshold energy of laser, energy conversion efficiency, dual-wavelength pumps called the up-conversion and ground state pump

PACC: 4255F, 4260

1. Introduction

Laser emission of Tm^{3+} ions at 1.47μm for the transition from the $^3F_4$ to $^3H_4$ state has been extensively studied recently. It is a four-level laser system with a lower threshold. A commercial semiconductor laser can pump the Tm^{3+} laser. However, the fluorescence branch ratios corresponding to the $^3F_4 \rightarrow ^3H_5$, $^3F_4 \rightarrow ^3H_4$ and $^3F_4 \rightarrow ^3H_6$ transitions are 0.02, 0.08 and 0.90 respectively. This indicates that the fluorescence intensity is comparatively weak. In addition, the lifetime of the $^3F_4$ state is much longer than that of the $^3H_4$ state, so the laser self-termination phenomenon exists. Therefore, in order that the Tm^{3+} laser at 1.47μm can be practically applied, further research must be performed. Ermeneux *et al*[1] and Huang *et al*[2] have discovered that if the Tb^{3+} (or Ho^{3+}) and Tm^{3+} ions are co-doped, the laser self-termination phenomenon can be eliminated due to the interaction between Tb^{3+} (or Ho^{3+}) and Tm^{3+} ions. Komukai *et al*[3] have found that using lasing light at 1.06μm to pump Tm^{3+} ions can produce the laser at 1.47μm wavelength due to the action of the up-conversion. Based on their work, DiGiovanni *et al*[4] suggested that the Tm^{3+} laser could be excited with a dual-wavelength pump-light simultaneously, which is called the ground state pump and up-conversion pump. For example the dual wavelengths are 0.8μm and 1.4μm or 0.8μm and 1.06μm. The electrons excited from the ground state to $^3F_4$ state by pump-light at 0.8μm are diexcited to the $^3H_4$ state and emit lasing light at 1.47μm simultaneously. The electrons of the $^3H_4$ state are re-excited to the $^3F_4$ state by the up-conversion pump light. Thus the intensity of the laser at 1.47μm is enhanced.

In this paper, we derive the expressions of the threshold energy and the slope efficiency, which contain some relevant parameters, such as the radiant transition rate, the probability of the interaction between Tb^{3+} and Tm^{3+} ions from the transition-rate equation. We discuss that the influence of the Tb^{3+} ions and the second pump-light (taking the up-

*Project supported by the Natural Science Foundation of Zhejiang Province, China (Grant No 600087).

†E-mail: hll_2002cn@yahoo.com.cn, Tel. 0571-86914483.

conversion pump-light at 1.4μm as example) on the performance of the laser at 1.47μm of Tm^{3+} ions.

2. Theoretical analysis on laser threshold

2.1. Basis of theoretical analysis

The cross-relaxation interactions between Tm^{3+} ions and between Tb^{3+} and Tm^{3+} ions can be expressed as P, P_{C1} and P_{C2}, respectively. By taking into account the cross-relaxations between ions and using the dual pump-light at 0.8μm and 1.4μm wavelengths, the scheme of energy levels of ions including the interaction between the ions is shown in Fig.1. According to Fig.1, the transition-rate equations containing the laser can be written, respectively, as

$$\frac{dN_4}{dt} = -Q'_4N_4 + W_2N_2 + W_1N_1 + v[\sigma_{as}N_2 - \sigma_{es}N_4]\cdot[\rho_s^+(z) + \rho_s^-(z)], \quad (1)$$

$$\frac{dN_3}{dt} = Q'_{43}N_4 - Q_3N_3, \quad (2)$$

$$\frac{dN_2}{dt} = Q'_{42}N_4 + Q_{32}N_3 - Q'_2N_2 + PN_1, \quad (3)$$

$$N_1 + N_2 + N_3 + N_4 = N_0, \quad (4)$$

where

$$\begin{aligned} Q'_4 &= Q_4 + P_{c2} + P, \\ Q'_{42} &= Q_{42} + P, \\ Q'_{43} &= Q_{43} + P_{c2}, \\ Q'_2 &= Q_2 + P_{c1}, \end{aligned} \quad (5)$$

and where W_1 and W_2 are the pump rates from the ground state $^3H_6$ and the excited state $^3H_4$ to the excited state $^3F_4$ respectively; Q_{ij} is the summation of the radiant and non-radiant transition probabilities from the ith to jth level, while $Q_i = \sum_j Q_{ij}$ is the summation of the transition probabilities from the ith level to all the levers lower than the ith level. The P is the cross-relaxation probability for the $^3F_4 \rightarrow {}^3H_4$ and $^3H_6 \rightarrow {}^3H_4$ transitions of Tm^{3+} ions. N_0 is the concentration of Tm^{3+} ions, and N_i is the density of the population at the ith level.

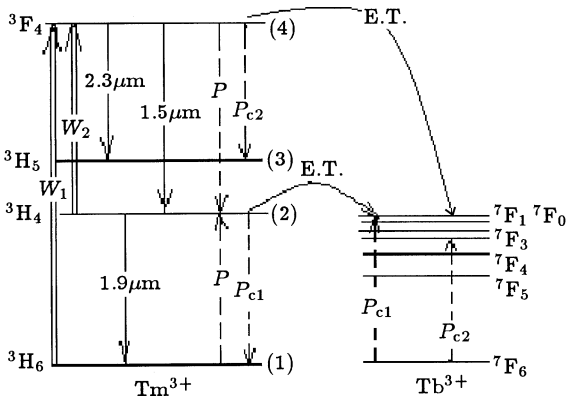


Fig.1. Scheme of energy levels of ions including the interaction between the ions.

According to the transition-rate equations of the levels and Ref.[5], the transmission equations of the laser and pump-light can be written, respectively, as

$$\frac{d\rho_{1p}(z)}{dz} = -\sigma_{1ap}\rho_{1p}(z)N_1, \quad (6a)$$

$$\frac{d\rho_{2p}(z)}{dz} = -\sigma_{2ap}\rho_{2p}(z)N_2, \quad (6b)$$

$$\frac{d\rho_s^+(z)}{dz} = (\sigma_{es}N_4 - \sigma_{as}N_2)\cdot\rho_s^+(z), \quad (7a)$$

$$\frac{d\rho_s^-(z)}{dz} = -(\sigma_{es}N_4 - \sigma_{as}N_2)\cdot\rho_s^-(z), \quad (7b)$$

where ρ_s, ρ_{1p} and ρ_{2p} represent the densities of photon number of the laser, the pump-lights from the ground state and the excited state $^3H_4$, respectively. The superscripts of ρ_s, '+' and '–', indicate the direction of the laser as being the same as and opposite to the pump-light respectively. $W_1 = v\sigma_{1ap}\rho_{1p}(z)$ and $W_2 = v\sigma_{2ap}\rho_{2p}$, where σ_{1ap} and σ_{2ap} are the absorption cross-sections of the ground state and up-conversion pump-light, respectively. σ_{es} and σ_{as} represent the emission and absorption cross-sections for the lasing light at 1.47μm,

Table 1. Optical parameters.

	Transition probabilities							
$Q_{i,j}/s^{-1}$	Q_2	Q_{32}	Q_3	Q_{41}	Q_{42}	Q_{43}	Q_4	
	184	3.89×10^4	3.89×10^4	793	70	18	885	
	Transition frequencies ν/cm^{-1}			Transition cross-sections/$10^{-20}cm^2$				
	ν_{gp}	ν_{up}	ν_s	σ_{1ap}	σ_{2ap}	σ_{es}	σ_{as}	
	12560	7143	6803	0.31	0.031	0.1	0.1/3	
	Cross-relaxation probabilities between Tm^{3+} ions P/s^{-1}			Cross-relaxation probabilities between Tm^{3+} and Tb^{3+} ions P_{c1} and P_{c2}/s^{-1}				
	P			P_{c1}		P_{c2}		
	$45x^2$			$2381xy$		$778xy$		

Note that: The concentration of Tm^{3+} and Tb^{3+} ions are N_0x and N_0y, respectively, both are in a units of $10^{20}cm^{-3}$.

respectively. v is the light speed in the medium. These probability parameters are calculated according to the Judd–Ofelt and Dexter theories adopted in Ref.[6]. The optical parameters quoted from Ref.[6] are listed in Table 1.

According to the transition-rate equations of the steady state, we obtain the following equations:

$$N_2 = \frac{1}{Q_2'Q_3}(Q_{42}'Q_3 + Q_{43}'Q_{32}) + \frac{P}{Q_2'}N_1, \quad (8)$$

$$N_4 = \frac{Q_2'Q_3}{\alpha}\left[N_0 - \left(1 + \frac{P}{Q_2'}\right)N_1\right], \quad (9)$$

where

$$\alpha = Q_{43}'Q_2' + Q_{42}'Q_3 + Q_{43}'Q_{32} + Q_3Q_2'. \quad (10)$$

The gain is defined as

$$G = \int_0^L (\sigma_{es}N_4 - \sigma_{as}N_2)\mathrm{d}z. \quad (11)$$

Inserting Eqs.(8) and (9) into Eq.(11) and combining Eqs.(5)–(7), we can obtain the threshold condition subject to the gain equal to the loss as shown below:

$$-\ln R = \frac{A}{\alpha}N_0L - \frac{B}{\alpha}\frac{\Psi}{\sigma_{1ap}}, \quad (12)$$

where

$$A = \sigma_{es}Q_2'Q_3 - \sigma_{as}(Q_{42}'Q_3 + Q_{43}'Q_{32}), \quad (13a)$$

$$B = \sigma_{es}(Q_2' + P)Q_3 - \sigma_{as}[(Q_{43}'Q_3 + Q_{43}'Q_{32}) - P(Q_3 + Q_{43}')]. \quad (13b)$$

Adding Eqs.(6a) and (6b) together, multiplying by dz both sides of the resulting equation, and then integrating it from 0 to L, we can obtain the photon number density $\rho_p(0)$ of the pump-light at the input end. According to the definition of the threshold power density, namely $P_{th} = v\rho_p(0)h\nu_p\tilde{A}$, and $E_{th} = P_{th}Q_4''$, the expressions for the threshold energy E_{th} and slope efficiency η_s can be written, respectively, as

$$E_{th} = \tilde{A}h\nu_{gp}\frac{Q_2'Q_3Q_4''}{Q_4'}\left\{\left[1 - \left(1 + \frac{P+M}{Q_2'}\right)\frac{A}{B}\right]\frac{N_0L}{\alpha} - \left(1 + \frac{P+M}{Q_2'}\right)\frac{\ln R}{B}\right\}\Big/[1 - \exp(\Psi)], \quad (14)$$

$$\eta_s = \frac{\nu_s}{\nu_{gp}}\frac{(1-R_2)\sqrt{R_1}}{(1-R)(\sqrt{R_1}+\sqrt{R_2})}[1 - \exp(-\Psi)], \quad (15)$$

$$\Psi = \sigma_{1ap}\left(\frac{A}{B}N_0L + \frac{\alpha}{B}\ln R\right). \quad (16)$$

In Eq.(14)

$$Q_4'' = Q_4' - W_2(Q_{42}' + Q_{43}'/Q_2', \quad (17)$$

$$M = W_2P\frac{Q_2' + Q_{42}' + Q_{43}'(Q_2' + Q_{32})/Q_3}{Q_2'Q_4''}, \quad (18)$$

and $\tilde{A}$ is the area of a facula of the pump-light if the cross-section of the crystal rod is larger than that of the pump-light, L represents the length of the crystal rod, h is Planck's constant, ν_s, ν_{gp} and ν_{up} respectively represent the frequencies of the laser, the ground state pump-light and up-conversion pump-light, $R = \sqrt{R_1R_2}$, where R_1 and R_2 represent the reflectivities of the input and output mirrors of the resonant cavity, respectively. Because the laser rod is shorter, the loss of light in the resonant cavity at different wavelengths is approximately independent of the length of the laser rod. So the backward transmission loss can be regarded as a constant and is included in R_2. In this paper, $R_1 = 0.99$ and $R_2 = 0.94$ are assumed.

2.2. Analysis of results

Inserting the parameters in Table 1 into the threshold expression Eq.(14), we can obtain the following results.

1. When the sample doped with Tm^{3+} (namely x=2, y=0) and the sample co-doped with Tm^{3+} and Tb^{3+} ($x = y$=2) are both excited by the pump-light from the ground state, their relationships of threshold energy E_{th} versus the length of the laser rod are respectively shown in Fig.2.

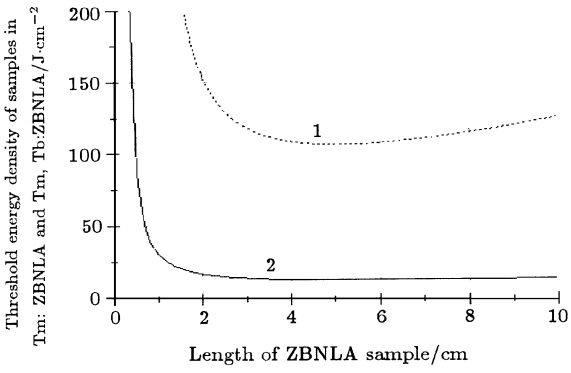


Fig.2. Threshold energy density versus length of sample-rod. Curve 1, Tm:ZBNLA, curve 2, Tm, Tb:ZBNLA.

2. If the length L of the laser rod co-doped with Tm^{3+} and Tb^{3+} ions is equal to 5cm and the medium rod is excited by the pump-light from the ground

state, the relationships of threshold energy $E_{\rm th}$ versus the concentration y of Tb^{3+} ions are shown in Fig.3.

3. A ratio γ of the threshold energy with the sample excited only by the ground state pump light to that with the sample co-excited by pump light of dual-wavelength (called the ground state and up-conversion pump, respectively) is

$$\gamma=\frac{E_{\rm th}(W_2\neq 0)}{E_{\rm th}(W_2=0)}=\frac{Q_4''}{Q_4}\frac{\left\{\left[1-\left(1+\dfrac{P+M}{Q_2'}\right)\dfrac{A}{B}\right]\dfrac{N_{0\rm L}}{\alpha}-\left(1+\dfrac{P+M}{Q_2'}\right)\dfrac{\ln R}{B}\right\}}{\left\{\left[1-\left(1+\dfrac{P}{Q_2'}\right)\dfrac{A}{B}\right]\dfrac{N_{0\rm L}}{\alpha}-\left(1+\dfrac{P}{Q_2'}\right)\dfrac{\ln R}{B}\right\}}. \quad (19)$$

The ratio γ versus the up-conversion pump rate W_2 is shown in Fig.4.

3. Discussions

1. Generally, the threshold energy of a four-level laser system is slightly dependent on the length of medium rod.[7] In Fig.2 the optimal length of the laser rod corresponding to the minimum of the threshold energy is about 5cm due to action of the cross-relaxation between Tm^{3+} ions. If the cross-relaxation between Tm^{3+} ions does not exist, namely P=0, the threshold energy equation (14) can be rewritten as follows:

$$E_{\rm th}=\tilde{A}h\nu_{\rm gp}Q_2'Q_3\left\{-\frac{\ln R}{B}\right\}\Big/[1-\exp(-\Psi)], \quad (20)$$

where Ψ is an increasing function with the length of the rod. When the length of the rod exceeds a certain value, that is, $1-\exp(-\Psi)\to 1$, the threshold energy will slightly depend on the length of the glass rod.

Rosenblatt *et al*[8] have measured the laser threshold energy in six different concentrations of Tm^{3+} and Tb^{3+} ion co-doped ZBLAN glasses. Of them, we take two cases with the length of the glass rod L=1cm for example. One is the 0.5% Tm^3:ZBLAN and the other is the 1%Tm^{3+}, 1%Tb^{3+}:ZBLAN. The reflectivities of the input and output mirrors of the resonant cavity are R_1=100% and R_2=99.7%, respectively. The measured threshold energies are 130 and 185μJ, respectively. Under the above condition the threshold energies calculated from Eq.(14) are 320 and 106μJ, respectively. The calculated and experimental values have the same order of magnitude, therefore it is suitable to base the discussion about the threshold energy on Eq.(14).

2. When the concentration of Tm^{3+} ions and the length of the glass rod L are fixed, the relationships of threshold energy $E_{\rm th}$ versus the content y of Tb^{3+} ions are shown in Fig.3. From Fig.3 it can be seen that the doping of Tb^{3+} ions causes the threshold energy $E_{\rm th}$ to obviously descend. When the content of the Tb^{3+} ions exceeds (1–2)$\times 10^{20}$cm^{-3}, the threshold energy descends gradually and tends to a constant value. This indicates that the content of Tb^{3+} ions is not required to be too high and the suitable content is (1–2)$\times 10^{20}$cm^{-3}.

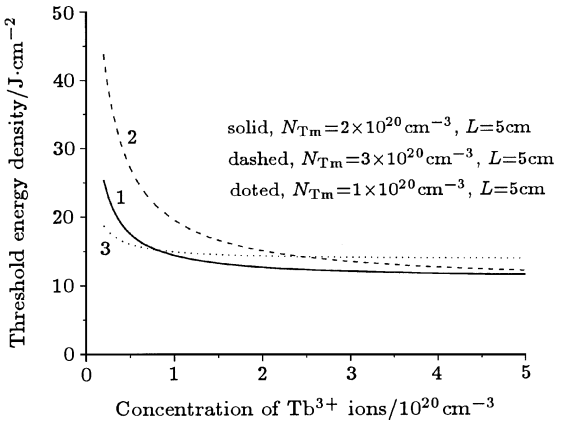


Fig.3. Threshold energy density versus concentration of Tb^{3+}: curve 1, x=2; curve 2, x=3; curve 3, x=1.

3. Figure 4 indicates that the up-conversing pump-light has a noticeable influence on the threshold energy in Tm^{3+}:ZBLAN glass. The ratio γ decreases with the increasing of the up-conversion pump rate W_2, but it hardly affects the threshold energy in the Tm^{3+}, Tb^{3+}:ZBLAN. According to the expressions for the ground state pump rate and the threshold energy, $W_1=v\sigma_{\rm 1ap}\rho_{\rm 1p}$ and $E_{\rm th}=\tilde{A}h\nu_{\rm gp}v\rho_{\rm 1p}/Q_4''$, when the input pump-light energy equals the threshold energy, the ground state pump rate can be expressed as $W_1=E_{th}\sigma_{\rm 1ap}Q_4'/(\tilde{A}h\nu_{\rm gp})$, the up-conversion pump rate as $W_2=E_{\rm th}\sigma_{\rm 2ap}Q_4'/(\tilde{A}h\nu_{\rm up})$ similarly. In this paper, the wavelength of the up-conversion pump-light is 1.47μm, thus $\sigma_{\rm 2ap}\approx\sigma_{\rm as}\approx\sigma_{\rm 1ap}/10$.

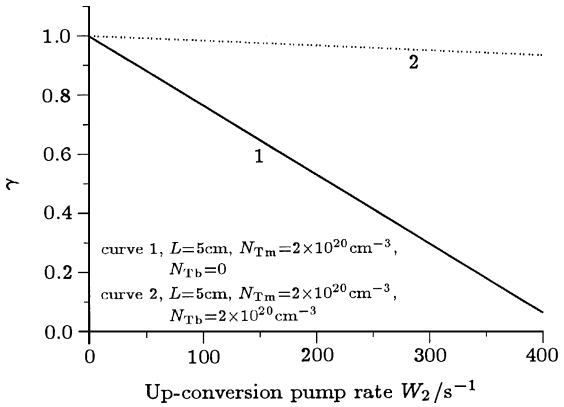


Fig.4. Ratio of threshold energy density versus pump rate under the conditions of double wavelength pump and single wavelength pump.

It can be seen from Fig.4 that when the up-conversion pump rate W_2=200s^{-1} and the length of sample L=5cm, the threshold energy of the Tm^{3+} laser decreases to 50%, namely γ= 0.5. This indicates that when the summation of the energy of both pump lights at 1.4μm and 0.8μm wavelengths is the same as that at single wavelength, the use of dual-wavelength pump-light can make the output energy increase due to the effect of the up-conversion.

According to the expression $E_{out} = \eta(E_{in} - E_{th})$ (where η is the slope efficiency), the energy conversion efficiency ξ from the up-conversion pump energy E_2 to the output energy can be derived, namely $\xi = \eta(1-\gamma)E_{th}/E_2$. Inserting the above values γ=0.5 and $E_2 = E_{th}$ into $\xi = \eta(1-\gamma)E_{th}/E_2$, we can obtain $\xi = 0.5\eta$. W_2 is relevant to the σ_{2ap}, which is related to the wavelength of the pump-light and the host material. Therefore, the energy conversion efficiency ξ is related to the pump-light from the ground state and up-conversion and the characteristics of the host materials. The relevant results will be published in another paper.

4. Conclusions

For the laser of Tm^{3+} ions at 1.47μm wavelength, a good method of improving the laser performance is the co-doping of Tm^{3+} and Tb^{3+} ions or the use of pump light of dual wavelengths, which is called the ground pump and excited state pump simultaneously. The co-doping of Tb^{3+} ions not only eliminates the laser self-termination phenomena, but enables the threshold energy to descend obviously. The suitable content of Tb^{3+} ions is (1–2)×10^{20}cm^{-3}. The Tb^{3+} ions have good capability to be sensitive to Tm^{3+} ions. If the pump-lights from the ground state and up-conversion are used to excite Tm^{3+} ions simultaneously, the laser threshold energy can be decreased while the output energy can be increased. The energy conversion efficiency from the up-conversion pump-light to output laser can be estimated based on the fundamental optical parameters measured.

References

[1] Ermeneux F S *et al* 1997 *Opt. Mater.* **8** 83

[2] Huang L L, Fu Y B and Wu L N 2003 *Chin. Phys.* **12** 1417

[3] Komukai T, Yamamoto T, Sugawe T and Miyajima Y 1992 *Electron Lett.* **28** 830

[4] DiGiovanni D J 2002 *Optical Fiber Communication Conference (OFC)*, p568 (ThZ 1)

[5] Huang L L, Wu L N and Fu Y B 2003 *Acta Opt. Sin.* **23** 887 (in Chinese)

[6] Huang L L, Cao G X and Zhang L 2003 *Optoelectron. Technol. Inform.* **16** (Supplement) 7 (in Chinese)

[7] Huang L L and Hong Z 1998 *Acta Phys. Sin.* **47** 1504 (in Chinese)

[8] Rosenblatt G H, Ginther R J, Stoneman R C and Esterowitz L 1989 *Tunable Solid State Laser Conf.* (Cape Cod, MA) **200** paper WE2-1