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ANALYSIS OF LASING PERFORMANCES OF Yb^{3+}-DOPED YAG, FAP, KYW CRYSTALS*

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The Yb^{3+} laser emitting at a 1.03μm wavelength has been evoking strong interest recently due to its advantages of long fluorescence lifetime, broad absorption band and the fact that it never shows concentration quenching. On the other hand, as a laser of three-level system it has, in general, a relatively high threshold power, which makes it important to seek some suitable host crystals to reduce this. Here, we present a comparison of the lasing performances of Yb^{3+}-doped YAG [$Y_3Al_5O_{12}$], FAP [$Ca_5(PO_4)_3F$] and KYW [$KY(WO_4)_2$] crystals, including threshold power and slope efficiency, with those of the Nd:YAG laser based on the threshold formula of three- and four-level systems deduced by the authors. The results show that the Yb^{3+} laser can output a power larger than the Nd:YAG laser does in the case of comparably higher pumping power, if the length of the lasing rod and the concentration of the active ions satisfy some conditions. The theoretical results are also close to the experimental results reported.

Keywords: lasing performance, Yb^{3+} ions, YAG, FAP and KYW crystals
PACC: 4260, 4255, 4270

I. INTRODUCTION

The configuration of Yb^{3+} is $4f^{13}$. There are only two energy levels, namely the ground state $^2F_{7/2}$ and the excited state $^2F_{5/2}$. The Yb^{3+} laser operating on the $^2F_{7/2}$–$^2F_{5/2}$ transition emits lasing light at a 1.03μm wavelength, close to that of Nd:YAG. But compared with the Nd^{3+} ion, Yb^{3+} has a longer fluorescence lifetime (about 3–4 times as long as that of Nd^{3+}) and broader absorption band (about 10–20 times as large as that of Nd^{3+}). In addition, the Yb^{3+} laser has only one excited level, $^2F_{5/2}$, which offers advantages in avoiding the attenuation of lasing intensity from concentration quenching and energy upconversion. Due to these advantages much more research attention is being paid to the Yb^{3+} laser.[1–4] On the other hand, as a three-level system, the Yb^{3+} laser has a higher threshold power compared with the Nd^{3+} laser. Only under the condition of large pumping power could the Yb^{3+} laser show advantages in lasing performance.[5] Choosing an appropriate host crystal for decreasing the threshold power is one of the important tasks. From Refs.[4] and [6] it is clear that KYW and FAP crystals are promising candidates.

The lasing threshold power and the slope efficiency, as a token of lasing performance, are determined by parameters such as the size of the crystal rod, the concentration of doped ions, the design of resonant cavity and the character of the pumping light beam. References [2–4] have shown experimentally the lasing performances of Yb^{3+}-doped YAG ($Y_3Al_5O_{12}$), FAP ($Ca_5(PO_4)_3F$) and KYW ($KY(WO_4)_2$) crystals. But some of the characteristics, including those of the resonant cavity and the pumping beam, were not defined fully. Therefore, quantitative study is difficult in determining the relations between the lasing performance and the designing parameters.

This paper evaluates quantitatively the lasing performances of Yb^{3+}-doped YAG, FAP, and KYW crystals on the basis of the formula of threshold power and slope efficiency deduced by the authors[7] from the transition-rate equations and transmission equations of the photons in the resonant cavity. We present the critique for the lasing performances of these three Yb^{3+}-doped crystals, and point out how to choose the length of crystal rod, the concentration of doped ions and the cavity parameters to gain the optimal operation of these lasers.

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II. THE BASIS OF THEORY AND THE CALCULATED RESULTS

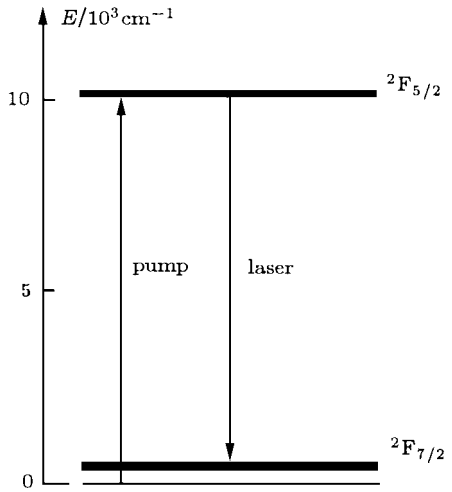


Fig.1. Stark energy levels of Yb:YAG.

The energy levels of the Yb^{3+} ion in the host crystals are shown in Fig.1. The Yb^{3+} ions stimulated by a pumping light of a 0.94μm wavelength will emit lasing light at a wavelength of 1.03μm. The Yb^{3+} laser is a three-level system. Its threshold power P_{th} and slope efficiency η_{s} are given by[7]

$$P_{\mathrm{th}}^{(3)} = Ah\nu_{\mathrm{p}}\left[N_0L - \frac{\Psi(\lambda)}{\sigma_{\mathrm{ap}}}\right] \cdot \frac{Q_{21}}{[1-\exp(-\Psi^{(3)}(\lambda))]}, \quad (1)$$

$$\eta_{\mathrm{s}}^{(3)} = \frac{\nu_{\mathrm{s}}}{\nu_{\mathrm{p}}}\frac{(1-R_2)\sqrt{R_1}}{(1-R)(\sqrt{R_1}+\sqrt{R_2})} \cdot [1-\exp(-\Psi^{(3)}(\lambda))], \quad (2)$$

in which

$$\Psi^{(3)}(\lambda) = \frac{\sigma_{\mathrm{ep}}}{\sigma_{\mathrm{es}}+\sigma_{\mathrm{as}}}[\ln R + \sigma_{\mathrm{es}}N_0L], \quad (3)$$

where ν_{p} and ν_{s} are the frequencies of pumping and lasing light, respectively; σ_{ap} and ν_{as} are the absorption cross sections of Yb^{3+} ions at the wavelengths of the pumping light and the lasing light, respectively; σ_{es} is the efficient emission cross section at the lasing wavelength; $Q_{21} = 1/\tau_{21}$ is the transition probability for $^2F_{5/2} \rightarrow {}^2F_{7/2}$. The effective reflectivities of the input and output mirrors are expressed by R_1 and R_2, respectively (the one-way transmission loss of the cavity is included in R_2), and $R = \sqrt{R_1R_2}$. L and N_0 denote the length of the crystal rod and the density of doped Yb^{3+} ions, respectively. A is the cross-sectional area of the pumping beam at the end-face of the crystal rod, and h is the Planck constant.

The parameters, such as the absorption and the efficient emission cross section, the wavelengths of the pumping and the lasing light of YAG, FAP and KYW crystals, are listed in Table 1. The structures of the crystals FAP and KYW are hexagonal (a=0.93697nm, c=0.68843nm) and monoclinic (a=0.805nm, b=1.035nm, c=0.754nm, β=94°), respectively, whose optic behaviours are anisotropic. Therefore, the orientation of the crystal rod must be indicated. In terms of the size of the crystal cell and the number of molecules in the crystal cell, the numbers of 1at% Yb^{3+} ions in YAG, FAP and KYW crystals can be calculated to be 1.38, 1.91 and 0.64 ($\times 10^{20}\mathrm{cm}^{-3}$), respectively.

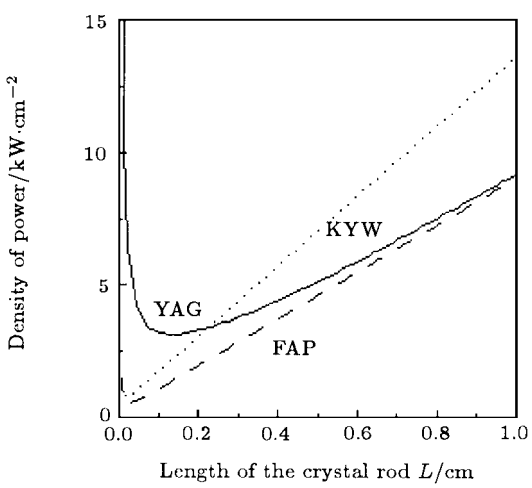


Fig.2. The density of threshold power versus the length of the crystal rod L for N_0=6.5×1.38 × $10^{20}\mathrm{cm}^{-3}$.

Table 1. Optic parameters for calculation.

Crystal	λ_{p}/μm	λ_{s}/μm	$\sigma_{\mathrm{ap}}/10^{20}\mathrm{cm}^{-2}$	$\sigma_{\mathrm{as}}/10^{20}\mathrm{cm}^{-2}$	$\sigma_{\mathrm{es}}/10^{20}\mathrm{cm}^{-2}$	$Q_{21}(1/\tau_{\mathrm{s}})/\mathrm{s}^{-1}$
YAG[1]	0.941	1.030	0.7	0.1	1.8	862
FAP[6]	0.905	1.043	6.9	0.3	5.9($//\vec{c}$)	926
KYW[4]	0.981	1.025	12.0	0.2	3.0($//\vec{a}$)	1163

Figures 2 and 3 illustrate the density of threshold power (P_{th}/A) calculated using Eqs.(1)–(3) versus the length (L) of the crystal rod and the density (N_0) of Yb^{3+} ions doped, respectively. In the calculation, we take R_1=0.99, R_2=0.90. The slope efficiencies for the three lasers versus the length of the crystal rod are shown in Fig.4, in which R_1 and R_2 are the same as in Figs.2 and 3.

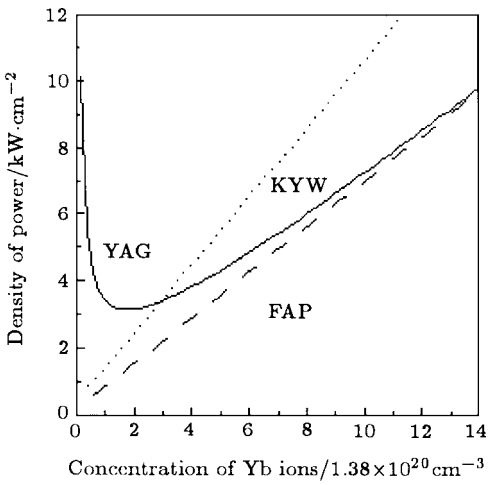


Fig.3. The density of threshold power versus the concentration of doped Yb^{3+} ions for the length of the crystal rod L_0=0.5cm.

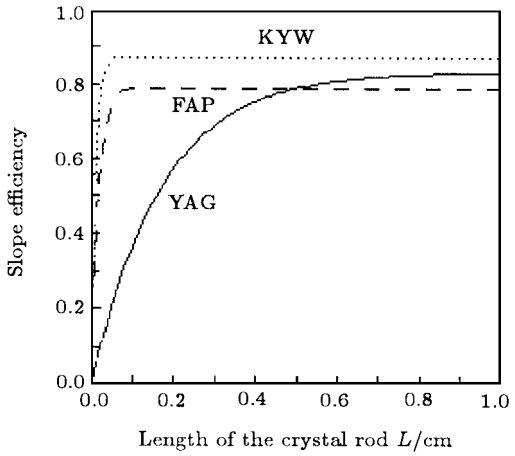


Fig.4. The slope efficiency versus the length of the crystal rod L for N_0=6.5×1.38 × 10^{20}cm^{-3}.

III. DISCUSSION

Table 2 illustrates the experimental and calculated lasing performances of Yb^{3+}-doped YAG, FAP and FAW crystals. In the table the experimental data, represented by the superscript "exp", are taken from Refs.[3,4,8], and the calculated values ("cal") are obtained from Eqs.(1)–(3) in this paper. It can be seen that the calculated values are close to the experimental data. This indicates that Eqs.(1)–(3) can be used as a basis for the comparison of the lasing performance of these crystals.

Table 2. The comparison of the experimental data with the calculated values.

Crystal	N_0 /10^{20}cm^{-3}	x /at%	L /cm	A /μm^{-2}	$P_{th}^{exp}A^{-1}$ /kW·cm^{-2}	$P_{th}^{cal}A^{-1}$ /kW·cm^{-2}	η_s^{exp} /%	η_s^{cal} /%
YAG[8]	27.6	20	0.10	(37×156)	(3.5)	3.8	30	70
FAP[3]	0.36	0.2	0.54	37×156	0.8	0.54	40	56
KYW[4]	3.2	5	0.10	(37×156)	(1.2)	0.93	78	84

A. Selection of the length and the density of Yb^{3+}-doped YAG, FAP, and FAW crystals

There are an optimal length of the crystal rod and density of doped ions corresponding to minimum lasing threshold power for the three crystals. Differentiating with respect to the variable (N_0L) in Eq.(1), we can obtain the optimum $(N_0L)_{opt}$ which satisfies the following equation:

$$\frac{\sigma_{ap}}{\sigma_{es}+\sigma_{as}}\left[\sigma_{es}(N_0L)_{opt}+\frac{1}{2}\ln(R_1R_2)\right] = \ln\left\{\frac{[\sigma_{as}(N_0L)_{opt}-\ln\sqrt{R_1R_2}]\sigma_{ap}\sigma_{es}}{\sigma_{as}(\sigma_{es}+\sigma_{as})}+1\right\}. \quad (4)$$

Solving Eq.(4), the optimal $(N_0L)_{opt}$ obtained are 1.215, 0.205 and 0.185 ($\times10^{20}$cm^{-2}) for YAG, FAP and KYW crystals, respectively, corresponding to the minimum of the threshold power density, $(P_{th}A^{-1})_{min}$, of 3.0, 0.51 and 0.83kW·cm^{-2}. So if FAP and KYW are used as host crystals, the lasing threshold power of the Yb^{3+} laser can be as low as one-sixth and one-third, respectively, of the YAG host crystal.

From Figs.2 and 3 it can be seen that the curve of P_{th}-L or P_{th}-N_0 for FAP and KYW crystals will cut with that of the YAG crystal at certain N_0 or L. This indicates that the predominance of YAP and KYW crystals compared with the YAG crystal will lose if

the density of doped ions is too high or the length of the crystal rod is too long. On the basis of Eqs.(1)–(3), the nodical equation of the curves of $P_{\rm th}$-L (or $P_{\rm th}$-N_0) of the two crystals can be written as

$$\left\{h\nu_{\rm p}\frac{(\sigma_{\rm as}N_0L-\ln\sqrt{R_1R_2})}{\sigma_{\rm as}+\sigma_{\rm es}}Q_{21}[1-\exp(-\Psi(\lambda))]^{-1}\right\}_{\rm YAG}$$
$$=\left\{h\nu_{\rm p}\frac{(\sigma_{\rm as}N_0L-\ln\sqrt{R_1R_2})}{\sigma_{\rm as}+\sigma_{\rm es}}Q_{21}[1-\exp(-\Psi(\lambda))]^{-1}\right\}_{\rm FAP,KYW}, \quad (5)$$

where the subscripts YAG, FAP and KYW represent the host crystals. By solving Eq.(5), we can obtain the condition under which the threshold powers of Yb^{3+}-doped FAP and KYW crystals are lower than that of the YAG crystal. This condition is that the product of the density of Yb^{3+} ions N_0 and the length of the crystal rod L, (N_0L), is smaller than 14.25 and 2.05 ($\times10^{20}{\rm cm}^{-2}$), for FAP and KYW, respectively. For example, if N_0=6.5×1.38×$10^{20}{\rm cm}^{-3}$, corresponding to the atomic fraction x=0.065, the lengths of the crystal rod L of FAP and KYW should be shorter than 1.6 and 0.2cm, respectively. If the length of the crystal rod L=0.5cm, the densities of Yb^{3+} ions in FAP and KYW crystals, N_0, should be less than 28.5×$10^{20}{\rm cm}^{-3}$ ($x\leq0.149$ in the FAP crystal) and 4.1×$10^{20}{\rm cm}^{-3}$ ($x\leq0.64$ in the KYW crystal), respectively.

B. The relationship between the output power and the pump power

A good laser design should be that the lasing threshold power $P_{\rm th}$ is low and the slope efficiency $\eta_{\rm s}$ is high. Hence, it is necessary to discuss the relations between the output power and the pump power for the three Yb^{3+}-doped lasers and for the Nd:YAG laser.

If the length of the crystal rod of Yb:FAP and Yb:KYW is longer than 0.2cm, then the slope efficiency $\eta_{\rm s}$ will increase to the maximum; thus we let L=0.2cm as the basis for the following discussion. The densities of Yb^{3+} ions in the FAP and KYW hosts calculated by the optimum product N_0L are listed in Table 3. In the table the density of Yb^{3+} ions in YAG is the same as that in the experiment of Lacova,[1] and the density of Nd^{3+} ions and the length of the Nd:YAG crystal rod are taken from Ref.[5].

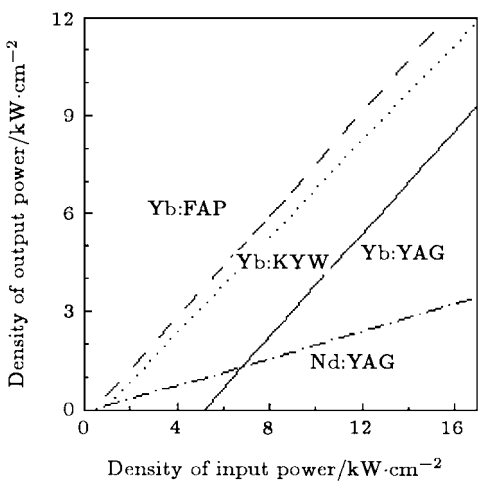


Fig.5. The density of output power versus the density of input power.

Table 3. The parameters of the four crystals such as the density of doped ions, the length of the crystal rod, threshold power and slope efficiency.

Crystal	Concentration of Yb^{3+} or Nd^{3+} N_0 /$10^{20}{\rm cm}^{-3}$	Length of crystal rod L /cm	Density of threshold power $P_{\rm th}A^{-1}$ /kW·cm^{-2}	Slope efficiency $\eta_{\rm s}$ /%	Pumping light wavelength $\lambda_{\rm p}$ /μm
Yb:YAG	6.5×1.38	0.4	4.5	76	0.941
Yb:FAP	0.55×1.91	0.2	0.41	79	0.905
Yb:KYW	1.45×0.64	0.2	0.81	74	0.981
Nd:YAG[5]	1.0×1.38	1.0	0.25	55	0.810

The relationship between output power and pump power can be easily written as $P_{\rm out} \approx \eta_{\rm s}(P_{\rm in} - P_{\rm th})$, and their curves for different lasers are shown in Fig.5. It can be seen from Fig.5 that for Yb:FAP and Yb:KYW lasers, if the pump power is larger than 1 and 2.5kW·cm^{-2} respectively, the output power of these two lasers will be greater than that of the Nd:YAG laser. But for the Yb:YAG laser, the pump power should be larger than 15kW·cm^{-2}.

IV. CONCLUSION

The lasing performances of Yb^{3+}-doped YAG, FAP and KYW crystals, including the threshold power and slope efficiency, have been investigated theoretically. The results show that by choosing an appropriate length of crystal rod and density of doped ions, the lasing threshold powers for FAP and YKW crystals can be as low as one-sixth and one-third that of the Yb^{3+}:YAG crystal, respectively, which is only a little higher than that of the Nd:YAG laser. But the slope efficiencies for the three lasers are as high as about 80%, much larger than that of Nd:YAG. Therefore, FAP and KYW are good Yb^{3+}-doped laser crystals. The theoretical results are also close to the experimental results reported.

References

[1] Lacovara P, Choi H K, Wang C A, Aggarwal R L and Fan T Y 1991 *Opt. Lett.* **16** 1089

[2] Marshall C D, Smith L K, Beach R J, Emanuel M A, Schaffers K I, Skidmore J, Payne S A and Chai B H T 1996 *IEEE J. Quantum Electron.* **32** 650

[3] Payne S A, Smith L K, Deloach L D, Kway W L, Tassano J B and Krupke W F 1994 *IEEE J. Quantum Electron.* **30** 170

[4] Kuleshov N V, Lagatsky A A, Shcherbitsky V G, Mikhailov V P, Heumann E, Jensen T, Diening A and Huber G 1997 *Appl. Phys.* B **64** 409

[5] Huang L L and Hong Z 2000 *Proc. SPIE* **3929** 338

[6] Deloach L D, Payne S A, Chase L L, Smith L K, Kway W K and Krupke W F 1993 *IEEE J. Quantum Electron.* **29** 1179

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

[8] Yang P Z, Deng P Z, Xu J, Huang G S, Chen W and Qiao J W 1999 *Acta Opt. Sin.* **19** 132 (in Chinese)