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Judd–Oflet analysis of spectrum and laser performance of Ho:YAP crystal end-pumped by 1.91-μm Tm:YLF laser*

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The Ho:YAP crystal is grown by the Czochralski technique. The room-temperature polarized absorption spectra of Ho:YAP crystal was measured on a c-cut sample with 1 at% holmium. According to the obtained Judd–Ofelt intensity parameters $\Omega_2 = 1.42 \times 10^{-20}\,\mathrm{cm}^2$, $\Omega_4 = 2.92 \times 10^{-20}\,\mathrm{cm}^2$, and $\Omega_6 = 1.71 \times 10^{-20}\,\mathrm{cm}^2$, this paper calculated the fluorescence lifetime to be 6 ms for ${}^5I_7 \rightarrow {}^5I_8$ transition, and the integrated emission cross section to be $2.24\times10^{-18}\,\mathrm{cm}^2$. It investigates the room-temperature Ho:YAP laser end-pumped by a 1.91-μm Tm:YLF laser. The maximum output power was 4.1 W when the incident 1.91-μm pump power was 14.4 W. The slope efficiency is 40.8%, corresponding to an optical-to-optical conversion efficiency of 28.4%. The Ho:YAP output wavelength was centred at 2118 nm with full width at half maximum of about 0.8 nm.

Keywords: Ho:$YAlO_3$, solid-state lasers, Judd–Ofelt analysis, Tm:YLF laser
PACC: 2320C, 4255R, 6170, 4260D

1. Introduction

Solid state lasers emitting in the 2 μm region are of great interest for eye-safety applications like Doppler radar wind sensing,[1] range finding or water vapour profiling.[2] Also, high-power quasi-continuous wave 2 μm lasers with high peak power are effective pump sources of optical parametric oscillators for frequency conversion in the 3–12 μm range.[3]

Tm and Ho co-doped media with large emission cross section can meet the requirement of generating high peak power laser pulse, but they suffer from more high up-conversion effects and energy transferring between Tm and Ho.[4,5] One way to alleviate these effects is to make Ho and Tm in separate crystals. With the quickly development of high power 1.9 μm laser as an efficient pump source, the 2 μm lasers based on Ho-doped crystals have become prominent in these applications, and the host materials for these Ho lasers are usually $Y_3Al_5O_{12}$ (YAG),[6,7] $LiYF_4$ (YLF).[8] The room-temperature Ho:LuAG[9] and Ho:ZnS[10] have been also demonstrated. For rare-earth ions doped laser host materials, YAP was chosen for study as a promising efficient singly doped laser material.[11–13] The natural birefringence of YAP, which combined with similar mechanical properties to YAG, is beneficial in the capability to provide clean linearly polarized beams with virtually no depolarization loss.[14] Some papers on laser actions of Tm:YAP and Tm, Ho:YAP have been published.[15–17] However, the laser actions of in-band pumping Ho:YAP crystal at room temperature have never been reported to date.

In this paper, we firstly report on the room-temperature Ho:YAP lasing at 2.12 μm end-pumped by a 1.91-μm Tm:YLF laser. In the first experimental step, the Ho:YAP polarized absorption spectrum is measured. From the absorption spectrum, we calculate such spectral parameters as the intensity parameters, oscillation strength, spontaneous emission probabilities, fluorescence lifetime, absorption cross sections and emission cross sections of several Ho^{3+} transitions according to the Judd–Ofelt theory. Furthermore, the laser actions of Ho:YAP crystal is investigated.

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2. Experimental and theory of Ho:YAP spectroscopy

The Ho:YAP crystal is grown by the Czochralski technology in Shanghai Institute of Optics and Fine Mechanics, China. The absorption spectrum experiment is performed with a 1-mm-long, $4\times4\,\mathrm{mm}^2$ aperture, 1 at%-doped c-cut (Pbnm notion, along growth direct direction) Ho:YAP crystal.

The Ho:YAP crystal is taken on a c-cut sample and the absorption spectrum is shown in Fig.1. The spectrum was measured by the JASCO V-570 spectrophotometer (ultraviolet/visible/near-IR, 1 nm resolution). As can be seen from Fig.1, some small splits in the vicinity of 645 nm, 1150 nm and 1930 nm are due to the Stark energy splitting in the final state. Many intensive absorption peaks in Ho:YAP crystal occur around 1871, 1885, 1907, 1923, 1931, 1946, 1970 and 1983 nm. The Ho:YAP broad absorption at $2\,\mu$m makes it to be very easy for free running approximately $2\,\mu$m Tm-doped laser pumping, it is unlike the Ho:YAG which has very narrow absorptive peak at $1.91\,\mu$m.

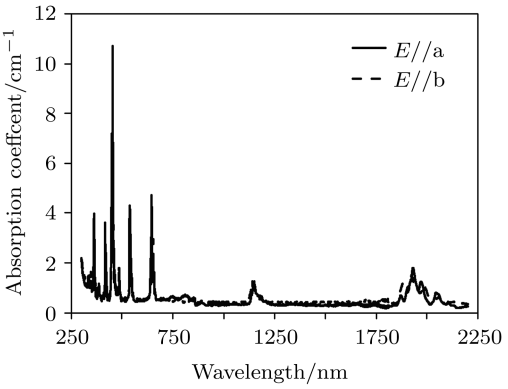


Fig.1. Room-temperature polarized absorption spectrum of Ho:$YAlO_3$.

The radiative transition within the $4f^N$ configuration of a lanthanide ion can be analysed using the Judd–Ofelt approach. Radiative transitions of rare earth ions in solids are predominately of electric dipole nature. For transitions between multiplets of the $4f^N$ configuration in randomly oriented systems the experimental oscillator strengths, f_{exp}, corresponding to absorption bands can be obtained using the following formula:[14]

$$f_{\mathrm{exp}} = \frac{1}{N}\frac{m_{\mathrm{e}}c}{\pi e^2}\int k\,(\upsilon)\mathrm{d}\upsilon, \tag{1}$$

where m_{e} and e are the electron mass and charge respectively, c is the velocity of light in vacuum, N is the unit volume concentrations of Ho^{3+}, and $k(\upsilon)$ is the absorption coefficient.

According to the Judd–Ofelt approach the calculated oscillator strength of electric-dipole absorption transition from the initial state, $|(S,L)J\rangle$, to the finial state, $|(S',L')J'\rangle$, is given by

$$f_{\mathrm{e}} = \frac{8\pi^2 m_{\mathrm{e}}c}{3h\bar{\lambda}(2J'+1)}\frac{(n^2+2)^2}{9n}S_{JJ'}, \tag{2}$$

where $\bar{\lambda}$ is the average wavelength of the absorption band, m_{e} is the mass of the electron, c is the velocity of light in vacuum, h is Planck constant, J' is the total angular momentum of the finial state, n is the refractive index, and $S_{JJ'}$ is the electric-dipole line strengths.

The electric-dipole line strengths, $S_{JJ'}$, from the initial state, $|(S,L)J\rangle$, to the finial state, $|(S',L')J'\rangle$, can be expressed by the Judd–Ofelt intensity parameters,

$$S_{JJ'} = \sum_{t=2,4,6}\Omega_t|\langle 4f^N(SL)J||U^{(t)}||4f^N(S'L')J'\rangle|^2, \tag{3}$$

where Ω_t $(t=2,4,6)$ is the Judd–Ofelt (J–O) intensity parameters, f^N are wavefunctions of the states with N electrons in the $4f$ shell with total angular momentum J, J and J' are the total angular momentum of the initial and the final state, respectively, and $||\langle U^{(t)}\rangle||$ are the reduced matrix elements of unit tensor operators for radiative transitions which are considered to be independent of host matrix, and their values were taken from Ref.[18].

The electric-dipole spontaneous emission probabilities can be expressed by

$$A_{JJ'}[(S',L')J';(S,L)J] = \frac{64\pi^4e^2}{4h\bar{\lambda}^3}\frac{n(n^2+2)^2}{9\,(2J'+1)}S_{JJ'}. \tag{4}$$

By a least-square fitting, the J–O intensity parameters for Ho^{3+} in YAP crystals are calculated to be $\Omega_2 = 1.42\times10^{-20}\,\mathrm{cm}^2$, $\Omega_4 = 2.92\times10^{-20}\,\mathrm{cm}^2$, and $\Omega_6 = 1.71\times10^{-20}\,\mathrm{cm}^2$. Ho^{3+}:YAP crystal has larger J–O intensity parameters $\Omega_t(t=2,4,6)$ in comparison with other doped crystals (shown in Table 1). As known that Ω_2 is very sensitive to the structure and it is associated with the asymmetry and covalence of the lanthanide sites. The larger Ω_2 value indicates the stronger covalence characteristics of this

crystal. The values of the J–O intensity parameters are useful to calculate the spectroscopic quality factor Ω_4/Ω_6 which is critically important in predicting the stimulated emission for the laser active medium. The spectroscopic quality factor of Ho^{3+}:YAP crystal is 1.71 which is larger than that of YAG, but smaller than that of $GdVO_4$, as listed in Table 1. Although Ho:$GdVO_4$ has larger spectroscopic quality factor, the high phonon energies at room temperature restrain the high power laser output. This relatively high Ω_4/Ω_6 value indicates that Ho:YAP is a promising material for efficient laser action.

Table 1. The J–O intensity and the spectroscopic quality factor for Ho^{3+} doped various crystals.

crystal	$\Omega_2/(\times10^{-20}\,\mathrm{cm}^2)$	$\Omega_4/(\times10^{-20}\,\mathrm{cm}^2)$	$\Omega_6/(\times10^{-20}\,\mathrm{cm}^2)$	Ω_4/Ω_6	Refs.
YAP	1.42	2.92	1.71	1.71	this paper
YVO_4	7.5	4.0	1.9	2.10	[19]
$LiNO_3$	4.30	5.11	1.89	2.70	[20]
YAG	0.04	2.67	1.89	1.41	[21]
$GdVO_4$	8.17	10.99	2.77	3.97	[22]
LaF_3	2.28	2.08	1.73	1.20	[23]

Based on J–O approach and Fig.1, the oscillator strength f_{exp}, the absorption cross section σ_{abs}, the spontaneous emission probability $A_{JJ'}$, fluorescence lifetime τ and emission cross section σ_{em} are calculated and listed in Table 2. The longer fluorescence lifetime (5.99 ms) and larger integrated emission cross sections ($2.23\times10^{-20}\,\mathrm{cm}^2$) promise Ho:YAP lasers for the generation of 2 μm wavelength radiation.

Table 2. Main absorption peaks corresponding to the transitions of Ho^{3+} ion from $^5I_8$ ground state, spontaneous emission probability, fluorescence lifetime and emission cross section in YAP crystal.

excited state	peak wavelength /nm	$\sigma_{\mathrm{abs}}/(\times10^{-20}\,\mathrm{cm}^2)$	$f_{\mathrm{exp}}/(\times10^{-6})$	A_{cal} / s^{-1}	τ/ms	$\sigma_{\mathrm{em}}/(\times10^{-18}\,\mathrm{cm}^2)$
$^5I_7$	1930	0.92	1.48	167	5.99	2.2388
$^5I_6$	1150	0.64	0.63	324.7	3.08	1.5455
$^5I_5$	859	0.29	0.16	307.6	3.25	0.8187
$^5F_5$	645	2.40	1.94	5232.7	0.19	7.8348
$^5F_4$	539	0.21	2.51	7240.2	0.14	7.5702
$^5G_4$	383	0.58	0.35	14653.4	0.07	7.7360
$^3H_6$	363	2.00	2.21	13356	0.07	6.3339

3. Lasing action of Ho:YAP

The schematic diagram setup of room-temperature Ho:YAP laser end-pumped by a laser diode (LD)-pumped Tm:YLF laser is shown in Fig.2. The Tm:YLF crystal, a-cut along the grown direction, doped with 4 at% Tm^{3+} ions, had a dimension of 3 mm×3 mm×12 mm(in length), whose two end surfaces were AR-coated at both 792 nm($R<0.5\%$) and 1.91 μm($R<0.3\%$). This Tm:YLF crystal was wrapped in indium foil and held in a copper heat-sink bonded on a thermal electric cooler (TEC) for precise temperature control. In this experiment, the temperature of Tm:YLF crystal was held at 15°C. The pump source was a fibre-coupled laser diode arrays which delivered 60 W content within fibre core of 0.4 mm and numerical aperture of 0.22. The collimated output of the fibre was split in half for dual end-pumping, and each half was relay-imaged into the gain medium with magnification of 1.80. With the choice of focused pump beam diameter of 0.72 mm, the Rayleigh length ($2\pi n\varpi_{\mathrm{p}}^2/M^2\lambda_{\mathrm{p}}$, where n (1.46) was the refractive index of YLF, ϖ_{p} was the pump beam radius, M^2 is the pump beam quality factor being equal to 175, λ_{p} was the pump wavelength) inside the Tm:YLF crystal was calculated to be ∼8.5 mm.

The compact plano-concave L-shaped resonator of the Tm:YLF laser consists of mirrors M1, M2 and M3. M1 is flat input mirror with 95%T at the diode wavelength and 99.5%R at the laser wavelength. M3 is a 250 mm radius of curvature concave output coupler with a reflectivity of 74% at 1.91 μm. M2 is a 45° dichroic mirror with reflectivity of 99.5% at 1.91 μm and a transmissivity of 95% at 792 nm. The physical length of the resonator was about 150 mm. The F–P etalon (0.1-mm thin) inserted in the resonator tuned the Tm:YLF lasing at 1.91 μm.

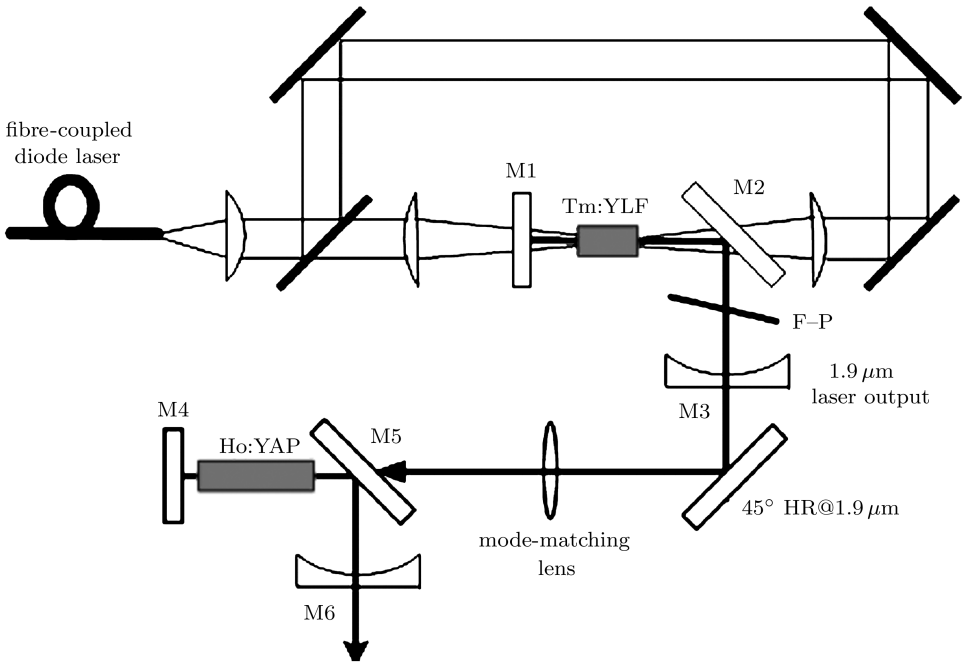


Fig.2. Experimental setup of room-temperature Ho:YAP laser end-pumped by a LD-pumped Tm:YLF laser.

Power performance of diode-pumped Tm:YLF laser is shown in Fig.3. The maximum continuous wave output power obtained was 14.4 W with incident pump power of 47.52 W, corresponding to the optical efficiency of 30.3%. A slope efficiency of 36.5% was yielded by linear fit of the experimental data with respect to the incident diode power. Laser emission was linearly σ polarization. The wavelength of Tm:YLF laser was measured with a monochrometer (300-mm focal length, 600 lines/mm grating blazed at 2.0 μm). The chopped input laser was detected by a InGaAs detector connected with a TDS-3012B digital oscilloscope. Tuning the F–P etalon, the Tm:YLF laser can operate at 1908 nm with full width at half maximum (FWHM) of about 1.0 nm.

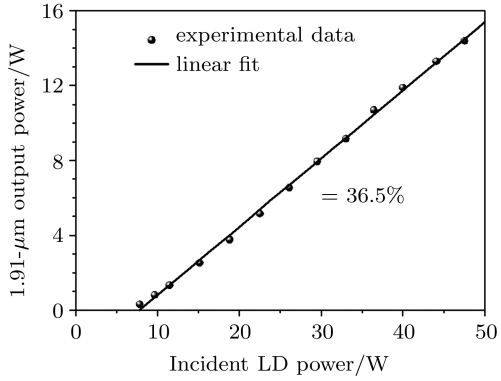


Fig.3. CW performance of the diode-pumped Tm:YLF laser.

The Ho:YAP crystal, b-cut along the grown direction, doped with 1 at% Ho^{3+} ions, had a dimension of 4 mm×4 mm×35 mm (in length), whose two end surfaces were AR-coated at both 1.91 μm ($R < 0.5\%$) and 2.12 μm ($R < 0.5\%$). This Ho:YAP crystal was wrapped in indium foil and held in a copper heatsink bonded on a TEC for precise temperature control. In this experiment, the temperature of Ho:YAP crystal was held at 15°C. The Ho:YAP crystal was placed in the vicinity of the focus formed by the 200 mm focal length mode-matching lens used for the Tm:YLF laser brightness determination experiments. The pump spot at the input surface of the Ho:YAP crystal was approximately 260 μm in diameter.

The compact plano-concave L-shaped resonator of the Ho:YAP laser consists of mirrors M4, M5 and M6. M4 is flat mirror with 99.5%R at the 1.91–2.12 μm. M6 is a 100 mm radius of curvature concave output coupler with a reflectivity of 66% at 2.12 μm. M5 is a 45° dichroic mirror with reflectivity of 99.5% at 2.12 μm and a transmissivity of 95% at 1.91 μm. The physical length of the resonator was about 80 mm.

Figure 4 shows the output characteristics of Ho:YAP laser. The maximum continuous wave output power obtained was 4.1 W with incident 1.91-μm pump power of 14.4 W, corresponding to the optical efficiency of 28.4%. A slope efficiency of 40.8% was yielded by linear fit of the experimental data with

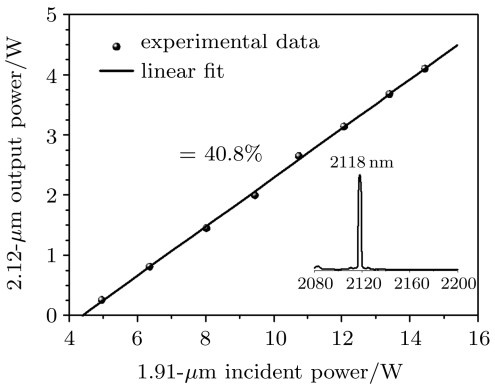


Fig.4. The output power of dual-pass pumped Ho:YAP laser at the function of the incident 1.91-μm laser power. Inset shows the output laser spectrum of Ho:YAP laser.

respect to the incident 1.91-μm pump power. Laser emission was linearly polarized and the contrast ratio was measured to > 30 dB. The output wavelength of Ho:YAP laser was measured with a monochrometer (300-mm focal length, 600 lines/mm grating blazed at 2.0 μm). The lasing radiation was monitored by an InGaAs detector with a SR830 lock-in amplifier for signal extraction. The output laser spectrum of Tm:YAP laser is shown in Fig.4. The output laser wavelength was centred at 2118 nm with FWHM of about 0.8 nm.

4. Conclusion

In conclusion, the spectral characteristics of Ho:YAP crystal are investigated according to J–O theory, and the experimental evaluation of laser performance end-pumped by a 1.91-μm Tm:YLF laser is also demonstrated. As we know, this is the first time to investigate the characteristics of Ho:YAP laser end-pumped by a 1.91-μm Tm:YLF laser. An output power of 4.1 W and a slope efficiency of 40.8% were obtained in this paper. The 2.12-μm Ho:YAP laser output was linearly polarized and the contrast ratio was measured to > 30 dB.

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