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Study of High-Repetition-Rate 2.94 μm Er^{3+}:YAG Laser

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Abstract Characteristics of Er level structure and laser rate equation of an Er^{3+}:YAG four-level system are analyzed. In the laser system, dual-lamp laser, double-elliptical cavity and spike pulse discharge are used to increase pump rate. Through increasing reflectivity of laser cavity and decreasing laser threshold Er^{3+}:YAG laser can output 2.94 μm high-repetition-rate spike pulse laser. In order to eliminate the influence of heat effect, high-tension and high-speed laminar flow cooling technology is adopted. 2.94 μm Er^{3+}:YAG laser with repetition rate of 40 Hz and single pulse energy of 0.5 J is achieved.

Key words Er:YAG laser; high-repetition-rate; double-elliptical cavity; dual-lamp

高重频 2.94 μm Er:YAG 激光器的研究

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摘要 分析了 Er^{3+} 离子的能级结构特性和 Er:YAG 四能级系统的激光速率方程。采用了双灯，双椭圆腔和窄脉冲放电等方式提高了抽运效率；通过提高激光谐振腔的反射率，降低阈值，从而实现了输出 2.94 μm 的高重频窄脉冲激光；采用高压高速层流冷却技术降低了热效应的影响。Er^{3+}:YAG 激光器的重复频率为40 Hz，单脉冲输出能量为 0.5 J，满足实际应用需要。

关键词 Er:YAG 激光器；高重复频率；双椭圆腔；双灯

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Er^{3+} spectrum and energy level structure of Er^{3+}:YAG crystal have been studied for a long time. 2.94-μm laser is obtained through adopting high dopant concentration Er^{3+}:YAG crystal at room-temperature. According to Er^{3+} absorption spectrum, fluorescence spectrum and energy level structure, it can conduct multi-wavelength lasering in infrared waveband, among which 2.94- and 1.54-μm wavelengths are important. 2.94 μm is approach to water maximum absorption peak, and it is the optimum medical applying wavelength. 1.54-μm laser has no damage to eye, and is widely applied in range finding.

In this paper, a high-repetition-rate Er^{3+}:YAG laser is developed, with high doping crystal, high energy pumping, and high reflectivity cavity. High pump rate is adopted to increase population inversion. And high reflectivity and lower transmissivity coupling output windows are used to decrease laser threshold. Then high-repetition-rate 2.94-μm spike pulse output is obtained.

Er^{3+} $4f$ level electric dipole transition is forbidden. But in Er^{3+}:YAG crystal, because of the action of Coulomb force, the forbiddance is removed partly. Energy level transition from 213-nm ultraviolet to 1500-nm near-infrared conducts, and transition absorption spectra can be observed from ground state $^4I_{15/2}$ to upper levels $^4G_{11/2}$, $^4H_{11/2}$, $^4S_{3/2}$, $^4F_{9/2}$, $^4I_{9/2}$, $^4I_{11/2}$, and $^4I13_{/2}$, shown in Fig. 1[1].

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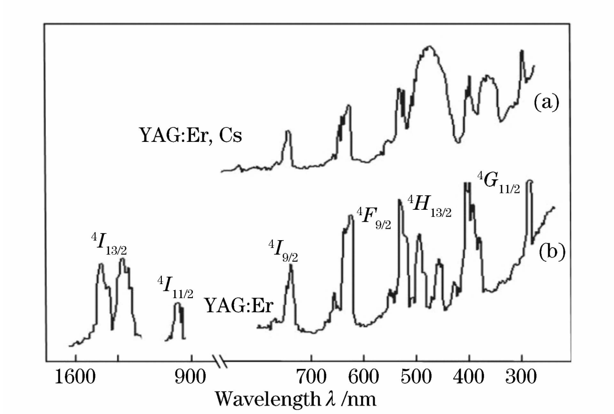

Fig. 1　Er^{3+}:YAG crystal absorption spectra

At room temperature, Er^{3+} transition fluorescent spectra in 0.8～3-μm waveband of Er:YAG crystal are shown in Fig. 2. Er^{3+} is of four-level laser system in Er^{3+}:YAG crystal, as shown in Fig. 3.

Equilibrium population of the laser lower level is given as

$$\frac{N_1}{N_0} = \exp\frac{-\Delta E}{kT}. \tag{1}$$

Under the optimum condition, 3 → 2 and 1 → 0 transition relaxation time are less than spontaneous emission lifetime of laser transition τ_{21}, so there is population only in E_1 and E_2[2~5].

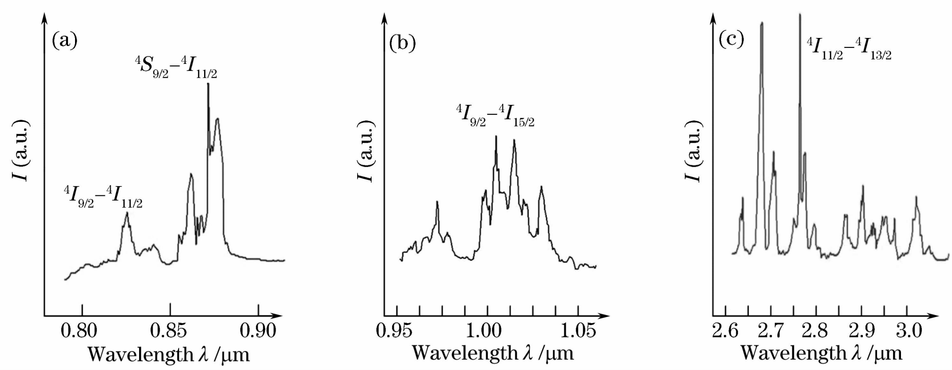

Fig. 2　Er^{3+} fluorescent spectra

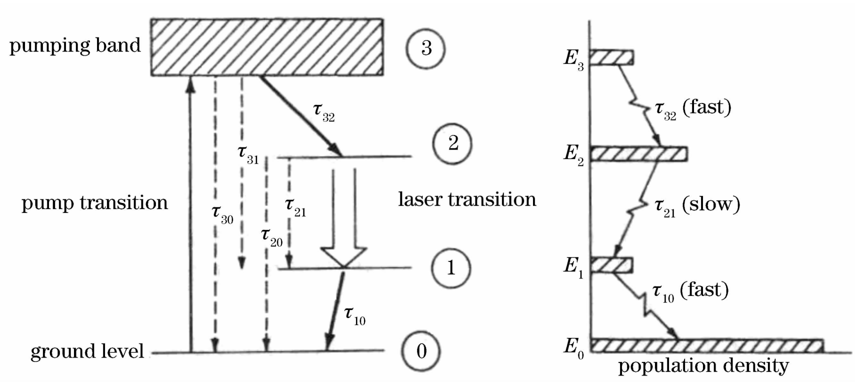

Fig. 3　Four-energy level laser diagram

If transition rate from pumping band to laser upper level is the fastest, namely $n_3 \approx 0$, in four-level system, the rate equation of population changing between two laser energy levels can be calculated by

$$\frac{dn_2}{dt} = w_\rho n_0 - \left(n_2 - \frac{g_2}{g_1}n_1\right)\sigma\phi c, \tag{2}$$

$$\frac{dn_1}{dt} = \left(n_2 - \frac{g_2}{g_1}n_1\right)\sigma\phi c + \frac{n_2}{\tau_{21}} - \frac{n_1}{\tau_{10}}, \tag{3}$$

$$n_{tot} = n_2 + n_1 + n_0. \tag{4}$$

If $\tau_{10} = 0$, then $n_1 = 0$, and for an ideal four-level system, $n = n_2$. Fluorescent decay time τ_f of the laser upper level is

$$1/\tau_f = 1/\tau_{21} + 1/\tau_{20}, \tag{5}$$

where $\tau_{21} = A_{21}^{-1}$ is effective radiation lifetime relative to the laser spectrum.

$$w_\rho = \eta_Q w_{03}, \tag{6}$$

where the quantum efficiency is decided by branching ratio as

$$\eta_Q = (1 + \tau_{32}/\tau_{31} + \tau_{32}/\tau_{30})^{-1} \leqslant 1. \tag{7}$$

Based on rate equation, laser upper level lifetime is shorter and spontaneous emission ratio is larger. Increasing the population loss of upper laser level will disadvantage the population accumulation. If the lower laser level lifetime is prolonged, single-pass gain becomes smaller. Population accumulation in lower level therefore strengthens, which is not propitious for population inversion. It causes heat effect, damages laser beam mass, and decreases output energy of laser[6~9].

Er^{3+} : YAG crystal with high dopant concentration is used as laser active material, whose diameter is $\phi 4$ mm and length is 90 mm. When two reflectors' curvature radii are $R_1=R_2=R$, Gaussian beam radius on reflectors is

$$\omega_{12}^2 = \frac{\lambda R}{\pi}\left(\frac{L}{2R-L}\right)^{1/2}. \tag{8}$$

When distances between two reflectors and Gaussian beam waist are $t_1 = t_2 = R/2$, central beam waist radius is

$$\omega_0^2 = \frac{\lambda}{2\pi}[L(2R-L)]^{1/2}. \tag{9}$$

If curvature radius is longer than cavity length L, namely $R \gg L$, then

$$\omega_{12}^2 = \omega_0^2 = (\lambda/\pi)(RL/2)^{1/2}. \tag{10}$$

To big curvature radius reflector cavity, from Eq. (10), beam radius change is irrelevant to location, so the mirror with bigger curvature radius of 2~10 m is usually used. The utilization rate of active material is bigger.

For high-repetition-rate, high energy, high power pumped Er^{3+} : YAG laser, the dual-lamp, double-elliptical cavity are adopted. Cavity is the most important part of a solid-state laser system. It influences not only total efficiency of laser, but also pump energy density distribution of active material. So it concerns output laser beam mass, divergence, optical distortion, etc.. Comparing double-elliptical cavity with single-elliptical cavity, the former's efficiency is low, but it can form even pump energy density distribution.

In high-repetition-rate and high energy output Er^{3+} : YAG laser, heat effect damages the laser beam mass. In the experiment, the heat effect of Er^{3+} : YAG laser is more serious than that of Nd: YAG laser. High-repetition-rate Er^{3+} : YAG laser is shown in Fig. 4. Double-elliptical cavity section is shown in Fig. 5.

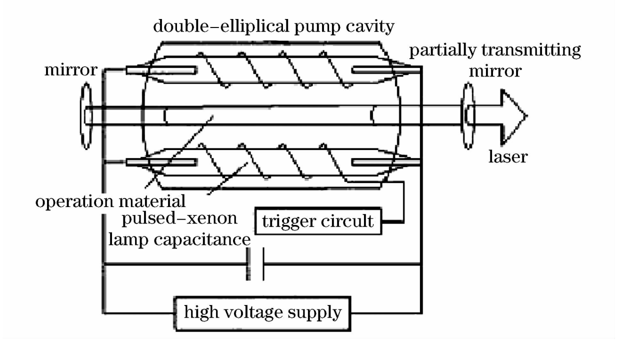

Fig. 4 High-repetition-rate Er^{3+} : YAG laser

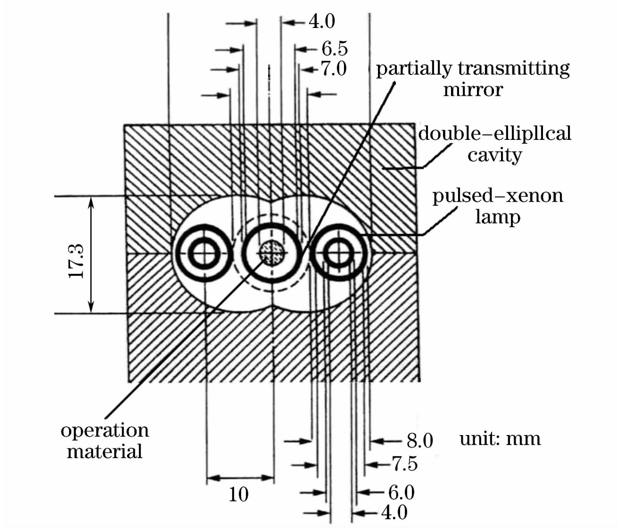

Fig. 5 Double-elliptical cavity section

High-repetition-rate Er^{3+} : YAG laser with pump pulse energy of 80~100 mJ, repetition-rate of 40 Hz, incremental efficiency of 80%, and output pulse energy of 0.6~0.8 J is designed. This laser can be widely used in many areas, such as batch manufacturing and engineering.

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