Frequency stabilization of a laser-diode-module-pumped single-frequency Cr,Nd:YAG laser

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A single-frequency passively Q-switched laser was constructed, in which a co-doped crystal served as an active element, a mode selector, and a passive Q-switch simultaneously. In order to obtain the frequency instability of 10^{-6}, a stable single-frequency operation was presented and its characteristics were determined. The experimental results showed that the stable single frequency could be maintained for half an hour and the linewidth was approximately 530 MHz at a pump power of 13 W.

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Stable, high-beam-quality, passively Q-switched (PQ) lasers with high peak power are good laser sources for light detecting and ranging, pollution monitoring, material processing, microsurgery, and so on. The effectiveness of applications of PQ lasers is largely governed by the stability of their parameters, particularly, the repetition rate and the lasing frequency. The repetition-rate stability can be improved by two kinds of technologies. One is modulation of the pump light of the PQ laser[1], and the other is hybrid Q-switching[2]. However, single-frequency stabilization of the pulsed laser is a difficult problem at all times[3,4]. Cr^{4+},Nd^{3+}:YAG is a new type co-doped crystal for self-Q-switching, and Chen *et al.* have reported that stable single-frequency operation can be achieved in a monolithic Cr^{4+},Nd^{3+}:YAG PQ laser[5]. A stable single-frequency operation condition is further given to be $L_{\mathrm{g}} \geq L$, where L_{g} is the length of saturable absorber and L is the cavity length[6]. However, the monolithic PQ laser is subjected to the low output lasing power[7] and some other disadvantages[8]. Can stable single-frequency operation be maintained in a non-monolithic PQ laser? In fact, the emission frequency of the PQ laser is extremely sensitive to thermal fluctuation. To our knowledge, there is no such report of the thermal effect on the instability of a PQ co-doped crystal laser. In this letter, we study the influence of the temperature of the resonator components on the passively linewidth operating stability of a single-frequency PQ laser and present its characteristics.

Frequency stability $S_\nu(\tau)$ may be defined as[4]

$$S_\nu\left(\tau\right) = \nu_{\mathrm{L}}/\Delta\nu_{\mathrm{L}}\left(\tau\right), \tag{1}$$

where ν_{L} is the average frequency of the laser and $\Delta\nu_{\mathrm{L}}(\tau)$ is some measure of the fluctuation of frequency during the observation period τ. In practice, one often speaks of stability, whereas usually a value of fractional frequency instability k

$$k = S_\nu\left(\tau\right)^{-1} = \Delta\nu_{\mathrm{L}}(\tau)/\nu_{\mathrm{L}}. \tag{2}$$

The gain profile of a laser transition is usually much broader than the cavity resonance profile. so, the laser frequency stability depends almost entirely on the stability of the cavity resonance. The cavity resonance frequency ν_{c} to a good approximation is given by

$$\nu_{\mathrm{c}} = qc/2nL, \tag{3}$$

where q is the longitudinal mode order number, c the light speed, n the refractive index, and L the cavity length. From Eqs. (2) and (3), the frequency instability k is given by

$$k = \Delta L\left(\tau\right)/L + \Delta n\left(\tau\right)/n. \tag{4}$$

To obtain a typical frequency instability of 10^{-6}, the cavity length change ΔL must be small to 50 nm for a cavity length of 50 mm. This is corresponding to a certain fractional change of the intermode spacing $\lambda/2$ under the influence of external factors

$$\gamma = kL/\left(\lambda/2\right), \tag{5}$$

where $\lambda = 1064$ nm is the lasing wavelength, and $\gamma = 0.1$ is equal to the product of the laser linewidth and pulse round-trip-time.

During laser action, a standing lightwave builds up in the cavity due to multiple reflections of the laser beam between the parallel mirrors, and spatial hole-burning (SHB) is formed. The SHB produces a spatially periodic light intensity and/or polarization distribution which changes the optical properties of the saturable absorber. Whereas SHB in the gain medium tends to promote multi-longitudinal-mode operation, the same hole-burning effect combined with distributed saturable absorbers can stabilize the single-longitudinal-mode operation. This is because that the lasing mode can bleach a loss grating in the saturable absorber and create a low-loss window to enhance itself. The spatial modulation of the saturable absorber acts as a loss grating and can be used as a mode selector[5,9].

The issue of the frequency stabilization is how to maintain the cavity length to a given constant and ensure the matching of the resonance frequencies of the mode selector and the resonator from the above analysis. Let us consider a case that the plane-plane resonator contains a co-doped crystal and air. According to Eq. (5), to obtain a typical frequency instability of 10^{-6}, the fractional change in half lasing wavelength should be assumed to equal 0.1. Any changes in cavity length and refractive index must be minimized if the laser frequency remains stable. There are various possible perturbations on the cavity length and refractive index. We will discuss the five external factors; the temperatures of the resonator spacer, water coolant, the instability of the pump power, and the air temperature and pressure in the resonator.

Variation of the temperature of the spacer material between the end plates which carry the cavity mirrors leads to a fractional change $\Delta L/L$ in the mirror separation given by

$$\Delta T < \gamma\lambda/2\alpha L, \tag{6}$$

where α is the coefficient of linear expansion of the spacer. For the dural LY12 CZ, $\alpha = 21.6\times10^{-6}$ K^{-1}[10]. When $\gamma = 0.1$ and $L = 20$ mm, $\Delta T < 0.12$ K. It can be seen from the estimate that the spacer temperature needs not be maintained quite so accurately to ensure stable operation of the laser.

The optical length of the resonator also varies with the temperature of the active element, which is governed by the water coolant temperature T_1 and also by the average pump power. The thermo-optic constant of the crystal is

$$W = (1/l)(\Delta s/\Delta T) = \beta + \alpha(n-1), \tag{7}$$

where Δs is the optical path change between the two reflectors due to the temperature increase ΔT of the laser material, l is the length of the laser rod, $\beta = \mathrm{d}n/\mathrm{d}T$ is the temperature coefficient of the refractive index n, and α is the linear expansion coefficient. We can derive the following expression for the change in the optical path ΔL at the center of a rectangular proflie active element:

$$\Delta L = lWf(\Delta T_1, \Delta P_\mathrm{t}) \approx lW\Delta T_1 + \Delta P_t W/8\Lambda, \tag{8}$$

where ΔT_1 is the change in the water coolant temperature; ΔP_t is the instability of the thermal pump power[11]; Λ is the thermal conductivity of the active element material. The first term of the right-hand side is related to the water-cooled temperature change; whilst the second term is related to the instability of the pump power. We note that this term does not depend on the length or rectangular sides of the active element.

Assuming that all the instability of the thermal power released in the active element is due to the instability of the operating current I for the laser diode delivered by the diode drivers, we find $\Delta P_\mathrm{t}/P_\mathrm{t} = 2\Delta I/I$, and since ΔP_t is obtained from Eq. (8), P_t is limited. For Cr,Nd:YAG laser crystal, $\Delta P_\mathrm{t} = 0.36$ W and $P_\mathrm{t} < 180$ W when $\Delta T_1 = 0$, $\Lambda = 12.13$ W·m^{-1}·K^{-1}, $\lambda = 1.064\times10^{-6}$ m, $\mathrm{d}n/\mathrm{d}T = 8.0\times10^{-6}$ K^{-1}, $\alpha = 7.8\times10^{-6}$ K^{-1}, $n = 1.82$, $\Delta I/I = 0.1\%$, and $\gamma = 0.1$[12]. It is interesting to note that the constraint on the thermal power is also a constraint on the single-frequency lasing power since they are proportional.

From Eqs. (5) and (8), the permissible instability of the water coolant temperature T_1 for active element materials ($l = 5.6$ mm, $\gamma = 0.1$, $\Delta P_\mathrm{t} = 0$) can be estimated. For Cr,Nd:YAG, $\Delta T_1 < 0.66$ K, which can easily be achieved in practice.

However, in our case, the co-doped crystal also acts as a longitudinal oscillation mode selector. A loss grating is formed in this crystal where the planes of the "lines" are perpendicular to the resonator optic axis and their repetition periods determine the resonance frequency. The shift of the resonance frequency dependent on temperature is[13]

$$\Delta\nu/\Delta T = -\nu(\beta/n + \alpha), \tag{9}$$

where ν is the frequency. For Cr,Nd:YAG, $\Delta\nu/\Delta T = -0.115$ cm^{-1}/K. If $\gamma = 0.1$ and the resonator length is 20 mm, the Cr,Nd:YAG temperature should be maintained to within $\Delta T_3 < 0.174$ K. It is not difficult to achieve this temperature stability in practice. Because the active element and mode selector are the same crystal, the real constraint for stable single-frequency operation of PQ laser is the change domain of the Cr,Nd:YAG temperature ΔT_3 compared with ΔT_1.

The air temperature and pressure will also influence the optical length of the resonator[3,14,15]. At the 1.064-μm wavelength when $T = 25$ °C and $p = 760$ Torr, $\mathrm{d}n/\mathrm{d}T = -1\times10^{-6}$ K^{-1}, $\mathrm{d}n/\mathrm{d}p = 3.5\times10^{-7}$ Torr^{-1}. If the path length of the radiation in air inside the resonator is 15 mm, then $\Delta T < 3.55$ K and $\Delta p < 10.13$ Torr ($\gamma < 0.1$). So the influence of the air can be neglected.

In the experiments, the laser resonator made of dural was 19.5 mm long. The co-doped crystal was 5.6 mm long and had the initial transmissions of 75.5% at 1064 nm and 49% at 808 nm. The co-doped crystal was used as gain medium and saturable absorber simultaneously. A 30-W fiber-coupled continuous wave (CW) laser-diode-module (LDM) was used for pumping and its temperature was maintained at 25 ± 0.1 °C. The crystal temperature was maintained at $T_1 = 17 \pm 0.1$ °C whilst the room temperature was maintained at 15 °C. The laser housing was nonhermetic. The plane resonator mirrors had reflection coefficients of 100% and 70% respectively. The co-doped crystal also served as a dynamic stop to isolate the TEM$_{00}$ oscillation mode.

The lasing emission spectrum was measured using a Fabry-Perot interferometer (FPI). For a 20-mm-optical-length resonator, the longitudinal mode spacing is 7.5 GHz. The space of FPI is 30 mm and total finesse of FPI is 50. Thus the resolution of FPI is 100 MHz. It is sufficient to resolve two adjacent axial modes. A convex lens with focus length of 50 cm was mounted behind the FPI and the laser beam was focused and imaged on a piece of ground glass.

A charge coupled device (CCD) camera is used to record the fringe pattern which is imaged by the lens into the plane of the ground glass during the laser pulse. An actual photograph of the fringe field will show the average spectral characteristic of the emission during a pulse. If the lens, the focal length of which is known accurately, is used to photograph the fringe pattern, the lasing wavelength can be measured by[16]

$$\lambda = d\left(d_1^2 - d_0^2\right)/4f^2, \tag{10}$$

and the mode spacing or linewidth can be calculated through[17]

$$\Delta\lambda = \lambda\left(d_\mathrm{out}^2 - d_\mathrm{in}^2\right)/8f^2, \tag{11}$$

where d_0 and d_1 are the diameters of the central and second fringe rings, d_{in} and d_{out} are the inside and outside diameters of the central fringe rings of the same order, respectively. The diameters are measured directly on the screen for circles of equal intensity on either side of a bright ring or group of rings.

The experiments were carried out as follows. The laser emission spectrum was initially a single longitudinal mode. Emission of a single longitudinal mode then continued as long as the resonances of the selector and the resonator were matched. Then we changed the crystal temperature and the LDM pump power. The fringe ring will hop to another. One fringe ring corresponds to a round-trip optical path length change of one optical wavelength. When the resonances were matched again, there will be a single set of fringe ring on the FPI. The accuracy of the temperature stability was sufficient to ensure single-frequency operation (without altering the resonator length) for half an hour.

The characteristics of the PQ laser regime are presented in Fig. 1. The average output power of the PQ laser is approximately 1 W and a maximum repetition rate of 27.8 kHz can be obtained at the highest LDM pump power. The output power linearly increases with pump power while the pulse period and duration decrease.

The typical spectral fringe rings of Cr,Nd:YAG laser radiation are shown in Fig. 2(a). The maximum linewidth is 830 MHz at 14.2-W pump power (Fig. 2(b)), where the linewidth is full width linewidth, not FWHM width. When the power changed approximately 0.5 W (from 12.6 to 13.1 W), the longitudinal mode hoped from one to another. Because the transmission at 808 nm is 49%, only 1/2 of the pump power can be absorbed by the lasing crystal.

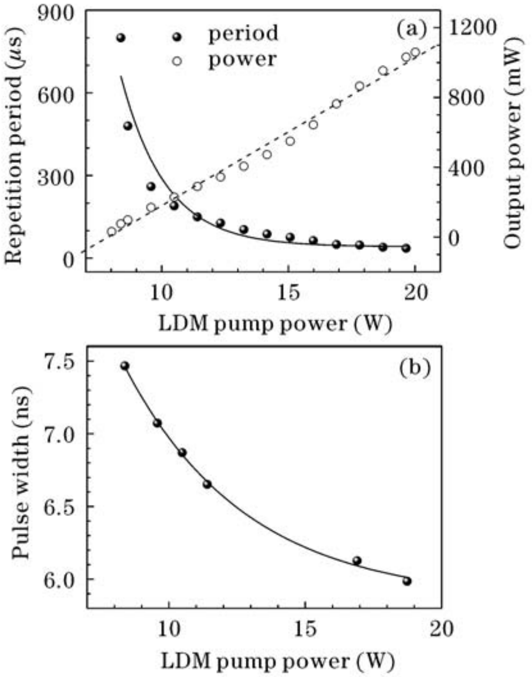

Fig. 1. (a) Repetition period and output power of PQ laser versus LDM pump power, (b) pulse duration versus LDM pump power. Cavity length is 19.5 mm.

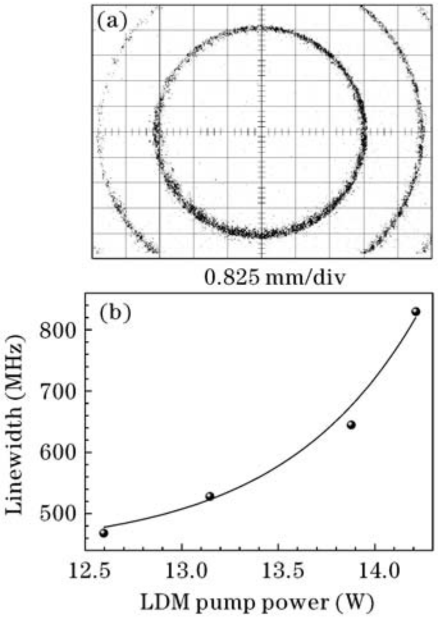

Fig. 2. (a) Typical single-frequency fringe ring of the PQ laser pumped at 12.6 W, (b) linewidth of the PQ laser versus LDM pump power.

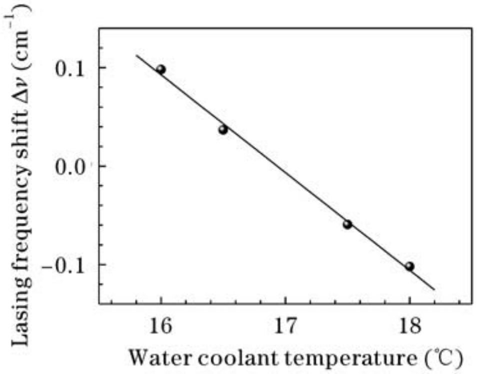

Fig. 3. Dependence of the lasing frequency shift $\Delta\nu$ on the water coolant temperature.

The lasing frequency was governed by the Cr,Nd:YAG temperature. It was measured using the beats on the screen of a Tektronix TDS 3052 oscilloscope, and the signal was recorded with a 1-ns rising-time Si p-i-n DET200 photodiode. Figure 3 gives the lasing frequency shift as a function of the water coolant temperature. When the temperature was altered by 1 °C, the frequency changed by -0.1 cm^{-1}. The straight line gives the least squares approximation using the formula $\Delta\nu = -0.1 \times T + 1.695$. The value $\mathrm{d}\nu/\mathrm{d}T = -0.1$ cm^{-1}/K is determined from the graph. These experimental results fit the theoretical analysis well.

In conclusion, a single-frequency PQ laser using a Cr,Nd:YAG crystal as a longitudinal mode selector is described. A spectrally selective grating is formed in this crystal during operation. In order to obtain the frequency instability of 10^{-6}, the estimates give those parameters of the configuration which need to be improved to enhance the long-term frequency stability. The adopted measures can give stability of the laser radiation frequency better than 530 MHz for half an hour. With the above analysis, we can conclude that the crystal temperature stability and the pump power are the most important influence on the single-frequency operation without mode hopping. If we directly coat films of the resonator mirror on both sides of the co-doped crystal rod to construct a monolithic PQ laser, the length of cavity will be always equal to the length of mode selector, and more stable single-frequency operation can be achieved[5].

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