Stable intracavity doubling of orthogonal linearly polarized modes in diode-pumped Nd:YAG lasers

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The stability of the output light from a diode-pumped intracavity frequency-doubled Nd:YAG laser was studied. An intracavity nonlinear crystal, such as Type II phase-matched potassium titanyl phosphate, was used for frequency doubling. The incident beam consisted of two orthogonal linearly polarized modes. When the polarization eigenvectors were parallel to the E and O axes of the crystal, a large amplitude fluctuation was observed; however, when the azimuthal angle between the polarization eigenvectors and the axis was 45°, the light output was stabilized. The experimental results are explained by analyzing the coupling of the two orthogonal linearly polarized modes through a sum-frequency-generation process.

Recent developments in high-power laser diodes have hastened the development of efficient miniature infrared or frequency-doubled solid-state lasers pumped by a laser diode.[1–4] Specifically, intracavity frequency doubling of a diode-pumped Nd:YAG laser has attracted attention. This device permits the efficient generation of green coherent light owing to the presence of a high-intensity light confined in the laser resonator.

However, a "green problem,"[5] which results in a strongly modulated second-harmonic light output, is a major concern for practical uses such as reading a signal from an optical disk. A resonant external cavity[6] is a solution to this problem, although an additional control circuit is required to stabilize the external resonator.

The nature of the green problem is as follows. Several oscillating modes are possible in a linear laser resonator. These modes can be coupled through the sum-frequency-generation process in a nonlinear crystal. As a result, the second-harmonic light output can be strongly modulated. Coupling between multilongitudinal modes in a nonlinear crystal was studied by Baer.[5]

In Baer's model, the temporal characteristics of second-harmonic output are explained by rate equations of the various multilongitudinal modes including the loss terms, but the polarizations of the fundamental and second-harmonic modes are ignored. We propose that the mechanism for the instability is coupling of polarization modes. We have found experimental evidence that indicates that the instability arises from a coupling of polarization modes of the fundamental wave in the unpolarized laser. The instability due to the coupling of polarization modes is effectively suppressed by inserting a quarter-wave plate (QWP) at the fundamental laser wavelength, $\lambda = 1.064\ \mu\text{m}$, inside the cavity.

The second-harmonic output from a Type II phase-matched nonlinear crystal, such as potassium titanyl phosphate (KTP), can be considered as sum-frequency generation of an ordinary wave and an extraordinary wave. In this case, the nonlinear polarization $P(2\omega)$ induced by the fundamental waves is[7]

$$P(2\omega) = d_{\text{eff}} E_o(\omega) E_e(\omega),$$
$$d_{\text{eff}} \equiv (d_{24} - d_{15}) \sin 2\theta \sin 2\phi - (d_{15} \sin^2 \phi + d_{24} \cos^2 \phi) \sin \theta, \tag{1}$$

where E_o is the ordinary wave component, E_e the extraordinary wave component, θ the angle relative to the z axis, and ϕ the angle in the x–y plane relative to the x axis in KTP. This causes coupling between polarization states in an unpolarized laser cavity, where two orthogonally polarized modes are allowed to oscillate independently.

Since the polarization states of eigenmodes are unchanged after a round trip in a laser cavity, the polarization modes can be characterized by the eigenvectors of a round-trip Jones matrix.[8,9] Figure 1 shows the configuration of the laser cavity. Angle α is the angle that the fast axis of the inserted QWP makes with the direction of the **E** vector of the ordinary wave in KTP, and δ is the amount of single-pass birefringence of the

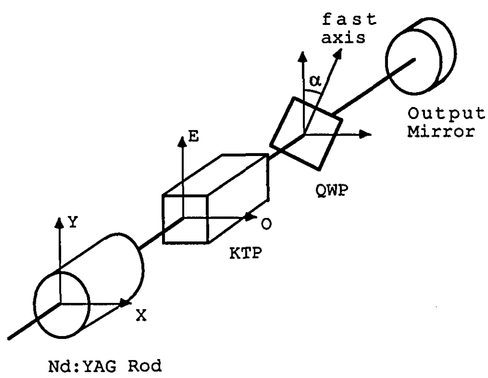

Fig. 1. Schematic of the laser cavity. The fast axis of the QWP makes an angle α with respect to the E axis of the KTP.

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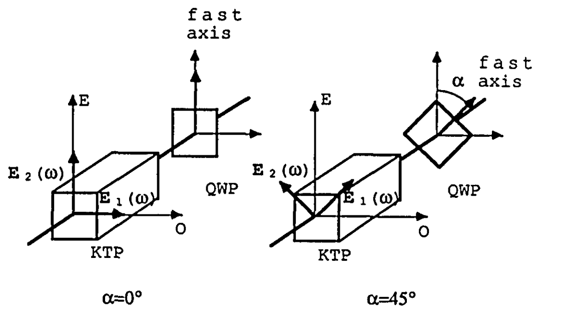


Fig. 2. Relation between the eigenvectors and the direction of the QWP.

fundamental wave caused by the KTP. A round-trip Jones matrix can be described as

$$M = C(\delta)R(\alpha)C(\pi/2)C(\pi/2)R(-\alpha)C(\delta), \qquad (2)$$

where $C(\delta)$ is the matrix for the birefringence of KTP, $R(\alpha)$ the matrix for the rotation angle of the QWP, and $C(\pi/2)$ the matrix for the retardation of the QWP. Substituting $C(\delta)$ and $R(\alpha)$ into Eq. (2), we have

$$M = i\begin{bmatrix} \exp(i\delta)\cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\exp(-i\delta)\cos 2\alpha \end{bmatrix}. \qquad (3)$$

Two eigenpolarization states, $\mathbf{E}_1(\omega_1)$ and $\mathbf{E}_2(\omega_2)$ at the Nd:YAG crystal, are the eigenvectors of matrix M. They are in general elliptically polarized. However, for the cases when $\alpha = 0°$, $\alpha = 45°$, and $\alpha = 90°$, they are orthogonal and linearly polarized, as shown in Fig. 2, and can be expressed as

$$\mathbf{E}_1(\omega_1) = E_1\begin{pmatrix}1\\0\end{pmatrix}, \qquad \mathbf{E}_2(\omega_2) = E_2\begin{pmatrix}0\\1\end{pmatrix} \qquad (\alpha = 0° \text{ or } \alpha = 90°), \qquad (4a)$$

$$\mathbf{E}_1(\omega_1) = \frac{\sqrt{2}}{2}E_1\begin{pmatrix}1\\1\end{pmatrix}, \qquad \mathbf{E}_2(\omega_2) = \frac{\sqrt{2}}{2}E_2\begin{pmatrix}1\\-1\end{pmatrix} \qquad (\alpha = 45°), \qquad (4b)$$

where $E_i = |E_i|\exp[i(\omega_i t + \phi_i)]$.

Note that the eigenvector is not affected by the amount of birefringence in the $\alpha = 45°$ KTP setup. Using Eqs. (1) and (4), we find the nonlinear polarization:

$$P(\omega_1 + \omega_2) = d_{\text{eff}}E_1E_2, \quad (\alpha = 0° \text{ or } \alpha = 90°), \qquad (5a)$$

$$P(\omega_1 + \omega_2) = \tfrac{1}{2}d_{\text{eff}}(E_1^2 - E_2^2) \qquad (\alpha = 45°). \qquad (5b)$$

Given the intensities of the two polarization modes I_1 and I_2 and substituting into Eqs. (5), the time-averaged second-harmonic output power $I(2\omega)$ is given by

$$\begin{aligned} I(\omega_1 + \omega_2) &= \langle P(\omega_1 + \omega_2)P(\omega_1 + \omega_2)^*\rangle = d_{\text{eff}}^2|E_1|^2|E_2|^2 \\ &= d_{\text{eff}}^2 I_1 I_2 \qquad (\alpha = 0° \text{ or } \alpha = 90°), \qquad (6a) \end{aligned}$$

$$\begin{aligned} I(\omega_1 + \omega_2) &= \langle P(\omega_1 + \omega_2)P(\omega_1 + \omega_2)^*\rangle \\ &= \tfrac{1}{4}d_{\text{eff}}^2\langle[(E_1^2 - E_2^2)(E_1^2 - E_2^2)^*]\rangle \\ &= \tfrac{1}{4}d_{\text{eff}}^2\{|E_1|^4 + |E_2|^4 - 2|E_1|^2|E_2|^2 \\ &\quad \times \langle\cos 2[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)]\rangle\} \\ &= \tfrac{1}{4}d_{\text{eff}}^2(I_1^2 + I_2^2) \qquad (\alpha = 45°), \qquad (6b) \end{aligned}$$

where ⟨ ⟩ stands for the time average. The frequencies of the fundamental waves ω_1 and ω_2 differ by half of the resonance frequency spacing owing to a quarter-wave optical path difference between the two orthogonal polarization modes in an $\alpha = 45°$ KTP setup. Hence the time average of the cross term $\cos 2[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)]$ vanishes.

These results indicate that if the QWP angle α is 0° or 90°, the second-harmonic output is proportional to the product of the two polarization mode intensities. Thus the two polarization modes are coupled by the loss that is due to sum-frequency generation in the nonlinear crystal. On the other hand, if the QWP angle α is 45°, the second-harmonic output is obtained by adding the squares of the polarization mode intensities. Thus the loss is caused only by the doubling of each mode. Since Baer's model explains that the instability arises from the coupling of modes through sum-frequency generation, it is expected that in the $\alpha = 45°$ setup the second-harmonic output will not exhibit instability. To confirm this theoretical discussion, the following experiments were carried out.

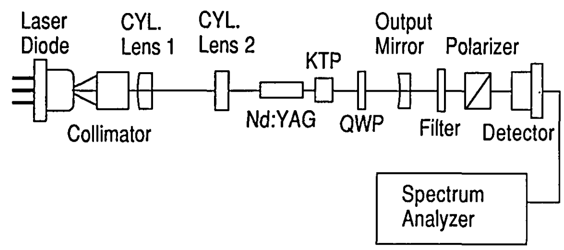


Fig. 3. Experimental setup for the noise measurements of the laser output from the intracavity frequency-doubled Nd:YAG laser pumped by a laser diode.

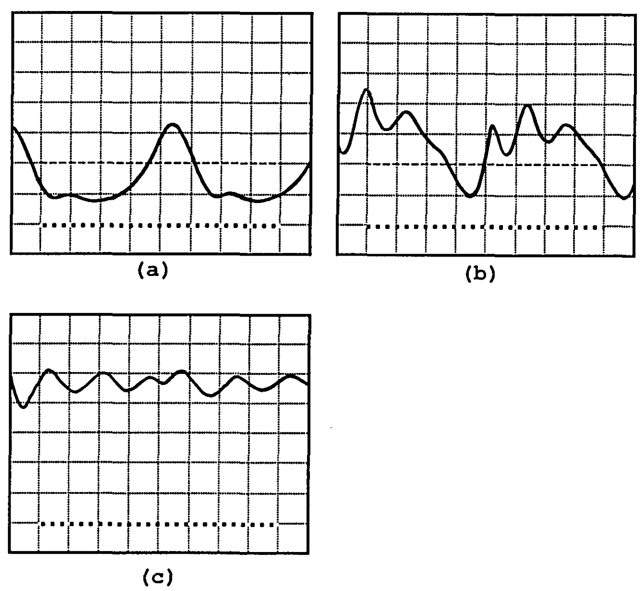
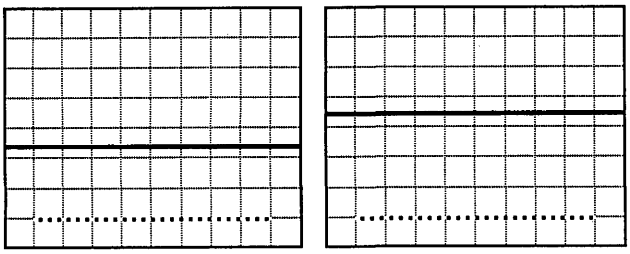
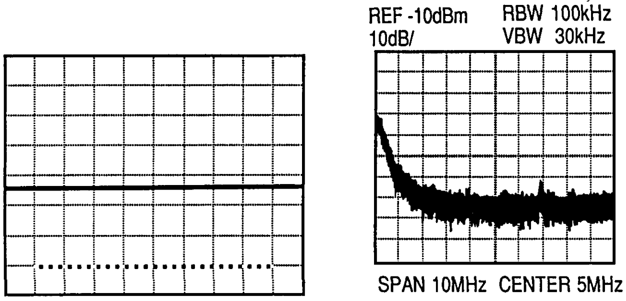


Fig. 4. Oscilloscope traces of the laser output at 1.06 μm. The dashed lines indicate the average level; the dotted lines show the ground level. The horizontal scale is 50 μsec/division; the QWP angle α is 0°. (a) Waveform with polarizer angle 0°, (b) waveform with polarizer angle 90°, (c) waveform without the polarizer.



(a) (b)

Fig. 5. Oscilloscope traces of the laser output at 1.06 μm when the QWP angle α is 45°. (a) Waveform with polarizer angle 45°, (b) waveform with polarizer angle −45°.



(a) (b)

Fig. 6. (a) Oscilloscope traces of the laser output at 0.532 μm when the QWP angle α is 45°. (b) Noise spectrum measured by a spectrum analyzer when QWP angle α was 45°. Resolution bandwidth, 100 kHz; video bandwidth, 30 kHz.

A 7-mm-long Nd:YAG rod with a Nd^{3+} concentration of 1.1 at. % was pumped by a Sony SLD304 laser diode.[10] To correct for beam divergence and astigmatism, two cylindrical lenses were employed. The focal lengths of the cylindrical lenses were 60 mm for the direction perpendicular to the junction of the laser diode and 10 mm for the direction parallel. One end of the Nd:YAG rod and an output mirror with a 40-mm radius of curvature formed the cavity. Both surfaces were coated to have high reflectivities ($R > 99.8\%$ at a wavelength of 1.06 μm). A 3.4-mm-thick KTP crystal was inserted into the cavity. When the cavity length was 30 mm, the radius of the Gaussian spot in the KTP was ~80 μm. Typically, 4-mW green laser output was obtained with ~400-mW laser-diode power in this configuration. As is shown in Fig. 3, the intensities of the two fundamental polarization modes, I_1 and I_2, were measured through a band-pass filter at wavelength of 1.06 μm and through a polarizer rotated to the angles α and $\alpha + 90°$. As is shown in Figs. 4(a) and 4(b), both with and without the QWP at an angle $\alpha = 0°$, unstable chaotic oscillation was observed in each polarization mode. Since the sum of the two modes, measured by removing the polarizer, stays nearly constant, as shown in Fig. 4(c), it is interpreted that mode coupling between the two modes through sum-frequency generation is the origin of the instability, as expected from Eq. (6a). The green output also exhibits large amplitude fluctuations, which contain much noise over a wide frequency range. On the other hand, at a QWP angle $\alpha = 45°$, the unstable oscillations disappeared, as expected from Eq. (6b) [see Figs. 5(a) and 5(b)]. The resultant green output was stabilized, and the signal-to-noise ratio was improved to 80 dB at 5 MHz, as shown in Figs. 6(a) and 6(b).

In the experiment, no attempt was made to force single-longitudinal-mode oscillation. Thus it was found that the fundamental wave oscillated in multilongitudinal modes in both the $\alpha = 0°$ and the $\alpha = 45°$ setups. Further analysis based on both polarization modes and longitudinal modes will be reported in another publication.

In conclusion, the output stability of a laser-diode-pumped intracavity-doubled Nd:YAG laser using a Type II phase-matched nonlinear crystal has been studied. Mode coupling between the two independent polarization modes in the unpolarized cavity was found. By inserting a QWP at the fundamental laser wavelength with its azimuthal angle at 45° with respect to the E and O axes of the crystal, the instability caused by the coupling of two polarization modes was effectively suppressed, yielding a signal-to-noise ratio of 80 dB. Therefore the green problem in the unpolarized resonator was solved simply by adding a QWP to the cavity. With this stabilized laser, practical applications can be expanded.

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