A High Efficient Stable Intracavity Doubling Nd:YAG Laser Pumped by a Laser Diode

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ABSTRACT By using a quarter-wave plate at fundamental laser wavelength in an intracavity frequency doubling laser, the difference of optical distance between the orthogonal polarized modes in KTP crystal is compensated and the instability caused by sum-frequency generation is eliminated. A high efficient, stable intracavity doubling Nd:YAG laser pumped by a laser diode has been established. The second harmonic maximum output single-side TEM_{00} mode is measured to be 105mW, the amplitude fluctuation is less than ±3% in ten minutes, and total optical coversion efficiency is 14.4%.

KEY WORDS intracavity harmonic, Nd:YAG laser, LD pumped laser

1. Introduction

There has been a recent surge of interest in diode laser (LD) pumped solid-state lasers of coherent visible light due to their extensive applications ranging from medical diagnostics to optical data storage[1,2]. Especially, the attention has been concentrated on the intracavity doubling of LD-pumped Nd:YAG lasers with KTP crystal[3~6]. T. Baer has studied the "green problem" which results in a strongly modulated second-harmonic output due to longitudinal mode coupling in a linear laser resonator[3]. For the second-harmonic output from a type II phase-matched KTP crystal the large amplitude fluctuation arises from the coupling of polarization modes and the instability can be effectively suppressed by inserting a quarter-wave plate (QWP) at the fundamental laser wavelength when the angle between the fast axis of the QWP and the e_2 axis of the KTP is equal to 45°[5]. We indicate that in the $\psi = 45°$ KTP setup the optical distance difference between the two orthogonal polarization modes e_1 and e_2 of the fundamental wave can be automatically compensated during a round-trip. Therefore the simultaneous resonance of e_1 and e_2 modes can be easily realized, then the high efficiency of frequency-doubling is obtained.

2. Experimental setup and results

The experimental setup is shown in Fig. 1. The pump source is a SDL-2482-P1 laser diode with a focusing and coupling optical system. The beam waist of pump laser is about $\phi 250 \mu m$ in laser medium of Nd:YAG. The size of Nd:YAG rod and KTP crystal are $\phi 3 \times 5 mm^2$ and $5 \times 5 \times 6 mm^3$, respectively. The input coupler of laser is a plane mirror with the reflectivities $R_{809} < 5\%$, $R_{1064} > 99.7\%$ and $R_{532} < 10\%$ for pump wave (809nm), fundamental wave (1064nm) and second harmonic wave(532nm) respectively. The output coupler is a mirror with 100mm-radius of curvature and the reflectivities $R_{1064} > 99.7\%$ and $R_{532} < 10\%$ respectively. The configuration of the laser cavity is near confocal and the measured length of cavity is 54mm. The waist size of the cavity is about 260μm. By adjusting carefully the focusing and coupling optical system the section of pumping beam and the mode volume of laser was perfectly matched so that the laser was operated at TEM_{00} mode.

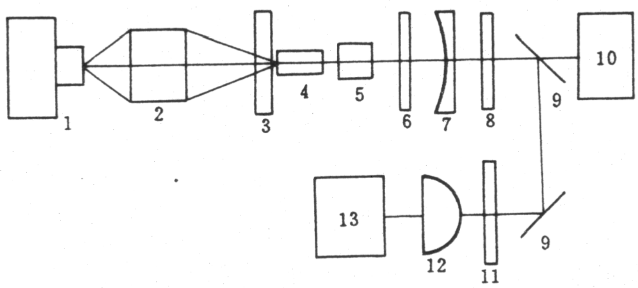

Fig. 1 Experimental setup of the intracavity frequency-doubling Nd:YAG laser pumped by laser diode
1—Laser diode; 2—Focusing optics; 3—Input coupler; 4—Nd:YAG crystal; 5—KTP crystal; 6—QWP; 7—Output coupler; 8—Filter; 9—Beam spliter; 10—Power meter; 11—Damper ; 12—Detector; 13—Oscilloscope

Fig. 2 shows three experimental curves of one-side measured second-harmonic output powers versus the pump powers absorbed by Nd:YAG rod. These curves correspond respectively to three cases: with QWP at $\psi = 0°$ and $\psi = 45°$ as well as without QWP in the laser cavity.

The two curves without QWP and with QWP at $\psi = 0°$ almost overlap in our precision of measurement. The measured second harmonic output power through the output coupler is 28mW at the absorbed pump power of 1.45W. The light to light conversion efficiency is 1.9%, the lasing threshold of absorbed pump power is 39mW. Because of existence of above

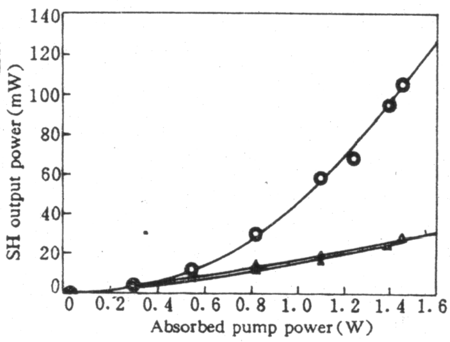

Fig. 2 SH output power versus absorbed pump power

○: with QWP ($\psi = 45°$); ◇: with QWP($\psi = 0°$); △: Without QWP

mentioned "green problem" the strong fluctuation of output second harmonic amplitude was observed (Fig. 3).

With the same absorbed pump power of 1.45W when the ψ angle was set at 45° the output power up to 105mW was measured, the light to light conversion efficiency was 7.2%. If counting of the output from the input coupler (the transmissivity for 532nm $T_{532} > 90\%$), the total conversion efficiency should be 14.4%. The Intensity profile of second-harmonic output was measured by using a detector with a pin-hole to scan the section

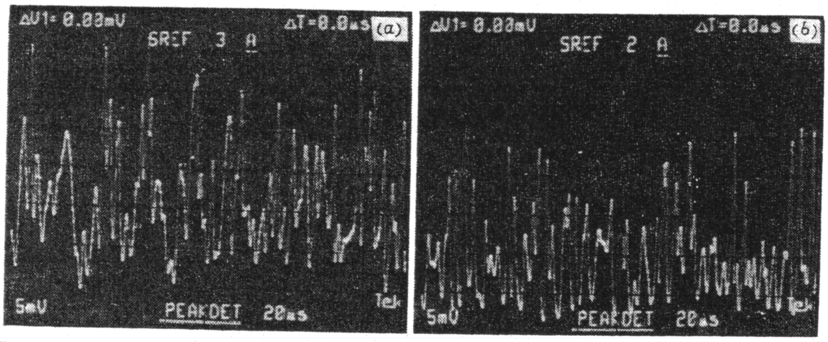

Fig. 3 Oscilloscope traces of the laser output at 532nm without QWP(a) and with QWP $\psi = 0°$(b). The lowest line is the ground level

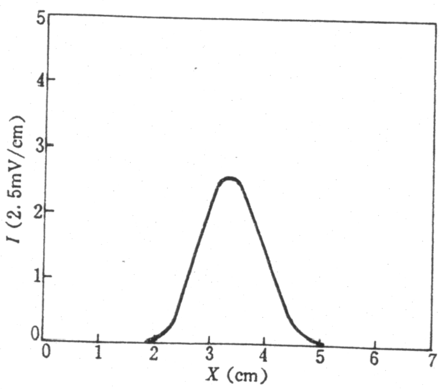

Fig. 4 Intensity profile of SH output

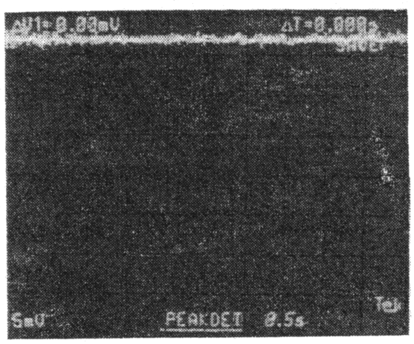

Fig. 5 Oscilloscope traces of the laser output at 532nm with QWP $\psi = 45°$. The lowest line is the ground level

of laser beam at the distance of 2. 5m from the output coupler. The fine Gaussian profile (Fig. 4) shows that the TEM_{00} mode of second-harmonic output with the divergent angle of 6 mrad has been achieved. In this case, due to eliminating the coupling modulation of polarization modes through sum-frequency generation the instability of output green lights was vanished[5]. The stable second-harmonic output with the intensity fluctuation less than $\pm 3\%$ in ten minutes was performed (Fig. 5).

3. Theoretical analyses

The rate equations of the various multilongitudinal modes including a QWP in the laser cavity are expressed as follows[6]:

$$\tau_c = \frac{dI_j}{dt} = [G_j - \alpha_j - g\varepsilon I_j - 2(1-g)\varepsilon \sum_{k-1, k\neq j}^{N} I_k]I_j \tag{1}$$

$$\tau_f \frac{dG_j}{dt} = G_j^0 - G_j(1 + \beta_j I_j + \sum_{k=1, k\neq j}^{N} \beta_{jk} I_k) \tag{2}$$

here $j = 1, 2, \cdots, N, \tau_c$ is the round-trip time of the laser in the cavity, τ_f is the fluorescent lifetime, α_i is the intracavity loss of the jth mode, G_j^0 is the small-signal gain, β_j and β_{jk} are the saturation and cross saturation parameters, ε is the nonlinear coupling coefficient of KTP, the coefficient g is dependent on the angle ψ. In the intracavity-doubling laser with multilongitudinal modes the intensity of the fundamental waves is $I(\omega) = \sum_{j=1}^{N} I_j$, the intensity of SHG consists of two parts: the doubling of each mode and the sum-frequency generation of different modes, that is $I(2\omega) = \varepsilon[g \sum_{j=1}^{N} I_j^2 + 4(1-g) \sum_{j,k,j\neq k}^{N} I_j I_k]$.

When $\psi = 0°$ or $90°$, $g = 0$

$$I(2\omega) = 4\varepsilon \sum_{j,k,j\neq k}^{N} I_j I_k \tag{3}$$

When $\psi = 45°$, $g = 1$

$$I(2\omega) = \varepsilon \sum_{j=1}^{N} I_j^2 \tag{4}$$

The equations (3) and (4) clearly show that at $\psi = 0°$ and $90°$ the second-harmonic waves are just produced through the processes of sum-frequency between the different modes. According to the Baer' s model the second-harmonic output will exhibit strong instability due to the coupling modulation between the different modes[3]. On the other hand, if $\psi = 45°$ the output of green light is obtained only by adding the squares of the polarization mode intensities, i. e. by the doubling of each mode without the coupling of modes through sum-frequency generation, therefore the instability arose from the coupling of modes will not appear. The experimental results have confirmed above theoretical discussions (Fig. 3 andFig. 5).

If $I_j = I_k$ in the equation (3) and (4) the second-harmonic intensity at $\psi = 0°$ or $90°$ should be four times larger than that at $\psi = 45°$. This conclusion is completely opposite to the experimental results of Fig. 2. We consider that the contradiction is caused from the birefringence of the nondegenerate fundamental polarization modes e_1 and e_2 in the KTP crystal. The phase difference between e_1 and e_2 modes after passing once through KTP crystal of length L is

$$\delta = \frac{2\pi}{\lambda}(n_{e_1} - n_{e_2})L \tag{5}$$

here n_{e_1} and n_{e_2} are the refractive index of modes e_1 and e_2 in KTP. In the cases without QWP and with QWP at $\psi = 0°$ or $90°$, the additional phase difference between mods e_1 and e_2 during a round-trip is 2δ, so that the double-resonance of e_1 and e_2 can not be realized in such a simple laser cavity without the elements to compensate the optical distance difference. But with QWP at $\psi = 45°$ after the modes e_1 and e_2 are reflected back from the output coupler and pass through QWP once again the polarization orientation of both modes e_1 and e_2 will rotate $90°$, therefore when the light go back into KTP the original e_1 become e_2, vice versa. Obviously, the phase difference from the birefringence of modes e_1 and e_2 in KTP will be automaticly compensated during a round-trip, so that the double-resonance of the two orthogonal polarization modes of the fundamental waves can be easily established. Undoubtedly, the intracavity intensities of the fundamental modes are resonantly strengthened, then the conversion efficiency is raised. Especially, by inserting a QWP at $\psi = 45°$ the phase difference between a pair of polarization mode e_1 and e_2 corresponding to each longitudinal mode can be compensated. The double-resonance of the multilongitudinal modes further increase the intracavity intensity of the fundamental waves and the conversion efficiency. Otherwise the optical distance compensation for the multilongitudinal-mode laser is difficult to be reached.

4. Conclusion

By inserting a QWP at $\psi = 45°$ in the LD-pumped intracavity-doubling Nd:YAG laser the amplitude fluctuation caused by sum-frequency coupling modulation has been suppressed. The birefringence optical distance difference in KTP between a pair of orthogonal polarization modes e_1 and e_2 has been compensated for each longitudinal mode. The compact stable green laser with high output power has been demonstrated. The practical application of this stabilized intracavity doubling laser must be quite extensive.

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Biography

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