A High-Power Single-Frequency 540 nm Laser Obtained by Intracavity Frequency Doubling of an Nd:YAP Laser *

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(Received 9 January 2012)

By analyzing the relation between the transmission of the output mirror and the output power in an intracavity frequency doubling laser, we choose an optimal transmission of the output mirror according to the laser application requirements. As a result, a high-power single-frequency laser at 540 nm is obtained with a maximum output power of 8 W and a power stability of ±1% for three hours, whose beam quality M^2 is better than 1.2. At the same time, a moderate FW power of 1.2 W is coupled out, which is enough to meet the requirements for local oscillation light and injected signal optical beams in quantum optics experiments.

PACS: 42.55.Xi, 42.60.Da, 42.60.Lh, 42.60.Pk DOI: 10.1088/0256-307X/29/4/044208

Nd:YAP is a widely used laser crystal due to its stimulated emission wavelength of 1080 nm that can realize type-II non-critical phase-matching in α-cut KTP crystals.[1] Due to collinear transmission of the fundamental and harmonic waves in the case, the effect of beam walk-off is minimized and nonlinear conversion efficiency is increased. Thus single-frequency Nd:YAP lasers are suitable for pumping optical parametric oscillators (OPOs) and amplifiers (OPAs) and for generating optically squeezed and entangled states. Our group have designed and built single-frequency Nd:YAP lasers operating at wavelengths of both 540 nm and 1080 nm,[2,3] which can be used for entangled light generation[4,5] and quantum information experiments.[6]

In an actual quantum optics system based on an optical parameter amplifier (OPA), a strong harmonic wave (HW) output at 540 nm serves as the pump field to demonstrate the frequency-down-conversion in an optical cavity.[4,7] A fundamental wave (FW) output at 1080 nm is also needed, and provides the local oscillation light for homodyne detectors and the injected signal optical beams of OPAs.[4,7] In particular, in a complex quantum information network, more OPAs and more homodyne detectors are required, thus slight leakage of FW from the high-reflective output coupler cannot meet the requirement for quantum optics experiments. Recently, we designed and built a high-power single-frequency Nd:YAP/LBO laser,[8] and the output powers of 4.5 W for the HW (540 nm) and 1.5 W for the FW (1080 nm) were obtained simultaneously when the transmission of the output coupler (T) was equal to 0.6%.[8] However, the watt level of the FW is enough for the quantum optics experiment, and the higher the FW output power, the lower the HW power, which is related to the transmission of the output coupler, T. In the previous design, we did not consider the influence of T to the output power of the HW and FW, and did not optimize the output power of the laser.

In this Letter, we theoretically analyze the laser output power of the HW and FW as a function of output coupling T at a certain pump power. Based on the theoretical results, we choose a suitable output mirror and build a high-power single-frequency Nd:YAP/LBO laser. The maximal output powers of 8 W at 540 nm and 1.2 W at 1080 nm are simultaneously achieved. To the best of our knowledge, this is the highest single-frequency power achieved to date at 540 nm. The power stability of the HW is better than ±1% for three hours without mode hopping.

In an intracavity frequency-doubling laser with dual wavelength outputs, the oscillation condition can be expressed in the form[9]

$$gl = T + L + E_{\rm NC}, \tag{1}$$

where g is the gain coefficient per unit length, l is the gain medium length, T is the transmission of the output coupler, L is the round-trip linear loss, and $E_{\rm NC}$ is the nonlinear conversion efficiency. The gain coefficient g can be expressed as

$$g = \frac{g_0}{1 + I/I_0}, \tag{2}$$

where g_0 is the small signal gain coefficient, I is the power density in the gain medium, and I_0 is the saturation power density. In an ideal phase-matching condition, the nonlinear conversion efficiency is given

*Supported by the National High-tech R&D Program of China (2011AA030203), the National Basic Research Program of China (2010CB923101), the National Nature Science Foundation of China (61008001), and the Nature Science Foundation of Shanxi Province (2011021003-2).

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approximately by

$$E_{\mathrm{NC}} = \frac{8d_{\mathrm{eff}}^2 l_n^2}{\varepsilon_0 c\lambda^2 n^3} I\left(\frac{\omega}{\omega_0}\right)^2, \quad (3)$$

where λ is the wavelength of FW, d_{eff} is the effective nonlinear coefficient, l_n is the length of the nonlinear crystal, n is the refractive index of the nonlinear crystal, and ω and ω_0 are the beam radius at the position of the gain medium and nonlinear crystal, respectively. According to the laser parameters, the nonlinear conversion E_{NC} can be described by the power density I. If we substitute Eqs. (2) and (3) into Eq. (1), the power density I can be expressed in terms of the transmission of the output coupler (T). The output power of the FW and the power density are related to

$$P_{\mathrm{infrared}} = A \cdot T \cdot I, \quad (4)$$

where A is the beam cross-section at the position of the gain medium. Similarly, a simple relationship between the output power of the HW and the intracavity power density can be expressed as

$$P_{\mathrm{harmonic}} = E_{\mathrm{NC}} \cdot I \cdot A. \quad (5)$$

With the parameters of our laser configuration ($I_0 = 1.67 \times 10^3\,\mathrm{W/cm^2}$, $L = 3.4\%$, $g_0 l = 0.071 P_{\mathrm{in}}$, $\lambda = 1080\,\mathrm{nm}$, $d_{\mathrm{eff}} = 1.16 \times 10^{-12}\,\mathrm{m/V}$, $l_n = 15\,\mathrm{mm}$, $A = 0.84\,\mathrm{mm}^2$, $(\omega/\omega_0)^2 = 120$, where P_{in} is the absorption pump power) and expressions (4) and (5), we can calculate the output power of the FW and HW for a given absorption pump power as a function of output coupler T. At a pump power of 33.4 W, the output power of the FW and HW as a function of T are shown in Fig. 1. From Fig. 1, we can find that with an increase in T, the output power of the FW increases and the HW decreases monotonously.

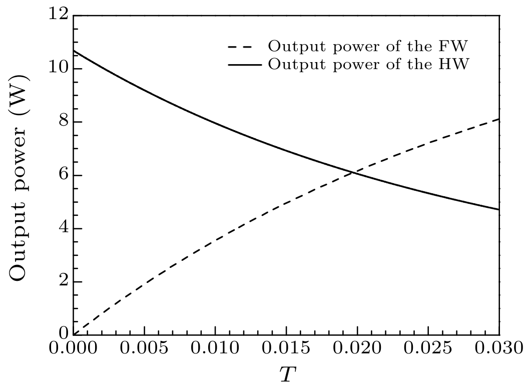

Fig. 1. The laser output power of the fundamental wave (FW) and harmonic wave (HW) as a function of the transmission of the output coupler, T, at a pump power of 33.4 W.

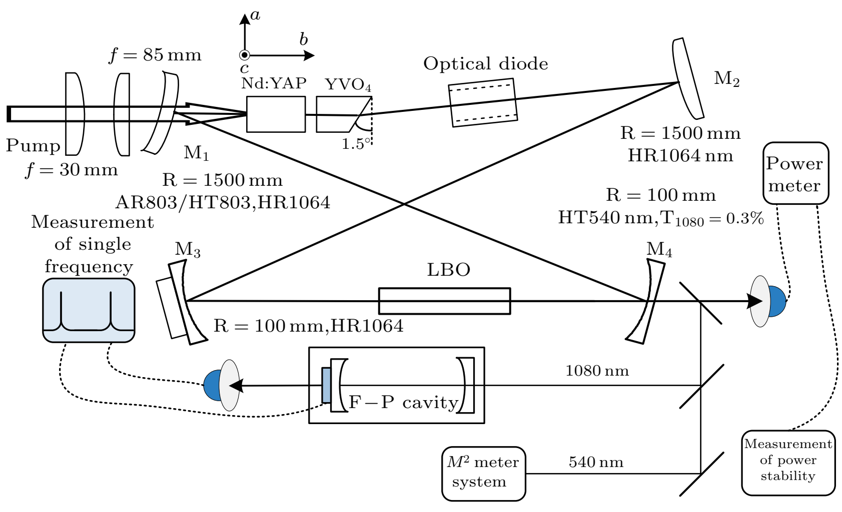

Fig. 2. Schematic diagram of a high-power single-frequency Nd:YAP/LBO laser.

The experimental setup is shown in Fig. 2. The pump source of the laser is a commercially available fiber-coupled diode array with a highest output power of 40 W and a central wavelength of 803 nm (LIMO-40-F400-DL803-EX1411). The coupling fiber has a core diameter of 400 µm and a numerical aperture (NA) of 0.22. The pump beam is imaged onto the gain medium by a telescope system with a radius of 567 µm. A figure-eight-shaped ring resonator is employed to ensure single-frequency operation, which is composed of two convex mirrors (the curvature radius is 1500 mm) and two concave mirrors (the curvature radius is 100 mm). The total length of the resonator is 678 mm and the distance between the two concave mirrors is 98 mm. An optical diode consisting of a Faraday rotator and a half-wave plate is used to maintain the unidirectional operation of the laser.[10] The gain medium of the laser is an Nd:YAP crystal 3 mm in diameter and 15 mm in length with an Nd concentration of 0.4%, which is cut along the b-axis. An additional wedge-shaped YVO_4 crystal of 1.5° on one end-facet is inserted inside the laser cavity to be a polarizer for suppressing the oscillation of the other modes, except the main mode, in the Nd:YAP laser.[8,11] An LBO crystal of $3\times3\times15\,mm^3$ with type-I non-critical phase-matching is used as the intracavity frequency doubler.[12] A Fabry–Perot (F-P) cavity with a free spectral range (FSR) of 750 MHz and finesse of 200 is employed to monitor the longitudinal mode of the laser, whose resolution is 3.75 MHz. The resolution is enough to distinguish the neighboring longitudinal modes of the laser (the separation of the longitudinal modes is 442 MHz). A small part of the HW is guided into the M^2 meter (DataRay Inc) to measure the beam quality. The power stability is recorded by a power meter and data acquisition card.

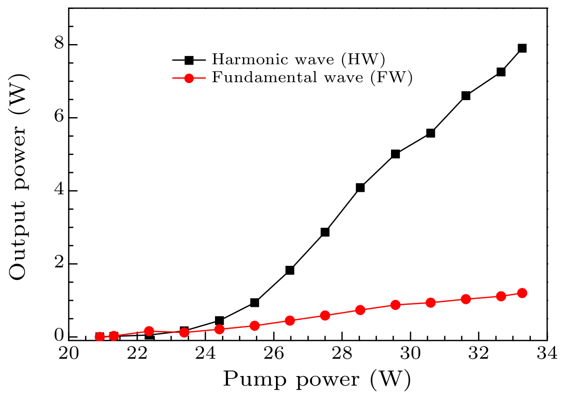

Fig. 3. The output power of the fundamental wave (FW) and harmonic wave (HW) versus pump power.

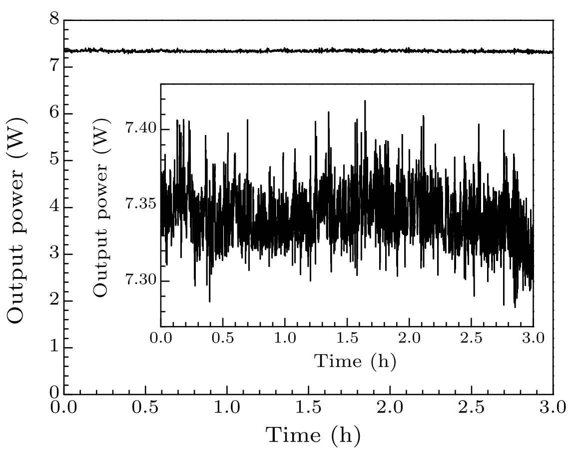

Fig. 4. The power stability of the harmonic wave (HW) over three hours.

According to the above analysis, we choose an output coupler with a transmission $T=0.3\%$ at 1080 nm and antireflection at 540 nm. This not only ensures enough FW power, but also generates higher HW output. Compared with Ref. [8] the output power of the FW decreases gently from 1.5 W to 1.2 W, but this is enough to meet the requirements for local oscillation light, multi-homodyne detectors and injected signal optical beams of more multi-OPAs. However, the output power of the HW increases greatly from 4.5 W to 8 W, which can serve as the pump field of more optical cavities to demonstrate the quantum information network. The output power of the FW is approximately in agreement with the theoretical analysis, while the HW power is slightly less than the theoretical prediction, which is induced from the incomplete transmission of the output coupler at 540 nm. Figure 3 shows the functions of the output powers of the FW and HW versus pump power. Under a pump power of 33.4 W (the absorption efficiency equals 94%), the maximum outputs at 540 nm of 8 W and 1080 nm of 1.2 W are generated, respectively. Further increasing the pump power will lead to degradation in the beam quality due to heat deformation in the Nd:YAP crystal.

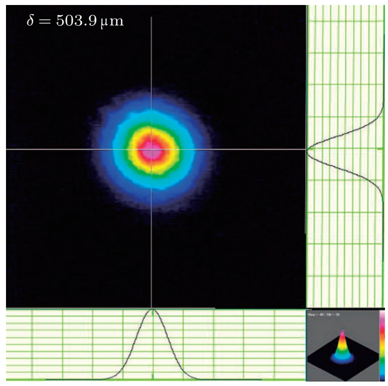

Fig. 5. Measurement of beam quality, spatial beam profile and intensity distribution.

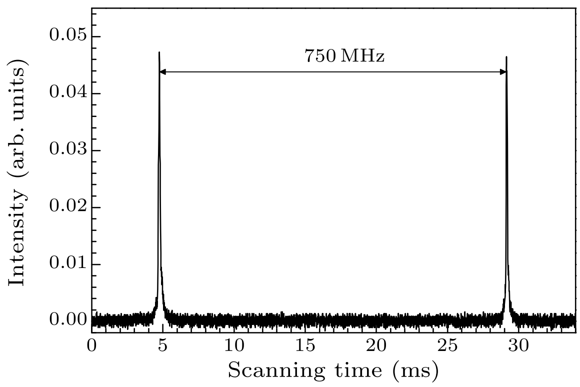

Fig. 6. The scanning confocal Fabry–Perot spectra of the fundamental wave, confirming the single-frequency operation.

When the HW power is 7.4 W or so, the laser can stably operate in single frequency. The long-term power stability of the HW is recorded by a power meter and data acquisition system (Fig. 4), which is better than ±1% for three hours, without mode hopping. The long-term power stability of the FW is superior to that of the HW, and a similar figure for FW is omitted.

The beam quality M^2 of the laser is measured by an M^2 meter (DataRay Inc). The measured values of M_x^2 and M_y^2 at 540 nm (1080 nm) are 1.15 (1.1) and 1.04 (1.05), respectively. The spatial beam profile and intensity distribution for 540 nm is shown in Fig. 5. The transmission curve of the fundamental wave through a scanned F-P cavity (Fig. 6) demonstrates that the laser operates in single-longitudinal mode.

In summary, we have designed and constructed a high-power single-frequency Nd:YAP/LBO laser with dual wavelength outputs, in which a figure-eight-shaped ring cavity is utilized. Based on the theoretical analysis, an optimal transmission of the output coupler at 1080 nm ($T = 0.3\%$) is chosen. Compared with the previous work,[8] a moderate FW power of 1.2 W is coupled out, which is enough to meet the local oscillation light requirements for homodyne detectors and injected signal optical beams of OPAs in quantum information network research. Meanwhile, a higher HW power of 8 W is obtained, which can pump more OPAs and promote research into quantum information networks.

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