Intracavity frequency-doubled and frequency-stabilized cw ring Nd:YAP laser

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A frequency-doubled and frequency-stabilized ring Nd:YAP laser with a six-mirror cavity is demonstrated. This laser satisfies both the thermal insensitivity and optimal frequency-doubling conditions. A second-harmonic output to 1 W at 0.54 μm is achieved. The intensity fluctuation is less than ±1.5% and the frequency stability is better than ±1 MHz (5 min). © 1998 Optical Society of America

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1. Introduction

The intracavity frequency-doubled and frequency-stabilized Nd:YAP laser is an important light source for nonlinear optics and quantum optics. Potassium titanyl phosphate (KTP) is a well-known crystal for frequency doubling Nd:YAG lasers (1.064 μm).[1] The large nonlinear coefficient together with a wide phase-matching temperature range, large acceptance angle, and extremely low absorption loss (between 0.5 and 1.4 μm) make KTP a promising candidate for high conversion efficiency application. However, it is difficult to realize type II 90° noncritical phase matching with one single KTP crystal for the 1.064-μm light emitted by a Nd:YAG laser. To eliminate the beam walk-off effect and to realize three-mode resonance, one must place a pair of properly oriented KTP crystals with angle phase matching in a laser cavity or optical parametric oscillator cavity.[1,2] In this case, the efficiency of frequency doubling and quantum correlation between the twin beams are inevitably degraded because of higher intracavity losses. Recently, Garmash *et al.*[3] reported type II 90° noncritical phase matching in an α-cut KTP crystal at 1.08 μm, thus suggesting new possibilities for better performance of KTP in intracavity cw frequency doubling. Ou *et al.*[4] reported the experiments for frequency doubling from 1.08 to 0.54 μm with a single α-cut KTP crystal inside an external cavity. Following this lead, here we report on an intracavity frequency-doubled and frequency-stabilized cw ring Nd:YAP laser with output of 1 W at 0.54 μm, intensity fluctuations of ±1.5%, and frequency stability of ±1 MHz (5 min).

2. Experimental Arrangement

A schematic diagram of the laser is shown in Fig. 1. The base of the laser housing is a granite stone structure upon which a six-mirror (M1–M6) ring cavity with a total length of ~140 cm was built. The laser head consists of one high-pressure krypton lamp and one single elliptical condenser to ensure high pump efficiency. The size of the Nd:YAP rod is 3 × 77 mmϕ, which was provided by the Fujian Institute of Research on Structure of Matters, Academia Sinica, China. M1, M2, and M4 are plane mirrors with a reflectivity of 99.8% at 1.08 μm. M3 is a thin-film polarizer with $R \approx 99.5\%$ for S polarization and $R < 8\%$ for P polarization. M5 and M6 are concave mirrors with a 102-mm radius of curvature and 99.8% reflectivity at 1.08 μm. M6 is the output coupler with antireflection coating for the second-harmonic wave at 0.54 μm. M5 and M6 form a near-confocal configuration. To reduce both the astigmatism from the concave mirrors and polarization imbalance of the KTP crystal, the incident angles on M5 and M6 are as small as possible (~3°). The two concave mirrors are symmetrically positioned in the laser, and thus the optical length PM1M4M5 is almost equal to PM2M3M6 = L2 (P is the center of the Nd:YAP rod). An α-cut KTP crystal of 3 mm × 3 mm × 10 mm is positioned in the center between M5 and M6, the location of the smallest beam waist. The tempera-

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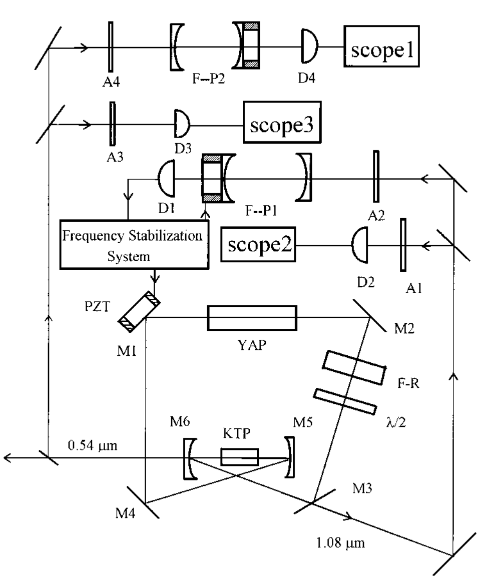

Fig. 1. Schematic diagram of the experimental setup: M1–M6, mirrors; λ/2, half-wave plate; F-R, Faraday rotator; D1–D4, photoelectric detectors; A1–A4, filters; F-P1, confocal reference cavity; F-P2, monitor cavity.

ture of the KTP crystal is actively stabilized around the phase-matching point of 63.5 °C with a precision of ±0.01 °C. The laser frequency is stabilized by a standard locking system and its stability is monitored with scope 1. The intensity fluctuations of the 1.08- and 0.54-μm lights are monitored with scopes 2 and 3, respectively.

3. Two Key Points for the Nd:YAP Laser Design

The Nd:YAP is an optical biaxial crystal with the space group of $D_{2h}{}^{16} - P6_{nm}$, which is more complicated than an isotropic Nd:YAG with a single axis. The polarization fluorescence spectrum of Nd:YAP presents obvious anisotropic characteristics. In the polarization fluorescence spectrum parallel with the C axis of the Nd:YAP crystal the radiation at 1.08-μm wavelength is much stronger than at 1.06 μm, but for the spectrum parallel with the A axis the radiation at 1.06 μm is higher than that of other spectra. In our laser all the cavity mirrors have higher reflectivities for an s-polarized laser than for a p-polarized laser. Therefore the orientation of the C axis of the Nd:YAP rod should be aligned parallel with the S-polarized cavity mirrors to ensure oscillation of the radiation at 1.08-μm wavelength. A Faraday rotator and a half-wave plate (λ/2) for 1.08 μm are positioned in the cavity to ensure that the laser operates in a unidirectional fashion. The ratio of the output powers in two directions is approximately 2000:1 in our system.

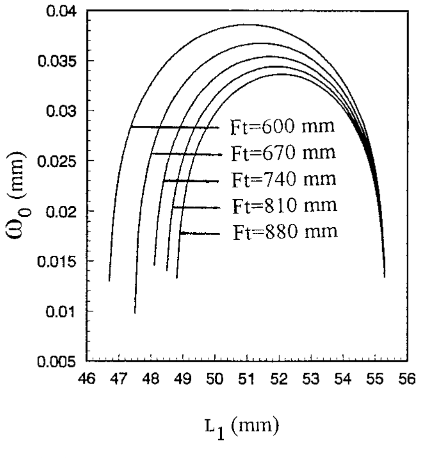

Fig. 2. Radii (ω_0) of TEM_{00} mode beams in the center of a KTP crystal versus L_1 with different Ft ($L_2 \approx 65$ cm).

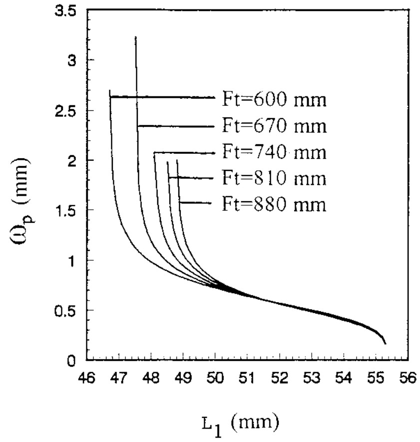

Fig. 3. Radii (ω_P) of TEM_{00} mode beams in the center of a Nd:YAP rod versus L_1 with different Ft ($L_2 \approx 65$ cm).

The thermal fluctuation of the laser rod results in unstable output power. Our laser was designed to conform with the condition of thermal insensitivity, which is $A + D = 0$,[5] where A and D are elements of the $ABCD$ transmission matrices of the laser cavity. To obtain high frequency-doubling efficiency, the configuration was also designed to satisfy optimum coupling for second-harmonic generation, which is ω_0/ω_p

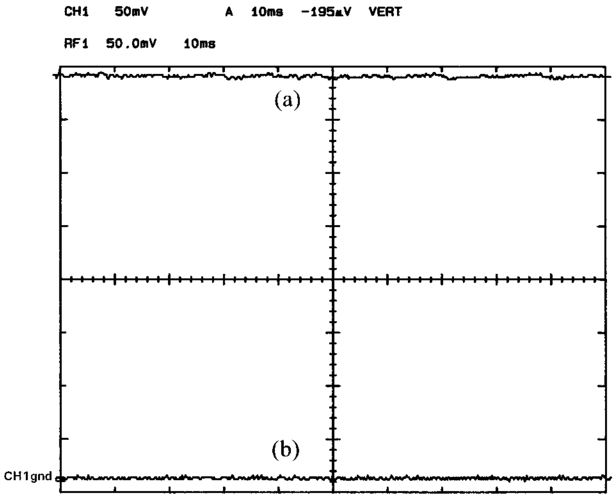

Fig. 4. Fluctuation of the green light (the detector was an FND100 photodiode): (a) the trace of green light fluctuation and (b) the trace of ground.

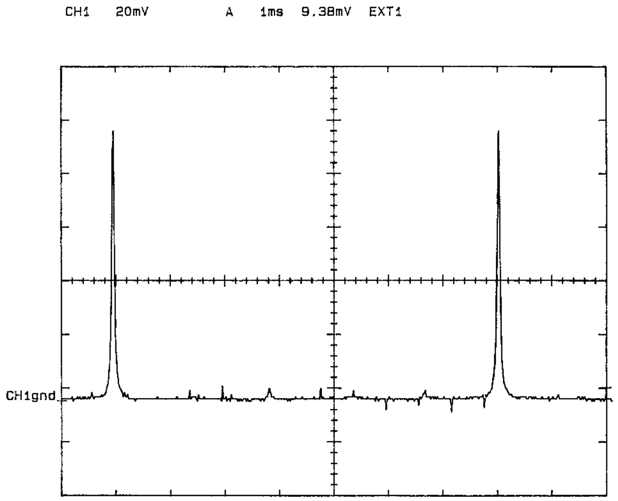

Fig. 5. Second-harmonic wave transmission through the scanning F-P2 cavity.

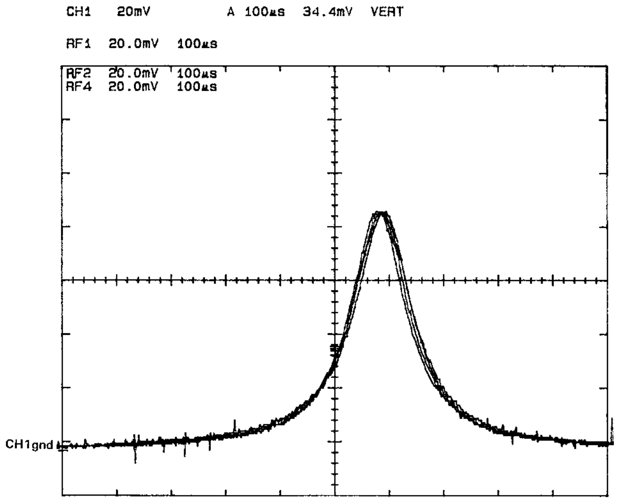

Fig. 6. Frequency stability of the second-harmonic wave through the scanning F-P2 cavity (5 min).

≈ 0.058,[6] where ω_0 and ω_p are the radii of the fundamental laser beam waists at the centers of the KTP crystal and the YAP rod, respectively. By use of numerical calculations on *ABCD* matrices, we obtained the optimum cavity parameters to achieve the best compatibility with the two above-mentioned conditions (see Figs. 2 and 3). Under a pump power of 1.44 kW for the krypton lamp, the thermal lens of the laser rod has a focal length of $Ft \approx 74$ cm. With $L_2 \approx 65$ cm and $A + D = 0$, we obtained $L_1 \approx 51.8$ mm, $\omega_0 \approx 0.0356$ mm, and $\omega_p \approx 0.58$ mm. In this case $\omega_0/\omega_p \approx 0.061$ is close to 0.058.

4. Experimental Results

As shown in Fig. 1, F-P1 and F-P2 are two reference cavities with a stable Invar structure with 5 and 10-cm length, 3000- and 1500-MHz free spectral range, and a finesse of 410 and 550 for 1.08 and 0.54 µm, respectively. Figure 4 shows the output power fluctuation of green light at 0.54 µm. The average power is 1 W and the fluctuation is less than ±1.5%. The transmission curve (Fig. 5) of the second-harmonic wave through a scanned reference cavity (F-P2) demonstrates that the laser operates in a single longitudinal mode. Figure 6 plots the frequency drift of second-harmonic generation with the mode-locked system on. The frequency stability of the second-harmonic light calculated from the data given in Figs. 5 and 6 is better than ±1 MHz (5 min).

5. Conclusion

A cw intracavity frequency-doubled and frequency-stabilized ring Nd:YAP/KTP laser has been achieved. The configuration of the laser was designed to function under conditions of thermal insensitivity and optimal coupling for second-harmonic generation. The output at 0.54 µm can be employed to pump the optical parametric oscillator with an α-cut KTP crystal to produce nonclassical light through the frequency downconversion process of noncritical 90° phase matching. By using this system we obtained laserlike twin beams at 1.08 µm with an intensity difference noise of 7 dB below the shot-noise limit.[7] The high conversion efficiency and low intracavity losses are the most favorable characteristics for nonlinear and quantum optical experiments. The design principle can be applied to all-solid-state lasers to create a more compact system.

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