Quantum noise limited tunable single-frequency Nd:YLF/LBO laser at 526.5 nm

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We describe continuous wave single-frequency operation of an intracavity frequency-doubled Nd:YLF ring laser end-pumped by a fiber-coupled laser diode. Output power of 770 mW has been achieved at 526.5 nm. The amplitude noise of the laser reaches the quantum noise limit for frequencies above 5 MHz, and the phase noise reaches the quantum noise limit for frequencies above 10 MHz. The laser's emission frequency can be tuned over 12 GHz by using an intracavity $LiTaO_3$ electro-optic crystal based Fabry–Perot etalon. © 2009 Optical Society of America

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1. Introduction

In recent years, the generation of nonclassical optical quantum states has attracted great interest, owing to potential applications in quantum communication and quantum computing. The optical parametric oscillator (OPO) is one of the best sources of such nonclassical optical quantum states. For example, two-color continuous variable (cv) entangled beams can be prepared when an OPO operates above threshold [1,2]. To pump an OPO, continuous wave (cw) single-frequency laser sources with quantum noise limit (QNL) noise and output power of a few hundred milliwatts are desired. Here the noise performance of the laser is essential, because the excess noise (beyond the QNL) of the pump laser will transfer to the down-converted signal and idler fields and results in the degradation of the quantum correlation and entanglement [3,4]. In this paper, we report a 770 mW cw single-frequency operation of an intracavity frequency-doubled Nd:YLF ring laser at 526.5 nm [5,6] that is tunable, and its amplitude and phase noise can reach the QNL for frequencies above 5 MHz and 10 MHz, respectively. The laser can be directly used as a pump source of an OPO to generate nonclassical optical quantum states, particularly two-color cv quantum entangled beams at 795 nm and 1560 nm that are suitable for long-distance quantum information processing can be created according to the energy conservation relation $1/\lambda_p = 1/\lambda_s + 1/\lambda_i$, thanks to the pump wavelength of 526.5 nm.

2. Experimental Setup and Results

Figure 1 is a schematic diagram of the frequency-doubled Nd:YLF laser. The pump source is a fiber-coupled laser diode at a central wavelength of 797 nm whose beam is reshaped to a spot size of 660 μm diameter by telescope with a ratio of 1:1.7. A unidirectional ring resonator consisting of six mirrors (four flat mirrors and two 100 mm radius of curvature mirrors) is used to enforce single-frequency operation. The input coupler is high transmission (HT, $T = 96\%$) at 797 nm and high reflectivity (HR) at 1053 nm. The output coupler is HT (97%) at 526.5 nm and HR at 1053 nm. The other mirrors are HR at 1053 nm. A *c*-cut Nd:YLF rod (4 mm diameter, 10 mm long) with Nd doping concentration of 1% is mounted in a temperature-controlled copper block. To achieve linear polarized output, a Brewster plate was inserted into the laser cavity. Lithium triborate (LBO) was chosen as the nonlinear crystal that was put in a

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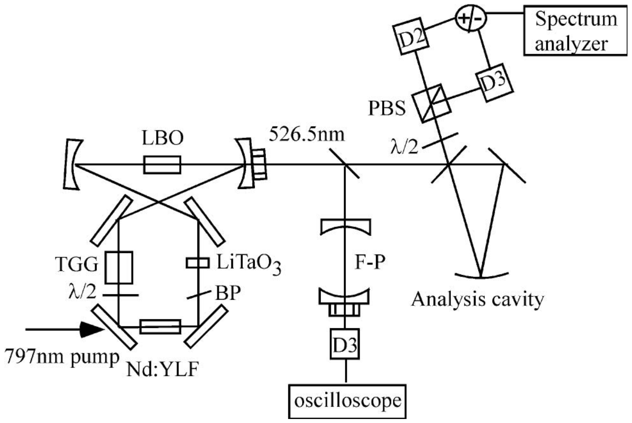

Fig. 1. Schematic diagram of the frequency-doubled Nd:YLF laser at 526.5 nm: BP, Brewster plate; D1–D3, photodetectors; PBS, polarizing beam splitter.

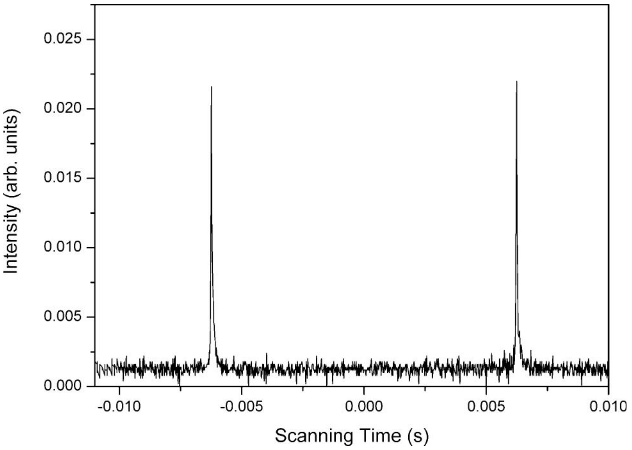

Fig. 3. Single-frequency operation of the 526.5 nm laser monitored by a scanning confocal F-P cavity.

temperature-controlled oven with accuracy of 0.01 °C to achieve type 1 noncritical phase matching. According to the cavity parameters and Gaussian beam propagation, the laser mode waist was calculated to be 270 μm inside the Nd:YLF and 45 μm inside the LBO.

Figure 2 shows the single-frequency cw 526.5 nm output power as a function of incident laser diode pump power. The pump threshold of the laser is 1.2 W; an output power up to 770 mW could be obtained with 10.6 W of pump power. The long-term power stability is less than 1% within 3 h. A scanning Fabry–Perot (F-P) interferometer with a free spectral range (FSR) of 750 MHz was used to monitor and verify single-frequency operation. Figure 3 shows a typical interferometer spectral scan.

Continuous frequency tuning is of interest in many applications, for example, to generate nonclassical optical quantum states at the absorption line of alkaline atoms, such as the rubidium $D1$ line. Doubly resonant OPOs (DROPOs) are usually employed to generate the optical quantum states [1,2,7], and it is difficult to continuously tune the wavelength by adjusting only the parameters of the DROPO (such as the cavity length or the crystal temperature) [8]. It was shown that the output wavelength of the DROPO can be tuned continuously by the tuning of the pump laser frequency [9]. In our experiment, in order to tune the laser, a LiTaO$_3$ electro-optic crystal based F-P etalon with dimensions of 2 mm × 2 mm × 1 mm, with a 1 mm length (x axis of the LiTaO$_3$) along the laser cavity axis, was employed [10]. Voltage was applied across the c axis (parallel to the polarization of the fundamental 1053 nm laser) of the LiTaO$_3$ crystal to tune the laser. A triangle wave voltage signal with amplitude of 1000 V and frequency of 0.05 Hz was applied on the crystal to demonstrate the tunability of the laser, and the wavelength was monitored by using a high-resolution wavelength meter. As shown in Fig. 4, the laser can be mode-hop tuned with a step size of 470 MHz (FSR of the laser cavity) over 12 GHz when 1000 V voltage is applied on the crystal and the tuning sensitivity is 12 MHz/V. To achieve continuous tuning, the laser frequency should be able to scan over one single longitudinal mode of the laser. In our experiment, this was

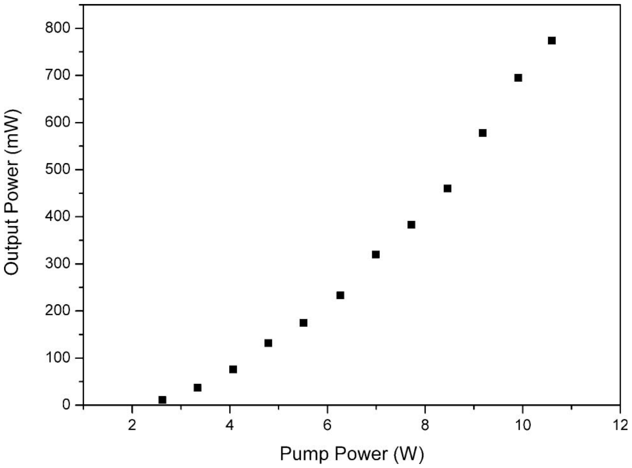

Fig. 2. Single-frequency output power at 526.5 nm versus incident laser diode pump power.

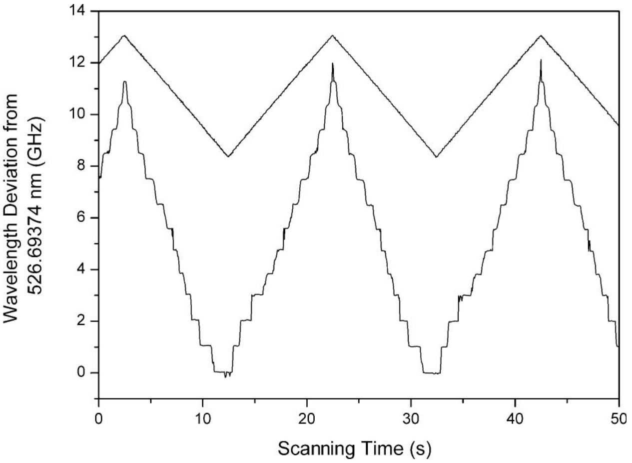

Fig. 4. Measured laser wavelength when a triangle wave voltage signal with an amplitude of 1000 V was applied to the LiTaO$_3$ electro-optic crystal.

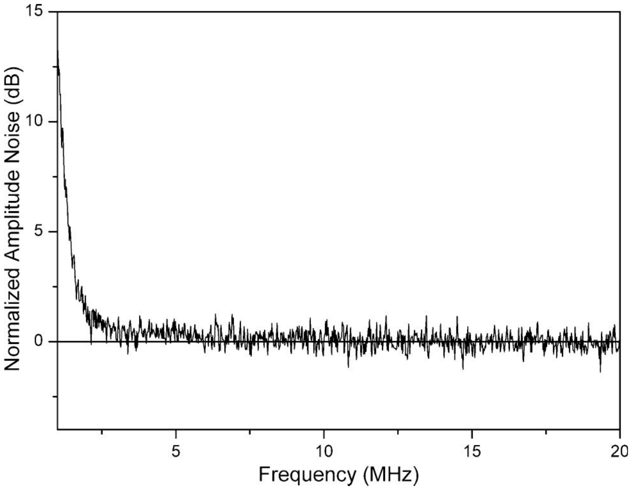

Fig. 5. Observed relative amplitude noise (normalized to the QNL) of the 526.5 nm single frequency laser from 1 MHz to 20 MHz. The detected photocurrent is 8 mA. The settings of the spectrum analyzer: resolution bandwidth is 10 kHz, and video bandwidth is 100 Hz.

realized by using a piezoelectric transducer that is mounted on one of the laser cavity mirrors.

As mentioned above, the noise properties of the laser are critical issues in some quantum optics experiments. In our experiment, the amplitude noise of the laser was detected directly by using a balanced homodyne detection system [11–13]. A half-wave plate in front of a polarizing beam splitter acts as a 50/50 beam splitter. The laser beams were detected using FND-100Q (EG&G) photodiodes, and the photocurrent signals were amplified by two radio frequency amplifiers. The sum and difference of the amplified signal were recorded using a spectrum analyzer (N9010A, Agilent). The amplitude noise of the laser at 8 mA of detected photocurrent is about 1 dB above the QNL at 2 MHz, as shown in Fig. 5, and decreases to QNL at frequencies above 5 MHz. To investigate the phase noise spectrum, a single-ended analysis cavity with a linewidth of 2.5 MHz is utilized as shown in Fig. 1, which was locked on half-maximum of the resonance peak [14]. The laser has a relatively high phase noise compared to its amplitude noise as shown in Fig. 6, which reaches the QNL at frequencies above 10 MHz.

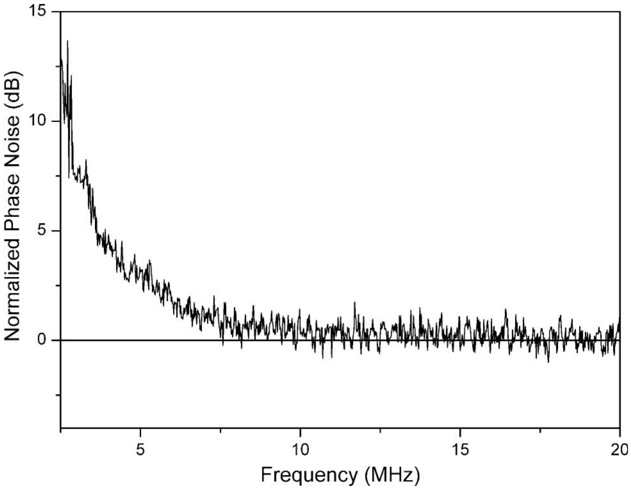

Fig. 6. Observed relative phase noise (normalized to the QNL) of the 526.5 nm single frequency laser from 2.5 MHz to 20 MHz. The detected photocurrent is 8 mA. For the settings of the spectrum analyzer, the resolution bandwidth is 10 kHz and the video bandwidth is 100 Hz.

3. Conclusion

In summary, we have demonstrated a 526.5 nm cw single-frequency operation of an intracavity frequency-doubled Nd:YLF ring laser end-pumped by a fiber-coupled laser diode. Output power of 770 mW has been achieved. The amplitude noise of the laser beam is coherent above 5 MHz around the carrier, and the phase noise is coherent above 10 MHz. The laser's emission frequency can be tuned over 12 GHz by using an intracavity $LiTaO_3$ electro-optic crystal based F-P etalon. The laser we demonstrated in this paper can be readily applied to the field of quantum optics. For example, it can be used to pump a DROPO to prepare two-color cv quantum entangled beams at 795 nm and 1560 nm that is suitable for long-distance quantum information processing.

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