High-efficiency generation of a continuous-wave single-frequency 780 nm laser by external-cavity frequency doubling

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We demonstrated a 670 mW continuous-wave single-frequency laser source at 780 nm by using external-cavity-enhanced second-harmonic generation of a seeded fiber amplifier in periodically poled lithium niobate. A maximum second-harmonic conversion efficiency of 58% was achieved. The source can work stably over 1 h by locking the frequency-doubling cavity, while the power stability is less than 2%. © 2007 Optical Society of America

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1. Introduction

Entangled light at an optical communication wavelength of 1.5 μm is very useful for long-distance quantum communication. So far, an optical parametric amplifier (OPA) has been verified to be the most successful technique to produce bright entangled light with high quality [1–6]. To generate continuous variable (CV) entanglement light at an optical communication wavelength, a high-power cw single-frequency 780 nm laser that can be used as a pump source of the OPA is required. On the other hand, it is well known that 780 nm is the transition wavelength of the D_2 line of rubidium. Thus, the cw single-frequency 780 nm lasers can also be used widely in many fields involving rubidium, such as laser cooling and manipulation [7], frequency standard [8], and quantum information storage [9].

Most of the above applications require that the 780 nm laser source can deliver high power (hundreds of milliwatts) with narrow linewidth (1 MHz). A Ti:sapphire laser can offer the desired characteristics, but this device is suffering from its cost and complexity. Recently, a relatively convenient approach has been used to achieve a high-power single-frequency 780 nm laser source [10,11] by frequency doubling a seeded fiber amplifier in a quasi-phase-matched (QPM) crystal. Maleki *et al*. [10] obtained a 900 mW cw laser at 780 nm by single-pass frequency doubling in a cascade of two crystals, and the conversion efficiency is 18%. Dingjan *et al*. obtained a nanosecond pulse laser source at 780 nm by single-pass frequency doubling with 10% conversion efficiency [11]. In this paper, we report on the high efficiency generation of a cw single-frequency laser source at 780 nm from a cavity-enhanced second-harmonic generation (SHG) of a seeded fiber amplifier. 780 nm laser output power up to 670 mW is produced at the pump power of 1.28 W, and the maximum conversion efficiency is 58%. The system can work stably over 1 h by locking the frequency-doubling cavity, and the power stability is less than 2%.

2. Design of the Frequency-Doubling Cavity

In our experiment, a single-ended linear singly resonant frequency-doubling cavity was used in which only the fundamental wave is resonantly enhanced. The second-harmonic (SH) output power and the reflected fundamental power are given by [12]

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$$P_2 = \gamma_{SH} P_c^{\,2}, \tag{1}$$

$$\frac{P_c}{P_1} = \frac{T_1}{\left(1-\sqrt{(1-T_1)(1-\delta)(1-4\gamma_{SH}P_c)}\right)^2}, \tag{2}$$

$$\frac{P_r}{P_1} = \frac{\left(\sqrt{(1-T_1)}-\sqrt{(1-\delta)(1-4\gamma_{SH}P_c)}\right)^2}{\left(1-\sqrt{(1-T_1)(1-\delta)(1-4\gamma_{SH}P_c)}\right)^2}, \tag{3}$$

where P_1 is the fundamental power incident on the cavity, P_2 is the SH output power, P_c is the circulating fundamental power inside the cavity, P_r is the reflected fundamental power, γ_{SH} is the single-pass conversion efficiency, T_1 is the power transmission coefficient of the input coupler, and δ is the round-trip intracavity linear loss.

To obtain high-efficiency SHG, several parameters of the frequency-doubling cavity have to be taken into consideration. The first is the Boyd–Kleinmann focusing factor [13]; in our case, it is 0.36. The other is the choice of the optimal input coupling (impedance matching) [12]. By combining Eq. (3) and $P_r = 0$, the impedance matching condition can be given by

$$T_{1\,opt} = \delta + 4\gamma_{SH}P_c. \tag{4}$$

In our experiment, the round-trip intracavity linear loss δ was determined to be 1% by measuring the finesse of the cavity and the single-pass conversion efficiency γ_{SH} was measured to be 0.2%/W. The transmission of the input coupler can be optimized using the above equations and the experimental parameters. The optimal input coupling $T_{1\,opt}$ was calculated to be 6.7% at the fundamental power of 500 mW.

3. Experimental Setup and Results

A schematic of the experimental setup is shown in Fig. 1. A commercial Er-doped fiber amplifier (IPG Photonics; the spectral range is from 1540 to 1563 nm) is seeded by a grating-stabilized single-frequency semiconductor laser (TOPTICA Photonics; the coarse tuning range is from 1550 to 1600 nm and the mode-hop-free tuning range is 10 GHz by adjusting the angle of the grating). The measured maximum output power of the fiber amplifier is 2.27 W at 1560 nm. A −40 dB isolator is employed to eliminate the back-reflection light. The single-frequency output of the fiber amplifier is monitored (Fig. 2) by a scanning confocal Fabry–Perot (FP) cavity (free spectral range of 750 MHz). The measured linewidth is 3 MHz, which is limited by the instrument resolution.

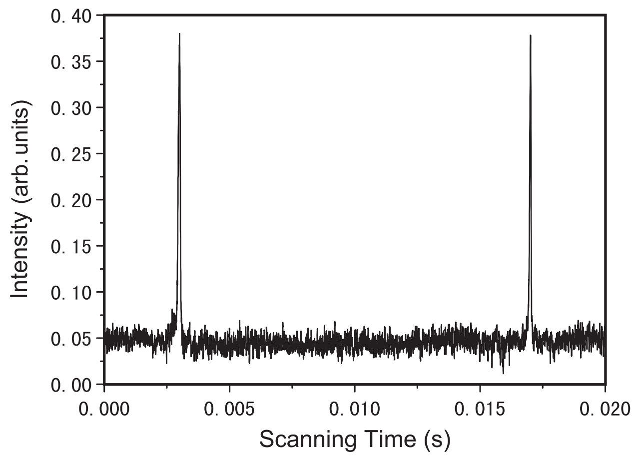

Fig. 2. Single-frequency operation of the fiber amplifier monitored by a scanning confocal FP cavity.

The transmission of the input coupler of the frequency doubler is 6% at 1560 nm and high reflection at 780 nm ($R > 99.7\%$); the output coupler has high reflection at 1560 nm ($R > 99.7\%$) and high transmission at 780 nm ($T > 90\%$). The radius of curvature of the two curved mirrors is 30 mm and the length of the cavity is 55 mm. The periodically poled lithium niobate (PPLN) crystal with dimensions of 1 mm × 10 mm × 20 mm (thickness, width, length, respectively) was selected as the nonlinear crystal. The two end faces of the PPLN were dual-band (1560 and 780 nm) antireflection coated. The PPLN comprises six QPM-poled periods from 18 to 19 μm; in our present experiment, we explored the 18.6 μm period with a QPM temperature of 120 °C. The crystal was mounted in an oven. The oven was temperature controlled, and the actual temperature

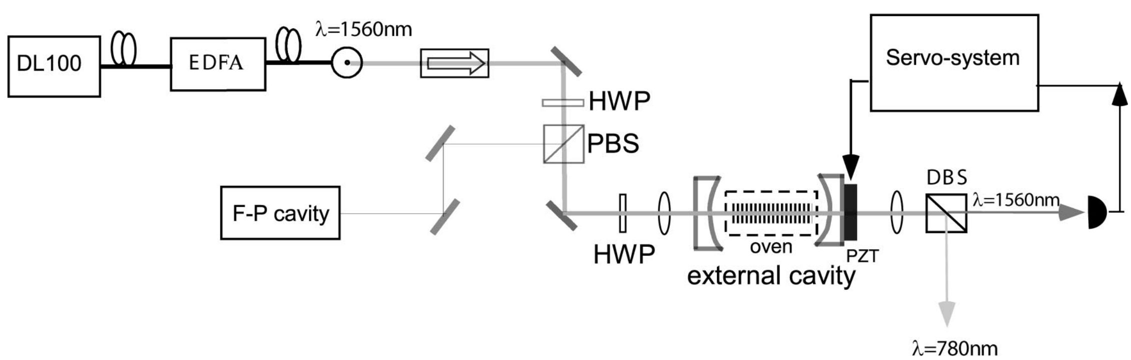

Fig. 1. Schematic of the experimental setup: EDFA, Er-doped fiber amplifier; DBS, dichroic beam splitter; HWP, half-wave plate; PBS, polarizing beam splitter; PD, photodiode.

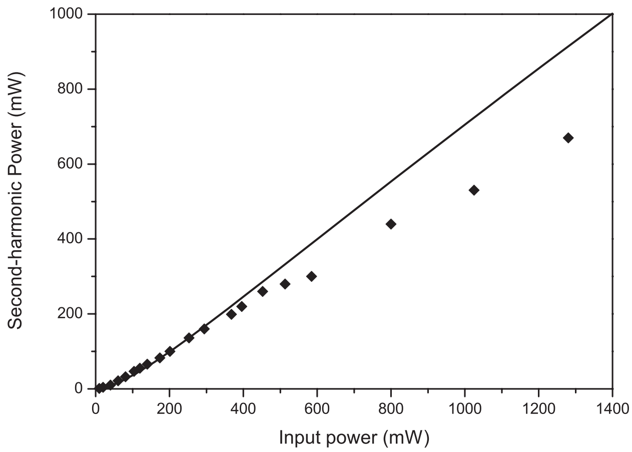

Fig. 3. Second-harmonic output power versus the input fundamental power. Solid rhombuses are the experimental results; the solid curve is the theoretical prediction using the experimental parameters.

stability of the oven is 0.01 °C. The beam waist of the fundamental beam inside the PPLN crystal is 80 μm. A set of lenses was used to carefully mode match the fundamental beam to the frequency doubler, and a 96% mode-matching efficiency was achieved.

A dither-locking method [14] was used to lock the frequency doubler to the fundamental wave frequency. A dichroic beam splitter (DBS) was used to separate the fundamental beam (transmitted) from the SH (reflected) beam. Figure 3 illustrates the measured SH output power as a function of the input fundamental power. The solid rhombuses are the experimental results, and the solid curve is the theoretical prediction calculated from experimental parameters. The experimental results are in good agreement with theoretical prediction, and the maximum conversion efficiency of 58% was achieved at the pump power of 500 mW (considering 96% mode-matching efficiency, the inferred maximum conversion efficiency is 60%). SH output power up to 670 mW is produced at the pump power of 1.28 W. Above 500 mW of input power, there exists a discrepancy between the experimental results and the theoretical prediction. This phenomenon is partly due to thermal effects caused by absorption of the fundamental and/or harmonic light. The other possible reason is that the nonlinear cascade process [15] emerged when the pump power increased to a certain level. Above this level, the generated SH begins to downconvert to nondegenerate optical parametric oscillator (NOPO) modes, which decreases the SH conversion efficiency. As mentioned above, the transmission of the input coupler was optimized at a fundamental power of 500 mW. If we optimize the input coupler with $T_{1\,opt} = 9.7\%$, which corresponds to the pump power of 1200 mW, higher 780 nm output power can be generated. Also the threshold of NOPO will increase; thus the NOPO modes can be suppressed effectively. At the SH output power of 600 mW, the frequency doubler can be locked stably over 1 h with peak-to-peak power stability less than 2%.

4. Conclusion

In summary, we have demonstrated a cw single-frequency 780 nm laser with external-cavity frequency doubling. The SH output power up to 670 mW is produced at the pump power of 1.28 W, and the maximum conversion efficiency is 58%. The system can work stably over 1 h with the power stability less than 2%. Although 670 mW output is enough to pump an OPA to generate the entangled source at 1.5 μm, the 780 nm output power can be further improved by optimizing the input coupler transmission. In the present experiment, we used the grating-stabilized semiconductor laser and EDFA, which both have wide tuning range, combined with adjusting the temperature and QPM periods in the PPLN crystal. The system presented here can be an attractive 780 nm cw single-frequency laser source with high efficiency and a wide tuning range.

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