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Influence of laser linewidth on external-cavity frequency doubling efficiency of a 1.56 μm master oscillator fiber power amplifier*

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By using an external-cavity frequency-doubling master oscillator fiber power amplifier (MOPA), a 700 mW continuous-wave single-frequency laser source at 780 nm is produced. It is shown that the frequency doubling efficiency is improved when the seed diode laser is optically locked to a resonant frequency of a confocal Fabry–Perot (F-P) cavity. This phenomenon can be attributed to the narrowing of the 1.56 μm laser linewidth and explained by our presented theoretical model. The experimental results are found to be in good agreement with the theoretical predictions.

Keywords: laser linewidth, external-cavity frequency doubling, conversion efficiency
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1. Introduction

A continuous-wave (cw) high-power single-frequency laser at about 780 nm in wavelength is required in a number of quantum optics experiments. For example, it can be used to pump an optical parametric oscillator (amplifier) to generate nonclassical states at a telecommunication wavelength, for the laser cooling and the internal state preparation of alkaline atoms. Recently, a relatively convenient approach has been used to achieve a high-power single-frequency 780 nm laser source by a frequency-doubling master oscillator fiber power amplifier (MOPA) using a quasi-phase-matched (QPM) crystal.[1−3] In the case of cw second harmonic generation (SHG), optical resonance produced by using a cavity is usually required to enhance the efficiency of SHG because of the low intensity of the cw fundamental laser. For simplicity, the fundamental laser is usually assumed to be a perfectly monochromatic wave with zero linewidth in previous theoretical studies.[4,5] Under such an assumption, one can solve the problem of second harmonic (SH) power versus the fundamental power. In practice, lasers have finite laser linewidth, mainly owing to phase fluctuation of the field. In this paper, we obtain a 700 mW laser at 780 nm in wavelength by using an external-cavity frequency-doubling MOPA. In particular, the effect of laser linewidth of the MOPA on the conversion efficiency of SHG is investigated.

2. Theoretical model

We consider a single-ended linear singly resonant frequency-doubling cavity in which only the fundamental wave is resonantly enhanced here. Let T_1 be the power transmission coefficient of the cavity input mirror, δ the round-trip intracavity linear loss (including the losses due to the crystal coating, absorption within the crystal, etc.), P_c the circulating fundamental power, and γ_SH the nonlinear conversion factor. The total round-trip losses (the linear loss and nonlinear loss due to the SHG) are assumed to be small so that P_c can be treated as a constant throughout the nonlinear crystal. The single-pass nonlinear loss is $\gamma_\mathrm{SH}P_\mathrm{c}$, and in the case of a single-ended linear cavity an extra factor of 4 arises ($4\gamma_\mathrm{SH}P_\mathrm{c}$) because the focused fundamental beam passes twice through the

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nonlinear crystal in a cavity round trip.

Due to the interaction of the beam with the environment, there will be phase diffusion fluctuation associated with the laser field. The pump field can therefore be described as[6]

$$E_{\mathrm{p}}(t) = E_{\mathrm{p0}} \exp\left(\mathrm{i}\,\theta(t) - \mathrm{i}\,\omega_0 t\right), \tag{1}$$

where E_{p0} is the amplitude and ω_0 is the angular frequency of the pump field. Assume $\theta(t)$ to be the random phase with Gaussian statistics which performs a Brownian motion described by the Wiener–Lev stochastic process

$$\langle\theta(t)\rangle = 0, \qquad \langle\theta(t)\theta(t')\rangle = D(t + t' - |t - t'|), \tag{2}$$

where $2D$ is the laser linewidth (full width at half maximum).

The pump field will be partially transmitted through the input mirror and it will circulate inside the cavity. The field amplitude $E_{\mathrm{cav}}(t)$ inside the cavity can be written as a sum of all circulating terms[7]

$$E_{\mathrm{cav}}(t) = E_0(t) + E_1(t - p/c) + E_2(t - 2p/c) + \cdots = \sum_{j=0}^{\infty} E_j(t - jp/c), \tag{3}$$

where

$$E_0(t) = \sqrt{T_1} E_{\mathrm{p}}(t), \qquad E_{j+1}\left(t - (j+1)p/c\right) = \sqrt{(1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})} E_j(t - jp/c) \tag{4}$$

with p being the optical path length for one round trip, and c the speed of light in vacuum. Assuming the cavity to be strictly resonant with the pump laser yields $p = n\lambda$, where n is an integer. In this case, expression (3) can be rewritten as

$$E_{\mathrm{cav}}(t) = \sum_{j=0}^{\infty} \left(\sqrt{(1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})}\right)^j \sqrt{T_1} E_{\mathrm{p0}} \exp\left(\mathrm{i}\theta(t - jp/c)\right). \tag{5}$$

The circulating fundamental power can be given by[6]

$$\begin{aligned} P_{\mathrm{c}} &\propto \langle E_{\mathrm{cav}}(t) E^*_{\mathrm{cav}}(t)\rangle \\ &= \sum_{i=0}^{\infty}\sum_{j=0}^{\infty} \left(\sqrt{(1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})}\right)^{(i+j)} T_1 \left|E_{\mathrm{p0}}\right|^2 \left\langle \mathrm{e}^{(\mathrm{i}\theta(t - ip/c))} \mathrm{e}^{(-\mathrm{i}\theta(t - jp/c))}\right\rangle \\ &= \frac{T_1 \left|E_{\mathrm{p0}}\right|^2}{1 - \sqrt{(1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})}\mathrm{e}^{-Dp/c}} \frac{1 + \sqrt{(1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})}\mathrm{e}^{-Dp/c}}{1 - (1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})}, \end{aligned} \tag{6}$$

thus we obtain

$$P_{\mathrm{c}} = \frac{T_1 P_1}{1 - \sqrt{(1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})}\mathrm{e}^{-Dp/c}} \frac{1 + \sqrt{(1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})}\mathrm{e}^{-Dp/c}}{1 - (1 - T_1)(1 - \delta)(1 - 4\gamma_{\mathrm{SH}} P_{\mathrm{c}})}, \tag{7}$$

where P_1 is the fundamental power incident on the cavity. In the case of a perfectly monochromatic wave, one has $D = 0$, and expression (7) becomes the same as expression (6) in Ref.[6].

The SH power P_2 is determined by P_{c} as follows:

$$P_2 = 4\gamma_{\mathrm{SH}} P_{\mathrm{c}}^2. \tag{8}$$

Expressions (7) and (8) will be used to predict the experimental results in the following part.

3. Experimental setup and results

A schematic diagram of the experimental setup is shown in Fig.1. A grating-stabilized single frequency diode laser (TOPTICA DL100) with an output power of 7 mW was used as a seed source. After a Faraday isolator of 40 dB, the diode laser was seeded into a commercial Er doped fiber amplifier (EDFA, IPG Photonics). The measured output power of the MOPA at a wavelength of 1.56 μm was 2 W at a seeded power of 1 mW and pump current of 2500 mA. A portion of the 1.56 μm laser was used to measure the linewidth of the MOPA. The remaining large power of the 1.56 μm laser was sent into the frequency doubler to produce the cw single-frequency laser at 780 nm via external cavity enhanced SHG.

The linewidth of the MOPA at 1.56 μm was measured by a high finesse Fabry–Perot (F-P) cavity (with a free spectrum range of 160 MHz and finesse of 800). When the seed diode laser was free running, the measured linewidth of the MOPA was 1.5 MHz and the laser frequency jittered seriously. For applications such as quantum optics, the narrow-linewidth laser is desirable. To narrow the linewidth of the laser system, we used the confocal F-P cavity feedback technique[8] to improve the performance of the seed diode laser. When the seed diode laser was optically locked to a resonant frequency of the confocal F-P cavity, the measured linewidth of the MOPA was 200 kHz which was limited by the instrument resolution and the laser frequency was more stable.

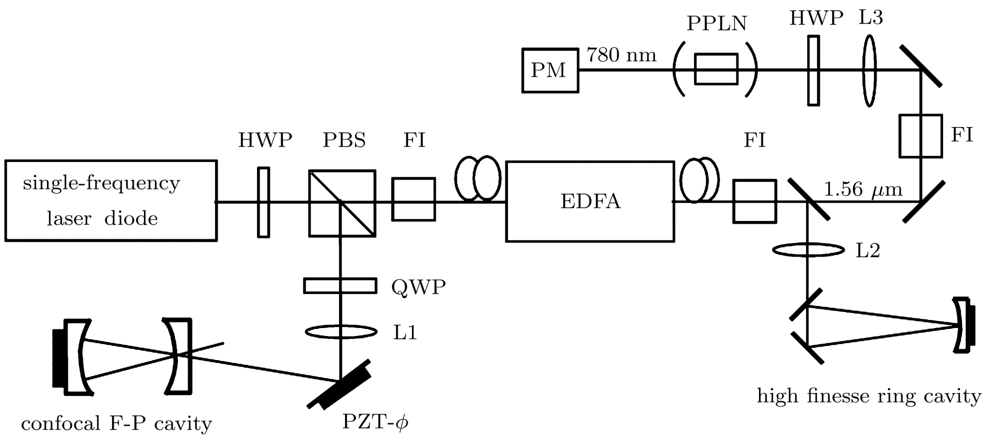

Fig.1. Schematic diagram of the experimental setup, where HWP: half wave plate; QWP: quarter wave plate; L1, L2, L3: mode-matching lens; PBS: polarizing beam splitter; FI: Faraday isolator; EDFA: Erbium doped fiber amplifier; PPLN: periodically poled LiNbO3 crystal. PM: Power meter.

The frequency doubler was a single-ended linear cavity and a periodically poled LiNbO3 (PPLN) was used as a nonlinear crystal. The transmission of the input coupler of the frequency doubler was 9% at 1.56 μm and reflection at 780 nm was larger than 99.7%, the output coupler reflection at 1.56 μm was higher than 99.7% and transmission at 780 nm was larger than 90%. The radii of curvature of the two curved mirrors both were 30 mm and the effective length of the cavity was 55 mm. The two end faces of the periodically poled LiNbO3 crystal (PPLN) were dual-band (1.56 μm and 780 nm) anti-reflection coated. The poled period of PPLN used in our experiment was 18.6 μm with a quasi-phase-matched (QPM) temperature of 120 °C. The PPLN was mounted in an oven that was temperature-controlled by using a home-made temperature controller with an accuracy of 0.03 °C. A set of lenses was used to carefully mode-match the 1.56 μm laser beam to the frequency doubler, and a 95% mode-matching efficiency was achieved. More than 700 mW of the single-frequency cw 780 nm laser was obtained at an incident fundamental power of 1.1 W with a conversion efficiency of about 65%. Figure 2 shows the measured SH conversion efficiency as a function of the incident power of the 1.56 μm laser. The triangles and squares represent the experimental results when the seed diode laser was free running and optically locked to the confocal F-P cavity, respectively. The difference between SH conversion efficiencies measured under the above two conditions is about 1.5%. The dash line and the solid line are the theoretical fitting curves that were plotted by using expressions (7) and (8) and the experimental parameters (the linewidths of the incident 1.56 μm laser were 1.5 MHz and 200 kHz, separately). There exists a discrepancy between the experimental results and the theoretical predictions when the pump power is higher than 500 mW. This phenomenon is due partly to thermal effects caused by the absorption of the fundamental and/or harmonic light.

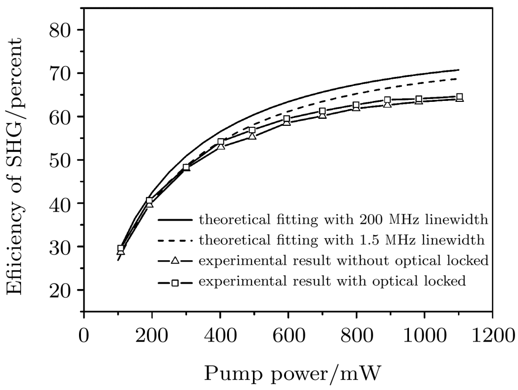

Fig.2. Frequency doubling efficiency versus the incident fundamental power.

4. Conclusions

By using an external-cavity frequency-doubling MOPA a 700 mW continuous-wave single-frequency laser source at 780 nm in wavelength is produced. It is shown that the frequency doubling efficiency is improved when the seed diode laser is optically locked to the resonant frequency of a confocal F-P cavity. This phenomenon is due to the finite pump laser linewidth, and a theoretical model for external-cavity-enhanced SHG with a finite pump laser linewidth is presented. The experimental results are in good agreement with the theoretical predictions.

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