Noise suppression, linewidth narrowing of a master oscillator power amplifier at 1.56μm and the second harmonic generation output at 780nm

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Abstract: We have demonstrated a 2 W cw single frequency 1.56 μm laser using a diode laser seeded Erbium doped fiber power amplifier, and a 715 mW cw single-frequency 780 nm laser by an external cavity enhanced second-harmonic-generation. The performance of the system was improved greatly by the seed diode laser optical locked to the resonant frequency of confocal F-P cavity. The linewidth of the 1.56 μm laser was narrowed from 2 MHz to 200 kHz, meanwhile, the intensity and phase noises were suppressed by 10 dB and 12 dB, respectively. The linewidth of the 780 nm laser was narrowed from 2 MHz to 300 kHz, meanwhile, the intensity and phase noises were suppressed by 11 dB and 13 dB, respectively.

OCIS codes: (140.3570) Lasers, single mode; (140.3515) Lasers, frequency doubled

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1. Introduction

High power, narrow linewidth and low noise continuous wave (cw) single-frequency laser sources in the 1.5-1.6 μm wavelength range are required in many scientific and engineering fields, such as in dense wavelength division multiplexing optical networks, high-resolution molecular spectroscopy, and atmospheric spectroscopy. Particularly, this kind of laser and its second harmonic generation (SHG) output around 780 nm are useful in the quantum optics experiment, such as pumping an optical parametric oscillator (OPO) to generate nonclassical state at telecommunication wavelength. Meanwhile, it is well known that 780 nm is the transition wavelength of the D2 line of Rubidium (Rb) atom and the tunable laser at this wavelength is widely used in atomic physics, such as laser cooling and internal state preparation of Rb atom. Up to now, various methods have been employed to obtain a 1.5-1.6 μm laser, including the OPO pumped by a mature high power 1.06 μm laser [1], the diode-pumped Er:Yb:YAB laser [2,3], and the master oscillator fiber power amplifier (MOPA) [4-9]. At present, the technique of MOPA is very attractive because of the ready availability of low-cost fiber-optical devices with high performance from the telecommunication industry. It has been shown that large excess noises are existed in MOPA system, and the spectral and noise properties of MOPA are determined by the performance of the seed laser, the pump source of the fiber amplifier, etc [10-12].

The MOPA system is sufficient to act a pump source for a frequency doubler as well as an OPO. But it is unsuitable for a number of quantum optics experiments, such as generation of bright squeezed state and quantum entanglement from an above threshold optical parametric amplifier (OPA) [13], due to the barriers of huge excess noise. It has been shown that excess intensity and phase noises of laser source can reduce or even eliminate completely the nonclassical characteristics of the generated nonclassical states of light. For the generation of bright nonclassical state by the above threshold OPA, the seed laser should be shot noise limited and the low noise pump laser is also essential. The tolerance of the excess noise of the pump laser can be approximately determined by the depletion ratio of the pump laser [14]. However, the experiment on generation of squeezing vacuum from a below threshold OPO is insensitive to the excess noise of the pump field [15].

In this paper, we presented a 2 W cw single frequency laser at 1.56 μm by a diode laser seeded Er doped fiber power amplifier, and 715 mW cw single frequency 780 nm laser via an external cavity enhanced SHG. By the seed diode laser optical locked to the resonant frequency of confocal Fabry-Perot (F-P) cavity, the intensity and phase noise of lasers were suppressed greatly and the linewidth of lasers were narrowed significantly. This system was applied to generate squeezing vacuum at telecommunication wavelength [15].

2. Experimental setup and results

A schematic of the experimental setup is shown in Fig. 1. A grating stabilized single frequency diode laser (TOPTICA DL100) with output power of 7 mW and tuning range from 1.55 μm to 1.57 μm 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) with the

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optical bandwidth from 1.54 μm to1.56 μm. The MOPA output power of 2 W at 1.56 μm was achieved at the seeded power of 1 mW and the pump current of 2500 mA. A portion of 1.56 μm laser was used to measure the linewidth, the intensity noise and the phase noise of the MOPA. The retained large power of 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.

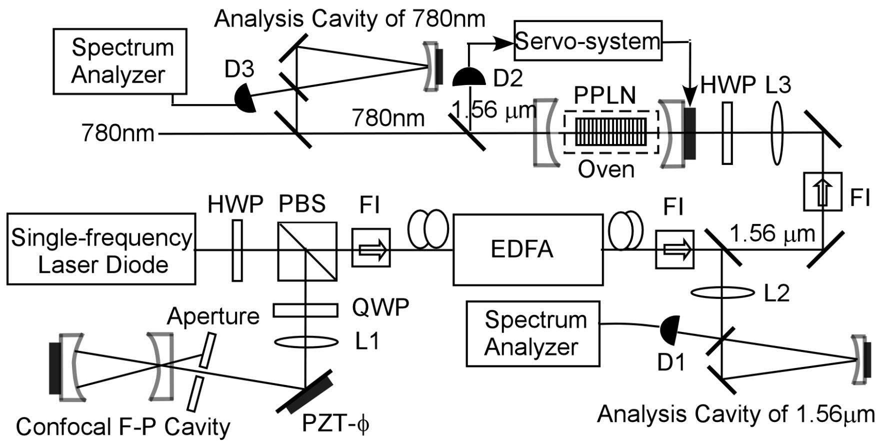

Fig. 1. Schematic of experimental setup. HWP: half wave plate; QWP: quarter wave plate; L1, L2, L3: mode-matching lens; PBS: polarizing beam splitter; FI: Faraday isolator; EDFA: Erbium doped fiber amplifier; D1, D2, D3: detector; PPLN: periodically poled $LiNbO_3$ crystal.

The frequency doubler was a single-ended linear cavity in which only the fundamental wave was resonant and a periodically poled $LiNbO_3$ (PPLN) was used as the nonlinear crystal. The transmission of the input coupler of the frequency doubler is 9% at 1.56 μm and high reflection at 780 nm (R>99.7%), the output coupler is high reflection at 1.56 μm (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 two end faces of the PPLN were dual-band (1.56 μm and 780 nm) anti-reflection coated. The poled period of PPLN used in our experiment is 18.6 μm with quasi-phase-matched (QPM) temperature of 120℃. The PPLN crystal was mounted in an oven that was temperature controlled using a home-made temperature controllor with the accuracy of 0.03℃. A set of lenses was used to carefully mode match the 1.56 μm laser beam to the frequency doubler and a 98% mode-matching efficiency was achieved. A dither-locking method [16] was used to lock the frequency doubler to the fundamental wave frequency. 715 mW of single-frequency cw 780 nm laser was obtained at incident fundamental power of 1.1 W with the conversion efficiency of 65%. Figure 2 shows the dependences of the output power of the 780 nm laser and the second-harmonic (SH) conversion efficiency on the power of the incident 1.56 μm laser. At the 780 nm output power of 700 mW, the frequency doubler can be locked stably over 1 hour with the power stability less than 2%.

The linewidth of the MOPA at 1.56 μm was measured by a high finesse F-P cavity (with free spectrum range of 160 MHz and finesse of 800), the measured result was more than 2 MHz and shown in Fig. 3(a) (curve I), The linewidth of the second harmonic (SH) output of frequency doubler at 780 nm was measured by another high finesse F-P cavity (with free spectrum range of 135 MHz and finesse of 800), the measured result was more than 2 MHz and shown in Fig. 3(b) (curve I). It can be seen that the frequency of 1.56 μm and 780 nm laser jittered seriously when the seed diode laser was free running.

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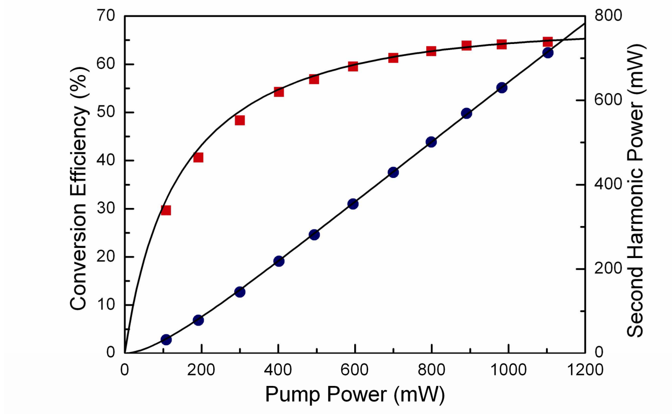

Fig. 2. Dependences of the SH output power and the conversion efficiency of SHG on the incident pump power. The solid lines are theoretical predictions.

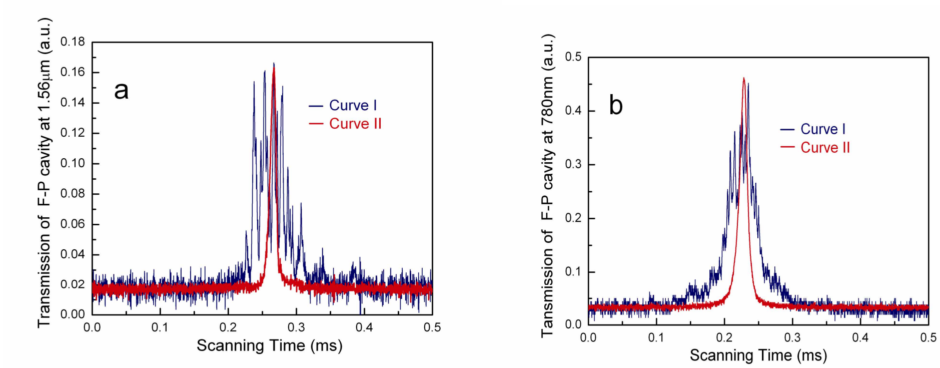

Fig. 3. Transmission of the scanned high finesse F-P cavity to measure the linewidth of laser. a: MOPA at 1.56 μm. b: Frequency doubler at 780 nm. Curve I: the seed diode laser is free running; Curve II: the seed diode laser is optical locked to the confocal F-P cavity.

The intensity noise of the MOPA at 1.56 μm was measured using an InGaAs photodetecter (GD3551Y). A constant DC photocurrent of 1 mA, corresponding to detected power of 1 mW, was adjusted. The recorded Radio Frequency (RF) noise spectrum, as shown in Fig. 4(a) (curve I), gives the intensity noise of the MOPA that is more than 30 dB above the shot noise limit (SNL) from 4 MHz to 20 MHz when the seed diode laser was free running. The SNL was calibrated by a thermal white light source, which has Poisson photon statistics and is quantum noise limited. Since the response of photo-diodes is wavelength dependent, the wavelength of the thermal white light was filtered to the same wavelength (about 80nm) in the experiment. The recorded RF noise spectrum, as shown in Fig. 4(a) (curve III), gives the SNL when the detector illuminated by the filtered thermal white light that generates the same DC photocurrent. The intensity noise of the SH output of frequency doubler at 780 nm was measured using a Silicon photodetecter (FND-100Q). A constant DC photocurrent of 1 mA, corresponding to detected power of 2 mW, was adjusted. The recorded RF noise spectrum, as shown in Fig. 4(b) (curve I), gives the intensity noise of the SH output of frequency doubler at 780 nm that is more than 26 dB above the SNL from 4 MHz to 20 MHz when the seed diode laser was free running. The SNL was also calibrated by a filtered thermal white light source that generates the same DC photocurrent, as shown in Fig. 4(b) (curve III).

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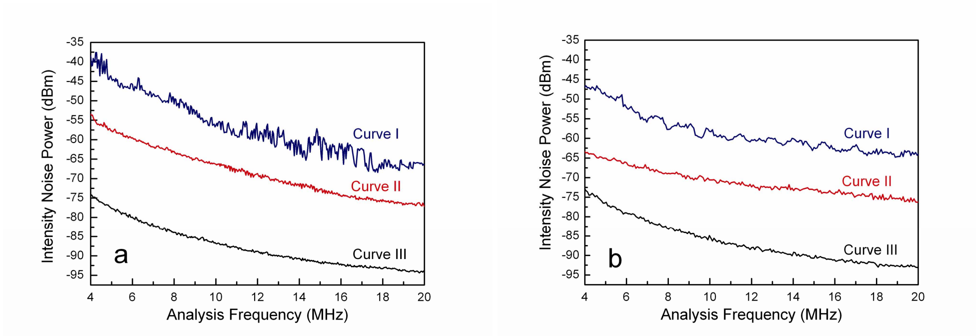

Fig. 4. Measured intensity noises of laser. a: MOPA at 1.56 μm. b: Frequency doubler at 780 nm. Curve I: the seed diode laser is free running; Curve II: the seed diode laser is optical locked to the confocal F-P cavity; Curve III: shot noise limit. The parameters of the spectrum analyzer: RBW=100 kHz; VBW=100 Hz, Sweep time=1.3 s.

To measure the phase noise of a laser beam, an empty detuned ring cavity (the analysis cavity in Fig. 1) was used as a phase-to-amplitude converter [17]. The analysis cavity is constructed by an input coupler with transmission of about 8% and two high reflectivity mirrors. The complex transmission of the device depends on the frequency but mean-field transmission does not depend on the cavity detuning. The phase noise of the MOPA at 1.56 μm was measured using an analysis cavity at 1.56 μm with the measured finesse of 80 and bandawidth of 8 MHz, as shown in Fig. 5(a) (curve I). The phase noise is more than 50 dB above the SNL from 4 MHz to 20 MHz when the seed diode laser was free running. The phase noise of the SH output of frequency doubler at 780 nm was measured using an analysis cavity at 780 nm with the measured finesse of 75 and bandawidth of 8 MHz, as shown in Fig. 5(b) (curve I). The phase noise is more than 50 dB above the SNL from 4 MHz to 20 MHz when the seed diode laser was free running.

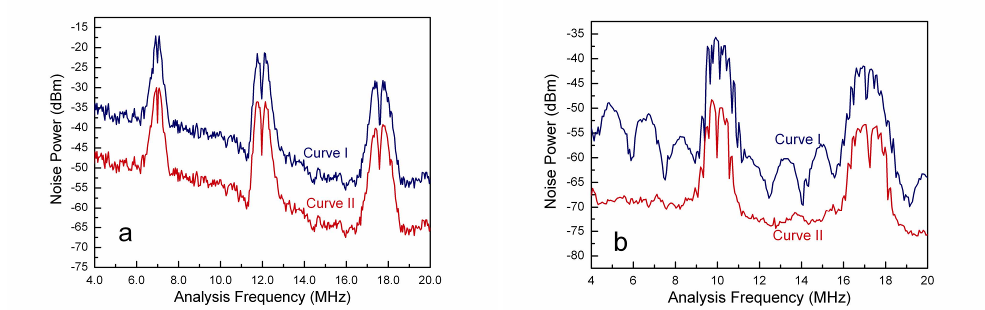

Fig. 5. Measured phase noises of laser. a: MOPA at 1.56 μm. b: Frequency doubler at 780 nm. Curve I: the seed diode laser is free running; Curve II: the seed diode laser is optical locked to the confocal F-P cavity. The parameters of the spectrum analyzer: RBW=100 kHz; VBW=10 kHz, Sweep time=1 s.

It can be seen that the measured linewidthes of the MOPA at 1.56 μm and the SH output of frequency doubler at 780 nm were large and frequency jittered seriously, measured intensity and phase noises were far above the SNL. It is known, the spectral and noise properties of the MOPA and its SH are mainly determined by the performance of the seed diode laser. The typical linewidth of seed diode laser we used was more than 2 MHz, and the measured intensity and phase noises of diode laser were 10 dB and 65 dB above the SNL, respectively. For the applications such as quantum optics, the narrow-linewidth and low noise laser is desired. To improve the spectral and noise properties of the laser system, we used the confocal F-P cavity feedback technique [18-20] to improve the performance of the seed diode laser. Such method is relatively simple and efficiency, it does not require any modification of

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commercial diode laser or any extremely fast electronic servo systems [18].

As shown in Fig. 1, a half wave plate (HWP) and a polarizing beam splitter (PBS) acted as a laser power splitter; a small portion of the power of diode laser was split off for feedback. A quarter wave plate (QWP) was used to adjust the feedback intensity. Lens L1 was used to mode match the laser into the confocal F-P cavity and the aperture before the cavity blocks the unwanted feedback while passing the desired feedback. The PZT-ϕ was used to optimize the feedback phase. Figure 6 shows the transmission of the confocal F-P cavity as a function of the cavity length. A flat top transmission curve indicates optical locking of the laser frequency to the resonant frequency of confocal F-P cavity and the locking range is about 150 MHz.

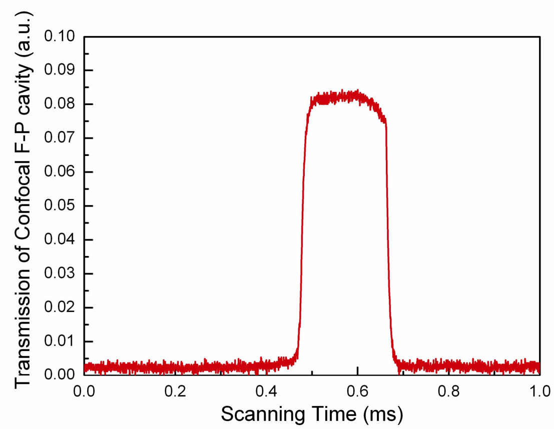

Fig. 6. Transmission of the confocal F-P cavity as the length of the cavity is scanned.

When the seed diode laser was optical locked to the resonant frequency of confocal F-P cavity, the MOPA system can stably operate more than 3 hours. It was observed that the linewidth of the MOPA at 1.56 μm was significantly narrowed to be about 200 kHz, as shown in Fig. 3(a) (curve II). The linewidth of the SH output of frequency doubler at 780 nm was significantly narrowed to be about 300 kHz, as shown in Fig. 3(b) (curve II). It can be seen that the laser frequency was more stable.

The measured intensity noise and phase noise of the MOPA at 1.56 μm were shown in Fig. 4(a) (curve II) and Fig. 5(a) (curve II), when the seed diode laser was optical locked. More than 10 dB intensity noise suppression and 12 dB phase noise suppression from 4 MHz to 20 MHz were observed, respectively. However, they are still more than 20 dB and 38 dB above the SNL, respectively. It is likely due to two noise sources that contribute to the excess noises. One is that the optical locked diode laser still can not reach the SNL, especially the phase noise. Another is the intensity noise of pump diodes and the amplified spontaneous emission (ASE) noise of the Er doped fiber amplifier.

The measured intensity noise and phase noise of the output of frequency doubler at 780 nm were shown in Fig. 4(b) (curve II) and Fig. 5(b) (curve II), when the diode laser was optical locked and the frequency doubler was locked to the fundamental wave frequency. More than 11 dB intensity noise suppression and 13 dB phase noise suppression from 4 MHz to 20 MHz were observed, respectively. However, they are still more than 10 dB and 37 dB above the SNL, respectively. The excess noises of the SH is due to the noises of fundamental wave from the MOPA.

3. Conclusion

We have demonstrated a 2 W cw narrow linewidth, low noise single frequency laser at 1.56 μm using a diode laser seeded Erbium doped fiber power amplifier. By using an external confocal F-P cavity feedback setup, the linewidth of the MOPA at 1.56 μm was narrowed

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from 2 MHz to 200 kHz, meanwhile, the intensity and phase noises were suppressed by 10 dB and 12 dB, respectively. By external cavity enhanced frequency doubling the MOPA using a PPLN crystal, 715 mW cw single-frequency 780 nm laser was obtained. When the MOPA was optical locked and the frequency doubler was locked to the fundamental wave frequency, the linewidth of the SH output of frequency doubler was narrowed from 2 MHz to 300 kHz, meanwhile, the intensity and phase noises were suppressed by 11 dB and 13 dB, respectively. Although the noises of laser system are still above the SNL, it can be used to generate squeezing vacuum at telecommunication wavelength [15]. But for a number of quantum optics experiments, such as generation of bright nonclassical state by the above threshold OPA, it is required that the noise of pump laser reaches the SNL. For this purpose, one can utilize a narrow linewidth empty cavity as an optical filter to suppress the excess noise of a laser beam to the SNL [20, 21].

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