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Realization of 1.5 W 780 nm single-frequency laser by using cavity-enhanced frequency doubling of an EDFA boosted 1560 nm diode laser

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ABSTRACT

We demonstrated a continuous-wave (CW) 780 nm laser with Watt-level output power by using external-cavity-enhanced frequency doubling of an Erbium-doped fiber amplifier (EDFA) boosted 1560 nm diode laser in a periodically-poled magnesium-oxide-doped lithium niobate (PPMgO:LN) bulk crystal. A 780 nm laser with maximum output power of 1.5 W is obtained at an incident 1560 nm laser of 2.05 W, corresponding to a doubling efficiency of 73%. The typical fluctuation of 780 nm laser's power is 1.2% (rms) in about 30 min. This 780 nm laser can be potentially applied to laser cooling and manipulation of rubidium atoms, generating 1560 nm squeezed vacuum field as well as 1560 nm continuous-variable entanglement based on optical parametric oscillator if additional locking and noise suppression is applied.

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1. Introduction

780 nm laser can be applied to cooling and manipulating rubidium atoms [1,2], atomic frequency standard [3], quantum information storage [4], atomic gravimeter [5], etc. It can also be used as the pump source to generate squeezed light at 1.5 μm optical communication wavelength [6]. Applications mentioned above required high power as well as narrow linewidth for the source and the requirement could be met with Ti:sapphire laser, tapered amplifier (TA) boosted 780 nm diode laser, and 1.5 μm infrared laser's frequency doubling. In comparison, frequency doubling of all-solid-state 1.5 μm infrared laser is a good choice, if price factor, stability, durability and the beam quality are considered.

Till now, most people would prefer doubling the 1.5 μm laser light in the quasi-phase matched (QPM) nonlinear crystals in a single-pass configuration for its simplicity and compactness, since the 1.5 μm high power fiber laser, Erbium-doped fiber amplifier (EDFA), and high-quality QPM nonlinear crystals are available at reasonable price. Sane *et al.* demonstrated 11 W narrow linewidth 780 nm laser output by way of single-pass frequency doubling of a 1.5 μm laser in a PPLN bulk crystal (81.6 $^{\circ}\text{C}$) with 36% of doubling efficiency [7]. In the same year, Chiow *et al.* realized 43 W quasi-

continuous 780 nm laser output in two cascaded PPLN bulk crystals (150 $^{\circ}\text{C}$) and the conversion efficiency is close to 72% [8]. Our group also made some investigations and 600 mW single-frequency laser at 780 nm was achieved with 5 W input after passing through two cascaded 25 mm PPMgO:LN bulk crystals ($\sim 80^{\circ}\text{C}$) [9]. As we see, the conversion is not sufficient in low power regime and an enhancement cavity is necessary in this condition. Jinxia Feng *et al.* realized a 670 mW single-frequency laser at 780 nm with an incident 1560 nm power of 1.28 W, corresponding to an efficiency of 52%, by using standing-wave two-mirror cavity enhanced frequency doubling with a PPLN bulk crystal at $\sim 120^{\circ}\text{C}$ [10]. Ast *et al.* reached maximal conversion efficiency of 95% using a semi-monolithic PPKTP (45 $^{\circ}\text{C}$) bulk crystal and a mirror as the enhancement cavity [11]. These experiments have confirmed the effectiveness of the enhancement cavity for frequency doubling in low power range and the low-decoherence frequency conversion of quantum states of light, aiming at the construction of a practical quantum network [11]. Moreover, diode lasers together with amplifiers, QPM nonlinear crystals, and miniaturized enhancement cavities can be integrated onboard to produce quantum devices for quantum communication [12]. And the noise from amplified spontaneous emission and the intensity noise can be suppressed to some extent with the cavity-enhanced frequency doubling.

Non-QPM crystals cannot make use of the largest nonlinear coefficient in most cases and thus requires lower linear loss in cavity-enhanced frequency doubling, which is hard to realize [13].

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And with QPM nonlinear crystals, the result can be much better [11]. What's more, the critical phase matching with non-QPM crystals introduces the walk-off effect in, which lowers the doubling efficiency and the beam quality [14].

In the case of frequency doubling from 1560 nm to 780 nm, KTP and LiNbO₃ (LN) crystals are most commonly used. Both are ferroelectric which can be nicely periodically poled. In our case, a PPMgO:LN bulk crystal is chosen as the nonlinear material, since PPMgO:LN has got larger nonlinear coefficient than PPKTP and higher photon refractive damage threshold than PPLN [15]. The conversion should be more sufficient in the cavity enhanced frequency doubling with PPMgO:LN than that with PPKTP when the linear loss can only be lowered at higher price. A stable 780 nm laser with maximum output power of 1.5 W is demonstrated by using external-cavity-enhanced frequency doubling of an EDFA boosted 1560 nm diode laser, with a doubling efficiency of 73%. The typical fluctuation in about 30 min is 1.2% (rms). This 780 nm laser can potentially be used for rubidium cooling and manipulation with proper frequency locking. With further noise suppression on 780 nm laser light, another potential application is to pump the type I degenerate optical parametric oscillator to generate squeezing vacuum at 1560 nm [6] and to further produce entanglement at 1560 nm.

2. Experimental setup

The experimental setup is shown in Fig. 1. The external-cavity diode laser (ECDL, New Focus) seeds into an EDFA (Keopsys SA) to boost the 1560 nm laser to 2.20 W. Because of the loss of the optical isolator, the 45° high-reflectivity (HR) mirrors and the lens, the power of the fundamental wave laser in front of the doubling cavity is below 2.05 W.

We adopted a singly resonant ring cavity in a symmetric bow-tie configuration. M1, M2 are plane mirrors. M3, M4 are convex–concave mirrors with a radius of concave curvature of 100 mm. The total length of the cavity is 650 mm with a folding angle of 8°. The distance between M3 and M4 is 118 mm. The 1 mm × 3.4 mm × 25 mm PPMgO:LN bulk crystal (HC Photonics Corp.) with a poling period of 19.48 μm is mounted in the homemade copper oven, of which the temperature is controlled by a temperature controller (Newport, Model 350B) together with a Peltier element (TEC module) and a temperature sensor (AD592). There are two input couplers with

different transmissivities at 1560 nm ($T_{M1} @ 1560 \text{ nm} = 9.8\%$ and $T'_{M1} @ 1560 \text{ nm} = 14.0\%$). M2, M3 and M4 are HR mirrors for the fundamental wave laser and the transmissivity of M4 at 780 nm is 97%. The waist in the crystal for the fundamental wave laser beam is ~50 μm. The half-wave plate placed in front of the cavity serves to adjust the polarization of the fundamental wave laser beam. A phase-type electro-optic modulator (EOM, New Focus) is placed between the ECDL and the EDFA to modulate the seed laser with a 25 MHz sinusoidal radio frequency signal, which serves to actively stabilize the cavity length by using the Pound–Drever–Hall modulation side-band method [16]. The enhancement cavity can be locked on resonance with the fundamental wave laser, yet the pull-in range can still be extended if modulation of higher frequency is applied on the EOM.

The fundamental wave laser is mode matched into the cavity via a lens $f = 500 \text{ mm}$ and the typical mode matching efficiency is 94%, as shown in Fig. 2 (a). When the PPMgO:LN crystal is controlled off the optimized QPM temperature, the fundamental wave laser is preserved. A large part of the fundamental is converted to the second harmonic wave laser when the crystal's temperature is controlled to realize optimal QPM, leading to a decrease of the finesse of the cavity, as shown in Fig. 2 (b). The typical finesse of the cavity with $T_{M1} @ 1560 \text{ nm} = 9.8\%$ input coupler are 32 and 19, respectively. The typical finesse of the cavity with $T'_{M1} @ 1560 \text{ nm} = 14.0\%$ input coupler off and on QPM temperature are 26 and 16, respectively.

3. Experimental results and discussion

Fig. 3 shows the power of the generated 780 nm laser versus the temperature of the PPMgO:LN crystal in the single-pass configuration after removing the input coupler M1. In this way, the focusing condition in the single-pass configuration is nearly the same with the one when the cavity is on resonance. To avoid the unwanted thermal effect and the cascaded nonlinear process, a power of 350 mW for the fundamental light is chosen. The measured QPM temperature is 81.3 °C with a full-width half-maximum bandwidth of about 3.5 °C, as shown Fig. 3. Through averaging the nonlinear conversion coefficients measured at different input fundamental powers we get the $E_{NL} = 1.05\%/W$ in this focusing condition.

We measured the power of the second harmonic wave laser versus the power of the fundamental wave laser after the enhancement cavity is actively stabilized. The power of the

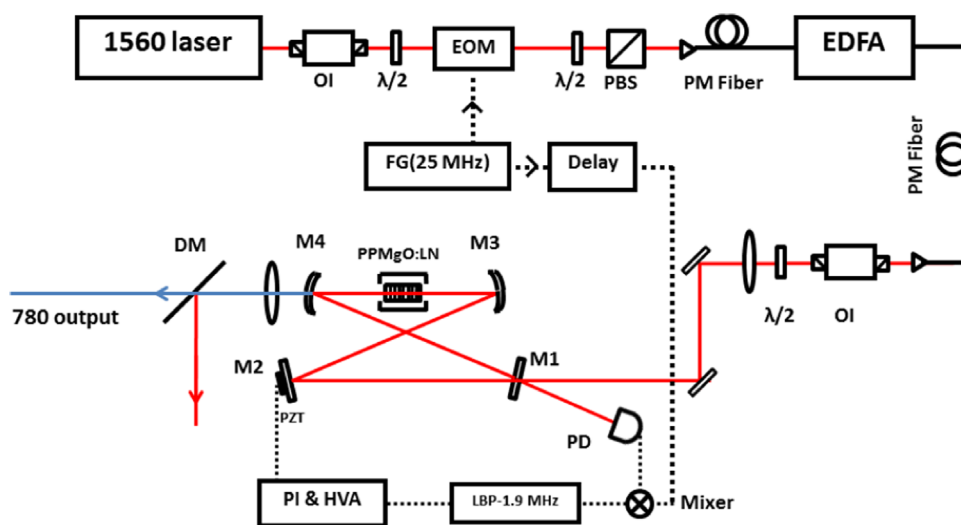


Fig. 1. The schematic diagram of the experimental setup. The key to the figure: OI: Optical isolator, EOM: Electro-optic phase-type modulator, $\lambda/2$: Half-wave plate, PBS: Polarization beam splitter cube, PM Fiber: Polarization-maintaining optical fiber, DM: Dichromatic mirror, PD: Photo-diode, FG: Function generator, LBP: Low-band-pass filter, PI: Proportion and integration amplifier, HVA: High voltage amplifier, PZT: piezoelectric ceramic transducer.

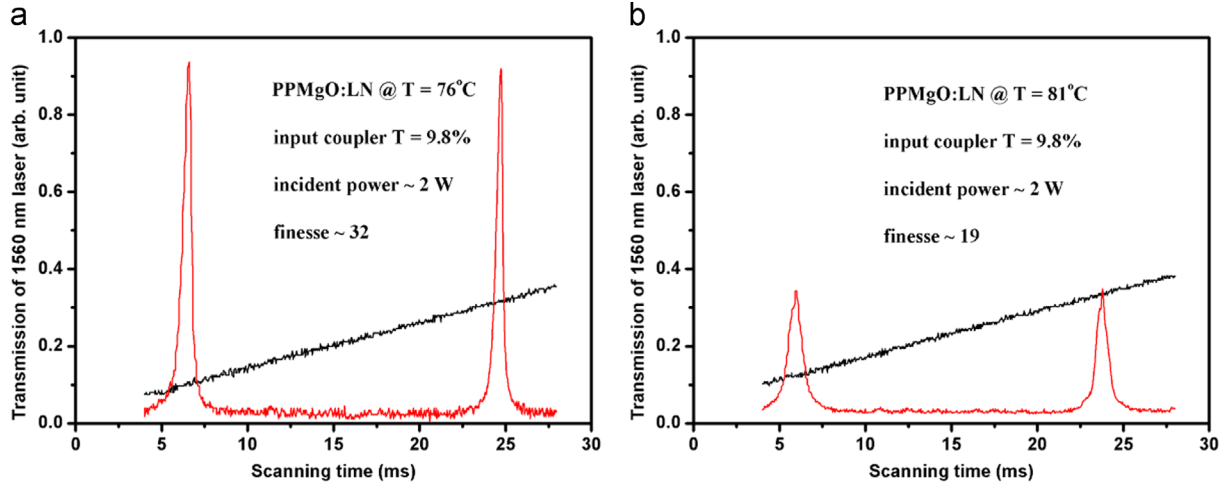


Fig. 2. The typical mode matching results for stabilizing the PPMgO:LN crystal's temperature at 76 °C (a) and 81 °C (b). The QPM temperature is 81.3 °C for frequency doubling of 1560 nm laser, see Fig. 3.

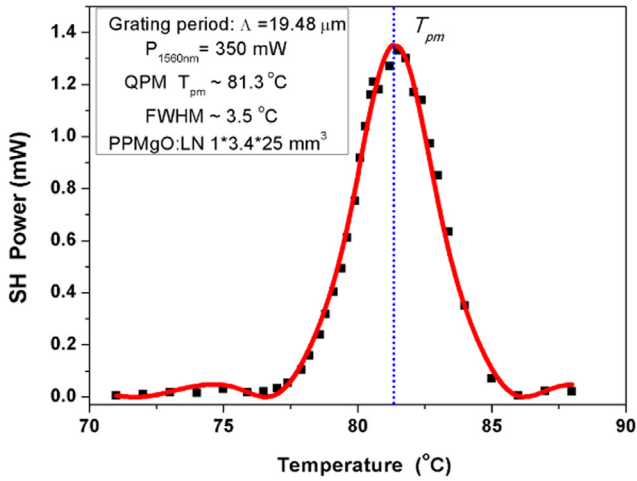


Fig. 3. The measured temperature tuning data of the PPMgO:LN crystal. The poling period of the PPMgO:LN bulk crystal is 19.48 μm. Power of the fundamental is 350 mW, and QPM temperature is 81.3 °C with a FWHM of 3.5 °C. The solid curve is theoretical fitting.

780 nm laser and the corresponding doubling efficiency is shown in Fig. 4. The transmissivities of the output coupler, the lens, and the dichromatic mirror at 780 nm are taken into consideration. Black squares and blue triangles represent the data measured in the experiment. Red solid lines and green solid lines are the calculation results according to the measured parameters T_{M1} , L , α , and E_{NL} [17]. In the formula (1)–(4), T_{M1} , L , α , P_{in} , E_{NL} , η , and P_{SH} represent the transmissivity of the input coupler for the fundamental wave laser, the linear loss of the cavity, the mode matching efficiency, the incident power of the fundamental, the nonlinear conversion coefficient, the frequency conversion efficiency and the power of the second harmonic, respectively. Variables β and ρ are introduced to simplify the expression. In this simulation, we assume that the absorption of the 780 nm laser is weak. So the absorption that is proportional to the square of the circulating power of 1560 nm laser light is not considered.

$$\beta = T_{M1} + L \quad (1)$$

$$\rho = 4\alpha T_{M1} P_{in} E_{NL} \quad (2)$$

$$\eta = \frac{\beta^2}{9P_{in}E_{NL}} \left\{ \left[1 + \frac{27\rho}{2\beta^3} \left(1 + \sqrt{1 + \frac{4\beta^3}{27\rho}} \right) \right]^{1/6} - \left[1 + \frac{27\rho}{2\beta^3} \left(1 + \sqrt{1 + \frac{4\beta^3}{27\rho}} \right) \right]^{-1/6} \right\}^4 \quad (3)$$

$$P_{SH} = \frac{\beta^2}{9E_{NL}} \left\{ \left[1 + \frac{27\rho}{2\beta^3} \left(1 + \sqrt{1 + \frac{4\beta^3}{27\rho}} \right) \right]^{1/6} - \left[1 + \frac{27\rho}{2\beta^3} \left(1 + \sqrt{1 + \frac{4\beta^3}{27\rho}} \right) \right]^{-1/6} \right\}^4 \quad (4)$$

The linear loss of the cavity estimated from transmitted fundamental wave dramatically deviates from the actual value compared with the one derived from the reflected field. This is partly due to the vibration of the cavity and the nonlinearity of the PZT. We adopted the latter and a 3.2% linear loss is deduced from the reflected field with formula (5) [17]. In the formula, Ω represents the ratio of the reflected fundamental wave laser's power on resonance over the reflected power when the cavity is off resonance. When we measure the linear loss of the cavity, the PPMgO:LN crystal should be controlled off the QPM temperature.

$$L = \frac{1 - \sqrt{\Omega}}{1 + \sqrt{\Omega}} T_{M1} \quad (5)$$

As we see, the calculated curves fit well with the experimental data while there are small discrepancies at high input power regime. This might be the result of the model we chose to simulate. In this model the absorption of 780 nm laser is neglected, but the absorption is no longer negligible when the power of 780 nm laser rises to 1 W. This should also be attributed to the cascaded nonlinear process involving both up-conversion and down-conversion. Note that the calculated curve with the 14.0% input coupler fits better than the one with the 9.8% input coupler. We conclude that higher transmissivity of the input coupler can match the loss of the cavity better and lift the threshold of the cascaded nonlinear process at the same time [10]. The optimal transmissivity, calculated from formula (6), for the frequency doubling cavity of this configuration and of similar optical

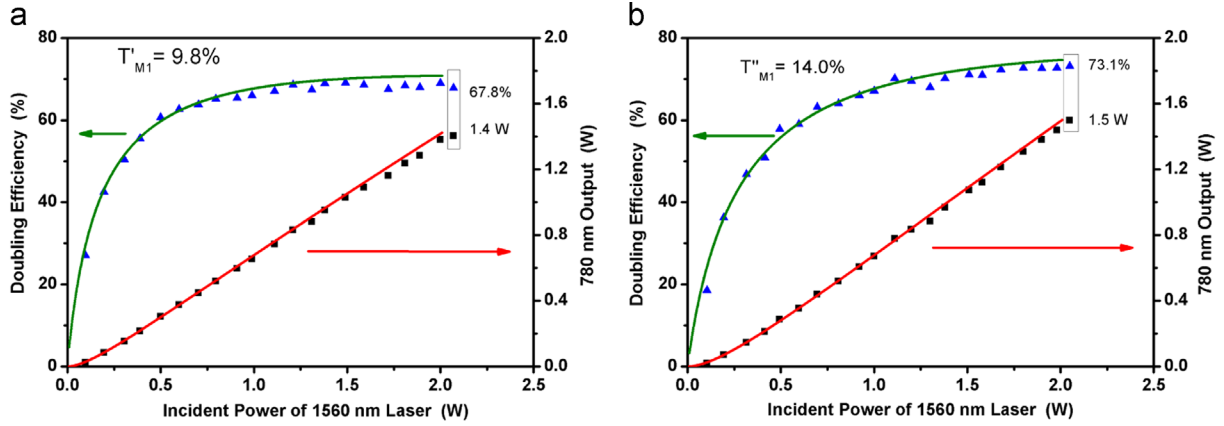


Fig. 4. The power of the second harmonic and the conversion efficiency versus the power of 1560 nm laser with input coupler $T_{M1}=9.8\%$ (a) and $T''_{M1}=14.0\%$ (b). The transmissivities of the output coupler, the lens and the dichromatic mirror at 780 nm are taken into consideration. The linear loss L is 3.2%, and the nonlinear conversion coefficient E_{NL} is 1.05%/W.

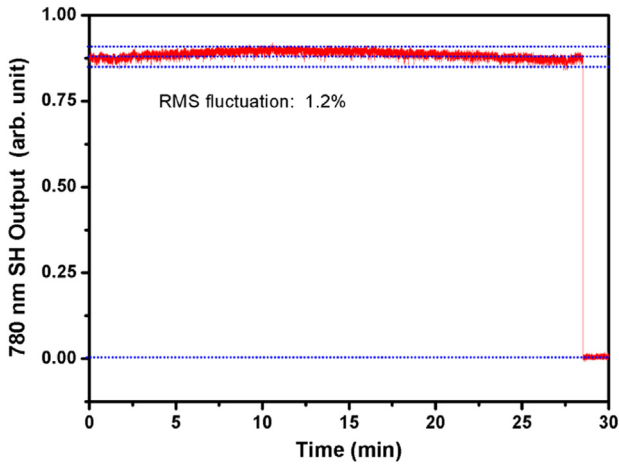


Fig. 5. The measured fluctuation of the output second harmonic wave laser. Typical fluctuation is 1.2% (rms) in 30 min.

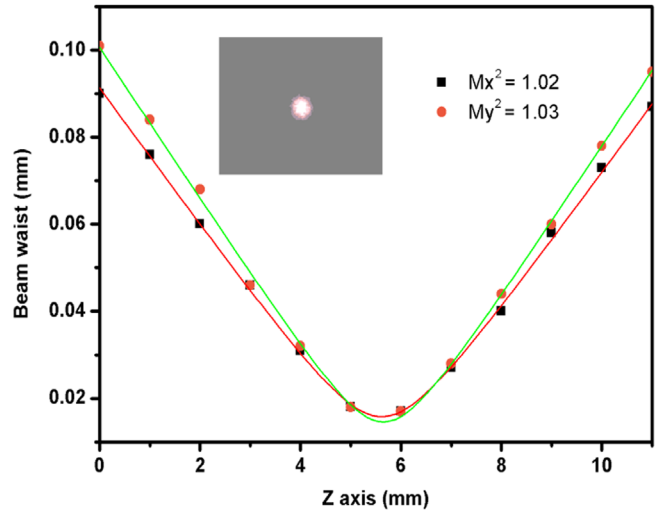


Fig. 6. Beam quality M^2 values of the second harmonic laser beam. Inset shows the typical intensity profile of the second harmonic laser beam.

quality is 16.2% at 2 W input in Ref. [18].

$$T_{opt} = \frac{L}{2} + \sqrt{\left(\frac{L}{2}\right)^2 + E_{NL}P_{in}} \quad (6)$$

To increase the doubling efficiency at level of 2 W 1560 nm input power, possible solutions are following:

- 1) The fundamental wave could be focused more tightly to increase the single pass conversion efficiency. The beam waist of our cavity is about 50 μm , which corresponds to a focusing factor of 1.16. According to Boyd–Kleinmann’s theory, the best waist size is 32 μm in our condition (optimal focusing factor is 2.84) [19]. But in fact, the conversion efficiency would not decrease dramatically when the focusing factor is loosened to 1–6. Moreover, tight focusing would drive the cavity to near-unstable region and the heating of the crystal would become more serious. The heating induced asymmetry in the present condition is already observed on fundamental wave fringe when scanning the PZT of the enhancement cavity at high input power.
- 2) The input coupler could be changed to meet the impedance matching. The current frequency doubling cavity can be impedance matched at 2 W of fundamental wave laser input power

with an optimal input coupler which has a transmissivity of 16.2% at 1560 nm.

- 3) If the linear loss of the cavity could be lowered, the doubling efficiency will rise greatly. The main reason for the low doubling efficiency is the large linear loss brought by the transmission and scattering of the cavity mirrors, the scattering on the surface of the crystal, and the absorption of the crystal. If these components are changed with counterparts of better quality, the linear loss would be lowered, thus improving the doubling efficiency.

The stability of the output power of 780 nm laser at an incident 1560 nm laser’s power of 2 W is monitored for about 30 min with a detector (UniQuanta, PED100-LN, the bandwidth DC to 1 MHz), and typical result was shown in Fig. 5. The fluctuation is less than 1.2% (rms) and this fluctuation should partly be attributed to the slow variation of the fundamental power. The noise of 780 nm laser can be further suppressed with a mode cleaner.

The beam quality of the output 780 nm laser beam is evaluated with M^2 in two orthogonal transverse directions x and y . The measured M_x^2 in the horizontal direction is 1.02 and the M_y^2 in the vertical direction is 1.03, as shown in Fig. 6.

The linewidth estimation of the 780 nm laser is carried out with a confocal Fabry–Perot cavity (the cavity mirror’s radius of

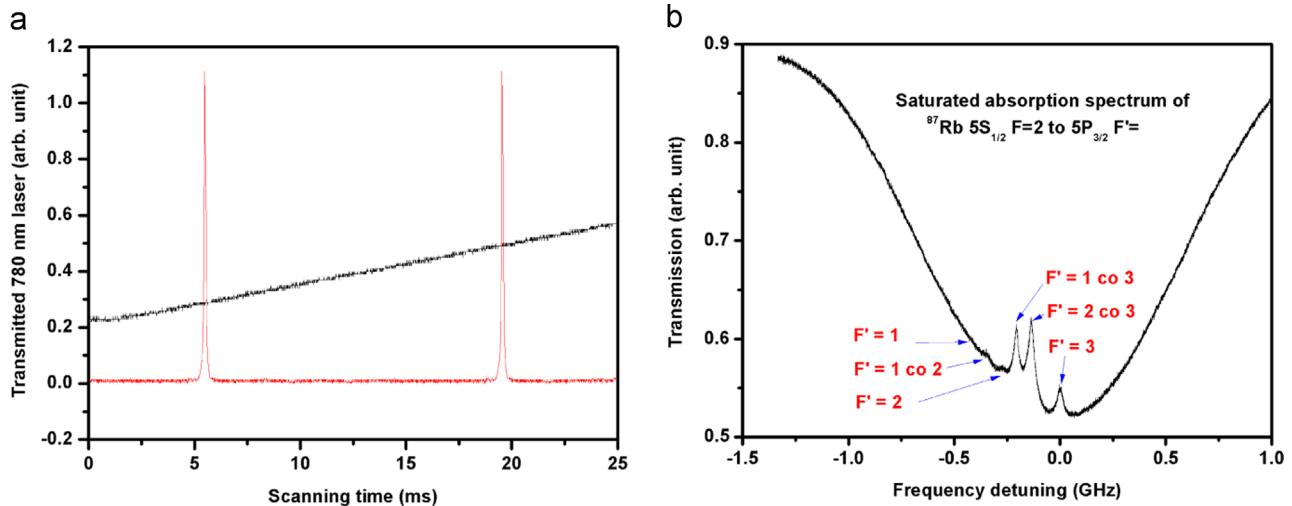


Fig. 7. The linewidth estimation of 780 nm laser with a confocal Fabry–Perot cavity with a FSR of 2.5 GHz (measured finesse ~ 160 gives an upper bound of the 780 nm laser's linewidth of 16 MHz) (a) and the continuous frequency tuning range of 780 nm laser with measured saturation absorption spectra of $^{87}\text{Rb } 5S_{1/2} (F=2) - 5P_{3/2} (F'=1, 2, 3)$ transitions in D₂ line (b).

curvature is 30 mm, the finesse of the confocal cavity is ~ 160 , and the free spectral range is 2.5 GHz). The upper bound of the 780 nm laser's linewidth should be less than 16 MHz. This is limited by the reflectivity of the cavity mirror. The result is shown in Fig. 7 (a). The generated 780 nm laser is also tunable over several nanometers. The coarse tuning range is mainly limited by the linear loss of the enhancement cavity. A 781.0 nm laser light with an output power of 1.2 W is obtained at an input power of 2.05 W. For this wavelength, the QPM temperature is changed to 90.2 °C. The continuous tuning range is mainly limited by the PZT of the enhancement cavity we applied. The typical continuous tuning range is over 1 GHz around 1560 nm. When the length of the cavity is continuously scanned there's no need to change the temperature of the PPMgO:LN crystal since the changes in wavelength of 1560 nm laser is relatively small and the output power is not significantly affected. With the help of a wavelength meter, the 780 nm laser can be tuned to different hyperfine transitions in rubidium D₂ line. In the experiment, we obtained a saturation absorption spectra of $^{87}\text{Rb } 5S_{1/2} (F=2) - 5P_{3/2} (F'=1, 2, 3)$ transitions in D₂ line, as shown in Fig. 7 (b), through scanning the PZT of the ECDL and locking the enhancement cavity to the laser frequency. The typical scanning speed for the 1560 nm laser is about 115 MHz/s, with which the enhancement cavity can be kept locked. Due to the frequency drift of the fundamental wave and the imperfect locking of the enhancement cavity, the saturation absorption spectra is degraded.

4. Conclusion

A tunable continuous-wave 780 nm laser light with an output power of 1.5 W is demonstrated via ring-cavity-enhanced frequency doubling of an EDFA boosted 1560 nm diode laser, corresponding to a doubling efficiency of 73%. Typical fluctuation is 1.2% (rms) in about 30 min. The doubling efficiency for now is mainly limited by the linear loss of the enhancement cavity. Applying cavity mirrors and nonlinear crystals of better quality should improve doubling efficiency effectively. The Watt-level 780 nm laser implies its wide application in cooling and manipulating rubidium atoms and generating squeezing and entanglement at 1.5 μm if additional locking and noise suppression is applied.

Acknowledgments

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