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Efficient frequency doubler of 1560 nm laser based on a semi-monolithic resonant cavity with a PPKTP crystal

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ABSTRACT

We have demonstrated 1.61 W of 780 nm single-frequency continuous-wave laser output with a semi-monolithic periodically poled potassium titanyl phosphate (PPKTP) crystal doubler pumped by a 2-W erbium-doped fiber amplifier boosted 1560 nm diode laser. The measured maximum doubling efficiency is 77%, and the practical value should be 80% when taking into account the fundamental-wave mode matching efficiency. The measured beam quality factor of 780 nm output, M^2, is better than 1.04. Typical root-mean-square fluctuation of 780 nm output is less than 0.5% in 30 minutes. This compact frequency doubler has good mechanical stability, and can be employed for many applications, such as laser cooling and trapping, atomic coherent control, atomic interferometer, and quantum frequency standard with rubidium atoms.

1. Introduction

With the development of the periodically poled nonlinear crystals and the 1.5 μm telecom-band erbium-doped fiber amplifier (EDFA), laser frequency doubling becomes an alternative way to realize 780 nm single-frequency continuous-wave laser with high output power and good beam quality. Comparing with the semiconductor tapered amplifier boosted 780 nm diode laser, the frequency doubling of an EDFA-boosted 1560 nm laser has lower spontaneous emission noise, much better beam quality, higher output power, and reasonable narrow linewidth. Moreover, in contrast to a Ti:Sapphire laser, the frequency doubling system is much more cheap, compact and stable.

High power single-frequency 780 nm laser can be employed for laser cooling and trapping [1,2], atomic coherent control [3], atomic interferometer [4], and quantum frequency standard [5] with rubidium atoms. In addition, the 780 nm radiation can be used to prepare the squeezed and entangled fields at 1.5 μm by an optical parametric oscillator, which has important application in continuous-variable quantum communication [6], gravitational wave detection [7] and so on.

In respect of second-harmonic generation (SHG) of 1560 nm laser, if the fundamental laser has medium or high power, efficient frequency doubling can be accomplished by single passing periodically poled nonlinear crystals [8]. If the fundamental laser has low power, using a waveguide can also bring considerable conversion efficiency. But if requiring 780 nm output at watt or higher level, the cavity enhanced frequency doubling scheme can be employed [9–12].

For the doubling cavity choice, comparing a semi-monolithic cavity (SMC) with a bow-tie type four-mirror ring cavity (BTRC), SMC can effectively reduce the linear loss and improve the mechanical stability. BTRC has more mirrors, so mechanical stability is relatively poor, and the linear loss is a bit large. As demonstrated in our previous work [12], high efficient frequency doubling is achieved in a BTRC with a periodically poled magnesium-oxide-doped lithium niobate (PPMgO:LN) bulk crystal, even the linear loss is large(3.2%). Although the nonlinear coefficient of PPMgO:LN crystal is large (d_{eff}= 17.2 pm/V), it has heavier absorption at both fundamental-wave and second-harmonic-wave than periodically poled potassium titanyl phosphate (PPKTP) crystal, which may lead poorer thermal stability. As for PPKTP crystal, the nonlinear coefficient is slightly smaller (d_{eff}= 10.8 pm/V), it can benefit from the lower absorption loss for fundamental-wave and second-harmonic-wave lasers. One can also expect comparable high doubling efficiency in the case of combination of PPKTP crystal and SMC [9,13].

We setup a 1560 nm SMC frequency doubler by using a PPKTP crystal which is flat at one end and is spherical convex at the other

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end, and a separate plane-concave input coupler. While injecting 2.09 W of 1560 nm fundamental-wave power, we can achieve 1.61 W of single-frequency continuous-wave 780 nm laser. The measured maximum doubling efficiency is 77%, while the practical maximum doubling efficiency should be 80% if taking into account the fundamental-wave mode matching efficiency. This doubling laser can operate continuously and stably for several hours.

2. Experimental setup and design of doubler

Fig. 1 shows the schematic diagram of the frequency doubling system and a photo of the doubler. The master-oscillator power fiber amplifier (MOPFA) consists of a 15-mW external-cavity diode laser (ECDL from New Focus) at 1560.5 nm and a 2-W EDFA (Keopsys), followed by an optical isolator for restraining laser feedback and ensuring the stability of EDFA. Half-wave plate and polarization beam splitter (PBS) cube are used for controlling fundamental power, and settling the proper polarization for the frequency doubling process.

Our PPKTP-crystal SMC doubler is made up of a plane-concave input coupler with a curvature radius of 30 mm and a 1mm × 2 mm × 10 mm PPKTP crystal (Raciol Crystal), shown in the dotted box in Fig. 1(a). The input coupler is coated with a transmissivity of $T_{in}=10.9\%$, and a reflectivity of $R>98\%$ at 780 nm. The PPKTP crystal has the poling period of 24.925 μm (Type-zero phase matching). One end of the crystal is flat with antireflection coating of $R<0.1\%$ for both of fundamental wave and second harmonic wave; the other end is spherical convex with a curvature radius of $r'=15$ mm, and is coated with high reflection at 1560 nm ($R>99.8\%$) and high transmission at 780 nm ($T\sim89\%$).

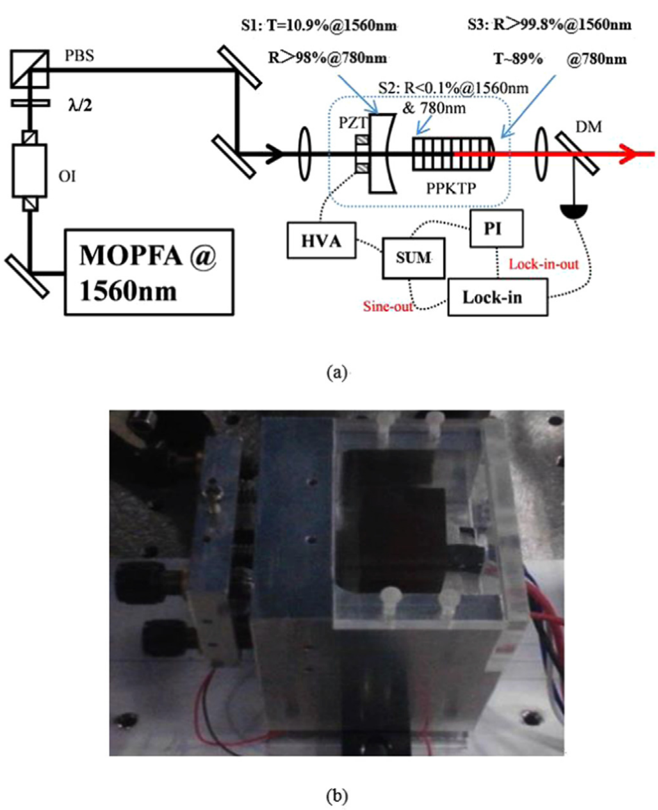

Fig. 1. (a) Schematic diagram of semi-monolithic resonant cavity frequency doubling system; (b) Photo of the SMC. MOPFA: master-oscillator power fiber amplifier, OI: optical isolator, λ/2: half-wave plate, PBS: polarization beam splitter cube, PZT: piezo-electric transducer, DM: dichroic mirror, Lock-in: lock-in amplifier, PI: proportional and integral amplifier, SUM: summator, HVA: high-voltage amplifier.

The crystal's convex end serves as the output coupler. The crystal is placed inside a home-made bronze oven which is covered by a polysulfone piece (the brown part in Fig. 1(b)), and is temperature stabilized by a precision temperature controller (temperature instability is less than 5 mK). The cavity length of the doubler is 36 mm, with a waist radius of ~40 μm inside the crystal. The plano-concave input coupler is glued on a pizeo-electric transducer (PZT), and settled on the movable part. The movable part with the three fine screws (as shown in the left side of Fig. 1(b)) is connected with a duralumin base (supports the crystal oven) by using of two tension springs. The doubler can be coarsely adjusted via the three screws, and finely adjusted by a voltage applied on the PZT. Two organic glass pieces which are at the top and the right side of duralumin base are employed to reduce the influence of air flow and to keep the doubler cleaning. The PPKTP-crystal SMC doubler can be locked to 1560 nm laser's frequency by using the dither locking scheme via a lock-in amplifier, a proportional and integral amplifier (PI), and a high-voltage amplifier (HVA).

To optimize the size and the location of fundamental-wave laser's waist inside the PPKTP crystal, we calculated the waist radius of fundamental-wave TEM_{00} mode inside SMC versus the cavity length with different concave curvature radius r of the input coupler. When the length of PPKTP crystal is 10 mm, and the curvature radius of the convex end is $r'=15$ mm, the corresponding results are shown in Fig. 2.

For different curvature radius of the plane-concave input mirrors ($r=15$ mm, 20 mm, 25 mm, and 30 mm), we only need to change the cavity length to get the approximately same waist radius of fundamental-wave TEM_{00} mode. For the curvature radius of the input coupler $r=30$ mm, when the waist radius of fundamental-wave is small in the cavity, its location is close to the crystal's convex end. Although the maximum fundamental-wave intensity is large, the Rayleigh length is short, so that we cannot make full use of the whole piece of PPKTP crystal. Further when the input power is high, it may also increase PPKTP-crystal thermal effect due to residual absorption.

We also calculated the waist radius of fundamental-wave TEM_{00} mode inside SMC, which depends upon the cavity length and different curvature radius r' of the PPKTP crystal's convex end. When the length of PPKTP crystal is 10 mm, and the curvature radius of the input coupler is $r=30$ mm, the corresponding results are shown in Fig. 3.

Choosing different curvature radius of the semi-monolithic

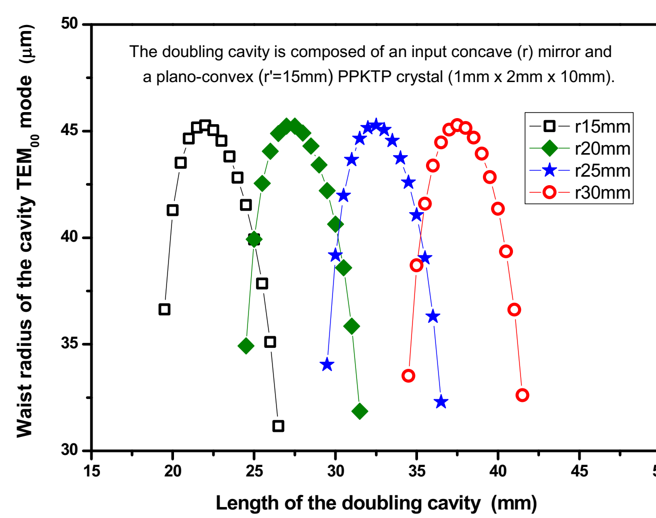

Fig. 2. The calculated waist radius of fundamental-wave TEM_{00} mode in SMC versus the cavity length with different concave curvature radius r of the input coupler.

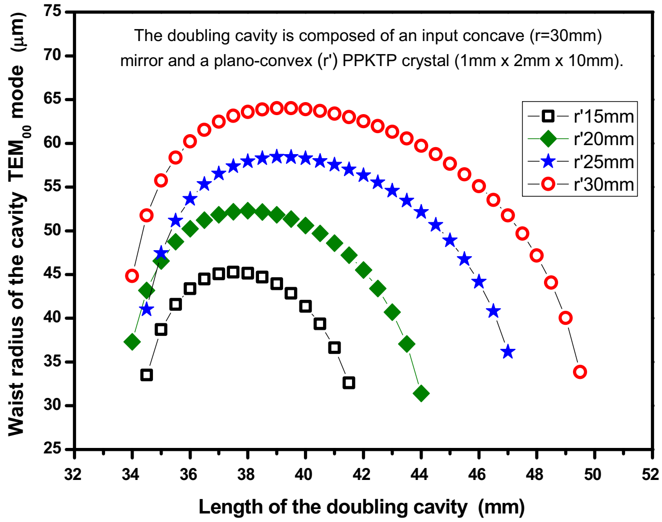

Fig. 3. The waist radius of fundamental-wave TEM_{00} mode in SMC versus the cavity length with different curvature radius r′ of semi-monolithic PPKTP crystal's spherical convex end.

PPKTP crystal's spherical convex end ($r' = 15$ mm, 20 mm, 25 mm, and 30 mm) can significantly change the waist radius of fundamental-wave TEM_{00} mode. The larger the PPKTP-crystal convex end's curvature radius is, the larger the waist radius of fundamental-wave TEM_{00} mode will be. For PPKTP crystal is 10 mm long and the curvature radius of the input coupler is $r = 30$ mm, when the curvature radius of the semi-monolithic PPKTP crystal's spherical convex end is $r' = 15$ mm, the waist radius of fundamental-wave TEM_{00} mode can change from ~30 μm to ~45 μm along with different cavity length. We choose 36-mm-long cavity, the correspond waist radius of fundamental-wave TEM_{00} mode is ~40 μm, and the waist position is roughly in the middle of PPKTP crystal.

3. Experimental results and discussion

The quasi-phase matching temperature data for 1560 nm laser passing the 10-mm-long PPKTP crystal are shown in Fig. 4. When the fundamental-wave power is 125 mW, and focused by a lens ($f = 60$ mm), we can get the optimized doubling temperature $TEMP_{opt} \sim 75.9$ °C with a full width at half maximum

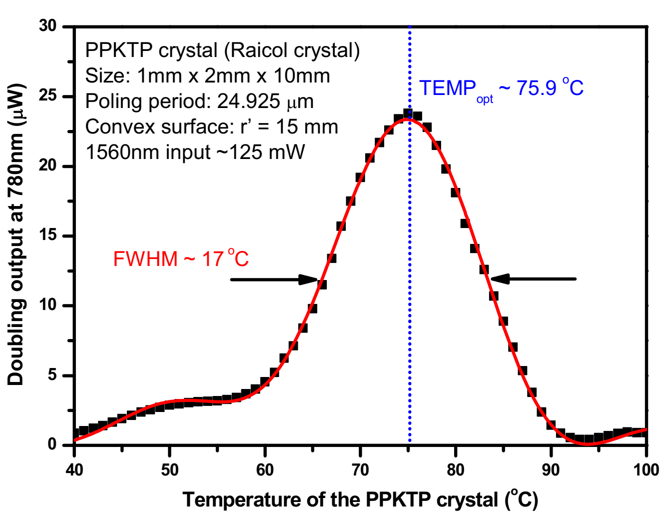

Fig. 4. Phase matching temperature data points and theoretical fitting.

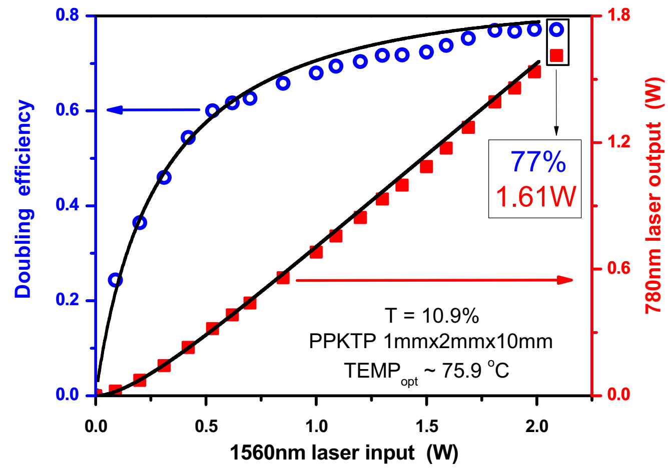

Fig. 5. Experimental results of frequency doubling by using the PPKTP-crystal SMC doubler. Red squares are the doubling laser output power, blue circles are the doubling efficiency, and solid lines are theoretical calculation results. (The mode matching efficiency of fundamental-frequency laser is not considered.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

FWHM ~ 17 °C, and the nonlinear conversion coefficient $E_{NL} \sim 0.49\%$/W. The asymmetry of temperature curve maybe due to the optical inhomogeneity in crystal [14]. Due to different focusing conditions and waist position of fundamental-wave beam in the crystal, the measured nonlinear conversion coefficient cannot precisely represent the situation in SMC, but the optimized temperature and the *FWHM* bandwidth should be roughly the same. In the case of using 30-mm-long PPKTP crystal [15] with same poling period and phase matching condition, the bandwidth of matching temperature is *FWHM* ~ 6 °C. The bandwidth of periodically poled nonlinear crystal's quasi-phase matching temperature is inversely proportional to the length of crystal approximately [16], therefore using a 10-mm-long PPKTP crystal now have greater temperature bandwidth (~17 °C). Obviously this is beneficial for second-harmonic wave's power stability, and it will lower the requirement for control precision of temperature.

Using the above-mentioned PPKTP-crystal SMC, the measured frequency doubling results are shown in Fig. 5. The red solid squares and the blue circles represent harmonic wave's output and doubling efficiency versus the fundamental-wave laser input, respectively. The solid lines are theoretical results. The linear loss of SMC, $L \sim 1.1\%$ is estimated, which does not include the input coupling transmissivity ($T_{in} = 10.9\%$) and the nonlinear conversion loss. When incident fundamental-wave power is 2.09 W, we achieve a stable output of 1.61 W at 780 nm. The measured highest doubling efficiency is 77%. If further taking into account 96% of typical mode-matching efficiency of fundamental-wave laser to SMC, the doubling efficiency should be 80%.

In the theoretical calculation for Fig. 5, the second-harmonic wave's output P_{SH} and the doubling efficiency η can be represented as follows [17]:

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

$$\eta = P_{SH}/P_{in} \tag{2}$$

In order to simplify the expressions, here the variables β and ρ are introduced, $\beta = T_{in} + L, \rho = 4\alpha T_{in} P_{in} E_{NL}$, in which T_{in}, L, α, P_{in} and E_{NL} represent the input coupling transmissivity, the linear loss of doubling cavity, the mode matching efficiency of fundamental-

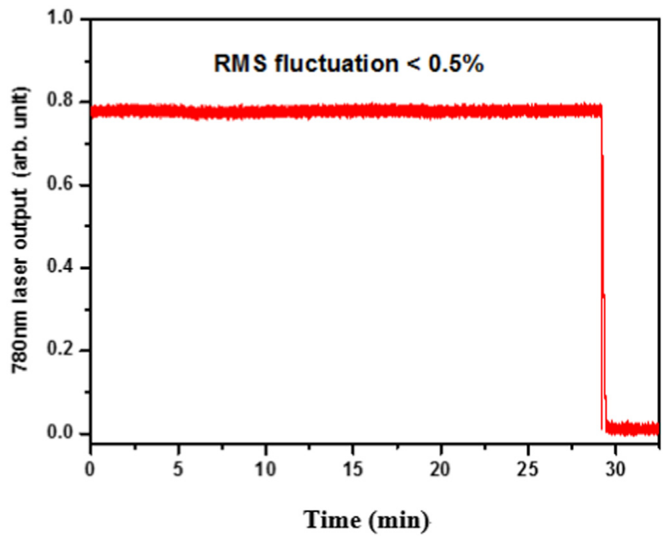

Fig. 6. The stability of second-harmonic wave's output power.

wave laser into doubling cavity, the incident fundamental-wave power, and the nonlinear conversion coefficient, respectively.

For given incident power of fundamental-wave laser P_{in}, if the input coupling transmissivity of doubling cavity T_{in} reaches the optimized value T_{opt}, the doubler will fulfill the so-called "impedance matching" condition.

$$T_{opt} = \frac{L}{2} + \sqrt{\left(\frac{L}{2}\right)^2 + E_{NL}P_{in}} \tag{3}$$

The fundamental-wave laser will be completely coupled into the doubling cavity to participate the doubling process. T_{opt} mainly depends on L and P_{in} for the given doubling crystal and given focusing condition of fundamental-wave laser beam, according to Eq. (3). In our experiment, $E_{NL}\sim 0.49\%/\mathrm{W}$ and $L\sim 1.1\%$ are estimated, for 2.09 W fundamental-wave incident power $P_{in}\sim 2.09$ W (must consider the mode matching efficiency ~96%), $T_{opt}\sim 10.48\%$ can be derived according to Eq. (3). In practice, we use an input coupling transmissivity $T_{in}\sim 10.9\%$. According to ref. [18], the expected maximum doubling efficiency is $\eta_{max}=T_{in} / (T_{in}+L)$. In our case, $T_{in}\sim 10.9\%$ and $L\sim 1.1\%$ yield $\eta_{max}\sim 90.8\%$.

The lower the linear loss L of doubling cavity, the higher the doubling efficiency will be. We can reduce the linear loss and increase the output transmissivity at 780 nm by improving the quality of cavity mirror, PPKTP crystal and all the coating. We can also improve the power spectral density by narrowing fundamental-wave laser's linewidth. All these points will enhance the doubling efficiency.

We have experimentally evaluated the harmonic-wave output beam's quality factor, M^2, by using the single knife scanning method. $M_x^2\sim 1.04$ for the horizontal direction and $M_y^2\sim 1.03$ for the vertical direction are measured. These indicate that the 780 nm output beam has excellent quality.

In 30 min, a typical root-mean-square (rms) fluctuation of 780 nm laser power is less than 0.5%, as shown in Fig. 6. Comparing with the case of PPMgO:LN crystal in a BTRC doubling cavity (typical rms fluctuation is less than 1.2% for 30 min) [12], here the stability has a significant improvement. This is due to much better mechanical stability of our PPKTP-crystal SMC doubler and much broader FWHW temperature bandwidth of PPKTP crystal.

The 780 nm output light can be tuned to D_2 lines of ^{85}Rb and ^{87}Rb atoms by slowly scanning the 1560 nm fundamental-wave laser's frequency. The typical continuously tunable range is ~1 GHz. Actually the ECDL at 1560 nm can be continuously tuned more than 20 GHz. Here the harmonic-wave laser's continuously tunable range is mainly limited by the doubling cavity's PZT. If we replace a new longer PZT, the SMC doubling cavity should be kept locked following the ECDL frequency scanning at a broader range. Of course, if using single-pass doubling configuration with PPMgO: LN, PPLN, or PPKTP crystals, we can obtain much larger continuously tunable range (can roughly follow the continuously tunable range of the fundamental laser) of 780 nm laser, but the doubling efficiency is lower.

4. Conclusion and prospects

In conclusion, we achieve 1.61 W of 780 nm single-frequency laser output from a PPKTP-crystal SMC doubler, when the incident 1560 nm fundamental-wave power is 2.09 W, the measured highest doubling efficiency is 77%, while the practical doubling efficiency should be 80% if taking into account the fundamental-wave mode matching efficiency. The 780 nm output laser has a good beam quality ($M^2 < 1.04$), and can stably operate for several hours. In 30 min, typical power fluctuation is less than 0.5% (rms).

At present, the main factor which limits doubling efficiency is the linear loss L of fundamental-wave in the doubler. Now it is still a bit large ($L\sim 1.1\%$). L should be reduced to be as lower as possible. This moment the optical quality of the input coupler substrate and the coating are not perfect, and these may cause some scattering and transmission losses. Also the optical quality of the PPKTP crystal we used, the flat and convex surfaces, as well as the coating are not perfect, and these can cause some residual reflection, transmission, and scattering losses. If the linear loss L of SMC doubler can be lowered to be less than 0.5%, when the input-coupling transmissivity is around $T_{in}\sim 10\%$, the doubling efficiency can be increased to be more than 95% in principle.

The PPKTP-crystal SMC can also constitute an efficient 1560 nm laser frequency doubler with a commercial butterfly-packaged distributed feed-back (DFB) laser and telecom EDFA module. It is very compact and stable, and can be applied to high-resolution spectroscopy, laser cooling and trapping of atoms, frequency standard, and atomic interferometer with rubidium atoms (^{85}Rb or ^{87}Rb).

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