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Generation of high-power single-frequency 397.5 nm laser with long lifetime and perfect beam quality in an external enhancement-cavity with MgO-doped PPSLT

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Abstract: Continuous-wave single-frequency high power 397.5 nm laser with long lifetime and perfect beam quality is one of the essential resource to generate the squeezed and entanglement states of optical beams resonant with D_1 line of Rubidium atoms at 795 nm. In this paper, We present the experimental generation of single-frequency high power 397.5 nm ultra-violet (UV) laser with long lifetime and perfect beam quality by using periodically poled MgO-doped stoichiometric lithium tantalate (MgO:PPSLT) crystal as the frequency doubler in an external enhancement ring cavity. When the transmission of the input coupler is 5.5%, the maximal output power of single-frequency 397.5 nm UV laser of 407 mW is obtained under the incident pump power of 1.9 W with the corresponding conversion efficiency of 22.8%. When the output power is 290 mW, the measured power stability and the beam quality are lower than 0.28% and 1.02, respectively. Moreover, any damage is not observed in our experiment which lasts about 1 year.

OCIS codes: (140.3610) Lasers, ultraviolet; (140.3515) Lasers, frequency doubled; (140.6810) Thermal effects; (140.3560) Lasers, ring.

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1. Introduction

Stable continuous-wave (CW) single-frequency ultra-violet (UV) laser is in great demand not only for many industrial applications but also for more fundamental researches including atom cooling, quantum information, quantum optics and so on. Especially in the research field of the quantum internet composed of quantum nodes and quantum information transmission channel, one of the main task is to establish multi-partite continuous-variable (CV) polarization squeezed and entangled states of optical field, the wavelength of which should correspond to the energy transition line of the atoms (for instance, D_1 line of Rubidium (Rb) atoms at 795 nm) [1]. The generated CV polarization squeezed and entangled states of optical field are utilized to implement optical storage and realize the interaction between light and Rb atoms [2]. To this end, a stable and high-power single-frequency 397.5 nm UV laser is necessarily required to pump a degenerate optical parameter amplifiers (DOPAs) to generate the CV polarization squeezed or entangled states.

Experimental generations of single-frequency 397.5 nm UV laser by frequency doubling in an extra or intra-cavity including nonlinear crystals have been demonstrated in recent years and many candidates are proposed to act as the frequency doubler. The most popular crystal is periodically poled potassium titanyl phosphate (PPKTP). Using it, the output power of single-frequency 397.5 nm UV laser reached up to 408 mW [3]. However, the wavelength of 397.5 nm is at the transmission cut-off wavelength of the PPKTP crystal. The severe absorption in 397.5 nm laser induces the severe thermal effect and limits the further improvement of 397.5 nm laser power [4]. Moreover the intrinsic disadvantage of grey tracking effect severely shortens the lifetime of the PPKTP crystal as well as the generated 397.5 nm laser source [5]. To prolong the life time of the PPKTP crystal and prevent it from damage, high fundamental power as well as long-term illumination should be avoided and the generated 397.5 nm laser is generally limited to low power. Other nonlinear crystals, such as Lithium triborate (LBO), Bismuth Triborate (BIBO) and so on, were also used for second-harmonic-generation (SHG) at high power level. Some commercial versions of the UV laser sources have been developed by Toptica, Coherent and so on by using these nonlinear crystals as the frequency doubler to improve the lifetime of the generated UV laser [6, 7]. In 2015, our group obtained 1.58 W and 0.78 W single-frequency

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397.5 nm UV laser with using the BIBO and LBO crystals in an intracavity frequency doubled Ti:Sapphire laser, respectively [8]. Later, Wen et al. compared the frequency-doubling characteristics of the LBO, BIBO, and PPKTP crystals in an external enhanced cavity [9]. However, the photo-refractive effect of BIBO crystal limited the frequency doubling process and the intrinsic walk-off effect of the angular phase-matched BIBO and LBO crystals badly influenced the output beam quality. Recently, a novel periodically poled Mg-doped stoichiometric lithium tantalate (MgO:PPSLT) crystal has drawn greater attention owing to its high effective nonlinear coefficient, high thermal conductivity, high photo-refractive damage as well as broad transmission wavelength range and has been successfully used to obtain the stable single-frequency 532 nm and 589 nm laser [10–14]. In 2009, Ricciardi et al. realized a 7 mW 355 nm laser in PPSLT crystal [15]. Later, Hirobashi et al. obtained 0.7 W 355 nm pulse laser [16].

In this letter, we report the experimental results of generation of single-frequency high power 397.5 nm UV laser with long lifetime and perfect beam quality by using MgO:PPSLT crystal as the frequency doubler in an external enhancement ring cavity. By means of measuring the nonlinear conversion coefficient and analyzing the thermal lens effect of the MgO:PPSLT crystal, the optimal transmission of the input coupler is chosen and the maximal output power of 407 mW is achieved. The corresponding conversion efficiency can reach up to 22.8%.

2. Experimental setup

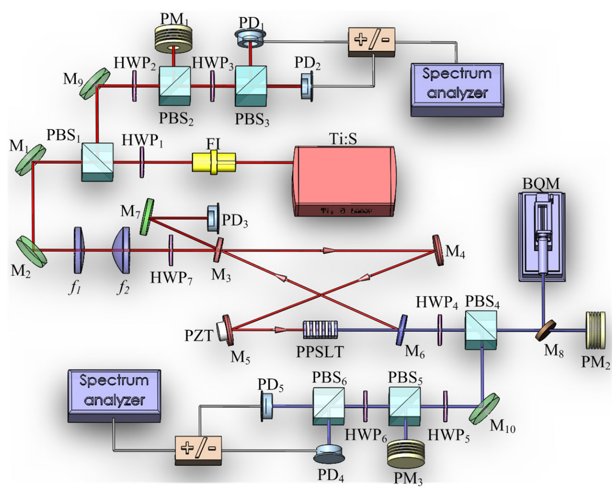

Fig. 1. Schematic diagram of frequency doubling system. f_1,f_2: coupling lens; HWP: half-wave plate; PBS: polarization beam splitter; PM: power meter; BQM: beam quality meter; PD: photodiode detector.

The schematic diagram of generation of single-frequency 397.5 nm laser with perfect beam quality in an external enhancement ring cavity is shown in Fig. 1. The 795 nm source employed in this experiment is a home-made CW Ti:sapphire laser (CTSL-III, Yuguang Co., Ltd.) with the maximal output power of 2 W [17, 18], which is pumped by a home-made single-frequency 532 nm laser (FG-VIIIB, Yuguang Co., Ltd.) with the output power of 18 W [19, 20]. The power stability of the Ti:sapphire laser is better than 0.47% rms in 2 hours and the oscillating wavelength can be tuned from 750 nm to 860 nm. Especially, the frequency of the Ti:sapphire laser can be scanned around the D_1 transition of ^{87}Rb atoms and locked to any transition line, which enables the 397.5 nm laser stabilization. In the case, the Ti:sapphire laser can work in single-frequency operation [17]. The optical Faraday Isolator (FI) is placed between the Ti:sapphire laser and external enhancement ring cavity to prevent the optical feedback into the Ti:sapphire laser. The beam from the Ti:sapphire laser is phase modulated by an electro-optical modulator (EOM), which can be utilized to lock the external enhancement ring cavity to the injected fundamental-wave laser via the Pound-Drever-Hall (PDH) method. In order to precisely adjust the incident pump power, a power adjuster including a half-wave-plate (HWP_1) and a polarization beam splitter (PBS_1) is adopted. The optical coupler is composed of two lenses f_1 and f_2 with the focal length of 110 mm and 40 mm, respectively. Compared to single lens, battery of lenses is easier to realize the mode-matching between the injected laser beam and the enhancement ring cavity. HWP (HWP_7) in front of the external enhancement ring cavity can effectively align the polarization of the injected fundamental-wave laser to satisfy the requirement of the frequency doubler. The external enhancement ring cavity is designed in a symmetric bow-tie ring configuration which includes two plane mirrors (M_3 and M_4)and two plano-concave mirrors (M_5 and M_6) with radius of curvature of 100 mm. The input coupler M_3 is coated with part transmission films at the wavelength of 795 nm. M_4 and M_5 are coated with high-reflection (HR) films at the wavelength of 795 nm. The output coupler M_6 is coated with HR films at the wavelength of 795 nm and anti-reflection (AR) films at wavelength of 397.5 nm. The main part of the generated single-frequency 397.5 nm UV laser is measured by a power meter (LabMax-Top, Coherent) and two small parts are used to measure the beam quality and the intensity noise, respectively. The reflected from the enhancement ring cavity is leaded to a photo-diode (PD_3) by M_7 to implement the locking of the enhancement ring cavity.

The nonlinear MgO:PPSLT crystal with the length of 10 mm and the section of 2×0.8 mm^2 is made by Oxide corporation. Two end faces are coated with AR films for wavelength of both 795 nm and 397.5 nm. Because the injected fundamental wavelength is as short as 795 nm and the MgO:PPSLT crystal with 2nd-order of the quasi-phase-matching (QPM) structure is not commercially available, the adopted periodic poled crystal has to be made into 3rd-order quasi-phase-matching (QPM) structure and the poling period is 9.18 μm @ 30°C [21]. The absorption coefficient at 397.5 nm of 0.015 cm^{-1} is supplied by the manufacturer. In order to precisely control the temperature of the crystal for realizing the perfect phase-matching, the crystal is wrapped by an indium foil and placed in a closed copper block oven which is temperature controlled to 30°C with an accuracy of ±0.001 °C. To achieve the maximal output power of 397.5 nm laser, the MgO:PPSLT crystal is placed at the waist (ω_0) between M_5 and M_6. When the distance between M_5 and M_6 is 114.2 mm, and total cavity length is 534 mm, the calculated beam waist radius ω_0 is 42.18 μm according to the ABCD Matrix formalism.

3. Experimental results

In the experiment, the nonlinear conversion coefficient of the MgO:PPSLT crystal was firstly measured by recording the output power of the generated 397.5 nm UV laser for single-pass configuration when the input coupler M_3 was replaced by a mirror coated with AR films at 795 nm, which was shown in Fig. 2. According to the measured results and fitting line, a nonlinear conversion efficiency E_{nl}=8.63(0.22)$\times10^{-4}$ W^{-1} and nonlinear conversion coefficient d_{eff} of MgO:PPSLT crystal of 2.85 pm/V were obtained, respectively. According to the measured parameters, the transmission of the input coupler can be optimized by [22],

$$T_{opt} = \frac{L}{2} + \sqrt{\frac{L^2}{4} + E_{nl}P_{in}} \tag{1}$$

where L is the distributed round-trip loss, E_{nl} is the conversion efficiency and P_{in} is the incident pump power of 795 nm laser.

The distributed round-trip loss was 2.5%, which was obtained by measuring the transmission spectra of the external enhancement ring cavity when the input coupler coated with high reflection film was adopted [23]. When the incident pump power was 1.9 W, the optimal transmission of the input coupler of 5.5% was theoretically calculated. In the experiment, the output char-

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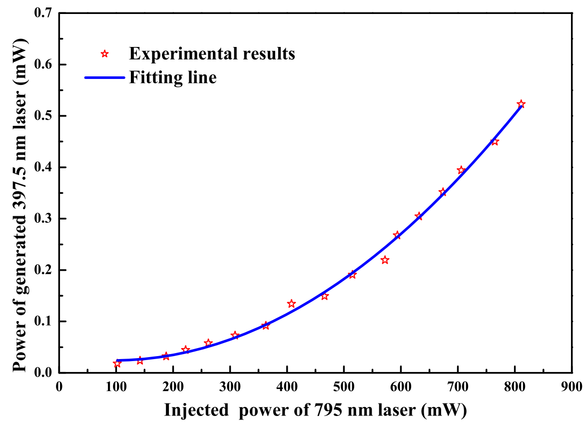

Fig. 2. SHG power from the MgO:PPSLT crystal used in single pass at the output of the crystal.

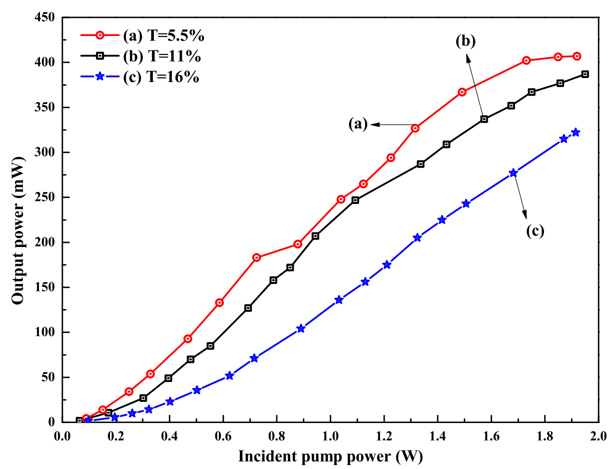

Fig. 3. Output power of the single-frequency 397.5nm UV laser.

acteristics were compared when the input coupler transmission of 5.5%, 11% and 16% were adopted, respectively. The output power curves and corresponding conversion efficiency curves were depicted in Figs. 3 and 4. When the transmission of 5.5% was used, the maximal output power was 407 mW with the incident pump power of 1.92 W. The corresponding conversion efficiency was 21.2%. Take the mode-matching efficiency between the injected pump laser with the external enhancement-cavity into account, the conversion efficiency can reach up to 22.8%. When the transmission of 5.5% was replaced by 11% and 16%, the output power were 387 mW and 322 mW, respectively. The corresponding conversion efficiency decreased to 19.8% and 16.8%, respectively.

The experimental results showed that the transmission of 5.5% provided best output power and conversion efficiency among all transmission used in the experiment. However, the system was difficult to work at the level of 407 mW because the external enhancement ring cavity was difficult to lock to the top of its transmission peak, which was ascribed to the heating of the crystal owing to the absorption of the circulating FW and generated SHW. The heating of the crystal not only caused the thermal lens effect of the nonlinear crystal but also induced bi-

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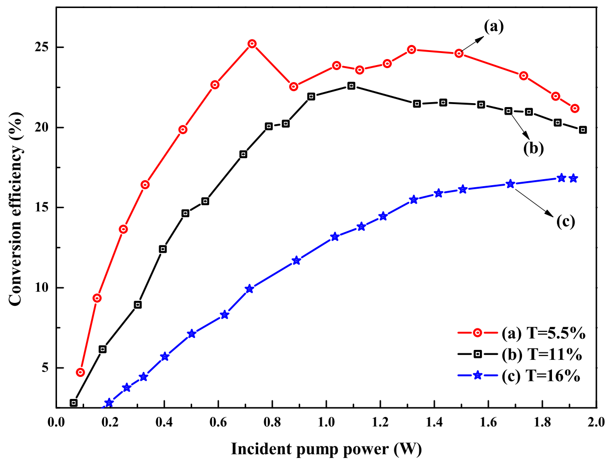

Fig. 4. Conversion efficiency versus the incident pump power.

stability-like phenomenon of the external enhancement ring cavity. By detuning the cavity, the bi-stability-like phenomenon of the external enhancement ring cavity was easy to observed in the experiment, which was similar to the PPKTP crystal [24] and shown in Fig. 5(a). It was easy to identify the contribution of the FW and SHW to the heating of the crystal by detuning the phase-matching temperature of the MgO:PPSLT crystal. When the temperature was the optimal phase-matching value, the obvious broadened spectrum as shown in Fig. 5(a) can be observed. However, it was narrowed [shown in Fig. 5(b)] when the temperature was detuned far from the optimal phase-matching value where the power of the SHW can be ignored. The phenomenon denoted that the main contribution to the heating of the crystal was still absorption of the generated 397.5 nm UV laser.

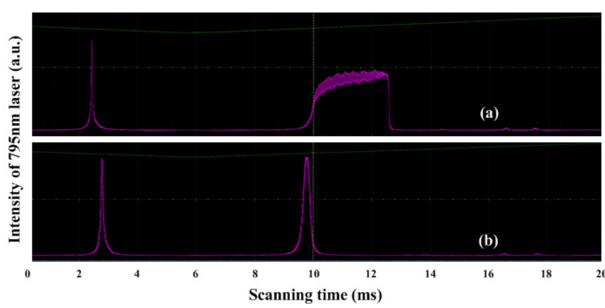

Fig. 5. The resonant signals of the cavity. (a) optimal phase-matching temperature, (b) detuning far from the phase-matching temperature.

The temperature tuning curves were also measured for the cavity configuration with the input coupler transmission of 5.5% and incident pump power of 300 mW, 600 mW, 1.0 W and 1.5 W, corresponding to the SHW power of 52 mW, 135 mW, 200 mW, and 368 mW, respectively, which were shown in Fig. 6. With the increase of the incident pump power and SHW power, the phase-matching temperature peak declined from 30.7 °C to 30.2 °C and the curve shapes became more and more asymmetrical, which also attributed to the heating of the crystal and bi-stability-like phenomenon of the external enhancement cavity. The full-width at half-maximum of the temperature tuning curve of 0.85 °C was measured at 52 mW SHW output.

At last, the output power stability and MgO:PPSLT lifetime were also investigated. When the

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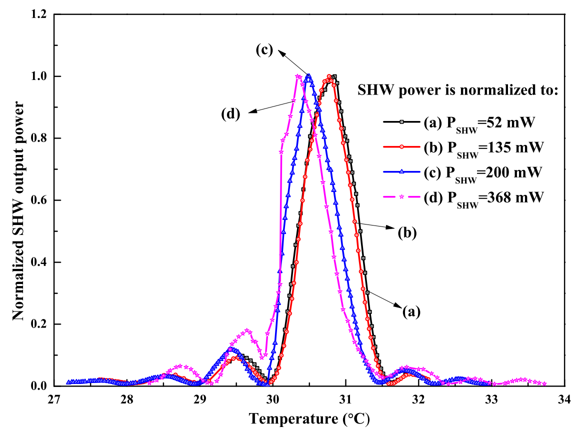

Fig. 6. The temperature tuning curve of the MgO:PPSLT crystal.

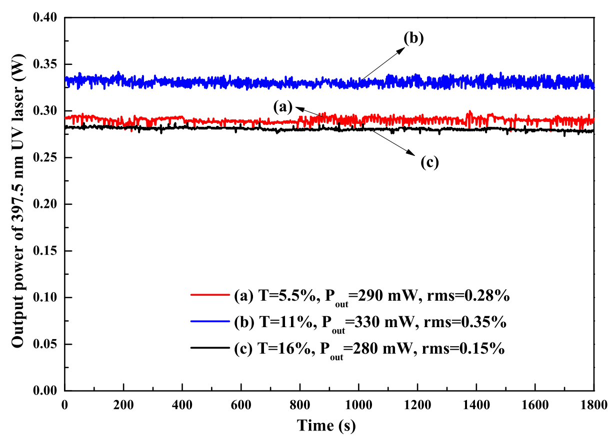

Fig. 7. Power stability of the 397.5 nm UV laser for 30 min.

transmissions of the input coupler were 5.5%, 11% and 16%, the output power were stabilized to 290 mW, 330 mW and 280 mW, respectively, to measure the long term power stability, which were shown in Fig. 7. The measured power stability were 0.28% [Fig. 7(a)], 0.35% [Fig. 7(b)] and 0.15% [Fig. 7(c)] for 30 min, respectively. The power stability was related to not only the pump source as well as the locking system but also the value of the output power which can influence the thermal stability. The measured frequency drift was less than 573 kHz in 10 seconds, which was depicted in Fig. 8. The largest superiority of the adopted MgO:PPSLT crystal compared to the PPKTP crystal was its service life. Up to now, any damage was not observed in our experiment which lasted about 1 year and the adopted crystal worked about 8 hours in every day (the weekend and holidays excepted). We also measured the beam quality M^2 value by a beam quality meter (M2SETVIS, Thorlabs) under the condition of Fig. 7(a) and the measured values of M_x^2 and M_y^2 were both 1.02. The measured caustic curve and the corresponding spatial beam profile were shown in Fig. 9 and its inset. The intensity noise spectra of the 397.5 nm and 795 nm laser were measured by two sets of self-homodyne-detectors. The noise spectra shown in Fig. 10 were recorded and analyzed by a spectral analyzer with the resolution bandwidth (RBW) of 100 kHz and the video bandwidth (VBW) of 100 Hz. It was clear that double peaks of the 397.5 nm laser were similar to that of the 795 nm. The first peak was contributed by

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the intensity noise of the green laser which acted as the pump source of the single-frequency Ti:sapphire laser, and the second one was the relaxation resonant oscillation (RRO) peak. In the frequency doubling process, the intensity noise of the 795 nm laser transferred to the generated 397.5 nm laser. Moreover, the intensity noise of the 397.5 nm and 795 nm can reach the quantum noise limit (QNL) at the frequency of 2.5 MHz and 3 MHz, respectively.

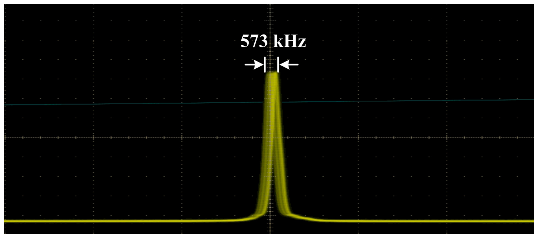

Fig. 8. Frequency drift of the 397.5 nm laser.

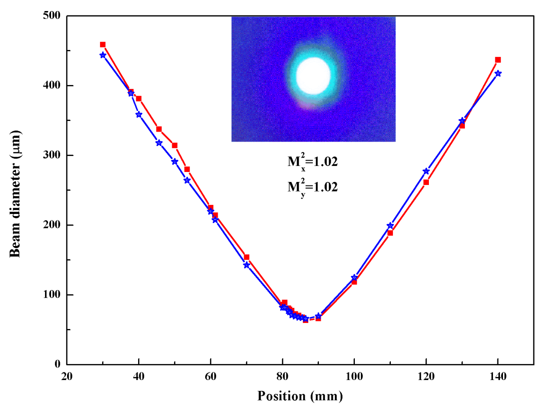

Fig. 9. Measured M^2 values and the spatial beam profile for the 397.5 nm UV laser.

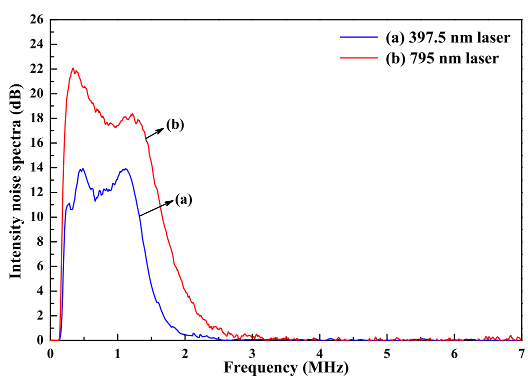

Fig. 10. Measured intensity noise of the generated 397.5 nm laser compared to 795 nm laser.

4. Summary

In conclusion, we report the experimental results of generating the single-frequency 397.5 nm UV laser by frequency-doubled 795 nm laser in an external enhancement cavity. The nonlinear conversion coefficient of 2.85 pm/V from 795 nm to 397.5 nm laser is firstly measured by using a mirror coated with AR films at 795 nm to replace the input coupler of the enhancement ring cavity. Then, the output power characteristics of the 397.5 nm UV laser are compared by adopting different transmission of the input couplers. When the transmission of the input coupler of 5.5% is utilized and the incident pump power is 1.9 W, the maximal 407 mW output power of single-frequency 397.5 nm UV laser is achieved with the corresponding conversion efficiency of 22.8%. At the output power of 290 mW, the measured rms power stability and the beam quality are lower than 0.28% for 30 min and 1.02, respectively. The high output power and power stability as well as the perfect beam quality make the obtained 397.5 nm UV laser well suitable to establish and generate the CV polarization squeezed or entangled states resonant with D_1 line of Rb atoms at 795 nm. In addition, the power of generated 397.5 nm laser should be increased if the size of the adopted MgO:PPSLT crystal is optimized according to the Lim's method [25].

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