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Sodium guide star laser generation by single-pass frequency doubling in a periodically poled near-stoichiometric $LiTaO_3$ crystal

YUAN Ye[1], ZHANG Lei[2], LIU YanHua[1], LÜ XinJie[1*], ZHAO Gang[1], FENG Yan[2] & ZHU ShiNing[1]

[1]*National Laboratory of Solid State Microstructure, Nanjing University, Nanjing 210093, China;*
[2]*Center for Space Laser and Information Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*

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We report in this work a continuous wave (CW) narrowband 589 nm light generation for the purpose of laser guide assisted adaptive optics. A 39 mm long 1 mm thick periodically poled near stoichiometric $LiTaO_3$ crystal with duty cycle near 50% was fabricated using electrical poling at room temperature and pumped by a Raman fiber amplifier. We tested two temperature control ovens, and a maximum conversion efficiency of about 14.3%, corresponding to 4 W of yellow light with 28 W of fundamental power, and bandwidth less than 0.18 GHz was achieved.

sodium guide star laser, periodically poling, stoichiometric $LiTaO_3$, Raman fiber amplifier, frequency conversion

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1 Introduction

The 589 nm laser precisely tuned to sodium D2 line can excite the resonance fluorescence of sodium atoms in the atmospheric ionosphere. This technique can be used to create the reference light of adaptive optics (AO), which compensates the fuzziness caused by atmospheric turbulence, and has significant effects on high definition astronomical imaging, space target recognition, and free-space laser communication. Thus, it has become a research hotspot in laser technology.

Sodium laser guide star (LGS) based on the mesospheric sodium backscatter requires laser with linewidths $\Delta\nu < 2$ GHz at 589 nm, either CW, Quasi-CW or pulsed. Nowadays there are three methods [1] to generate sodium guide star laser that can be usable: i) dye laser which suffers from the large scale and low reliability; ii) solid sum-frequency generation laser which is mostly developed and has been commercially used; and iii) Raman fiber amplifier based laser that has made great progress during these years with stable output as much as solid yellow-light laser and attracted lots of attention because of its advantages such as compact structure, good beam quality, and simple thermal management. Since there is no solid gain medium to generate yellow light directly, the frequency conversion technology is indispensable for the last two methods.

The Raman fiber amplifier based laser works with the Raman fiber amplification of a narrow bandwidth (~100 kHz) 1178 nm seed laser and sequential frequency doubling in a LBO crystal in an external resonant cavity [2, 3]. The cavity is locked using the Pound-Drever-Hall method [4]

*Corresponding author (email: myxinjie@gmail.com)

which is well established and ideal for high power CW output. However, some disadvantages of this method are nonnegligible. For example, it is more complicated, comparablely costly, and may have difficulty in pulsed laser output.

Quasi phase-matching (QPM) in periodically poled ferroelectric crystals has become a well assessed and versatile technique for frequency conversion and engineering of new optical devices, which benefits from the flexible use of the biggest nonlinear coefficient of crystals over birefringent phase-matching (BPM). Recently, among the ferroelectric crystals, near-stoichiometric $LiTaO_3$ (SLT) has shown improved performance [5, 6] in terms of high optical damage threshold, high thermal conductivity, and low infrared absorption, which makes it suitable for high power applications. Periodically poled SLT (PPSLT) with duty cycle 50% can offer effective nonlinear coefficient one order of magnitude larger than LBO, which makes high efficiency frequency coversion possible even in the single pass condition [7, 8]. Hence, fabrication of high quality PPSLT samples is of crucial importance. We have improved the process of electrical poling of SLT and successfully made PPSLT with duty cycle near 50% and high uniformity in large scale. Then we have obtained an average 4 W CW 589 nm light output at the fundamental power of 28 W via single-pass frequency doubling of PPSLT pumped by Raman fiber amplifier.

2 Fabrication of PPSLT

SLT has much less inherent defect concentration compared to congruent $LiTaO_3$ (CLT), so it leads to a much better optical performance. However, less defect concentration also introduces side effect in the periodically poling of SLT. Because defect can be the nucleation center of domain reverse [9] and little defect concentration may result in a low nucleation rate which is the key point of periodically poling. As a result, PPSLT suffers from uncontrollable duty cycle with some places over poled and others unpoled. To solve this problem we submerged the SLT substrate into hydrofluoric acid for 5 minutes to introduce defects artificially and then took the steps of traditional electrical poling [10]. By doing this we succeeded in fabricating uniform domain structure in wafer scale SLT.

In this experiment we preset the period of the PPSLT = 10.4 μm according to the QPM theory. The sample was 39 mm long, 1 mm thick and was fabricated by the improved electrical poling technique. Figure 1 shows the etched surfaces of the sample. The uniform domain structure is revealed on both +*z* and −*z* surfaces as shown in Figures 1(a) and (b). From Figure 1(c), we can see the duty cycle is very close to 50%. Using 2D Fourier transform method [11], we calculated the magnitude of the first order reciprocal vector to be $|g_1|$=0.608 (Figure 2). Since the perfect value is 2/π=0.6366, the poling quality is reliably high.

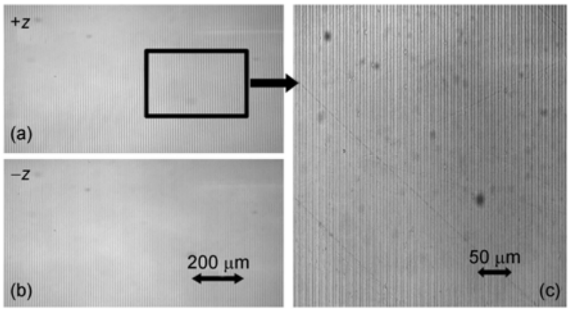

Figure 1 Micrography of the PPSLT sample. (a) +*z* face; (b) −*z* face, both with 100× magnification; (c) +*z* face with 500× magnification.

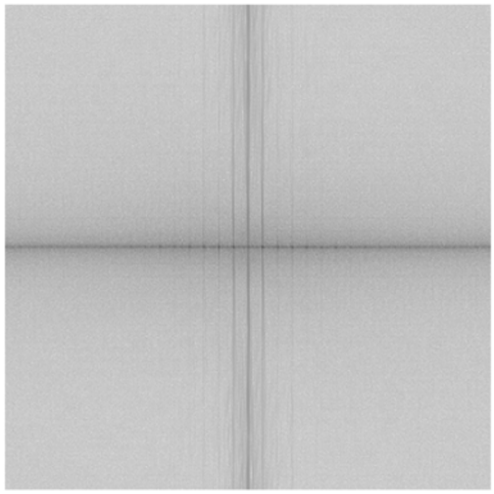

Figure 2 Fourier transform result of Figure 1(c).

3 Optical experiment setup and analysis

The experimental setup of the single-pass frequency doubling in PPSLT is shown in Figure 3. The fundamental source used in our experiment was a Raman fiber amplifier, which is tunable from 1174 to 1180 nm and can output CW laser as high as 28 W with linewidth less than 1.5 MHz.

The PPSLT crystal was embedded in an oven whose accuracy of temperature control was of ±0.1°C to get a steady output. The end faces of the crystal were antireflection coated for 1178 nm and 589 nm (< 0.2%).

For single pass CW frequency doubling,

$$I_{\text{SHG}}(z) = I_0(\tanh(\Gamma \times \sqrt{I_0} \times z))^2.$$

For best conversion, the confocal range is approximately one third of the sample length, specifically,

$$2Z_R \sim L_{\text{sample}} / 2.84.$$

A lens of 150 mm focal distance was used to meet this condition. And the pump light was focused onto the crystal with a beam diameter of about 80 μm.

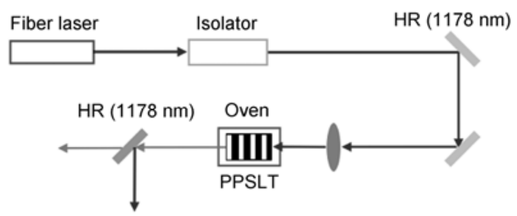

Figure 3 The schematic experiment setup of the 4 W 589 nm laser generation via single-pass frequency doubling.

4 Experiment results and discussion

Figure 4 shows the temperature tuning curve of the second harmonic generation. The measured phase-matching temperature is 167.3°C with the full width at half maximum (FWHM) of about 0.9°C, which is close to the theoretical one. An average output of 4 W was obtained at the maximum fundamental power of 28 W with 14.3% conversion efficiency as shown in Figure 5. No beam quality degradation due to photorefraction was observed at the pump power density up to 0.6 MW/cm^2, which is less than one third of the optical damage threshold of SLT (>2 MW/cm^2). That indicates that further increase of pump power is permitted. The conversion efficiency increased with the increasing pump power. This relationship matches the theoretic expectation and we can predict that by raising the pump power it is quite possible to get a higher output of yellow light with higher conversion efficiency.

Figure 6 is the 589 nm laser spectrum measured with the spectrometer ELIAS III Echelle. The measured FWHM was ~0.2 pm limited by the device resolution, which suggested the actual FWHM was less than 0.18 GHz. Since the bandwidth of D2-a line of sodium atoms is about 1 GHz, the yellow light generated here is suitable for the sodium guide star. However, one thing we have to point out is that the center wavelength measured here was 589.2976 nm, not precisely tuned to sodium D2-a line. Since the pump source we used has a tunable range from 1174 to 1180 nm, it's not a problem when a frequency stabilization system is available in practical application [12].

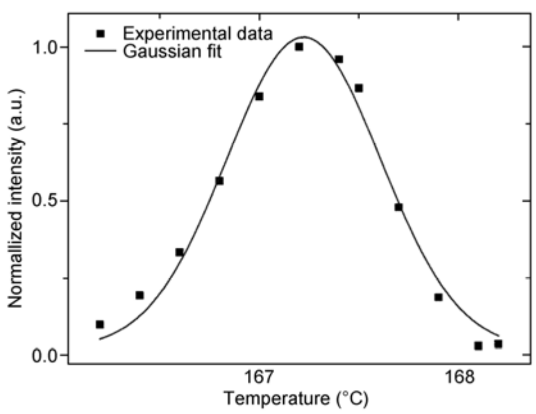

Figure 4 Measured temperature tuning curve for yellow light.

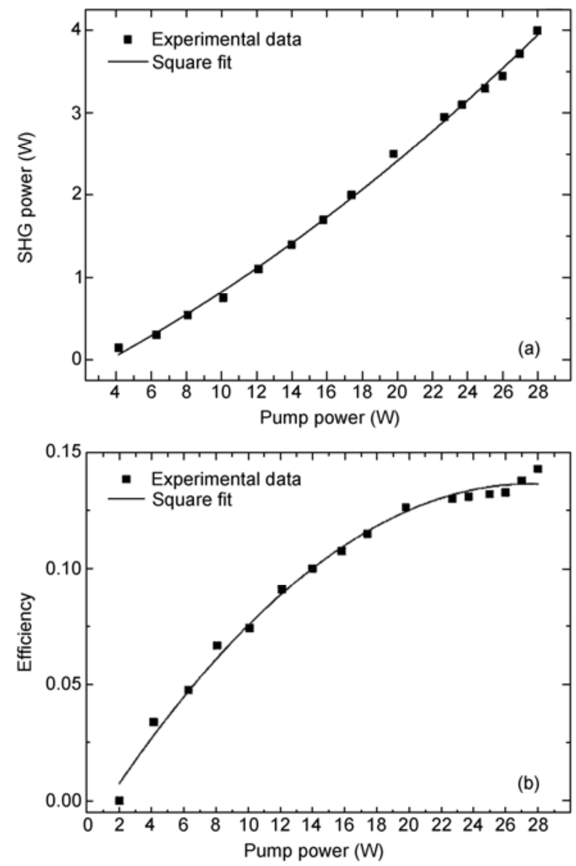

Figure 5 Laser output versus the input power at the temperature of 167.3°C. (a) Average power of yellow light; (b) experimental SHG efficiency.

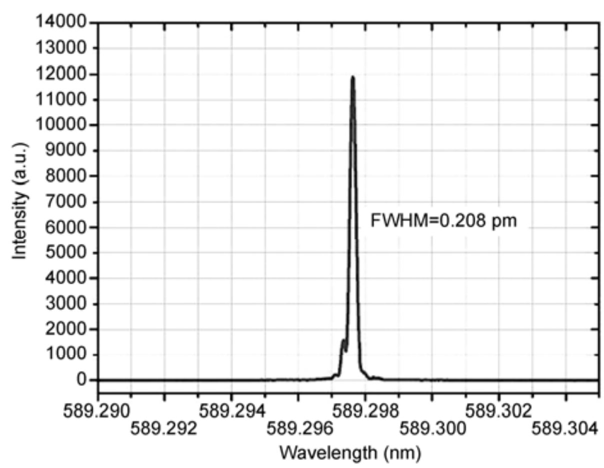

Figure 6 The 589 laser spectrum measured with the spectrometer ELIAS III Echelle.

Furthermore, the ovens used to control the crystal temperature also influenced the conversion efficiency, as shown in Figure 7. Under the same pumping power and focusing condition, the output was quite different when different

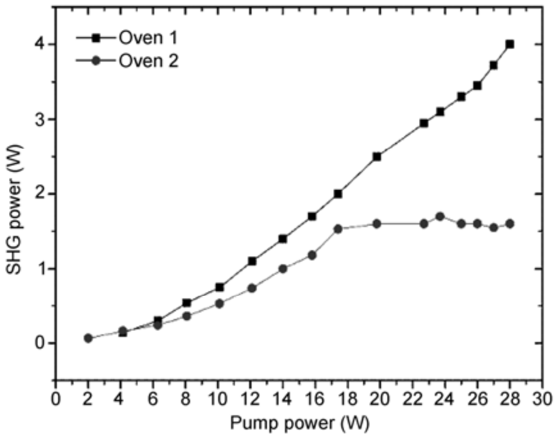

Figure 7 Average power of yellow light versus pumping power at phase-matching temperature controlled by the two ovens.

ovens were used. There was more than 100% deviation at the high pump power. This phenomenon could be explained as follows. The output power is sensitive to temperature variation due to the narrow temperature bandwidth of the PPSLT sample (Figure 2) while localized heating is ongoing especially at higher pump powers. Because the ovens we used here (even the better one) are not well designed (the contact between the sample and the oven is not good enough and the heating medium is aluminum whose thermal conductivity is lower compared to copper etc.). Further work is to focus on better thermal management of the crystal to minimize the thermal dephasing caused by the heat.

5 Conclusion

We have improved the process of electrical poling of SLT and fabricated PPSLT crystal with high uniformity and duty cycle close to 50%. An efficient yellow light generation based on sing-pass frequency doubling of PPSLT has been demonstrated. An average 4 W output was maintained at the fundamental power of 28 W with 14.3% conversion efficiency. The bandwidth is less than 0.18 GHz and can satisfy the specification of sodium guide star laser.

Since it is not difficult to improve of thermal management of the crystal via a better heating design, and a new light source with two times high output will come into service within short timescale, a 10 W class CW 589 nm narrowband source may be achieved easily.

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