Compact high-power red-green-blue laser light source generation from a single lithium tantalate with cascaded domain modulation

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Abstract: 1W quasi-white-light source has been generated from a single lithium tantalate with cascaded domain modulation. The quasi-white-light is combined by proper proportion of the red, green and blue laser light. The red and the blue result from a compact self-sum frequency optical parametric oscillation when pumped by a single green laser. The efficiency of quasi-white-light from the green pump reaches 27%. This compact design can be employed not only as a stable and powerful RGB light source but also an effective blue laser generator.

OCIS codes: (140.0140) Lasers and laser optics; (190.4410) Nonlinear optics, parametric processes; (160.4330) Nonlinear optical materials.

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1. Introduction

Red, green, and blue (RGB) are the three primary colors in the visible world. It can be used to produce most of the visual colors including the white-light by weighted combination. Hence it is very useful in the laser display, laser TV, laser illumination and so on. A variety of

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solutions are made to produce high-power RGB laser light source. Usually people have to use more than one nonlinear crystal to realize the three primary colors if the birefringence-phase-matching (BPM) technique is adopted [1]. But using several nonlinear crystals brings the complexity to the experimental setup. A simpler setup especially one single nonlinear optical crystal involved is preferred. One solution based self-doubling and self-sum-frequency generation from a single laser crystal has been reported [2,3]. Quasi-phase-matching (QPM) materials also called $\chi^{(2)}$-modulated crystal is another unique solution for this high-power and compact-design light source. Most of the previous works are concentrated on harmonics generations through a single QPM crystal pumping by several fundamental laser sources [4–6].

In this paper we report a red-green-blue laser light source based on a QPM single lithium tantalate. The crystal is structured by a tandem domain modulation. Two different periods of $\chi^{(2)}$-modulation are designed for parametric down conversion (PDC) which generates the red light and sum-frequency-generation (SFG) which generates the blue light, respectively. The generated red and blue light together with the residual green pump constitute the primary three colors. By proper proportion, >1W quasi-white-light is obtained by this single 25 mm long QPM wafer.

2. Experimental setup

The micrograph of the sample structure is shown in Fig. 1(a). It is fabricated by pulse electric field poling technique at room temperature. The first segment is periodically poled with period a_1 = 11.527 μm which can meet the momentum conservation requirement in the PDC process. The signal at 630 nm and the idler at 3420 nm can be obtained when the lithium tantalate is pumped by the 532 nm laser at 160°C. The second part is designed with a_2 = 8.458 μm which converts the idler 3420 nm to 460.4 nm by sum-frequency-generation with the pump. The two segments are 15 mm and 10 mm, respectively. The dimensions of the sample are 25 mm in length, 2 mm in width and 0.8 mm in thickness. The end faces are polished and antireflection coated for 630 nm, 460.4 nm and 532 nm. The crystal is embedded in an oven with ± 0.1°C precision. Then it is inserted into a flat-flat optical cavity. The input mirror M_1 has a high reflection at 630 nm and high transmittivity at 532 nm and the output mirror M_2 has a reflection of 65% at 630 nm. The total length of this OPO cavity is 56 mm. It is worth noted here that the pump 532 nm laser (DS20H-532, Princeton Industries) is focused by a f = 200 mm cylindrical lens which shaping an elliptical spot at the focus plane. As illustrated in Fig. 1(b), the elliptical spot has a FWHM of 713 μm along the long axis and 79 μm along the short axis. This oblate spot is designed to match the sample's shape which is a thick wafer. The pump laser has a repetition rate of 10 kHz, a pulse duration of 12.2 ns and linewidth of 0.15 nm.

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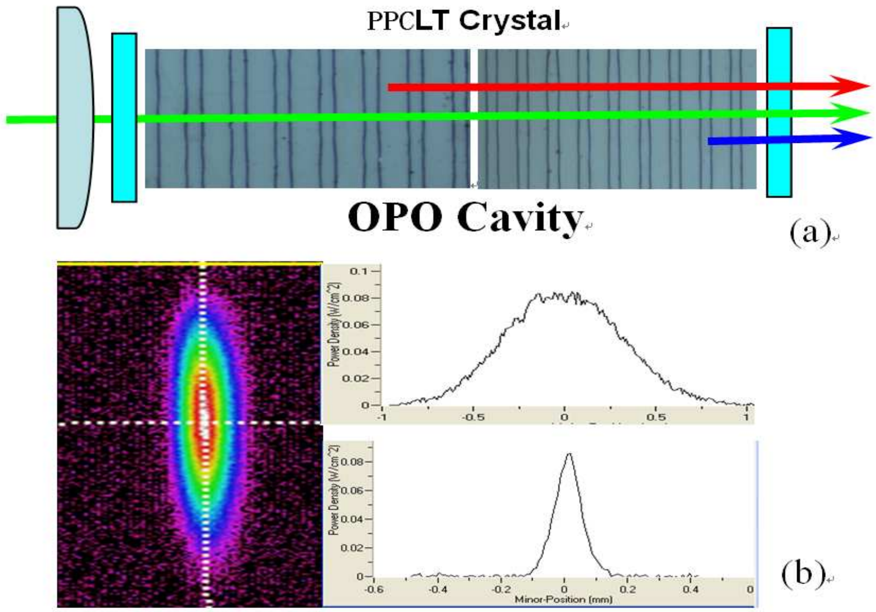

Fig. 1. (a) The micrograph of the tandem periodically poled lithium tantalate and the cavity design. (b) The elliptical spot at the focus plane of the pump.

3. Experimental results and discussion

When setting the temperature at around 150.3°C, the oscillation threshold is around 2.3 W, which corresponding to the peak intensity at the beam waist to be 10.6 MW/cm^2. When increasing the pump power, the signal power increases linearly as shown in Fig. 2. When the pump increasing to its maximum 3.7 W, the red signal reaches 525 mW. The red conversion efficiency is 14.2% and the slope efficiency is 30%. The red light has a stable output power with rms = 2% over hours. Meanwhile the blue light appears along with the red. The power goes quadratically with the pump power. The maximum power is about 130 mW when the pump runs at its full power. The efficiency from the primal pump to the blue is around 3.5%. The rms of the blue power is 5% and it is a little bit worse than the red light. This is due to the blue light is generated from the cascaded nonlinear process so more disturbance such as the temperature and the fluctuation of pump power should be accounted. Here we find that the optimal temperature for the SFG blue light is deviated from the theoretical design. It could come from the deviation of actual refraction index from the used Sellmeier equation and thermal expansion etc [7]. According to the CIE chromaticity diagram, we can obtain 1 W quasi-white-light by adding 345 mW residual green pump into this 525 mW red and 130 mW blue. The conversion efficiency from the green pump to the quasi-white-light is 27%. The chromaticity coordinates are (0.39, 0.402, 0.207) and the corresponding color temperature is 3918K. Since the red and blue are converted from the green, the power of green, the red and blue are balanced. But the ratio between them is fluctuated due to the power fluctuation of the red (rms = 2%) and blue (rms = 5%). This results in a color temperature deviation of ~ ± 100K from the central color temperature. In addition we can get a color balanced white power of 548.4 mW (R = 243.5 mW, G = 174.9 mW, B = 130 mW), a warm white-light of 913.8 mW (R = 525 mW, G = 288.8 mW and B = 100 mW) and a cool white-light of 720.9 mW (R = 347.8 mW, G = 243.1 mW, B = 130 mW). In above experimental test, several optical elements are used to separate the red, green and blue. Taking the linear loss by these filters into account, the original red power directly after the OPO cavity should be 802 mW and the blue should be 190 mW. So the effective quasi-white-light in this experiment has exceeded 1

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W. The insert is a photo of the RGB light source and the combined quasi-white-light taken by a digital camera.

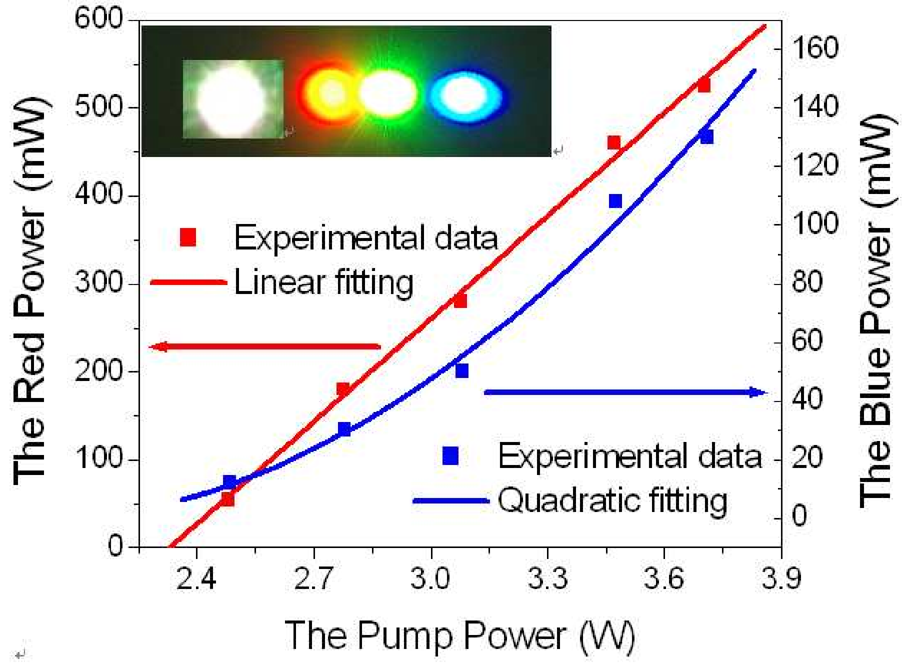

Fig. 2. The red and blue power when the pump power increases. The insert photos are taken by a digital camera.

Figure 3 is the temperature dependence of the red and blue power. The pump power is set at 3.5 W. The temperature FWHM of the SFG blue light is around 3°C which is consistent with the theoretical calculation. The red has a power dip when the blue light gets optimally phase-matched. This is due to that the maximum blue light generation equals that the maximum absorption of the idler beam and this offers additional loss for the first OPO process and makes the OPO work less efficient. The red power should keep the same when no efficient SFG cascaded. But in Fig. 3, the red power drops when the temperature lower than 148°C. This probably comes from the photorefractive effect. When the temperature is above 151°C, the red power gets increased by roughly 10 percents. This indicates that the sample should be designed to work at a higher temperature. Furthermore, by using stoichiometric lithium tantalate (SLT) especially MgO-doped lithium tantalate (MgSLT), photorefractive effect can be greatly suppressed [7–11]. But for SLT and MgO-doped SLT, the difficulty for the poling is increased. More imperfections on the domain inversion are observed. Comparing one of our previous works [7] which works in a very similar scheme based on SLT, it does show a much better performance on photorefractive effect. But the oscillation threshold and the efficiency of red power are comparable with this experiment although the cavity here is

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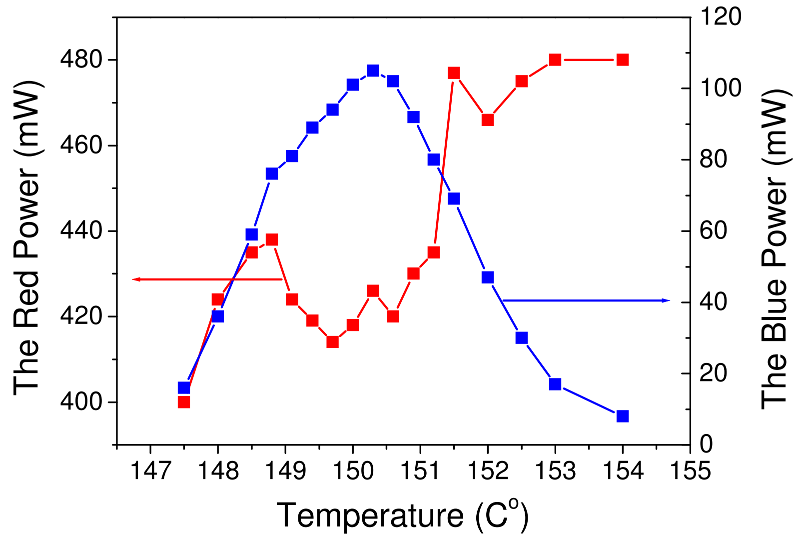

Fig. 3. The power dependence of the red and blue on the temperature.

longer and the sample is shorter. It can be deduced that the poling quality of this sample is much better. So the congruent lithium tantalate (CLT) used in this experiment is worth being attempted in some cases.

When the crystal's temperature is set at 150.3°C, the linewidth of the red and the blue is 0.15 nm and 0.16 nm, respectively. Figure 4 records the dependence of the central wavelength of the red and the blue on temperature. The red wavelength decreases while the blue

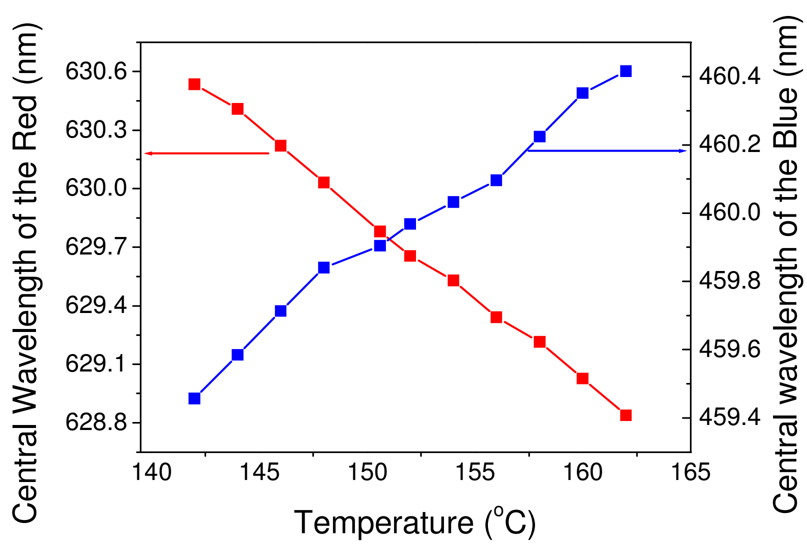

Fig. 4. The dependence of the central wavelength of the red and the blue on the temperature.

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wavelength increases when the temperature increases, which consists well with the theoretical calculation. Both the central wavelength of the red and the blue are not sensitive to the temperature. As in Fig. 4 when the temperature varies by 20°C, the central wavelength of the red and the blue shift only by 1.7 nm and 1.0 nm, respectively. From Fig. 3 and Fig. 4, it concludes that to generate the red light through PDC process is reliable since the both power and spectrum are not sensitive to the temperature. Hence the cascaded blue power can always has efficient generation only the SFG temperature may shift a little when taking all the fabrication errors into account. From this point of view, the SFG cascaded PDC process to generate RGB light has superiority than the one based on several harmonic generations which can hardly possess the same QPM temperature for the red, green and blue [4,5]. Also this scheme has better performance in the power stability since only one pump is required while the scheme adopted in Ref. 4 and Ref. 5 cannot produce comparatively stable output since there is competition between 2 near-infrared pumps.

It worth noted here that the cylindrical lens used in this setup is a unique choice to increase the interaction volume so as to make the OPO work at a high average power regime. To further increase the output RGB power, one can utilize more powerful pump laser, fabricate a longer tandem crystal, or design a quasi-periodic or other dual-QPM samples. Since the blue light goes quadratically with the pump power, these improvements will work especially effective for the blue light generation. So this self-sum-frequency OPO is a valuable way to generate the blue laser.

4. Conclusion

In conclusion a compact high power red-green-blue laser light source has been generated from a single lithium tantalate with cascaded domain modulation. The red and the blue are generated from the OPO and the cascaded SFG process with the conversion efficiency of 14.2% and 3.5%, respectively. 1 W quasi-white-light is obtained when adding certain power of the residual green. The efficiency of quasi-white-light from the pump reaches 27%. This self-sum-frequency OPO is employed not only as a stable and powerful RGB light source but also an effective blue laser generator.

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