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2 W Quasi-White-Light Based on Idler-Resonant Optical Parametric Oscillation Cascading Sum-Frequency Generation with PPSLT[1]

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Abstract—We present a high power red-green-blue (RGB) laser light source based on cascaded quasi-phase-matched wavelength conversions in a single stoichiometric lithium tantalate. The superiority of the experimental setup is: the facula of the incident beam is elliptical to increase interaction volume, and the cavity was an idler resonant configuration for realizing more efficient red and blue light output. An average power of 2 W of quasi-white-light was obtained by proper combination of the RGB three colors. The conversion efficiency for the power of the quasi-white-light over pump power reached 36%. This efficiency and powerful RGB laser light source has potential applications in laser-based projection display et al.

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1. INTRODUCTION

In the past few years, laser-based projection display (LBPD) has developed rapidly due to the progress of modern optics technology [1]. Principally all vivid colors in the visible world can be constituted through a suitable combination of the three elemental colors: red (R), green (G), and blue (B). LBPD has several advantages over conventional display technology, such as high brightness, high saturation, high spectral purity and no chromaticity errors. Moreover, the large focal depth of a laser beam allows for projection even on curved surfaces [2]. A variety of solutions to generate RGB laser source have been made. Usually there are two main routines to obtain high power RGB laser using bulk nonlinear crystals. One is based on frequency doubling or sum-frequency mixing of multiple fundamental sources [3–7]. The other is based on several discrete stages of frequency doubling following parametric process [2]. Using multiple fundamental sources or several nonlinear crystals both greatly add to the complexity and cost in commercial display system. For compact, efficient, high-power RGB source, a simple setup involving several frequency conversions are preferred [8–10].

In this paper, we present a high-power RGB laser light source based on cascaded frequency conversions using two periodically poled domain sections in tandem on one stoichiometric lithium tantalite (SLT) crystal. The first domain section was designed to generate red light from a frequency down-conversion process pumped by an incident green light in an optical parametric oscillation (OPO) setup. The second section was used to generate blue light by frequency mixing of the residual green light with the mid-IR idler radiation of the OPO. The generated red and blue lights together with some residual green pump light constitute a RGB laser source. By weighted combination, 2 W quasi-white-light was obtained. We chose SLT as the nonlinear crystal. In SLT, the nonstoichiometric defect density is greatly reduced, which leads to a great reduction of the coercive field by one or two orders of magnitude, thus wafers with thickness more than 1 mm can be poled for large aperture frequency conversion devices [11–14]. SLT has more merits such as high damage threshold, low thermo-optic coefficient and wide transmission [11, 14]. Thus, periodically poled SLT (PPSLT) is a promising material for efficient second harmonic generation, optical parametric oscillation, and frequency mixing for generating a wide spectrum covering almost ultraviolet to near infrared regions.

2. EXPERIMENTAL SETUP

The optical superlattice was poled by pulse electric field poling at room temperature. The crystal contains two periodic gratings. Using the Sellmeier equation of SLT, the period of the first grating is 11.67 μm, which compensates momentum mismatch for 532 nm frequency down-conversion to generate 630 nm signal and 3420 nm idler at 190°C. The 460.4 nm blue light is obtained by frequency summing of the 3420 nm idler and the 532 nm pump light. Thus the period of the sec-

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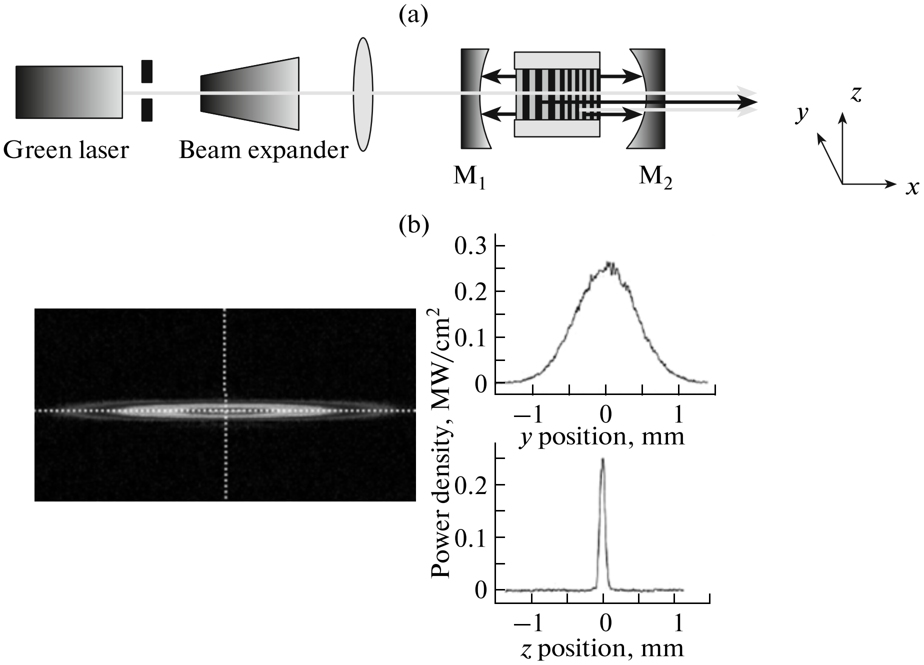

Fig. 1. (a) Schematic experimental setup for RGB laser generation. The two gratings with different period are designed in a single SLT. (b) The elliptical spot of pump light at the focus plane.

ond grating should be 8.58 μm. The sample is a thin wafer with 1mm in thickness and 3 mm in width, respectively. Both of the first and second gratings are 20 mm long. The two end faces of the sample were optically polished and coated for antireflection at 460.4, 532, 630, and 3420 nm. The crystal was embedded in an oven with a controlling accuracy of ±0.1°C. The oven was put in a concave-concave optical cavity for a singly resonant optical parametric oscillation of idler light as shown in Fig. 1. Mirror M$_1$ is a circularly concave mirror with the curvature radius of 600 mm and coated for high reflection ($R > 96\%$) at 3420 nm and antireflection ($R < 4\%$) at 532 nm. Mirror M$_2$ is a cylindrically concave mirror with the curvature radius of 100mm and coated with high reflection ($R > 96\%$) at 3420 nm and antireflection ($R < 4\%$) at 460.4, 532, and 630 nm. The generatrix of M$_2$ is parallel with y axis. The OPO cavity length was 60 mm. The corresponding beam waist of the cavity fundamental mode at the pump wavelength was calculated to be ω_{cav} = 92 μm along z axis.

The OPO cavity used in our experiment was in an idler resonant configuration for realizing a more efficient red and blue light output. And there were two advantages over our previous works [9, 10], which used a flat-flat signal resonant OPO cavity. Firstly, the signal light, or the red light, could be more efficiently exported out of the cavity; secondly, the idler mid-IR light, which is not needed for constructing quasi-white-light, was kept resonant in the cavity, thus a higher power intensity could be achieved for more efficient frequency mixing of the pump and idler light to generate blue light. Moreover, a concave-concave cavity can reduce the diffraction loss compared with a flat-flat one, thus the OPO cavity was working at a high-Q state.

The schematic experimental setup is shown in Fig. 1a. The pump light source was a high-power 532 nm green laser (DS20H-532, Princeton Industries), with a repetition rate of 10 kHz, a pulse duration of 12.2 ns and a linewidth of 0.15 nm. The pump beam was doubly expanded by an inverted telescope beam expanding system, and then focused onto the centre of the OPO cavity by a cylindrical lens with a focal length of 300 mm. It is worth noting that the cylindrical lens used in our experiment is unique choice to increase the interaction volume. The elliptical beam was estimated to be $\omega_z = 79$ μm and $\omega_y = 911$ μm at the focus plane. The beam waist of the pump light matched well with the waist of the cavity mode. And it was z-polarized, propagating along x axis.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The crystal temperature was firstly set at 199°C. There was only OPO process and no sufficient sum-frequency generation (SFG) occurred. The oscillation threshold was around 2.45 W and the corresponding peak power density at the beam waist was 8.9 MW/cm^2. The power of red light increased linearly when increasing the pump power, and reached 1.1 W

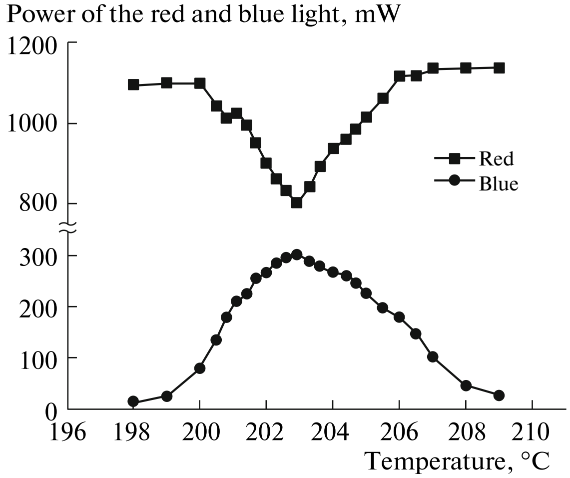

Fig. 2. Average output power of red and blue lights as a function of the crystal temperature.

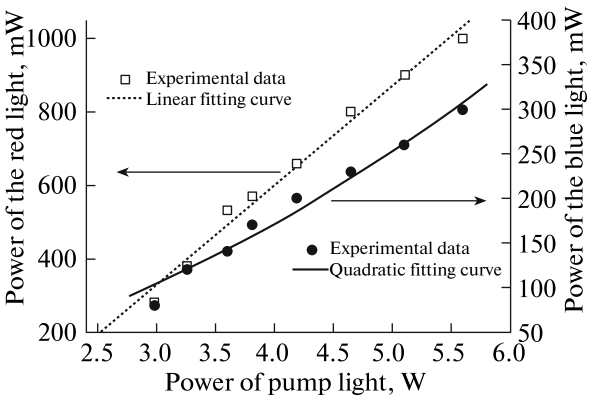

Fig. 3. The dependences of output powers of red and blue on pump power.

at a pump power of 4.65 W with an efficiency of 24%, the slope efficiency being 43%. SFG for blue light generation occurred while raising the crystal temperature. From the temperature tuning curves in Fig. 2, we can see the quasi-phase-matching condition for SFG was satisfied at 202.9°C and the maximum output power of blue light is 230 mW. Meanwhile, the power of red light dipped to 800 mW. And the main reason caused this dip was that part of the idler light was converted to blue light, thus providing additional loss for the OPO process. The fitted temperature full width at half maximum (FWHM) was around 3.5°C.

Figure 3 shows the dependences of the output power of red and blue on input power at the temperature of 202.9°C. The power of blue light increased quadratically with increasing the pump power. When the pump power reached 5.6 W, the measured power of red was 1.01 W and that of blue was 300 mW. The conversion efficiency for red light was 18% with a slope efficiency of 27% while the conversion efficiency of the power of red and blue over pump power was 23%.

By proper combination of the generated red, blue and residual green light, we could obtain 2 W quasi-white-light which comprised 1.01 W red, 690 mW green, and 300 mW blue. The facula of the quasi-white-light and the three RGB beams separated with a prism were recorded after an aperture as shown in Fig. 4. The conversion efficiency from power of quasi-white-light to pump power was 36%. The power proportion of RGB was 3.4:2.3:1, and the corresponding color coordinates in the standard Commission Internationalede de l'Eclairage (CIE) chromaticity diagram were (0.38, 0.39) which was close to the cool-white point. The color temperature of the 2 W quasi-white-light was calculated to be about 4100 K. In addition, from the three points on the radiation curve of Planckian radiators in the CIE chromaticity diagram, if we use the full power of blue, then 1.27 W of day light (R = 565 mW, G = 405 mW, and B = 300 mW) and 1.67 W of cool light (R = 810 mW, G = 560 mW, and B = 300 mW) were obtained. And if the full power of red light was used, then warm light (R = 1010 mW, G = 550 mW, and B = 190 mW) at 1.75 W could be obtained.

It has been estimated that in order to illuminate a 180 inch 16:9 screen (4 m wide, 2.25 m high) to display, 2730 lm of RGB (R: 642 nm, G: 532 nm, B: 457 nm) laser source is required [15]. Given 30% source-to-screen efficiency, the luminous flux on the screen is 820 lm. In our experiment, 2 W RGB laser

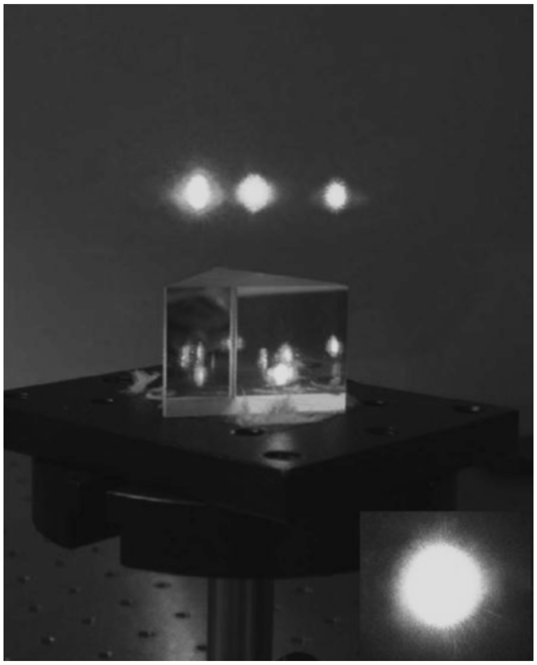

Fig. 4. The RGB beams and quasi-white-light recorded with a digital camera after an aperture.

corresponds to the luminous flux of 610 lm. Considering the efficiency from laser source to screen, there is 180 lm on the screen. It is estimated the laser source can illuminate a 45 inch 16:9 screen for projection.

When increasing the pump power above 5.6 W, the corresponding power density being 20.3 MW/cm^2, green-induced infrared absorption (GRIIRA) and photorefractive effect came forth with beam distortion and power roll off in the output light, which show the similar performance in one of our previous works [9]. In some earlier work it has been demonstrated that PPSLT can withstand photorefractive damage up to 58 MW/cm^2. In our experiment the low threshold is mainly due to the imperfection of the inverted domains. Before the optical measurements, the sample was etched in HF acid for several hours to reveal the domain patterns, finding that there were some imperfect domains in the sample and the domain duty cycle was a little non-uniform. It is mainly attributed to the variation of the coercive field, which originates from the compositional variation on the wafer periphery. To fabricate a QPM structure with a uniform domain duty cycle, more compositional homogeneity in wafers and precise control of the applied electrical field is essential. A high quality QPM device can not only raise the photorefractive damage threshold but also has higher optical conversion efficiencies.

The power fluctuation of the output red light was measured to be 2.5% within hours, and that for blue light was 4%, which is a little bit worse than that of the red light. Considering that the blue light was generated from the cascaded nonlinear process, so more disturbances such as fluctuation of the pump power and temperature of the crystal should be accounted.

Using other nonlinear crystals can further improve the performance of the OPO and SFG, such as periodically poled magnesium doped SLT (MgO:PPSLT) or lithium niobate (MgO:PPLN), PPKTP and KTA [16–30].

4. CONCLUSIONS

In conclusion, we have constructed an efficient high-power RGB laser source based on cascaded frequency conversion in a single periodically-poled SLT crystal. An idler resonant configuration for the OPO cavity together with a special designed cylindrical lens focusing system were used to realize more efficient red and blue light output. Powerful quasi-white-light of 2 W was achieved which comprised 1.01 W red, 690 mW green, and 300 mW blue. The equivalent luminous flux of the quasi-white-light was 610 lm. It is estimated this laser light source can illuminate a 45 inch 16:9 screen for laser-based projection display.

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