Efficient Generation of Red and Blue Light in a Dual-Structure Periodically Poled $LiTaO_3$ Crystal *

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We demonstrate the efficient generation of red light at 671 nm and blue light at 447 nm from a diode-pumped Q-switched 1342 nm Nd:YVO_4 laser together with a periodically poled $LiTaO_3$ (PPLT) crystal. The sample used in this experiment is a dual-structure PPLT crystal with the period of 14.9 μm for the second harmonic generation and that of 4.9 μm for the third harmonic generation. The red and blue light, with the respective average power of 752 mW and 153 mW were obtained in a single path under an average fundamental power of 1.74 W, corresponding to the conversion efficiencies of 43.2% and 8.8%, respectively. These results indicate that the dual-structure PPLT can be used to construct a compact and efficient all-solid-state red-and-blue dual-wavelength laser.

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Red, green and blue light are three elementary colors that may constitute all colors in our vision world. Compact and reliable red, green and blue coherent light sources are required for many applications such as high-resolution laser printing and full-color laser display. The conventional approach generating visible light from a diode-pumped solid state laser is by frequency doubling of a near-infrared laser source with the Nd ion laser host such as Nd:YVO_4 or Nd:YAG, using a nonlinear optical crystal by birefringence phase matching (BPM). Recently, optical superlattices, such as periodically poled $LiNbO_3$ (PPLN), periodically poled $LiTaO_3$ (PPLT) and periodically poled KTP (PPKTP) have become attractive materials for the frequency conversion based upon the quasi-phase-matching (QPM) scheme due to the significant advantages: the interacting waves can be chosen so that the coupling occurs through the largest tensor element of the second order nonlinear coefficients and any interaction within the transparency range of the material can be noncritically phase matched for the arbitrary fundamental wavelength. The red, green and blue generations from a diode pumped Nd^{3+} lasers at near infrared range had been realized by QPM with the optical superlattices, respectively.[1-4] Red (660 nm) and blue (440 nm) laser sources was also reported,[5] which is a two-step process using two discrete PPLN crystals: the first one generated the second harmonic (red light at 660 nm) of Nd:YAG laser at 1320 nm by using second-harmonic generations (SHG), and the second produced the third harmonic wave (blue light at 440 nm) through sum-frequency generation (SFG) of the fundamental wave and its second harmonic wave. In our previous work,[6,7] the simultaneous blue and red light generation in PPLT was reported. The first-order and third-order reciprocals of PPLT were designed to compensate for the phase mismatches of SHG and SFG. In this Letter, we present red and blue generation by QPM frequency doubling and tripling using a single PPLT crystal with dual-structure. The fundamental infrared laser source is a Nd:YVO_4 laser at 1342 nm, as an excellent gain crystal, Nd:YVO_4 has a strong emission of 1342 nm with the polarization along the z axis, corresponding to the ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition of Nd^{3+} ions.

The experimental arrangement is shown in Fig. 1. The fundamental source was an 1342 nm Nd:YVO_4 laser pumped by a 15 W fibre-coupled diode laser (OPC-D015-FPCS-808) with a numerical aperture of 0.12. A focusing lens with 45 mm focal length and 90% coupling efficiency was used to re-image the pump beam onto the laser crystal. The waist diameter of the pump beam was about 750 μm. The laser host was an a-cut, 0.5 at.% Nd^{3+} doped, 5 mm long Nd:YVO_4 crystal, and its front surface was coated with the high reflection at 1342 nm ($R > 99.8\%$) as a cavity mirror coated high transmission at 808 nm, and the other end surface had an antireflection coating at 1342 nm. The flat output coupler was coated with the reflectivity of $R = 95\%$ at 1342 nm. The flat-flat resonator cavity length was ∼7.5 cm. In this laser system, an acoustic-optical Q-switch was placed inside the cavity, producing Q-switched pulses of ∼35 ns duration (FWHM) at a pulse repetition rate of 10 kHz. The average fundamental power of 1.95 W was obtained under an incident pump power of 14 W, corresponding to a peak power of 5.6 kW and pulse energy of 19.5 μJ. After focusing by the lens F_2 with the focal

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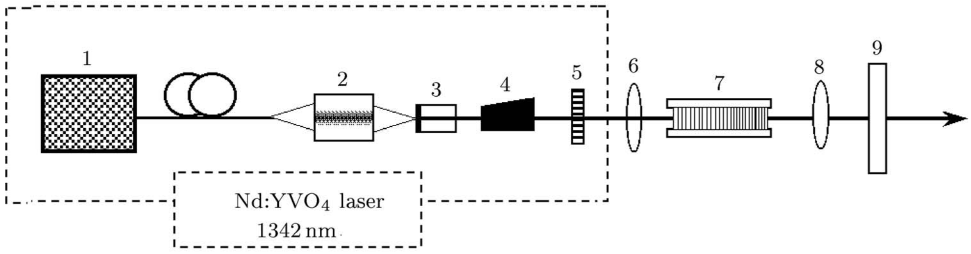

Fig. 1. Experimental arrangement for red and blue light generation. 1: laser diode, 2: coupling lens, 3: Nd:YVO_4, 4: acousto-optic Q-switch, 5: plane mirror, 6: focus lens, 7: PPLT and oven, 8: collimating lens, 9: filter.

length of 50 mm, an average power of 1.74 W in a linearly polarized fundamental transverse mode was incident on the PPLT ($\sim$ 13% fundamental power might be loss due to uncoated front of the crystal sample). The dual-structure PPLT sample was put in an oven and heated by a temperature controller with an accuracy of 0.1°C (Model OTC-PPLN-20, Super Optronic). The QPM temperature was set at an elevated value of 74.6°C

The PPLT crystal used in this experiment is composed of two cascaded periodic structures. The first periodic structure carries out SHG process of 1342 nm wavelength to achieve red light at 671 nm by using its first order reciprocal; the second structure performs SFG process of the fundamental wave and its second harmonic wave by use of the first order reciprocal to obtain the third harmonic wave (blue light at 447 nm). Compared to a single period structure PPLT, in which the first and third order reciprocals are used for the SHG and SFG processes, consequently, the double-structure PPLT should have the more high efficiency in the theory. In the SHG process, the QPM condition is

$$k_s - 2k_f - \frac{2\pi}{\Lambda_1} = 0, \qquad (1)$$

where k_f and k_s are, respectively, the wavenumbers of the fundamental and the second harmonic and Λ_1 is the period of the first structure. Similarly, the QPM condition for the SFG process is

$$k_t - k_s - k_f - \frac{2\pi}{\Lambda_2} = 0, \qquad (2)$$

where k_t is the wavenumber of the third harmonic and Λ_2 is the period of the second structure. According to the temperature-dependent Sellmeier equation of $LiTaO_3$,[8] the periods of the first and second structures can be determined to be 14.9 and 4.9 μm by Eqs. (1) and (2), respectively, for the fundamental of 1342 nm and the working temperature at 74.6°C. For the PPLT sample, the lengths of the first and second structures were 20 mm and 10 mm, respectively.

We fabricated one kind of periodic domain-reversal dual-structure Z-cut LT wafer through an electric field that was poled at room temperature.[9,10] The periodic domain patterns were observed on the etched $+c$ and $-c$ surfaces of sample using an optical microscope.

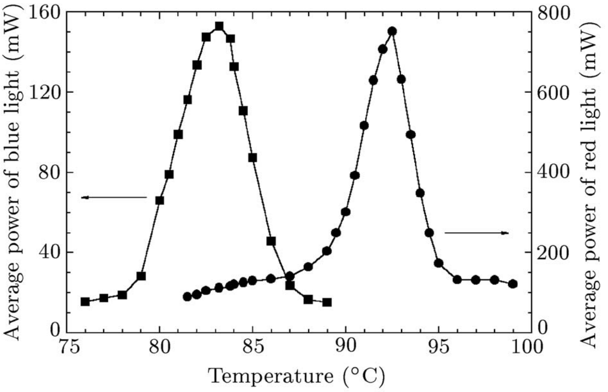

Fig. 2. Measured temperature tuning curves for red and blue light generation of PPLT.

According to the SFG theory, in order to achieve the maximum SFG efficiency, the photon numbers of the fundamental wave and the second harmonic wave should be equal before they enter the second domain structure of the PPLT sample for the SFG process, that is to say, the power of second harmonic wave should be twice of the fundamental. Since the position of focus point of fundamental beam inside the first structure and the working temperature can control the output of second harmonic, the maximum third harmonic power of 153 mW at 83.2°C was obtained by moving the PPLT sample and tuning the crystal temperature carefully, and the second harmonic power was only 112 mW at the same temperature. The maximum average power of 752 mW appears at 92.3°C for the second harmonic while the third harmonic is very low. Figure 2 shows the measured temperature-tuning curve of the second and third harmonic powers. The optimal QPM temperatures for SHG and THG are 92.3°C and 83.2°C, with the respective full width at half maximum (FWHM) of 3.2°C and 4.5°C, respectively. The peak of blue light lies on the shoulder of the curve of the red light. Both of them deviate from the expected working temperature 74.6°C. This may be caused by the following reasons. The first is that the Sellmeier equation in Ref. [8] may not match the

QPM wavelengths near 671 nm to 1342 nm with the same high precision as it matches in the 532–325 nm. This may cause the shift of the QPM temperature and the peak separation of the blue and red light. Second, due to the limit of lithographic precision, the actual domain period may be different from the nominal domain period. It is well known that the QPM temperature has critical dependence upon the period of the domain structure. Therefore, small deviations from the calculated domain period will cause great shifts of the QPM temperature of the SHG and THG processes as well as separation between them.

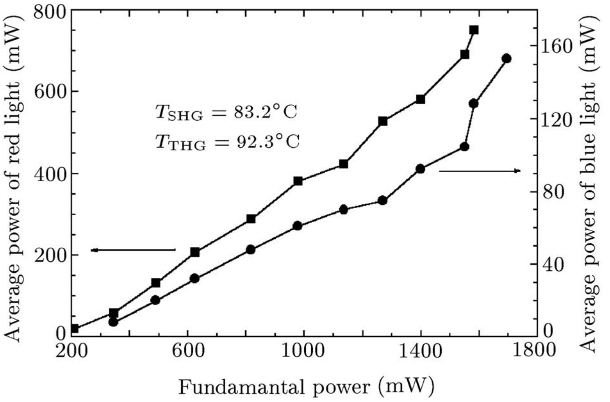

Fig. 3. Average power of red and blue light versus incident fundamental wave power at the working temperatures 83.2°C and 92.3°C, respectively.

The conversion efficiency is defined as $\eta = P_s/P_f$, where P_s is the average power of red or blue lights, and P_f is the average power of fundamental of 1342 nm incident on the crystal. As shown in Fig. 3, with average incident power of 1.74 W at 1342 nm, 153 mW of blue and 752 mW of red light was generated in a single pass, at the working temperatures 83.2°C and 92.3°C, respectively, corresponding to conversion efficiency of 43.2% and 8.8%. The fluctuation of power of blue light at its peak was ∼2.3% at one hour period, the output was fairly stable throughout the whole measured times. Provision of coatings for the crystals and optimization of beam overlap in the SHG and SFG process should offer a significant improvement in performance.

In conclusion, we have reported an efficient simultaneous generation of red light with 752 mW at 671 nm and blue light with 153 mW at 447 nm by frequency doubling and tripling of a diode-pumped Nd:YVO_4 1342 nm laser in a dual-structure PPLT, corresponding to conversion efficiencies of 43.2% and 8.8%. The high conversion efficiency and output power make it practical scheme to obtain high-quality all-solid-state red and blue dual wavelength lasers.

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