High-power red-green-blue laser light source based on intermittent oscillating dual-wavelength Nd:YAG laser with a cascaded $LiTaO_3$ superlattice

X. P. Hu,[1] G. Zhao,[1] Z. Yan,[1] X. Wang,[1] Z. D. Gao,[1] H. Liu,[1] J. L. He,[2] and S. N. Zhu[1,*]

[1]*National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing, 210093, China*

[2]*Institute of Crystal Materials, Shandong University, Jinan, 250100, China*

**Corresponding author: zhusn@nju.edu.cn*

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We demonstrate a high-power red-green-blue laser source based on the quasi-phase-matching and intermittent oscillating dual-wavelength laser technique. A cascaded $LiTaO_3$ superlattice was used to achieve the generation of red light at 660 nm, green light at 532 nm, and blue light at 440 nm to obtain the output of red-green-blue laser light from a diode-side-pumped Q-switched intermittent oscillating dual-wavelength Nd:YAG laser. The average output power of red-green-blue of 1.01 W was achieved under the total fundamental power of 5.1 W, which corresponds to the conversion efficiency of 20%. © 2008 Optical Society of America

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Red, green, and blue (RGB) are the three elemental colors in the visible world, and most visual colors can be obtained by a weighted combination of these three colors. Hence RGB's three elemental colors can be used in projection displays and other high-tech applications. Diode-pumped infrared solid-state lasers based on an Nd^{3+} ion provide an excellent possibility to develop such devices when combined with nonlinear frequency conversion to the visible. An Nd^{3+} ion has multiple allowed transitions departing from the metastable level $^4F_{3/2}$ to the lower-lying-energy Stark sublevels $^4I_{13/2}$, $^4I_{11/2}$, and $^4I_{9/2}$, leading to potential laser radiations $\sim$1.3, 1.06, and 0.94 μm, respectively. By frequency doubling the lines $\sim$1.3 and 1.06 μm, and by frequency tripling the line $\sim$1.3 μm, we can obtain simultaneous RGB generation, as several works have reported previously [1–3].

As is well known, for the Nd^{3+} ion, the two transitions, $^4F_{3/2}$–$^4F_{11/2}$ and $^4F_{3/2}$–$^4F_{13/2}$, share the same upper level $^4F_{3/2}$, and thus in dual-wavelength operation must compete for the energy stored by pumping to that level; this makes the dual-wavelength laser operation unstable. In this Letter, we used an intermittent oscillating dual-wavelength Nd:YAG laser [4] operating at 1319 and 1064 nm as the fundamental source, which had a stable dual-wavelength output, and an optical superlattice in an $LiTaO_3$ crystal as the nonlinear frequency converter. With this scheme, we obtained 660 nm red light, 532 nm green light, and 440 nm blue light, i.e., RGB three-color light output; the total power reached 1 W, and the output is relatively stable.

Blue generation is a key factor in this Letter, which can be realized by third-harmonic generation (THG) of the fundamental wave at 1319 nm in a quasi-periodic [5], aperiodic [6], or dual-periodic [7] structures. In this Letter, we used a quasi-periodically optical superlattice in an $LiTaO_3$ crystal to obtain simultaneously, second-harmonic generation (SHG) at 660 nm (red) and THG at 440 nm (blue) of the fundamental wave at 1319 nm. The theory of a quasi-periodical superlattice for frequency conversion was described in [5]. Experimentally, the superlattice consists of five parallel channels and each of them has a similarly quasi-periodical domain reversion structure. These channels are 1 mm wide with a nominal phase-matching temperature at 140°C, for SHG at 660 nm, but with different phase-matching temperatures, 136°C, 138°C, 140°C, 142°C, and 144°C, for THG at 440 nm. As we all know, a small fabrication error of the domain widths may lead to a large deviation between the phase-matching temperature of SHG and THG; thus fewer red photons will be involved in the THG process, so we designed this multichannel structure providing an 8°C temperature tuning range to let these two temperature tuning curves overlap more for efficient blue light generation. Also, we can optimize the proportion of red and blue by the selection of a proper channel. Obviously, the structure parameters for these five channels are different from one another. The detailed structure parameters of the five channels were given in Table 1. From Table 1 we can see that the parameter differs among five channels; however, they are very small due to very closely matching temperatures. The reciprocal vectors $G_{1,1}$ of these quasi-periodical channels were used for quasi-phase matching (QPM) frequency doubling of fundamental at 1319 nm to generate the red light at 660 nm, whereas $G_{3,4}$ was used to generate the blue light at 440 nm by QPM frequency adding fundamental and second harmonics. Theoretically, the effective nonlinear coefficients for the above two processes are $d_{\mathrm{eff}(R)}=0.55d_{33}$ and $d_{\mathrm{eff}(B)}=0.205d_{33}$, respectively, and they are almost the same for the five channels. The five-channel quasi-periodical superlattice is cascaded by a periodically

Table 1. Structure Parameters of the Five Quasi-Periodical Channels in First Segment[a]

Channel	T_{THG} (°C)	D_A (μm)	D_B (μm)	l (μm)	tan θ
1	136.0	17.850	13.744	6.870	0.054212
2	138.0	17.840	13.737	6.870	0.056165
3	140.0	17.830	13.730	6.860	0.058151
4	142.0	17.820	13.723	6.860	0.060144
5	144.0	17.820	13.715	6.860	0.062170

[a] D_A and D_B are the widths of blocks A and B, respectively; l is the width of the positive domain in both blocks A and B; and θ is the projection angle.

optical superlattice with the period of 7.63 μm on the same $LiTaO_3$ wafer, which is used for the frequency doubling of another fundamental wave at 1064 nm to generate green light at 532 nm at 140°C. The corresponding nonlinear coefficient $d_{\mathrm{eff}(G)}=0.64d_{33}$. The two segments, quasi-periodical and periodical, are arranged in a series and fabricated in the same $LiTaO_3$ wafer using the conventional electrical-poling technique [8,9]. The wafer is 0.5 mm in thickness, and the two segments are 30 and 10 mm, respectively, in length.

The experimental setup is shown in Fig. 1. The fundamental source was an intermittent oscillating dual-wavelength Nd:YAG laser, which was well described in [4]. The driving current of the Nd:YAG laser module (RD40-1C2, CEO Corp.) was adjustable within the range of 0–25 A, but when the driving current exceeded 19 A, multimode output would appear. Thus we set the operating current of the laser diode (LD) to be 19 A and the repetition rate of Q switch to be 3.2 KHz; then 5 W total average power and TEM_{00} profile were obtained. The output two IR radiations were both horizontal polarized, and the corresponding pulse durations of 1319 and 1064 nm are 260 and 90 ns, respectively. The lens F with the focus length of 100 mm was used to focus two polarized fundamental beams into the superlattice sample with a beam waist of 300 μm inside the crystal. A heater was used to heat the $LiTaO_3$ crystal to the phase-matching temperature with an accuracy of 0.1°C. The two ends of the sample were polished for optical measurement but not coated. A filter was put behind the sample to filter the IR at 1319 and 1064 nm for convenient measurement of the output power. The output RGB light was separated with a prism with transmittance of 100% and detected by a power meter, respectively.

The temperature tuning curves for RGB light are shown in Fig. 2. The curves were measured at a certain fundamental power, 3.9 W for 1319 nm and 1.2 W for 1064 nm; the corresponding LD driving current was 19 A and the delay time ΔT was 10 μs. From Fig. 2, one can see that the maximum output powers of RGB light are 856, 154, and 112 mW, and the corresponding phase-matching temperatures are 129.2°C, 129.6°C, and 128.7°C, respectively. The temperature tuning curves overlapped in a temperature region. At 129.3°C, we got 780 mW of red light, 146 mW of green light, and 84 mW of blue light from the second channel. The output laser operates in a high repetition manner (3.2 kHz), which is rather smaller than the time resolution of the human eyes, so we can see a quasi-white-light output from the instrument, which had the total power of 1.01 W. The power proportion of RGB at this temperature was 9.3:1.7:1, which was close to the cool-white point indicating in the Commission Internationale de l'Eclairage (CIE) chromaticity diagram [10]. The luminous flux corresponding to this cool white is 118 lines/m, and the corresponding color temperature is about 5000 K. At the same time, the blue light generated from other channels was also measured, and the corresponding average power was 4, 1, 0.25, and 0.05 mW, respectively, rather lower than that from the second channel due to larger phase mismatching at the measurement temperature. We changed the temperature from 128.0°C to 130.0°C in steps of 0.5°C, finding that outputs of RGB changed accordingly; however, the proportion of RGB outputs was still in the quasi-white-light region ac-

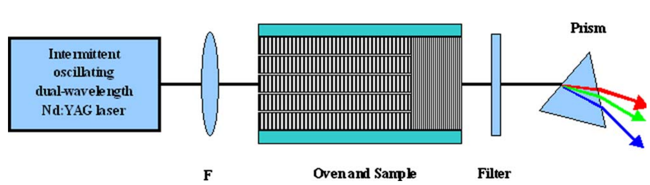

Fig. 1. (Color online) Experimental setup for RGB three colors generation.

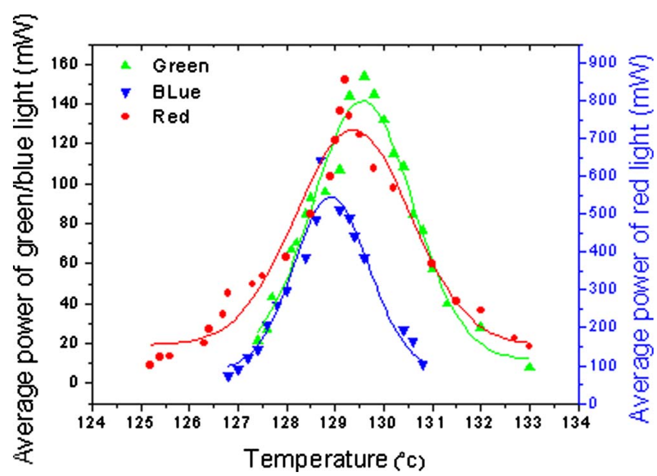

Fig. 2. (Color online) Measured temperature tuning curves of RGB lights. A simple Gaussian fit for three sets of data is to guide the eye. The Gaussian fit did not consider the wave coupling during the THG process, but the experimental data demonstrated the coupling effect.

cording to the CIE diagram. The wide temperature bandwidth indicates that the scheme is of practical use. Figure 3 is a photo of the RGB beams separated by a prism from the setup.

The fluctuation of the total output power of RGB was measured to be ~6.5% within 1 h. The main reason leading to the fluctuation was the fluctuations of the fundamental wavelengths, 3.6% for 1319 nm and 2.6% for 1064 nm, respectively. Gain competition was observable in our experiment. Optimizing the parameters and structure of the laser cavity for raising the stability of output is still under consideration.

In summary, we used a cascaded $LiTaO_3$ optical superlattice to achieve the generation of red light at 660 nm, green light at 532 nm, and blue light at 440 nm to obtain RGB laser output from a diode-side-pumped, Q-switched, intermittent oscillating dual-wavelength Nd:YAG laser. A total average power of 1.01 W of the RGB laser was obtained at 129.3°C, and the corresponding fundamental powers were 3.9 W for 1319 nm and 1.2 W for 1064 nm, respectively. The result indicates that the scheme is an attractive way to construct a compact all-solid-state RGB laser, raising the fundamental power and using thicker periodically poled stoichiometric or MgO-doped stoichiometric $LiTaO_3/LiNbO_3$ crystals [11] that can easily scale the output to a higher power.

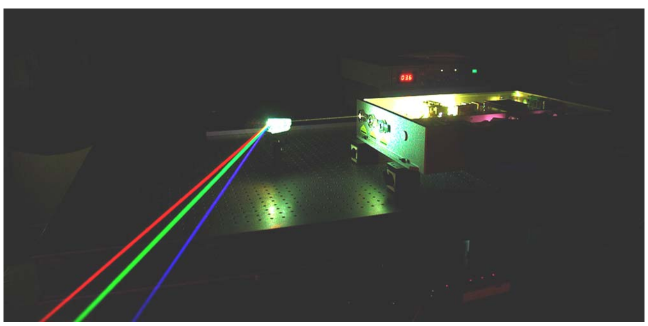

Fig. 3. (Color online) Photo of the RGB beams separated by a prism from the setup.

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