Single-pass sum-frequency-generation of 589-nm yellow light based on dual-wavelength Nd:YAG laser with periodically-poled $LiTaO_3$ crystal

L. N. Zhao, J. Su, X.P. Hu[1], X. J. Lv, Z. D. Xie, G. Zhao, P. Xu, and S. N. Zhu[2]

National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing, 210093, People's Republic of China
[1]xphu@nju.edu.cn
[2]zhusn@nju.edu.cn

Abstract: We demonstrate a compact all-solid-state yellow laser source based on Q-switched dual-wavelength Nd:YAG laser and periodically-poled $LiTaO_3$ crystal. 589-nm yellow light was generated by single-pass sum-frequency generation of the fundamental IR waves at 1064 and 1319 nm. The maximum output power of yellow light was 506 mW and the corresponding conversion efficiency was ~5.5% [$W^{-1}cm^{-1}$].

OCIS codes: (140.7300) Visible lasers; (130.7405) Wavelength conversion devices; (160.4330) Nonlinear optical materials.

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1. Introduction

Laser light sources at 589 nm are important for a numerous applications in medicine, communication, biology, ophthalmology, Bose-Einstein condensation, display technology,

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and such sources for guide stars through resonance fluorescence in the mesosphere sodium layer [1–3]. An interesting coincidence of nature is that the sum frequency of the two lines of Nd:YAG lasers operating at 1064 and 1319 nm may be made resonant with the sodium D_2 line. A number of different scenarios have been demonstrated: the possibility of producing 589 nm yellow light by an intracavity sum-frequency generation (SFG) in an Nd:YAG laser operating simultaneously at two lines: 1064 and 1319 nm was confirmed by Danailov [4]; SFG of 1.7GHz linewidth at 589 nm was presented in a single-cavity Q-switched Nd:YAG laser with an intracavity type II KTP crystal [5]; 400 mW of SFG power was achieved with a doubly resonant congruent lithium niobate resonator [6]; a 20 W cw single-frequency SFG system at 589 nm has been developed in a doubly resonant external ring cavity [7]; 11 mW single-mode tunable 589 nm radiation has been generated using single-pass SFG of two single-mode Nd:YAG lasers with a periodically-poled lithium niobate as the nonlinear frequency converter [8]. The double resonant and the ring cavity scheme using two Nd:YAG lasers dramatically enhanced the output power, but they greatly added to the complexity and cost of the system. An all-solid-state, high-efficient, portable yellow light source with a proper nonlinear crystal is preferred.

In this paper, we demonstrate an all-solid-state, compact and efficient scheme to generate 589 nm yellow light based on dual-wavelength Q-switched Nd:YAG laser operating at 1064 and 1319 nm with a periodically poled $LiTaO_3$ (PPLT) crystal. As is well known, Nd:YAG crystal has two strong emission lines at 1064 and 1319 nm, and is a promising gain media for diode pump multi-wavelength laser operation. To solve the problem that the two lines at 1064 and 1319 nm compete for the same upper energy level, we used a three-mirror cavity proposed by Chen [9] for dual-wavelength operation. The three-mirror cavity scheme cannot only balance the gain competition, but also adjust the energy proportion between the two emission lines for high efficiency sum-frequency generation.

2. Experimental setup

The advantage of using PPLT as the nonlinear frequency converter lies in the fact that quasi-phase-matching (QPM) allows the use of the highest nonlinear coefficient d_{33} for high-efficiency SFG [10]. For SFG process of 1064 and 1319 nm, the grating period can be calculated using the Sellmeier equation of congruent LT crystal where the momentum conservation should be satisfied [11].

$$\Delta k = \frac{2\pi n_3}{\lambda_3} - \frac{2\pi n_2}{\lambda_2} - \frac{2\pi n_1}{\lambda_1} = \frac{2\pi}{\Lambda} \tag{1}$$

In Eq. (1) Λ is the grating period of the periodically poled sample, and n_i is the refractive index at wavelength λ_i. Here $i = 1, 2, 3$ for λ represents the wavelength at 1064, 1319 and 589 nm, respectively. We set the phase-matching temperature for SFG process to be 180°C to avoid photorefractive effect, and Λ is 10.265μm. The PPLT sample was 30-mm in length, 0.5-mm in thickness, cut from a z-cut congruent $LiTaO_3$ wafer, fabricated using the electrical poling technique at room temperature [12]. After poling, the sample was etched in HF acid for several hours to reveal the domain patterns. Figure 1 shows the domain patterns of the + C surface using an optical microscope. We can see that the domains on the + C surface are uniform and the duty cycle is close to 50%. The end faces of the sample were polished but not coated.

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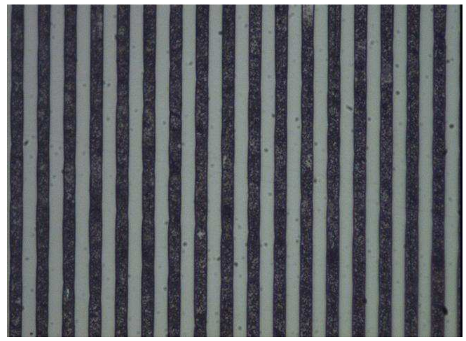

Fig. 1. Optical micrograph of the + C surface of the PPLT sample revealed by etching.

The schematic experimental setup is shown in Fig. 2. The fundamental source comprises a LD-side-pumped Nd:YAG laser module (RD40-1C2, CEO). The oscillating wavelength of LD is 808nm. The doping concentration of Nd^{3+} in Nd:TAG crystal is 0.6%. The Nd:YAG module locates in a linear three-mirror cavity oscillating at both 1064 and 1319 nm. For a three-mirror dual-wavelength laser, the cavity parameters should be carefully chosen and precisely aligned to obtain good temporal and spatial overlap, and proper fundamental waves' power proportion, for efficient SFG [13]. In our experiment, we chose the following cavity parameters. Mirror M1 was a flat mirror coated for high reflection (R>99%) at 1319 nm and antireflection (R<1%) at 1064 nm. Mirror M2 was a flat mirror with high reflection(R>99%) at 1064 nm. The output coupler M3 was a flat mirror with a transmission of 30% at 1319nm and 43% at 1064nm respectively. The cavity length between M1 and M3 was 37.5 cm for 1319 nm oscillation, and the distance between M2 and M3 was 70.0 cm for 1064 nm oscillation. An acousto-optical Q-switch in the cavity was used to change the continuous output to the pulse with a repetition rate adjustable within the range 1-50 kHz. Because Nd:YAG is an isotropic laser media and emits unpolarized radiation, a Brewster plate was put into the cavity in order to obtain polarized output. The fundamental waves were focused at the centre of PPLT crystal by a lens with a focal length of 100 mm and the beam waists inside the crystal were estimated to be about 80μm. The PPLT sample was embedded in an oven with controlling accuracy of 0.1°C. The generated yellow light was detected with a power meter after the two IR fundamental waves were filtered.

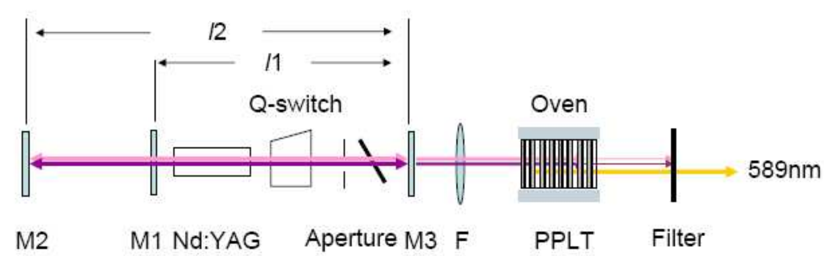

Fig. 2. Schematic experimental setup for yellow light generation.

3. Experimental results and discussion

Firstly we tested the powers and pulse widths of fundamental lights under different repetition rate for a fixed diode current 19A. Both the pulse widths and the average power of fundamental lights increased when the repetition rate increasing from 1 kHz to 5 kHz. The peak power reached its maximum at around 2 kHz for both 1064 and 1319 nm. Then we made a detailed measurement about the power of the generated yellow light under different

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repetition rate. We found during 2 kHz to 3 kHz the average power was high and did not change much. Nevertheless, the crystal may suffer from the high peak power at 2 kHz, so we finally set the repetition rate of Q-switch at 3 kHz. We set the operating current of LD to be 22 A, the output powers of the fundamental IR beams were 1.94 and 1.57 watt for 1064 and 1319 nm, respectively. The pulse widths were 295 and 400 ns for 1064 and 1319 nm respectively, and the pulse width of 589 nm was 292 ns. The temporal overlap of 1064 and 1319 nm has a great impact on the SFG efficiency. In experiment, the pulse width for 1064nm was shorter than 1319 nm under the same pump condition, and that the pulse width of yellow light at 589 nm was almost equal to that of fundamental light at 1064 nm. This means that the pulse at 1064 nm was totally superpose on the pulse of 1319 nm. In order to optimize the overlap of two fundamental pulses, a three-mirror configuration was designed. The two fundamental waves had different cavity-lengths, which could be realized by changing the positions ($l1$ and $l2$) of two cavity mirrors, M1 and M2, respectively. Under the optimum temporal overlap, $l1$ = 37.5 cm and $l2$ = 70.0 cm, the maximum sum-frequency power at 589 nm was 506 mW under fundamental power 3.51 W. The corresponding SFG conversion efficiency was ~5.5% [$W^{-1}cm^{-1}$]. Figure 3 shows the dependence of yellow power on the total power of the fundamental waves at the optimum phase-matching temperature. The insert photo on left-top was the facula of yellow light which exhibited a circular shape with a near Gaussian profile at far field. The insert diagram on right-bottom shows the spectrum of yellow light and the spectral width was 0.16nm.

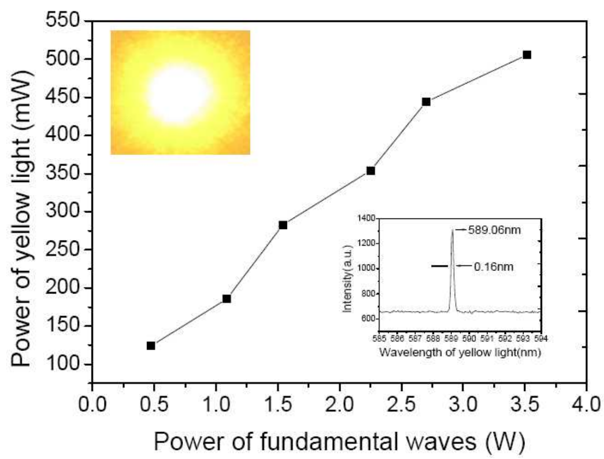

Fig. 3. The dependence of output yellow power on the total fundamental powers. The insert photo on left-top is taken by a digital camera and the insert diagram on right-bottom is the yellow spectrum.

Figure 4 shows the temperature tuning curve of yellow light. The measured phase-matching temperature was 167.3°C with the full width at half maximum (FWHM) of ~1.65°C. This actual phase-matching temperature was deviated from the theoretical design 180°C, and it may result from thermal expansion which deduced the deviation between actual grating period and theoretical calculation. The measured temperature bandwidth was close to the theoretical one (1.2°C) which indicated that the process was phase-matched over the whole length of 30 mm and the refractive index inside the crystal was uniform in the wavelength range.

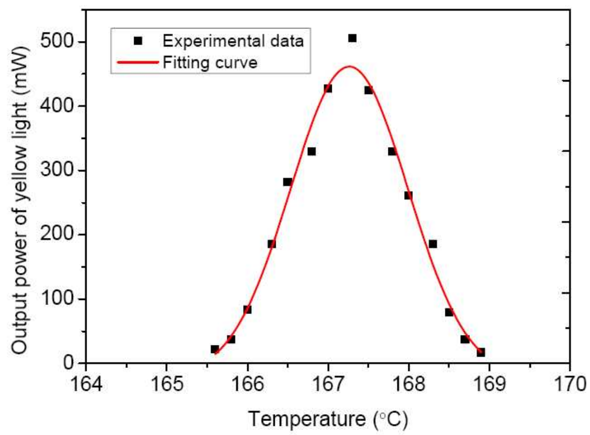

Fig. 4. Measured temperature tuning curve for yellow light. A Gaussian fit is to guide the eye.

The fluctuation of the output power of yellow light (Fig. 5) was measured to be ± 4.5% within 1 h and no photorefractive effect was observed during the period. The main reason leading to this fluctuation was the fluctuations of the fundamental wavelengths, ± 5.4% for 1064 nm and ± 2.2% for 1319 nm. The output power of 1319 nm was more stable than that of 1064 nm, which might ascribe to its smaller emission cross section. Moreover, because the emission of 1064 nm and 1319 nm take the same upper level, $^4F_{3/2}$, therefore, the fluctuation of emission intensities of 1064 nm and 1319 nm are complementary. This relationship favored the stabilization of yellow power that was direct proportion in the product of two fundamental waves. Therefore, the fluctuation of yellow was in fact smaller than that of 1064 nm emission. Optimizing the cavity parameters for raising the stability of output is still under consideration.

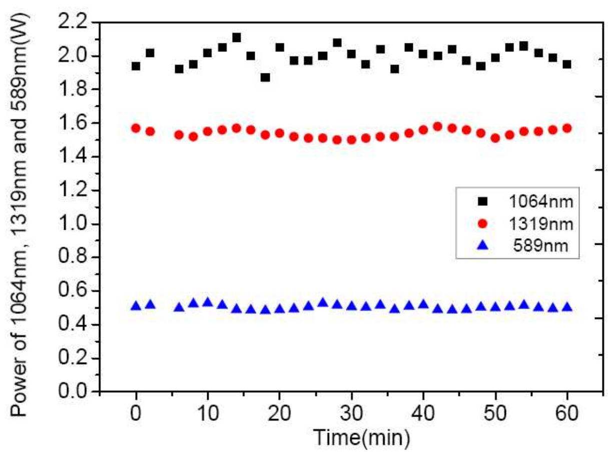

Fig. 5. Power fluctuation of 1064 nm, 1319 nm and 589 nm

The experimental results demonstrate the advantages of the three-mirror-cavity scheme. The first one is that it reduces the complexity of cavity configuration, therefore, the cost constructing a yellow laser source is greatly reduced. Secondly, the linear cavities make sure the colinearity of the fundamental waves, so it is easier to achieve the optimum spatial overlap of the two IR beams. Thirdly, the energy proportion is balanced and the optimum temporal overlap can be achieved by changing the cavity-length ratio $l1/l2$. In summary, this kind of configuration can be used to construct compact, all-solid-state yellow laser source based on efficient sum-frequency generation.

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4. Conclusion

In conclusion, we used a periodically poled $LiTaO_3$ to obtain 589 nm yellow light by single-pass sum frequency generation. The fundamental source was a diode-side-pumped, three-mirror dual-wavelength Q-switched Nd:YAG laser operating at 1064 and 1319 nm. 506 mW of yellow light was obtained with a conversion efficiency of 5.5% $[W^{-1}cm^{-1}]$. The result indicates that this scheme is an attractive way to construct compact all-solid-state 589 nm yellow laser. For further development, optimizing the cavity parameters for more efficient SFG output and using thicker periodically-poled stoichiometric or MgO-doped $LiNbO_3$/$LiTaO_3$ crystals [14] can scale the output to a higher power.

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