Compact yellow-orange Nd: YVO_4/PPMgLN laser at 589 nm*

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We propose and make a compact yellow-orange laser of the Nd-doped yttrium vanadate (Nd: YVO_4)/periodically poled Mg-doped lithium niobate (PPMgLN) module by Raman frequency-doubling at 589 nm. By reasonably designing the size of the Nd: YVO_4 and 5 mol% PPMgLN crystals, cavity length and coating parameter, a compact 589 nm laser module with a total size of 3 mm×10 mm×1.5 mm is fabricated. In the laser module, the input surface of Nd: YVO_4 crystal is end-pumped by an 808 nm laser diode (LD). Under the effect of linear resonant cavity structure, the output surface of PPMgLN crystal with a period of 9.48 μm generates 589 nm yellow-orange light. The experimental results show that the maximum output power at 589 nm is 390 mW at the pump power of 3 W with the optical-optical conversion efficiency of 13% and the stability of the output power is less than 2% within 3 h.

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Yellow-orange light source at 550—600 nm has broad application prospects in biomedicine[1], laser display[2], atmosphere detection[3], high-resolution spectroscopy[4], and adaptive optics[5]. The 589 nm yellow-orange laser plays an important role in sodium laser beacon[6]. The methods to obtain 589 nm light source include Raman fiber technology[7,8], dye laser technology, all-solid-state laser technology by intra-cavity or extra-cavity frequency doubling[9-12]. In recent years, many articles about 589 nm Raman fiber and all solid state yellow-orange lasers have been reported.

In 2004, FENG et al[7] reported a yellow-orange laser at 589 nm based on intra-cavity frequency-doubling of a Raman fiber in a lithium triborate (LBO) crystal with a length of 20 mm. When the pump power was 23 W, the maximum output power was 10 mW with an optical-optical conversion efficiency of 0.8%. In 2009, YUE et al[8] reported a yellow-orange laser at 589 nm based on extra-cavity frequency doubling of an Nd-doped yttrium aluminium garnet (Nd: YAG) laser in a periodically poled Mg-doped lithium niobate (PPMgLN) crystal with a length of 20 mm. The output power was 18 mW at the pump power of 1.15 W with the optical-optical conversion efficiency of 1.57%. In 2016, YUAN et al[9] reported a yellow-orange laser at 589 nm based on intra-cavity sum frequency by a laser diode (LD) pumped two Nd: YAG lasers in a LBO crystal. The maximum output power of 589 nm is 0.102 W with the optical-optical conversion efficiency of 5.1%. In 2021, CHEN et al[10] reported a passively Q-switched yellow laser at 589 nm based on intra-cavity frequency doubling of a c-cut yttrium vanadate (YVO_4)/Nd-doped yttrium vanadate (Nd: YVO_4)/YVO_4 self-Raman laser in a LBO crystal. The average output power was 660 mW at the pump power of 17.5 W with the optical-optical conversion efficiency of 3.8%. In 2022, LI et al[11] reported a compact 589 nm laser based on intra-cavity frequency-doubling of a c-cut YVO_4/Nd: YVO_4/YVO_4 Raman laser in a LBO/barium borate (BBO) crystal. The Cr^{4+}: YAG/YAG crystal was used as a Q-switched crystal. The continuous yellow laser output of 589 nm was 780 mW at the absorbed power of 16.25 W with the optical-optical conversion efficiency of 4.8%. At present, most 589 nm light resources are generated by the sum frequency of nonlinear optical crystals (such as BBO/LBO/$KTiOPO_4$ (KTP)) in the market. Due to the problems of large volume, low nonlinear coefficient, and spatial walk-off in nonlinear crystals, the optical-optical conversion efficiency and beam quality of the all-solid-state laser are not good. However, PPMgLN crystal based on the quasi-phase matching[12] has very high nonlinear coefficients of d_{33} (16—22 pm/V) and doesn't have spatial walk-off[13-15],

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which can realize any wavelength conversion within the light transmission range.

In this paper, we propose and make a small size yellow-orange laser module at 589 nm, and a compact 589 nm laser is packaged by using the laser module. The laser module is composed of Nd: YVO_4, PPMgLN, silicon substrate, and aluminum shell with an overall size of 3 mm×10 mm×1.5 mm, which is very suitable for small-volume lasers.

Nd: YVO_4 laser crystal is a positive uniaxial crystal, belonging to the tetragonal system, and is a laser crystal with excellent performance. PPMgLN crystal belongs to the tetragonal system and has a high second-order nonlinear coefficient (d_{33}=16—22 pm/V), which plays an important role in optical frequency conversion.

The self-Raman process of Nd: YVO_4 in the Nd: YVO_4/PPMgLN module is that under the excitation of 808 nm LD, the crystal will generate an energy level transition ($^4F_{3/2}\rightarrow{}^4F_{11/2}$) and emit the wavelength of 1 066 nm. After the 1 066 nm frequency shift, the first-order strokes wavelength of 1 178 nm can be obtained.

The frequency conversion process of PPMgLN in the Nd: YVO_4/PPMgLN module is that 589 nm yellow-orange light is obtained by the frequency-doubling effect of the PPMgLN crystal. The frequency-doubling process of PPMgLN crystal based on quasi-phase matching technology when the nonlinear frequency conversion can be expressed as

$$\begin{cases}\omega_3=\omega_1+\omega_2\\ \omega_1=\omega_2\end{cases}, \tag{1}$$

whose phase mismatch Δk_{SHG} can be expressed as

$$\Delta k_{SHG}=k_3-2k_1-(2\pi q/\Lambda_{SHG}), \tag{2}$$

where q is the order of the period, q=1, 2, 3, 4, 5, Λ_{SHG} is the poling period, and k_1 and k_3 are the two wave vectors involved in the nonlinear process. $n_i(T, \lambda_i)$ is the refractive index of the two light waves participating in nonlinear process, and Sellmeier equation[16] can be used to calculate as

$$n_i(T,\lambda_i)=(5.756+2.86\times10^{-6}F+\frac{0.098\,3+4.7\times10^{-8}F}{\lambda_i^2-(0.020+6.113\times10^{-8})}+\frac{189.32+1.516\times10^{-4}F}{\lambda_i^2-12.52^2}-1.32\times10^{-2}\lambda_1^2)^{\frac{1}{2}}, \tag{3}$$

where F is the temperature constant, which can be expressed as

$$F=(T-24.5\ ^\circ\mathrm{C})(T+570.82\ ^\circ\mathrm{C}), \tag{4}$$

where T is the temperature of PPLN crystal under normal operation. Δk_{SHG} is the phase mismatch constant, where SHG means second harmonic generation. When $\Delta k_{SHG}\neq0$, phase mismatch situation will occur. In order to meet high energy conversion in the nonlinear frequency-doubling process, it must follow Δk_{SHG}=0.

So the poling period of PPMgLN crystal can be expressed as

$$\Lambda_{SHG}=1/(\frac{n_3(T,\lambda_3)}{\lambda_3}-2\frac{n_1(T,\lambda_1)}{\lambda_1}). \tag{5}$$

The formula of optical frequency-doubling power can be calculated as

$$P_3=\frac{8p_1^2L^2d_{eff}^2\pi^2}{n_1(T,\lambda_1)n_3(T,\lambda_3)c\lambda_1^2\varepsilon_0S_{eff}}\mathrm{sinc}^2\left[\frac{\Delta k_{SHG}(T,\lambda)}{2}L\right], \tag{6}$$

where p_1 is the power at the PPMgLN input surface in the laser module. When Δk_{SHG}=0, the frequency-doubling efficiency of complete conversion can be expressed as

$$\eta=\frac{P_3}{p_1}=\frac{8p_1L^2d_{eff}^2\pi^2}{n_1(T,\lambda_1)n_3(T,\lambda_3)c\lambda_1^2\varepsilon_0S_{eff}}, \tag{7}$$

where c is the speed of light and d_{eff} is the second-order nonlinear constant.

In this paper, the 589 nm laser module is mainly composed of c-cut[17] Nd: YVO_4 laser crystal and z-cut PPMgLN crystal. Among them, the PPMgLN crystal is prepared by applying pulse voltage poling method[18-20]. The preparation processes included lithography mask design, electron beam evaporation coating, lithography, electric field poled, and crystal cutting. The technological processes of PPMgLN wafer are completed within level hundred laboratory, including wafer cleaning, coating, glue throwing, baking, exposure, development, corrosion, poling, and crystal cutting. The single poling period of PPMgLN is taken as 9.48 μm, which is suitable for realizing the frequency conversion of 1 178 nm optical wavelength near 26 °C. According to Eqs.(3) and (5), Fig.1 can be obtained. Fig.1 shows the relationship between the poling period of PPMgLN and temperature. It can be seen that the poling period gradually decreases with the increase in temperature. At the temperature of 26 °C, the poling period of PPMgLN at 589 nm is 9.48 μm.

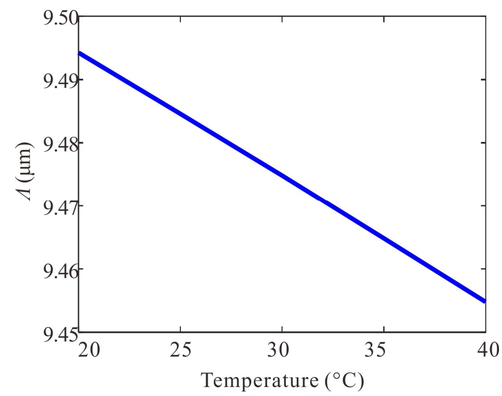
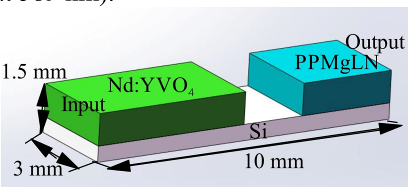
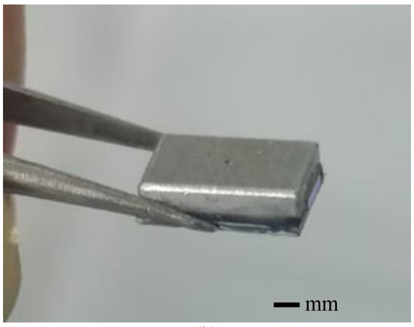


Fig.1 Relationship between the poling period of PPMgLN and temperature

Fig.2 shows the schematic and real diagram of the Nd: YVO_4/PPMgLN module, which is composed of Nd: YVO_4, PPMgLN, silicon substrate, and aluminum shell. Nd: YVO_4 coating parameters are as follows. The S_1 surface of Nd: YVO_4 is coated with 808 nm high transparent film (HT) (T>99.9%), while 1 066 nm fundamental frequency light and 1 178 nm first-order Stokes light high reflection film (HR) (R>99.9% at 1 066 nm, 1 178 nm). The S_2 surface of Nd: YVO_4 is coated with 1 178 nm HT and 589 nm HR (R>95% at 589 nm) for frequency doubling yellow light. The PPMgLN coating parameters are as follows. The S_3 surface of PPMgLN is coated with 1 178 nm HT (T>99.9% at 1 178 nm) and 589 nm HR. The S_4 surface of PPMgLN is coated with 1 178 nm HR (R>99.9% at 1 178 nm) and 589 nm HT (T>95% at 589 nm).



(a)



(b)

Fig.2 (a) Physical schematic diagram and (b) real diagram of Nd: YVO_4/PPMgLN

Fig.3 shows the experimental diagram of the yellow-orange laser module of 589 nm based on intra-cavity Raman frequency-doubling of an LD. The device adopts a straight cavity structure, pumped by an 808 nm LD with an average powerof 3 W, and a laser resonant cavity structure of 1 178 nm is formed between the S_1 surface of Nd: YVO_4 and the S_4 surface of PPMgLN. The temperature controller (CTL-100, precision 0.1 °C) of CTL Photonics Inc. is used to control the temperature of the Nd: YVO_4/PPMgLN laser module. The 589 nm light source is received by the Thorlabs optical power meter.

In order to test the performance of the 589 nm yellow-orange light laser module, we use the experiment structure of Fig.3. Fig.4 shows the output power at 589 nm. When the pump power is 208 mW, yellow-orange light starts to appear. The maximum output power is 390 mW at the pump power of 3 W with the optical-optical conversion efficiency of 13%. As shown in the illustration in Fig.4, it can be clearly seen that the color of the light spot changes from purple to yellow, and the light intensity gradually increases. The curves in the X and Y directions represent the normalized Gaussian distribution field (unit: a.u.) strength of the light spot in the horizontal and vertical directions, respectively. The quality of the laser output spot is nearly round (obtained by the combination of the Spiricon laser test software and the Beam-Gage beam analyzer).

Fig.5 shows the output spectrum of the yellow-orange light module at 589 nm at the pump power of 3 W, with full wave at half maximum ($FWHM$) of about 0.92 nm and a central wavelength of 589.02 nm (measured by the Thorlabs optical fiber spectrometer). Fig.6 shows the relationship between $FWHM$ and pump power. With the pump power increases, the $FWHM$ remains unchanged.

The output power change curve of 589 nm yellow-orange light in the temperature range of 18—38 °C is measured in Fig.7. When the pump power is 3 W and the temperature is around 26 °C, 390 mW yellow-orange light output power is obtained. In addition, there are multiple peaks of variation between 26 °C and 32 °C. The reason for this phenomenon is that the relationship between frequency doubling power and temperature in PPMgLN crystal is exactly with the sinc^2 function curve as shown in Eq.(6). When Δk_{SHG}=0, the conversion efficiency of SHG is the highest and the matching temperature is 26 °C. On the contrary, fluctuations will occur at other temperatures, which is just with the peak change between 27 °C and 30 °C in Fig.6 of the experimental test.

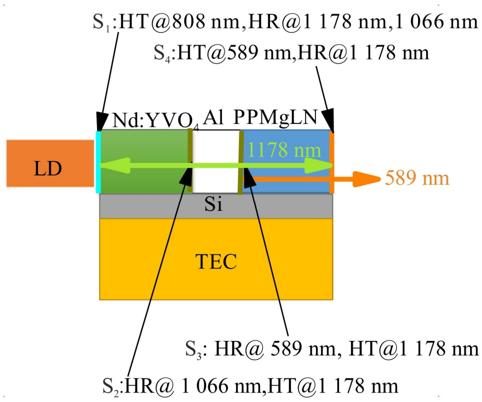


Fig.3 Schematic diagram of the 589 nm yellow-orange laser module based on intra-cavity Raman frequency-doubling of an LD

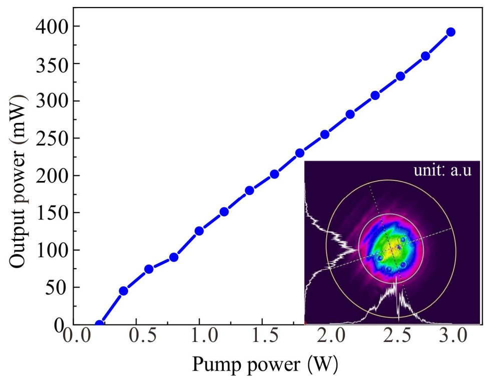


Fig.4 Output power at 589 nm and the spot at 390 mW

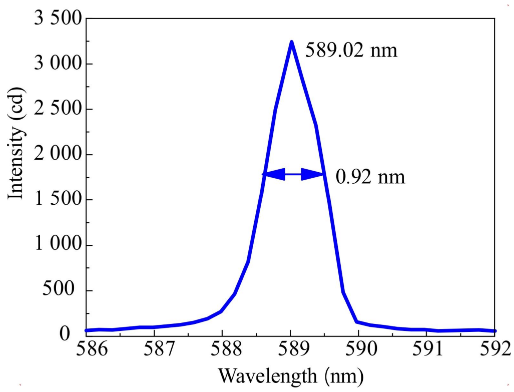


Fig.5 Output spectrum at 589 nm in the pump power of 3 W

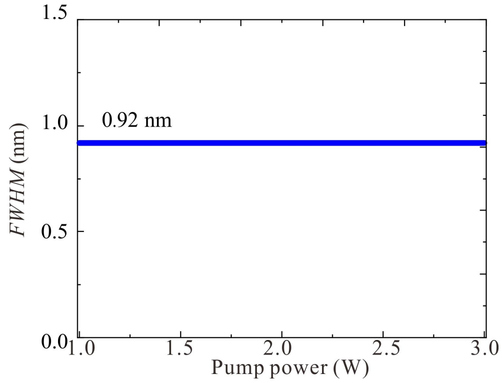


Fig.6 Relationship between *FWHM* and pump power

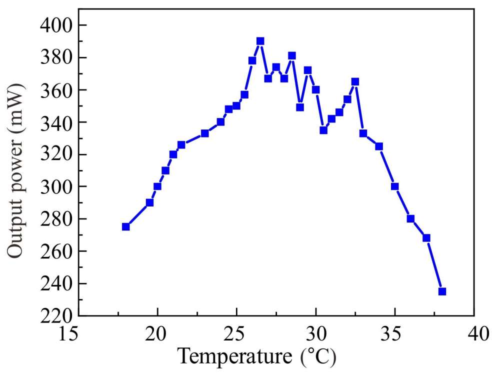


Fig.7 Output power at different temperatures at 589 nm

The power output stability of the 589 nm yellow-orange light laser module at 589 nm is measured in Fig.8. The pump power of an LD is set to 3 W, and the output power change within 3 h is recorded. The power stability is obtained by the Ophir Vega laser power meter, and the stability of the output power is less than 2% within 3 h.

The output characteristics of yellow-orange light are given in Tab.1 at 589 nm. Using a BBO/LBO crystal as the nonlinear crystal[7,9-11], an etalon needs to be inserted into the cavity, so the laser volume at 589 nm is relatively large. However, our work is competitive and valuable for high conversion effciency laser, and the size of the 589 nm laser module is only 3 mm×10 mm×1.5 mm.

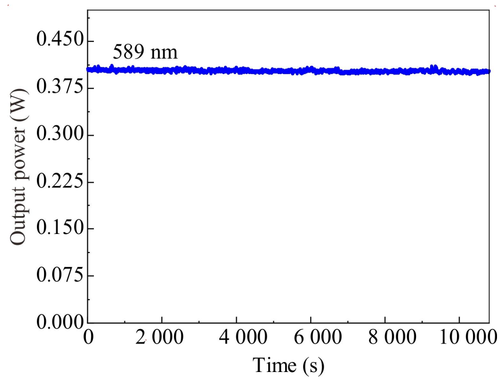


Fig.8 Output power stability at 589 nm

Tab.1 Output characteristics of some 589 nm yellow-orange light

Year	Laser	System stucture	Power	Conversion efficiency
2004[7]	Raman fiber	CW+589+LBO+ intracavity	10 mW	0.8%
2009[8]	Nd: YAG	Single pass+589+PPLN +extracavity	18 mW	1.15%
2016[9]	Nd: YAG	CW+589+LBO+ intracavity	102 mW	5.1%
2021[10]	YVO_4/Nd: YVO_4/ YVO_4	CW+589+LBO+ intracavity	660 mW	3.8%
2022[11]	YVO_4/Nd: YVO_4/ YVO_4	CW+589+LBO/ BBO+intracavity	780 mW	4.8%
Here	589 laser module	CW+589+PPLN +intracavity	392 mW	13%

In conclusion, we proposed and made a compact yellow-orange light laser of the Nd: YVO_4/PPMgLN module by Raman frequency-doubling at 589 nm. To test its performance, the 589 nm laser module was end-pumped by an 808 nm LD. The output power at 589 nm was 390 mW at the pump power of 3 W. The optical-optical conversion rate was 13%, and the stability of the output power was less than 2% within 3 h. The Nd: YVO_4/PPMgLN laser module at 589 nm is a good choice for yellow-orange laser with high conversion efficiency.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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