## Intracavity sum-frequency diode side-pumped all-solid-state generation yellow laser at 589 nm with an output power of 20.5 W

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A laser diode side-pumped all-solid-state pulse laser at 589 nm with high power, high conversion efficiency, and a small volume is demonstrated by intracavity sum-frequency generation. By carefully optimizing the cavity and adopting various techniques, a quasi-cw free oscillation yellow laser source, which has a maximum output power of 20.5 W, a repetition rate of 14.49 KHz, and a pulse width of 157 ns, is developed. The optical-to-optical conversion efficiency is up to 5.11%, and the power stability is better than 2% in 2 h. © 2013 Optical Society of America

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In recent years, a 589 nm yellow laser has been broadly applied to sodium laser guide stars (LGSs) [1], laser radar [2], laser medical [3], and many other fields [4-6]. Much research has been done on 589 nm lasers since the 1990s, and many achievements have been accomplished. There are several methods for obtaining a 589 nm yellow laser, such as using a dye laser [7–9], a Raman fiber amplifier laser [10,11], or an all-solid-state nonlinear sum-frequency laser. Compared with other methods, the all-solid-state 589 nm yellow laser has a much higher efficiency, smaller volume, longer lifetime, and better beam quality, and it has become of the highest interest for this research field [12]. Denman et al. produced a high-power single longitudinal mode laser at 1064 and 1319 nm by inputting a seed laser into a ring cavity to lock the amplification, and a 50 W cw yellow laser at 589 nm was achieved with a resonantly enhanced ring cavity [13]. In 2008, Lockheed Martin Coherent Technologies developed a laser diode (LD)-pumped Nd:YAG laser at

589 nm with an output power of 55 W [14]. Tracy et al. reported a 16.5 W yellow laser at 589 nm in 2009 in which a periodically poled stoichiometric lithium tantalite crystal was adopted as the nonlinear sumfrequency crystal [15]. In 2010, Shirakawa et al. produced 14.5 W radiation at 589 nm by single-pass frequency doubling of an ytterbium-doped photonic bandgap fiber amplifier by a periodically poled MgO-doped stoichiometric lithium tantalite [16]. In the same year, Taylor et al. demonstrated a highpower, narrow linewidth 1178 nm laser by inputting a 1178 nm seed laser into a Raman fiber laser to amplify. After coherently combining a 60 W fundamental beam, they obtained a 589 nm cw yellow laser with a power of 50 W, in which the frequency was doubled by a resonantly enhanced ring cavity [17].

All the methods above use extracavity sum frequency, and the laser system are complicated. Several achievements regarding a high-power 589 nm yellow laser obtained with intracavity sum frequency have also been reported. In 2006, Geng *et al.* demonstrated an average power of 3 W with a 589 nm cw intracavity sum-frequency generation yellow laser with a V-shaped cavity [18], and in 2008, they demonstrated an average power of 8.1 W with a

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repetition rate of 1.1 kHz for an intracavity sumfrequency yellow laser at 589 nm [19]. In 2008, Liang et al. demonstrated an intracavity sum-frequency yellow laser at 589 nm with an average power of 10.5 W and a repetition rate of 5 kHz [20]. In 2011, Changchun New Industries Optoelectronics Technology Corporation reported a 19 W yellow laser at 589 nm [21,22]. Based on the previous research work, an LD side-pumped all-solid-state pulse laser at 589 nm with high power, high conversion efficiency, and a small volume is demonstrated by intracavity sum-frequency generation. By carefully optimizing the cavity and adopting various techniques, a quasi-cw free oscillation yellow laser source, which has a maximum output power of 20.5 W, a repetition rate of 14.49 KHz, and a pulse width of 157 ns, is developed. The optical-to-optical conversion efficiency is up to 5.11%, and the power stability is better than 2% in 2 h.

The schematic of the 589 nm laser is demonstrated in Fig. 1. The laser system consists of two resonators: the  $10\overline{64}$  nm resonator cavity is made up of highreflection mirror M1, beam splitter M3, 589 nm output mirror M4, 589 nm high-reflection mirror M5, acousto-optic (AO) Q-switching for a 1064 nm laser, and a Nd:YAG laser module (A); the 1319 nm resonator is composed of high-reflection mirror M2, beam splitter M3, 589 nm output mirror M4, 589 nm highreflection mirror M5, AO Q-switching for a 1319 nm laser, and a Nd:YAG laser module (B). Mirrors M3, M4, and M5 are shared by the two resonators and thus form the cofolding arm. The yellow laser at 589 nm is generated in the potassium titanyl phosphate (KTP) crystal and outputs from mirror M4. The nonlinear sum-frequency crystal KTP is cut at  $\theta = 78.7^{\circ}$ ,  $\varphi = 0^{\circ}$ , with the dimension of  $6 \text{ mm} \times 6 \text{ mm} \times 9 \text{ mm}$ . It was placed at the composite arm of the two fundamental waves to generate the 589 nm yellow laser.

The laser module consists of a pump source and a Nd:YAG laser crystal. The pump source is homemade and consists of 12 diode bars with an emission wavelength at 808 nm, and they supply the total pump power of 480 W, as shown in Fig. 2. The laser crystal is a 1% Nd<sup>3+</sup>-doped Nd:YAG crystal with dimensions of  $\phi 4 \times 65$  mm that is antireflection coated at 1064 and 1319 nm on both sides. The use of a low doping concentration results in a uniform gain distribution in the Nd:YAG rod and hence can produce a better beam quality.

In order to achieve two linearly polarized fundamental waves at 1064 and 1319 nm that are perpendicular to each other, the special design of the coating condition on beam splitter M3 is adopted. The S1 side of M3 is antireflection coated for the *p*-polarized direction of 1064 nm at an angle of 45° and high-reflection coated for the *s*-polarized direction. The S2 side of M3 is antireflection coated for 1064 nm at an angle of 45°, antireflection coated for the *p*-polarized direction of 1319 nm at an angle of 45°, and high-reflection coated for the *s*-polarized direction. The transmissivity curves of sides S1 and S2 on beam splitter M3 are shown in Figs. <u>3</u> and <u>4</u>, respectively, in which the blue and red curves represent the *p*- and *s*-polarized directions.

There are two strong spectral lines of Nd:YAG around 1.3  $\mu$ m, which are the transitions at 1319 and 1338 nm with the same emission cross section [23]. Therefore, the oscillations of 1338 and 1064 nm should be suppressed in a 1319 nm laser cavity. Special coatings and etalons are adopted to achieve the unique oscillation at 1319 nm. The 1319 nm



Fig. 1. (Color online) Schematic for the intracavity sum-frequency 589 nm Nd:YAG/KTP yellow laser.



Fig. 2. (Color online) Transmissivity of the S1 side of beam splitter M3 of the 589 nm laser.

high-reflection mirror M2 is antireflection coated at 1064 nm and high-reflection coated at 1319 and 1338 nm, and the reflectivity of the 1338 nm line is much lower than that of 1319 nm. The reflection mirror M5 with high parallelism (etalon) is used to make sure that the transmissivity of 1319 nm is a little higher than that of 1338 nm. Therefore the 1319 nm spectral line could oscillate independently, which leads to higher sum-frequency laser power.

The Nd:YAG crystal has different gain and threshold power at the two fundamental waves of 1064 and 1319 nm; therefore, it is rather difficult for the two pulse signals to synchronize in the time domain. The two fundamental pulse waves should be synchronous during the sum-frequency progress to achieve a yellow laser with high conversion efficiency. A synchronous system of electrical signal delay was designed to control the synchronicity of



Fig. 3. (Color online) Transmissivity of the S1 side of M3 of the 589 nm laser.



Fig. 4. (Color online) Transmissivity of the S2 side of M3 of the 589 nm laser.

two fundamental pulse waves, in which the phase difference of the 1064 nm pulse wave and 1319 nm pulse wave could be compensated by adjusting the delay module. In the Nd:YAG crystal, an emission cross section of 1064 nm is much bigger than that of 1319 nm. In order to achieve the same pulse width of the two fundamental generation, we should reduce the pulse width of the 1319 nm laser (the laser cavity of the 1319 nm is 380 mm) and broaden the pulse width of the 1064 nm laser (the laser cavity of 1064 nm is 460 mm) at the same time. By using the optimized laser cavity configuration and driving signal of the AO driver, the best overlap of the 1064 and 1319 nm laser pulses in the time domain was satisfied, which is shown in Fig. 5.

Based on the foregoing work, we optimized the polarization direction of the two fundamental generation parameters of pulse synchronous matching, suppressed mode competition, and developed the



Fig. 5. (Color online) Temporal profile of two synchronous laser pulses.



Fig. 6. (Color online) Photograph of the laser system.

experiment of a high-power 589 nm yellow laser, Figure  $\underline{6}$  is the photograph of the laser system. When the pump currents of 1064 and 1319 nm were 18 and 23 A, respectively, which correspond to the 808 nm pump powers 176 and 225 W, an average power of 20.5 W output laser at 589 nm was obtained, with the repetition rate of 14.49 kHz and the pulse width of about 157 ns. A High Finesse LSA-035 wavelength meter was used to measure the spectrum of the output laser at 589 nm, and a spectral line was simulated through these data, which was inserted into the temporal profile of a single laser pulse (shown in Fig.  $\underline{7}$ ). The optical-to-optical conversion efficiency from the 808 nm pump source to the 589 nm output laser is 5.11%.

Using a PC Link power meter and its test software to measure the real-time laser power, the stability of output power over 2 h is shown in Fig. 8, and the calculated power stability is better than 2%. There are several advantages to this experimental system: it has compact configuration, small volume, and high optical-to-optical conversion efficiency, which is good for industrial development. In-depth research of



Fig. 7. (Color online) Temporal profile and spectrum of yellow (589 nm) output pulse.



Fig. 8. (Color online) Power stability of the output laser over 2 h.

beam quality and linewidth will be concentrated on in future work to obtain a 589 nm yellow laser with high intensity and narrow linewidth.

In conclusion, an LD side-pumped all-solid-state pulse laser at 589 nm with high power, high conversion efficiency, and a small volume is demonstrated by intracavity sum-frequency generation. By carefully optimizing the cavity and adopting various techniques, a quasi-cw free oscillation yellow laser source, which has a maximum output power of 20.5 W, a repetition rate of 14.49 kHz, and a pulse width of 157 ns, is developed. The optical-to-optical conversion efficiency is up to 5.11%, and the power stability is better than 2% in 2 h.

In the coming months we will work on improving the power scaling, narrow linewidth, and beam quality of intracavity sum-frequency generation at 589.159 nm, which will be applied to LGS.

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