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LASERS
AND THEIR APPLICATIONS

All-Solid-State Side-Pumped Intracavity Sum Frequency Generation Yellow Laser at 589 nm with the Output Power of 11.4 W[1]

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Abstract—A laser diode side pump all-solid-state pulse laser at 589 nm with high power and high conversion efficiency and small volume is demonstrated by intracavity sum frequency generation. By optimizing the cavity and adopting etalon techniques, a quasi continuous wave at 589 nm laser source, which has a maximum output power of 11.4 W, a repetition rate of 5 kHz, and a pulse width of 135 ns, is developed. The optical to optical conversion efficiency is up to 6.5% and the power stability is better than 2% in 8 hours.

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INTRODUCTION

In recent years, 589 nm yellow laser has been broadly applied to sodium laser guide star, laser radar, laser medical, city view, stage performances, defense and military and many other fields. Many research on 589 nm laser started since 1990s and many achievements have been accomplished. There are several methods to obtain 589 nm yellow laser, such as dye laser [1–3], Raman fiber amplifier laser [4, 5], and all-solid-state nonlinear sum-frequency laser. Compared with other methods, the all-solid state 589 nm yellow laser has much higher efficiency, smaller volume, longer lifetime, and better beam quality, and it becomes the hottest interest of this research field [6]. Denman et al. produced high power single longitudinal mode laser at 1064 nm and 1319 nm by inputting a seed laser into a ring cavity to lock the amplification, and 50 W continuous-wave yellow laser at 589 nm was achieved by a resonantly enhanced ring cavity [7]. In 2008, Lockheed Martin Coherent Technologies developed a LD pumped Nd:YAG laser at 589 nm with the output power of 55 W [8]. Tracy et al. reported a 16.5 W yellow laser at 589 nm in 2009, in which a PPSLT crystal was adopted as the nonlinear sum-frequency crystal [9]. In 2010, Olausson et al. produced 14.5 W radiation at 589 nm by single-pass frequency doubling of ytterbium-doped photonic bandgap fiber amplifier by a PPMgSLT[10]. At the same year, Taylor et al. demonstrated a high power, narrow linewidth 1178 nm laser by inputting 1178 nm seed laser into a Raman fiber laser to amplify. After coherently combining 60 W fundamental beam, they obtained 589 nm continuous-wave yellow laser with the power of 50 W, in which the frequency was doubled by a resonantly enhanced ring cavity [11].

All the methods above are using extracavity sum-frequency, and the laser system are complicated. High power 589 nm yellow laser obtained by intracavity sum-frequency has rarely been reported till now. In 2008, Liang X.B. et al. demonstrated a intracavity sum-frequency yellow laser at 589 nm with the average power of 10.5 W and the repetition rate of 5 kHz [12]. In 2011, Changchun New Industries Optoelectronics Technology Corporation reported a 19 W yellow laser at 589 nm [13, 14]. Based on the previous research work, a laser diode side pump all-solid-state pulse laser at 589 nm with high power, high conversion efficiency and small volume is demonstrated by intracavity sum frequency generation. By carefully optimizing the cavity and adopting various techniques, a quasi continuous wave free oscillation yellow laser source, which has a maximum output power of 11.4 W, a repetition rate of 5 kHz, and a pulse width of 135 ns, is developed. The optical to optical conversion efficiency is up to 6.5% and the power stability is better than 2% in 8 hours.

EXPERIMENTAL SETUP

The schematic of the 589 nm laser is demonstrated in Fig. 1. The laser system consists of two resonators: the 1064 nm resonator cavity is made up of high-

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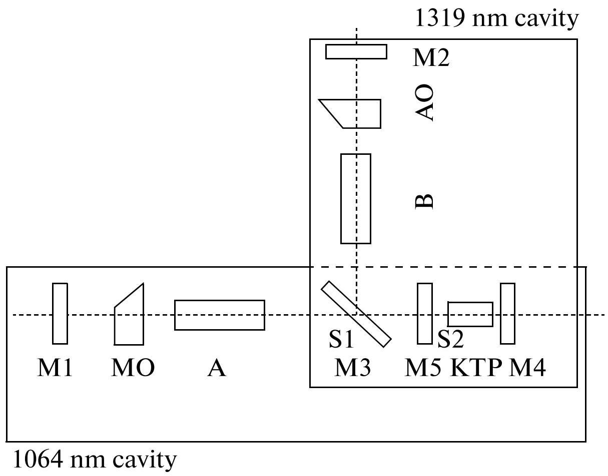

Fig. 1. Schematic for the intracavity sum-frequency 589 nm Nd:YAG/KTP yellow laser.

reflection mirror M1, beam splitter M3, 589 nm output mirror M4, 589 nm high-reflection mirror M5, acousto-optic Q-switching for 1064 nm laser, and 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 high-reflection mirror M5, acousto-optic Q-switching for 1319 nm laser, and Nd:YAG laser module (B). The mirrors M3, M4 and M5 are shared by the two resonators and thus form the co-folding-arm. The yellow laser at 589 nm is generated in the KTP crystal and outputs from the mirror M4. The nonlinear sum-frequency crystal KTP is cut at $\theta = 78.7°$, $\varphi = 0°$ with the dimension of $6 \times 6 \times 10$ mm^3. It was placed at the composite arm of the two fundamental waves to generate the 589 nm yellow laser. The laser module consists of pump source and laser crystal. The pump source consists of twelve diode bars with emission wavelength at 808 nm, and they supply the total pump power of 480 W. The laser crystal is a 1% Nd^{3+} doped Nd:YAG crystal with dimension of $\varphi 4 \times 65$ mm, and antireflection coated at 1064 nm and 1319 nm on both sides. The use of low doping concentration results in a uniform gain distribution in Nd:YAG rod hence can produce a better beam quality.

In order to achieve two linearly polarized fundamental waves at 1064 nm and 1319 nm which is perpendicular with each other, the special design of coating condition on beam splitter M3 is adopted. S1 side of M3 is antireflection coated for *p*-polarized direction of 1064 nm at the angle of 45° and high-reflection coated for *s* polarized direction. S2 side of M3 is antireflection coated for 1064 nm at the angle of 45°, antireflection coated for *p* polarized direction of 1319 nm at the angle of 45°, and high-reflection coated for *s* polarized direction. The transmissity curves of side S1 and S2 on beam splitter M3 are shown in Fig. 2 and Fig. 3, respectively in which blue and red curve represent *p* and *s* polarized direction.

There are two strong spectral lines of Nd:YAG around 1.3 μm which is the transition at 1319 nm and 1338 nm with the same emission cross-section [15]. Therefore, the oscillation of 1338 nm and 1064 nm should be suppressed in 1319 nm laser cavity. Special coatings and etalons are adopted to achieve the unique oscillation at 1319 nm. The 1319 nm high-reflection mirror M2 is anti-reflection coated at 1064 nm and high-reflected coated at 1319 nm and 1338 nm, and the reflectivity of 1338 nm line is much lower than that

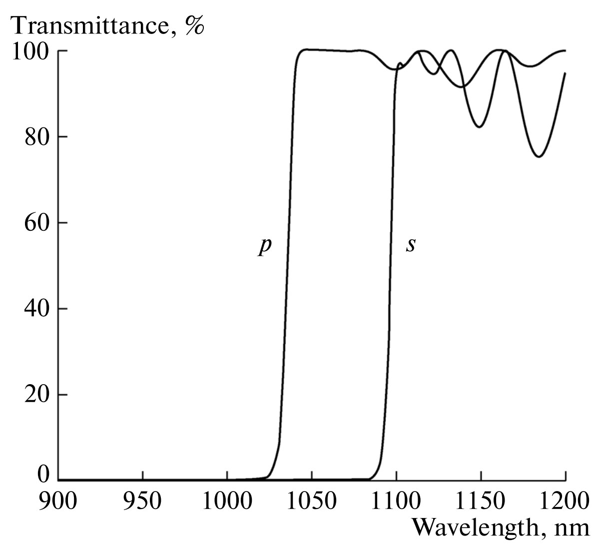

Fig. 2. Transmissivity of S1 side of M3, *s*- and *p*-polarizations.

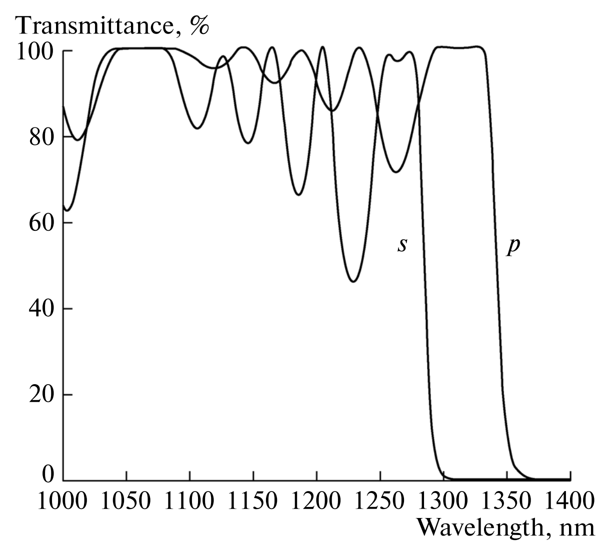

Fig. 3. Transmissivity of S2 side of M3, *s*- and *p*-polarizations.

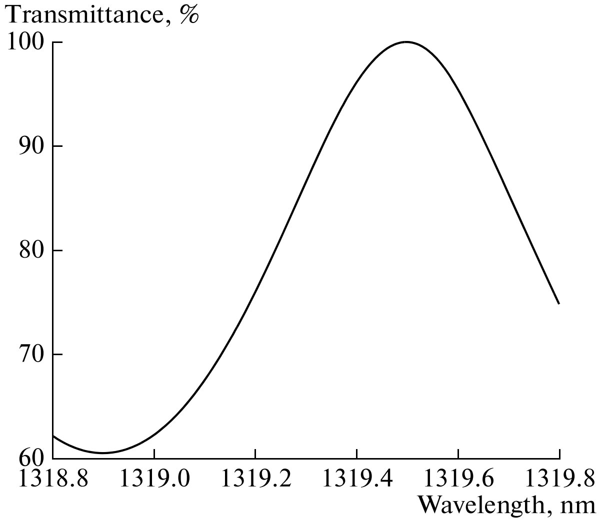

Fig. 4. Transmissivity of etalon around 1319 nm.

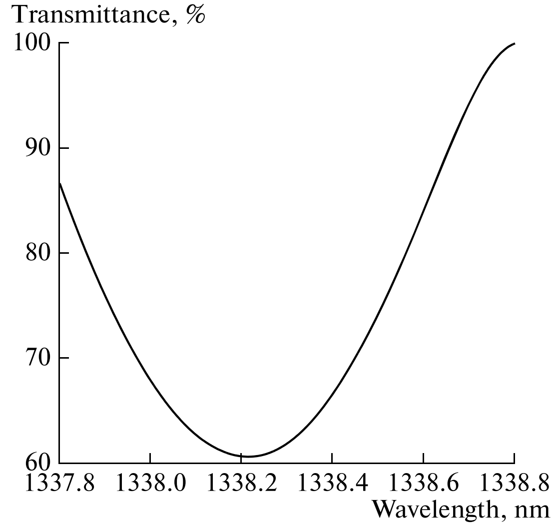

Fig. 5. Transmissivity of 0.8 mm etalon around 1338 nm.

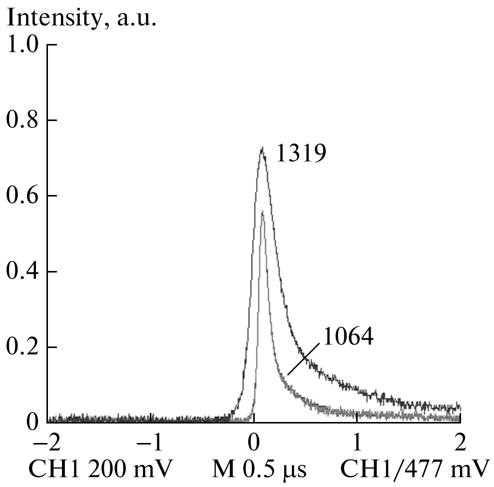

Fig. 6. Temporal profile of two synchronous laser pulses at 1064 and 1319 nm.

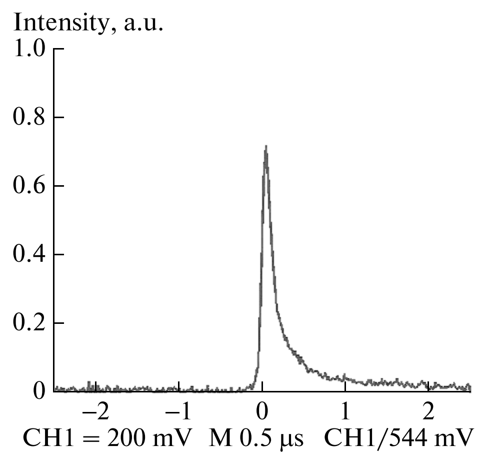

Fig. 7. Temporal profile of a single pulse at 589 nm.

of 1319 nm. The reflection mirror M5 with high parallelism is used to make sure that transmissivity of 1319 nm is a little higher than that of 1338 nm, shown in Fig. 4 and Fig. 5. It can be seen from the figures that loss of 1338 nm is higher than that of 1319 nm in laser cavity, and the 1338 nm line was suppressed, therefore 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 wave of 1064 nm and 1319 nm, therefore, it is rather difficult for the two pulse signals to synchronize in time domain. The two fundamental pulse wave should be synchronous during the sum-frequency progress to achieve Q-switched yellow laser with high conversion efficiency. A synchronous system of electrical signal delay was designed to control the synchronous of two fundamental pulse wave, in which phase difference of 1064 nm pulse wave and 1319 nm pulse wave could be compensated by adjusting the delay module. In Nd:YAG crystal, 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 1319 nm (the laser cavity of 1319 nm is 300 mm), and broaden the pulse width of 1064 nm (the laser cavity of 1064 nm is 410 mm) at the same time. By using the optimized laser cavity configuration and driving signal of Q-switcher, the best overlap of Q-switched 1064 nm and 1319 nm laser pulse in time domain was satisfied, which is shown in Fig. 6.

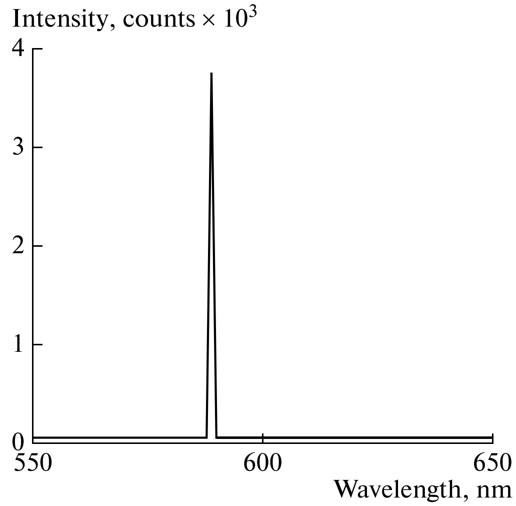

Fig. 8. Spectrum of the output laser at 589 nm.

RESULTS AND DISCUSSIONS

Based on the foregoing work, we optimized the polarization direction of the two fundamental generation, parameters of pulse synchronous matching, and suppressed mode competition, and developed the experiment of high power 589 nm yellow laser. When the pump current of 1064 nm and 1319 nm were 9 A and 12 A, respectively, which are corresponding to the 808 nm pump power 100 W and 120 W, an average power of 11.4 W output laser at 589 nm was obtained, with the repetition rate of 5 kHz and the pulse width of about 135 ns. The temporal profile of single laser pulse is shown in Fig. 7. The optical-to-optical conversion efficiency from 808 nm pump source to 589 nm output laser is 6.5%.

A High Finesse LSA-035 wavelength meter was used to measure the spectrum of output laser at 589 nm, which is shown in Fig. 8. There are several advantages of 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 beam quality and linewidth will be concentrated on in future work to obtain 589 nm yellow laser with high intensity and narrow linewidth.

CONCLUSIONS

In conclusion, a laser diode side pump all-solid-state pulse laser at 589 nm with high power, high conversion efficiency and small volume is demonstrated by intracavity sum frequency generation. By carefully optimizing the cavity and adopting various techniques, a quasi continuous wave free oscillation yellow laser source, which has a maximum output power of 11.4 W, a repetition rate of 5 kHz, and a pulse width of 135 ns, is developed. The optical to optical conversion efficiency is up to 6.5% and the power stability is better than 2% in 8 hours.

ACKNOWLEDGMENTS

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