33 W quasi-continuous-wave narrow-band sodium D_{2a} laser by sum-frequency generation in LBO

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We demonstrate an all-solid quasi-continuous-wave (QCW) narrow-band source tunable to sodium D_{2a} line at 589.159 nm. The source is based on sum-frequency mixing between lasers at 1064 nm and 1319 nm in a LBO crystal. The 1064 nm and 1319 nm lasers are produced from two diode side-pumped Nd:YAG master oscillator power amplifier (MOPA) laser systems, respectively. A 33 W output of 589 nm laser is obtained with beam quality factor $M^2 = 1.25$, frequency stability better than ±0.2 GHz and linewidth less than 0.44 GHz. A prototype 589 nm laser system is assembled, and a sodium laser guided star has been successfully observed in the field test.

Keywords: sodium beacon laser, sum-frequency mixing, Nd:YAG laser, diode pumped solid-state laser

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1. Introduction

589 nm lasers, happening to correspond with the D_{2a} absorption line of sodium atoms in the mesosphere, can be used for adaptive optics (AO) systems.[1] Recently, two main designs for generating this wavelength have been developed, i.e., the sum frequency generation (SFG) of all solid state Nd:YAG lasers[2–7] and the frequency doubling technology of Raman fiber amplifier.[8,9] For examples, Denman *et al.* provided a continuous wave (CW) laser for Starfire Optical Range. With SFG, they developed a 50 W single frequency, diffraction limited 589 nm beam from injection-locked ring Nd:YAG lasers of 1064 nm and 1319 nm.[4,5] Also, Hankla *et al.* developed commercial mode-locked solid state sodium beacon guide star laser systems for Gemini North, Keck I and Gemini South telescopes, respectively. The maximum output power of these systems has exceeded 50 W.[6] Taylor *et al.* developed a 50 W CW 589 nm laser for European Southern Observatory via frequency doubling of three coherently combined narrow-band Raman fiber amplifiers.[8,9]

Comparing with these sodium beacon lasers operating at CW mode, those operating at quasi continuous wave (QCW) mode can provide a gateable pulse mechanism to eliminate the interference of atmospheric Rayleigh scattering and therefore reduce the stretching phenomenon of the imaging spot for sodium guide stars, so the astronomical adaptive optical telescopes can achieve better correction effect and higher resolution observation images. On the other hand, high peak powers of mode-locked lasers would provide high absorption saturation of sodium atoms in the mesosphere. Therefore, high duty cycle QCW laser sources are preferable.[10] In this letter, we report a high power QCW tunable yellow laser system at 589.159 nm. Two high power, high beam quality, narrow linewidth diode side-pumped Nd:YAG master oscillator power amplifier (MOPA) laser systems at 1064 nm and 1319 nm were developed as the fundamental pump sources. A 33 W 589 nm laser was obtained from single-pass SFG in a LBO crystal with beam quality factor M^2 of 1.25, frequency stability better than ±0.2 GHz and linewidth less than 0.44 GHz. By adjusting the angle of Fabry–Perot etalon inserted in the 1064 nm oscillator, the wavelength was tuned to the sodium D_{2a} line. To the best of our knowledge, this is the highest-power QCW source at 589 nm.[2,3,7]

2. Experimental setup

The experimental configuration of the 589 nm laser is shown in Fig. 1. We employed two MOPA schemes for 1064 nm and 1319 nm, respectively. In order to obtain narrow-linewidth lasers, two unidirectional three-mirror ring

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traveling-wave cavities were adopted for both oscillators of 1064 and 1319 nm. Since the 1064 and 1319 nm oscillators shared the same structure, only the 1064 nm oscillator was presented in detail. LM1 and LM2 were laser diode (LD) side-pumped Nd:YAG laser modules. In fact, in all ten laser modules of the system, each Nd:YAG rod was side-pumped by three LD arrays at 808 nm in three-fold symmetric directions. The maximum available pump power of each laser module was 240 W under the repetition rate of 500 Hz and a pulse width of 180 μs. The Nd:YAG rods (Φ 3 mm × 80 mm) were doped with 0.6% of Nd^{3+}. Meanwhile, both end faces of each rod were antireflection (AR) coated at 1064 nm. Two convex mirrors M1 and M2, which were high-reflectance (HR) coated at 1064 nm, and had a radius of curvature of 1000 mm, which result in improvement of the output power and the beam quality due to that fact that it increase the fundamental mode volume and higher order diffraction loss.[11] A thin film polarizer P1 at Brewster's angle was used as the output coupler to select the polarization state, and the output coupling ratio of cavity could be optimized by rotating the half-wave (HW) plate to tune the polarization of oscillating light. A 90° quartz rotator QR1 located between the two laser modules was used to compensate the thermally induced birefringence. The oscillator operated unidirectional by the combination of P1, HW and a Faraday rotator FR. A Fabry–Perot etalon FP, whose temperature was controlled by a temperature controller with a precision of ±0.1 °C, was inserted in the cavity. Moreover, the angle of the etalon was controlled by a stepper motor. For the 1319 nm oscillator, only the coatings were different from that of the 1064 nm oscillator.

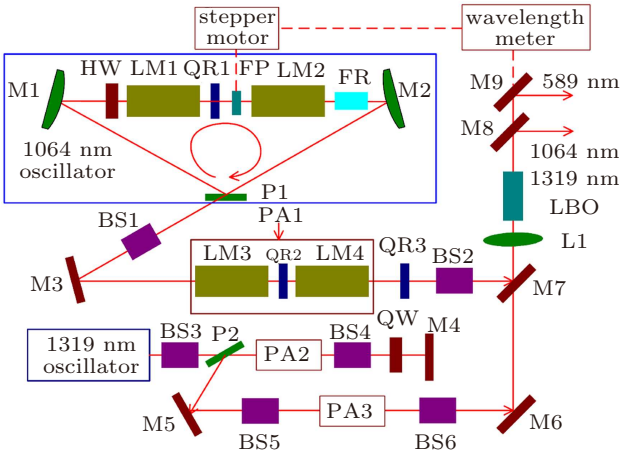


Fig. 1. (color online) Experimental configuration of 589 nm laser.

The output of each oscillator was directed to its respective amplifier after beam shapers BS1 and BS3. The beam of 1064 nm oscillator was amplified by single passing power amplifier PA1 composed of two laser modules LM3, LM4, and a 90° quartz rotator QR2. Theoretically, SFG of a photon at 1319 nm and a photon at 1064 nm would produce a photon at 589 nm and it corresponds to a power ratio of 1.24:1 between the 1064 nm and 1319 nm output. Because the stimulated emission cross section of 1319 nm line was lower, two stages of power amplifiers were adopted. In the first stage, the 1319 nm output of the oscillator was amplified by double passing power amplifier PA2. A quarter-wave plate QW was used to adjust the polarization of the laser beam to make sure the laser output is vertically (s-) linear-polarized from the polarizer P2 after passing the first amplifier twice. The beam shaper BS4 was used to achieve mode matching when the 1319 nm laser passed PA2 the second time. After overpassing the beam shaper BS5, the 1319 nm laser was amplified by single passing the second stage of amplifier PA3. The PA2 and PA3, similar to PA1, contained two laser modules and a 90° quartz rotator, respectively.

Lithium triborate (LBO) supplied by Shandong university of China was chosen as the nonlinear material for SFG based on its low absorption, high damage threshold, and non-critical type-I phase matching at a low phase-matching temperature (40 °C). The LBO crystal (4 mm × 4 mm × 60 mm, $\theta = 90°$ and $\varphi = 0°$) was AR coated at 1064 nm, 1319 nm, and 589 nm on both faces. A 90° quartz rotator QR3 was used to make the polarization of the 1064 nm beam from the amplifier consistent with that of the 1319 nm beam. After beam shapers BS2 and BS6, the collimated and expanded fundamental beams were combined into the LBO crystal with a dichroic mirror M7 and a Lens L1 whose focal length was 150 mm to generate 589 nm light. The SFG beam was separated from two fundamental beams by a dichroic mirror M8, which was HR coated at 1064 nm and 1319 nm, and AR coated at 589 nm.

3. Experiment and discussion

The oscillator was operated at the border of the thermally near-unstable resonator in order to obtain high output power and high beam quality.[12] The cavity length of the oscillator was designed by using ABCD ray propagation matrix based on the accurate measurement of the thermal focal lengths of the Nd:YAG rods.[13] The etalon was used to suppress the linewidth and select appropriate laser wavelength. The wavelength of the laser can be adjusted accurately by controlling the temperature and angle of the etalon. When the temperature was controlled at a fixed value by a temperature controller, the wavelength can be tuned by fine-adjusting the angle of the etalon. The wavelength of the laser changes with the angle according to[14]

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\theta} = -\lambda \tan\theta, \tag{1}$$

where λ is the wavelength of the laser, and θ is the incidence angle at the etalon. When the wavelength of 1319 nm was fixed, the wavelength of 589 nm could be tuned by adjusting

the angle of the etalon inserted in the 1064 nm oscillator. Under the repetition rate of 500 Hz, the average output powers were measured to be 61 W at 1064 nm under pump power of 247 W and 21.7 W at 1319 nm under pump power of 257 W. The corresponding optical to optical efficiency was 24.7% and 8.4%, respectively. The beam-quality factor was measured by a beam quality analyzer (M^2-200, Spiricon Inc.) and it was $M_x^2 = 1.15$ in horizontal axis and $M_y^2 = 1.15$ in vertical axis for 1064 nm, and $M_x^2 = 1.16$ and $M_y^2 = 1.24$ for 1319 nm, respectively.

After amplifier, the average output power at 1064 nm was amplified to 90.3 W under pump power of 276 W with $M_x^2 = 1.35$ and $M_y^2 = 1.35$, and the average output power at 1319 nm was amplified to 59.8 W under pump power of 576 W with $M_x^2 = 1.34$ and $M_y^2 = 1.52$. The extraction efficiency of 1064 nm and 1319 nm amplifiers were 10.6% and 6.6%, respectively.

Single-pass SFG in LBO crystal was employed because the conversion efficiency is high enough for the high peak intensity of QCW lasers. The optimal beam waists in the crystal were calculated to be $\omega_{1064} = 47$ μm, $\omega_{1319} = 53$ μm.[15] To increase the SFG efficiency, the temporal overlap of the fundamental beams should be optimized. A digital pulse generator (DG1022, RIGOL Inc.) with two output channels was used to trigger the LD power supply for the two fundamental beams, while the fine pulse overlap of the two beams was achieved by adjusting the delay between the two channels with an accuracy of 1 μs. The maximum output power of 589 nm laser was measured to be 33 W, corresponding to the SFG conversion efficiency of 22%.

The beam quality of 589 nm laser is measured to be $M^2 = 1.25$ ($M_x^2 = 1.25$ and $M_y^2 = 1.25$), as shown in Fig. 2. It exhibited the TEM_{00} Gaussian mode. The pulse repetition rate and the pulse profile of the 589 nm laser were measured by a fast photo detector (DET025A, Thorlabs, rise time 150 ps) and a 1 GHz bandwidth digital oscilloscope (DPO 4104, Tektronix). The pulse train and an expanded shape of a sub pulse train were shown in Fig. 3. It indicated that the pulse repetition rate and the width of sub-pulse-train were 500 Hz and 105 μs, respectively.

The wavelength and linewidth of the 589 nm beam was measured with a wavelength meter (WS-7, HighFinesse GmbH). When the frequency was walked away from the central frequency of the sodium D_{2a} line, an error signal would be generated and fed back to the stepper motor to tune the angle of etalon inside the 1064 nm oscillator. Figure 4 shows that the central wavelength of the laser located at 589.159 nm. The wavelength stability was determined to be better than ±0.23 pm and the linewidth at FWHM was less than 0.5 pm, corresponding to that the frequency stability was better than ±0.2 GHz and linewidth was less than 0.44 GHz.

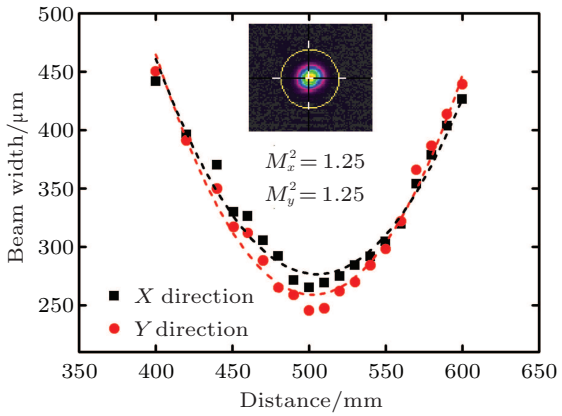


Fig. 2. (color online) Measurement of beam quality M^2 for the 589 nm laser.

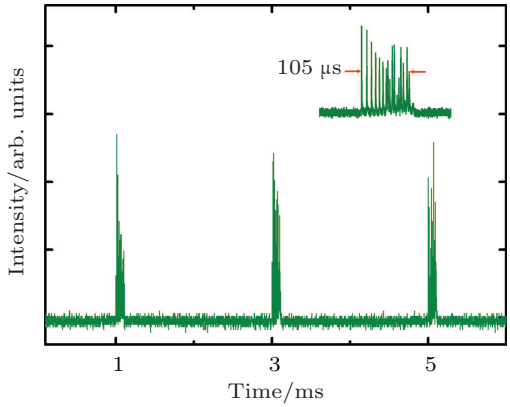


Fig. 3. (color online) Typical oscilloscope trace of 589 nm laser. Inset of top right corner: expanded shape of a sub-pulse train.

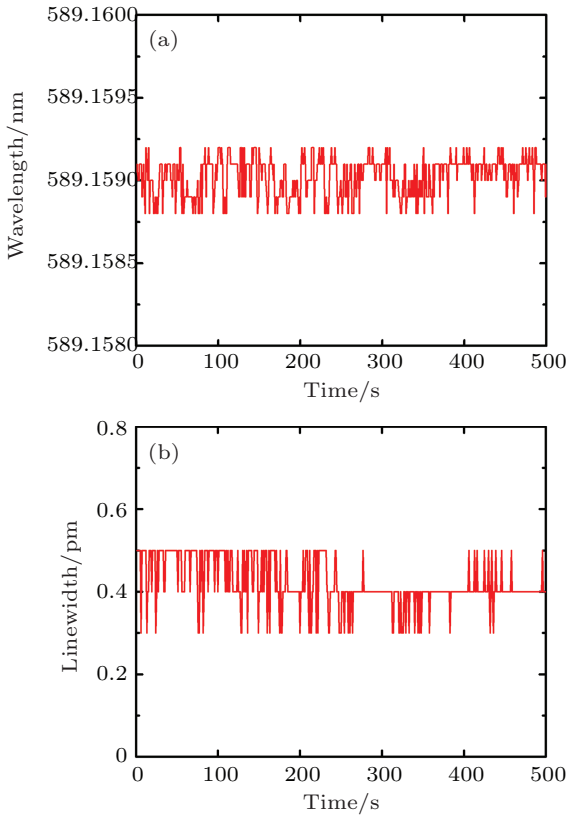


Fig. 4. (color online) Measurement of wavelength and linewidth of 589 nm laser: (a) wavelength and (b) linewidth.

With such a laser system the imaging accuracy of astronomical telescopes is expected be improved to 6 to 7 times by reducing Rayleigh scattering and the spot elongation of sodium laser guided star. A prototype of this laser system was assembled and a sodium laser guided star has been successfully observed in the field test.

4. Conclusion

In summary, we demonstrated a laser system of sodium D_{2a} around 589 nm operated at QCW mode. The 589-nm laser was generated by a single-pass SFG in a LBO crystal by mixing two laser beams at 1064 nm and 1319 nm. The maximum output power is 33 W at 589.159 nm with beam quality factor $M^2 = 1.25$, frequency stability better than ± 0.2 GHz and linewidth less than 0.44 GHz.

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