All solid-state sum-frequency generation of 1.12-W continuous-wave laser at 588 nm

Yanfei Lü (吕彦飞), Xihe Zhang (张喜和), and Zhihai Yao (姚治海)

Department of Physics, Changchun University of Sciences and Technology, Changchun 130022

Received December 20, 2006

A new resonator design for doubly resonant continuous-wave (CW) intracavity sum-frequency mixing (SFM) is reported. 1.12 W of coherent radiation at 588 nm is generated by mixing 1062-nm Nd:GdVO$_4$ laser and 1319-nm Nd:YAG laser. The optical-to-optical conversion efficiency is up to 3.7%.

OCIS codes: 140.3480, 140.3580, 140.3530, 190.7070.

Coherent continuous wave (CW) light sources in the visible spectral range have become interesting for many technical applications in medicine, lithography, communications, display, and so on. Recently, frequency-doubled, diode-pumped Nd^{3+} lasers have been established as compact, efficient, all-solid-state sources in the blue, green, and red spectral regions[1−3]. Unfortunately, radiation in the spectral region between 550 and 650 nm cannot be generated with second-harmonic generation because of the absence of efficient fundamental lasers. However, radiations near 620 and 590 nm are required for display technology and medical applications, respectively. Therefore, other ways of generating coherent light at these wavelengths have to be found. One possibility is sum-frequency generation (SFG), in which coherent frequencies of ω_1 and ω_2 are mixed, generating radiation of frequency $\omega_3 = \omega_1 + \omega_2$.

Yellow light generation has attracted increased attention in the recent years. The laser has been required in many applications, such as medicine, lidar measurement in the atmosphere, and such source for creating guide stars through resonance fluorescence in the mesosphere sodium layer. An interesting coincidence is that the sum frequency of two lines of Nd:YAG lasers operating near 1064 and 1319 nm may be made resonant with the sodium D2 transition wavelength. In 1994, Danailov confirmed the possibility of producing 589-nm light by an intracavity SFG in an Nd:YAG laser, operated simultaneously at two lines 1064 and 1319 nm[4]. After this, Nd:YAG lasers have already been used for the SFG of yellow light both *Q*-switched and CW[5−7]. CW SFG is of interest especially because of its potential to yield very narrowband radiation[6]. Moreover, intracavity frequency mixing with a nonlinear optical crystal exploits higher intracavity intensities and ensures a high degree of spatial overlap between the beams[8]. However, high power CW yellow light was yielded only by co-folding-arm plane-plane symmetrical L-shaped Nd:YAG laser[9], when the incident pumping power was 558 W, the yellow output power was 3.23 W, with low efficiency and complicated structure, it is not suitable for commercial production. In this letter we propose a doubly resonant intracavity approach to sum-frequency laser at 588 nm with output power of 1.12 W, with high conversion efficiency.

The schematic of the experimental setup is shown in Fig. 1. The doubly resonator consists of one shared and two separated arms. The separated arms include the laser crystals and independent alignment of the lasers, which are joined with a diachronic beam splitter (M1).

Nd:GdVO$_4$ at 1062 nm and Nd:YAG at 1319 nm were chosen as laser materials for mixing into the yellow spectrum at the 588-nm wavelength. The Nd:GdVO$_4$ crystal with dimension of $3 \times 3 \times 6$ (mm) was 1% Nd^{3+} doping, *a*-axis cut off. One side of Nd:GdVO$_4$ was coated anti-reflection (AR) at 808 nm and high-reflection (HR) at 1062 nm and other side was AR at 1062 nm. The Nd:YAG ($\phi 4 \times 3$ (mm)) was 1% Nd^{3+} doping. One side of Nd:YAG was coated AR at 808 nm and HR at 1319 nm and the other side AR at 1319 nm. In addition, considering that the stimulated emission cross section at 1319 nm (0.43×10^{-19} cm^2)[10] is estimated to be $\sim 10\%$ of that at 1064 nm (4.6×10^{-19} cm^2)[8] and quantum efficiency at 1319 nm is also lower than that at 1064 nm, the HR coating of the Nd:YAG crystal was also of low reflectance near 1064 nm to avoid laser oscillation at this wavelength. One side of M1 ($\rho = \infty$) was coated AR for the vertically polarized 1319-nm field and the other side was HR for the parallel polarized 1064-nm field and AR for the vertically polarized 1319-nm field. Concave mirror M2 ($\rho = 200$ mm) was coated HR at both 1062 and 1319 nm and AR at 588 nm and other side was AR at 588 nm. One side of M3 ($\rho = 50$ mm) was coated HR at 1062, 1319, and 588 nm. The laser crystals were wrapped with indium foil and mounted in a semiconductor cooled copper blocks. KTP has to be critically phase-matched for type II SFG. Calculated by SNLO[11], a $2 \times 2 \times 5$ (mm) flux grown KTP crystal cut at $\theta = 78.8°$, $\varphi = 0°$ is located in the shared arm. This device permits type II critical phase-matching for 1062 nm (o-light) and 1319 nm (e-light), producing 588 nm

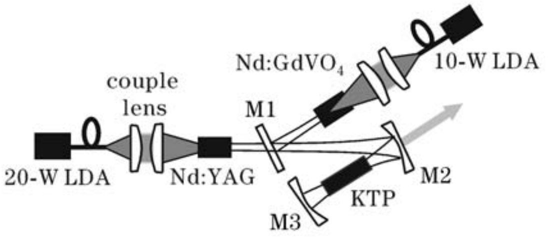

Fig. 1. Experimental setup of yellow laser.

(o-light). A high effective nonlinear coefficient of $d_{\text{eff}} = 3.43$ pm/V, and relatively small 19-mrad walk-off angle of the 1319-nm beam from the phase-matching direction are expected. Two ends of KTP were coated AR at 1062, 1319, and 588 nm. Two pump sources used in the experiment were commercially available fiber-coupled laser diode arrays (LDAs), which delivered the maximum output powers of 10 and 20 W respectively at the wavelength of 808 nm from the fiber bundle ends. The fibers were drawn into round bundles of 0.4-mm diameter with the numerical aperture of 0.22. The two pump beams from the fiber bundle ends were focused into the laser crystals with the same spot diameter of 0.4 mm. The pump light was focused inside each crystal with two achromatic collimating lenses. The cavity length was 8 cm for 1319-nm oscillation and the other cavity length was 10 cm for 1062-nm emission.

When the incident pumping power for Nd:YAG was 20 W, the variation of 588-nm yellow laser output power with pumping power of Nd:GdVO$_4$ was measured. When the incident pumping power for Nd:GdVO$_4$ was 10 W, the same variation was measured as well, as shown in Fig. 2. It is shown that the threshold power of laser was 4.1 W (1.6 W + 2.5 W). When the incident pumping powers were 20 W for Nd:YAG and 10 W for Nd:GdVO$_4$ respectively, 588-nm CW yellow light was generated, whose power was 1.12 W.

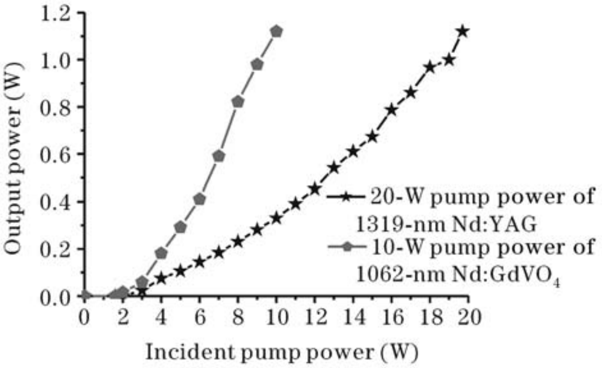

Fig. 2. SFM 588-nm output power versus pump power of Nd:GdVO$_4$ and Nd:YAG.

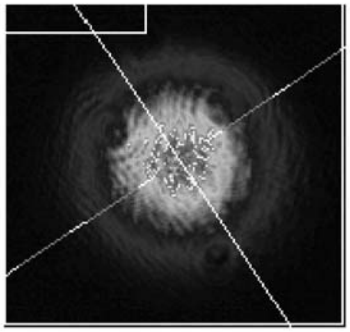

Fig. 3. TEM$_{00}$ energy distribution of far-field spot.

The TEM$_{00}$ energy distribution diagram of 588-nm laser for spots recorded by a beam profiler (made by Photon Inc.) is shown in Fig. 3. The ellipticity of spot is 0.98.

In conclusion, we have demonstrated doubly resonant sum-frequency mixing (SFM) of two laser diode arrays pumped CW Nd^{3+} lasers to generate coherent radiation in the yellow spectral region at 588 nm, and output power of 1.12 W was achieved. The M^2 beam quality factor of the SFM yellow laser was estimated by use of the algorithms of the knife-edge technique to be less than 1.5. Experimental results show that the intracavity SFM is an efficient method for 588-nm laser and it can be applied to other two laser crystals to obtain more all-solid-state lasers with different wavelengths.

This work was supported by the Foundation Research Program for National Defense of Commission of Science Technology and Industry for National Defense of China under Grant No. A3620060122. Y. Lü's e-mail address is custlaser@163.com.

References

1. Y.-F. Chen, T.-M. Huang, C.-L. Wang, and L.-J. Lee, Appl. Opt. **37,** 5727 (1998).
2. C. Czeranowsky, E. Heumann, and G. Huber, Opt. Lett. **28,** 432 (2003).
2. Z. Sum, K. Li, Y. Bi, X. Yang, Y. Bo, Y. Zhang, G. Wang, W. Zhao, H. Zhang, W. Hou, D. Cui, and Z. Xu, Opt Commun. **241,** 167 (2004).
4. M. B. Danailov and P. Apai, Appl. Phys. **75,** 8240 (1994).
5. P. H. Chiu, A. Magana, and J. Davis, Opt. Lett. **19,** 2116 (1994).
6. H. Moosmüller and J. D. Vance, Opt. Lett. **22,** 1135 (1997).
7. Y. Lü, H. Tan, and L. Qian, Chin. Opt. Lett. **4,** 25 (2006).
8. J. Lu, J. Lu, T. Murai, K. Takaichi, T. Uematsu, J. Xu, and K. Ueda, Opt. Lett. **27,** 1120 (2002).
9. A. Geng, Y. Bo, X. Yang, H. Li, Z. Sun, Q. Peng, X. Wang, G. Wang, D. Cui, and Z. Xu, Opt. Commun. **255,** 248 (2005).
10. S. Singh, R. G. Smith, and L. G. Van, Phys. Rev. B **10,** 2566 (1974).
11. SNLO, free software for modeling nonlinear frequency conversion processes in nonlinear crystals, http://www.sandia.gov/imrl/X1118/xxtal.htm.