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LASERS
AND THEIR APPLICATIONS

All-Solid-State Doubly Resonant Intracavity Frequency Sum Mixing Orange Yellow Laser with 3.2 W Output Power at 593.5 nm[1]

P. F. Zhu[a], B. Li[b, c], W. Q. Liu[b, c], T. H. Liu[b, c], C. X. Fang[b, c], Y. Zhano[b, c], Y. Yao[b, c], and Q. Zheng[b, c]

[a] *College of Fundamental Studies, Shanghai University of Engineering Science, Shanghai, 201620 China*
[b] *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun Jilin, 130033 China*
[c] *Changchun New Industries Optoelectronics Tech. Co., Ltd. 130012 China*
e-mail: yaoyi@cnilaser.com

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Abstract—A compact and efficient 593.5 nm orange–yellow laser is realized using doubly resonant intracavity sum frequency mixing. Two Nd : YVO_4 crystals are employed as the gain crystals. In two sub-cavities, 1064 nm radiation from one Nd : YVO_4 and 1342 nm radiation from the other Nd : YVO_4 are mixed to generate 593.5 nm orange–yellow laser. In the overlapping of the two cavities, sum frequency mixing is achieved in a type I critical phase matching (CPM) LBO crystal. An output power of 3.2 W at the wavelength of 593.5 nm is obtained with total incident pump power of 38 W. The optical to optical conversion efficiency is up to 8.4% and the stability of the output power is better than 2.48% in 8 h. To the best knowledge, this it the highest watt-level laser at 593.5 nm generated by diode end pump all-solid-state technology.

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INTRODUCTION

Coherent continuous wave (CW) light sources in the visible spectral range have become interesting for, many scientific applications in medicine, display, and other areas because of the advantages o compactness, robustness, high efficiency, good beam quality, environment protection, and so on [1–5]. Unfortunately, because of the absence of fundamental lasers, the yellow radiation from 580 nm to 600 nm can not be achieved by frequency doubling as the blue, green, and red radiation. But other ways of generating the yellow laser have been found which is sum frequency generation where the coherent radiation of frequencies ω_1 and ω_2 is mixed and generating radiation of frequency $\omega_3 = \omega_1 + \omega_2$. One way to obtain dual wavelength laser transition is to use different energy levels of the active ion in one single crystal. However, dual wavelength operation is difficult to achieve because of the strong gain competition between the two laser lines which influence the efficiency of sum frequency mixing and the beam quality of harmonic wave. Another way is to use doubly folded resonator for intracavity sum frequency mixing in two different cavities sharing an overlapping cavity. This concept combines the advantage of implementing two independent gain media with separate pump source and partially independent resonators with the advantage of higher intracavity powers that are benefit for frequency conversion process.

After Y.K. Bu et al. had firstly demonstrated an efficient intracavity sum frequency generation with 1064 nm and 1342 nm in a nonlinear optical crystal of LBO where 85 mW laser at 593.5 nm is obtained [6], the output power is enhanced up to 700 mW in 2005 using a PPKTP as the frequency doubling crystal by J. Jiri et al. [7] and no watt-level output at 593.5 nm is reported [8, 9].

In this letter, a compact and efficient 593.5nm orange–yellow laser is realized using doubly resonant intracavity sum frequency mixing. Two Nd : YVO_4 crystals are employed as the gain crystals. In two sub-cavities, 1064 nm radiation from one Nd : YVO_4 and 1342 nm radiation from the other Nd : YVO_4 are mixed to generate 593.5 nm orange–yellow laser. In the overlapping of the two cavities, sum frequency mixing is achieved in a type I CPM LBO crystal. An output power of 3.2 W at a wavelength of 593.5 nm is obtained with total incident pump power of 38 W and the stability of the output power is better than 2.48% in 8 h. To the best knowledge, this it the highest watt-level laser at 593.5 nm generated by diode end pump all-solid-state technology.

EXPERIMENTAL SETUP

The experimental schematic of intracavity sum frequency generation of 593.5 nm orange-yellow laser is shown in Fig. 1. The two pump sources used in the experiment are commercially available fiber coupled laser diode arrays, which deliver the maximum output

[1] The article is published in the original.

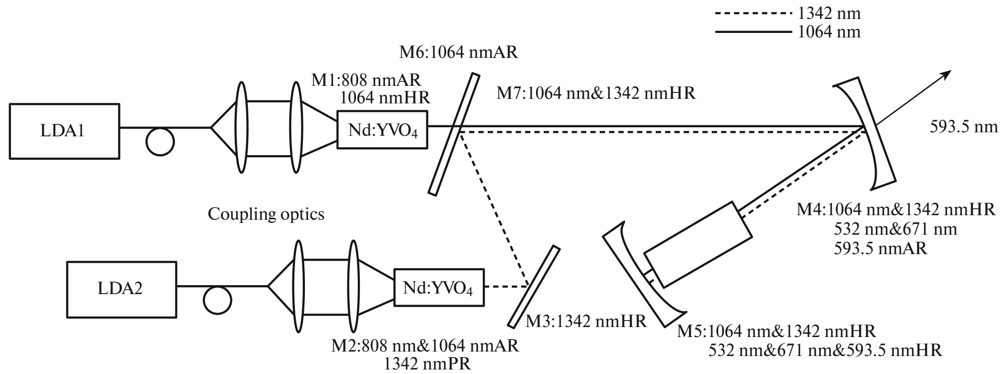

Fig. 1. Schematic for the intracavity sum frequency generation of 593.5 nm orange–yellow laser.

power of 20 W at the wavelength of 808.5 nm at room temperature from the fiber bundle end. The fibers are drawn into round bundles of 400 μm diameter with the numerical aperture of 0.22, and the emission central wavelength could be tuned by changing the temperature of the heat sink to match the best absorption of the two laser crystals. The spectral width (FWHM) of the pump source is about 1.5 nm. The coupling optics consists of two identical plano-convex lenses with focal length of 15 mm used to re-image the pump beam into the laser crystal at a ratio of 1 : 1. The coupling efficiency is up to 98%. Because the pump intensity is high enough in the pump spot regions, the first lens must be well adjusted to collimate the pump beam, since it will strongly affect the focal spot. However, the distance between the two lenses can be freely adjusted by experiment. For the aberration, the average pump spot radius is about 220 μm.

One laser crystal is an *a*-cut 0.1 at %-doped Nd^{3+}, 3 × 3 × 5 mm^3 size Nd : YVO_4. The pumping side of the Nd : YVO_4 crystal acting as one mirror (M_1) of the cavity is coated with antireflection (AR) at 808 nm and high reflection (HR) at 1064 nm. The opposite side is antireflection coated at 1064 and 808 nm. The other laser crystal is also an *a*-cut 0.1 at %-doped Nd^{3+}, 3 × 3 × 5 mm^3 size Nd : YVO_4. The pumping side of the Nd : YVO_4 crystal is AR coated at 808 and 1064 nm and partial reflection (PR) coated at 1342 nm to suppress the strong parasitical oscillation at 1064 nm transition. The other side of this crystal is AR coated at 808, 1064, and 1342 nm. Low doped and long laser crystal is favorable to reduce thermal lens which guaranteeing to absorb enough pump energy.

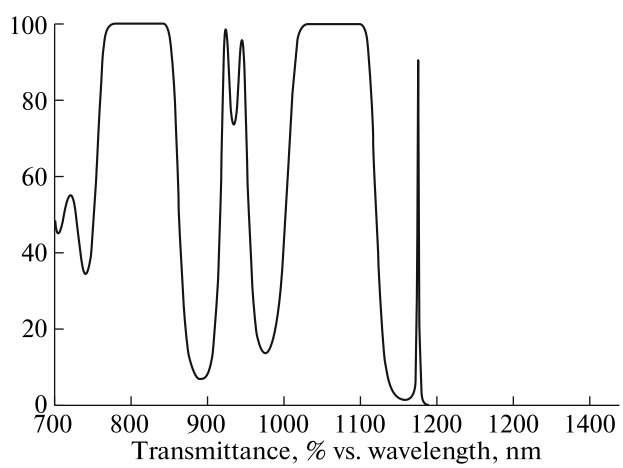

Fig. 2. The transmissivity of the surface of Nd : YVO_4 M_2 of 593.5 nm laser.

The cavity configuration we used is a doubly resonant three-mirror folded cavity, which has two separate beam waists, one waist could satisfy the mode matching condition and the other could enhance the intracavity frequency mixing efficiency. The radii of the concave faces are 60 and 400 mm for M_4 and M_5, respectively. L_1 is the length of the separate arm and L_2 is the length of the share arm of the cavity. L_1 and L_2 are about 82 and 46 mm, respectively. The beam incident angle on the folded mirror is set to be as small as possible to reduce the astigmatism without additional optical astigmatism-compensating elements. The LD, the whole cavity, and the crystals are cooled by the thermoelectric controller for active temperature control with a stability of ±0.1°C.

THEORETICAL ANALYSIS

Considering the performance of main laser lines of Nd : YVO_4 crystal as a laser gain medium, since the stimulated emission cross section for the 1342 nm transition is approximately three times smaller than that for the 1064 nm line, operation of the Nd : YVO_4 laser at 1342 nm requires suppression of the competing transition at 1064 nm. In our experiment, the stronger transition near 1064 nm is suppressed by use of specifically coated mirror especially on the end of the crystal Nd : YVO_4 (M_2) which is convenience for coating progress and commercial utility. Although the ideal

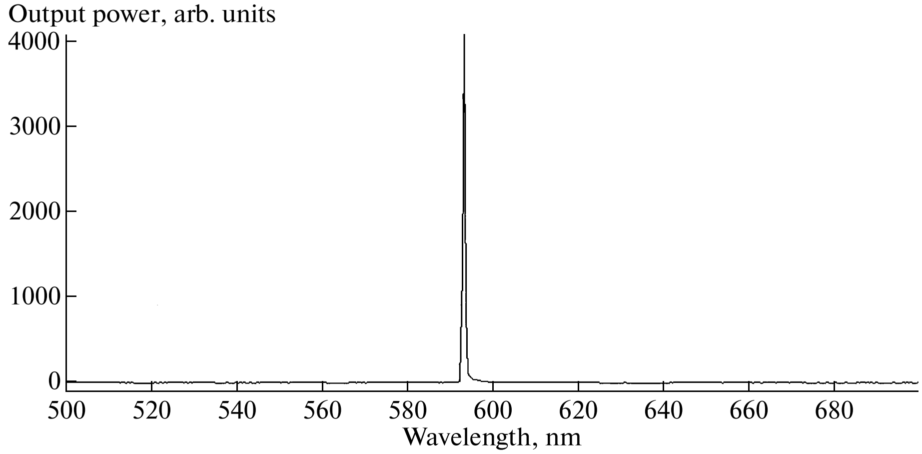

Fig. 3. The spectrum of 593.5 nm orange–yellow laser emission.

coating condition is HR coated at 1342 nm and AR coated at 1064 nm, the two chief laser lines at 1064 nm and 1342 nm influence each other that the ideal condition is impossible to achieve. Therefore, the coating condition of the end of the crystal is AR coated at 1064 nm and PR coated at 1342 nm which could suppress the oscillation at 1064 nm but some loss at 1342 nm line also exists.

Figure 2 is the coating curves of the ending surface of the crystal on M_2. The left side of Nd : YVO_4 is AR coated at 808 nm and 1064 nm, 1342 nm PR. The other facet of Nd : YVO_4 is antireflection coated at 1064 nm, 1342 nm and 808 nm. The concave facet of M_4 is AR coated at 532 nm, 671 nm and 593.5 nm and HR coated at 1064 nm and 1342 nm. The piano facet of M_4 is antireflection coated at 593.5 nm, 532 nm and 671 nm. The end mirror M_5 is high reflection coated at 593.5 nm, 671 nm and 532 nm in visible region, as well as 1064 nm and 1342 nm in infrared region LBO is a $2 \times 2 \times 10$ mm^3 nonlinear crystal ($\theta = 90°$, $\varphi = 2.6°$). Though BIBO has a high nonlinearity of 2.25 pm/V in sum frequency mixing of 1064 nm and 1342 nm laser, the large walk-off angle of 82.92 mrad, which gets the beam spot with low beam quality, makes BIBO not suitable for this application. LBO is selected as the frequency doubling material in our experiment for its small walk-off angle of 1.58 mrad. Although the nonlinear coefficient of LBO is 0.837 pm/V, the length of LBO could be extended to compensate the relatively smaller value of nonlinear coefficient. Both facets of the LBO crystal are antireflection coated at 593.5 nm, 532 nm, 671 nm, 1064 nm and 1342 nm to reduce the reflection losses in the cavity. It is mounted in a copper block, which is also fixed on a TEC for an active temperature control.

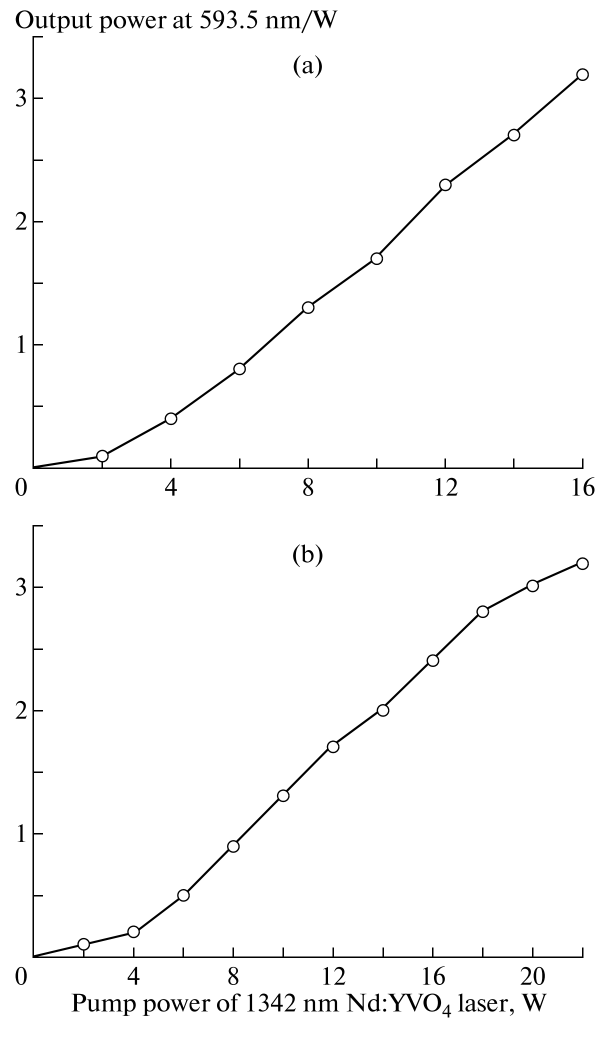

Fig. 4. Input–output characteristics of the sum-frequency mixing orange–yellow laser at 593.5 nm: output power vs. pump power at 1064 nm (a) and 1342 nm (b).

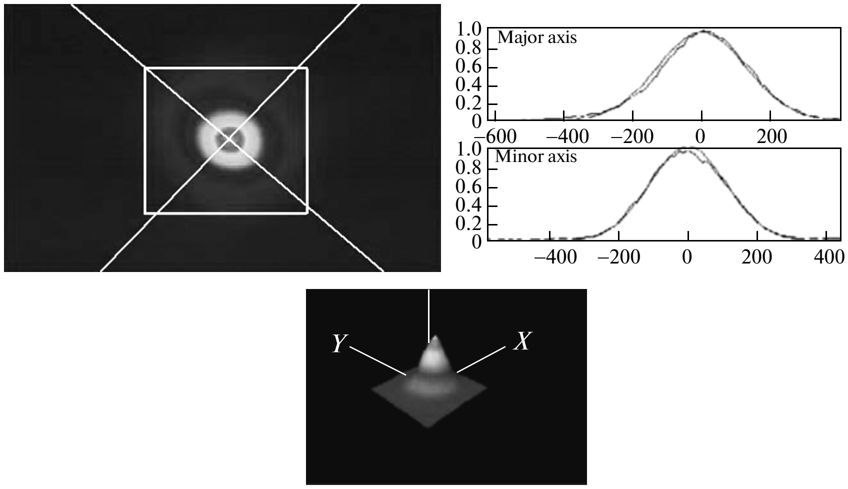

Fig. 5. Beam profile distribution of 593.5 nm orange–yellow laser on 2D, 3D energy distribution and Gaussian Fitting Curve.

RESULTS AND DISCUSSION

The laser output at 1064 nm and 1342 nm is linearly polarized, so it is not necessary to insert a Brewster plate for the sum frequency mixing. For the SFG experiment, a 10 mm length LBO is inserted into the cavity close to the end mirror M_5 of the shared arm to take advantage of the high power density of the laser beam waist in the cavity. Using the LABRAM-UV spectrum analyzer to scan SHG laser and dealing with the data by software, the spectrum of the SFG laser is shown in Fig. 3.

By variation of the pump power of one of the fundamental laser, the output power at 593.5 nm laser versus the incident pump power is shown in Fig. 4. Figure 4a shows the continuous wave output power at 593.5 nm as a function of pump power which is injected into the Nd : YVO_4 crystal generating the 1064 nm line. Then the pump power which is injected into the other Nd : YVO_4 crystal oscillate at 1342 nm line is fixed at 16 W, and the maximum orange–yellow laser of 3.2 W with total pump power of 38 W. Figure 4b demonstrates the continuous wave output power at 593.5 nm as a function of the pump power injected into the Nd : YVO_4 crystal generating the 1342 nm laser line. The output power is supposed to be higher with higher pump power for no power saturation or power decrease is observer. The M square factors are about 1.46 and 1.57 in horizontal and vertical directions respectively measured by knife-edge technique which shows that the laser output at 593.5 nm is operating at near TEM_{00} mode. The asymmetry of the M^2 factor in two directions is result from the walk-off between the fundamental wave and the second in direction of LBO. The Fig. 5 is the beam profile of the 593.5 nm laser on 2D, 3D energy distribution and Gaussian Fitting Curve which is measured by the Beam Quality Analysis of Spiricon.

Some stability testing is carried out by monitoring the orange–yellow laser with Field-Master-GS power-meter at 10 Hz. The fluctuation of the output power is about 2.48% in 8 h. The chaotic noise state is also stable when the environments without large fluctuations. The short term power stability is measured by LabMaster Ultima whose operates at 50 KHz and the rms noise value is 2.83%. Although no method for lowering the output noise is used, the output exhibits a low noise state. This is a general advantage of sum frequency mixing compared to second harmonic generation. In a frequency doubling laser, a co-action of cross saturation and sum frequency generation among different longitudinal modes will cause the laser energy to shift quickly among the longitudinal modes, causing longitudinal mode instabilities. Hence, the second harmonic output may exhibit large amplitude fluctuations, which is well known as the green problem. When two separate beams of substantially different wavelengths are sum frequency mixed, only the process of sum frequency mixing is phase matched in the nonlinear crystal, and not the doubling of each frequency, In the sum frequency mixing process, cross saturation is confined to longitudinal modes from the same fundamental radiation and cross sum frequency is suppressed by the modes from different fundamental radiations. So the co-action mentioned above is greatly weakened, and this makes the output laser obtain a much lower noise.

CONCLUSIONS

In conclusion a compact and efficient 593.5 nm orange–yellow laser is realized using doubly resonant intracavity sum frequency mixing. Two Nd : YVO_4 crystals are employed as the gain crystals. In two subcavities, 1064 nm radiation from one Nd : YVO_4 and 1342 nm radiation from the other Nd : YVO_4 are mixed to generate 593.5 nm orange–yellow laser. In the overlapping of the two cavities, sum frequency mixing is achieved in a type I critical phase matching LBO crystal. An output power of 3.2 W at a wavelength of 593.5 nm is obtained with total incident pump power of 38 W and the stability of the output power is better than 2.48% in 8 h.

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