Available online at www.sciencedirect.com
ScienceDirect
Optics & Laser Technology 40 (2008) 775–778
Optics & Laser Technology
www.elsevier.com/locate/optlastec

Compact 500.9 nm laser based on doubly resonant intracavity sum–frequency mixing

Xi-Hong Fu[a,b,*], Yi-Min Li[a,b], Gao Shen[a,b], Er-Juan Hao[a,b],
Hui-Ming Tan[a], Long-Sheng Qian[a]

[a] *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, Jilin 130033, China*
[b] *Graduate School of the Chinese Academy of Sciences, Beijing 100049, China*

Received 17 September 2007; received in revised form 17 November 2007; accepted 7 December 2007
Available online 21 February 2008

Abstract

A compact 500.9 nm laser was realized using doubly resonant intracavity sum–frequency mixing. An Nd:YAG crystal and an Nd:YVO_4 crystal were employed as the gain crystals. In two sub-cavities, 946 nm radiation from the Nd:YAG and 1064 nm radiation from the Nd:YVO_4 were mixed to generate 500.9 nm. In the overlapping of the two cavities, sum–frequency mixing was achieved in a type-II critical phase-matched KTP crystal. An output power of 78 mW at a wavelength of 500.9 nm was generated using a total incident pump power of 4 W and the output light exhibited low noise, with the root-mean-square value being 0.3%.

Keywords: Laser diode pumped; Sum–frequency mixing; 500.9 nm light

1. Introduction

Since the 1990s, solid-state lasers emitting in the blue and green range have been thoroughly investigated and their development has been encouraged by a variety of applications such as biomedical engineering, display science and technology, optical data storage, and communications. One promising way to realize such laser is through frequency doubling of the emission lines of neodymium doped crystals such as Nd:YAG, Nd:YVO_4, Nd:$GdVO_4$. In this way, green light at 532 nm, and blue light at 473 and 457 nm have been efficiently generated. Another way for lasers to reach the blue and green range is through sum–frequency mixing of two different emission lines. This method is used when a laser line cannot be directly generated or cannot be efficiently generated by frequency doubling. Several groups had reported the use of this method to realize lasers at 459 nm [1,2], 434.7 nm [3], 491 nm [4] and 492 nm [5].

Among the blue and green wavelength range, lines around 500 nm are seldom reported. Light around 500 nm, which can be called cyan, have special applications in biomedicine and also in underwater communications, as the line around 500 nm is near the transmission window of seawater. In 2006, Jacquement et al. [6] demonstrated a laser operating at 501.7 nm through second-harmonic generation of lasers with Yb^{3+}-doped crystals (Yb:YSO, Yb:KYW). However, the structure used was complicated and the crystals used were much more expensive, which would limit its use in some applications. Alternatively, sum–frequency mixing can be used to generate laser output around 500 nm. In 2002, 20 mW at 501 nm was realized by mixing radiations of 1064 and 946 nm which simultaneously oscillated in a linear cavity containing a single Nd:YAG crystal [7]. However, for the Nd:YAG crystal, the ratio of stimulated emission cross sections for the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition (corresponding to 946 nm radiation) and $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition (corresponding to 1064 nm radiation) is about 1:12 [8]. Hence, there exists a strong competition between the two emissions for the

---

*Corresponding author at: Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, No. 6142, Renmin Street, Changchun, Jilin 130022, China. Tel.: +86 431 85696132; fax: 86 431 85261802.

E-mail address: fuxh_80@163.com (X.-H. Fu).

0030-3992/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.optlastec.2007.12.003

inverted populations. Also, in a quasi-three level system, the $^4F_{3/2}\rightarrow{}^4I_{9/2}$ transition suffers from a considerable reabsorption loss due to thermal population at the lower laser level. Thus it is difficult to realize efficient dual wavelength operation of 1064 and 946 nm in a single Nd:YAG crystal, and this demands highly on the coating-design for the cavity mirrors. Meanwhile, the balance between the gains of the two emission lines will improve the emission threshold and lower the emission efficiency.

In this paper, doubly resonant intracavity sum–frequency mixing was employed to generate laser output at 500.9 nm. Here, a Nd:YAG crystal and a Nd:YVO$_4$ crystal were pumped by two laser diodes in two sub-cavities. In the two cavities, wavelengths of 946 nm from Nd:YAG and 1064 nm from Nd:YVO$_4$ were mixed to generate light at 500.9 nm. In the overlapping section of the two cavities, sum–frequency light was generated with a type-II critical phase-matched KTP crystal. About 78 mW stable output at 500.9 nm was obtained at the total incident pump power of 4 W. Remarkably, the output light was really low noise with a root-mean-square (RMS) value of 0.3% compared to SHG output and the result was contributed to the method which was used here.

2. Experimental setup

The experimental setup is shown schematically in Fig. 1. The sub-cavitiy for 946 nm radiation was composed of Nd:YAG crystal, mirror M1 and mirror M2. The sub-cavity for 1064 nm radiation was composed of Nd:YVO$_4$ crystal and mirror M2. The two cavities were combined by a combiner mirror M1 and shared the path from M1 to M2. In the shared part of the cavity, sum–frequency mixing was done using a nonlinear crystal. The Nd:YVO$_4$ crystal was a-cut with Nd^{3+} concentration of 1 at.% and dimensions of $3\times3\times2\,\text{mm}^3$. One side of the crystal was anti-reflection (AR) coated at 808 nm and high reflection (HR) at 1064 nm to act as an end mirror for the 1064 nm laser. The other side was AR coated at 1064 nm. The $3\times3\times1.5\,\text{mm}^3$ Nd:YAG crystal had an Nd^{3+} concentration of 0.5 at.%. One side was AR coated at 808 nm, HR at 946 nm and AR 1319 nm to act as an end mirror for the 946 nm laser, while the other side was AR coated at 946 nm. Two LDs were employed as the pump sources, LD1 with a maximum output power of 2 W and LD2 with a maximum pump power of 5 W. Light from the LDs was reshaped and focused to a spot of 100 μm in radius by the coupling systems and injected into the laser crystals. A plane–parallel mirror with diameter of 8 mm acted as the combiner mirror M1. As type-II critical phase matching was carried out here, the two fundamental radiations at 1064 and 946 nm involved in the sum–frequency mixing must have polarizations perpendicular to each other. Thus the right side of the mirror was coated AR for the parallel (p-) polarized 1064 nm field and HR for the vertically (s-) polarized 946 nm field. The left side was coated AR for the p-polarized 1064 nm field. Here, the AR coatings for the 1064 nm on M1 can prevent the 1064 nm line from lasing in the Nd:YAG crystal. The output coupler M2 was a plane-concave mirror with a radius of curvature of 50 mm. The concave side was coated HR at 946 and 1064 nm, AR at 500.9 nm and the plane side was coated AR at 500.9 nm.

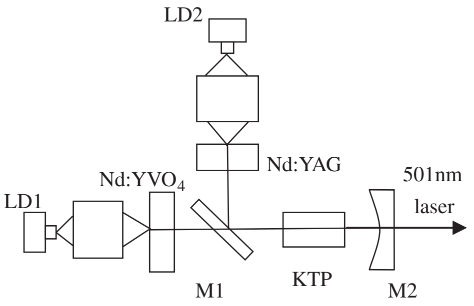

Fig. 1. Experimental setup.

A $2\times2\times5\,\text{mm}^3$ KTP crystal which was cut for type-II phase matching ($\theta=90^\circ$, $\varphi=45.9^\circ$) was employed as the nonlinear crystal for the sum–frequency mixing. Both ends of the KTP crystal were AR coated at 946 nm, 1064 nm and at 500.9 nm to reduce cavity losses. The whole cavity and LDs were fixed on separate thermoelectric coolers (TECs) for an active temperature control to $\pm0.1\,^\circ\text{C}$.

3. Results and discussions

During the process of frequency conversion, one photon at 1064 nm and one photon at 946 nm combine to produce one photon of 500.9 nm. So optimum sum–frequency mixing can be obtained when the ratio of the photon densities for 1064 and 946 nm radiations approaches 1:1. Here, as the two laser crystals were pumped by two LDs, the gains for the 1064 and 946 nm radiations can be modulated separately by modulating the currents of the two LDs separately. Thus an optimum ratio of 1:1 for the photon densities can be achieved and the two fundamental radiations can be fully used.

Meanwhile, for nonlinear sum–frequency mixing ($\omega_1+\omega_2\rightarrow\omega_3$), the intensity I_3 of the generated light satisfies [9]

$$I_3=\gamma_{\text{SFM}}I_1I_2,$$

where I_1 and I_2 are the intracavity intensities for the two fundamental radiations, γ_{SFM} is sum–frequency coefficient which depends on the nonlinear coefficients of the nonlinear crystal, the frequencies involving in the frequency conversion process and the parameters of the Gaussian-beam in the cavity. For fixed cavity structure and crystals, γ_{SFM} has a fixed value. So, when the intensity of one fundamental light (for example I_1) is fixed, the intensity of the sum–frequency light I_3 will vary linearly with I_2.

Fig. 2 shows the curve of the output power at 500.9 nm as a function of the incident pump power on Nd:YAG crystal when the pump power on Nd:YVO$_4$ crystal is fixed at 1.3 W. This means that the intracavity intensity of the 1064 nm radiation is fixed at a certain value. It can be seen

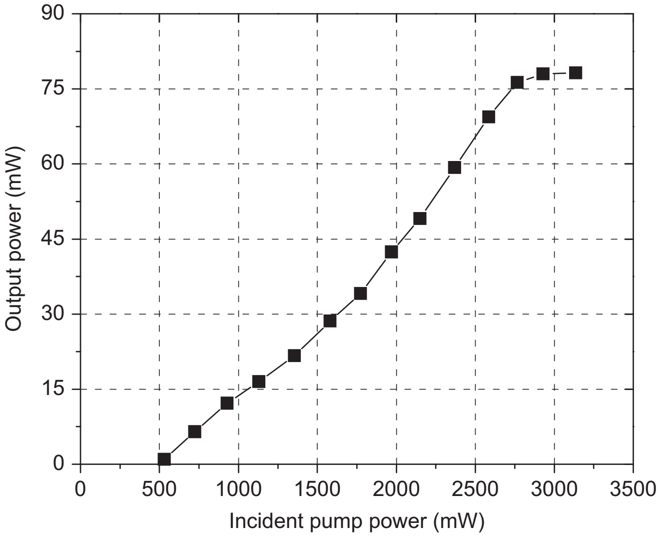

Fig. 2. Output power of 500.9 nm as a function of the pump power on Nd:YAG.

from Fig. 4 that the output power of 500.9 nm increases linearly with the incident pump power on the Nd:YAG crystal. Maximum power of 78 mW is obtained when the pump power on Nd:YAG approaches 2.7 W. Then further increase in the pump power will not contribute to the output power at 500.9 nm. This may be because when the pump power reaches 2.7 W, photons of 1064 nm radiation are fully exploited during the sum–frequency-mixing process. As the pump power on the Nd:YAG crystal increases, extra photons of 946 nm radiation will not participate in the frequency conversion due to the lack of 1064 nm photons. Thus the output at 500.9 nm becomes saturated. Further increase in the output power requires an increase in the pump power on the Nd:YVO_4 crystal at the same time.

The laser spectrum was measured with a grating monochromator as shown in Fig. 3. The sum–frequency output is centered at 500.9 nm with a FWHM bandwidth of 0.4 nm. In order to investigate the noise characteristic of the sum–frequency light, the output power at 500.9 nm was monitored by a fast silicon photoelectric diode and displayed in an oscilloscope. The result is shown in Fig. 4. Although no method for lowering the output noise was used, the output exhibits a low noise state with the RMS value calculated to be 0.3% (10 kHz–100 MHz). This is a general advantage of sum–frequency mixing compared to second harmonic generation. For comparison, the $2 \times 2 \times 5\,\text{mm}^3$ KTP crystal used for the sum–frequency mixing was replaced by a $2 \times 2 \times 5\,\text{mm}^3$ KTP crystal which was cut at $(\theta, \varphi) = (90^\circ, 23.5^\circ)$ for frequency doubling of 1064 nm. The noise characteristic of the 532 nm light was shown in Fig. 5 and the RMS value was calculated to be 5.2%.

In a frequency-doubled 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

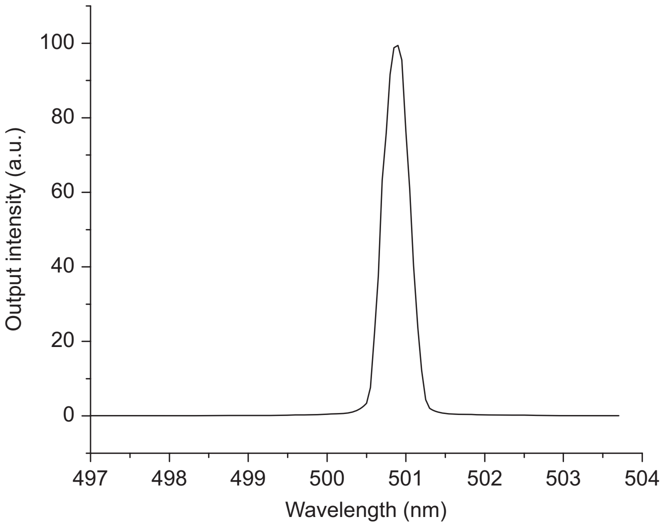

Fig. 3. Spectrum of the output light.

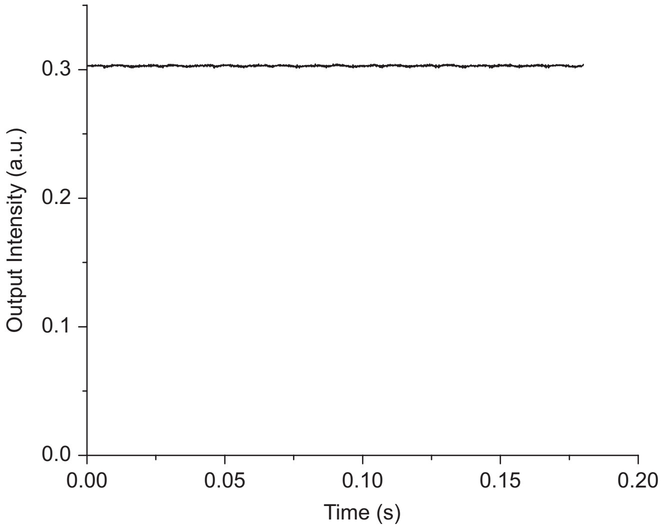

Fig. 4. Noise characteristic of the output light at 500.9 nm.

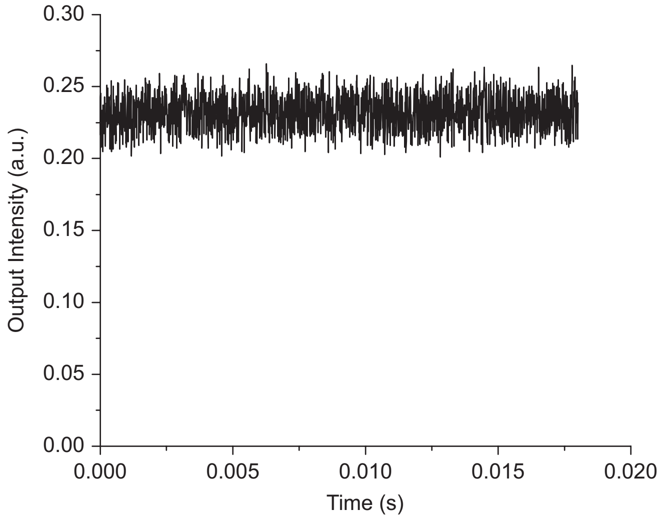

Fig. 5. Noise characteristic at 532 nm.

instabilities. Hence, the second-harmonic output may exhibit large amplitude fluctuations, which are known as the "green problem" [10]. 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 process, cross-saturation is confined to longitudinal modes from the same fundamental radiation and cross sum–frequency is confined to longitudinal modes from different fundamental radiations. So, the co-action mentioned above is greatly weakened, and this makes the output light exhibit a much lower noise in the sum–frequency laser than in the frequency-doubled laser.

4. Conclusion

In summary, a compact diode-pumped CW 500.9 nm laser based on doubly resonant intracavity sum–frequency mixing has been demonstrated. At the total incident pump power of 4 W, the maximum output power of 78 mW at 500.9 nm was obtained employing a type-II critical phase-matched KTP crystal. The output light was low noise with a RMS value of 0.3% (10 kHz–100 MHz). Higher output power of 500.9 nm can be achieved if the cavity is carefully designed and laser diodes with higher output power are employed.

Acknowledgments

We acknowledge the support from the Changchun New Industries Optoelectronics Co., Ltd. (CNI). This work was also supported by the National High-Tech 863 plan of People's Republic of China (No. 2002AA311140).

References

[1] Risk WP, Lenth W. Diode laser pumped blue-light source based on intracavity sum frequency generation. Appl Phys Lett 1989;54(9): 789–91.

[2] Keana PN, Standley RW. Generation of 20 mW of blue laser radiation from a diode-pumped sum–frequency laser. Appl Phys Lett 1993;63(3):302–4.

[3] Fluck D, Günter P. Efficient generation of CW blue light by sum–frequency mixing of laser diodes in $KNbO_3$. Opt Commun 1997; 136:257–60.

[4] Herault E, Balembois F, Georges P. 491 nm generation by sum–frequency mixing of diode pumped neodymium lasers. Opt Express 2005;13(15):5653–61.

[5] Johansson S, Wang S H, Pasiskevicius V, et al. Compact 492-nm light source based on sum–frequency mixing. Opt Express 2005;13(7): 2590–5.

[6] Jacquemet M, Domenech M, Lucas-Leclin G, et al. Single-frequency cw vertical external cavity surface emitting semiconductor laser at 1003 and 501 nm by intracavity frequency doubling. Appl Phys B 2007;86(3):503–10.

[7] Bu Y K, Zheng Q, Xue Q H. Design and manufacture of optical thin Films for 500.8 nm Nd:YAG laser. Acta Photonica Sinica 2006; 35(1):79–83 [in Chinese].

[8] Li P X, Li D H, Li C Y, et al. Simultaneous dual-wavelength continuous wave laser operation at 1.06 and 946 nm in Nd YAG and their frequency doubling. Opt Commun 2004;235:169–74.

[9] Yao J Q. nonlinear optic frequency conversion and laser tuning technology. Beijing: Science Press; 1995. p. 72 [in Chinese].

[10] Baer T. Large-amplitude fluctuations due to longitudinal mode coupling in diode-pumped intracavity-doubled Nd:YAG lasers. J Opt Soc Am B 1986;3(9):1175–80.