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Frequency doubling and sum-frequency mixing operation at 469.2, 471, and 473 nm in Nd:YAG

Bin Xu,1,2 Patrice Camy,1,* Jean-Louis Doualan,1 Alain Braud,1 Zhiping Cai,2 François Balembois,3 and Richard Moncorgé6

1Centre de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP), UMR 6252 Commissariat à l’Énergie Atomique–CNRS Ecole Nationale Supérieure d’Ingénieurs de Caen, Université de Caen, 14050 Caen, France
2Department of Electronic Engineering, Xiamen University, Xiamen 361005, China
3Laboratoire Charles Fabry de l’Institut d’Optique (LCFIO), UMR CNRS-Institut d’Optique Graduate School, Université de Paris-Sud, 91127 Palaiseau, France
*Corresponding author: patrice.camy@ensicaen.fr

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We report CW blue laser operation at 469.2, 471, and 473 nm by efficient intracavity second-harmonic generation and sum-frequency generation of the $R_1 \rightarrow Z_2$ (938.5 nm) and $R_1 \rightarrow Z_2$ (946 nm) $^4F_{3/2} \rightarrow ^4I_{9/2}$ intermultiplet transitions in Nd:YAG with an LiB$_3$O$_5$ nonlinear crystal. Single-wavelength laser operation at 469.2 nm and multiwavelength operation at 469.2, 471, and 473 nm are obtained with maximum output powers of 1.4 and 0.15 W, respectively, by using a glass etalon as frequency selector. The 469 nm blue laser is an efficient pumping source of Pr$^{3+}$-doped materials. © 2012 Optical Society of America

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1. INTRODUCTION

Quasi-three-level laser emissions around 940 nm in neodymium-doped mixed garnets like YGG/YAG/GGG and YSGG/GSAG/GSGG have received a great deal of attention in the past decades for different applications [1–4] such as laser remote sensing (differential absorption lidar) of atmospheric water vapor (H$_2$O). Moreover, along with other Nd-doped crystals such as vanadates, and by using intracavity frequency doubling [5–7], they also allow for very efficient laser emissions of blue light around 470 nm, with interesting applications in the fields of high-density optical data storage, color display, submarine communication, and biology.

On the other hand, with the increasing interest for Pr$^{3+}$-doped materials as laser media for RGB video-projectors, blue lasers with specific wavelengths at around 445, 469, or 479 nm are required to pump these Pr$^{3+}$-doped laser hosts [8–13]. Gallium nitride (GaN) diode lasers operating around 445 nm offer the most compact and simple pump source for the development of such lasers but are still limited to about 1 W (without any significant improvement over the last three years), and the beam quality of such laser diodes is considerably degraded for powers higher than 500 mW [10,13]. Frequency-doubled optically pumped semiconductor lasers offer the possibility of higher pump powers with a better beam quality, but they remain on demand, noncommercially available thus rather expensive laser devices.

For these reasons, we show here the details of an alternative solution, which is a simple, efficient, and potentially powerful solid-state laser based on a diode-pumped and intracavity frequency-doubled three-level Nd:YAG laser emitting at 469.2 nm, thus right at the wavelength corresponding to an absorption band of Pr$^{3+}$ [14]. For that purpose the laser has to work on the 938.5 nm transition line of Nd:YAG, which has been far less studied than the 946 nm one. In fact, such laser emission was first reported by Koch et al. [15], and second-harmonic generation (SHG) at 469.2 nm was first demonstrated by Bjurshagen et al. [16], but only with a maximum output power of 200 mW by using a periodically poled potassium titanyl phosphate frequency doubler and a Z-type laser resonator. In the present communication, we report on a substantial improvement in the laser output power at this blue laser wavelength by using a compact V-type cavity. We also report, for the first time to our knowledge, 946 and 938.5 nm dual IR laser emission, 471 nm blue laser emission resulting from frequency summing, and simultaneous blue laser emission at about 469, 471, and 473 nm by using an intracavity glass etalon as frequency selector.

2. EXPERIMENTAL CONDITIONS

The experimental setup is shown schematically in Fig. 1. The laser crystal is a 3 mm × 3 mm × 3 mm, 0.5% Nd-doped YAG. No particular effort has been made to optimize the Nd$^{3+}$ doping concentration and crystal length. However, we have considered that a relatively low concentration should be advantageous for alleviating thermal loading [6,17] compared to more commonly used ~1% Nd-doped crystals. The crystal was wrapped into an indium foil and mounted on a copper heat sink. The temperature of the laser crystal cooled by flowing water was maintained at 8 °C with an accuracy of ±0.2 °C. A 30 W fiber-coupled laser diode emitting around 808 nm was used as the pump source. The end of the fiber has a 200 μm core diameter and an N.A. of 0.22. To optimize the absorption in the crystal, the temperature of the diode was adjusted to 29.7 °C (±0.2 °C). So, at the maximum output power, the pump wavelength was 807.8 nm, with a spectral width (FWHM) of around 2.2 nm. Under these conditions, the crystal absorbed around 37% of the pump radiation. With a collimating doublet of 35 mm focal length and a focusing doublet of...
60 mm focal length, the end face of the fiber was imaged into the laser crystal with a spot radius of 170 μm. The left-hand side of the laser crystal acted as the input resonator mirror thanks to a high reflection coating at 938–946 nm and a high transmission coating at 1064 nm. The right-hand side was anti-reflection coated at 900–1100 nm. A 15 mm long LiB₃O₃ (LBO) crystal cut for type I critical phase-matching condition (θ = 90°, φ = 19.9° at 303 K for 469 nm) and mounted in a water-cooled copper holder was used for frequency doubling. A pinhole was also inserted before the LBO crystal to avoid the thermal heating of the copper holder arising from the residual pump radiation. This V-shaped cavity was designed to be stable by using the standard ABCD matrix method. After a slight readjustment of the designed arm lengths upon laser operation, the cavity arm lengths L1 and L2 were found to be optimal at 68 and 35 mm, respectively.

As the 938.5 nm laser line has a stimulated emission cross section about 10% weaker than the 946 nm one [18], an appropriate selective element, namely a simple glass plate serving as etalon, was inserted inside the laser cavity to enforce laser operation on one line or the other or both. The glass etalon had a thickness d = 0.15 mm and a refractive index n = 1.45

3. LBO PHASE MATCHING

For low conversion efficiencies, the second harmonic versus the fundamental wave optical power can be approximated by the expression [19]

$$P_{2\omega} = 2\varphi^2 \tilde{\alpha}^2 d_{\text{eff}}^2 \frac{P_{\omega}^2}{\lambda} \sin^2 \left( \frac{\Delta k l}{2} \right).$$  \hspace{1cm} (1)

where l is the length of nonlinear crystal, \( \varphi \) the plane-wave impedance, \( d_{\text{eff}} \) the effective nonlinear coefficient, and \( \omega \) and \( A \) the angular frequency and the area of the fundamental beam, respectively. From Eq. (1), one can see that, for a certain nonlinear crystal, the power of the second-harmonic wave mainly depends on the intracavity fundamental power \( P_{\omega} \) and the phase mismatch \( \Delta k \). The \( \sin^2 \) term in Eq. (1) is also called normalized SHG conversion efficiency. The phase mismatch \( \Delta k \) can be also expanded in a Taylor series as

$$\Delta k = \Delta k(\Delta \phi, \Delta \lambda, \Delta T)$$

$$= \Delta k(0) + \frac{\partial(\Delta k)}{\partial T}_{\Delta \phi, \Delta \lambda} \Delta T + \frac{\partial(\Delta k)}{\partial \phi}_{\Delta \lambda, \Delta T} \Delta \phi + \frac{\partial(\Delta k)}{\partial \lambda}_{\Delta \phi, \Delta T} \Delta \lambda. \hspace{1cm} (2)$$

where \( \Delta k(0) = 0 \) corresponds to perfect phase matching, which means that \( \Delta \phi = \Delta \lambda = \Delta T = 0 \) and that the maximum output power should be achieved at the operating wavelength. From Eq. (2), the phase mismatch due to one parameter, e.g., \( \Delta \lambda \), can be compensated by enforcing phase mismatch onto other parameters, e.g., \( \Delta \phi \) or \( \Delta T \) or both. Figure 2 shows the normalized SHG conversion efficiency of LBO, which was designed for a 938.5 nm fundamental wave. When angular and temperature phase matching are satisfied, i.e., \( \Delta T = \Delta \phi = 0 \), the FWHM of the sinc function is about 0.58 nm in the blue region (1.16 nm for the fundamental wave). It is apparent that, when keeping constant the angle and temperature of the
LBO crystal, one cannot obtain frequency doubling at 946 nm. However, by setting the LBO at an angle of \( \Delta \phi = -0.6^\circ \), an effective frequency doubling at 946 nm can still be achieved.

To confirm the theoretical conclusions, we first achieved laser operation at 946 nm without glass etalon inside the V-shaped cavity. A maximum output power of up to 1.1 W at 473 nm was obtained by inserting and tilting the LBO. Compared with results of frequency doubling of 938.5 nm (as given in Section 4), the output power obtained by frequency doubling of 946 nm through the misadjustment of the LBO crystal is limited by extra reflection and extra walk-off losses. According to our calculations (see Fig. 2), this compensation can be also carried out by temperature tuning of the LBO crystal [20].

As SHG is a special situation of sum-frequency generation (SFG) where the interactive wavelengths are equal, we also simulated the SFG within the LBO crystal with two wavelengths (938.5 and 946 nm) oscillating simultaneously in the cavity. In fact, thanks to the spectral proximity of the two wavelengths, the operating conditions of LBO for SFG of 938.5 and 946 nm \([\theta = 90^\circ \text{ and } \varphi = 19.6^\circ \text{ at } 30^\circ \text{C} \text{ with type I (ordinary-ordinary-ordinary) phase matching}]\) are very close to the SHG conditions at 938.5 nm. As shown in Fig. 2, the 471 nm radiation, which is the SFG of 938.5 and 946 nm, has only little coincidence with the SHG at 469.2 and 473 nm in the side lobes, which implies the possibility of a single 471 nm generation.

### 4. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 3 gives the calculated transmission of the glass etalon at different wavelengths when a tilt angle of 8.8° was applied, which corresponds to a maximum transmission (100%) at 938.5 nm and sufficient extra losses to suppress the 946 nm laser emission. The tilt angle was adjusted by detecting the reflected rays out of the cavity, and it was found in good agreement with the calculated value. By setting the etalon to an angle of 8.8° and inserting the LBO crystal, the corresponding SHG at 469.2 nm was successfully generated, and the CW output power reached 1.4 W as recorded in Fig. 4. In the output direction, the IR and blue laser beams were measured to have a linear polarization of 11:1 and 25:1, respectively. It has to be noticed that, before inserting the LBO, the polarization ratio of the 938.5 nm wave was measured to be 2.1:1. Since YAG is an isotropic material and should emit unpolarized
radiation, the polarization of the 938.5 nm wave probably comes from the V-type asymmetric cavity. In fact, we did not observe any polarized output of the IR beam when using a linear (symmetric) cavity. However, it should be certainly interesting to scale the SHG output power with our LBO (type I) doubling crystal by inserting a Brewster plate and a quarter-wave plate between the input mirror and laser crystal, as reported in [5], which is not possible here because of the cavity compactness but will be our next investigation by using a longer Z-shaped cavity.

By tilting the glass etalon to an angle of around 8.0° and a synchronous angle tuning of the LBO crystal, we also achieved simultaneous triple-wavelength operation at ~469, ~471, and ~473 nm (see Fig. 5 for the registered spectra), as simulated above, where the simultaneous dual-wavelength lasing at 938.5 and 946 nm was first observed as a precondition for the simultaneous laser operation of the three blue laser wavelengths. The total maximum output power of three blue lasers can be modified by slightly tilting the glass etalon and adjusting the LBO tilt angles.

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REFERENCES


