High-power direct green laser oscillation of 598 mW in Pr^{3+}-doped waterproof fluoroaluminate glass fiber excited by two-polarization-combined GaN laser diodes

Jun Nakanishi,[1] Yuya Horiuchi,[2,3] Tsuyoshi Yamada,[1] Osamu Ishii,[4] Masaaki Yamazaki,[5] Minoru Yoshida,[2] and Yasushi Fujimoto[5,*]

[1] *Nidek Co., Ltd., 34-14 Maehama, Hiroishi-cho, Gamagori, Aichi 443-0038, Japan*

[2] *Kinki University, Faculty of Science and Engineering, 3-4-1 Kowakae, Higashiosaka City, Osaka 577-8502, Japan*

[3] *Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan*

[4] *Production Engineering Section, Optical Glass Production Department, Sumita Optical Glass, Inc.,*
174-1 Tabehara, Tajima, Minamiaizu-gun, Fukushima 967-0004, Japan

[5] *Glass Research Division, R&D Department, Sumita Optical Glass, Inc., 4-7-25 Harigaya, Urawa-ku,*
Saitama City, Saitama 330-8565, Japan

**Corresponding author: fujimoto@ile.osaka-u.ac.jp*

Received February 24, 2011; accepted April 9, 2011;
posted April 14, 2011 (Doc. ID 143225); published May 9, 2011

We demonstrated a high-power and highly efficient Pr-doped waterproof fluoride glass fiber laser at 522.2 nm excited by two-polarization-combined GaN laser diodes and achieved a subwatt output power of 598 mW and slope efficiency of 43.0%. This system will enable us to make a vivid laser display, a photocoagulation laser for eye surgery, a color confocal scanning laser microscope, and an effective laser for material processing. Direct visible ultrashort pulse generation is also expected.

OCIS codes: 140.7300, 060.2320.

Visible lasers, especially green lasers, are widely applicable in display technology, medicine, laser processing, biology, metrology, and optical storage. In a visual system, because green light is the most vivid color in the photopic luminous efficiency function, such light sources are very attractive for laser pointers and displays. The color reproduction characteristics of the laser display are superior to the LCD in the chromaticity diagram [1]. A green laser is also used for a photocoagulation laser in diabetic retinopathy [2] because of the high absorbance of green light in melanin on retinal pigment epithelial cells [3]. Another aspect of a shorter wavelength laser is that the optical absorbance of the metal surface increases with a shortening of the wavelength of light in most metals. Although the copper absorbance is below 10% at 1 μm, the absorbance reaches 40% in the case of green light [4]. Since general laser processing uses a thermal process, a shorter wavelength laser is more effective than a longer one. Green lasers are also more effective than IR lasers in laser processing.

Several techniques for green laser generation have been developed, including an Ar ion laser, a copper bromide vapor laser [5], a dye (coumarin6) laser, and solid-state lasers with second harmonic generation (SHG) or optical parametric oscillator (OPO). Direct green laser oscillation remains fascinating. Gas and dye lasers, which are direct green lasers, have often been used in such scientific research; however, because of the delicate operation and the progress of nonlinear crystals, SHG or OPO techniques are now becoming mainstream in such visible laser development. On the other hand, visible semiconductor lasers are well developed for projector devices, and the power of a GaN laser diode (LD) at 445 nm continues to increase. A 1 W blue LD package has been provided by the Nichia Corporation. These semiconductor lasers are very easy to use, but the laser power between 500 and 600 nm is 50 mW, which is currently the best [6]. Therefore, the appearance of a high-power green laser with a rigid structure and low cost is significant.

The trivalent praseodymium ion (Pr^{3+}) is very attractive for visible solid-state lasers because it generates several transitions in the red, orange, green, and blue spectral regions [7–9]. Since fluoride materials show lower phonon energy than oxide ones, the luminescent intensity is higher without multiphonon relaxation. On the other hand, general fluoride materials, such as BeF_2 or ZBLAN, are susceptible to water exposure. Thus, the development of a waterproof fluoride glass and fiber is eagerly anticipated. Our group successfully fabricated a rare earth-doped waterproof AlF_3 system glass and drew optical gain medium fibers at a low loss (0.1–0.3 dB/m) and at a high concentration of rare earth ions [8,10,11].

In previous reports, we achieved a multiwavelength fiber laser with a Pr-doped waterproof fluoroaluminate glass fiber (Pr:WPFGF) laser excited by a GaN LD [8]. In 2010, the laser power from the Pr:WPFGF at 638 nm increased to 311.4 mW [10]. The slope efficiency was calculated to be 41.6%. Another topic is a yellow direct laser by a Dy-doped waterproof fluoroaluminate glass fiber (Dy:WPFGF) laser at 575 nm [11]. The maximum output power was 10.3 mW at 72.5 mW of absorbed power, the threshold power was 10.2 mW, and the slope efficiency was calculated to be 17.1%. Thus, visible fiber lasers with waterproof fluoroaluminate glass are increasing the power and spreading the possibility of color selectivity in the visible region.

This Letter reports a new subwatt green laser with a downconversion scheme. We constructed a polarization-combined excitation setup of two GaN LDs and achieved a subwatt class AlF_3-based Pr:WPFGF laser at 522.2 nm oscillation.

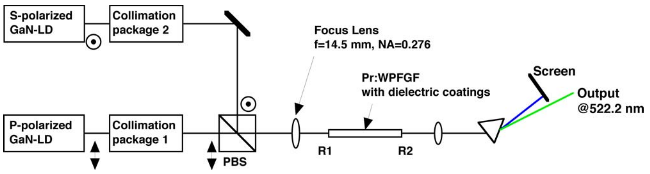

Fig. 1. (Color online) Experimental setup of a Pr:WPFGF laser excited by two-polarization-combined GaN LDs.

The setup of the laser oscillation experiment is illustrated in Fig. 1. Two GaN LDs (Nichia Corporation, NDB7352E) were used as excitation sources. Each collimation package includes a collimation lens ($f = 8.0\,\mathrm{mm}$, $\mathrm{NA} = 0.5$) and an anamorphic prism pair with a magnification of 4. The slow axis of GaN LD was set to the magnifying axis in the anamorphic prism pair. The two GaN LD beams in Fig. 1 are put in the P and S polarizations because GaN LD is polarized to the slow axis [12]. The two beams are combined in a polarizing beam splitter (PBS) to the one beam line and focused onto a Pr:WPFGF input surface by a focusing lens with a focal length of 14.5 mm and an NA of 0.276. The residual excitation beam from the Pr:WPFGF is separated by a prism and cut by a screen.

Both GaN LDs were operated at the maximum operating current (1200 mA). The maximum outputs of the P- and S-polarized GaN LDs were 971 and 1364 mW, respectively. The difference of the maximum output powers is an individual difference. The polarization ratio to the slow axis of both GaN LDs was measured to be around 90%. The transparent loss of the PBS was 9.8%, and we roughly estimated that more than 80% of the power of the two GaN LDs can go through by combining the PBS polarization.

An Pr:WPFGF with dielectric multilayered coatings (DMC) was used as a laser medium. Its Pr concentration was 3000 ppmw. It was fastened in a zirconia ferrule; the core–clad diameters were $16/300\,\mu\mathrm{m}$ and the fiber length was 40 mm. The GaN LD peaks were at 444 nm and the absorption coefficient of Pr:WPFGF was $0.56\,\mathrm{cm}^{-1}$; therefore, 89.4% of the GaN LD light was absorbed by the fiber. The NA of Pr:WPFGF was 0.235 at 444 nm. DMCs were deposited on both end surfaces of the Pr:WPFGF as resonator mirrors. The reflectivity at 719, 638, 605, and 522 nm and the transmittance at 444 nm of the R1 surface were 20.6%, 69.4%, 94.0%, 99.95%, and 99.0%, respectively. To selectively oscillate at 522 nm, the reflectivities at 719, 638, 605, and 522 nm of the R2 surface were 6.0%, 4.6%, 0.7%, and 94.9%, respectively.

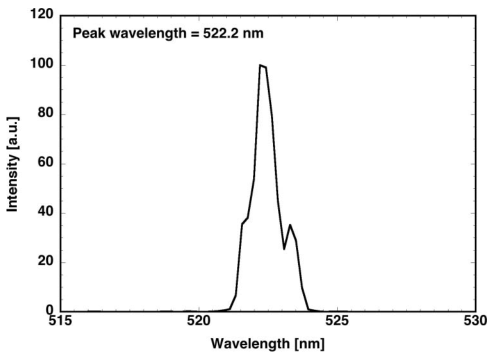

Fig. 2. Output spectrum of a Pr:WPFGF laser at 522.2 nm.

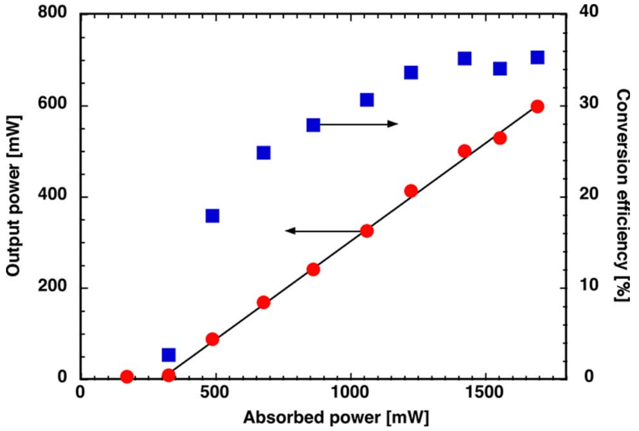

Fig. 3. (Color online) Input–output characteristics for 522.2 nm oscillation. Threshold power was 293.2 mW. Slope efficiency and maximum conversion efficiency were 43.0% and 35.3%, respectively.

The output spectrum of the Pr:WPFGF laser oscillation is shown in Fig. 2. The peak exists at 522.2 nm. The FWHM of the spectrum at 522.2 nm is calculated to be 1.2 nm, assuming a Gaussian spectrum shape. The input–output characteristics and the conversion efficiency of the Pr:WPFGF laser are shown in Fig. 3. The horizontal, left, and right vertical axes show the absorbed power in the Pr:WPFGF, the output power at 522.2 nm, and the conversion efficiency, respectively. The threshold power was 293.2 mW, and the maximum output power of 598 mW was obtained at an excitation power of 1,695 mW. The slope efficiency and the maximum conversion efficiency were 43.0% and 35.3%, respectively.

Laser stability is very important issue on this experiment. We tested the material durability for a month with some bulk samples in three cases: (1) in air at room temperature (a usual room condition), (2) high humid condition at 80° in an oven, and (3) in water at room temperature. The sample that was put in air at room temperature did not show any change in transmittance spectrum even after one month. Although the surface of the sample in water became clouded by water infiltration, the sample in the high humid condition did not change in its appearance and the transmittance was slightly decreased in the violet region by 2% or 3%. Therefore, it can be said that this fiber material has enough durability in the usual room condition. This is also supported by the stable laser operation with enough reproducibility of the laser power in the long term (one or more months).

We demonstrated a high-power and highly efficient Pr:WPFGF laser at 522.2 nm excited by the polarization of two combined GaN LDs. We achieved a subwatt output power of 598 mW with a slope efficiency of 43.0% and easily recognized that an excitation system with counter-excitation and such polarization-combined GaN LDs will exceed a 1 W green laser from Pr:WPFGF. This laser power improvement compared with the previous work [8] was carried out by direct coating on the fiber end surfaces and much powerful excitation source. Since the fluoroaluminate glass system has a remarkable water resistance advantage over ZBLAN glass, this type of waterproof fluoride glass fiber can greatly contribute to the development of a visible fiber laser with high chemical durability without a frequency doubling technique. Such a green laser with increased power will be very useful for laser processing on copper materials, including solderless joints in electrical circuits, laser marking, annealing, cutting, and welding. This system will also enable us to make a vivid laser display, a photocoagulation laser for eye surgery, and a color confocal scanning laser microscope. Ultrashort pulse generation is also expected because of the wide spectra that originated from inhomogeneous broadening in fluoroaluminate glass [8].

References

1. Y. Hirano, in *Proceedings in LASE*, *Photonics West 2009* (2009), paper 7913-02.
2. A. Obana, Rev. Laser Eng. **29**, 438 (2001).
3. J. Francis and A. L'Esperance, *Ophthalmic Lasers*, 3rd ed. (Mosby, 1989), Vol. 1.
4. W. Koechner, *Solid-State Laser Engineering*, 6th ed., Springer Series in Optical Sciences (Springer, 2006), Vol. 1.
5. S. E. McCoy, Lasers Surg. Med. **21**, 329 (1997).
6. A. Avramescu, T. Lermer, J. Muller, C. Eichler, G. Bruederl, M. Sabathil, S. Lutgen, and U. Strauss, Appl. Phys. Express **3**, 061003 (2010).
7. R. G. Smart, J. N. Carter, A. C. Tropper, D. C. Hanna, S. T. Davey, S. F. Carter, and D. Szebesta, Opt. Commun. **86**, 333 (1991).
8. Y. Fujimoto, O. Ishii, and M. Yamazaki, Electron. Lett. **45**, 1301 (2009).
9. A. Richter, E. Heumann, G. Huber, V. Ostroumov, and W. Seelert, Opt. Express **15**, 5172 (2007).
10. J. Nakanishi, T. Yamada, Y. Fujimoto, O. Ishii, and M. Yamazaki, Electron. Lett. **46**, 1285 (2010).
11. Y. Fujimoto, O. Ishii, and M. Yamazaki, Electron. Lett. **46**, 586 (2010).
12. D. Sands, *Diode Lasers*, Series in Optics and Optoelectronics (Institute of Physics, 2005).