Intracavity frequency-doubled green vertical external cavity surface emitting laser

Yanrong Song (宋晏蓉)[1], Peng Zhang (张 鹏)[1], Xinping Zhang (张新平)[1], Boxia Yan (颜博霞)[2], Yi Zhou (周 翊)[2], Yong Bi (毕 勇)[2], and Zhigang Zhang (张志刚)[3]

[1] *College of Applied Sciences, Beijing University of Technology, Beijing 100022*

[2] *Academy of Opto-Electronics, Chinese Academy of Sciences, Beijing 100080*

[3] *College of Electronic Engineering and Computer Science, Peking University, Beijing 100871*

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An intracavity frequency-doubled vertical external cavity surface emitting laser (VECSEL) with green light is demonstrated. The fundamental frequency laser cavity consists of a distributed Bragg reflector (DBR) of the gain chip and an external mirror. A 12-mW frequency-doubled output has been reached at 540 nm with a nonlinear crystal LBO when the fundamental frequency output is 44 mW at 1080 nm. The frequency doubling efficiency is about 30%.

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Green lasers have many applications, such as laser projection display, optical storage, bioanalytical instruments, and trace-evidence recovery[1]. Although the blue radiation can be directly emitted from a GaN-based wide-band-gap semiconductor laser[2] and red radiation also can be directly emitted from an InGaP semiconductor laser[3], yet, to our knowledge, no direct emission green laser has been reported. Green lasers by frequency doubling of optically pumped vertical external cavity surface emitting lasers (VECSELs) are attractive because of its tunable wavelength, power scalability, good beam quality, high conversion efficiency, and other important benefits including extremely low amplitude noise and long lifetime.

So far, intracavity frequency-doubled green VECSELs with different operating wavelengths have been reported, such as 501 nm[4], 505 nm[5], 520 nm[6], 529 nm[7], 532 nm[8], and 535 nm[9] which used $KNbO_3$[4], BIBO[6,7], BBO[9], and LBO[8] as nonlinear crystal, respectively. The conversion efficiency from fundamental power to harmonic power reached 52%[7], and the conversion efficiency of 27% from pump power to harmonic power was achieved[9]. $KNbO_3$ is widely used in most of blue and green lasers. It has a very high effective nonlinear coefficient of about 15.8 pm/V, but its spectral and temperature acceptance is relatively low. BIBO is a good material for intracavity frequency doubling because of its large effective nonlinear coefficient of about 3.3 pm/V. The very broad spectral acceptance makes it easy to operate with semiconductor lasers which might shift in wavelength. The main disadvantage of BIBO is its large walk-off angle. BBO (effective nonlinear coefficient of $\sim$ 2.2 pm/V) has a small acceptance angle and large walk-off angle, so good pump laser beam quality is necessary for it to obtain high conversion efficiency. LBO has been widely used in commercially available frequency-doubled green lasers, because it has a very high laser damage threshold, large acceptance angle, moderate effective nonlinear coefficient of $\sim$ 1.2 pm/V, and small walk-off angle. In this letter, we present an intracavity frequency-doubled green VECSEL of 540 nm. Taking into account all of the factors that would influence the doubling process, we use type I LBO as the nonlinear crystal.

As shown in Fig. 1, the semiconductor wafer in our experiment contains a distributed Bragg reflector (DBR) of 27.5 GaAs/AlAs pairs grown on GaAs substrate, 6 layers of 8-nm-thick InGaAs strained quantum wells (QWs) above DBR, which are separated by GaAs barrier/spacer. To ensure structural stability of the wafer in the presence of multiple InGaAs compressive-strained wells, tensile-strained GaAsP layers paired with each QW can be used to produce a zero net strain in the structure. The incident pump light is absorbed in the pump-absorbing regions. The generated electrons and holes are captured by the QWs, where they provide gain for the laser light. QWs are located at the antinodes of laser standing wave and form the well-known periodic resonant gain (PRG) structure. An AlAs layer which is transparent for both of the laser output and the pump light is used as window to prevent carrier non-radiation recombination on the surface of the chip. A GaAs capping layer finishes the epitaxial structure.

The experimental setup is shown in Fig. 2. The radiation from an 808-nm laser diode is collimated and then

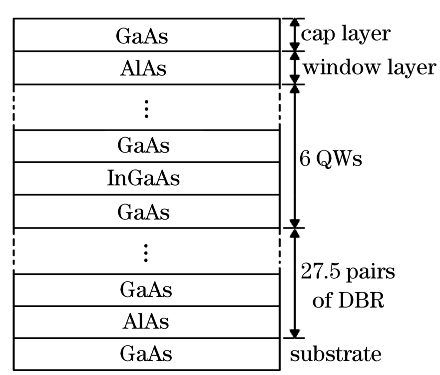

Fig. 1. Structure of gain chip.

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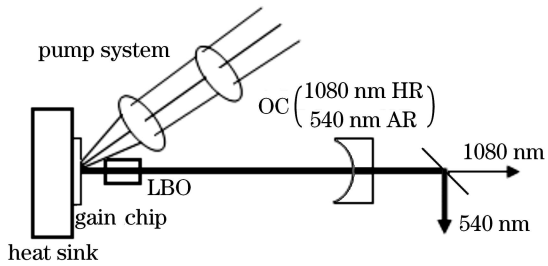

Fig. 2. Schematic of green VECSEL.

focused onto a semiconductor gain chip as a pump source. The diameter of the pump spot is about 100 μm. The laser cavity consists of the DBR of the gain chip and an external mirror. The external mirror, together with the pump spot, controls transverse-mode operation of the laser. We use a plano-concave output coupler (OC) with the radius of curvature of 30 mm, high-reflection (HR) coated at 1080 nm, and anti-reflection (AR) at 540 nm. The LBO crystal ($2 \times 2 \times 5$ (mm)) should be put as close as possible to the gain chip to obtain a higher power density of the fundamental frequency laser. In the experiment, the LBO crystal was about 5 mm away from the gain chip and the diameter of laser spot on it is about 106 μm. We tried to get the fundamental frequency laser

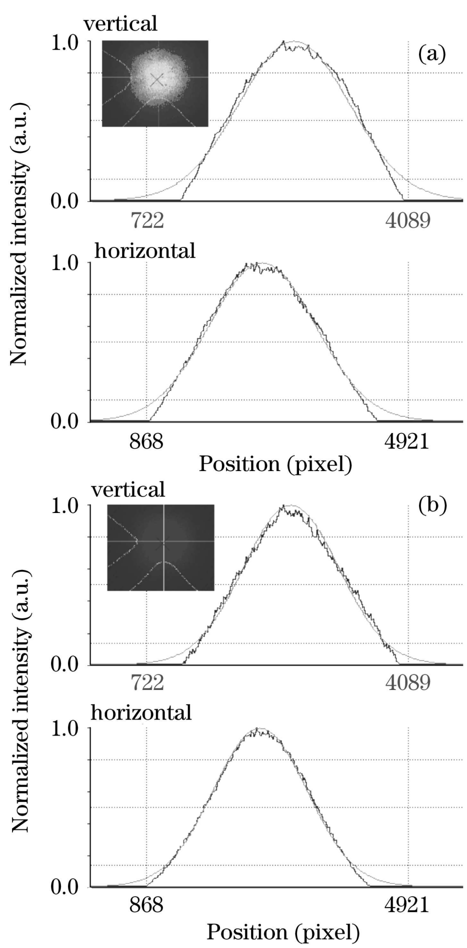

Fig. 3. Spatial profiles of the TEM_{00} mode of the (a) fundamental and (b) harmonic lasers showing near-Gaussian distribution. Insets show the laser spots.

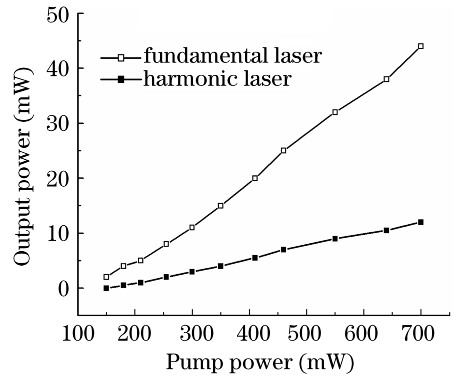

Fig. 4. Fundamental and harmonic output power versus pump power.

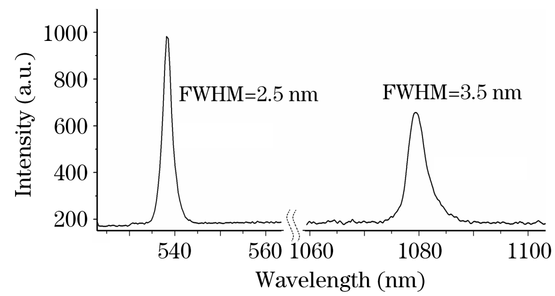

Fig. 5. Spectra of fundamental and harmonic signals.

without LBO. When the heat sink temperature was at 16 °C and the cavity was 28 mm long, a TEM_{00} mode continuous-wave (CW) laser at 1080 nm was obtained. After the LBO crystal was inserted into the cavity, a 12-mW green laser at 540 nm was achieved.

Figure 3 shows the spatial profiles of the TEM_{00} mode of the fundamental and harmonic lasers. The smooth curves are corresponding to the ideal Gaussian distribution, and the laser spots are shown in the insets.

Figure 4 shows the fundamental and harmonic output power versus the pump power. The corresponding frequency doubling efficiency is about 30%.

Figure 5 shows the operating spectra of 1080-nm fundamental and 540-nm harmonic signals, the widths (full-width at half-maximum, FWHM) of them are about 3.5 and 2.5 nm, respectively. In the experiment, either the spectral width or the power of fundamental signal would partly influence the conversion efficiency.

In conclusion, we demonstrate the 540-nm VECSEL by using LBO as nonlinear crystal. A 12-mW frequency-doubled output has been reached when the fundamental frequency output is 44 mW at 1080 nm. Future work includes increasing the fundamental power and narrowing the spectrum of it, then increasing the frequency doubling efficiency. Meanwhile, miniaturizing the size of the laser will make the green VECSELs portable.

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References

1. M. Schulze and A. Masters, Laser Focus World **42,** (12) 77 (2006).
2. S.-H. Park, J. Kim, H. Jeon, T. Sakong, S.-N. Lee, S. Chae, Y. Park, C.-H. Jeong, and G.-Y. Yeom, Appl. Phys. Lett. **83,** 2121 (2003).
3. M. Müller, N. Linder, C. Karnutsch, W. Schmid, K. P. Streubel, J. Luft, S.-S. Beyertt, A. Giesen, and G. H. Döhler, Proc. SPIE **4649,** 265 (2002).
4. M. Jacquemet, M. Domenech, G. Lucas-Leclin, P. Georges, J. Dion, M. Strassner, I. Sagnes, and A. Garnache, Appl. Phys. B **86,** 503 (2007).
5. W. Seelert, S. Kubasiak, J. Negendank, R. von Elm, J. Chilla, H. Zhou, and E. Weiss, Proc. SPIE **6100,** 610002 (2006).
6. S. Lutgen, M. Kuehnelt, U. Steegmueller, P. Brick, T. Albrecht, W. Reill, J. Luft, B. Kunert, S. Reinhard, K. Volz, and W. Stolz, Proc. SPIE **5737,** 113 (2005).
7. R. Hartke, E. Heumann, G. Huber, M. Kühnelt, and U. Steegmüller, Appl. Phys. B **87,** 95 (2007).
8. G. B. Kim, J.-Y. Kim, J. Lee, J. Yoo, K.-S. Kim, S.-M. Lee, S. Cho, S.-J. Lim, T. Kim, and Y. Park, Appl. Phys. Lett. **89,** 181106 (2006).
9. J. Lee, S. M. Lee, T. Kim, and Y. Park, Appl. Phys. Lett. **89,** 241107 (2006).
10. S. Cho, G. B. Kim, J.-Y. Kim, K.-S. Kim, S.-M. Lee, J. Yoo, T. Kim, and Y. Park, IEEE Photon. Technol. Lett. **19,** 1325 (2007).
11. L. Fan, T.-C. Hsu, M. Fallahi, J. T. Murray, R. Bedford, and Y. Kaneda, Appl. Phys. Lett. **88,** 251117 (2006).
12. L. E. Hunziker, C. Ihli, and D. S. Steingrube, IEEE J. Sel. Top. Quantum Electron. **13,** 610 (2007).