Continuous-wave dual-wavelength operation of a distributed feedback laser diode with an external cavity using a volume Bragg grating

Yujin Zheng*, Takashi Sekine, Takashi Kurita, Yoshinori Kato, and Toshiyuki Kawashima

Central Research Laboratory, Hamamatsu Photonics K.K., Hamamatsu 431-1202, Japan

*E-mail: y-zheng@crl.hp.co.jp

Received October 16, 2017; accepted November 30, 2017; published online February 8, 2018

We demonstrate continuous-wave dual-wavelength operation of a broad-area distributed feedback (DFB) laser diode with a single external-cavity configuration. This high-power DFB laser has a narrow bandwidth (<0.29 nm) and was used as a single-wavelength source. A volume Bragg grating was used as an output coupler for the external-cavity DFB laser to output another stable wavelength beam with a narrow bandwidth of 0.27 nm. A frequency difference for dual-wavelength operation of 0.88 THz was achieved and an output power of up to 415 mW was obtained. The external-cavity DFB laser showed a stable dual-wavelength operation over the practical current and temperature ranges.

© 2018 The Japan Society of Applied Physics

High-power broad-area laser diodes (LDs) are the most commonly used optical sources in a wide range of applications because of their compact size, high efficiency, and low cost. However, the spectral linewidths of Fabry–Perot LDs are typically in the 2–4 nm range, which is too wide for some of the more demanding LD applications, including solid-state laser pumping,1,2) alkali-vapor laser pumping,3–6) and spin-exchange optical pumping.7,8) Spectrum narrowing has been achieved in high-power LDs using both internal and external techniques. External-cavity techniques using volume Bragg gratings (VBGs)9–12) have been used to narrow the spectral linewidths of these LDs to the 0.014–0.4 nm range. In 2011, Vijayakumar et al. reported an output power of 5 W with a narrow linewidth of 0.2 nm from a VBG-coupled tapered LD bar.13) We have recently reported a reduction in the spectral bandwidth of spatial beam-combining high-power LD stacks to 0.31 nm, with a 581 W peak power output for quasi continuous-wave operation when using a single VBG.14) However, complete locking of the wavelength for continuous-wave broad-area LDs is difficult in the practical current and temperature ranges because of the wavelength thermal shift of high-power LDs.1,9,12) Another potential linewidth reduction measure involves direct integration of a Bragg grating into the internal laser cavity. An output power of 1.1 W with a spectral width of 90 pm has been reported for continuous-wave 893 nm distributed feedback (DFB) lasers.15) In 2013, Garrod et al. reported high-efficiency 1 W output continuous-wave DFB lasers that operated at 1.4 µm with a linewidth of 0.5 nm, and the wavelength thermal shift of the DFB lasers (0.1 nm/°C) was much smaller than that of the broad-area LDs (0.45 nm/°C) in a temperature range of 10 to 30°C.16) Recently, we have reported a stable-spectrum DFB LD with a narrow linewidth of 33 pm that used a VBG.17)

Dual-wavelength lasers have also been rapidly developed for a wide variety of applications, including THz-wave generation, interferometry, and imaging systems. Dual-wavelength operation has also been achieved in LDs using external techniques. Dual-wavelength generation was reported with a maximum output power of 186 mW and a stable spectral separation of 0.62 THz from a quantum-dot-based medium that used a single VBG.18) Zolotovskaya et al. demonstrated both continuous-wave single- and dual-wavelength generations with a narrow bandwidth of 0.33 nm and a stable spectral separation ranging from 0.16 to 2.05 THz from a broad-area LD when using five VBGs at a drive current of 3 A.19) In 2011, Chi et al. reported that the frequency difference between the two wavelengths of their dual-wavelength laser was tunable from 0.5 to 5 THz when using a tapered amplifier with two diffraction gratings.20) We have recently demonstrated tunable continuous-wave dual-wavelength operation from +6.42 nm (2.63 THz) to −16.94 nm (7.1 THz) in an external-cavity superluminescent diode when using a VBG and a diffraction grating.21) However, to apply these techniques effectively, a significant number of additional optical components with precise alignment requirements were required to form two external cavities simultaneously.

In this work, we demonstrate the high-power continuous-wave dual-wavelength operation of a single external-cavity broad-area DFB laser based on the simple use of a VBG. This high-power DFB laser with its narrow bandwidth (<0.29 nm) was used to achieve single-wavelength operation. The VBG was then used as an output coupler to allow the external-cavity DFB laser to lock on another narrow-bandwidth (<0.27 nm) wavelength. On the basis of this external-cavity design, a dual-wavelength operating frequency difference of 1.92 nm (0.88 THz) was achieved and an output power of 415 mW was obtained for dual-wavelength operation at a drive current of 2.5 A. The external-cavity DFB laser showed a stable dual-wavelength operation over the entire practical current and temperature ranges.

Figure 1 shows a schematic diagram of the external-cavity DFB laser. A high-power broad-area InGaAs/AlGaAs DFB laser (Hamamatsu Photonics) was used to perform the experiments. This laser had a center wavelength of ~810 nm and broad areas of 150 × 1 µm² along both the slow and fast axes. The diode’s cavity length was 2000 µm. The beam divergence angles on the slow and fast axes were approximately 4 and 28°, respectively. The front facet of the DFB laser had a 3% reflectivity coating, while the rear facet had a coating with a high reflectivity of 95%. The device threshold current was 1.22 A. An aspheric lens (focal length f = 2.75 mm, numerical aperture NA = 0.55) was used to collimate the divergent beam output by the DFB laser to achieve...
optimal coupling. A VBG with a high reflectivity of 91% was positioned at $Z = 35$ mm to feed the narrow-bandwidth resonating beam back more effectively and also served as a cavity mirror for the external-cavity DFB laser. The VBG uses its wavelength selection function (measured center wavelength $\lambda = 808.09 \pm 0.5$ nm, spectral bandwidth $\Delta \lambda < 0.5$ nm) to reflect only selected spectral components as feedback to the DFB laser’s active area to achieve a narrow bandwidth. The VBG also serves as an output coupler for the external cavity at a selected wavelength, and the rear facet of the emitting element acts as an end mirror for the external-cavity DFB laser. We therefore achieved continuous-wave dual-wavelength operation using a DFB laser with a single external cavity simply through the use of a VBG.

We measured the output spectra of the broad-area DFB laser with and without the external cavity and the reflectance spectrum of the VBG using a fiber-guided spectrum analyzer (Ando Electric AQ-6315). Figure 2(a) shows the spectral profile of the original DFB laser at a drive current of 1.13 A, which is below the threshold current. The gain-switching regime of the continuous-wave DFB laser is $\sim 17$ nm FWHM centered at 809.36 nm, in which the emission of any wavelength can resonate to become emit laser, when the gain of the cavity is over the threshold for the wavelength. Figure 2(b) shows the measured reflectance spectrum of the VBG. The center wavelength is 808.09 nm with a spectral bandwidth of 0.47 nm FWHM. Figure 3 shows the variations in both the center wavelength and spectral bandwidth of the original DFB laser operating without the VBG as a function of drive current at an operating temperature of 20°C. When the drive current increases from 1.5 to 2.5 A, the center wavelength shifts from 809.74 to 810.16 nm. The center wavelength shift of the DFB laser is thus 0.42 nm/A. The spectral bandwidth (FWHM) remains narrow (0.277 nm or less) over the entire drive current range considered. The spectral profile of the DFB laser without the VBG at a drive current of 2.5 A is shown in the inset of Fig. 3.

Figure 4 shows the center wavelengths and spectral bandwidths of the original DFB laser at different operating temperatures at a drive current of 1.7 A. When the operating temperature increases from 15 to 29.5°C, the DFB laser’s center wavelength shift is 0.068 nm/°C. The spectral bandwidth (FWHM) remains narrow (0.283 nm or less) over the entire temperature range considered.

We then adjusted the VBG to form a continuous-wave dual-wavelength external-cavity DFB laser configuration. Figure 5(a) shows the output spectrum of the dual-wavelength external-cavity DFB laser when operating at a drive current of 2.5 A and a temperature of 20°C. A spectral separation of 1.38 nm (0.63 THz) and a side-mode suppression ratio of $\sim 26$ dB were obtained. Figure 5(b) shows the dual wavelengths of the VBG and DFB modes at an operating temperature of 20°C for different DFB laser drive currents. When the drive current increases from 1.3 to 2.5 A, the center wavelength of the DFB
laser mode in the external-cavity DFB laser changes from 809.66 to 810.2 nm. The center wavelength shift is 0.45 nm = °C. The center wavelength of the VBG-locked mode varied from 808.7 to 808.82 nm. The spectrum difference between the two wavelengths changed from 0.96 nm (0.44 THz) to 1.38 nm (0.63 THz).

Figure 6 shows the output spectra of the dual-wavelength external-cavity DFB laser at different DFB laser operating temperatures and a drive current of 2.5 A. When the DFB laser operating temperature increased from 16.1 to 29.8 °C, the center wavelength of the DFB laser mode also changed from 809.84 to 810.8 nm, which is a center wavelength shift of 0.07 nm/°C. The center wavelength of the VBG-locked mode varied from 808.76 to 808.88 nm, which was located at the long wavelength side of the VBG’s reflectance spectrum (FWHM). The long center wavelength shift arose from the greater emission gain at the longer wavelength, because the gain peak of DFB was located at the long wavelength side of the VBG’s reflectance spectrum, as shown Fig. 2(a). The tunable spectrum difference between the two wavelengths changed from 1.08 nm (0.5 THz) to 1.92 nm (0.88 THz).

The output efficiency is defined as the ratio of the total output power of the external-cavity DFB laser to that of the original DFB laser without the VBG. Figure 7(a) shows the measured total output power and output power for each mode and the output efficiency of the external cavity as functions of the drive current at an operating temperature of 20 °C. The total output power of the external-cavity DFB laser at a drive current of 1.3 A is 30 mW, which is equivalent to 93.8% of the radiated power of the DFB laser without the external cavity. When the drive current is increased to 2.5 A, the external-cavity DFB laser’s output power increases to 415 mW, which is approximately 89.6% of the power radiated by the DFB laser without the VBG. Moreover, the output power for each mode appeared unstable at low drive currents near the threshold. With the increased in drive current, the output power became stable. Figure 7(b) shows the measured total output power of the external-cavity DFB laser and the output power for each mode as functions of the operating temperature at a drive current of 2.5 A. With the increase in operating temperature, the total output power of the external-
In conclusion, we have demonstrated a technique of fabricating a fine-tunable continuous-wave dual-wavelength DFB laser using a single external-cavity design based on a VBG that did not require careful alignment to form the two external cavities required for normal dual-wavelength lasers. At a drive current of 2.5 A and an operating temperature of 29.8 °C, a frequency difference between the two wavelengths of 1.92 nm (0.88 THz) was achieved. The output power of the dual-wavelength DFB laser reached 415 mW. Moreover, the external-cavity DFB laser showed dual-wavelength operation even with apparent changes in current and temperature. This technique is suitable for application to other wavelength ranges.

Acknowledgments The authors would like to thank H. Kitajima and A. Higuchi of Hamamatsu Photonics K.K. for providing the high-power DFB LD.

Fig. 7. (Color online) (a) Total output power and output efficiency of external-cavity DFB laser versus drive current at an operating temperature of 20 °C; solid squares: total output power of the DFB laser without the VBG; solid triangles: total output power of the external-cavity DFB laser with VBG; solid circles: output efficiency of the external cavity with VBG; hollow triangles: output power of the DFB mode; hollow circles: output power of the VBG mode. (b) Total output power and output power for each mode of external-cavity DFB laser versus operating temperature at a drive current of 2.5 A; solid triangles: total output power of the external cavity DFB laser; hollow triangles: output power of the DFB mode; hollow circles: output power of the VBG mode.

cavity DFB laser decreases owing to the heat effect, leading to a low emission. Moreover, the output power for the VBG-locked mode also decreases at a high temperature of 29.8 °C, because the emission spectrum of the DFB laser shifts to longer wavelengths with increasing temperature. We believe that the output power for the VBG-locked mode can be enhanced further by using a lower-reflectivity coating on the front facet of the DFB laser. Therefore, this external cavity design provides a high-efficiency laser source with a fine-tunable continuous-wave THz frequency difference that can be used as a light source in THz device applications.