Characteristics of a Dual-Wavelength Semiconductor Laser Near 1550 nm

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Abstract— The implementation of a widely tunable, dual-wavelength semiconductor laser near 1550 nm is reported. The characteristics of its operation under different conditions of injection current and output feedback are discussed. Because the gain spectrum of this laser varied significantly with the injection current level, the signals of the two oscillating wavelengths interplay through the competition for the carriers. Generally, the feedback of the signal of one wavelength enhanced its own output power and suppressed the other unless the gain of the former is significantly lower than the later.

Index Terms—Laser tuning, semiconductor lasers.

THE STUDY on external-cavity semiconductor laser is beneficial to controlling and improving laser characteristics, exploring laser principles and physical phenomena. Tunable single-longitudinal-mode external-cavity semiconductor lasers have been applied to optical communications, high-resolution measurements of displacement, spectroscopy and so on [1]–[3]. Meanwhile, dual-wavelength semiconductor lasers are attractive for the applications of interferometry, wavelength-division-multiplexing (WDM) communications, laser dynamics study, etc. Although several dual-wavelength semiconductor lasers have been implemented [4], [5], they were mostly based on GaAs–AlGaAs materials with wavelength limited below 1 μm . Recently, a tunable dual-wavelength semiconductor laser near 1500 nm based on a grating-lens external cavity structure was reported [6]. The wavelength tuning was implemented by controlling the length of the external cavity. In this letter, we report the implementation of a widely tunable, dual-wavelength semiconductor laser near 1550 nm. We used a double-slit to enhance the selectivity of the separation and spectral locations of the two wavelengths. Meanwhile, the dependence of dual-wavelength operation on injection current and output feedback were studied.

The external-cavity laser setup is shown in Fig. 1. It included a commercially available multimode laser element (LD, about 250 μm in length) with one-facet antireflection (AR) coated (10^{-3} – 10^{-4} reflection). The facet without coating served as the output coupler (with lens L3) of the external-cavity laser system. After an aspherical lens (L1) from the AR-coated side of the laser diode the signal was first diffracted by a holographic grating (G1) of 1200 lines/mm and its first-

Fig. 1. Setup of the external-cavity semiconductor laser. M: Mirror. G: Grating. LD: Laser diode. OSA: Optical spectrum analyzer. PM: Power meter.

order diffracted beam was returned by a retro-reflected mirror (M1, the end mirror). This mirror was placed near the focal point of a lens (L2) after the grating. All the lenses were appropriately AR-coated. The dual-wavelength operation was accomplished by placing a double-slit right in front of the end mirror M1. Without this double-slit, single-longitudinal-mode operation was achieved with the continuously tuning range from 1510 to 1610 nm. Typically, the output frequency bandwidth was small than the measurement limit of our Fabry–Perot spectrum analyzer, which was 6 MHz. Also, the frequency drifts with temperature and injection current variations were typically around $-400 \text{ MHz}/^\circ\text{C}$ and $-30 \text{ MHz}/\text{mA}$, respectively, which indicated the stable operation of this laser system.

With the double-slit, stable dual-longitudinal-mode operation could be easily obtained. By translating laterally the double-slit and by changing the separation of the two slits, various output wavelengths and various wavelength separations in the aforementioned tuning range could be achieved. The wavelength separation could be as small as one modal spacing, which was about 1.5 nm. The data trace with label 1 in Fig. 2 shows the spectrum of a typical dual-wavelength output. This figure shows the case of 16 modal spacings.

To understand the interplay between the signals of the two wavelengths, we measured their light output versus current (I – I) dependencies simultaneously. The solid curves connecting the filled squares and circles in Fig. 3 show such dependencies of a case with 1504.7 (short- λ) and 1509.3 (long- λ) nm. We can see that the long- λ signal started to oscillate first at the threshold current around 56 mA. The short- λ signal started to oscillate at a larger injection current near 62 mA. Because of the competition for carriers, the turn-on of the short- λ signal is smoother. In Fig. 3, we also show the electroluminescence (EL) at the two wavelengths. Although not absolutely accurate, EL data indicate more or less the gain

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Fig. 2. Spectra of the simultaneous oscillation of 1503.0 and 1528.4 nm. Data traces 1, 2, and 3 represent the spectra without feedback, with short-wavelength feedback and with long-wavelength feedback, respectively.

Fig. 3. L - I (solid curves with the left ordinate) and EL (dashed curves with the right ordinate) curves of the case of 1504.7 (filled circles) and 1509.3 (filled squares) nm.

levels in laser operation. Meanwhile, laser operation depends not only on the gain level but also on the loss factor of the cavity. Despite of several uncertainties, the L - I and EL data are quite consistent. With the injection current below 60 mA, the EL levels of the two wavelengths are about the same. The long- λ signal started to oscillate first because of its lower loss factor. Beyond 60 mA, the gain level of the short- λ signal became higher leading to its own oscillation. However, the slope efficiency could not be large because its gain level dropped below that of the long- λ signal and failed in dominating the competition for carriers.

Fig. 4 shows the similar data of a case with the two wavelengths at 1503.2 (short- λ) and 1530.0 (long- λ) nm. In this case, the short- λ signal started to oscillate first because of the higher gain near 60-mA injection current. However, its output power started to drop near 66 mA at which the long- λ signal started to oscillate. This result can be attributed to

Fig. 4. L - I (solid curves with the left ordinate) and EL (dashed curves with the right ordinate) curves of the case of 1503.2 (filled circles) and 1530.0 (filled squares) nm.

Fig. 5. L - I curves without feedback (solid curves) and with feedback of the short-wavelength component (dashed curves) of the case of 1511.9 (filled circles) and 1516.6 (filled squares) nm.

the relatively stronger EL and carrier competition capability of the long- λ signal. The behaviors of the two wavelengths in the case of Fig. 4 can be used for current-control frequency switching or modulation.

Next, we consider the effects of output feedback of the laser system [7], [8]. For this purpose, we retro-reflected one of the wavelength components of the laser output with the setup including a grating (G2) and three mirrors (M2, M3, and M4)—see Fig. 1. Although it was difficult to accurately calculate the feedback level, it was estimated to be below 0.1% of the power inside the semiconductor element. Figs. 5 and 6 show the comparisons between the situations without and with feedback in a case of 1511.9 (short- λ) and 1516.6 (long- λ) nm. Without feedback, the two wavelengths had about the same threshold current; however, the output power of the short- λ signal was higher before the injection current reached 70 mA, beyond which it saturated and diminished. As shown in Fig. 5, the feedback of the short- λ signal enhanced the dominance

Fig. 6. L - I curves without feedback (solid curves) and with feedback of the long-wavelength component (dashed curves) of the case of 1511.9 (filled circles) and 1516.6 (filled squares) nm.

of its own oscillation and delayed its saturation. Basically, the effect of feedback here was to reduce the loss factor of the laser cavity. Then, in Fig. 6 the feedback of the long- λ signal caused relatively more complicated interplay between the two wavelength signals. With the feedback, the threshold of the long- λ signal was unchanged; however, that of the short- λ signal was increased. The dominance of the long- λ signal was switched when the injection current was in the range between 63 and 72 mA. This could be attributed to the relatively stronger gain for the short- λ signal within this injection current range.

To observe the effects of feedback from the spectroscopic viewpoint, we fixed the injection current at 70 mA and observed the spectral variations caused by output feedback. Fig. 2 shows the case of 1503.0 (short- λ) and 1528.4 (long- λ) nm. Data traces 1, 2, and 3 represent the spectra without feedback, with short- λ feedback and with long- λ feedback, respectively. We can see clearly that the feedback does enhance its own output. However, the extent of enhancement varies with wavelength. For instance, the feedback of the short- λ signal almost suppressed the oscillation of the long one. Because the feedback changed the oscillation condition, the carrier distribution and hence the refractive-index of the semiconductor element, the modal pattern of the laser system was expected to be slightly shifted. In all of our measurements, the feedback caused a red shift by a spectral range from 0.04 to 0.16 nm. The spectral shift depended on the amount of feedback and the laser output wavelengths. Its measurement was actually limited by the resolution of our spectrum analyzer.

From the viewpoint of carrier distribution among energy states, it might be expected that the interplay between the two

wavelengths of a smaller separation was stronger than that of a larger separation. However, we observed no clear evidence for this expectation. The interplay of the two wavelength signals was essentially controlled by the complicated gain spectrum variations with the injection current level. Such gain spectrum variations depended not only on the subtle EL spectra, but also on the complex coupled-cavity structure. The latter might affect the effective loss factor of the laser cavity.

In summary, we have implemented a widely tunable, dual-longitudinal-mode semiconductor laser based on a commercially available multimode laser element near 1550 nm. The variations of the output power of the two wavelengths with injection current showed different competition situations between them. Under appropriate conditions, injection-current-control frequency modulation or switching was feasible. Also, the implementation of output feedback was shown to generally enhance the oscillation competition of the signal of the same wavelength. Finally, it is possible to implement simultaneous oscillation of three or more wavelengths in our laser system. However, the preliminary results showed the degraded sidemode suppression ratio in three-wavelength oscillation.

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