Simultaneous Generation of Eight Wavelengths With About 20-nm Spacing From a Single Semiconductor Laser

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***Abstract*—Simultaneous generation of eight wavelengths spanning from 1367.1 to 1526.9 nm with about 20-nm channel spacing is achieved using a single semiconductor laser. The full-width at half-maximum of each mode is smaller than 0.3 nm. The sidemode suppression ratio is larger than 28 dB and the ratio of the signal to the background noise is larger than 30 dB. With careful adjustment of the loss for each mode, the power difference among those modes can be less than 3 dB. The performance of the eight-wavelength laser system can be further improved with the reduced loss of the external cavity.**

***Index Terms*—Coarse wavelength-division multiplexing (CWDM), multiple wavelength, optical amplifier, quantum-well (QW) laser, semiconductor laser.**

MULTIPLE-WAVELENGTH laser systems have many potential applications such as a wavelength-division multiplexing communication system, two-wavelength interferometry, laser spectroscopy, differential lidar, optical signal processing, and so on. In the past, many approaches have been used to achieve simultaneous two-wavelength oscillation with a fiber laser or semiconductor laser. Those approaches can be categorized into multiple gain media [1], [2] and single gain medium [3], [4]. Simultaneous four-wavelength oscillation has also been achieved using vertical-cavity laser arrays [5]. Multiple-wavelength oscillation from a single device has the advantage of lower cost and the simplicity of packaging the whole system. However, with only a single device, the number of simultaneous oscillation modes is usually limited by the available bandwidth of the laser gain and the complexity of system configuration. In this work, we demonstrate simultaneous oscillation of eight wavelengths covering from 1367.1 to 1526.9 nm using a single semiconductor laser. The wavelength separation between two adjacent modes is about 20 nm.

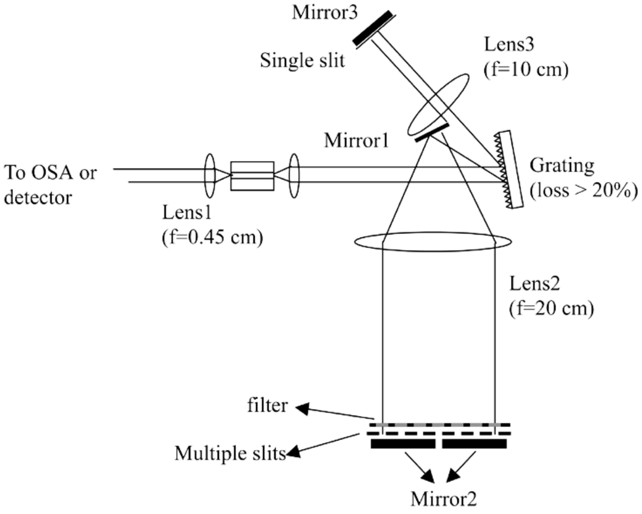

Fig. 1. Experimental setup.

A broad-band semiconductor optical amplifier (SOA) is used as the gain medium. The SOA has a nonidentical InGaAsP quantum-well (QW) structure [6] and has very broad-band characteristics. The external-cavity semiconductor laser with such a gain medium can be tuned from 1300 to 1540 nm under single-wavelength operation [7]. Because the bent-stripe structure used in [7] has large internal loss, here we use a Fabry–Pérot laser diode (FP-LD) instead. The resonant wavelength of the FP-LD is about 1374 nm. The threshold current is about 143 mA. In the experiment of multiwavelength oscillation, the device is operated at the current of 146 mA and the temperature of 22.7 °C

The experimental setup is shown in Fig. 1. The optical path in the external cavity is separated to two different directions by Mirror1. The reason will be discussed later. A handmade filter is placed in front of the multiple slits for controlling the power of each mode. The filter is made up of seven glass bars hung on a box, which is illustrated in Fig. 2. The light impinges on the glass bar is partially reflected and partially transmitted. The output light of the FP-LD is mainly transverse-electric polarized, corresponding to the p-wave with respect to the glass-bar surface. The reflection and transmission coefficients at the glass–air boundary are given by [8]

$$R \equiv -\frac{n_2 \cos\theta_i - n_1 \cos\theta_t}{n_2 \cos\theta_i + n_1 \cos\theta_t} \tag{1a}$$

$$T \equiv \frac{2n_1 \cos\theta_i}{n_2 \cos\theta_i + n_1 \cos\theta_t} \tag{1b}$$

where θ_i, θ_t, n_1, and n_2 are the incident angle, transmitted angle, the refractive indexes in the air and the glass, respectively.

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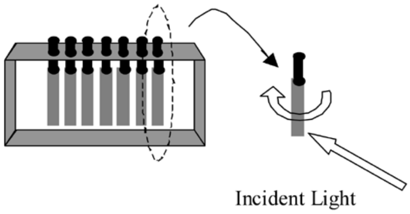

Fig. 2. Detailed configuration of the filter in front of the multiple slits and the interpretation of its function: Rotation of the glass bar.

Therefore, when we rotate the glass bar, θ_i is changed and the amount of the transmitted light varies accordingly. Each glass bar can be rotated separately, so the loss of each light path can be controlled independently.

The slit spacing of the multiple slits is about 2.5 mm. Each slit has a width of ~0.2 mm. The width of the homemade glass bars is also 2.5 mm, so the optical path in the external cavity is aligned in a way that the 20-nm wavelength spacing corresponds to 2.5 mm of the physical spacing. A lens (Lens2) with a large focal length of 20 cm is used for this purpose. On the other hand, the large focal length of Lens2 causes the physical spacing of the longest and shortest wavelength to be as large as 2 cm. As a result, both the shortest wavelength and the longest wavelength pass through the rim of Lens2. This leads to difficulty of simultaneously focusing the rim beams and the center beams due to the lens aberration, making the loss of the rim paths large. In particular, the long-wavelength mode is easily prohibited from lasing by the large loss. Therefore, we use Mirror1 to break the optical path into two different directions. The one with Lens3 and Mirror3, is used for the longest-wavelength mode at 1526.9 nm. The other with Mirror2 and Lens2 is used for the other seven wavelengths. Mirror2 actually consists of two physically separated mirrors [9] in order to have better alignment freedom. The diffraction angle of the grating also has to be properly adjusted to achieve the multiwavelength oscillation. The configuration shown in Fig. 1 is bulky due to the available optics in our laboratory. It can be simplified using miniaturized optics.

The spectrum is measured using an optical spectrum analyzer (OSA). To obtain good signal-to-noise ratio (SNR) of the spectrum on OSA, the coupling efficiency of the output light to the fiber connected to the OSA has to be large. It can be achieved by making the light beam incident normally on the fiber facet, which, however, returns some portion of light back to the laser system, influencing the oscillation of the lasing modes. Therefore, the fiber facet is slightly off the normal direction. The coupling efficiency of the output light to the OSA fiber is about 40%.

The simultaneous generation of multiple channels could be achieved by careful adjustment of the losses in the filter. The experimental spectrum of the eight wavelengths is shown in Fig. 3. Simultaneous generation of eight wavelengths with the channel spacing around 20 nm is demonstrated. The eight wavelengths (in nanometers) are 1367.1, 1390.7, 1408.8, 1436.5, 1451.1, 1477.4, 1494.5, and 1526.9, as demonstrated in Fig. 3. The wavelength spacing is not the same because the handmade slits do not accurately correspond to the wavelength spacing. In addition, the glass bar is 1 mm thick. It could cause the refraction of light to experience some wavelength shift. With better design and adjustment of the filter, the channel spacing could be controlled accurately. The losses introduced by the glass bars for simultaneous eight-wavelength oscillation with the approximately same power are measured and listed in Fig. 3. The loss is defined as the percentage of optical power that does not transmit through the glass along the path of the lasing mode. The center modes need a larger loss because the SOA has a larger gain at the center wavelengths.

Wavelength (nm)	Loss (%)
1367.1	10.7
1390.7	8.6
1408.8	24.1
1436.5	38.8
1451.1	34.0
1477.4	26.7
1494.5	9.9
1526.9	0

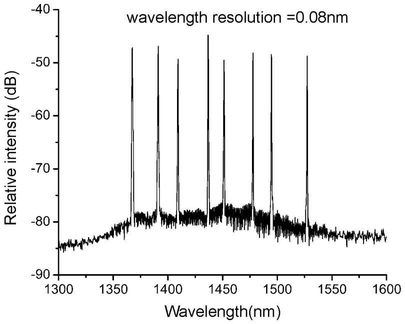

Fig. 3. Experimental spectrum of the eight wavelengths. The wavelengths of the modes (from left to right, in nanometers) are 1367.1, 1390.7, 1408.8, 1436.5, 1451.1, 1477.4, 1494.5, 1526.9.

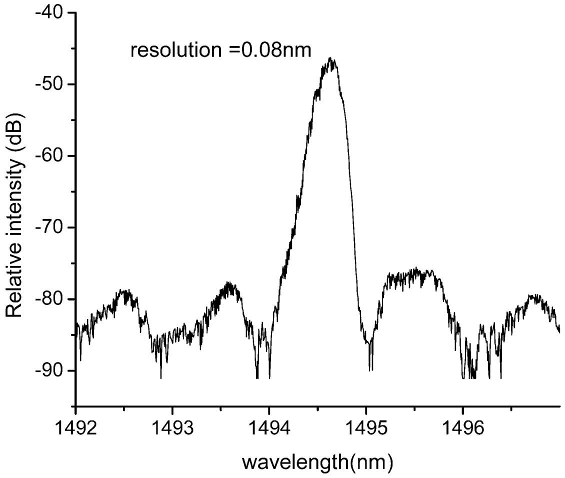

Fig. 4. Detailed spectrum of the mode at 1494.5 nm.

The detailed spectra of some individual modes are shown in Fig. 4. The sidemode suppression ratio (SMSR) is larger than 28 dB. The ratio of the peak power of the lasing mode to the background is larger than 30 dB. This measurement is limited by the coupling efficiency of the output light to the optical fiber connected to the OSA. If the coupling efficiency is increased, the power ratio to the background level will increase.

The absolute power of each mode is about 0.27 mW. The power difference of each mode can be made smaller than 3 dB when the orientation of each glass bar is properly adjusted. The full-width at half-maximum (FWHM) of each mode is smaller than 0.3 nm.

The loss introduced by the glass bar influences the relative power of each mode. This loss is calibrated with the following procedures. First, the laser is operated at one of the eight wavelengths without the use of the homemade filter. Second, a commercial variable ND filter of wheel type is placed at the laser output to experiment on the relation of the ND filter rotation angle and the loss of the ND filter. Third, the ND filter is moved to the location of the homemade filter in the external cavity. The relation between the ND filter rotation angle and the laser output power can be obtained. Combining the relations obtained in Steps 2 and 3, we have the variation of the output power with the loss inserted in front of the slit at that particular wavelength. Those steps are repeated for all eight wavelengths. Then the variable filter is removed and the homemade glass bar is used instead. With the other seven wavelengths blocked, the loss introduced by the glass bar at a certain orientation can be identified.

Our experiment also shows that by increasing the loss of some modes, the oscillation of those modes can be eliminated, while other modes remain oscillating with small change of their relative power. In other words, random selection on some of the eight channels is possible by adjusting the loss for each mode. The above phenomenon and the simultaneous oscillation of eight wavelengths indicate that the competition among those modes is weak. The reason is possibly because the gain spectrum is broad, so the gain is simultaneously contributed from different types of QWs. The carrier transport between QWs is a relatively slow process (typically >5 ps), compared to the intraband relaxation (typically <1 ps). In addition, the short-wavelength mode could provide some gain to the long wavelength due to the anticompetition [10]. Thus, the competition is weak. More than eight channels with the same spectral separation should be possible with a better cavity layout.

Our experiment shows that the broad-band SOA [6] is able to support gain simultaneously for eight widely separated coarse wavelength-division multiplexing (CWDM) channels. This laser system can also be used to simplify optical system parallel testing and potentially used for CWDM applications. For the latter applications, the individual modulation of each wavelength is necessary. This could possibly be achieved by adding a modulator in each wavelength path and shortening the external-cavity configuration. However, cost reduction will need some effort.

In conclusion, simultaneous generation of eight wavelengths is demonstrated from a single semiconductor laser with a broadband gain medium, spanning from 1367.1 to 1526.9 nm. The channel spacing is about 20 nm. With careful adjustment of the loss for each mode, the power difference among those modes can be less than 3 dB. The SMSR is larger than 28 dB, and the SNR is larger than 30 dB. The FWHM of each mode is smaller than 0.3 nm. Better performance can be obtained with reduced loss of the external cavity.

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