Development of a variable spectral-width, wavelength-tunable light source using a superluminescent diode with optical feedback

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We have constructed a variable spectral-width, wavelength-tunable light source using a non-fiber-coupled broadband superluminescent diode device with an optical feedback mechanism. As lasing occurs, a strong output light which is linearly polarized and monochromatic is obtained. The spectral width varies with the injection current and the optical feedback ratio. By incorporating a dispersing prism into the feedback branch, a wavelength-tunable, external-cavity-feedback laser source is achieved. The result is a convenient, inexpensive apparatus suitable for experiments in undergraduate optics courses.
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I. INTRODUCTION

Broadband light sources such as light-emitting diodes (LEDs) and superluminescent diodes (SLDs) have been widely used in optical measurements and optical communications.[1] High-power LEDs have been widely used in traffic signal lights, automotive brake and tail lights, large-area displays, and television displays, for example. In addition to applications in optical gyroscopes, SLDs play an important role in optical coherence tomography systems,[2,3] which are often used to observe biological tissue.

The structure of a typical SLD is very similar to that of a laser diode.[1] However, the internal optical feedback and the stimulated emission are massively suppressed due to the antireflection coatings on the end surfaces of a general SLD device with a straight waveguide.[3,4] Therefore, this type of SLD can be viewed alternatively as a laser diode with a higher threshold current. SLDs with a tilted waveguide can also significantly reduce the stimulated emission without the requirement for antireflection coatings on both facets; such SLDs can deliver broadband light with high optical power but low intensity noise.[5] The tilted waveguide of the gain medium is oriented at 7° to the normal of the facet to eliminate the facet retroreflectivity and avoid the double-path amplification of spontaneous emission. A bent-waveguide SLD has also been demonstrated[6] and can be used in an external-cavity semiconductor laser.[7] A high-power semiconductor optical amplifier that uses a tapered-waveguide device has also been proposed.[8,9]

SLDs have high optical power (such as laser diodes) and high spatial coherence; however, they have low temporal coherence due to their broad optical spectrum, which is similar to that of LEDs.[10] The extremely high optical gain in a SLD active region may result in significantly high optical power sensitivity to external optical feedback and cause significant difficulty when conducting an optical coherence tomography experiment using a non-fiber-coupled SLD device as the broadband light source. If optical isolators are not used, the intensity of the output light can be amplified after the occurrence of the stimulated emission due to optical feedback, and evident variations in the optical polarization state and spectrum shape can also be observed. Although commercial external-cavity semiconductor lasers and semiconductor optical amplifiers have been developed by using fiber-coupled SLD gain chips,[10] we are motivated to investigate the performance of an inexpensive non-fiber-coupled SLD chip in building an external-cavity-feedback laser source system.

The development of external-cavity semiconductor lasers by using various light diodes has been popular for several decades because, in a fiber communication and a fiber sensor system, the linewidth and spectral characteristics of a single-mode semiconductor laser are significantly affected by optical feedback from the numerous optical component interfaces.[11–13] The construction of external-cavity semiconductor lasers using various SLDs has also been demonstrated.[7,14] In most cases the SLDs have two output facets and a tilted or bent waveguide. SLDs with only a single output facet and a straight waveguide with antireflection coatings are seldom used for constructing external-cavity semiconductor lasers. Nevertheless, in such compound SLD light source systems, a larger number of optics phenomena can be observed compared to compound laser diode light source systems.

In this paper we discuss an experimental system which uses a non-fiber-coupled broadband SLD device as the light source for observing the difference in the output light characteristics when an optical feedback mechanism is present. In comparison to the popular external-cavity-feedback semiconductor laser which uses a laser diode, the external-cavity-feedback SLD light source provides a novel and simple approach for achieving a spectral-width-tunable light source, which can be controlled by adjusting the SLD injection current or the optical feedback ratio. The intensity stability of the SLD lasing light is also discussed. We successfully achieve a wavelength-tunable, external-cavity-feedback laser source when a dispersing prism is incorporated into the feedback branch of the SLD system. The tunable optical feedback mechanism in the spectral domain can be used to select the output wavelength of the SLD laser source.

II. INFLUENCE OF AN OPTICAL FEEDBACK MECHANISM ON A SLD LIGHT SOURCE SYSTEM

A. Experimental setup

We use a broadband light-emitting device (Hamamatsu SLD 8414-04) (Ref. 15) as the basic light source for the external-cavity-feedback experimental system. This particular device has only one output facet, and hence is seldom used as a semiconductor optical amplifier. A photodiode chip is mounted on another facet within the device package and is

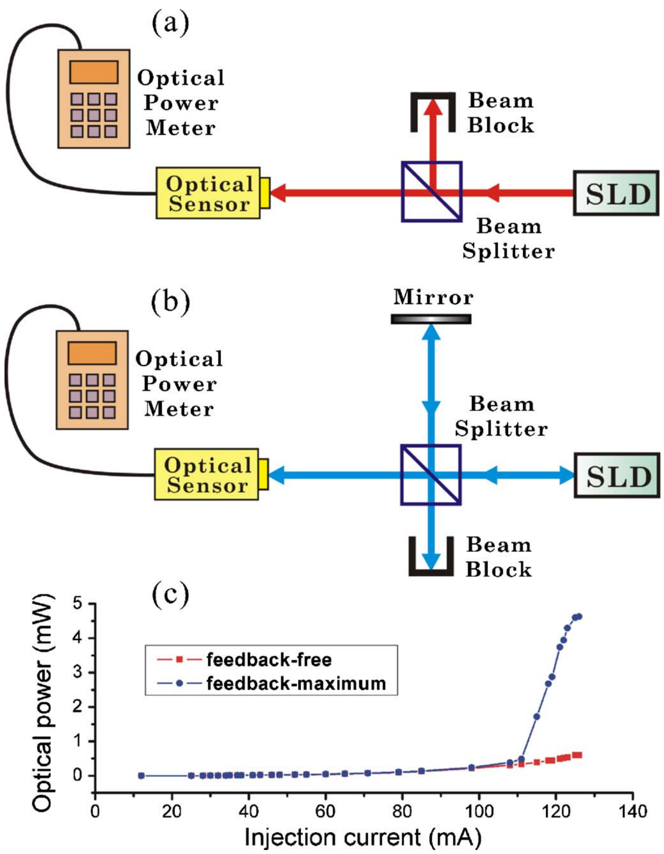

Fig. 1. Experimental setup of the SLD system (a) without optical feedback as the mirror is blocked and (b) with optical feedback when the mirror is used. (c) The measured light power-current characteristic curves without optical feedback and with a maximum optical feedback ratio of approximately 0.37.

prepared for monitoring and stabilizing the SLD output via a feedback circuit or a precision current controller which is not used in our experiments. For a two-output-facet SLD in an external-cavity-feedback laser configuration, the optical-feedback branch and the laser-output branch may be different.[7] In our experiment the optical-feedback branch and the laser-output branch must share the same device facet (see Fig. 1), and only one reflection mirror is used, forming a compound Fabry-Perot resonant cavity together with the SLD facets.

The SLD device has a nominal center wavelength of 836 nm and a nominal spectral width of 19 nm at an operation current of 96 mA.[15] Hence, we conjecture that the composing material is GaAs/AlGaAs with a refractive index of approximately 3.5 as described in Ref. 1 for example. The SLD device is biased by a home-built regulator circuit driven by a dc power supply. The operation current of the SLD can be limited to a safe range of ~0–100 mA as the injection current displayed on the dc power supply is adjusted to between the range ~0–126 mA. The emission light of the SLD device is collimated by an antireflection-coated aspheric focusing lens (ThorLabs C110TM-B) with focal length $f = 6.24$ mm and numerical aperture NA=0.40, which is mounted in a collimation tube (ThorLabs LT110P-B) together with the SLD device.

The output light of the SLD device is separated into the reflection arm and the transmission output arm using a nonpolarizing cubic beam splitter (Lambda Research Optics BNPB-25.4B-45R-550) with a splitting ratio of $R/T=7/3$, where R and T represent the optical intensity of the reflection and the transmission light waves. The light of the reflection arm is reflected by a flat mirror and returned to the beam splitter. We tune the reflection mirror to allow the secondary reflection beam to return into the SLD device to provide the optical feedback. This type of external-cavity-mirror arrangement is similar to that used in Ref. 12. From our experience this method is safer than that used in Ref. 16, where the mirror is placed in the transmission arm and thereby increases the possibility of damage to the lasing SLD device by a photocurrent spike when the beam splitter is removed. We measure the SLD output light characteristics such as its optical power, output spectrum, and polarization state of the transmission output light emerging from the beam splitter for no optical feedback (blocking the reflection mirror) and for the case with optical feedback (utilizing the reflection mirror), respectively.

The SLD output light characteristics are also influenced by the strength of the optical feedback. We control the feedback ratio by placing a variable optical attenuator, which consists of a circular neutral density filter (Edmund Optics W54-082), between the beam splitter and the reflection mirror in the feedback branch. The feedback ratio is defined to be the square of the one-way power ratio $(P_f/P_i)^2$, which is an easy-to-measure reference level; P_i is the initial optical power of the collimated output light from the SLD device and P_f is the optical power of the first-time transmitted light through the neutral density filter in the reflection arm. The coupling efficiency between the SLD device and the external cavity is not included in the feedback ratio because we did not measure it. Therefore, the feedback ratio in this case is similar to the equivalent external cavity reflection coefficient[16] if only the losses in the beam splitter and the variable optical attenuator are considered, along with the assumption that the reflection mirror in the feedback branch has perfect reflectivity.

B. Light power-current characteristics

We measured the optical powers of the SLD output light for various injection currents for the setup without optical feedback [see Fig. 1(a)] and for a setup with a maximum optical feedback ratio of approximately 0.37 in the absence of a neutral density filter [see Fig. 1(b)]. The optical power meter (Advantest TQ8210) is equipped with an optical sensor (Advantest Q82014A) in the spectral range 400–1100 nm. Figure 1(c) shows the measured light power-current (L-I) curves for the two cases, feedback-free and feedback maximum. We see that the L-I curve without optical feedback varies smoothly and grows gradually.[1] That is, the spontaneous emission is dominant in this configuration because the light loss is larger than the gain; thus, the carrier density in the active layer is too low to cause population inversion. The L-I curve with maximum optical feedback has a sharp knee at approximately 110 mA that corresponds to the threshold current required for the occurrence of stimulated emission, which increases as the optical feedback is reduced.[16] If the SLD injection current exceeds the threshold at 110 mA, lasing is caused by the dominant stimulated emission due to the optical feedback in this configuration, and the optical power increases linearly with the injection current for a slope efficiency of approximately 0.288 mW/mA. When the SLD is driven by an injection

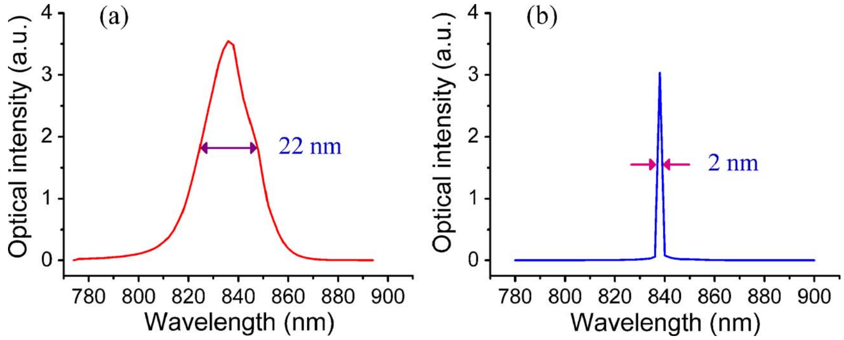

Fig. 2. Measured low resolution output spectra of the SLD system (a) without optical feedback and (b) with maximum optical feedback for a SLD injection current of 126 mA.

current of 126 mA, the measured optical power of the lasing light is approximately seven times the incoherent light power of the SLD system without optical feedback. These observations confirm the occurrence of lasing oscillations in the SLD system with optical feedback.

C. Low resolution output spectrum characteristics

We measured the optical spectrum of the SLD output light using a fast-scan fiber-coupled spectrometer (Ocean Optics S2000) with a low resolution of ≈0.5 nm. The output spectrum of the SLD system without optical feedback is broad with a spectral width (full width at half maximum) of 22 nm and a center wavelength of 836 nm [see Fig. 2(a)]. The output spectrum of the SLD system with maximum optical feedback shows a sharp peak with a narrow spectral width of 2 nm and a center wavelength of 838 nm [see Fig. 2(b)]. Therefore, when lasing occurs due to optical feedback, the SLD output light becomes monochromatic as a result of competition between the lasing modes. Hence, by constructing an external-cavity-feedback light source using a broadband SLD device, we can obtain a narrow-band laser source with higher output power. The lasing wavelength shows a slight redshift with respect to the gain center of the spontaneous emission[6] due to the variation in the refractive index of the gain medium, which is caused by the tremendous increase in the carrier density and temperature.[1]

We next explored the effect on the overall output spectra of increasing the injection current or the optical feedback. We set the SLD feedback ratio to a constant maximum value of 0.37 and then increased the injection current while monitoring the SLD output spectrum. Then, we set the SLD injection current to a constant value of 126 mA and gradually increased the feedback ratio from zero to the maximum value while monitoring the SLD output spectrum.

The measured spectral widths of the SLD output spectra for various injection currents or feedback ratios are plotted in Fig. 3. The SLD system with sufficiently strong optical feedback behaves like a laser source. As the injection current is tuned from 40 mA across the lasing threshold current of approximately 110 mA, the output light intensity of the SLD system with a feedback ratio of 0.37 increases abruptly [see Fig. 1(c)] and the spectral width shrinks significantly [see Fig. 3(a)]. Similarly, a SLD system with sufficiently high injection current, which emits only spontaneous emission light with a broad spectral width if no optical feedback is present, will produce laser oscillations and deliver larger amounts of stimulated emission light with a relatively narrow spectral width when the feedback ratio is increased from zero. For a SLD system driven by an injection current of 126 mA, the spectral width begins decreasing at a feedback ratio of around 0.05 and saturates at a feedback ratio of around 0.15 [see Fig. 3(b)].

In comparison to general laser diodes, the lasing threshold current of a SLD system is very high. The significant advantage of a SLD system with optical feedback is that it provides a spectral-width or temporal coherence-length tunable light source.[17] The temporal coherence length is $L_c = k\lambda^2/\Delta\lambda_{1/2}$, where the coefficient k depends on the spectrum form, λ denotes the center wavelength, and $\Delta\lambda_{1/2}$ denotes the spectral width.[10] If we assume that the SLD spectral profile is a Gaussian, $k \approx 2 \ln 2/\pi$.[18] In our case the predicted temporal coherence length of the SLD system without optical

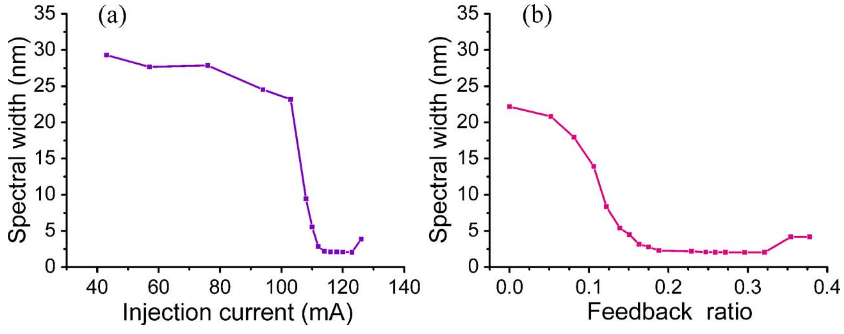

Fig. 3. (a) Variation of the SLD spectral width with the injection current at a constant maximum feedback ratio of 0.37. (b) Variation of the SLD spectral width with the feedback ratio at a constant injection current of 126 mA.

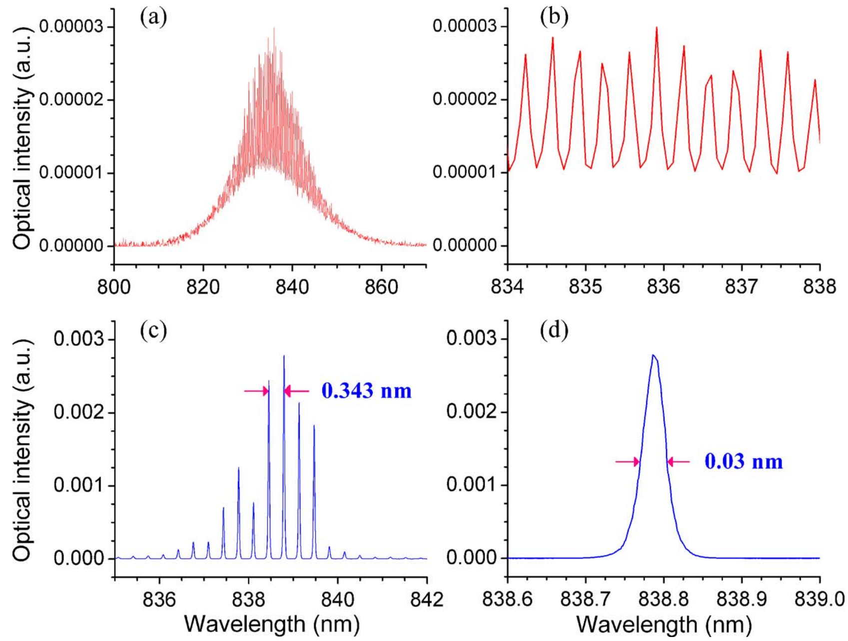

Fig. 4. (a) The measured fine spectrum of the spontaneous emission light from a SLD system without optical feedback. (b) The enlarged fine spectrum of the SLD spontaneous emission. (c) The measured fine spectrum of the stimulated emission light from a lasing SLD system with maximum optical feedback. (d) The enlarged lasing SLD fine spectrum. The SLD injection current is 126 mA.

feedback is $L_c = 0.44\lambda^2/\Delta\lambda_{1/2} = 14\ \mu\text{m}$, where $\lambda = 836$ nm and $\Delta\lambda_{1/2} = 22$ nm [Fig. 2(a)]. For a SLD system with optical feedback, the spectral width narrows and the temporal coherence length increases with the optical feedback. From the low resolution output spectrum [Fig. 2(b)] of the SLD system with maximum optical feedback, it can be observed that the temporal coherence length of the multimode lasing SLD output light becomes $L_c = 0.44\ \lambda^2/\Delta\lambda_{1/2} = 154\ \mu\text{m}$, where $\lambda = 838$ nm and $\Delta\lambda_{1/2} = 2$ nm. This value is close to the temporal coherence length of a typical multimode laser diode,[1] and satisfies the relation of inverse proportionality between L_c and $\Delta\lambda_{1/2}$. Based on the measured spectral linewidth (0.03 nm) of the single (internal-cavity) longitudinal mode discussed in Sec. II D, if the SLD output light can be converted to the single mode by adding a narrow-band optical filter in the feedback branch, L_c can be further increased by approximately two orders of magnitude.

D. Fine spectrum measurement of the resonant modes

The lasing of a SLD system with optical feedback has been illustrated by the change in the optical power, polarization, and spectrum of the output light. To further examine the existence of the lasing oscillation, we detect the output spectrum using an optical spectrum analyzer (Advantest Q8384) with a resolution of 0.01 nm. Figure 4 shows the measured fine spectra of the spontaneous emission light from a SLD system without optical feedback and the stimulated emission light from a SLD system with an optical feedback ratio of approximately 0.37 for a SLD injection current of 126 mA.

From the fine spectrum of the SLD spontaneous emission light [see Fig. 4(a)], we see that the broad spectral profile is mixed with many resonance modes, which implies the existence of optical feedback or light reflection in the internal cavity of the SLD. The spectral ripple is estimated to be as large as 60%, which is considerably higher than that of a tilted waveguide or a bent waveguide.[7] Hence, we conjecture that the SLD used has a straight waveguide,[15] and, consequently, the spontaneous emission inside the waveguide may be amplified and cause interference due to multiple passes and reflections between the antireflection-coated facets. From the enlarged spectrum in Fig. 4(b), we find that the mode spacing of the spectral ripple is equal to that in the lasing SLD fine spectrum [see Fig. 4(c) and the following discussion]. The spectral ripple implies some Fabry-Perot resonance occurs in the SLD waveguide cavity, although external optical feedback is absent. Nevertheless, the waveguide cavity loss continues to remain sufficiently high to prohibit the SLD from lasing at the present level of injection current. As a result, the output spectrum of the SLD system without optical feedback reveals an amplified-spontaneous-emission spectral profile mixed with spectral modulation due to the Fabry-Perot resonance.

From the fine spectrum of the SLD stimulated emission light [Fig. 4(c)], the intermode wavelength spacing $\Delta\lambda$ of the multimode lasing light is measured to be approximately 0.343 nm, which represents the mode spacing of the internal cavity longitudinal modes of the SLD device. The lasing center wavelength λ is ≈ 838.8 nm, and the intermode frequency spacing is given by $\Delta\nu = c/(2\ nL_d) = \Delta\lambda(c/\lambda^2)$, where c denotes the light speed and n and L_d denote the refractive index and the diode cavity length of the gain medium, respectively.[19] Accordingly, the effective cavity length of the SLD active layer is given by $(n\ L_d) = \lambda^2/(2\Delta\lambda)$, which is calculated to be 1.026 mm. We assume that the gain medium has a refractive index $n = 3.5$ and conjecture that the real cavity length L_d of the SLD waveguide is $\approx 293\ \mu\text{m}$,[15] which is a reasonable value as given in Ref. 1. These internal-cavity resonant modes have a linewidth of approximately 0.03 nm [see Fig. 4(d)] and confirm the occurrence of lasing in the SLD system with optical feedback. From another point of view, the lasing SLD fine spectrum [Fig. 4(c)] shows the existence of multiple internal-cavity longitudinal

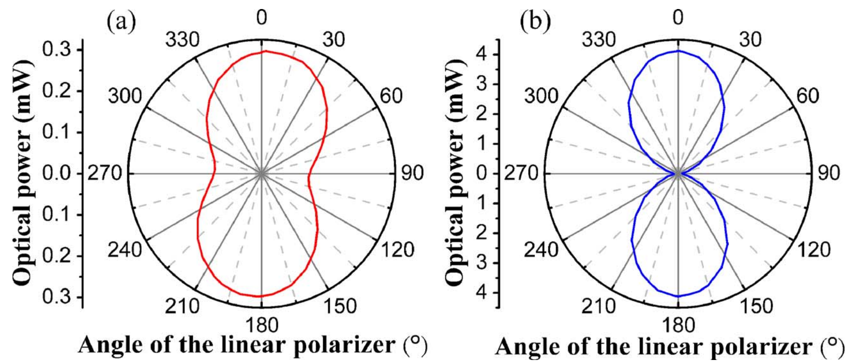

Fig. 5. Variation of the measured transmitted optical power with the angle of the linear polarizer in polar coordinates (a) without optical feedback and (b) with maximum optical feedback and a SLD injection current of 126 mA.

modes, which again implies that the SLD device is an edge-emitting Fabry-Perot structure with multimode laser output.[20] A nearly single-mode oscillation may be achieved by driving the SLD with a larger injection current and strengthening the gain competition between the lasing internal-cavity modes; we did not perform such a test so as not to damage the device.

The length of the external cavity between the SLD device and the reflection mirror in our system is approximately 50 cm, which corresponds to an external-cavity mode spacing of 0.0007 nm. This value exceeds the resolution limit of the optical spectrum analyzer by a huge margin; hence, these modes cannot be observed. A high-finesse scanning Fabry-Perot interferometer would need to be used to observe these external-cavity longitudinal modes.[21] To study the influence of external optical feedback on a single-mode semiconductor laser, alternate light sources such as a vertical-cavity surface-emitting laser diode,[16,21] distributed-feedback laser diode,[22,23] or distributed-Bragg-reflector laser diode[24] can be used. These single-mode laser diodes cannot deliver incoherent broadband light with the same strength as that of the SLD, thereby lessening their pedagogical usefulness. For sufficiently strong optical feedback the laser output spectrum does not remain in the single internal-cavity mode but exhibits multi-external-cavity-mode behavior. The larger the optical feedback, the wider the envelope of the multi-external-cavity-mode spectrum.[16] The SLD output goes into a coherence collapse regime with an increase in the feedback strength.[25] To obtain a single-external-cavity-mode laser output, a volume-Bragg-grating can be used as the reflection mirror in the external cavity to provide an ultranarrow-linewidth optical filtering effect.[26]

E. Optical polarization characteristics

To explore the optical polarization state of the output, we passed the SLD output light through a linear polarizer and measured the optical power variations in the transmitted light while rotating the polarizer. The spontaneous emission output of the SLD system without optical feedback is found to be elliptically polarized with the TE/TM polarization ratio =3:1 [see Fig. 5(a)] and the stimulated emission light of the SLD system with maximum optical feedback is nearly linearly polarized with TE/TM=20:1 [see Fig. 5(b)] for the 126 mA SLD injection current, where TE and TM represent the optical intensity of the transverse-electric and the transverse-magnetic light waves. The transition from elliptical to linear polarization with the onset of lasing is related to the crystal orientation of the gain medium in the SLD active layer.[21] Lasing in the TE mode generally predominates because of the difference in the threshold gains of the TE and TM modes.[1] As a result, we conjecture that the spectral widths of the spontaneous emission light of the SLD system without optical feedback in the preceding low resolution output spectrum experiment are polarization dependent.

F. Intensity stability of the SLD system with optical feedback

We have shown that, if the SLD system is driven by a sufficiently high injection current and subjected to a sufficiently strong optical feedback, it becomes a laser source. However, as shown in Fig. 3, exceedingly high injection currents (>123 mA) or feedback ratios (>0.32) can lead to slight spectral broadening, which occurs due to the mode instability of lasing oscillations and is also observed for a laser diode with external-cavity optical feedback.[27] There are many experimental and theoretical investigations on the intensity fluctuation and nonlinear chaotic dynamics in semiconductor lasers with optical feedback.[20,28,29] We discuss here a simple measurement of the intensity fluctuation of the SLD output light and briefly investigate the relation between the intensity stability of the SLD output light and its injection current and optical feedback ratio.

While increasing the injection current, we monitored the optical power of the output light from the SLD system with the maximum optical feedback ratio of 0.37 using a power meter that is connected to a digital oscilloscope (Agilent 54621A). We then used the digital oscilloscope to automatically calculate the average value and the standard deviation (root mean square) of the scanned data in a 500 s interval. Figure 6(a) shows the measured optical intensity as a function of the injection current with the noise oscillation amplitude indicated by the error bar. This *L-I* characteristic curve has a sharp knee at approximately 110 mA, which corresponds to the threshold current. Strong oscillations are observed when the injection current is ≈113 or 125 mA. The output intensity is unstable near the onset of lasing because the spontaneous emission and the stimulated emission induced by optical feedback compete for the gain of the SLD active region. The output intensity has lower fluctuations for injection currents in the range of ≈116 to 123 mA. Excessive injection current beyond 123 mA again produces large fluctuations in the output intensity.

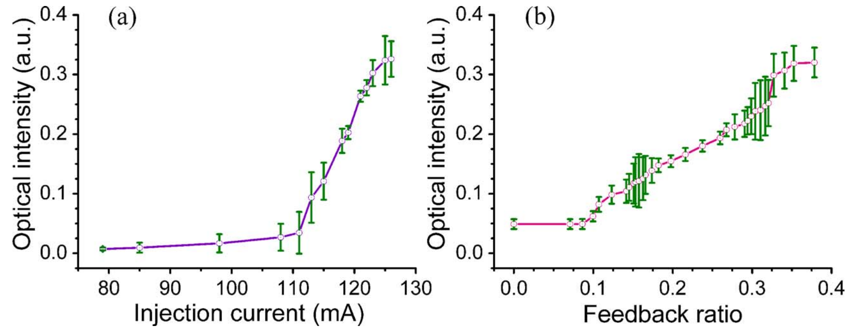

Fig. 6. The measured stability characteristic curves for the variation of the SLD optical intensity with (a) the injection current at a constant maximum feedback ratio of 0.37 and (b) the feedback ratio at a constant injection current of 126 mA. The error bars indicate the fluctuation amplitude of the output light intensity.

We next used a variable neutral density filter to vary the optical feedback ratio and recorded the fluctuating output light intensity of the SLD system using a power meter and a digital oscilloscope as before. The SLD injection current was set at a constant 126 mA. As shown in Fig. 6(b), the lasing begins to occur at a threshold feedback ratio of approximately 0.09. Near a feedback ratio of approximately 0.15, large intensity fluctuations occur. The fluctuations are small over a feedback ratio range of approximately 0.18 to 0.27. The fluctuations increase again near a feedback ratio of ≈ 0.30. We attribute the stronger intensity fluctuations to the generation of multiple external-cavity longitudinal modes at higher injection currents and optical feedback ratios. In brief, we can obtain a more stable multimode laser source by using a SLD system with optical feedback by setting the injection current and optical feedback ratio within appropriate ranges.

For high optical feedback strengths the single-mode (internal-cavity) semiconductor laser coupled to an external cavity can exhibit strong multimode (external-cavity) oscillations,[12,16] and the intensity fluctuation noise can simultaneously be observed.[27] It has been shown that a series of broad peaks in the intensity noise spectrum appears with center frequencies located at $mc/(2L_{\mathrm{ext}})$, where $m = 0, 1, 2, \ldots$; L_{ext} is the external cavity length.[27] These values are equal to the integer multiples of the intermode frequency spacing of the external-cavity longitudinal modes. Hence, the intensity fluctuation noise in a single-mode semiconductor laser with strong optical feedback could result from the modulation of the dielectric constant in the semiconductor diode cavity due to the beating of the electric fields for the external-cavity lasing modes, which are induced by the significantly increased optical feedback strength.[27] The resultant carrier density variation will influence the gain refractive index and the lasing wavelength, and introduce intensity fluctuations in reverse. In some aspects, these observations have implicitly explained why excessive injection current and excessive optical feedback can lead to the unstable output power in the SLD system with optical feedback.

Because the SLD system with optical feedback behaves like a Fabry-Perot-type multimode semiconductor laser, we can introduce the results of a previous study[20] to discuss the stability improvement methods applicable to the external-cavity-feedback SLD system. Multimode semiconductor lasers simultaneously operating in several closely spaced longitudinal modes are used in many applications such as optical data recording and optical data links.[20] Thus, it is also important to investigate the intensity stability of multimode semiconductor lasers exposed to external optical feedback. When the optical feedback exceeds a threshold value, the intensity noise is significantly enhanced and the system performance degrades.[20] The laser will enter a coherence collapse regime, which is associated with a dramatic transition from a continuous-wave periodic state of long coherence length to a chaotic state of short coherence length.[20] Optical chaos in multimode lasers is generally accompanied by mode hopping, which induces intensity fluctuations. A multimode laser will be forced to oscillate in a single longitudinal mode by optical feedback above a threshold level. The laser will hop from a dominant longitudinal mode to another mode randomly. The feedback-induced intensity noise and optical chaos in multimode lasers can be controlled using high-frequency injection-current modulation.[20,30] This technique of chaos control was not performed in our experiment. It can be included in advanced-level optoelectronics courses for exploring the stability performance enhancement of multimode semiconductor lasers for practical applications.

III. SLD WAVELENGTH-TUNABLE LASER SOURCE

In this section we describe the construction of a wavelength-tunable laser source using a SLD.[31] As before, we constructed a SLD system subject to optical feedback (initial feedback ratio 0.37), and then inserted a dispersing equilateral prism (Edmund Optics W43-495) between the beam splitter and the reflection mirror. We were able to select the lasing wavelength by tuning the angle of the reflection mirror slightly, as shown schematically in Fig. 7. An optical grating could also be used to select the output wavelength as discussed in Ref. 14; however, this use would significantly increase the cost. With the SLD injection current set to a constant value of 126 mA, we monitored the variation in the low resolution laser output spectrum using a fiber-coupled spectrometer with a resolution of approximately 0.5 nm while tuning the lasing wavelength. The SLD output light must be attenuated by a neutral density filter before measurement to prevent the saturation of the intensity signals in the spectrometer.

As observed from the low resolution spectra (see Fig. 8), the tunable extent of the laser output wavelength ranges from approximately 830 to 850 nm, reflecting the spectral width of the SLD spontaneous emission light [Fig. 2(a)]. The laser output had a maximum intensity of around 842–844 nm and was measured directly by a power meter to be ≈ 3 mW. Although the SLD injection current was set to 126 mA, prism loss may reduce the feedback ratio slightly. Thus, the carrier density in the SLD active layer will differ from that in the

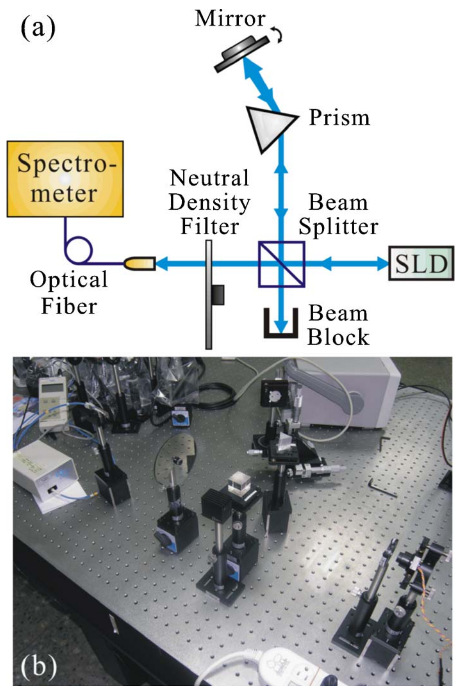

Fig. 7. (a) Schematic diagram and (b) photograph of the experimental setup for the SLD wavelength-tunable laser source.

lasing SLD without a prism. When the lasing wavelength is shifted from 842–844 nm, the output optical intensity will be reduced gradually due to the decrease in gain of the SLD at other wavelengths. The measured spectral widths of the low resolution laser output spectra are nearly 2 nm, and the output spectra are observed to be stable during the measurement. By simultaneously monitoring the SLD lasing output spectrum in a fast-scan and low resolution spectrometer, we can reproducibly and smoothly tune the lasing center wavelength to any desired value in the gain region, because the reflection mirror is mounted on a precision rotary stage capable of being adjusted continuously. We thereby produce a wavelength-tunable laser source using a SLD system with an optical feedback mechanism which incorporates a dispersing prism. For low resolution spectra, the output wavelength could be considered to be continuously tunable. However, for fine spectra, the output wavelength is quasicontinuously tunable due to the multimode operations in both the internal and the external resonant cavities. To significantly enlarge

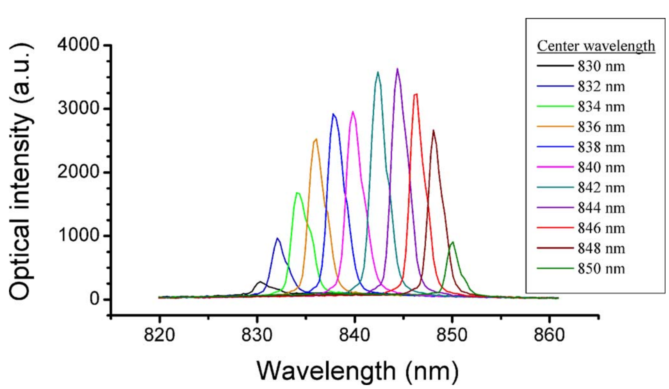

Fig. 8. Representative low resolution output spectra of the SLD wavelength-tunable laser source for a SLD injection current of 126 mA.

the tunable range of an external-cavity-feedback semiconductor laser, the SLD might be changed to that of quantum wells[14,17,32] or quantum dots,[33,34] which is beyond the scope of this paper.

IV. CONCLUSION

We have measured the output light characteristics of a non-fiber-coupled SLD broadband light source subject to an optical feedback mechanism. When lasing occurs, a relatively high intensity output which is linearly polarized and monochromatic can be obtained. By coupling to an external resonant cavity with high reflectivity, a semiconductor gain medium (superluminescent diode), originally displaying spontaneous emission, becomes a semiconductor laser diode displaying stimulated emission. The spectral width of the light source is tunable by varying the SLD injection current or the optical feedback ratio. The lasing wavelength of the light source is tunable by incorporating a dispersing prism into the feedback branch to select the desired wavelength. This simple and novel laser system serves as a low cost tunable light source with multiple functions and is suitable for demonstrating various lasing phenomena in undergraduate optics laboratory courses.

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