High-Power, Ultralow-Noise Semiconductor External Cavity Lasers Based on Low-Confinement Optical Waveguide Gain Media

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ABSTRACT
For the past several years, we have been developing a new class of high-power, low-noise semiconductor optical gain medium based on the slab-coupled optical waveguide (SCOW) concept. The key characteristics of the SCOW design are (i) large (> 5 x 5 μm), symmetric, fundamental-transverse-mode operation attained through a combination of coupled-mode filtering and low index-contrast, (ii) very low optical confinement factor (Γ ~ 0.3-0.5%), and (iii) low excess-optical loss (αi ~ 0.5 cm⁻¹). The large transverse mode and low confinement factor enables SCOW lasers (SCOWLs) and amplifiers (SCOWAs) having Watt-class output power. The low confinement factor also dictates that the waveguide length be very large (0.5-1 cm) to achieve useful gain, which provides the benefits of small ohmic and thermal resistance. In this paper, we review the operating principles and performance of the SCOW gain medium, and detail its use in 1550-nm single-frequency SCOW external cavity lasers (SCOWECLs). We investigate the impact of the cavity Q on SCOWECL performance by varying the FBG reflectivity. We show that a bench-top SCOWECL having a FBG reflectivity of R = 10% (R = 20%) has a maximum output power of 450 mW (400 mW), linewidth of 52 kHz (28 kHz), and RIN at 2-MHz offset frequency of -155 dB/Hz (-165 dB/Hz).

Keywords: semiconductor laser, external-cavity laser, high power, narrow linewidth, low confinement, quantum well

1. INTRODUCTION
High-power, low-noise, single-frequency lasers are important for a variety of applications including coherent communications and laser radar, microwave photonic links, and precision optical metrology. Ultimately, the noise characteristics of these lasers are limited by both the quality factor (Q) of the laser cavity and the laser output power. One important measure of a laser’s noise is the phase noise on the optical carrier. For a laser whose noise is solely due to quantum-limited spontaneous emission, the spectral lineshape is Lorentzian with a full-width-at-half-maximum (FWHM) linewidth $\Delta \nu_0$ given by the Schawlow-Townes equation:

$$\Delta \nu_0 = \frac{4\pi h \nu_0}{P_{out} Q^2}$$

(1)

where $h$ is Planck’s constant, $\nu_0$ is the optical frequency, and $P_{out}$ is the laser output power. This quantum-limited performance is often not obtained due to the presence of other noise sources (e.g., cavity length fluctuations, power-supply noise, 1/f noise).

To date, fiber and solid-state lasers have exhibited superior noise performance relative to semiconductor lasers due to their larger intracavity powers, smaller intracavity losses, and negligible gain/index coupling. The main limitation of fiber and solid-state lasers is that their power conversion efficiency is low (typically < 10%) due to optical pumping inefficiencies. Directly-pumped semiconductor lasers offer the potential of higher power efficiency provided that they can be designed to have sufficient noise performance.

We have recently developed a new class of high-power semiconductor optical gain media referred to as the slab-coupled optical waveguide amplifier (SCOWA) [1]. The SCOWA has several attributes that are beneficial for realizing low-noise optical sources: (i) large (5 x 7 μm) fundamental optical mode due to low index-contrast and mode filtering, (ii) large saturation output power (~ 1 W) due to low optical confinement factor (Γ), and (iii) small excess optical loss ($\alpha_i \sim 0.5$ cm⁻¹) due to low overlap between the mode and the high-loss p-doped cladding layers. SCOWA applications that
have been demonstrated at 1.5-μm include Watt-class power amplifiers, actively mode-locked external-cavity lasers (ECLs) with record-low timing jitter, monolithic passively mode-locked lasers with > 200-mW average output power, and single-frequency fiber Bragg-grating (FBG) SCOWA-based ECLs (SCOWECLs) [2].

For a semiconductor single-frequency ECL comprising an active semiconductor gain medium and a passive external cavity, the modified Schawlow-Townes linewidth can be written as:

$$\Delta \nu_0 = \frac{v_g \left( \Gamma g_{\text{th}} \right)}{4\pi} \left( \frac{1}{N_p V_p} \right) n_p \left( 1 + \alpha^2 \right) \left( \frac{n_a L_a}{n_p L_p + n_p L_p} \right)^2$$

(2)

where $v_g$ is the group velocity in the gain medium, $\Gamma$ is the optical confinement factor in the gain medium, $g_{\text{th}}$ is the threshold material gain, $N_p$ is the photon density, $V_p$ is the optical mode volume in the gain medium, $n_p$ is the population inversion factor, $\alpha$ is the linewidth enhancement factor, $n_a$ ($n_p$) is the group index of the active (passive) section, and $L_a$ ($L_p$) is the length of the active (passive) section. The product $\Gamma g_{\text{th}}$ is the threshold modal gain required from the gain medium to overcome the losses of the active section, the passive section, and the coupling between the sections.

Equation (2) illuminates the advantages of using the SCOWA gain medium to obtain narrow-linewidth from semiconductor ECLs. The advantage of using an external cavity is evident in the last term of Eq. (2) where the length of the passive section is usually much larger than that of the active section (i.e., $n_p L_p >> n_a L_a$). The threshold modal gain $\Gamma g_{\text{th}}$ of a SCOWA-based ECL is reduced by the small loss of the active region (~ 0.5 cm$^{-1}$) and the large SCOWA optical mode which enables efficient coupling between the active and passive sections. The large intracavity power (> 1 W) enabled by the SCOW medium implies that the $N_p V_p$ product is larger than can be attained by conventional gain media.

In this paper, we report the results of an investigation of the relationship between the Q of a high-power SCOWECL cavity and the SCOWECL’s output power, relative intensity noise (RIN), and spectral linewidth. The Q is varied by varying the reflectivity of a fiber Bragg grating (FBG) that serves as a wavelength-selective output coupler in the cavity. The laser performance is compared for FBG reflectivities of $R = 10\%$ and $20\%$. This comparison reveals that the SCOWECL with $R = 10\%$ has a moderate increase in maximum output power relative to $R = 20\%$ (450 vs. 400 mW), but exhibits degraded noise performance. As $R$ was reduced from 20% to 10%, the full-width-at-half-maximum (FWHM) linewidth increased from 28 to 52 kHz, and the RIN at 2-MHz frequency offset increased from -165 to -155 dB/Hz.

2. SLAB-COUPLED OPTICAL WAVEGUIDE EXTERNAL CAVITY LASER CAVITY DESIGN

The SCOWECL consists of four principal elements: a double-pass, curved-channel SCOWA gain medium, lensed fiber, a narrow-bandwidth fiber Bragg grating (FBG), and an optical isolator. A schematic of the external cavity laser is provided in Fig. 1. The lensed fiber and FBG were fusion spliced to create the passive section of the external-cavity laser. The symmetric lensed fiber had a nominal $1/e^2$ spot-size diameter of 6.5 μm and a working distance of 25 μm. This spot size is optimal for coupling to the 5x7 μm SCOWA transverse optical mode. Using this type of lensed fiber, SCOWA-to-fiber coupling efficiency of 90% has been previously demonstrated. Care was taken to minimize the length.
of the lensed-fiber section to minimize the free spectral range (FSR) of the laser cavity. The lensed fiber was cleaved to a length of ~3 cm, which is the minimum length necessary for handling in our fusion splicer. The FBGs used in this work had a center wavelength of 1550 nm, a bandwidth of 20 pm (2.5 GHz), and a reflectivity of either R = 10% or 20%. Separate lensed-fiber/FBG assemblies were constructed to explore the different reflectivities. Prior to splicing, an optical backscatter reflectometer was used to identify the beginning of the FBG index profile so that excess fiber could be removed from the FBG as well. An optical isolator having 60-dB isolation and 0.6-dB insertion loss was spliced to the FBG output to minimize backreflections into the cavity.

The active section of the SCOWECL consists of a 1-cm-long double-pass, curved-channel SCOWA. The SCOWA material was grown via organo-metallic vapor-phase epitaxy on an n-type (100) InP substrate. The material design comprised a 5-μm-thick lightly n-doped InGaAsP waveguide (5x10^{16} cm^{-3} S, λ_G = 1.03 μm), a nominally undoped quantum-well (QW) active region, a p-InAlAs electron blocking layer, and n-type and p-type InP cladding layers. The QW active region contained four 7-nm-thick compressively strained (1%) InGaAlAs wells with tensile-strained (0.3%) InGaAlAs barrier and bounding layers. The peak room-temperature photoluminescence wavelength of the QW layers was 1562 nm. A curved-channel waveguide geometry was used to provide both a high-reflectivity flat facet and a low-reflectivity 5-degree-angled facet. A large (10 cm) radius of curvature was used to minimize radiation losses from the weakly confined waveguide. After depositing appropriate facet coatings, the estimated reflectivity of the rear and front facets was R > 95% and R < 10^{-5}, respectively. The SCOWA was mounted junction-side down to a Cu-W heatsink and temperature controlled using a thermo-electric cooler.

The small-signal gain spectra of the double-pass SCOWA were measured as a function of bias current using the setup shown in Fig. 2. The measurement setup consists of a continuous wave (CW) tunable laser, a polarization controller, a polarization-independent optical circulator, an optical power meter, and the double-pass SCOWA. The polarization controller was adjusted to maximize the SCOWA gain. A lensed-fiber having a 6.5-μm spot-size diameter was used to maximize the fiber-to-SCOWA coupling efficiency. The circulator provides > 30-dB isolation and the circulator losses were calibrated in order to accurately determine the SCOWA gain.

![Figure 2. Measurement setup for the gain characteristics of the double-pass SCOWA.](image-url)
Figure 3 shows the measured gain spectra for bias currents of 1 to 4 A under small-signal input conditions (amplified output signal power < 10 mW). At a wavelength of 1550 nm, the gain is 10.5 dB at 1-A bias and increases to ~21 dB at 4-A bias. It is worth commenting on the gain spectrum at 1-A bias since the SCOWECL threshold current is approximately 1 A, as will be shown below. The SCOWECL 1550-nm operating wavelength, defined by the center wavelength of the FBG, is slightly smaller than the 1553-nm peak wavelength of the 1-A gain spectrum. It is well known that the linewidth enhancement factor ($\alpha$) of a semiconductor gain medium decreases with decreasing wavelength [3]. By designing the laser to operate at a wavelength on the shorter wavelength side (“blue” side) of the gain peak, $\alpha$ is expected to be smaller, thereby reducing the quantum-limited laser linewidth and increasing the sidemode suppression. The ripples in the gain spectra are only present at the larger bias currents when the gain of the amplifier is large. High resolution wavelength sweeps ($\Delta \lambda = 1$ pm) revealed that the period of the ripples is much smaller than the 34.4-pm (4.3 GHz) FSR of the 1-cm-long double-pass SCOWA, indicating that the ripples are not Fabry-Perot fringes associated with the SCOWA. One possible cause of the gain ripples is the leakage of amplified signal power into the tunable laser, causing the laser performance to degrade. The power of the amplified leakage signal from the input port of the circulator will be on the order of the laser output power since the circulator isolation is only 30 dB and the gain of the double-pass SCOWA is as large as 23 dB. If the gain ripples are an artifact of the gain spectra measurement, they will obviously not affect the performance of the SCOWECL when the SCOWA is incorporated into the external cavity.

3. SCOWECL PERFORMANCE COMPARISON FOR 10% AND 20% FBG REFLECTIVITY

3.1 Power-Current (L-I) Characteristics

The SCOWECL cavity was assembled by coupling the active and passive cavity sections using micro-positioners mounted to a vibrationally isolated plate on an optical bench. A plexiglass box was placed over the cavity to minimize thermal fluctuations. The same double-pass SCOWA characterized above was used for all of the SCOWECL results.
Figure 4. Plot of measured (squares) and simulated (solid line) L-I characteristics for a SCOWECL having FBG reflectivity $R = 10\%$. The dashed line represents the theoretical L-I without two photon absorption (TPA) effects. SCOWA baseplate $T = 16 \, ^\circ\text{C}$.

Figure 5. Plot of measured (squares) and simulated (solid line) L-I characteristics for a SCOWECL having FBG reflectivity $R = 20\%$. The dashed line represents the theoretical L-I without two photon absorption (TPA) effects (TPA). SCOWA baseplate $T = 16 \, ^\circ\text{C}$.
reported here. The power-current (L-I) characteristics of the SCOWECL were measured using a variable current source and an optical power meter.

The measured L-I characteristics of the SCOWECLs having FBG reflectivities of R = 10% and 20% are shown in Figs. 4 and 5, respectively. Table 1 provides a comparison of the maximum CW output power, threshold current, and differential quantum efficiency (DQE) for the two different reflectivities. The data reveal that the R = 10% SCOWECL has larger maximum output power, threshold current, and DQE as expected. The ripples in the L-I characteristics are due to longitudinal mode hopping as the bias current is varied. However, at a fixed bias current and optimal coupling between the active and passive sections, the SCOWECLs were able to operate in a stable single-longitudinal-mode for more than ten minutes.

The data of Figs. 4 and 5 also show that the L-I curves for both reflectivities exhibit roll-over for bias current greater than ~1.5 A. We attribute this roll-over to a combination of two-photon absorption (TPA) and thermal effects. We have previously observed that TPA limits the output power of single-pass SCOWAs [4]. The solid lines in Figs. 4 and 5 are simulated L-I characteristics where only the impact of TPA has been included using the TPA parameters previously reported in [4]. Note the excellent agreement between the measured L-I curves and the TPA-limited simulated L-I curves for bias current less than ~4 A. The additional roll-over at higher current (I > 4 A) cannot be explained by TPA and we attribute it to thermal effects.

### Table 1: Power-current (L-I) comparison between R = 10% and 20% FBG SCOWECLs.

| FBG Reflectivity | Maximum CW Output Power (mW) | Threshold Current (A) | Differential Efficiency (%) |
|------------------|-------------------------------|-----------------------|-----------------------------|
| 10%              | 450                           | 1.15                  | 26.7                        |
| 20%              | 400                           | 0.95                  | 21.9                        |

3.2 Relative Intensity Noise (RIN) Measurements

The laser RIN was measured using two different measurement configurations due to the availability of two photodiodes having different current-handling capabilities and different bandwidths. Thus, the RIN was measured over a low frequency range (10 kHz – 2 MHz) and a high frequency range (10 kHz – 10 GHz). A system diagram of the two configurations is provided in Fig. 6. In both configurations, the output of the SCOWECL was first split via a 50:50 coupler. One of the splitter taps is monitored by an optical power meter (PM), while the other tap is directed to a

![Figure 6. Low and high frequency laser RIN measurement configurations.](image-url)
variable optical attenuator (VOA). In the low-frequency RIN measurement configuration, the VOA output is detected by a 1 GHz bandwidth photodiode. The detected signal is then amplified by a 3.15-GHz bandwidth RF amplifier and processed by an Agilent 89410A vector signal analyzer (VSA). In the high-frequency RIN measurement, a 40-GHz photodiode is used along with a 26-GHz RF amplifier. The amplifier output is directed to a HP8565E electrical spectrum analyzer (ESA). The RIN measurement configurations were calibrated using the RIN transfer standard method.

The low-frequency RIN spectra measured at I = 4 A are shown in Fig. 7. Similar RIN performance was achieved at bias currents of 2 and 3 A. The spectra reveal that neither the R = 10% nor the 20% SCOWECLs operate at the shot noise limit for offset frequency less than 2 MHz. However, the noise performance of the 20% FBG laser (-165 dB/Hz) is noticeably better than that of the 10% laser (-155 dB/Hz). Excess RIN at low offset frequencies in single-frequency semiconductor lasers has been attributed to the incomplete suppression of the longitudinal side modes. Therefore, the larger RIN of the R = 10% SCOWECL is likely due to the reduced frequency selectivity of the lower reflectivity FBG. Figure 7 also shows evidence of a spectral peak near 200 kHz. This peak is part of the electronic detection system since it was present even when the optical signal was blocked. The increase in RIN at the lower offset frequencies is likely due to 1/f-noise from either the SCOWA’s current supply or from the SCOWA itself.

The high-frequency RIN spectra measured at I = 4 A are shown in Fig. 8. The spectra reveal that the excess RIN of the R = 20% SCOWECL is below the shot-noise limit across the 10-GHz offset frequency span. The RIN of the R = 10% SCOWECL is slightly higher and the spectrum also exhibits a sharp RIN peak at an offset frequency of ~2.4 GHz. We attribute this peak to the beating of two incompletely suppressed side modes. The estimated side-mode frequency spacing is 1.2 GHz. Thus, the 2.4-GHz peak corresponds to a beat note of modes spaced exactly two free spectral ranges apart. The peak near 1.3 GHz likely corresponds to the beat between two adjacent side modes but is not far enough above the shot noise floor to allow a definitive conclusion. Similarly, the peak at 2.6 GHz seen in the R = 20% SCOWECL RIN spectrum may also be due to side-mode beating. We note the absence of any spectral feature resembling a relaxation oscillation in either of the high-frequency RIN spectra in Fig. 8. Theoretical calculations of the RIN spectra indicate that the relaxation oscillation should have a peak frequency in the range of 1 to 3 GHz and a peak
amplitude of less than -165 dB/Hz. Thus, the relaxation oscillation peak is below the shot-noise floor of the present high-frequency RIN measurement. We also note that the RIN data reveal that the side-mode suppression ratio (SMSR) is greater than 75 dB for both R = 10% and 20%.

3.3 Linewidth Measurements

The spectral lineshape of the SCOWECL output was characterized using the delayed self-heterodyne measurement technique with a fiber delay of 50 km (250 μs). The optical frequency of the delayed signal was shifted by 35 MHz using an acousto-optic modulator to frequency shift the beat spectrum away from 0 Hz. The technical noise associated with the lineshape measurement was minimized by using a low-noise current supply, isolating the SCOWECL from vibrations by using foam blocks and a floating optical table, and enclosing the SCOWECL in a plexiglass box to provide thermal and acoustic isolation.

The measured lineshape spectra of the R = 10% and 20% FBG SCOWECLs at a bias current of 4 A are shown in Fig. 9. The lineshape spectra exhibit a Voigt distribution comprising a Gaussian distribution at low offset frequencies and a Lorentzian distribution at high offset frequencies. This distribution results from a Lorentzian (white-noise limited) source that is spectrally broadened by 1/f noise. The Gaussian linewidth was extracted by performing a Gaussian fit around the center of the Voigt function. The Lorentzian linewidth can estimated by fitting a Lorentzian function to the tails of the lineshape. The Gaussian and Lorentzian linewidths found using this method were 52 kHz and 15 kHz, respectively, for the R = 10% FBG SCOWECL, and 28 kHz and 6 kHz, respectively, for the R = 20% FBG SCOWECL. These results are summarized in Table 2. To our knowledge, these linewidths are the smallest that have been observed for semiconductor-based lasers having output power greater than 100 mW. The data also reveal that both the Gaussian and Lorentzian contributions to the linewidth are larger for the R = 10% SCOWECL. The increase in the Lorentzian linewidth is readily explained by the decrease in the quality factor Q associated with decreasing FBG reflectivity. The increase in the Gaussian linewidth indicates that the 1/f noise is directly related to the SCOWA and is not due to technical noise associated with the current supply or environmental stability. We expect that the SCOWECL linewidth can be further reduced through the use of laser feedback stabilization techniques.

![Figure 8](image_url)

**Figure 8.** High-frequency RIN spectra for (a) R = 10% and (b) R = 20% FBG SCOWECLs. The shot-noise RIN level is indicated in each case with a dashed horizontal line. Photocurrents of 7 mA in (a) and 6 mA in (b) were used to derive the shot noise levels. The SCOWA was operated at 4-A bias and maintained at a baseplate temperature of T = 16 °C in both trials.

| FBG Reflectivity | Gaussian Linewidth (kHz) | Lorentzian Linewidth (kHz) |
|------------------|--------------------------|-----------------------------|
| 10%              | 52                       | 15                          |
| 20%              | 28                       | 6                           |

Table 2: Linewidth fits to R = 10% and 20% FBG SCOWECLs for a current bias of 4 A.
4. CONCLUSION

In this work, we have investigated the impact of FBG reflectivity on the output power and noise performance of a high-power semiconductor slab-coupled optical waveguide external cavity laser (SCOWECL) operating at a wavelength of 1550 nm. The FBG reflectivities investigated were R = 10% and 20%. The results showed that the SCOWECL incorporating a R = 20% FBG exhibited lower RIN and narrower linewidth with only a modest (~10%) decrease in maximum output power. The R = 20% FBG SCOWECL exhibited a maximum output power of 400 mW with RIN below -165 dB/Hz for offset frequencies greater than 2 MHz. Modeling of the L-I characteristics indicate that two-photon absorption (TPA) may limit the output power of external-cavity lasers based on low-confinement semiconductor gain media. The SCOWECL’s Gaussian and Lorentzian linewidths were found to be 28 kHz and 6 kHz, respectively. The combination of high power and low noise enabled by the SCOWA gain medium is expected to have significant impact on analog optical links and coherent optical communication systems.

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