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Experimental investigation on feedback-insensitivity in semiconductor ring lasers

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The insensitivity to optical feedback is experimentally measured for a semiconductor ring laser (SRL) and compared to that of a Fabry-Perot laser (FPL) fabricated with the same technology and on the same material. Analysis of the optical spectra reveals that the SRL remains nearly unaffected for values of optical feedback as strong as -23 dB. Furthermore, through both optical linewidth and self-mixing measurements we show that the tolerance to feedback in SRLs is 25-30 dB stronger than in FPLs. This property makes SRLs very interesting candidates for the development of feedback-insensitive optical sources.

OCIS codes: *(140.5960) Semiconductor lasers; (140.3560) Lasers, ring; (190.3100) Instabilities and chaos.*

Semiconductor lasers are ubiquitous as light sources for optical fiber communications, yet they are very sensitive to any possible backreflection from the downstream of a fiber link. This external feedback light can invoke complex nonlinear dynamics in the laser, causing coherence collapse of the laser emission, which is detrimental to the quality of communication links [1–4]. To minimize the feedback power, semiconductor lasers are often packaged with optical isolators, which are built around magneto-optical materials that cannot be easily integrated monolithically with the lasers. As a consequence, optical isolators significantly add cost to the packaging of the optical source.

Intuitively, semiconductor ring lasers (SRLs) hold promise for eliminating the isolators [5–13]. In fact, a SRL supports longitudinal modes in counter-clockwise (CCW) and clockwise (CW) directions due to its ring geometry but, because of the strong cross gain saturation in quantum well gain media, SRLs tend to exhibit robust unidirectional operation [6–8]. With the SRL lasing in one direction, any downstream backreflection would merely feedback into the other direction. This makes the SRL ideally insensitive to optical feedback as the lasing and feedback light do not interact except through some weak backscattering within the cavity or nonlinear optical processes [6, 7]. Although the feedback-insensitivity has been previously anticipated [7, 12, 14], its magnitude has yet to be quantified by experiments through comparing the SRLs to other lasers such as conventional linear cavity Fabry-Perot lasers (FPLs).

In this Letter, a SRL operating in unidirectional regime is investigated experimentally with regards to its insensitivity to optical feedback. The SRL is compared to a FPL fabricated on the same material and with the same waveguide dimensions. The optical feedback is mimicked by a retroreflecting mirror with a controlled attenuation and with the feedback ratio R defined as the portion of the emission power from the laser that is fed back into the optical cavity. Measurements on the spectral stability and lasing linewidth of the lasers under varying levels of feedback showed that the tolerance to feedback in SRLs is 25-30 dB stronger than in FPLs. This result was confirmed by measuring the intensity of the fed-back field that is coupled to the lasing mode through self-mixing interferometry [15–17].

Figure 1(a) shows the experimental setup for investigating a SRL subject to optical feedback from a retroreflecting mirror. The SRL chip is fabricated on an InP multi-quantum-well structure with lasing wavelength near 1.56 μm when temperature-stabilized at 20°C [18, 19]. A ring waveguide forms the laser cavity with a perimeter of 1.7 mm that corresponds to a free-spectral range (FSR) of about 0.4 nm. Two parallel waveguides are fabricated on the top and bottom of the ring cavity for realizing Couplers 1 and 2. Both output/input waveguides have independent bias sections that act as semiconductor optical amplifiers SOAs 1 and 2 in Fig. 1(a). The two waveguides are tilted to an angle of 12° from the normal to the cleaved chip facets for minimising the Fresnel reflection at the semiconductor-air interface [18, 19].

As previously reported [6], the optical powers for the counter-propagating ring cavity modes switch between the CCW and CW direction with increasing bias current injected into the SRL as shown in the LI curves of Figs. 1(b-i) and 1(b-ii). The normalized bias current J in Fig. 1(b) is the ratio of the bias current to the measured threshold of 114 mA [19, 20].

The experimental setup of Fig. 1(a) mimics a communication link with downstream backreflection. The SRL is biased for

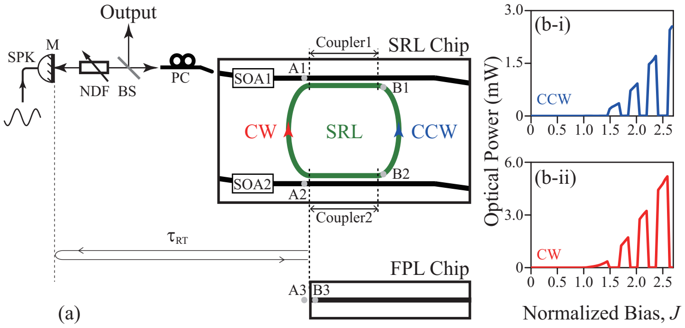

Fig. 1. (a) Schematic of a SRL subject to optical feedback from a retroreflecting mirror. SRL, semiconductor ring laser; SOA, semiconductor optical amplifier; PC, polarization controller; BS, beam splitter; NDF, neutral-density filter; M, retroreflecting mirror; SPK, loudspeaker. The same setup is used to compare the effect of optical feedback on a Fabry-Perot laser (FPL). (b) Optical output power from the SRL chip for the CCW and CW emissions in absence of feedback as functions of the bias current normalized to the threshold.

CCW unidirectional operation and the light is amplified through SOA1 before being coupled to a lensed fiber. The optical signal is then passed through an in-fibre polarization controller PC, collimated to free-space by a collimator and transmitted through a neutral-density filter NDF into a retroreflecting mirror M. A beam splitter BS is inserted in the light path to divert some of the SRL emission for monitoring. The propagation lengths in the optical fiber and free-space give an overall feedback round-trip time τ_{RT} of 33 ns. The polarization of the feedback light entering the chip is aligned to that of the waveguide by PC. Each SOA in Fig. 1(a) introduces an additional loss of 1.5 dB at zero bias current and the coupling loss from the SRL chip to free-space is 1.7 dB due to Fresnel reflection. By adding together the optical fibre coupling loss of 4.7 dB, the BS single-pass transmission loss of 1 dB and the mirror M loss due to imperfect alignment of 5.2 dB, the round-trip feedback attenuation amounts to -23 dB at point $A1$. Coupler 1 has a coupling efficiency of 25%, so an additional 6-dB loss is introduced when feeding light in the CW direction from point $A1$ to point $B1$, which is located inside the ring cavity, immediately to the right of the coupler. Therefore, the ratio of the feedback power at $B1$ to the emission power at $A1$ for the SRL in CCW operation amounts to $R = -29$ dB.

Similarly, when the SRL is biased for CW unidirectional operation, the lensed fiber is moved and aligned to the bottom waveguide in Fig. 1(a). In this case, optical feedback from the mirror M is fed back into the SRL at point $B2$ located immediately to the right of Coupler 2. Although the rest of this work focuses only on the CCW operation, similar feedback-insensitivity is observed for CW operation as well. For either CCW or CW operation, the feedback ratio R can be reduced by increasing the attenuation of the NDF or increased by forward-biasing the associated SOA. As a consequence, the feedback ratio can be tuned over a very wide range extending from -8 dB down to -69 dB.

The same setup of Fig. 1(a) is also used to assess the feedback insensitivity on a FPL that is fabricated using the same waveguide transverse dimensions and material as the SRL. The FPL has a threshold current of 54 mA, a FSR of 0.34 nm, and a wavelength of around 1.55 μm when temperature-stabilized at 16°C. The feedback ratio R for the FPL is defined as the ratio of the feedback power at $B3$, a point located inside the cavity immediately to the right of the output mirror, to the emission power at $A3$, a point located in free-space immediately to the left of the FPL output mirror [15, 16]. The setup and the associated losses are the same as those described in the previous section with the only difference that the lack of an SOA reduces the range over which the feedback ratio can be adjusted to 40 dB, which is the attenuation range of the NDF used in the experiment. By deliberately increasing the losses of the FPL coupling to the optical fibre, the feedback ratio R for the FPL could be adjusted from -40 dB down to -80 dB.

Generally, the optical spectra of the laser emission serve as important indicators on the influence of feedback. The optical spectra of the SRL and FPL are measured in Fig. 2. In all measurements the centre of the horizontal axis is set to the free-running wavelength of the laser. The mirror is kept stationary, whereas the feedback ratio R is adjusted by the NDF in Fig. 1(a). The output light after the beam splitter is measured by an optical spectrum analyzer (Agilent 86140B) with a resolution of 0.06-nm for Fig. 2(a). The optical spectra of the output light is also measured with a finer resolution of 1-MHz through heterodyne detection and reported in Fig. 2(b). For the heterodyning, the output light is combined by a fiber coupler with light from a continuous-wave tunable laser (Agilent 8164A) slightly detuned by less than 0.03 nm with respect to the free-running lasing wavelength, resulting in a beat signal that is detected by a photodetector (u^{2}t XPDV2320R) and monitored onto an electrical spectrum analyzer after a low-noise amplifier [21].

Column (i) of Fig. 2 shows the spectra of the FPL at a current bias of $J = 1.4$. The FPL has essentially a single-mode spectrum with a 15-dB side mode suppression ratio (SMSR) when it is free-running. As Fig. 2(a-i) shows, the single-mode spectrum can only be maintained when the feedback is very weak. The amplitude of the longitudinal modes separated by multiples of the FSR increases when R increases, with a consequent reduction of the SMSR to 5 dB at $R = -53$ dB. The FPL is driven into multimode emission when the feedback is further strengthened to above $R = -43$ dB. For the central emission mode of the FPL, Fig. 2(b-i) shows the detailed optical spectra that reveal the emergence of external cavity modes narrowly separated by $\tau_{RT}^{-1} = 30$ MHz, which often lead to instabilities in the continuous-wave emission characterised by low-frequency fluctuations [1]. When R is higher than only about -60 dB, the external cavity modes are clearly enhanced along with a significant spectral broadening, which is a characteristic of the onset of coherence collapse due to chaotic nonlinear dynamics [22]. These measurements confirm that a feedback of merely $R = -53$ dB is sufficient to disrupt the single-mode continuous-wave operation of a FPL in Fig. 2(a-i) [1], where a feedback with R of only -60 dB can cause spectral broadening of the central emission mode as Fig. 2(b-i) shows.

Column (ii) of Fig. 2 then shows the spectra of the SRL biased at $J = 2.7$. The SRL has a clear single-mode spectrum with a 26-dB SMSR when it is free-running. Even when a strong feedback of $R = -23$ dB is applied, the longitudinal modes separated by multiples of the FSR remain too weak to be observed in Fig. 2(a-ii) because of a nearly unchanged SMSR of 25 dB. The detailed optical spectrum in Fig. 2(b-ii) is also nearly unaffected by the feedback with only a slight sharpening of the lasing mode and no emergence of external cavity modes. Further strengthening the feedback can cause a switching of the lasing direction [18, 20, 23]. Thus, the SRL is maintained in single-mode continuous-wave operation even for a strong feedback ratio R of -23 dB.

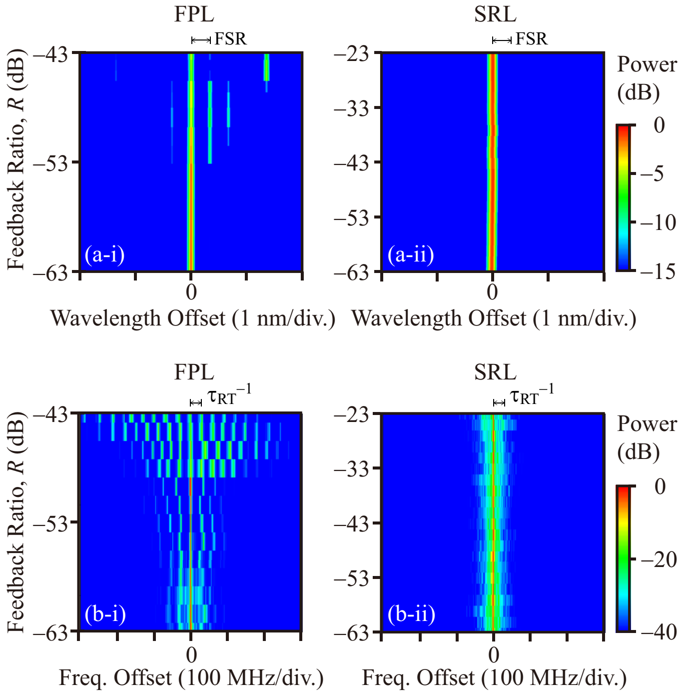

Fig. 2. Optical spectra as the feedback ratio R varies for the (i) FPL and (ii) SRL. The relative optical power is shown in color. The spectra are recorded in (a) 4-nm broad span and (b) 600-MHz narrow span.

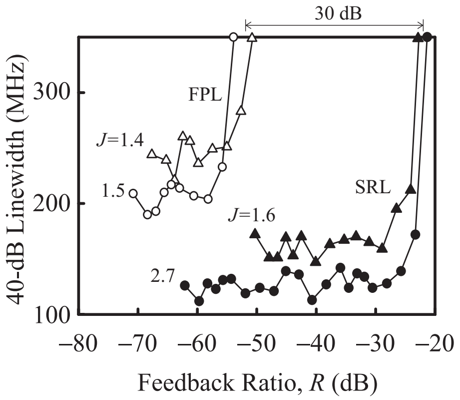

Fig. 3. Optical linewidth of the central emission mode of a laser as a function of the feedback ratio R.

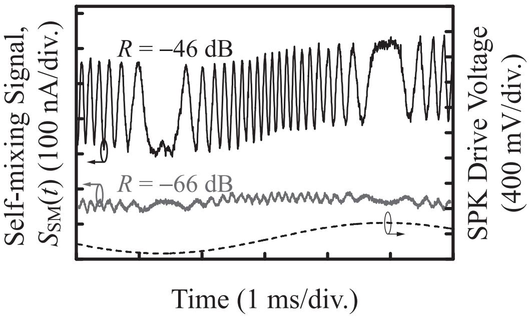

Fig. 4. Self-mixing signal $S_{SM}(t)$ for the SRL subject to feedback from the moving mirror. The feedback ratio $R = -46$ dB (black) and −66 dB (gray). The dashed curve is the drive voltage applied to the loudspeaker.

For completeness, the linewidth corresponding to the optical spectra shown in Fig. 2(b) is also evaluated. In lieu of the usual 3-dB linewidth, the linewidth is measured 40 dB below the peak maximum to reduce measurement errors due to frequency fluctuations of the lasing mode. Figure 3 shows the optical linewidth of the central emission mode as a function of R. For the FPL, the open circles and triangles are obtained at current bias values of J = 1.5 and 1.4, respectively. Both datasets show that the linewidth of the FPL quickly increases as R becomes stronger than approximately −60 dB due to the insurgence of external cavity modes on the onset of chaos, as Fig. 2(b-i) exemplifies. As for the SRL, the closed circles and triangles are respectively obtained at current bias values of J = 2.7 and 1.6. The linewidth of the SRL is nearly unaffected by the feedback until values of R as high as −30 dB, after which an increase of the linewidth is observed. Further increment of R to above −23 dB can finally induce directional switching of the lasing mode in the SRL, as already observed in previous experiments [18, 24]. The results of Fig. 3 clearly shows a 30-dB improvement of the tolerance to feedback for a single-mode continuous-wave operation.

To confirm the figures extracted from the optical spectrum measurements, the effect of the optical feedback on the lasing mode was further evaluated by a very sensitive optical heterodyning technique known as self-mixing [16]. The self-mixing signal quantifies the coupling of the feedback field to the lasing field through backscattering and gain saturation [6, 7]. Figure 4 shows time domain traces of the self-mixing signal on the SRL lasing mode induced by moving the retroreflecting mirror M with a sinusoidal signal. In this measurement, the SRL was biased at J = 2.7 for CCW operation and the mirror in Fig. 1(a) was mounted on a loudspeaker. The mirror vibrates with an amplitude on the order of 10 μm when the loudspeaker is driven by a sinusoidal voltage with a peak-to-peak voltage of 480 mV at 145 Hz, as the dashed curve in Fig. 4 shows. The vibration causes a Doppler shift on the feedback light that, through frequency-mixing with the light inside the laser, modulates the emission intensity of the laser. The self-mixing signal on the laser output is recorded after the beam splitter (see Fig. 1(a)) and is subsequently attenuated to a constant time-averaged value of 2 μW, monitored by an amplified detector (Thorlabs PDA10CS-EC) with a conversion gain of 10^3 A/W. The self-mixing signal $S_{SM}(t)$ is shown as the black solid curve in Fig. 4 when the feedback ratio is set to a value of $R = -46$ dB. The oscillatory self-mixing signal whose instantaneous frequency is proportional to the rate of change of the drive voltage [15, 16] becomes barely observable when R is further reduced to −66 dB, as the grey solid curve in Fig. 4 shows. Self-mixing interferometry is a highly sensitive technique that has been extensively applied in various metrological measurements [17, 25–27] and in the characterisation of optical feedback in semiconductor lasers [16].

The magnitude of the optical feedback can be quantified by measuring the electrical power P_{SM} associated with the oscillation of $S_{SM}(t)$ [16]. The self-mixing signal power P_{SM}, in practice, is measured by sending the signal $S_{SM}(t)$ to a 50-Ω power spectrum analyzer (R&S FSV40) and then integrating the spectrum over a frequency ranging from 0.5 to 20 kHz. The frequency span includes the Doppler shift frequencies, but excludes the frequency of the drive signal to minimise any noise from the signal generator or electrical ground loops. Figure 5 shows the relationship between P_{SM} and the feedback ratio R for both the

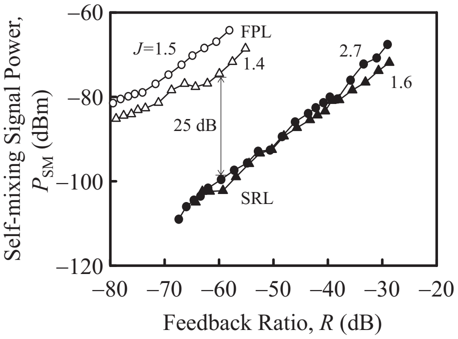

Fig. 5. Self-mixing signal power P_{SM} for a laser subject to feedback from the moving mirror as a function of the feedback ratio R.

FPL and SRL and for different values of bias currents normalised to the lasing threshold.

As expected, the self-mixing signal power P_{SM} in the FPL is stronger than in the SRL because the feedback light directly interferes with the standing-wave laser light inside the cavity, thereby perturbing the charge carriers that yield the intensity modulation. As R increases, P_{SM} generally increases linearly as in other self-mixing experiments [15, 16]. As the bias J increases, P_{SM} also increases due to an increased saturation inside the cavity [16]. In the case of the SRL, the self-mixing signal power P_{SM} is consistently weaker because the feedback light is not co-directional with the lasing light and therefore mixing only occurs through optical nonlinearities or backscattering within the cavity [13, 20]. By comparing the two lasers in Fig. 5, P_{SM} differs by over 25 dB over the feedback range considered in the experiment, a value which is in good agreement with the measurements of Fig. 3. The self-mixing signal on the FPL could only be recorded up to feedback ratios in the order of −55 dB as stronger feedback values perturb the laser excessively with the result of completely distorting the self-mixing signal.

In summary, the insensitivity to optical feedback on SRLs is experimentally verified. Both optical linewidth measurements and self-mixing interferometry indicate that a SRL can tolerate 25-30 dB higher feedback ratios when compared to a FPL under the same feedback conditions. As a consequence, SRLs can maintain single and stable mode lasing operation for extremely strong optical feedback as high as −23 dB, a property which makes them a very interesting option for isolator-free optical sources for telecommunications.

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