Direct modulation bandwidth enhancement of strongly injection-locked SG-DBR laser

A. Bhardwaj, S. Ristic, L.A. Johansson, C. Althouse and L.A. Coldren

Significant enhancement in the direct amplitude modulation bandwidth of an SG-DBR laser has been demonstrated under strong injection-locking conditions, where the wavelength detuning between the master and the free-running SG-DBR slave laser is varied from −8.58 to 13.6 nm. It is demonstrated that the relaxation resonance frequency of a strongly injection-locked SG-DBR laser increases from 1.05 GHz for the free-running case to over 20 GHz.

Introduction: It is well known that the direct modulation bandwidth of a semiconductor laser is limited by the relaxation oscillations arising from the coupled rate equations that describe the dynamics of the carrier and photon densities inside the laser cavity. It has been shown that the relaxation resonance frequency of a laser can be increased using injection-locking, resulting in an enhancement of its direct modulation bandwidth. Strong optical injection-locking has attracted attention recently for its potential for providing high-speed laser transmitters, as it improves the dynamic response of directly modulated semiconductor lasers, as well as for enhancing the relaxation oscillation frequencies, suppressing nonlinear distortions and relative intensity noise, and reducing chirp [1–3]. In the strong injection-locking regime, the optical power of the light injected from the master laser into the slave cavity is much larger than the optical power of the free-running slave laser. Recent demonstrations include enhancement of the resonance frequency beyond 100 GHz in a directly modulated strongly injection-locked vertical-cavity surface-emitting laser (VCSEL) [4].

In this Letter, we consider the injection-locking of a widely tunable sampled grating distributed Bragg reflector (SG-DBR) laser that is designed with high-speed gain and phase modulator sections. We study the direct amplitude modulation response of the SG-DBR laser when it acts as a slave laser and is strongly injection-locked to an external master laser. We demonstrate that a strongly injection-locked SG-DBR laser shows significant enhancement in its direct modulation bandwidth, even when the wavelength detuning between the master and the free-running SG-DBR slave laser is varied between −8.58 and 13.6 nm (corresponding to a frequency detuning of 1.072 and −1.68 THz, respectively). To the best of our knowledge, this is the first demonstration of direct modulation bandwidth enhancement of a strong injection-locked SG-DBR laser over a large wavelength detuning range from its free-running state.

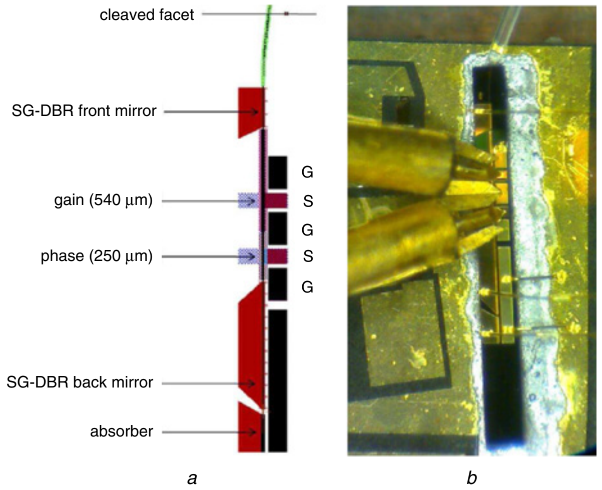

Fig. 1 *Mask layout of SG-DBR laser with high-speed gain and phase modulator sections; and photograph of SG-DBR laser probed using G-S-G-S-G probe with lensed-fibre coupled to its output*

a Mask layout of SG-DBR laser
b Photograph of SG-DBR laser

Device design and fabrication: A widely tunable SG-DBR laser [5] was designed and fabricated using a standard offset quantum well material platform on an indium phosphide (InP) substrate [6] that allows monolithic integration of active and passive waveguide sections. In this platform, light is guided by a 300 nm-thick passive $In_xGa_{1-x}As_yP_{1-y}$ based quaternary 1.4Q bulk layer (with a bandgap corresponding to the energy of a photon at 1.4 µm) that forms a basis for waveguiding, as well as modulation through current injection, or the Franz-Keldysh effect if reverse biased. Above this layer, light couples evanescently to an 'active' compressively strained $In_xGa_{1-x}As_yP_{1-y}$ based quaternary multiple-quantum-well (MQW) layered structure that is present only in the regions that form the active sections of the SG-DBR laser.

The sampled gratings define the front-side and back-side mirrors of the SG-DBR laser. The targeted grating depth is around 100 nm into the 1.4Q layer and the duty cycle is 50%. The front-side mirror consists of five grating bursts, each 6 µm long and repeats periodically with an interval of 61.5 µm. The back-side mirror consists of 12 grating bursts, each 4 µm long and repeats periodically with an interval of 68.5 µm. The width of the surface ridge waveguide is 3.5 µm. The gain section is 540 µm long and the phase section is 125 µm long. The high-speed gain and phase sections have top-side N-metal pads on either side of the corresponding P-metal pad so that they can be probed with a high-speed G-S-G-S-G RF probe. The pitch between the G-S-G-S-G pads is 150 µm. The waveguide beyond the back-mirror is flared and fed into an active region, which acts as an absorber. The access waveguide at the front facet is flared to 5 µm and angled by 7° to suppress reflections. No anti-reflection coating was applied to the front facet of the SG-DBR laser. The layout of the SG-DBR laser is shown in Fig. 1*a*.

Experiment and results: A G-S-G-S-G RF probe was used to apply bias currents to the gain and phase sections of the SG-DBR laser, as shown in Fig. 1*b*. To study the direct amplitude modulation response of the SG-DBR laser, a DC forward-bias current was combined with an RF modulation generated from a vector network analyser (VNA) using a high-speed bias-tee and applied to the gain section of the SG-DBR laser. To characterise the small-signal RF modulation response, the VNA (Agilent 8703A) was calibrated from 130 MHz to 20 GHz to normalise the RF response arising from the electrical front-end of the VNA, the RF cables and the photodetector at the optical front-end of the VNA. The response of the G-S-G-S-G probe was not calibrated and it is embedded in the measured RF response from the VNA. The output from the SG-DBR laser passed through the circulator and was sent to an optical spectrum analyser and the high-speed photodetector at the optical front-end of the VNA. The experimental setup is shown in Fig. 2.

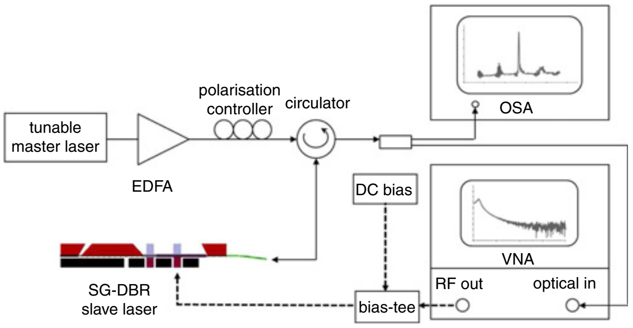

Fig. 2 *Experimental setup to study strong external injection-locking of SG-DBR laser*

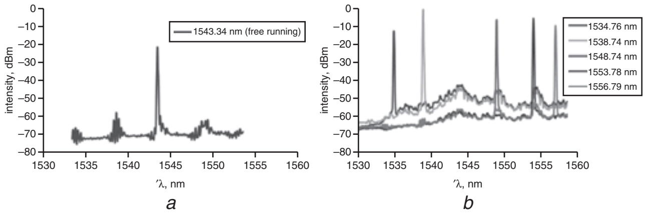

Fig. 3 *Optical spectra*

a Free-running SG-DBR laser
b SG-DBR slave laser strongly injection-locked at different wavelengths

The DC forward bias current applied to the gain section of the SG-DBR laser was 41 mA, just above its lasing threshold. In this study, no bias currents were applied to the front mirror, back mirror or the phase section. The free-running wavelength of the SG-DBR laser was 1543.34 nm and its optical spectrum is shown in Fig. 3*a*. The output from the free-running SG-DBR laser was coupled into a lensed-fibre and the total optical power was measured to be −9.5 dBm.

To study injection-locking of the SG-DBR laser, light from a tunable external cavity laser (which acts as the master laser) was amplified using a high-power erbium-doped fibre amplifier (EDFA) and injected into the SG-DBR laser using the lensed-fibre after passing through a variable optical attenuator, a polarisation controller and the circulator, as shown in Fig. 2. The optical power of the amplified light from the master laser was increased until the SG-DBR laser could be injection-locked to the master laser for large wavelength detunings between the master and the free-running slave lasers. To get an estimate of the optical power injected into the SG-DBR laser, a reverse bias was applied to its gain section. The photocurrent resulting from the absorption of the injected light was measured to be ∼8.8 mA, which corresponds to ∼+8.65 dBm of injected light into the slave cavity. Fig. 3*b* shows the optical spectrum of the SG-DBR laser under strong injection-locking where the wavelength of the master laser is set at different wavelengths varying from 1534.76 to 1556.79 nm (corresponding to a wavelength detuning of −8.58 and 13.6 nm, respectively). It should be noted that the ability to amplify light from the master laser to achieve strong injection-locking outside the 1530–1560 nm range was limited by the gain bandwidth of the EDFA.

The direct amplitude modulation response (S_{21}) of the SG-DBR laser was characterised using an RF electrical power of −10 dBm from the output of the VNA. As shown in Fig. 4*a*, the direct modulation bandwidth of the free-running SG-DBR laser biased at 41 mA is limited by its relaxation resonance frequency of 1.05 GHz. Enhancement of the direct amplitude modulation bandwidth of the SG-DBR laser was observed under strong injection-locking over the entire locking range. Fig. 4*b* shows the direct amplitude modulation response of the SG-DBR laser that is injection-locked at different wavelengths. In each case, the relaxation resonance frequency of the injection-locked SG-DBR laser is larger than 20 GHz, which is the highest frequency that can be measured with the VNA.

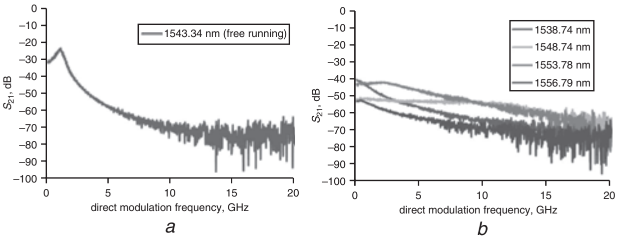

Fig. 4 *Direct amplitude modulation response*

a Free-running SG-DBR laser
b SG-DBR laser strongly injection-locked at different wavelengths

Conclusions: We have demonstrated a significant enhancement of the direct amplitude modulation bandwidth of a strongly injection-locked SG-DBR laser as the wavelength detuning between the master laser and the free-running SG-DBR slave laser is varied from −8.58 to 13.6 nm. The relaxation resonance frequency of the strongly injection-locked SG-DBR laser increases from 1.05 GHz from its free-running state to greater than 20 GHz over this wavelength detuning range.

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One or more of the Figures in this Letter are available in colour online.

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