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Amplitude Modulation Response and Linearity Improvement of Directly Modulated Lasers Using Ultra-Strong Injection-Locked Gain-Lever Distributed Bragg Reflector Lasers

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Directly modulated fiber-optic links generally suffer higher link loss and larger signal distortion than externally modulated links. These result from the electron-photon conversion loss and laser modulation dynamics. As a method to overcome the drawbacks, we have experimentally demonstrated the RF performance of directly modulated, ultra-strong injection-locked gain-lever distributed Bragg reflector (DBR) lasers. The free-running DBR lasers exhibit an improved amplitude modulation efficiency of 12.4 dB under gain-lever modulation at the expense of linearity. By combining gain-lever modulation with ultra-strong optical injection locking, we can gain the benefits of both improved modulation efficiency from the gain-lever effect, plus improved linearity from injection locking. Using an injection ratio of R=11 dB, a 23.4-dB improvement in amplitude response and an 18-dB improvement in spurious-free dynamic range have been achieved.

Keywords : Optical injection locking, Directly modulated semiconductor laser, Gain-lever modulation

OCIS codes : (140.5960) Semiconductor lasers; (140.3520) Lasers, injection-locked

I. INTRODUCTION

Direct modulation of semiconductor lasers has been widely investigated in analog fiber-optic applications such as cable television distribution systems, antenna remoting in cellular networks, and phased arrayed antennas [1]. In digital links, 40-Gb/s transmission through a directly modulated link has been successfully demonstrated [2]. The requirements for analog and digital signal transmissions are quite different. Low radio-frequency (RF) link loss and small nonlinear distortions are needed to achieve good analog performance, while high modulation bandwidth, low chirp and high extinction ratios are important for digital links [3, 4]. Link loss in directly modulated links is mainly due to the electrical-to-optical conversion process in lasers. Several approaches have been proposed to increase the modulation efficiency of semiconductor lasers, including gain-lever modulation [5-7] and cascaded lasers [8-11]. Cascaded lasers achieve higher efficiency by recycling the RF modulating current through multiple lasers connected in series. First proposed using discrete lasers [8], a serial connection of six discrete lasers with a link gain of +3.78 dB was demonstrated. However, the measured link bandwidth was about 60 MHz, whereas the 3-dB bandwidth of the individual lasers was greater than 3 GHz. This was due to the parasitics of the series-connected lasers. To realize a bandwidth closer to the individual components, monolithically-integrated versions were proposed using surface-emitting [9] and edge-emitting lasers [10, 11]. Improved link performance exhibiting > 100% differential efficiency and a spurious-free dynamic range (SFDR) of 120 dB · $Hz^{2/3}$ operating at 500 MHz has been demonstrated [10].

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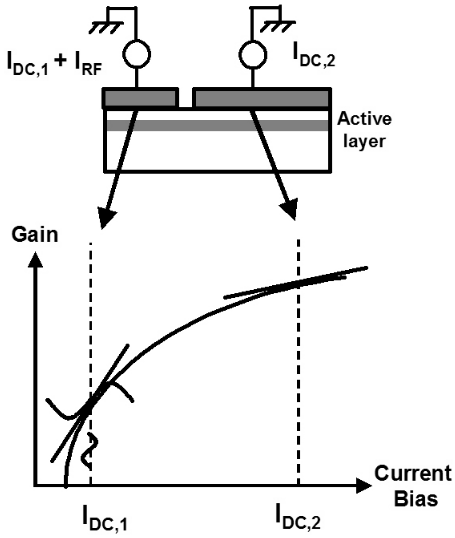

FIG. 1. Gain-lever effect in semiconductor lasers, after [3].

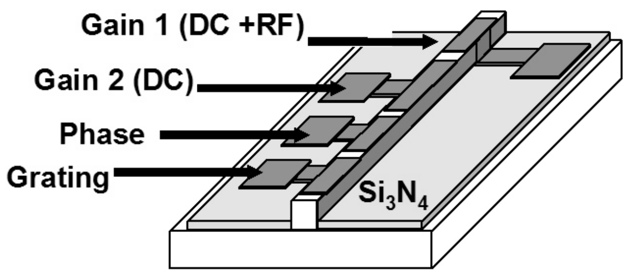

FIG. 2. Schematic of distributed Bragg reflector (DBR) laser for gain-lever modulation.

Among the techniques, gain-lever lasers are structurally simple and directly compatible with the standard fabrication process of conventional lasers. Gain-lever lasers take advantage of the nonlinear gain-versus-current characteristics in quantum-well gain media. Figure 1 illustrates the principle of gain-lever modulation. GaAlAs/GaAs single quantum well [5, 6] and InGaAsP/InP multiple quantum well [7] gain-lever lasers have been demonstrated. Unfortunately, the improved amplitude modulation (AM) efficiency is obtained at the expense of linearity. Furthermore, the previous gain-lever devices were Fabry-Perot lasers operating in multiple longitudinal modes, and are not suitable for practical system applications.

Strong optical injection locking is a promising technique to suppress the nonlinear distortion as well as increase the resonance frequency of directly modulated semiconductor lasers [12-17]. The nonlinear distortions are more pronounced near the relaxation oscillation frequency of the laser due to the nonlinear coupling between electrons, photons, and phase difference between master and slave. By pushing the resonance to frequencies much higher than the signal band, the nonlinear distortions can be significantly reduced. This has been successfully demonstrated in directly modulated links using distributed feedback lasers [14] and vertical-cavity surface-emitting lasers [16]. In addition, the frequency chirp and the relative intensity noise are also reduced in injection-locked lasers [12, 18].

Recently, we successfully demonstrated an improvement in RF performance by injection locking gain-lever-modulated distributed Bragg grating (DBR) lasers [19]. In this paper, we provide a detailed characterization of the gain-lever modulation and further performance enhancement by ultra-strong injection locking (injection ratio R=11 dB) on top of the previously reported injection locking of gain-lever DBR lasers. This combination provides simultaneous enhancement of modulation efficiency as well as a reduction of nonlinear distortions. With gain-lever modulation and ultra-strong optical injection locking, a 23.4-dB increase in AM efficiency (12.4 dB by gain-lever modulation and 11 dB by ultra-strong optical injection) and 18-dB enhancement of SFDR have been demonstrated.

II. EXPERIMENTAL RESULTS

Figure 2 shows the device schematic of the gain-lever DBR laser. The gain-lever DBR laser consists of four sections: a grating, phase, and two electrically-isolated gain sections. The grating and phase sections are designed to perform coarse and fine wavelength tuning with single-mode operation. Various split ratios, defined as the length of the shorter gain section divided by the total length of the gain sections, are used to investigate the optimum gain-lever geometry. The laser is designed with a capped-mesa buried heterostructure. After epitaxial growth of the capped-mesa buried heterostructure, a ridge height of ~3-4-μm is formed to reduce parasitic capacitance. A 500-nm layer of silicon nitride passivates the surface. P-metal contacts for the grating, phase, and gain sections are formed using Ti/Pt/Au. The bottom n-contact is comprised of Au/Sn/Au. The contact resistance obtained was typically less than 10 Ω after annealing. A final, 0.5-μm deep isolation etch is performed to increase the electrical isolation among the sections. The resistance between the adjacent sections is greater than 4 kΩ.

Figure 3 shows the experimental setup for measuring the performance of the gain-lever DBR laser, with and without optical injection locking. A gain-lever DBR laser with a split ratio of 0.5 is used for all the measurements presented in this paper. A tunable laser with an external cavity is used as the master laser. The output of the master laser is amplified by an Erbium-doped fiber amplifier to achieve ultra-strong injection locking. An inline optical attenuator controls the injection power. A polarization controller and an optical circulator with > 40-dB isolation complete the master laser module. The output of the gain-lever DBR laser is monitored by a

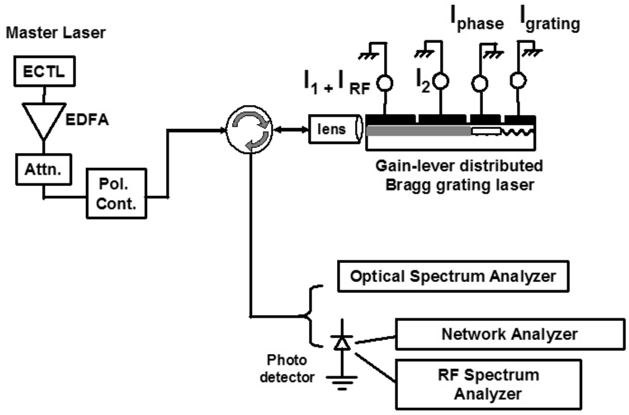

FIG. 3. Experimental setup for measuring RF performance of a gain-lever DBR laser with and without injection locking. (ECTL: external cavity tunable laser; EDFA: Erbium-doped fiber amplifier; Attn.: optical attenuator; Pol. cont.: polarization controller).

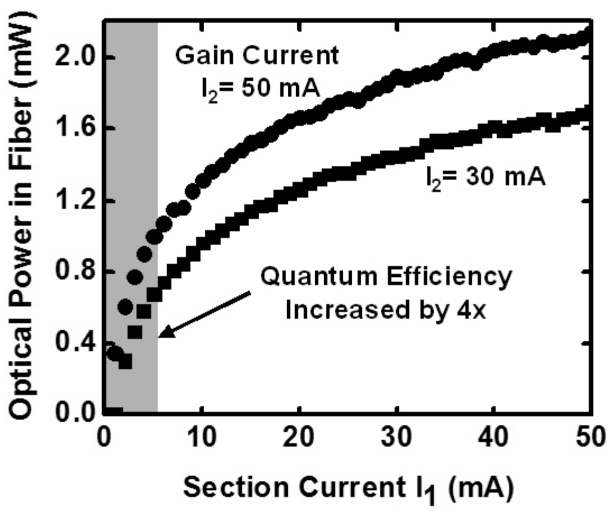

FIG. 4. Measured optical power versus the bias current on section showing the effect of gain-lever modulation.

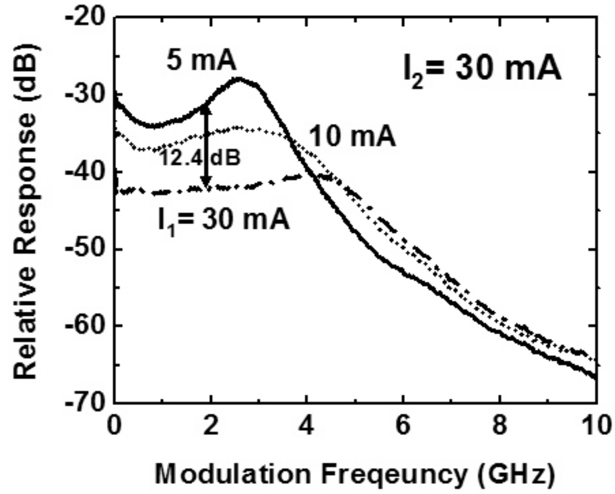

FIG. 5. Measured modulation responses of the gain-lever DBR laser for various operating conditions.

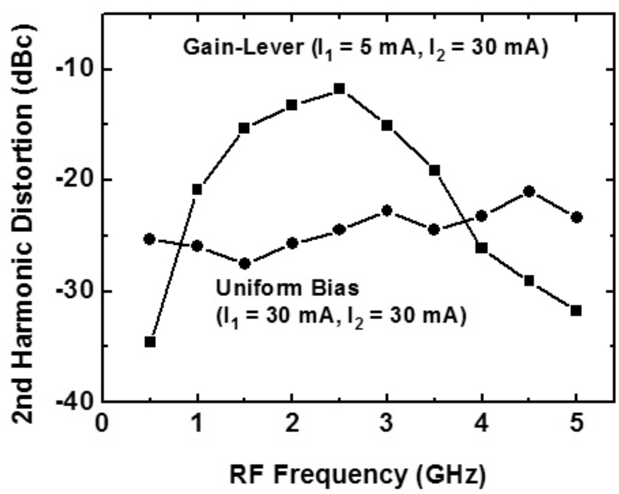

FIG. 6. The second harmonic distortion versus modulation frequency for gain-lever and uniform bias condition. The second harmonic product is measured at twice the RF modulation frequency.

high-resolution (0.01 nm) optical spectrum analyzer. To observe the RF modulation characteristics such as frequency response, nonlinear distortions, and SFDR, a DC bias (I_1) and RF signal (I_{RF}) are applied to one of the gain sections, while the other gain section is biased at a constant DC current (I_2). The modulated output is coupled to a high-speed (34-GHz) photodetector and monitored by a network analyzer or RF spectrum analyzer.

The DC light-versus-current curves are shown in Fig. 4. The current I_2 (see Fig. 3 for the definition of current symbols) is fixed either at 30 or 50 mA, while current I_1 is varied from 0 to 50 mA. As depicted in the shaded area in Fig. 4, a four-fold increase of the quantum efficiency (equivalent to an RF efficiency increase of 12 dB) is achieved when the RF modulation section (=section 1) is biased at a low level (< 5 mA).

The modulation response of the gain-lever DBR laser is shown in Fig. 5. As the bias current on the modulation section (section 1) decreases, the differential gain increases, producing a higher modulation response. Compared with the uniformly biased condition (I_1=30 mA, I_2=30 mA), a 12.4-dB improvement in modulation efficiency has been achieved by the gain-lever modulation (I_1=5 mA, I_2=30 mA). However, as a consequence of the low current bias necessary for gain-lever modulation, the modulation bandwidth decreases and nonlinear distortion increases. The resonance frequency of the laser is decreased from 5 GHz to 3 GHz. The measured second harmonic distortion as a function of modulation frequency is shown in Fig. 6. The laser is modulated with a 2-GHz RF signal. The free-running gain-lever laser (I_1=5 mA, I_2=30 mA) shows a severe distortion of -10.5 dBc at

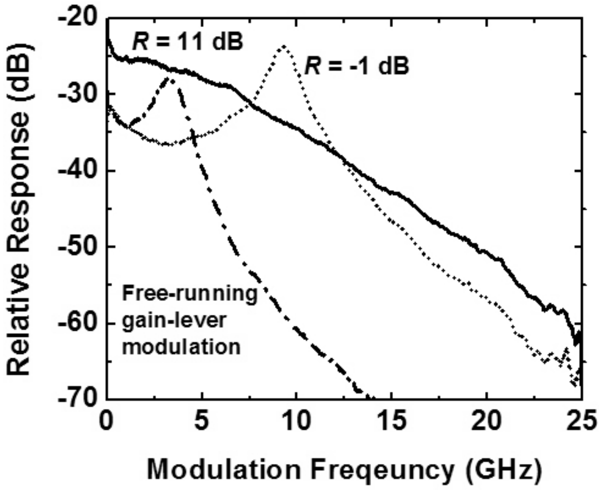

FIG. 7. Measured frequency responses of a free-running, strong (R=-1 dB, Δf=-7.4 GHz), and ultra-strong (R= 11 dB, Δf=-32 GHz) injection-locked DBR laser with gain-lever modulation.

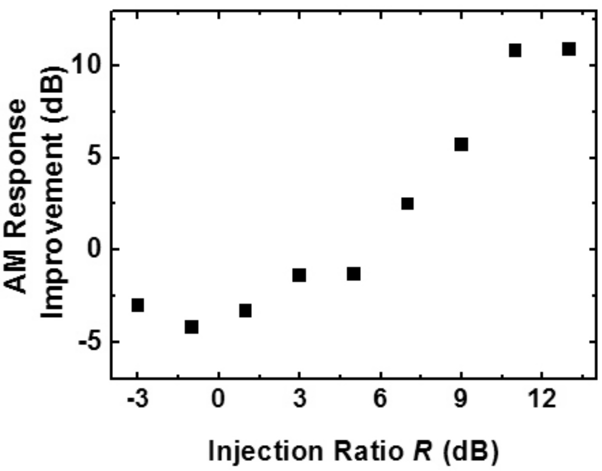

FIG. 8. Measured AM response improvement for various injection ratios. Frequency detuning values are adjusted for the corresponding injection ratios to achieve the largest AM improvement.

2.5-GHz modulation; 15-dB higher than that of the uniform bias condition. This is due to laser nonlinearity originating from both nonlinear light-versus-current curves of the gain-lever modulation (Fig. 4) and the laser resonance peak at ~3 GHz (Fig. 5).

Figure 7 shows the measured frequency responses of the gain-lever laser under free-running, strong injection-locking (R=-1 dB, Δf=-7.4 GHz), and *ultra*-strong injection-locking (R=11 *dB*, Δf=-32 GHz) conditions. The frequency detuning, Δf, is defined as the frequency difference between the master and the free-running slave lasers ($\Delta f = f_{\mathrm{master}} - f_{\mathrm{free,slave}}$). Injection ratio, R, is defined as the power ratio between the injected power and the lasing power of the free-running slave laser inside the

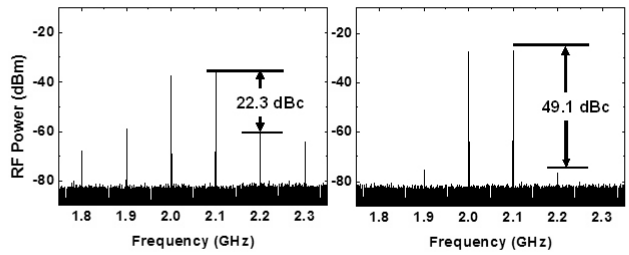

FIG. 9. Measured RF spectra showing the two-tone intermodulation distortions (f_1=2.0 GHz, f_2=2.1 GHz) of the gain-lever DBR laser under (a) free-running and (b) ultra strong injection-locking conditions (R=11 dB, Δf=-32 GHz).

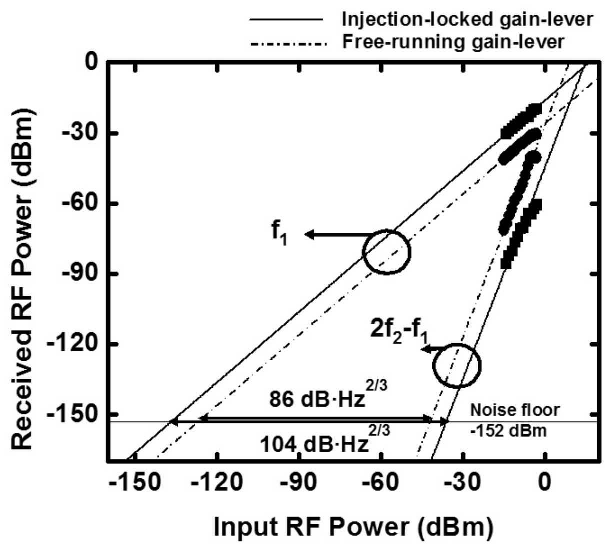

FIG. 10. Measured SFDR of the link with a directly modulated gain-lever DBR laser (f_1=2.0 GHz, f_2=2.1 GHz).

laser cavity. When the gain-lever DBR laser is injection-locked with R=-1 dB, the resonance frequency is increased to 8.7 GHz without severely compromising the enhanced AM efficiency of the gain-lever modulation. Under a high injection level of R=11 dB, the AM efficiency is enhanced by 11 dB around 2 GHz. Frequency detuning is optimized to achieve the highest modulation efficiency under the injection ratio of R=11 dB. The improvement of the AM efficiency is due to a cavity resonance effect causing an amplitude response increase at a low frequency band, combined with the increased optical power under ultra-strong injection. In optical injection locking system, the role of the modulated slave laser is similar to the conventional optical modulator. However, the modulation response of the slave laser exhibits significantly different characteristics from the conventional optical modulator by tuning the two injection locking parameters, Δf and R [17]. We have utilized the large negative detuning regime for the AM response improvement by the injection-locked laser on top of the improvement by the gain-lever modulation.

Figure 8 shows the dependence of the AM response improvement under 2-GHz RF modulation for various injection ratios. The improvement is calculated by dividing RF power at 2-GHz under a given injection ratio with the value of free-running gain-lever modulation. Frequency detuning values are adjusted for the corresponding injection ratios to achieve the largest AM improvement. The gain-lever laser is biased with I_1=5 mA and I_2=30 mA. It is modulated by a single-tone RF signal on section 1 (f=2 GHz, modulation power =-10 dBm). The received RF power at 2 GHz is measured and normalized by that of the free-running gain-lever state. The AM response improvement reaches its maximum with the ultra-strong injection ratio of ~11 dB. The largest improvement of 11 dB is achieved with the injection ratio of 11 dB, which is a 23.4-dB improvement over the free-running uniform bias case. No more improvement is observed with larger than 12-dB injection ratio due to the saturation of the photodetector.

The third-order intermodulation distortion (IMD3) is measured by a two-tone RF modulation signal (f_1= 2.0 GHz, f_2=2.1 GHz, modulation power=-10 dBm). As shown in Fig. 9, with ultra-strong injection locking (R=11 dB and Δf=-32 GHz), the fundamental tones at 2.0 GHz and 2.1 GHz are increased by 11 dB above the free-running gain-lever modulation tones. The IMD3 for the free-running laser is -22.3 dBc. In comparison, the IMD3 of the injection-locked state is reduced considerably to -49.1 dBc, exhibiting a 26.8-dB reduction in IMD3 compared with the free-running gain-lever modulation.

An important figure of merit of analog fiber-optic links is SFDR. Figure 10 shows the received RF powers of the fundamental and the third-order inter-modulation product versus the input RF power for the free-running gain-lever and ultra-strong injection-locked gain-lever conditions (R=11 dB and Δf=-32 GHz). The laser is modulated with a two-tone RF signal (f_1=2.0 GHz, f_2=2.1 GHz). The SFDR of the injection-locked gain-lever DBR laser is enhanced by 18 dB compared with the free-running gain-lever modulation: 11 dB by the increase of amplitude response and 7 dB by the reduction of the third-order inter-modulation product.

III. CONCLUSION

The ultra-strong optically injection-locked gain-lever distributed Bragg reflector laser has been successfully demonstrated. Gain-lever modulation improves the amplitude modulation efficiency by 12.4 dB, at the expense of linearity. By combining the gain-lever modulation with ultra-strong optical injection locking with an 11-dB injection ratio, the amplitude response is increased by 11 dB above the gain-lever improvement and the third-order inter-modulation distortion has been suppressed by 26.8 dB. This results in an 18-dB improvement in spurious-free dynamic range. This new modulation scheme can improve the link loss, bandwidth and signal fidelity of directly modulated fiber-optic links.

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