Optical Injection-Locked Gain-Lever Distributed Bragg Reflector Lasers with Enhanced RF Performance

H. -K. Sung, Thomas Jung, D. Tishinin*, K.Y. Liou*, W.T. Tsang*, and Ming C. Wu

UCLA Electrical Engineering Dept. 63-128 Engineering IV Bldg.
420 Westwood Plaza, Los Angeles, CA 90095
Tel: 310-825-7338 Fax: 310-794-5513 Email: wu@ee.ucla.edu
**Multiplex Inc. 5000 Hadley Road, South Plainfield, NJ 07080*

Abstract—**Directly modulated fiber-optic links offers significant advantages in system cost and complexity. However, they often suffer from high link loss and inferior RF performance compared with externally modulated links. In this paper, we have experimentally investigated the amplitude modulation (AM) efficiency, modulation bandwidth, and the nonlinear distortions of a directly-modulated gain-lever distributed Bragg reflector (DBR) laser under external light injection for the first time. By combining gain-lever modulation with optical injection locking, increased modulation efficiency (10 dB) and bandwidth (3 times) as well as suppressed third-order intermodulation distortion (15 dB) have been achieved simultaneously.**

I. Introduction

Directly modulated (DM) semiconductor lasers are attractive low-cost sources for analog fiber-optic applications such as cable television (CATV) distribution systems, antenna remoting in cellular networks, and phased arrayed antennas [1]. Though high bit rate modulation (40 Gbit/sec) has been demonstrated for digital links [2], low RF link loss and small nonlinear distortions are needed to achieve good analog performance. Unlike externally modulated links, the link loss of DM links is independent of the optical power. Rather, it is proportional the square of the electrical-to-optical (E/O) conversion efficiency. This results in high link loss for most DM links. Several approaches have been proposed to increase the modulation efficiency of semiconductor lasers, including gain-lever modulation [3]-[5] and cascade lasers [6]-[8]. Narrowband technique such as resonant modulation is outside the scope of this paper. Cascade laser achieves higher efficiency by recycling the RF modulating current through multiple lasers that are connected in series. It was first proposed using discrete lasers [6]. Monolithic device in edge- emitting [7] and surface-emitting lasers [8] have been demonstrated. Improvement of spurious-free dynamic range (SFDR) of 5 dB has been observed [7].

Gain-lever lasers take advantage of the nonlinear gain-versus-current characteristics in quantum-well gain media. The RF modulation section is biased at lower current to increase the differential gain, while the DC section is biased at higher current. Gain-lever lasers with GaAlAs/GaAs single quantum well (QW) [3], [4] and InGaAsP/InP multiple QW lasers [5] have been demonstrated. Unfortunately, the enhanced AM modulation response is obtained at the expense of linearity [3]. Furthermore, the previous gain-lever devices were Fabry-Perot (FP) lasers operating in multiple longitudinal modes, and are not suitable for system applications.

Strong optical injection locking has been shown to be a promising technique to suppress the nonlinear distortion as well as increase the resonant frequency of directly modulated semiconductor lasers [9], [10]. The nonlinear distortions are more pronounced near the relaxation oscillation frequency due to the nonlinear coupling between electron and photon concentrations. By pushing the resonance to frequencies much higher than the signal band, the nonlinear distortions can be significantly reduced. Reduction of nonlinear distortions has been successfully demonstrated in DM links using DFB lasers [11], vertical-cavity surface-emitting lasers (VCSELs) [12], and monolithic injection-locked DFB lasers [13]. In addition, the frequency chirp and the relative intensity noise (RIN) are also reduced in injection-locked lasers. However, except for a few reports [12], the modulation efficiencies of the injection-locked lasers below resonance are usually the same as or lower than those of the free-running lasers.

In this paper, we combine optical injection locking with gain-lever modulation to simultaneously enhance the AM efficiency, increase the modulation bandwidth, and suppress the nonlinear distortions. We have fabricated a gain-lever distributed Bragg reflector (DBR) laser with

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two separate gain sections as well as a phase and a grating sections. Gain-lever effect under single-mode operation with side-mode suppression ratio of > 35 dB has been successfully demonstrated. When combined with strong optical injection locking, the gain-lever DBR laser exhibits a 10-dB increase in AM efficiency, and a 15-dB suppression of third-order intermodulation distortions (IMD3). The built-in wavelength tuning capability of the DBR laser enables on-chip control of detuning frequency between the master and the slave lasers.

II. Device and Experiment

Figure 1 illustrates the principle of gain levered modulation. The purpose of gain-levering is to increase modulation efficiency of a laser by modulating one of the two gain sections biased at a higher slope of the gain profile while maintaining a constant total gain [4]. The fabricated gain-lever DBR laser has four different sections as shown in Fig. 2. Typical lithography and waveguide etching processes are followed by an electrical isolation etch of 0.2-μm depth between sections [13]. The resistance between adjacent sections is greater than 4 kΩ. Various split ratios, defined as the length of the small gain section divided by the total length of the laser gain sections, are employed in the design.

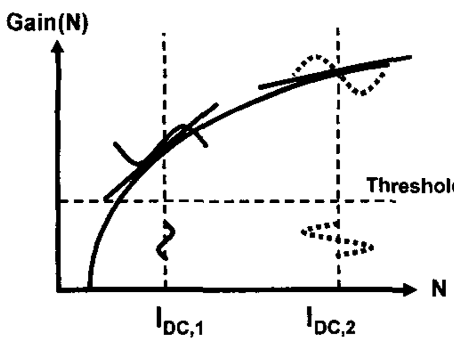

Fig. 1. Gain-lever effect in semiconductor lasers.

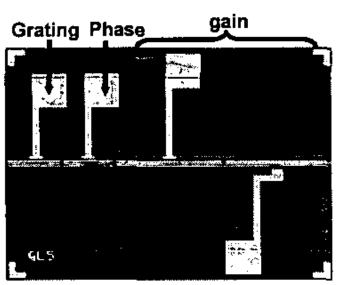

Fig. 2. Fabricated gain-lever DBR laser.

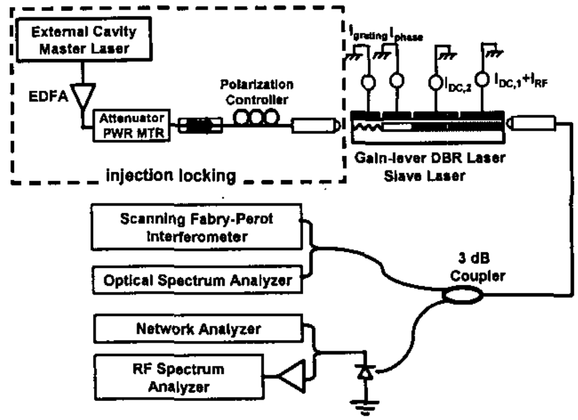

Fig. 3. Experimental setup: the setup inside the dotted box is for injection locking.

The experimental setup shown in Fig. 3 is used to measure the optical spectrum, frequency response, and nonlinear distortions of the gain-lever DBR lasers with and without external light injection. An external cavity laser is used as the master laser to lock the slave laser. Optical isolator with >40 dB isolation is used to prevent light coupling from the slave laser to the master laser and protect the slave laser against back-reflected light. The output of the master laser is amplified by an erbium-doped fiber amplifier (EDFA) to achieve strong injection locking. An inline power meter/attenuator is used to control the injection ratio. The output of the gain-lever DBR laser is then monitored on an optical spectrum analyzer and scanning Fabry-Perot interferometer. To observe the RF modulation characteristics, such as frequency response, nonlinear distortions, and SFDR, a DC current and RF signals are applied to the one of the gain sections of the gain-lever DBR laser through a bias-tee while the other gain section is biased at a constant DC current. The modulated output taken from the laser is coupled into a high-speed photodetector and the detected signal is directly monitored on the network analyzer or amplified by a low-noise RF amplifier with 20 dB gain to observe the RF spectrum.

The modulation response of the gain-lever DBR laser with a split ratio of 0.5 is shown in Fig. 4 for three different operating conditions. First, in the free-running gain-lever state, the differential gain increases, causing a higher modulation response as the bias current on the modulation section decreases. As a consequence of the lower total currents, the modulation bandwidth also decreases slightly. Compared with the case of uniform bias ($I_{DC,1}$=50 mA, $I_{DC,2}$=50 mA), an improvement in AM efficiency by 12 dB at 2 GHz range has been achieved at

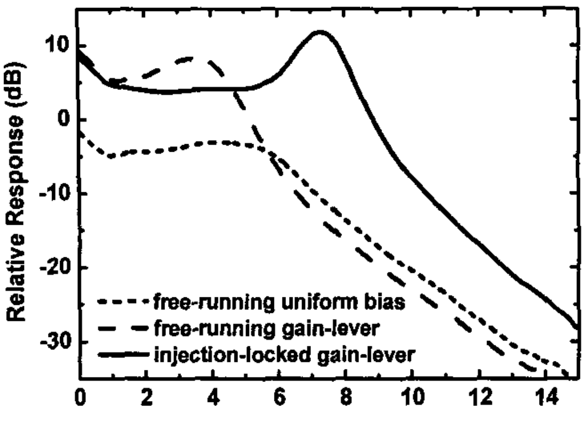

Fig. 4. Measured frequency response. Bias conditions:
free-running uniform bias: $I_{DC,1}$=50 mA, $I_{DC,2}$=50 mA
free-running gain-lever state: $I_{DC,1}$=4.5 mA, $I_{DC,2}$=50 mA
injection-locked gain-lever state: $I_{DC,1}$=4.5 mA, $I_{DC,2}$=50 mA

the free-running gain-lever state ($I_{DC,1}$=4.5 mA, $I_{DC,2}$=50 mA). However, there is a trade off between modulation bandwidth and AM efficiency. An increase in the modulation response resulted in a decrease in the resonance frequency of the laser from 4.5 GHz to 3 GHz due to the decrease of current bias at the free-running gain-lever state.

Optical injection locking of the gain-lever DBR laser can be employed to enhance the modulation bandwidth of the laser while maintaining the enhanced modulation efficiency. The goal is to utilize the optical injection locking to overcome the bandwidth tradeoff associated with the gain lever effect to achieve a device that exhibits both high modulation efficiency and high modulation bandwidth. To achieve an injection-locked state, the frequency detuning between master and slave laser is set at ~ -20 GHz and the injection ratio is set at -8 dB. The injection ratio is defined as the ratio of the injected master laser power that couples into the slave laser cavity to the DC output power of the free-running slave laser. With optical injection locking, the modulation bandwidth is increased to 8 GHz while maintaining significant enhancement of the AM efficiency compared with the free-running laser with uniform bias. The enhancement of AM efficiency is 10 dB around 2 GHz, and is greater than 7 dB from DC to 6 GHz. We also have observed the dependence of frequency response on the frequency detuning and injection ratio between the lasers. The resonant frequency of the laser increases with increasing injection ratio. Varying the frequency detuning controls the height of the resonance peak. Both results are

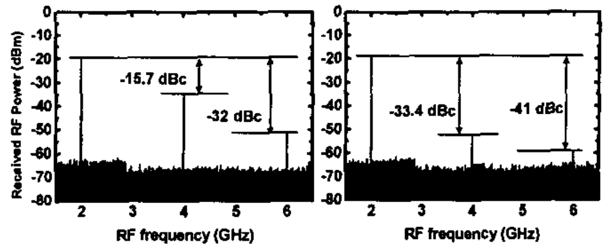

Fig. 5. Measured RF spectra of the gain-lever DBR laser modulated by a single-tone 2-GHz RF signal for (a) free-running gain-lever and (b) injection-locked gain- lever states.

consistent with previous work on the injection-locking of DFB lasers.

Injection locking of the gain-lever DBR laser also suppresses nonlinear distortion of the free-running gain-lever laser. To measure the second- and the third-harmonic distortions (2HD and 3HD), the front section of the laser is modulated by a single-tone RF signal (f = 2 GHz). The second harmonic and third harmonic products are at 4 GHz and 6 GHz, respectively. Figure 5 shows the measured RF spectra of the laser with and without optical injection at the gain-lever state. For the free-running laser, the 2HD and 3HD are measured to be -15.7 and -32.0 dBc, respectively. With optical injection, the 2HD and 3HD are significantly suppressed to -33.4 and -41.0 dBc, respectively.

In narrow-band applications, the system performance is mainly limited by IMD3. To observe the IMD3 due to the laser nonlinearities and its reduction by optical injection locking, the gain-lever DBR laser is modulated by a two-tone RF signal (f_1 = 2.0 GHz, f_2 = 2.1 GHz). As shown in Fig. 6, the IMD3 for the free-running laser is –37.2 dBc. In comparison, the IMD3 of the injection-locked state is considerably reduced to –52.2 dBc. One of the important figure-of-merits which characterizes fiber-optic link performance is SFDR. Figure 7 shows the received RF powers of the fundamental and the third-order intermodulation product

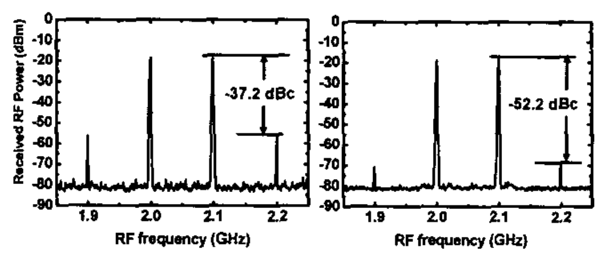

Fig. 6. Measured RF spectra of the gain-lever DBR laser modulated by a two-tone RF signal (f_1 = 2.0 GHz, f_2 = 2.1 GHz) for (a) free-running gain-lever and (b) injection-locked gain- lever states.

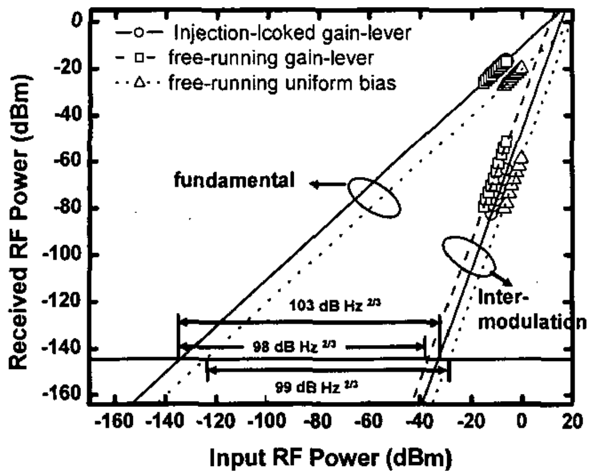

Fig. 7. Measured SFDR of the link with directly modulated gain-lever DBR laser at f_1=2.0 GHz and f_2=2.1 GHz for the free-running gain-lever, free-running uniform bias, and free-running gain-lever states.

(IMP3) versus the input RF power for the free-running gain-lever, free-running uniform bias, and injection-locked gain-lever states. The received fundamental powers are almost equal for the gain-lever, with and without injection, showing a 12-dB increase from the free-running uniform bias case. The SFDR of the injection-locked gain-lever DBR laser is increased by 4 dB and 5 dB compared with the free-running uniform bias and free-running gain-lever states, respectively.

III. Conclusion

We have successfully demonstrated the first optically injection-locked gain-lever distributed Bragg reflector (DBR) laser. By combining gain-lever modulation with strong optical injection locking, the AM modulation efficiency is increased by 10 dB while the bandwidth of the laser is increased by three times. The third-order intermodulation distortion (IMD3) has also been suppressed by 15 dB, resulting in a 5-dB improvement in spurious-free dynamic range. This new modulation scheme would improve the link loss, noise figure, and fidelity of directly modulated fiber-optic links.

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