Near-Single Sideband Modulation in Strong Optical Injection-Locked Semiconductor Lasers

Hyuk-Kee Sung, Erwin K. Lau and Ming C. Wu
Department of Electrical Engineering and Computer Sciences, 253M Cory Hall,
University of California, Berkeley, CA 94720, USA
Tel: +1-510-643-0808. Fax: +1-510-643-6637. Email: hyukee92@eecs.berkeley.edu

Abstract: Asymmetric modulation sidebands have been demonstrated by controlling frequency detuning of strong optical injection-locked semiconductor lasers. Near-single sideband generated by the technique significantly reduces fiber chromatic-dispersion effect with enhanced modulation bandwidth.

OCIS codes: (140.3520) Lasers, injection-locked; (060.2330) Fiber optics communications.

Introduction

Directly modulated semiconductor lasers are simple and low-cost sources for transmitting RF signals over optical fibers. Standard modulation generates two signal sidebands on both sides of the optical carrier. The dispersion in fibers causes a walk-off in the phases of the sidebands, resulting in degradation of the recovered RF signals [1]. This imposes a limit on the product of RF carrier frequency and fiber transmission distance. The laser chirp, or frequency modulation (FM) accompanying the intensity modulation (IM), further complicates the dispersion effect [2]. Single sideband modulation can alleviate the dispersion penalty; however, it requires sophisticated external modulators [1]. Sideband filtering using fiber grating has also been reported [3], however, it requires precise matching of wavelengths.

In this paper, we report on a novel near-single sideband modulation technique for semiconductor lasers using strong optical injection locking. Under some locking condition, we found that, in addition to enhancement of resonant frequency and reduction of chirp, the upper sideband is enhanced while the lower sideband is suppressed, resulting in a 12-dB asymmetry under 20-GHz RF modulation. The amount of the asymmetry can be controlled by the frequency detuning between the master and the free-running slave lasers. We have measured the RF performance of the free-running and injection locked link over 80-km fibers. The dispersion-limited RF bandwidth has been greatly increased by maintaining the variation of fiber transmission response to within 7 dB up to 20-GHz RF carrier frequency.

Experiment setup

Figure 1 shows the experimental setup. A tunable laser with external cavity is used as the master laser. Its output 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. An optical circulator with >40 dB isolation prevents light

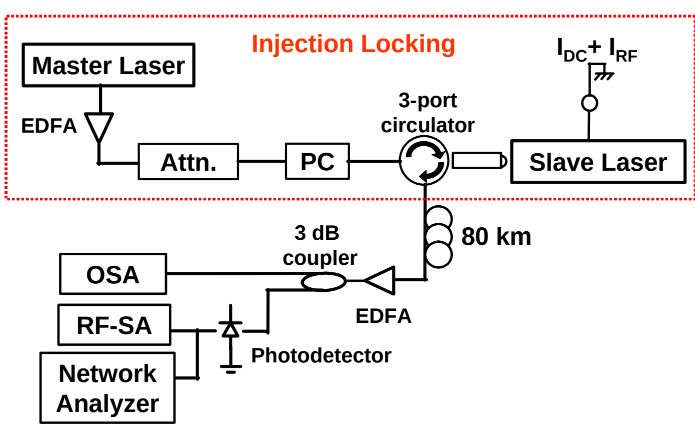

Fig. 1. Experimental setup: EDFA: erbium-doped fiber amplifier. Attn.: variable optical attenuator. PC: polarization controller. OSA: optical spectrum analyzer. RF-SA: RF spectrum analyzer.

coupling from the slave laser back to the master laser. The circulator also protects the slave laser against back-reflected light. A two-section DFB laser with bent waveguide [4] is used as the slave laser. In this experiment, only the section facing the circulator is biased and modulated. The output from the slave laser is monitored by an optical spectrum analyzer with 0.01 nm resolution. A high-speed photodetector (~ 34 GHz) converts the optical signal to electrical signal. An RF spectrum analyzer and network analyzer are used to characterize the RF performance. An 80-km optical fiber with negative dispersion (Corning MetroCor, D ~ -8 ps/km/nm) is used for transmission experiments. To compensate for the loss of the fiber link, the transmitted signal is amplified by an EDFA.

Asymmetric modulation sidebands under optical injection locking

Figure 2 shows the measured optical spectra of the RF-modulated slave laser (frequency f_{rf} = 20 GHz) under (a) free-running, and injection locking with (b) -8.2 GHz and (c) -38 GHz detuning conditions. The frequency detuning, Δf, is defined as the frequency difference between the free-running slave laser and the master laser ($\Delta f = f_{master} - f_{slave}$). The slave laser is biased at 12.3 mA (=$1.4I_{th}$). To achieve strong optical injection locking, the output power from the EDFA following the master laser is set to 8 dBm (injection ratio R ~ 11 dB). As shown in Fig. 2(a), the modulated sidebands are symmetric in free-running condition. Under strong optical injection locking, the modulation sidebands become asymmetric and the asymmetry varies with Δf. As shown in Fig. 2(b), the asymmetry is maximized when Δf is set at – 8.2 GHz. Figure 3 shows the corresponding frequency responses. The relaxation oscillation frequency of the free-running laser is ~ 3 GHz. When the laser is injection-locked, the original relaxation oscillation of the laser is damped, and the enhancement or damping of the new resonance frequency is observed. For Δf = - 8.2 GHz, the injection-locked laser shows the enhanced resonance frequency (> 20 GHz) beyond the measurable range of our equipment. For the injection locking condition of Δf = - 38 GHz, the injection-locked laser shows highly-damped frequency response. The phenomena are explained by the cavity resonance effect [5]. The asymmetry between the modulation sidebands are also related to the cavity resonance effect. As shown in Fig. 4, the power difference between upper and lower modulation sidebands (f_{rf} = 20 GHz) depends on Δf. Maximum asymmetry occurs at small positive detuning frequency (12 dB at Δf = -8.2 GHz)

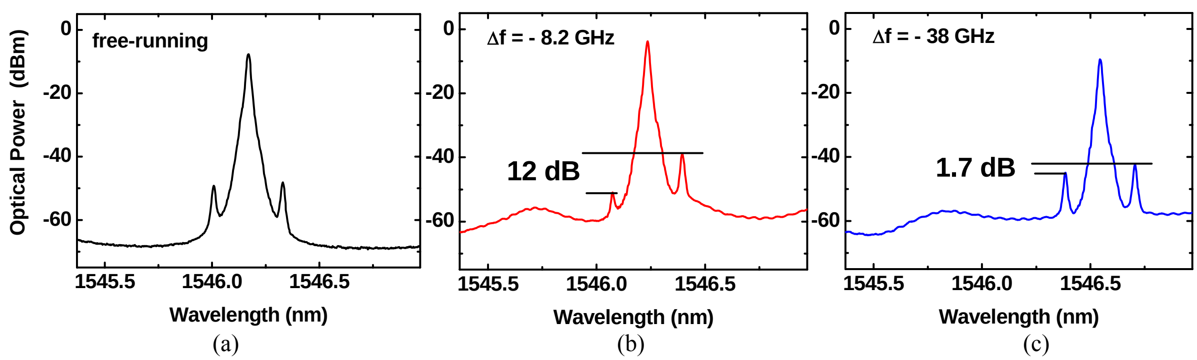

Fig. 2. Measured optical spectra of RF-modulated slave laser (f_{rf} = 20 GHz) under various conditions: (a) free-running; (b) injection-locking with Δf = -8.2 GHz; and (c) injection-locking with Δf = -38 GHz.

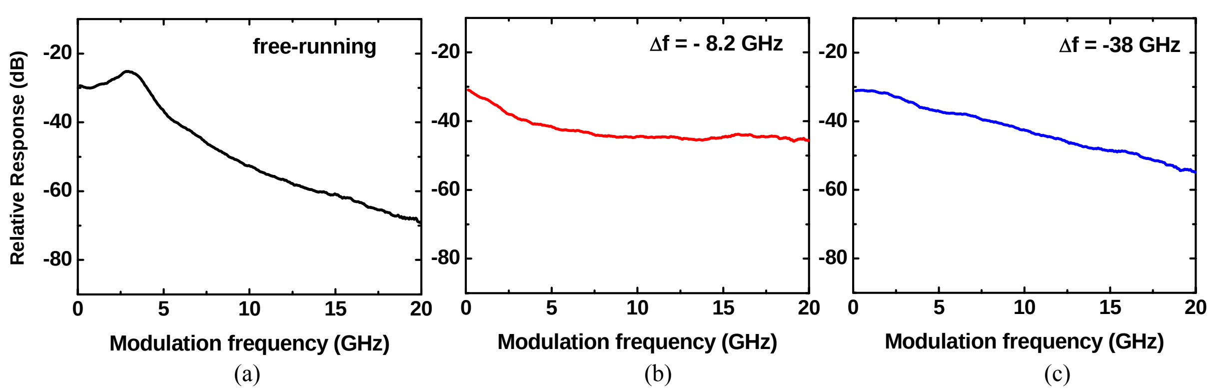

Fig. 3. Measured frequency response of the slave laser under various conditions: (a) free-running; (b) injection-locking with Δf = -8.2 GHz; and (c) injection-locking with Δf = -38 GHz.

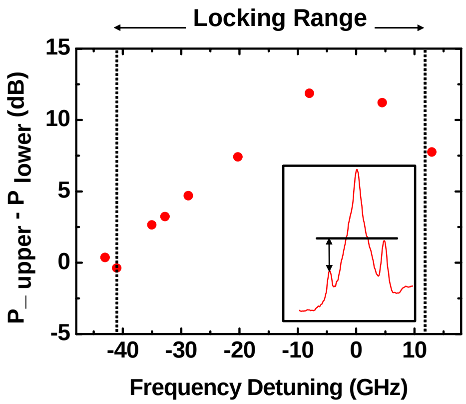

Fig. 4. Power difference between upper and lower modulation sideband versus frequency detuning.

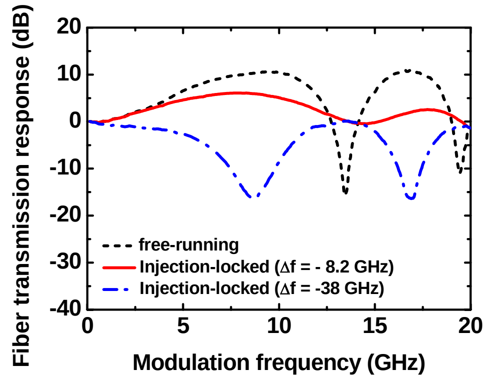

Fig. 5. Measured fiber transmission response for a free-running laser and injection-locked laser with difference detuning values.

Fiber transmission measurement

Figure 5 shows the measured fiber transmission response of 80-km of negative dispersion fibers (Corning MetroCor, D ~ -8 ps/km/nm). The fiber transmission response is measured by normalizing the frequency response after fiber transmission to the back-to-back frequency response of the laser. In free-running, the fiber transmission response shows pronounced dips of up to 27 dB at 13 and 19 GHz. The dips are due to interference of the signals from the symmetric sidebands. The increase of the response in low frequency range is due to IM to FM conversion of a directly-modulated laser combined with the effect of fiber chromatic dispersion [2]. In the injection-locked case (Δf = -38 GHz), the position of the dip is changed to the lower frequency due to the reduction of frequency chirping. To reduce the variation of the fiber transmission response, Δf is set at – 8.2 GHz. For the detuning value, the asymmetry becomes maximized (as shown in Fig. 2 (b) and Fig. 4) and resultant response only varies within 7 dB up to 20-GHz RF modulation frequency.

Conclusion

We have experimentally demonstrated near-single sideband modulation in strong optical injection-locked semiconductor lasers. Up to 12-dB difference in upper and lower sideband power is observed. The amount of asymmetry is controlled by the frequency detuning between the master and the free-running slave lasers. The RF performance of the near-single sideband laser after 80-km fiber transmission is significantly improved, and the bandwidth limit of the RF carrier frequency is eliminated.

Acknowledgment

The authors are grateful to Prof. C. J. Chang-Hasnain and Xiaoxue Zhao for helpful discussions. This work is supported in part by SBIR #FA8651-04-C-0253 and DARPA RFLICS program.

References

[1] G. H. Smith, D. Novak, and Z. Ahmed, "Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators," *IEEE Trans. Microwave Theory Techniques*, vol. 45, pp. 1410-1415, 1997.

[2] G. Meslener, "Chromatic dispersion induced distortion of modulated monochromatic light employing direct detection," *IEEE J. Quantum Electron.*, vol. 20, pp. 1208-1216, 1984.

[3] M. Matt, P. Eva, P. Dan, W. K. Marshall, and Y. Amnon, "Improved laser modulation response by frequency modulation to amplitude modulation conversion in transmission through a fiber grating," *Appl. Phys. Lett.*, vol. 71, pp. 879-881, 1997.

[4] H.-K. Sung, Erwin K. Lau, M. C. Wu, D. Tishinin, K. Y. Liou, and W. T. Tsang, " Large-Signal Analog Modulation Response of Monolithic Optical Injection-Locked DFB Lasers," *Proc. Conference on Lasers and Electro-Optics (CLEO 2005)*, Baltimore, Maryland, May 2005, CTuV7.

[5] T. B. Simpson and J. M. Liu, "Enhanced modulation bandwidth in injection-locked semiconductor lasers," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 1322-1324, 1997.