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Optical Single Sideband Modulation Using Strong Optical Injection-Locked Semiconductor Lasers

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***Abstract*—We report on the experimental demonstration of optical single sideband (SSB) modulation using a directly modulated semiconductor laser under strong optical injection-locking. Modulation sidebands with 15-dB power ratio between the lower and upper sidebands have been achieved. The longer wavelength sideband is resonantly amplified by the injection-locked laser cavity mode. The radio-frequency performance of the optical SSB after 80-km fiber transmission is significantly improved compared with a typical symmetric sideband modulation of a free-running laser. A 622-Mb/s data transmission on a 20-GHz subcarrier is demonstrated over an 80-km fiber link.**

***Index Terms*—Fiber chromatic dispersion, optical injection-locking, optical single sideband (SSB).**

I. Introduction

TRANSMISSION of radio-frequency (RF) signals over fiber has applications in various fiber-wireless systems [1]. Standard modulation generates two symmetric signal sidebands on both sides of the optical carrier. The dispersion in fiber causes a walkoff in the relative phases of the sidebands, resulting in degradation of the recovered RF signal [2]. This imposes a limit on the product of fiber transmission distance and the square of the RF carrier frequency. Single sideband (SSB) modulation can alleviate the dispersion penalty; however, it often requires sophisticated external modulators [2] or narrowband spectral filtering [3], [4]. Direct SSB of semiconductor lasers is an attractive alternative because of its simplicity. Recently, we have reported direct SSB modulation from an optically injection-locked semiconductor laser [5]. Single-sideband FM has also been demonstrated recently using optical injection-locking [6].

In this letter, we report on the comprehensive characterization of both the device and the link performance of SSB-modulated distributed feedback (DFB) lasers under strong optical injection-locking. Under certain frequency detuning conditions, we have found that, in addition to enhancement of the resonance frequency and reduction of chirp, the lower frequency sideband is enhanced, resulting in the lower-to-upper sideband power ratio of up to 15 dB for a 15- to 30-GHz RF carrier. The amount of sideband power ratio and the optimum RF frequency can be controlled by injection-locking parameters. We have measured the RF performance of the directly modulated links using free-running and injection-locked DFBs over 80-km fiber. The dispersion-limited RF bandwidth has been increased to greater than 20 GHz by the SSB modulation in injection-locked lasers. Data transmission of 622 Mb/s on a 20-GHz RF carrier is successfully demonstrated over an 80-km fiber using SSB modulation.

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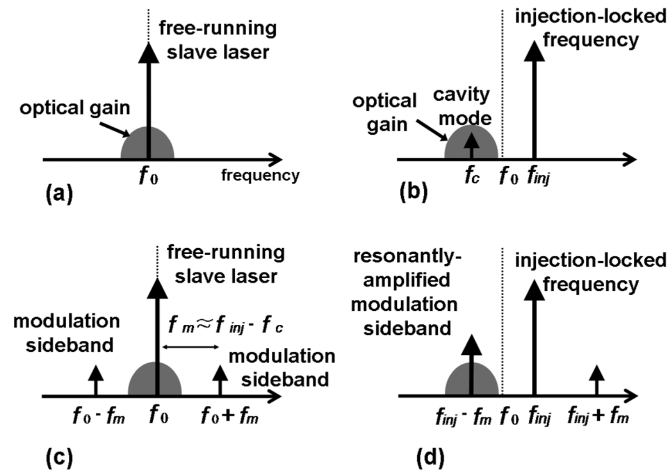

Fig. 1. Optical spectra illustrating SSB generation in directly modulated semiconductor lasers with strong optical injection-locking. (a) Free-running laser without RF modulation. (b) Injection-locked laser without RF modulation. (c) Free-running laser modulated by an RF signal with a modulation frequency of f_m. (d) Injection-locked laser modulated by an RF signal with a modulation frequency of f_m.

II. Principle and Experimetal Results

Fig. 1 illustrates the concept of the optical SSB generation by direct modulation of optical injection-locked semiconductor lasers. Directly modulated free-running lasers generate symmetric modulation sidebands on both upper and lower sides of an optical carrier f_0 regardless of modulation frequency [Fig. 1(c)]. On the other hand, strong injection-locked lasers with positive frequency detuning exhibit an injection-locked frequency f_{inj} and a residual cavity mode f_c, as shown in Fig. 1(b) without any external RF modulation [7]–[9]. When the injection-locked laser is modulated by an RF signal at f_m close to the frequency difference between the injection-locked and cavity mode frequencies ($f_m \approx f_{\text{inj}} - f_c$), the modulation sidebands become asymmetric because the lower sideband is resonantly amplified by the cavity mode, while the upper sideband remains unchanged [Fig. 1(d)]. The asymmetry can be controlled and maximized by fine-tuning injection-locking parameters: frequency detuning, Δf (frequency difference between the master and the free-running slave lasers), and injection ratio R (power ratio between the injected power and

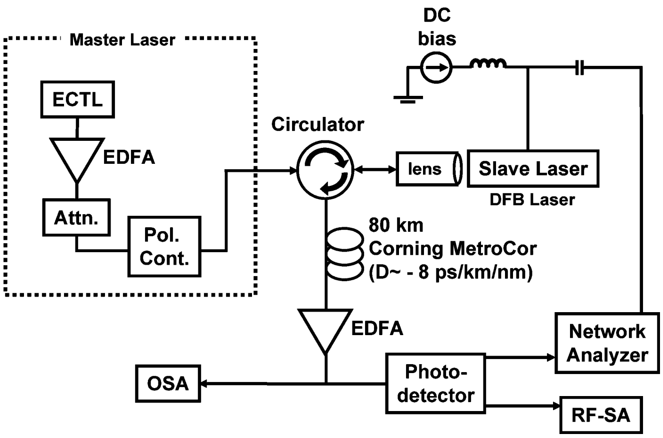

Fig. 2. Experimental setup for optical SSB modulation and RF performance characterization. (ECTL: external cavity tunable laser. Attn.: optical attenuator. Pol. cont.: polarization controller. OSA: optical spectrum analyzer. RF-SA; RF spectrum analyzer).

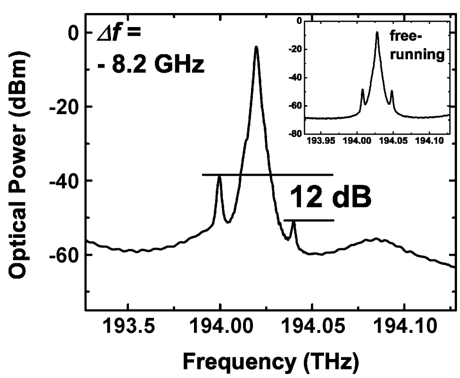

Fig. 3. Measured optical spectrum of an RF-modulated injection-locked laser ($f_m = 20$ GHz, RF power $= 0$ dBm) under a frequency detuning, $\Delta f = -8.2$ GHz and an injection ratio of $R \sim 11$ dB. Inset: optical spectrum of a RF-modulated free-running laser showing symmetric sidebands.

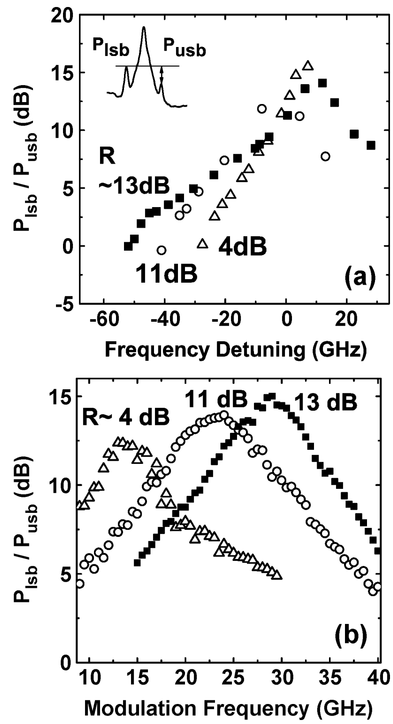

Fig. 4. Measured optical power ratio between lower and upper sidebands for various injection ratios versus (a) frequency detuning with fixed modulation frequency at 15 GHz (for $R \sim 4$ dB), 20 GHz (for $R \sim 11$ dB), and 30 GHz (for $R \sim 13$ dB). (b) Modulation frequency with fixed frequency detuning, $\Delta f = 0$ GHz (for $R \sim 4$ dB), $\Delta f = -8.2$ GHz (for $R \sim 11$ dB) and $\Delta f = 9$ GHz (for $R \sim 13$ dB). The RF modulation power is set at 0 dBm.

the lasing power of the free-running slave laser inside the laser cavity).

Fig. 2 shows the experimental setup for optical SSB modulation and RF characterization. An external cavity laser is used as the master laser. The output is amplified by an erbium-doped fiber amplifier (EDFA) to achieve strong injection-locking. An optical attenuator controls the injection ratio. An optical circulator with >40-dB isolation prevents coupling from the slave to the master laser. A DFB laser, biased at 12.3 mA($= 1.4 \cdot I_{\mathrm{th}}$) and output power of -3 dBm, is used as the slave laser. The output from the slave laser is monitored by an optical spectrum analyzer with a resolution bandwidth of 0.01 nm. A high-speed photodetector with a bandwidth of 34 GHz, RF spectrum analyzer, and network analyzer are used to characterize the RF performance of the system. To demonstrate transmission performance, an 80-km optical fiber with negative dispersion (Corning MetroCor, $D \sim -8$ ps/km/nm) is used. The loss of the fiber link is compensated by an EDFA.

Fig. 3 shows the measured optical spectrum under RF modulation ($f_m = 20$ GHz, RF power $= 0$ dBm) for the injection-locked laser ($\Delta f = -8.2$ GHz and $R \sim 11$ dB). The modulation sidebands show a 12-dB asymmetry, while the free-running lasers' are symmetric, as shown in the inset. The amount of asymmetry, measured by the lower-to-upper sideband power ratio $P_{\mathrm{lsb}}/P_{\mathrm{usb}}$, is controllable by varying Δf, as shown in Fig. 4(a). Δf is varied across the corresponding locking range for different injection ratios. Note that the RF signals with different frequencies are applied to achieve the largest $P_{\mathrm{lsb}}/P_{\mathrm{usb}}$ for the different injection ratios ($f_m = 15$ GHz for $R \sim 4$ dB, $f_m = 20$ GHz for $R \sim 11$ dB, and $f_m = 30$ GHz for $R \sim 13$ dB). The dependence of $P_{\mathrm{lsb}}/P_{\mathrm{usb}}$ on Δf stems from the evolution of the cavity mode across the locking range [8]–[10]. The largest asymmetry is observed for positive frequency detuning, where the cavity resonance effect is significant. Fig. 4(b) is the measured asymmetry as a function of the modulation frequency. The frequency detuning values are fixed at $\Delta f = 0$ GHz (for $R \sim 4$ dB), $\Delta f = -8.2$ GHz (for $R \sim 11$ dB), and $\Delta f = 9$ GHz (for $R \sim 13$ dB) for optimizing SSB modulation. The modulation frequency resulting in the largest $P_{\mathrm{lsb}}/P_{\mathrm{usb}}$ increases with injection ratio. Therefore, the SSB modulation with a desired RF modulation frequency can be achieved by tuning the injection ratio and frequency detuning.

The SSB fiber transmission response is experimentally measured and normalized to the back-to-back frequency response of the laser. Fig. 5 shows the measured transmission response through 80 km of negative dispersion fiber. In the free-running state, the fiber transmission response shows pronounced dips of up to 27 dB at 13 and 19 GHz. The dips are due to the interference between the symmetric sidebands. The enhanced response at low frequencies is due to the combination of laser chirp and fiber chromatic dispersion [3], [11]. In the injection-locked case with large negative frequency detuning ($\Delta f = -38$ GHz), the position of the dip is changed to

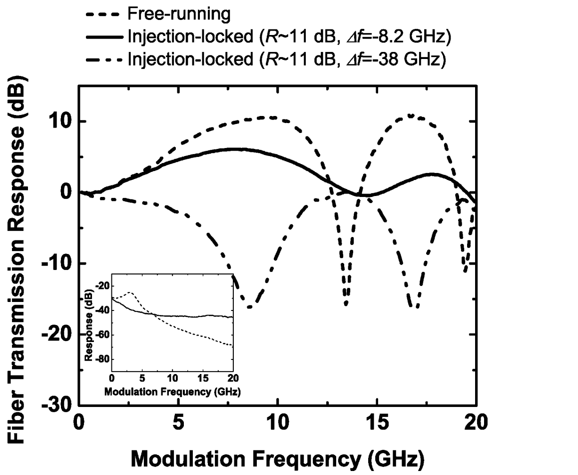

Fig. 5. Measured fiber transmission response for a free-running laser and injection-locked laser with different frequency detuning values. Inset: back-to-back frequency response of the free-running laser (dashed line) and the injection-locked laser (solid line) with $\Delta f = -8.2$ GHz and $R \sim 11$ dB.

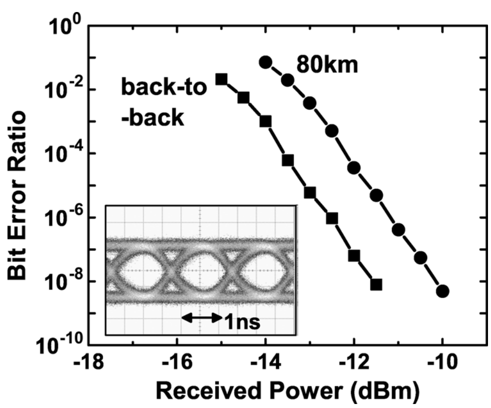

Fig. 6. Measured bit-error-ratio of the SSB link using an injection-locked laser ($\Delta f = -8.2$ GHz, $R \sim 11$ dB), back-to-back and after 80-km transmission. Inset: measured eye diagram after 80-km fiber transmission at received power of -10 dBm.

a lower frequency due to the reduction of frequency chirp. The dips are as severe as the free-running laser because the modulation sidebands are still symmetric for this detuning value [Fig. 4(a)]. For the injection-locked laser with frequency detuning $\Delta f = -8.2$ GHz, the RF power variation has been reduced to 7 dB across the entire frequency range (DC to 20 GHz) due to SSB modulation. It is interesting to note that the low frequency hump is also suppressed due to the chirp reduction. The inset of Fig. 6 shows the measured back-to-back frequency response of the free-running and injection-locked laser. The resonance frequency of the injection-locked laser is increased to >20 GHz, exhibiting 23-dB improvement in amplitude response compared with the free-running laser at 20-GHz band.

To verify data transmission, 622-Mb/s, $2^{23} - 1$ pseudo-random bit sequence, nonreturn-to-zero data on a 20-GHz subcarrier is sent over the link by modulating the injection-locked laser ($\Delta f = -8.2$ GHz and $R \sim 11$ dB). The measured bit-error-ratio after 80-km fiber transmission exhibits 1.5-dB power penalty compared with back-to-back case. The penalty is due to the residue fiber chromatic dispersion effect from the upper sideband.

III. Conclusion

Optical SSB generation using strong optical injection-locked lasers has been demonstrated. The asymmetric modulation sidebands are achieved by utilizing the resonantly amplified modulation sideband in strong optical injection-locked lasers. The asymmetry is controllable and depends on the frequency detuning and injection ratio of injection-locked lasers. By maximizing the asymmetry and generating near-SSB modulation, the dispersion-limited power penalty of the directly modulated link has been greatly reduced across a 20-GHz band after 80-km transmission, a 20-dB improvement over the free-running laser.

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