Improved Intrinsic Dynamic Distortions in Directly Modulated Semiconductor Lasers by Optical Injection Locking

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***Abstract*—The effects of optical injection locking on the nonlinear distortions of directly modulated semiconductor distributed feedback (DFB) lasers are investigated experimentally. The second harmonic distortion (SHD) and third harmonic distortion (THD), as well as the third-order intermodulation distortion (IMD3), are measured as functions of modulation frequency for both the free-running and injection-locked lasers. Under strong injection locking with −8-dB injection ratio, the SHD and THD of the DFB laser have been suppressed by 15 dB from 2 to 4 GHz. Moreover, nearly 15-dB reduction in IMD3 has been observed from 1.4 to 3.0 GHz with the same injection conditions. We also found that the injection locking is not effective in reducing the low-frequency distortions.**

***Index Terms*—Detuning frequency, harmonic distortion, injection-locked semiconductor lasers, injection ratio, intermodulation distortion, resonant frequency, stable locking range.**

I. Introduction

RECENTLY, there has been an increasing interest in subcarrier multiplexed (SCM) fiber-optic systems with direct laser intensity modulation for low-cost multichannel systems to support a wide range of analog and digital broadband services [1]–[3]. Analog video, digital telephony, and data transmission can all be simultaneously carried on the same optical carrier and detected by the same detector. The SCM fully exploits the broad bandwidth of high-speed semiconductor lasers, and can be combined with wavelength division multiplexing (WDM) to enhance the capacity of optical fibers. However, since analog modulation is used in the SCM, the system performance can be degraded severely by the nonlinearities of semiconductor lasers.

The nonlinear response of semiconductor lasers has been a main issue for SCM over the past ten years [4]. In low-frequency applications, such as cable TV systems (<1 GHz), the distortion is mainly due to the nonlinear light-versus-current characteristic (L–I), which is often referred to as the static nonlinearity. In contrast, for high-frequency SCM systems, such as cellular mobile communications and satellite communication systems, which operate in a multigigahertz range near the relaxation resonance frequency of typical semiconductor lasers, the nonlinearity introduced by the coupling between photons and elections in the laser cavity becomes dominant [4]–[6]. This nonlinear coupling also results in the relaxation oscillation resonance. Therefore, high-frequency nonlinearity is generally referred to as intrinsic dynamic distortion or resonance distortion.

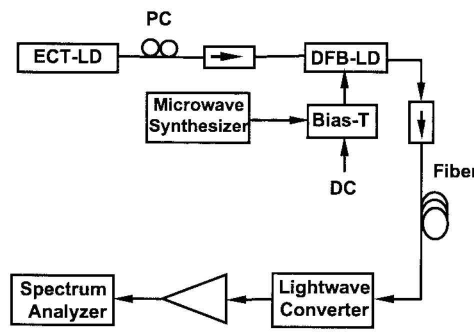

Fig. 1. Experimental setup. Polarization controller: PC, External cavity tunable laser diode: ECT-LD, DFB laser diode: DFB-LD.

Several approaches such as electrooptical feedback and feed-forward compensation methods have been proposed to suppress nonlinearities of semiconductor lasers [7], [8]. Injection locking has been extensively studied to improve the dynamics of semiconductor lasers since 1982 [9]–[12]. Recently, it has been theoretically shown that the intrinsic dynamic distortion can be substantially suppressed by using optical injection locking to increase the relaxation oscillation frequency [13]. Previously, we have experimentally shown that the second harmonic distortion (SHD) is effectively suppressed by optical injection locking [14]. In this paper, we report on the suppression of both the nonlinear harmonic distortions and third-order intermodulation distortion (IMD3) by optical injection locking. Under strong injection locking with an injection ratio of −8 dB, the relaxation oscillation frequency has been increased dramatically from 4.1 to 13.6 GHz. As a result, the SHD and third harmonic distortion (THD), as well as the IMD3 of the directly modulated distributed feedback (DFB) laser, have been successfully suppressed by 15 dB in the multigigahertz range near the relaxation oscillation frequency of the free-running laser.

II. Experimental Setup

Fig. 1 shows the experimental setup of a directly modulated DFB laser with external light injection. The master laser used in this experiment is a commercial external-cavity tunable

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laser diode (ECT-LD) at 1.55 μm with a 1-GHz tuning step size. The laser linewidth is less than 200 kHz. The continuous wave (CW) light from the ECT-LD is injected into the slave laser through a polarization controller with the extinction ratio of 30 dB and an optical isolator with the return loss of 50 dB. The slave laser is a 1.55-μm single-longitudinal mode DFB laser diode with a threshold current I_{th} of 23 mA and a linewidth of 40 MHz. The lasing wavelength of the slave laser is stabilized by controlling its temperature and bias current. An E-TEK laser optical-fiber interface (LOFI) with 35% coupling efficiency and long working distance is employed to couple the light from the fiber to the slave laser. The coupling efficiency has been verified by measuring the collection efficiency of LOFI from the DFB laser. The injection power is determined by measuring the output power from the fiber, taking into consideration the coupling efficiency of LOFI and the optical reflection at the DFB facet. Another optical isolator with the return loss of 50 dB is inserted after the slave laser to prevent the back reflection from the fiber connectors. The DFB laser is directly modulated by the subcarrier microwave signals through a bias-T. At the receiver end, the optical signal is detected and amplified by a 15-GHz lightwave converter (HP 11 982A) with a responsivity of 300 V/W for a 50-Ω load. The output is connected to a microwave spectrum analyzer (HP 8565E) for observing the nonlinear distortions. In addition, a modified delayed self-homodyne (MDSH) scheme suggested by Esman *et al.* [15] is used to determine the stability of injection locking by monitoring the reduction of the linewidth of the DFB laser [16]. The delayed line consists of a 2.3-km-long single-mode optical fiber, which provides a resolution of 44 kHz.

The SHD and THD are defined as the power ratio of the second harmonic wave and the third harmonic wave to the fundamental wave, respectively. The IMD3 is measured by two-tone modulation technique at frequencies f_1 and f_2 using the same setup. It is defined as the power ratio of the third-order intermodulation wave at $2f_2 - f_1 (f_2 = f_1 + \delta f)$ to the fundamental wave.

III. Results and Discussion

In our experiments, the slave laser is biased at 40 mA ($\cong 1.75 I_{\mathrm{th}}$) and the received optical power at the receiver end is -7 dBm. The relaxation oscillation frequency of the laser under this bias condition is found to be 4.1 GHz. The frequency response of the DFB laser is measured by a microwave network analyzer (HP 8510) with a lightwave test set (HP 83 420A). The locking behavior of semiconductor lasers strongly depends on two parameters: the injection ratio and detuning frequency [9]–[12]. The injection ratio is defined as the power ratio of the injected signal to the free-running optical signal inside the slave laser cavity. The detuning frequency is the frequency shift of the injected signal with respect to the free-running frequency of the slave laser.

The injection-locking stability is determined by monitoring the linewidth of the slave laser. Once the laser is injection locked, its linewidth reduces dramatically relative to its free-running value [16]. Fig. 2 is the measured locking range as a function of the injection ratio and detuning frequency. The stable injection-locking region is found to be bounded by two solid curves. The top curve is the boundary over which the laser exhibits chaotic behavior, and the bottom curve is the boundary below which the laser exhibits locking–unlocking bi-stability or multistability behavior, as predicted in [11]. In the following measurements, the injection ratio and detuning frequency are kept at -8 dB and -15 GHz, respectively, which is located in the middle of stable locking range and is sufficiently far away from the unlocking boundaries.

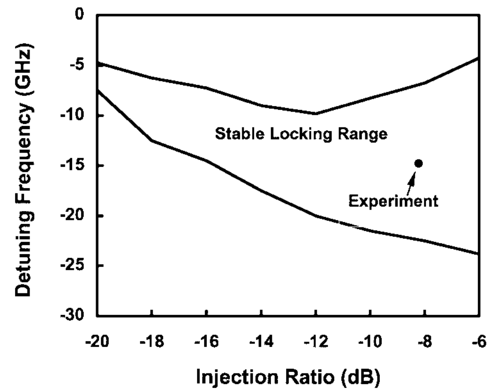

Fig. 2. The stable injection-locking range of the DFB laser as a function of the injection ratio and detuning frequency. The dot indicates the experimental injection condition (injection ratio $= -8$ dB, detuning frequency $= -15$ GHz) used in this paper.

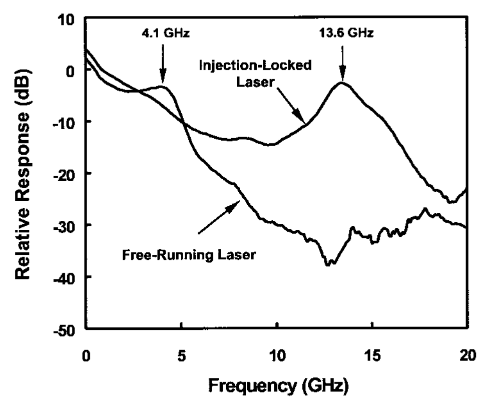

Fig. 3. Relative frequency responses of both the free-running and injection-locked lasers. The laser is biased at 40 mA ($\cong 1.75 I_{\mathrm{th}}$).

Fig. 3 plots the measured frequency response of the DFB laser with and without injection locking. The dip at frequencies below the resonance peak is due to the electrical parasitics of the laser [6]. The relaxation oscillation frequency of the DFB laser is dramatically increased from 4.1 to 13.6 GHz with optical injection from the ECT-LD.

A. Nonlinear Harmonic Distortion of the DFB Laser

It is known that the nonlinear distortion becomes more severe as the modulating frequency approaches the relaxation oscillation frequency due to the nonlinear coupling between electrons and photons. Therefore, if one can increase the relaxation oscillation frequency of the laser, the intrinsic nonlinear distortions in the multigigahertz range can be reduced. This

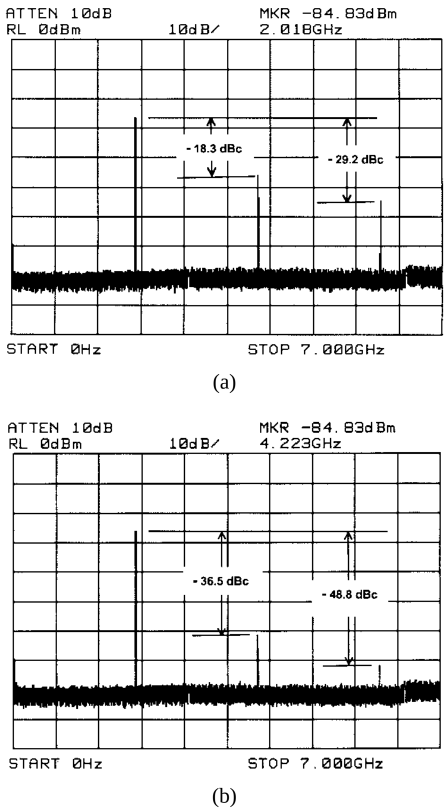

Fig. 4. Microwave power spectra at 2-GHz modulation frequency for: (a) the free-running and (b) injection-locked lasers. The RF power level (measured before the bias-T) is −2 dBm.

has been confirmed theoretically by small-signal analysis of the rate equations [5]. On the other hand, it has been shown both theoretically [10], [11] and experimentally [12] that optical injection locking can increase the relaxation oscillation frequency of semiconductor lasers. This suggests that the nonlinear distortion near the relaxation oscillation frequency of the free-running laser can be suppressed by optical injection locking, as theoretically predicted in [13].

Fig. 4 shows the power spectra of the free-running and injection-locked DFB lasers under a 2-GHz microwave modulation. The RF power level before the bias-T is −2 dBm, which corresponds to an optical modulation index of 20%. For the free-running laser, the SHD and THD are measured to be −18.3 and −29.2 dBc, respectively. These are comparable to the values previously reported by other groups [4]. With optical injection locking, the SHD and THD are greatly suppressed to −36.5 and −48.8 dBc, respectively, as shown in Fig. 4(b).

It should be noted that the nonlinear harmonic powers of the laser are much more sensitive to the residual optical reflections than the fundamental power. This has been investigated in detail by Helms [5]. In our experiments, we have observed fluctuation as much as 3–5 dB occasionally for the free-running laser, even in the presence of optical isolators. To minimize the effects of such fluctuations, all the data reported in this paper were obtained by averaging over three individual measurements. In each measurement, the data is averaged over 2 min. On the other hand, according to our experiences,

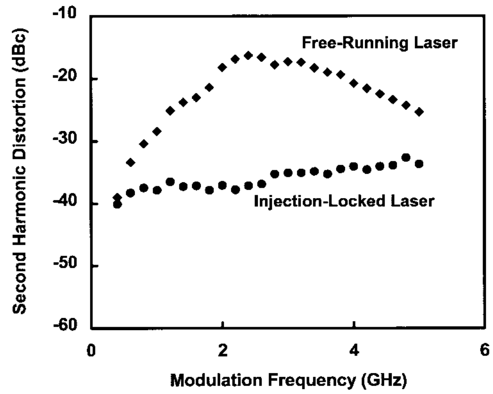

Fig. 5. SHD as a function of the modulation frequency for the free-running (♦♦♦) and the injection-locked (• • •) lasers.

the fluctuation of the nonlinear harmonic powers is greatly suppressed by the injection locking, particularly for high modulation frequencies. The decreased sensitivity to external optical feedback in semiconductor lasers has been previously observed [17].

In the following measurements, the power level of the RF signals before the bias-T is kept at −2 dBm over the entire frequency range for the free-running laser. Since the frequency response of the DFB laser is modified by the optical injection locking (see Fig. 2), the same RF input signal will produce a different modulation depth and different RF power at the receiver. It is, therefore, necessary to adjust the power of the RF modulation signals so that the received power at the fundamental frequency is equal to that of the free-running laser.

Fig. 5 shows the measured SHD as a function of the modulation frequency for both the free-running and injection-locked lasers. For the free-running laser, the SHD increases with increasing the frequency, until a maximum of −16 dBc is reached at 2.4 GHz (0.58 times the relaxation oscillation frequency). With optical injection locking, the SHD is substantially suppressed by 15 dB from 2 to 4 GHz. Unlike the free-running case, the SHD is not sensitive to the modulation frequency over the entire measurement region. On the other hand, we find that the suppression of the SHD is not significant for frequencies below 1 GHz.

Fig. 6 shows the THD versus the modulation frequency for both the free-running and injection-locked lasers. Without external optical injection, the THD varies a great deal with frequency. The maximum THD of −28.9 dBc occurs at 1.8 GHz. In contrast, the THD of the injection-locked laser is more uniform and less dependent on the modulation frequency. Compared with the free-running laser, the THD of the injection-locked laser has been suppressed by more than 13 dB from 1.4 to 3.2 GHz. Again we have noted that, as the modulation frequency reduces to below 1 GHz, the harmonic distortions become comparable for both the cases.

B. IMD3 of the DFB Laser

Intermodulation distortion occurs when the laser is modulated by two or more subcarriers. For narrow-band (suboctave) applications, the IMD3 of two closely spaced subcarriers is

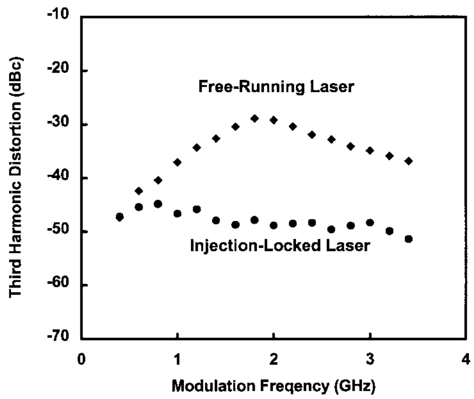

Fig. 6. THD as a function of the modulation frequency for the free-running (♦♦♦) and the injection-locked (• • •) lasers.

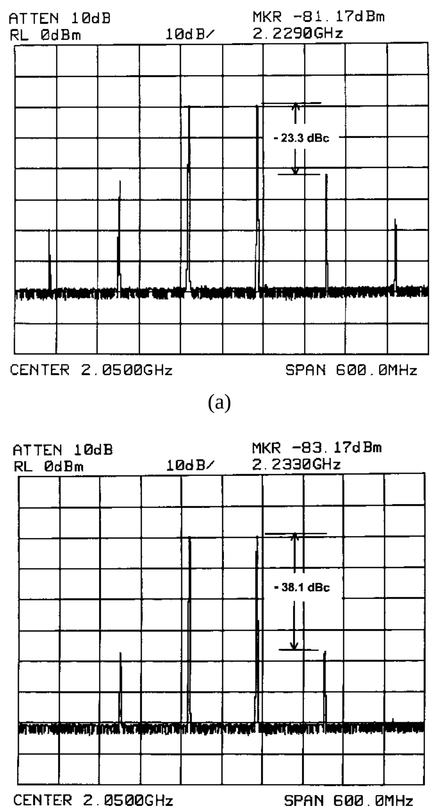

Fig. 7. Microwave power spectra of the DFB laser modulated by a two-tone microwave signal at $f_1 = 2.0$ GHz and $f_2 = 2.1$ GHz for: (a) the free-running and (b) injection-locked lasers.

most important because the IMD3 signals fall close to the original subcarrier frequencies. In this section, we report on the first experimental observation of the reduction of the IMD3 in directly modulated DFB lasers under strong injection locking. The power levels of both subcarriers before the bias-T are kept at 2 dBm over the entire modulation frequency range for the free-running laser. As noted above, we adjust the power of the RF modulation signals so that the received power at the fundamental frequency is equal to that of the free-running laser.

Fig. 7(a) shows the measured power spectrum of the free-running laser modulated by a two-tone microwave signal.

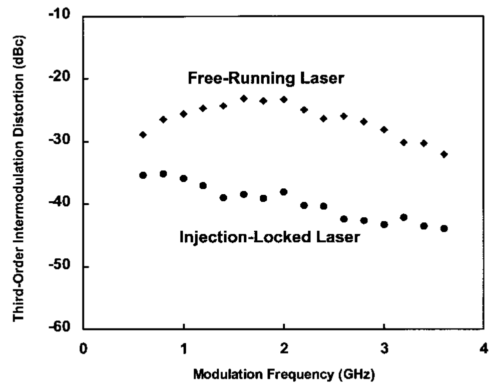

Fig. 8. IMD3 as a function of the modulation frequency f_1 for the free-running (♦♦♦) and the injection-locked (• • •) lasers. The frequency separation δf is maintained at 0.1 GHz.

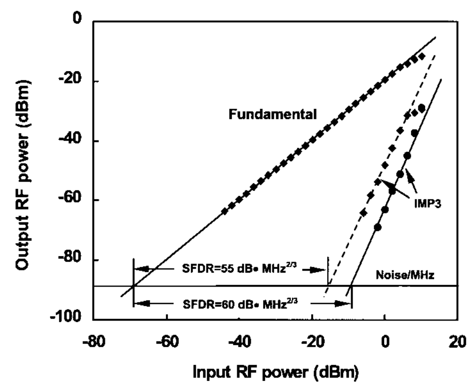

Fig. 9. The SFDR of the link with directly modulated DFB laser at $f_1 = 2.0$ GHz and $f_2 = 2.1$ GHz for the free-running (dashed line) and injection-locked (solid line) laser. IMP3: third-order intermodulation power.

The f_1 and δf are 2.0 and 0.1 GHz ($f_2 = f_1 + \delta f = 2.1$ GHz), respectively. The IMD3 (at $2f_2 - f_1$) is measured to be -23.3 dBc. On the other hand, Fig. 7(b) shows the corresponding power spectrum of the DFB laser under injection locking. The IMD3 are considerably reduced to -38.1 dBc. In addition, it is worth noting that the fifth-order intermodulation products are also suppressed at the same time by more than 20 dB.

Fig. 8 shows the IMD3 as a function of the modulation frequency f_1 for both the free-running and injection-locked lasers. The two-tone frequency separation δf is still kept at 0.1 GHz. The IMD3 is suppressed by 15 dB from 1.4 to 3.0 GHz by optical injection locking. Fig. 9 shows the RF output powers of the fundamental wave and the third-order intermodulation waves versus the RF input power for both the free-running and injection-locked lasers. Again, the f_1 and δf are 2.0 and 0.1 GHz, respectively. With optical injection locking, the spurious-free dynamic range (SFDR) has been improved from 55 dB·MHz$^{2/3}$ to 60 dB·MHz$^{2/3}$ (or 95 dB·Hz$^{2/3}$ to 100 dB·Hz$^{2/3}$ when normalized to 1-Hz bandwidth).

IV. Conclusion

We have experimentally investigated the effects of optical injection locking on the nonlinear distortions of directly modulated DFB lasers. The SHD and THD, as well as the IMD3, are measured as functions of modulation frequency with and without external optical injection. We found that under strong optical injection locking (injection ratio of -8 dB), the nonlinear distortions are suppressed by about 15 dB in the multigigahertz range. The improved nonlinear performance results from the dramatic increase of the relaxation oscillation frequency from 4.1 to 13.6 GHz under strong optical injection locking. These results demonstrate that optical injection locking is a very powerful technique for enhancing the performance of high-frequency SCM systems employing direct laser modulation such as cellular mobile communications.

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