Demonstration of an Analog Fiber-Optic Link Employing a Directly Modulated Semiconductor Laser with External Light Injection

Xue Jun Meng, Dennis T. K. Tong, Tai Chau, and Ming C. Wu, *Member, IEEE*

***Abstract*—We demonstrate an analog fiber-optic link employing a directly modulated semiconductor distributed-feedback (DFB) laser under optical injection locking. The results show that injection locking can significantly improve performances of analog fiber-optic systems at frequencies considerably beyond the bandwidth of free-running semiconductor lasers.**

***Index Terms*— Analog fiber-optic link, bandwidth, bit error, directly modulated semiconductor lasers, eye diagram, injection locking, subcarrier multiplexing.**

I. Introduction

MICROWAVE subcarrier multiplexed (SCM) fiber-optic systems have attracted extensive attention for their applications in broadband local access networks, and fiber-radio systems. The SCM can multiplex both analog (VSB-AM, FM) and digital modulations (BPSK, QAM) on a single optical carrier [1]–[3]. In simple SCM, many analog or digital baseband signals are first modulated onto electrical subcarriers with appropriate local oscillators at microwave frequencies. These subcarrier signals are then combined to modulate a semiconductor laser directly. At the receiver, the signal is downconverted by conventional microwave amplifiers and mixers to recover the original baseband signals. Compared with SCM systems using external modulators, the direct modulation approach is simpler and has lower cost.

The transmission capacity of the SCM system employing direct laser modulation is generally limited by the bandwidth of semiconductor lasers. Injection locking has been extensively studied to improve the dynamics of semiconductor lasers [4]–[8]. Recently, several research groups have shown theoretically that the injection locking technique can also increase the modulation bandwidth of semiconductor lasers, and hence improve the system performance at high frequencies [9]–[12]. In this letter, we present the first experimental demonstration of analog optical fiber communication systems employing a directly modulated semiconductor laser under optical injection locking. An increase in relaxation oscillation frequency of nearly 60% has been measured experimentally when the distributed-feedback (DFB) laser is injection locked. Fiber-optic transmission with bipolar phase-shift keying (BPSK) has also been successfully demonstrated (bit-error rate (BER) $<10^{-9}$) at subcarrier frequency of 1.8× the relaxation oscillation frequency of the free-running laser.

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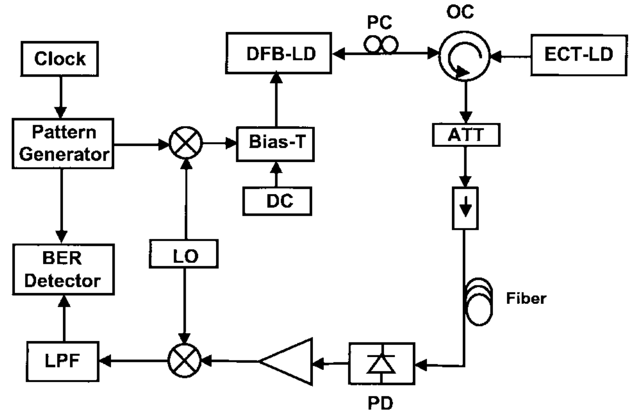


Fig. 1. Schematic diagram of the analog fiber-optic link. OC: optical circulator. PC: Polarization control. ECT-LD: External cavity tunable laser diode. DFB-LD: DFB laser diode. PD: Photodetector. ATT: Attenuator. The total fiber length is about 10 m.

II. Experimental Configuration

The experimental setup of the analog fiber-optic system employing a directly modulated semiconductor laser with external light injection is shown in Fig. 1. The master laser used in this experiment is a commercial external-cavity tunable laser diode (ECT-LD) at 1.55 μm with 1-GHz tuning step. The laser linewidth is less than 200 kHz. The CW light from the ECT-LD is injected into the slave laser through an optical circulator (OC). The slave laser is a 1.55 μm single-longitudinal mode DFB laser diode with a linewidth of 40 MHz. A polarization controller (PC) is employed to adjust the polarization of the injected light. An externally triggered pattern generator (HP 70 843A) provides a baseband signal with $2^{23}-1$ pseudorandom bit sequence (PRBS) at 120 Mb/s. The data is first modulated by BPSK on to a subcarrier at frequency f_c using a double balanced mixer, and then sent to the DFB laser through a bias-T. The DFB laser is biased at 35 mA (1.5× threshold), and RF power level before the bias-T is -7 dBm. The total fiber length is about 10 m from the output of the DFB laser to the receiver. At the receiver end, a broadband HP 83440D lightwave receiver converts the optical signal back to the electrical BPSK signal.

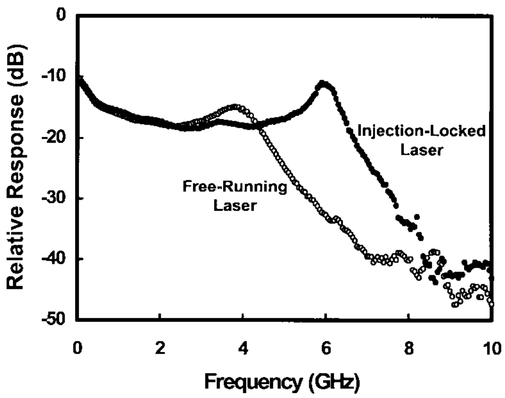
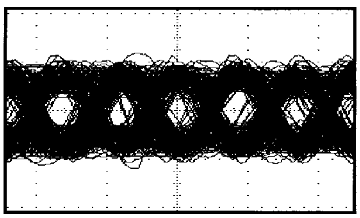
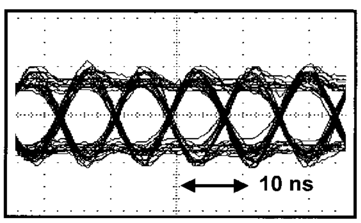


Fig. 2. Relative modulation responses of the free-running (○ ○ ○) and injection-locked (● ● ●) DFB lasers. The injection ratio is 0.08 and detuning frequency is −6.5 GHz.

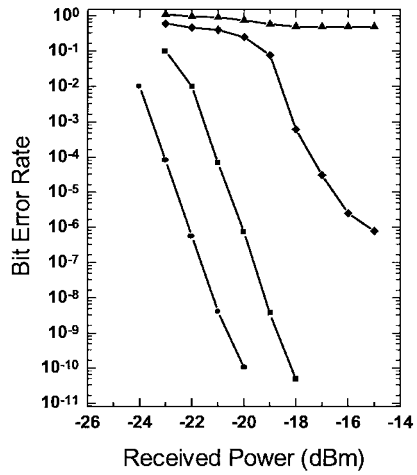


(a)

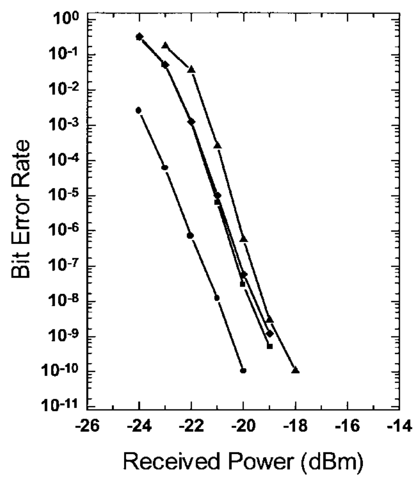


(b)

Fig. 3. (a) Received eye diagrams at subcarrier frequency of 6 GHz for free-running laser. (b) Injection-locked laser with injection ratio of 0.08 and detuning frequency of −6.5 GHz.



(a)



(b)

Fig. 4. Measured BER as a function of the received power for (a) free-running laser and (b) injection-locked laser at $f_c = 4$ GHz (● ● ●), 5 GHz (■■■), 6 GHz (◆◆◆), and 7 GHz (▲▲▲). The injection ratio is 0.08 and detuning frequency is −6.5 GHz.

The 3-dB electrical bandwidth and the dc responsivity of the receiver at 1.55 μm are 30 GHz and 15 V/W, respectively, for 50 Ω load. The output is amplified by a set of low noise microwave amplifiers that provide a total gain of 40 dB. The resulting BPSK signal is downconverted to baseband PRBS signal by mixing it with a replica of the original microwave carrier. A low-pass filter is added to filter out noise and to shape pulse waveforms. The demodulated baseband digital signal is monitored by a digital oscilloscope (HP 54 542C) and a BER testset (HP 70 843A) for eye diagram and BER measurement. In addition, we use a delayed self-heterodyne setup to determine stable injection locking by monitoring the reduction in linewidth of the DFB laser [13]. The delayed line is a 2.3-km-long single-mode optical fiber, which provides a resolution of 44 kHz.

III. Results and Discussion

The frequency response of the DFB laser with and without external light injection is measured by an RF network analyzer (HP 8510) with lightwave test set (HP 83 420A). The results are shown in Fig. 2. The dc bias of the DFB laser is kept at 1.5× threshold. The relaxation oscillation frequency of the DFB laser is increased from 3.8 to 6.0 GHz with CW light injection from the ECT-LD. The optimum detuning frequency and injection ratio are found to be −6.5 GHz and 0.08, respectively. Deviation from the optimum detuning frequency results in more damping of the relaxation oscillation peak. With injection locking, the bandwidth of the slave laser has been increased by nearly 60%. This agrees qualitatively with the theoretical analysis in [9] and [11]. When strong injection locking (injection ratio > 0.1) is realized, a bandwidth enhancement of over three times has been predicted by theory [11]. To go beyond the injection ratio of 0.08 in our current setup, the residual optical reflections from the fiber connectors need to be minimized. This is currently underway in our laboratory.

Fig. 3(a) and (b) shows the eye diagrams of the receiver output at −18-dBm received power and 6-GHz subcarrier frequency without and with injection locking, respectively. Because the subcarrier frequency is higher than the relaxation oscillation frequency of the free-running laser, the received eye pattern is almost closed [Fig. 3(a)]. With injection locking, the bandwidth of the DFB laser is increased to 6 GHz, and an open eye diagram is observed [Fig. 3(b)]. The injection parameters are identical to those used in Fig. 2.

The measured BER's of the BPSK system as functions of received optical power are displayed in Fig. 4 for various subcarrier frequencies. When the subcarrier frequency is less than or comparable to the relaxation oscillation frequency of the free-running laser, similar BER curves are observed for systems with and without optical injection locking. For free-running lasers, the BER degrades quickly with the increase of the subcarrier frequency and an error floor is observed at 6 GHz. With injection locking, BER of 10^{-9} is achieved for the subcarrier frequency as high as 7 GHz, with almost the same receiving sensitivity. This frequency is more than 1.8× the relaxation oscillation frequency of the free-running laser. These results demonstrate that the system performance of analog fiber-optic links employing direct laser modulation can be significantly improved by optical injection locking even when the carrier frequency is beyond the bandwidth of free-running lasers.

Finally, it should be emphasized that the bandwidth enhancement of the laser under injection locking is strongly dependent on the injection ratio. The previous theoretical results have shown that bandwidth enhancement as large as three times can be realized under strong optical injection-locking condition [11]. Our future experimental work will be focused on the implementation of stable strong injection locking to achieve even larger bandwidth enhancement.

IV. Conclusion

We have demonstrated an analog fiber-optic link employing a directly modulated semiconductor laser under injection locking. The performance of a BPSK subcarrier modulated fiber-optic system has been measured with and without injection locking. The bandwidth of the DFB laser has been enhanced by nearly 60% with moderate injection locking (injection ratio = 0.08). Open eye diagrams and BER $<10^{-9}$ have been achieved at subcarrier frequency of 1.8× the bandwidth of the free running laser.

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