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Injection-locked Semiconductor Lasers for Radio-on-Fiber Applications

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ABSTRACT

We have performed numerical and experimental investigations into characteristics of injection-locked semiconductor lasers for radio-on-fiber applications. We show that the injection-locking technique is very useful in suppressing distortions occurred by the intrinsic nonlinearities of semiconductor lasers and fiber chromatic dispersion along fiber-optic link for the giga-hertz applications. We also show that the injection-locking of semiconductor lasers can be employed in generating high frequency beat signals with very low phase-noises.

1. INTRODUCTION

The radio-on-fiber system has been attracting much attention since high frequency carriers and sub-carrier multiplexed data can be simultaneously transmitted through a single fiber from one central station to many base stations with low transmission loss. Many research groups have proposed and implemented various configurations for the fiber-on-radio systems [1-4]. Injection-locked semiconductor lasers can provide several functions required in such systems. In this paper, we present two cases for the application of injection-locked semiconductor lasers for radio-on-fiber systems. First, injection-locking can significantly reduce the frequency chirp in semiconductor laser and his can be utilized in reducing nonlinear characteristics in analog optical links using directly modulated lasers. Second, sideband injection-locking can generate high quality optical millimeter-wave signals. Research results for each application are presented.

2. IMD3 Suppression in Injection-Locked Semiconductor Lasers

Subcarrier multiplexed (SCM) fiber optic systems have many applications such as wireless local loops, cable television distributions and fiber-radio systems. The direct modulation of semiconductor lasers is a simple and low-cost approach for transmitting RF-range subcarriers. However, semiconductor laser nonlinearities and fiber chromatic dispersion cause harmonic and intermodulation distortions, and these can severely degrade overall system performance [5]. Although IMD3 is much smaller than second-order harmonic (2HD) and sum term intermodulation distortion (IMD2), the overall system performance is mainly affected by IMD3 in systems where 2HD and IMD2 frequencies lie outside the frequency band of interest [6]. Hence, it is crucial to suppress IMD3. Several techniques have been proposed in which fiber grating equalizers [7] or tilted etalons [8] are used to reduce the dispersion-induced distortions in SCM fiber optic systems. In addition, optical injection locking of semiconductor lasers has been investigated in order to suppress the semiconductor laser nonlinearities and IMD3 [9, 10].

We have performed the first experimental observation of the IMD3 variation of the injection-locked DFB-LD over fiber transmission [11]. Fig. 1 shows the measured RF spectra at the fundamental and IMP3 frequencies in the free-running (Fig. 1a, 1b) and injection-locked states (Fig. 1c, 1d) at 0Km (Fig. 1a, 1c) and 30Km fiber transmission (Fig. 1b, 1d). The IMD3 is defined as the ratio of the power at IMP3 frequency (= 2.8 GHz) to the power at the fundamental modulating frequency (= 2.7 GHz). The IMD3 for the free-running state is -21.5dBc at 0Km and increases to -14.0dBc at 30km. The reduction of power at the fundamental frequency after 30km transmission is due to fiber loss, but the power at IMP3 frequency is not as much reduced, resulting in 7.5dB increase in IMD3. For the injection-locked state (Fig. 2c, 2d), IMD3 is -27.17dBc at 0 km and -26.0dBc at 30 km. The IMD3 increases only by 1.17dB after the transmission. These results show that injection locking suppresses the laser nonlinearity as can be seen from the reduced 0Km IMD3 by 5.67dB, and also reduces the fiber dispersion-induced IMD3 by 12.0dB as can be seen from the much smaller increase in IMD3 after transmission.

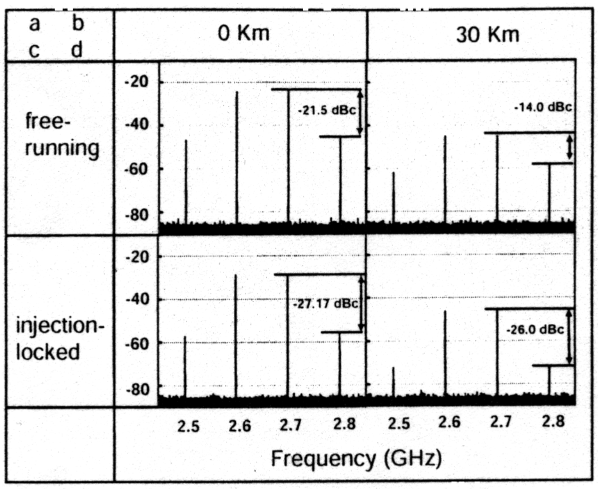


Fig. 1. Measured power spectra of the DFB-LD directly modulated by two-tone RF signals
a. free-running, 0km b. free-running, 30km
c. injection-locked, 0km d. injection-locked, 30km

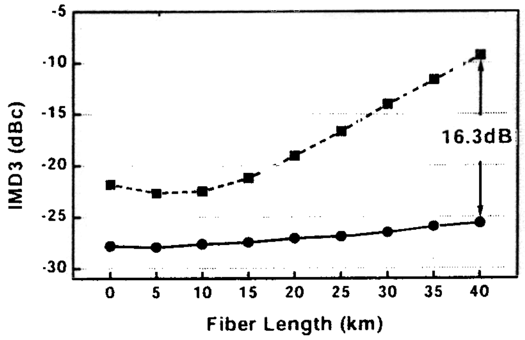


Fig. 2. IMD3 against fiber transmission length for free-running and injection-locked state
--- free-running
— injection-locked

The reduction of the dispersion-induced IMD3 for the injection-locked laser can be explained as follows. When the semiconductor laser is directly modulated by RF signals, its optical spectrum includes harmonic and intermodulation products due to the laser frequency chirp. During the transmission, the harmonic and intermodulation products can be affected by the fiber dispersion, depending on the modulation frequency and fiber length [5], which leads to IMD3 increase as shown in our experiments. The injection-locked semiconductor lasers have the reduced frequency chirp and thus, the modulated signal includes the smaller harmonic and inter-modulation products. Consequently, it is less affected by the fiber chromatic dispersion, and the fiber dispersion-induced IMD3 of the injection-locked DFB-LD does not increase much.

Fig. 2 shows the measured IMD3 at various transmission lengths. For the free-running state, IMD3 does not change much until 10Km. After 10km transmission, IMD3 starts to increase and reaches -9.31 dBc at 40km resulting in 12dB increase compared to 0km. On the contrary, for the injection-locked state, IMD3 increases only slightly. The IMD3 degradation is 1.55dB and its variation is maintained within about 1.5dB for the entire transmission length.

3. Optical Millimeter-Wave Generation using Sideband Injection-Locking

The sideband injection-locking technique is widely used for optically generating micro/millimeter-wave signals. It can easily produce very high frequency signals with low phase noises. Fig. 3 shows the operational principle of the sideband injection-locking technique. A DFB laser acting as Master Laser (ML) is RF-modulated and several sidebands are produced that have the frequency separation of the modulation frequency (Ω_m). Two of the sidebands having the target frequency separation are selected and used to injection-lock two separate DFB lasers acting as Slave Lasers (SLs). Two injection-locked SLs have the target frequency separation, and are synchronized to each other since they are both locked to the same ML. When the output lights from two SLs beat each other in a photodiode (PD), the desired micro/millimeter-wave signal is generated that has the target frequency and very low phase-noise.

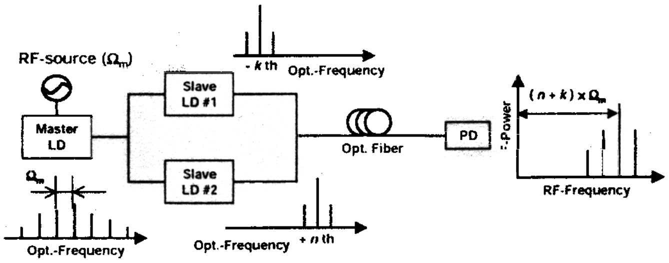


Fig. 3. Block diagram for optical micro-/millimter-wave generation with sideband injection locking

In the sideband injection-locking scheme, it is often the case that the ML modulation frequency is a sub-harmonic of the desired beat frequency. This can significantly reduce the required ML modulation bandwidth and the operating frequency for the RF source. For example, Braun *et al.* used 3.2 GHz in order to generate 64 GHz beat signals [4]. Consequently, a careful control in the SL lasing frequecies and the amount of ML light injected to SL is required in order to have each SL locked to the target sideband.

Recently, we have shown experimentally that, when the SL is injection-locked to a certain target sideband, the presense of adjacent ML sidebands that are not used for injection-locking process can influence the spectral characteristics of the resulting beat signals [12]. The presence of undesired beat signals is graphically illustrated in Fig. 3. Since these unselected sidebands can have significant influence on the overall system performance, it is very important to be able to analyze the characteristics of the undesired beat signals.

We have first performed the investigation into the effects of unselected ML sidebands on the characteristics of the undesired beat signals. We have also considered the influence of chromatic dispersion on the characteristics of those beat signals.

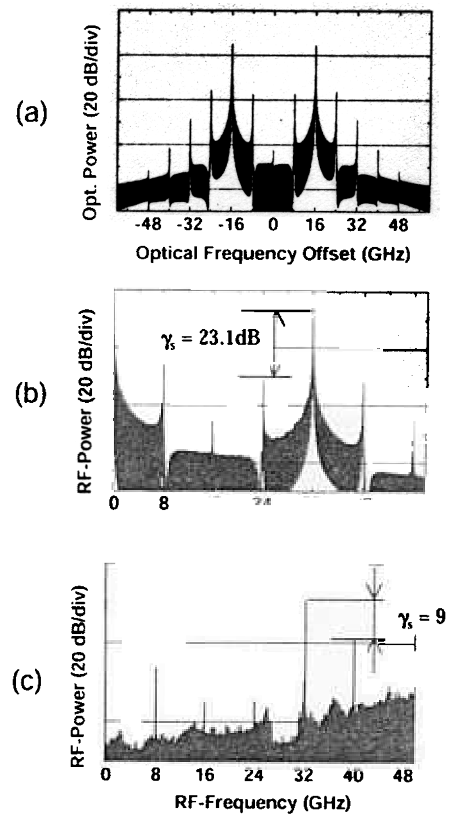
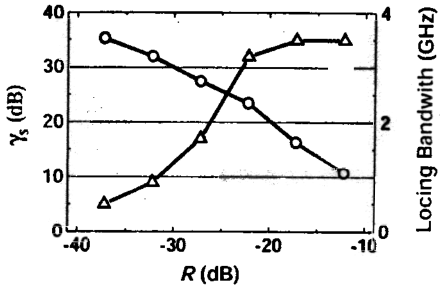
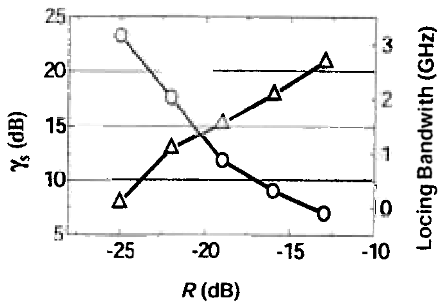


Fig. 4. Back-to-back optical and RF-spectra by two slave lasers when Ω_m=8GHz and n=k=2 in Fig. 3. Calculated optical (a) and RF-spectra (b) for R = -22.2 dB, and measured RF-spectra (c) for estimated R = -16 dB.

Fig. 3 shows the calculated optical output spectrum of two locked SLs in Fig. 3 and the resulting back-to-back RF-spectrum for R = -22.2 dB, where the center of the optical frequency axis in the figure represents the ML center lasing frequency (e.g., λ_0 = 1550 nm). R is defined here as the ratio between the average ML injection and free-running SL powers. Most of SL powers are shifted to the target sidebands. But, some of the undesired sidebands can have sufficient gains from SLs, since they could be in the unstable-locking regime. Consequently, the unwanted sidebands are not sufficiently suppressed (Fig. 4-(a)) and significant undesired beat signals are present in the back-to-back RF spectra (Fig. 4-(b)). Fig. 4-(c) shows a measured back-to-back RF-spectrum for estimated R = -16 dB.

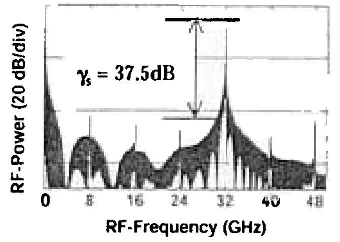


(a) Simulation

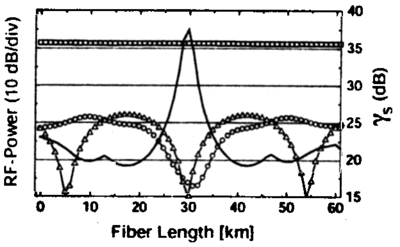


(b) Measurement

Fig. 5. Dependence of γ_s (circles) and stable-locking bandwidth (triangles) on R's.



(a) After 30 km of fiber.



(b)

Fig. 6. Calculated dispersion effect on the beat signals for R = -22.2 dB. The target frequency is 32 GHz (squares), and two adjacent frequencies are 24 GHz (circles) and 40 GHz (triangles). The solid line represents the suppression ratio of undesired beat signals (γ_s).

With increasing R, the undesired beat signal powers increase and can become comparable to the desired beat signal power in the RF spectrum. The decrease of R can suppress the undesired beat signals, but reduces the stable-locking range. The trade-off in R between the suppression of adjacent undesired beat signals (P_{24} @ 24 GHz, P_{40} @ 40 GHz) against target beat signal (P_{32} @ 32 GHz) and stable-locking banwidth is shown in Fig. 5 for the back-to-back case. Fig. 5 shows that the numerical results are qualitatively in good agreement with the experimental results.

Fig. 6 shows the calculated dispersion effect on the RF spectrum of the resulting beat signals. In order to consider fiber chromatic dispersion along the fiber-optic link between SLs and PD in Fig. 3, the optical fiber is simply modeled with a low-pass equivalent transfer function given by

$$H_{fiber}(f) = \exp[-j(\pi D f^2 \lambda^2 L/c)]$$

where $|D|$ = 16 ps/nm·km, and L is the fiber-optic length. Optical fiber loss is not included in the simulation in order to observe only the influence of fiber dispersion on the characteristics of undesired beat signals.

An RF-spectrum after 30 km of fiber (Fig. 6-(a)) clearly shows that the adjacent undesired beat signals are greatly suppressed by more than 14 dB compared to the back-to-back case (Fig. 4-(b)) under the same simulation conditions. It is because the fiber chromatic dispersion changes the optical phases of sidebands, and the sidebands cause the periodic fluctuations of beat signals after photo-detection as can be expected from [13]. Thus, it is possible that two adjacent undesired beat signals after a certain length of fiber can be both greatly decreased due to the destructive interference between multiple sidebands at their beat frequencies (24 GHz and 40 GHz, here) as shown in Fig. 6-(b). It occurs first at around 30 km of fiber in our simulation.

4. Summary

We have investigated the characteristics of injection-locked semiconductor lasers that are very useful in suppressing intermodulation distortions due to the combined effect of the intrinsic semiconductor laser nonlinearities and fiber chromatic dispersion. We have also investigated the optical millimeter-wave generation using sideband injection locking scheme and showed that the unselected ML sidebands produce undesired beat signals whose power can be comparable to the desired beat signal power. The decrease in the injection power ratio between the ML and SL can suppress the undesired beat signals, but reduces the locking bandwidth. In addition, we show that the undesired beat signals can be significantly suppressed depending on the transmission length.

We believe our investigations can provide useful guidelines in using injection-locked semiconductor lasers for radio-on-fiber applications.

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