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Nonlinear Distortion Suppression in Directly Modulated Distributed Feedback Lasers by Sidemode Optical Injection Locking

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We demonstrate a new nonlinearity reduction method in directly modulated distributed feedback (DFB) semiconductor lasers. By injecting external light into a DFB laser sidemode, the nonlinear distortion of the laser is significantly reduced. Compared to the previously reported main-mode optical injection locking scheme, greater distortion suppression and a wider stable locking range can be achieved. [DOI: 10.1143/JJAP.41.L136]

KEYWORDS: semiconductor laser nonlinearity, direct modulation, optical injection locking, sidemode optical injection locking, distortions, analog fiber optic link, locking range

Analog fiber-optic transmission systems have many applications such as CATV and fiber radio systems.[1] In these applications, the direct modulation of semiconductor lasers can be used for transmitting subcarrier-multiplexed signals at low cost. However, when semiconductor lasers are directly modulated, nonlinear distortions occur. Such distortions can cause severe system performance degradation, because they cause inter-channel interference that limits the number of channels as well as transmission distance.[2,3] In low frequency applications, nonlinear light-versus-current characteristics are the main cause of distortions. However, for direct modulation with RF-range frequency, the nonlinearity resulting from the coupling between photons and electrons in the laser cavity is dominant. This coupling also results in the relaxation oscillation resonance.[4]

To reduce nonlinear distortions in semiconductor lasers, several methods have been proposed, such as electrooptical feedback and feed-forward compensation.[5,6] Meng *et al.* have reported that laser distortion can be significantly suppressed by optical injection locking.[4] Light from an external master laser (ML) is used to lock the signal transmitting slave laser (SL). This technique can increase the laser relaxation oscillation frequency, which causes the intrinsic nonlinear distortion suppression in directly modulated semiconductor lasers. However, the injection locking occurs within the relatively narrow frequency detuning range between the ML and SL. This may limit the applicability of the injection locking technique for practical applications.

Recently, as a solution for increasing the detuning range, sidemode injection locking in distributed feedback (DFB) lasers was proposed and analyzed.[7] In this scheme, light is injected into a highly suppressed DFB laser sidemode instead of the DFB laser main-mode. In sidemode optical injection locking, as the sidemode lasing power is very low, the unstable locking characteristics due to mode beating between ML and SL do not easily occur, and the stable locking range can be extended. In this paper, we demonstrate the validity of sidemode injection locking for suppressing laser nonlinearities such as harmonic distortion and intermodulation distortion. Moreover, we show that compared to the previously reported main-mode optical injection locking scheme, greater distortion suppression and a wider stable locking range can be achieved in sidemode injection locking.

Figure 1 shows the experimental setup used for our investigation. The external-cavity tunable light source is used as the ML for simple control of injection wavelength and power. For the SL, a commercially available fiber-pigtailed, unisolated DFB laser is used. The coupling efficiency from the ML to the SL is estimated to be about 30%. The threshold current of the free-running (no optical injection) SL is about 7 mA. The SL wavelength is stabilized by controlling its temperature and bias current. An optical circulator is used to prevent the unwanted light coupling from the SL to the ML. The locked SL characteristics are observed by an optical spectrum analyzer and, after being converted into electrical signals, by an RF spectrum analyzer.

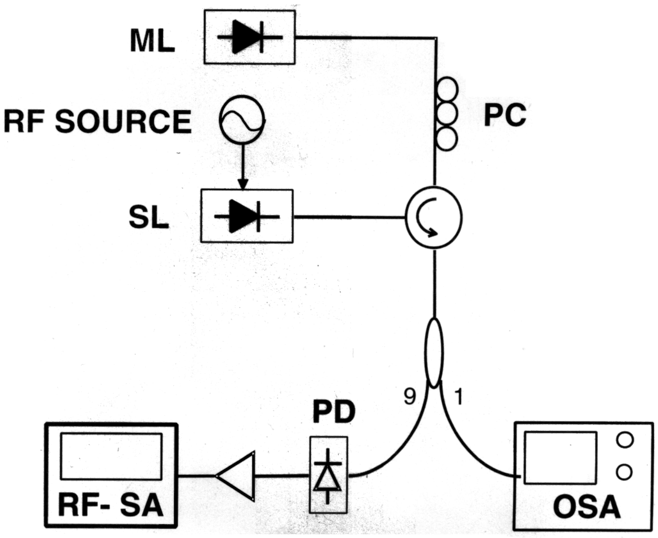

Fig. 1. Sidemode optical injection locking experimental setup (RF-SA: RF-Spectrum Analyzer, OSA: Optical Spectrum Analyzer, PC: Polarization Controller, PD: Photodiode).

Figure 2 shows the SL optical spectra in the free-running and the injection locked cases. When a sufficient amount of the ML light is injected into the sidemode marked as -1 mode in the figure, the main-mode becomes significantly suppressed and the sidemode becomes dominant. For a given ML injection wavelength, the SL main-mode suppression range can be determined and, from this, we can estimate the stable locking range as was done for a Fabry-Perot laser in ref. 8. In our case with a DFB laser, high injection power is needed to lock the sidemode and to suppress the main-mode sufficiently. In addition, the necessary injection power and the main-mode suppression range depend on the selected sidemode. By using the sidemodes near the main-mode, the SL locking can be

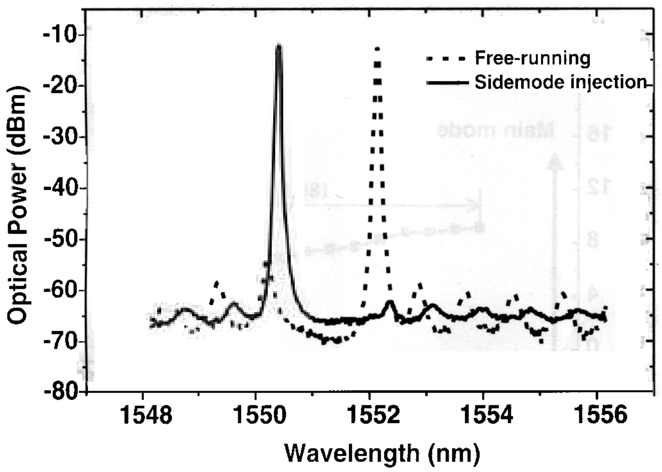

Fig. 2. Optical spectra of free-running laser (dotted lines) and sidemode injection-locked laser (solid lines).

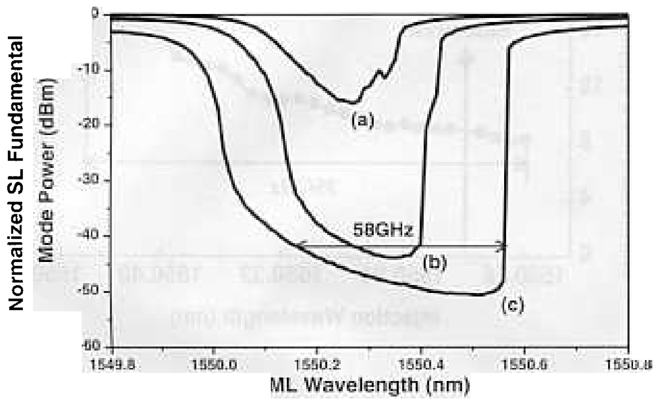

Fig. 3. Normalized peak power of the SL main-mode under sidemode optical injection. ML injection powers are −2 dBm (a), 2 dBm (b), and 6 dBm (c), respectively.

achieved with relatively low injection power.

In order to investigate the sidemode optical injection phenomena in detail, we observe the dependence of the SL main-mode suppression on the ML injection wavelength and power. We select the ML wavelength around the target sidemode located at 1550.2 nm (−1 mode) and change it from 1549.8 nm to 1550.8 nm in steps of 0.01 nm. The ML optical powers of −2 dBm, 2 dBm, and 6 dBm are used that are measured at the circulator output toward the SL. The SL bias current is maintained at 18 mA, which corresponds to about 2.5 times the threshold current. Figure 3 shows the amount of main-mode suppression normalized by the free-running main-mode peak power. As shown in the figure, with larger ML optical power, the main-mode is suppressed more and the main-mode suppression range widens. This means that with larger ML optical power, the SL locking range widens. We also observe the usual asymmetric locking range characteristics. For 6 dBm optical injection power, the main-mode can be suppressed by more than 40 dB, and the stable locking range is estimated at about 58 GHz. Under similar injection conditions, the stable locking range for the main-mode is measured to be about 26 GHz. Therefore, by means of sidemode optical injection, we can double the stable locking range. The reason for this wider stable locking range is believed that, since the sidemode power is very low, unstable locking characteristics due to mode beating between the ML and SL do not affect the locking range.

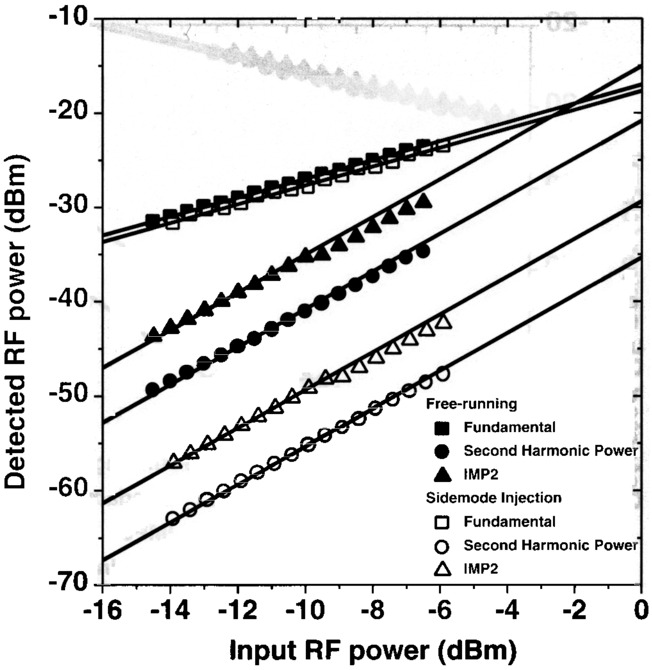

Fig. 4. Detected second harmonic ($2f_2$) powers and second order intermodulation distortion product powers (IMP2: $f_1 + f_2$) for free-running and sidemode injection-locked lasers.

Next, we investigate the nonlinear distortion characteristics of directly modulated lasers in the case of sidemode optical injection locking. For generating subcarriers, the SL is directly modulated by two RF signals ($f_1 = 2.8$ GHz and $f_2 = 2.9$ GHz). We measure the power of the second harmonic distortion (SHD), the second order intermodulation distortion (IMD2), and the third order intermodulation distortion (IMD3). For the sidemode optical injection experiment, the injection light power is set at 6 dBm, and the wavelength at 1550.434 nm. Under these conditions, the laser main-mode is suppressed about 50 dB. Figure 4 shows the detected RF powers of the second harmonic and the second order intermodulation distortion products (IMP2). The input RF power is measured at the RF signal generator output. The linearly fitted lines show that the slope of fundamental frequency power is one and that of the IMP2 is two as expected. As can be seen in the figure, the SHD and IMD2 are suppressed by more than 10 dB by sidemode optical injection locking.

We also investigate the reduction of the IMD3. Intermodulation distortion occurs when the laser is modulated by two or more subcarriers. For narrow band applications, the IMD3 caused by two closely spaced subcarriers has the largest impact on performance degradation, because the third order distortion signals fall close to the original subcarrier frequencies. Figure 5 shows the power of the third order intermodulation distortion product (IMP3) for the free-running and for the sidemode optical injection according to the input RF power. The slope of the IMP3 is three, as expected. From Fig. 5, we can see that the IMD3 can be suppressed by more than 10 dB, and we can also estimate the spurious-free dynamic range (SFDR) of the directly modulated DFB laser by linear-fitting.[4] As a result, we can achieve a dynamic range enhancement of more than 3 dB for the IMD3.

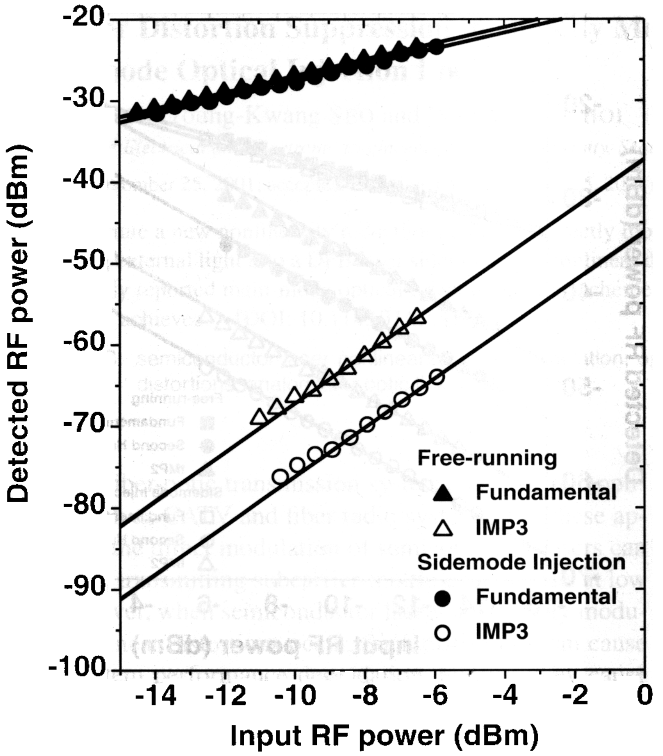

Fig. 5. Detected third order intermodulation distortion product powers (IMP3: $2f_2 - f_1$) for free-running and sidemode injection-locked lasers.

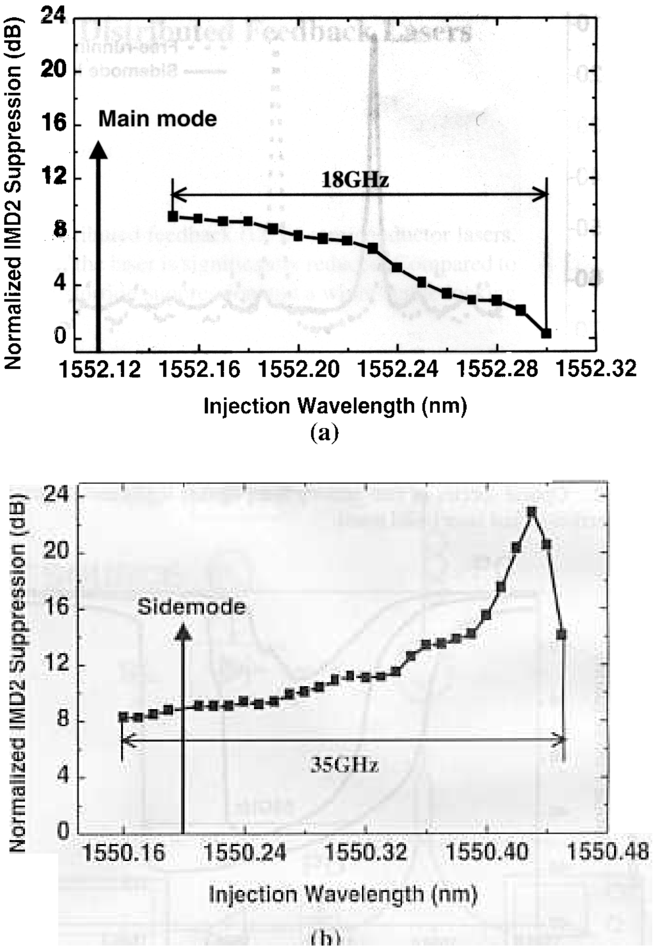

Fig. 6. Normalized IMD2 suppression for main-mode injection locking (a) and sidemode injection locking (b).

Finally, we compare the ML detuning range and distortion suppression of sidemode and main-mode optical injection. For fair comparison, the IMP2 is measured with the same optical injection power as the injection wavelength is swept within the stable locking range for each case. The IMP2 is selected for comparison since it is very simple to measure. The SL bias current is maintained at 18 mA. With the injection power of 4 dBm, we can achieve the stable locking range of 18 GHz by main-mode injection locking, and the 35 GHz range by sidemode injection locking. Figure 6 shows the experimental results. Since the detected RF power at modulation frequency changes slightly when injection-locked, the modulation power is set in order to make the detected RF power equal for all measurements.[4] In the case of sidemode injection locking, we can achieve IMD2 suppression ranging from 8 dB to 22 dB. On the other hand, with main-mode injection locking, the achieved IMD2 suppression is less than 8 dB. Although the identification of reasons for larger distortion suppression with sidemode injection locking requires further investigation, we believe that it is due to more suppressed relaxation resonance in the sidemode injection-locked laser. Evidence for this comes from the RIN spectrum measurement. Although the RIN peak at the relaxation oscillation frequency is clearly visible for the main-mode injection-locked DFB laser, it cannot be observed for the sidemode injection-locked DFB laser even if the same injection power is used. Further investigations are required in order to clarify how various injection conditions influence the modulation frequency responses as well as the nonlinear distortion characteristics of the sidemode injection-locked DFB laser.

We have experimentally investigated the effects of sidemode optical injection locking on nonlinear distortions of directly modulated DFB lasers. The SHD, IMD2, and IMD3 suppression is measured as functions of modulation RF powers with and without external sidemode optical injection. We found that under sidemode optical injection, nonlinear distortions are suppressed more than 10 dB. In addition, compared with the main-mode optical injection locking, distortion is suppressed more by the sidemode optical injection locking and the stable locking range is about twice wider. We believe that sidemode injection locking can be useful for providing nonlinearity suppressed lasers that can be used for optical analog transmission systems.

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