Nonlinear Distortion Suppression in Directly Modulated DFB Lasers by Sidemode Optical Injection

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Abstract — **We demonstrate a new method of suppressing nonlinear distortions in directly modulated DFB lasers. In our scheme, external laser light is injected into the sidemode of the DFB laser. Using this scheme, we achieved significant reduction in nonlinear distortions such as the second harmonic distortion (SHD), second order intermodulation distortion (IMD2), and third order intermodulation distortion (IMD3). In addition, we enhanced the external light detuning range.**

I. INTRODUCTION

Optical analog transmission of RF-range electrical signals is attracting much interest for WLL (wireless local loop), CATV, and satellite system applications [1]. In these applications, direct modulation of semiconductor lasers can be used for transmitting signals multiplexed by RF-range subcarriers for simple and low cost systems. However, when lasers are modulated with RF-range electrical signals, laser diode (LD) nonlinearity becomes a key issue in the system performance because it can impose signal distortions. These distortions cause inter-channel interference, which limits the number of channels as well as transmission distance [2, 3].

One method of overcoming the LD nonlinearity problem is using optical injection locking technique, where light from an external laser (master laser, ML) is injected into the signal transmitting laser (slave laser, SL). Meng *et al.* has recently found that laser nonlinearities can be significantly suppressed by the optical injection locking technique [4]. However, optical injection locking occurs within the relatively narrow lasing frequency detuning range between the ML and SL, and it is typically tens of GHz. This may limit the applicability of the injection locking technique.

As a solution for this problem, we propose a new technique - sidemode optical injection in which the ML light is injected into the DFB laser sidemode. Under strong optical injection, we successfully suppressed laser nonlinear distortions such as harmonic distortions and intermodulation distortions. Moreover, we can widen the distortion suppression range by a factor of about two compared with the case of main-mode injection locking.

II. EXPERIMENTAL SETUP AND RESULT

Fig. 1 shows the experimental setup used for our investigation. The external cavity tunable light source is used as the ML for simple control of incident wavelength and optical power. For the SL, a commercially available fiber-pigtailed, unisolated DFB laser (Samsung SDL-24) is used. The coupling efficiency from the external light source is about 30% and the threshold current I_{th} is about 7 mA. The lasing wavelength of the SL 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. An optical spectrum analyzer is used for measuring the optical spectrum change in case of light injection and an RF spectrum analyzer is used for observing nonlinear distortions.

Fig 2-(a) shows the SL optical spectrum in free-running (no optical injection). When a significant amount of the ML light is injected into the sidemode marked as -1 mode, the main-mode is significantly suppressed and the sidemode becomes dominant as can be seen in Fig. 2-(b). This is due to the XGM effect and this phenomenon is previously used for wavelength conversion and signal regeneration [5 - 7].

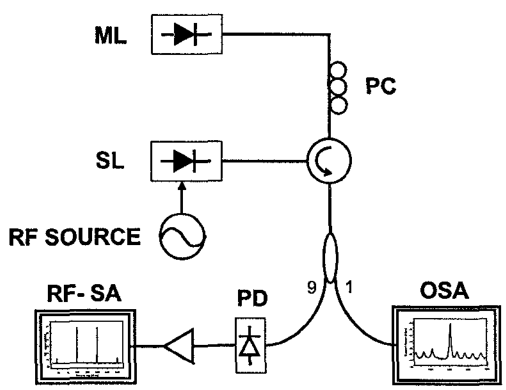

Fig. 1. Experimental setup. OSA: optical spectrum analyzer, PC: polarization controller, and RF-SA: RF spectrum analyzer

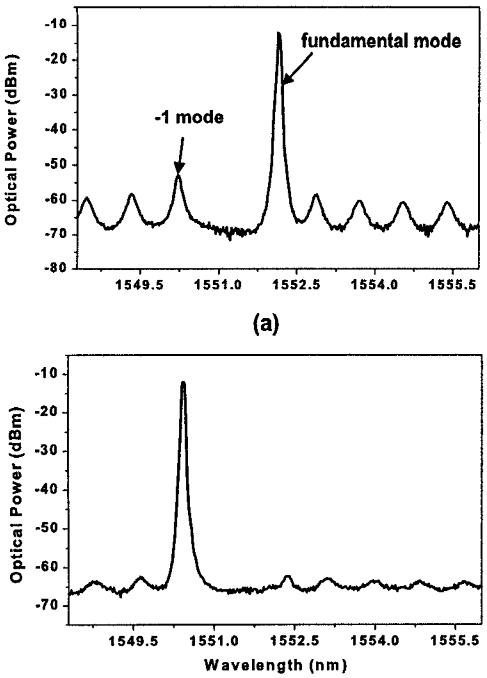

Fig. 2. SL optical spectra for free-running (a) and sidemode optical injection (b). Incident light wavelength and power are 1550.434 nm and 8 dBm, respectively.

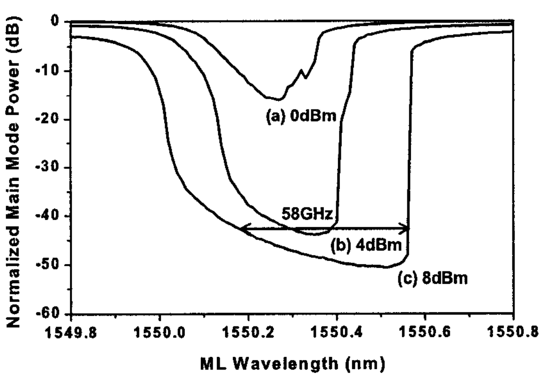

Fig. 3. Normalized peak power of SL main-mode under sidemode optical injection. ML injection powers are 0 dBm (a), 4 dBm (b), and 8 dBm (c), respectively.

A. Sidemode Injection Characteristics

In order to investigate the sidemode optical injection phenomenon in detail, we observe dependence of SL main mode power changes on the ML injection wavelength and the optical power. We select the ML wavelength around the target mode (-1 mode) and change the wavelength from 1549.8 nm to 1550.8 nm. The ML optical power, represented by the tunable light source output power, is changed from 0 dBm to 8 dBm. The SL bias current is 20 mA. Fig. 3 shows the normalized main- mode suppression range. The data are normalized by the free-running main-mode peak power. As shown in the figure, the more the ML power increases the wider the main-mode suppression range is. For 8 dBm injection, the main-mode can be suppressed more than 40 dB, and this suppression range is about 58 GHz. We select this range as the allowed sidemode injection wavelength range for single mode laser operation.

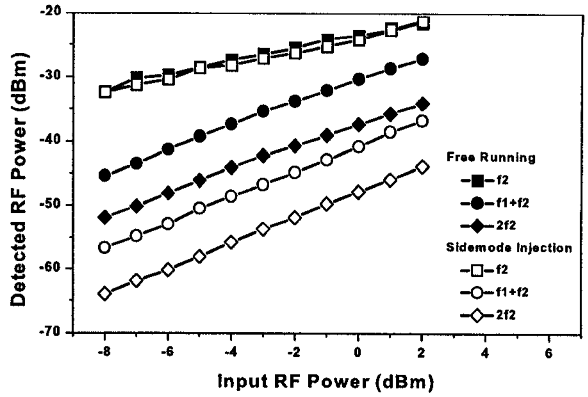

Fig. 4. The photo-detected second order intermodulation product power (IMD2: f_1+f_2) and second harmonic ($2f_2$) power for the free-running and sidemode injection.

B. Nonlinear Distortions of DFB Laser

Next, we investigate the nonlinear distortion change of directly modulated lasers in case of sidemode optical injection. For generating subcarriers, the SL is directly modulated by two RF signals (f_1 = 2.8 GHz and f_2 = 2.9 GHz). In these frequencies, the maximum nonlinear distortions occur for the laser used. In this experiment, we measure the second harmonic distortion (SHD), second order intermodulation distortion (IMD2), and third order intermodulation distortion (IMD3). The SHD is defined as the ratio of power at frequency $2f_2$ to the power at fundamental frequency. The IMD2 and IMD3 are defined as the ratio of powers at frequency f_1+f_2 and at frequency $2f_2$-f_1, respectively, to the power at fundamental frequency. For the sidemode injection, the tunable light source power is set at 8 dBm and the wavelength is set at 1550.434 nm. Under these conditions, the laser main-mode can be suppressed about 50 dB.

We measure SHD and IMD2. Fig. 4 shows the detected RF powers of the second harmonic and the second order

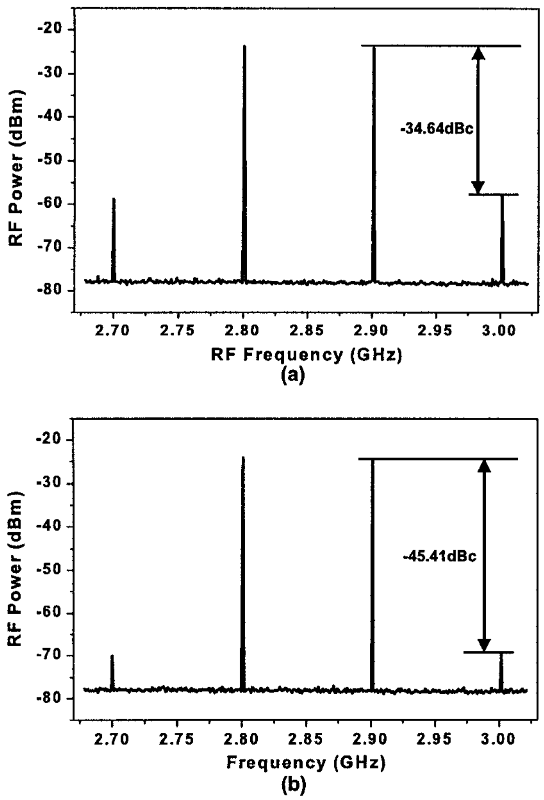

Fig. 5. RF-spectra for the free-running (a) and sidemode injection (b).

intermodulation product. The input RF power is measured at the RF signal generator output. Each result is averaged using 50 fixed step data. From fig. 4, we can see that by sidemode optical injection, we can suppress more than 10 dB SHD and IMD2.

Then, we observe the reduction of IMD3 in directly modulated DFB lasers under strong sidemode optical injection. Intermodulation distortion occurs when the laser is modulated by two or more subcarriers. For narrow band applications, the IMD3 of two closely spaced subcarriers is the most important because the IMD3 signals fall close to the original subcarrier frequencies. Fig. 5-(a) and (b) show the RF spectra for free running and sidemode optical injection respectively, where the applied RF power is 0 dBm. The measured IMD3 were -34.54 dBc for free running and -45.41 dBc for the sidemode injection. This result shows IMD3 can be suppressed more than 10 dB by sidemode optical injection. Fig. 6 shows the power of intermodulation distortion product (IMP3) for the free-running and for the sidemode optical injection according to the input RF power, which is also the RF signal generator output power. From this result, we can estimate spurious-free dynamic range (SFDR) of directly modulated

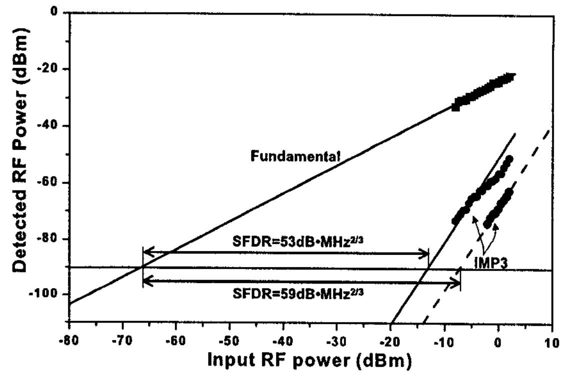

Fig. 6. SFDR of directly modulated DFB lasers for the free-running (solid line) and sidemode injection (dashed line).

DFB laser by linear-fitting. When the system noise floor is assumed -90 dBm, SFDR for free-running is about 53 dB·MHz$^{2/3}$ and SFDR for sidemode optical injection is about 59 dB·MHz$^{2/3}$. With sidemode optical injection, we can achieve 6 dB dynamic range enhancement.

C. Light Injection Detuning Range

Finally, we compare the ML detuning range for the stable operation of sidemode and main-mode optical injection. For comparison, we measure the normalized IMD2, determined by subtracting IMD2 of light-injection case from IMD2 of free-running case. In case of main-mode optical injection, the IMD2 is measured within the locking range, and in case of sidemode optical injection, the IMD2 is measured within the range where more than 40 dB main mode suppression is achieved. The laser bias current is 18 mA, and the injection power is 6 dBm, measured at the tunable light source output.

Fig. 7 shows the normalized IMD2 as function of the injected light wavelength. Fig. 7-(a) is the main-mode optical injection case. The main-mode wavelength is located at about 1552.12 nm. For the given injected light power, the locking range is determined to be from 1552.15 nm to 1552.3 nm. Within the locking range, the maximum IMD suppression is 8 dB. Fig. 7-(b) is the sidemode optical injection case. The sidemode wavelength is located at about 1550.2 nm and the range for more than 40 dB main-mode suppression is from 1550.16 nm to 1550.45 nm. Within this range, the IMD2 suppression is more than 8 dB, and at some injection wavelengths, the IMD2 can be suppressed more than 20 dB. The range for the IMD suppression is 35 GHz and this value is twice wider than the main-mode injection case. The reason for wavelength dependence of IMD2 suppression is not fully understood. The reason for increase in detuning range for

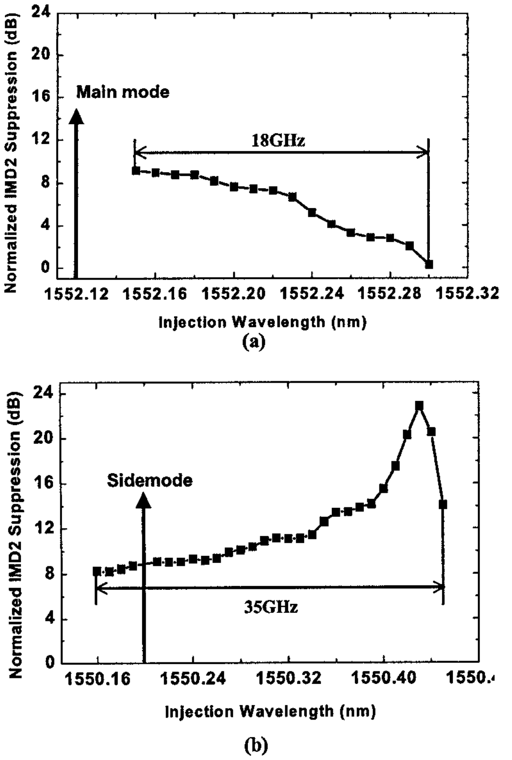

Fig. 7. Normalized IMD2 suppression of the main-mode optical injection case (a) and of the sidemode optical injection case (b).

the sidemode injection is believed to the enhanced ratio of the ML power to the SL mode power. It is well known that increasing the ML power increases the stable locking range for the main-mode injection case [8]. We achieved the same effect without increasing ML power by injecting the ML power into the DFB laser sidemode.

III. CONCLUSIONS

We have experimentally investigated the effects of sidemode optical injection on nonlinear distortions of directly modulated DFB lasers. The SHD, IMD2, and IMD3 are 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, the stable operating range of sidemode optical injection is twice wider than the main-mode optical injection locking range. Thus, we believe that our method can provide improved performance with better stability in using optical injection technique for laser diode nonlinearity suppression.

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