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Optical Feedback on Linearity Performance of 1.3 μm DFB and Multimode Lasers Under Deep Microwave Modulation

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1. Introduction

High-speed InGaAsP laser diodes (LDs) are expected to be extensively used in microwave analog fiber optic systems because of the low dispersion and attenuation in the 1.3μm wavelength region. In this paper, we examine the effect of optical feedback on the linearity performance of both a 1.3 μm single-longitudinal-mode (SLM) distributed feedback double-channel planar buried heterostructure (DFB-DC-PBH) LD [1] and a 1.3 μm multi-longitudinal-mode (MLM) buried heterostructure "window" [2] LD. Both lasers are intrinsically highly linear in the absence of optical feedback. The effect of optical feedback is examined by a quantitatively controlled reflection at the end of a 1~2 meter pigtail. Particular attention is paid to cases where both lasers are intensity modulated by large signals (current modulation index 50% to 80%) with frequencies above 1 GHz. Modulation signal power level, frequency, and laser bias level that affect the light coherent property, and hence laser linearity characteristics under optical feedback, are discussed.

2. Experimental Setup

The experimental setup to measure the optical power spectrum and RF behavior (linearity, relaxation oscillation, etc.) of both LDs with optical feedback is shown in Figure 1. The MLM window LD is packaged and has a 2 meter pigtial. The ac inputs of both LDs have 50 ohm- terminations. The reflection-controlled unit consists of a nearly reflection-free variable attenuator and a dielectric thin-film coating with about 80% reflectance [3]. The fraction of optical power reflected back into the input pigtail can be varied from 0.1% (-30 dB) to 22.4% (-6.5 dB). Threshold currents of the DFB-DC-PBH LD and the MLM window LD are 30 mA and 28 mA, respectively, at room temperature. Maximum 3-dB bandwidth is about 2.8 GHz for DFB LD and 6 GHz for MLM window LD. The bandwidth of the DFB LD is limited by its chip parasitics. The power coupled into the one meter jumper (see Figure 1) from the DFB LD is about 0.1 mw at bias level of 70mA. The power obtained at the pigtail end from the MLM window LD is about 0.7 mw at bias level of

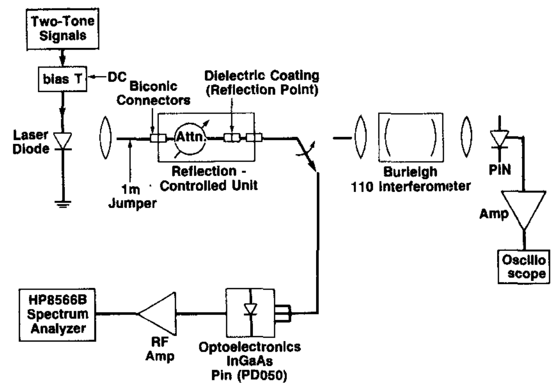

Figure 1 Experimental setup.

70 mA. The amount of reflected light power back into the active region of DFB LD is estimated to be about 15%, and is about 10% for the MLM window LD. Therefore the optical feedback power ratio can be controlled between -40 and -15 dB for both LDs.

3. Direct Intensity Modulation-induced Coherence Change

3.A Due to Large Modulating Signal

Figure 2 shows the optical power spectra of the DFB-DC-PBH LD under several different power

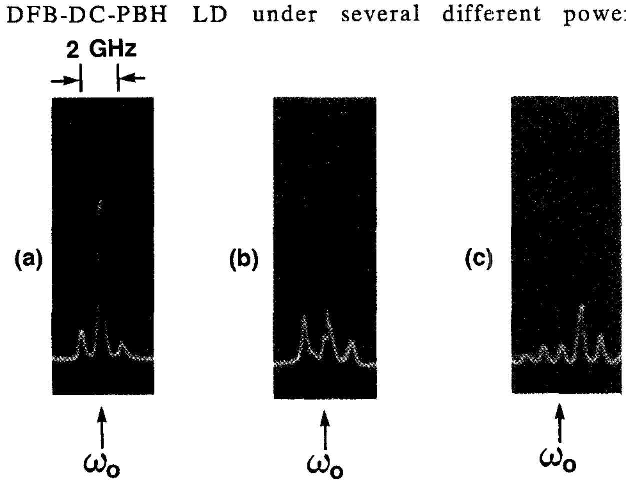

Figure 2 DFB laser optical spectra at three different power levels of 1 GHz intensity modulation; (a) 0 dBm, (b) 1.5 dBm, (c) 9 dBm.

levels of 1 GHz modulation signal. The LD is biased at 62 mA. In the absence of modulation the spectrum consists of a single narrow line (centered at ω_o) with a half-intensity bandwidth measured to be $\cong$ 40 MHz. As the 1 GHz modulation signal power increases, several side peaks at $\omega_o \pm n\omega_m$ appear. The higher the modulation signal power, the more side peaks occur due to the increasing AM and FM modulation indices, as can be seen in Figure 2 (a)-(c). When the modulating signal power is +9 *dBm* (current modulation index 62.5%), the linewidth is broadened to about 4 GHz. This reduces the coherence length to approximately 5 cm, resulting in incoherent optical feedback from the end of the 2 meter pigtail. The insensitivity of DFB LD to optical feedback under large signal modulation is illustrated in Figure 3, which shows the frequency response of DFB LD

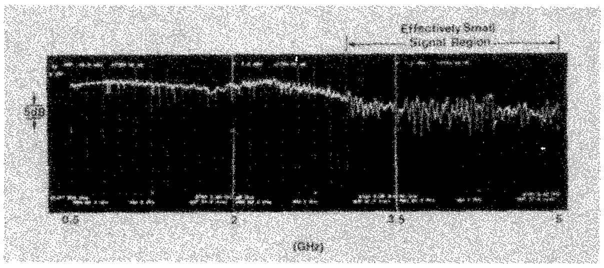

Figure 3 Frequency response from 0.5 to 5 GHz of the DFB-DC-PBH laser under 9 dBm intensity modulation.

(biased at 65 mA) under +9 dBm RF modulation. Microwave modulating signals beyond 2.8 GHz are effectively small signals, because 2.8 GHz was the chip parasitics-limited 3-dB bandwidth of the DFB LD. The period of the enhanced undulation beyond 3 GHz is $c/2n_fL_f$ (where c is the light velocity, n_f and L_f are the refractive index and fiber length, respectively), indicates the DFB LD became much more sensitive to reflection. The relaxation oscillation (RO) peaks at this bias level (65 mA) occurs at around 5.2 GHz, and the feedback power ratio is about -15 dB. When comparing the sensitivity of LD to optical feedback at large and small signal modulations within its 3-dB bandwidth, we obtian results shown in Fig.4. The upper and lower traces represent frequency responses under +9 dBm and 0 dBm RF modulations (from 500 MHz to 2 GHz),

Figure 4 Frequency response from 0.5 to 2 GHz of the DFB-DC-PBH laser under 9 dBm (upper trace) and 0 dBm (lower trace) intensity modulation.

respectively. It is shown that the LD is more sensitive to optical feedback at small signal modulation because frequency chirping is less.

As for the case of a MLM LD, it was observed previously that each individual longitudinal mode linewidth was also broadened with increasing modulation depth [4].

3.B Due to Modulating Signal Frequency

By using the existence of RO peaks (induced by high level optical feedback [5,6]) observed on the spectrum analyzer as an indication of coherent optical feedback, we observed periodic suppression and enhancement of the RO peaks by tuning the frequency of a large RF modulating signal. Whenever the modulation frequency was tuned close to $\frac{N}{\tau_r}$ (where $\tau_r = c/2n_fL_f$) strong RO peaks were observed as shown in Figure 5(b). At modulation frequency between $\frac{N}{\tau_r}$ and $\frac{N+1}{\tau_r}$, the RO peaks are suppressed as shown in Figure 5(d). Optical power spectrum corresponding to Figure 5(b) has narrow linewidth (Fig. 5(a)), and the one corresponding to Figure 5(d) is chirping-broadened (Fig. 5(c)).

Periodic suppression and enhancement of RO peaks were also observed for a large signal (> 4 dBm) intensity modulated MLM window LD. Note that the optical feedback generated from the end of a 2 meter pigtail is still within the coherence length of the MLM window LD under CW operation.

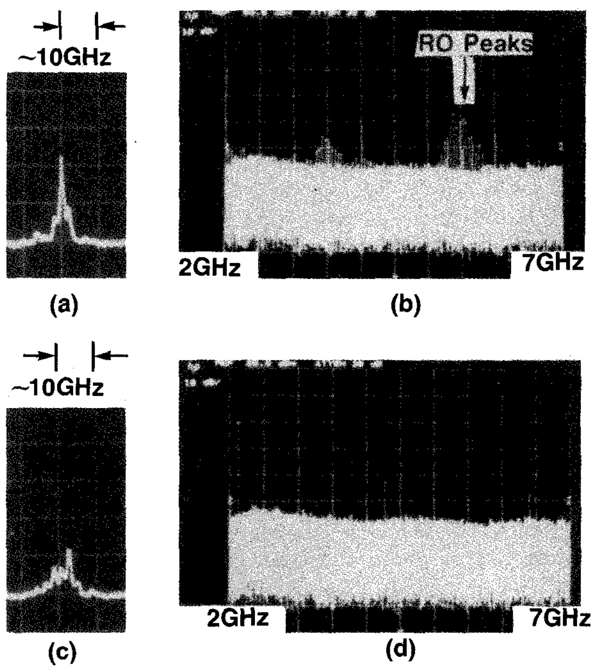

Figure 5 Optical and intensity noise spectra of the large signal (9 dBm, around 2 GHz) intensity modulated DFB-DC-PBH laser in the presence of optical feedback (-15 dB)

The optical linewidth remains narrow when the RF large signal frequency equals to $\frac{N}{\tau_r}$ (N=1, 2, 3, ...) because of the phase match between optical fields in the LD and the external cavity.

3.C Other Effects

LD linewidth is inversely proportional to the CW output light power [7] and can be broadened by strong optical feedback, as has been previously reported [8-12]. The former effect can be seen when the DFB-DC-PBH LD was biased above 70 mA, at which case both the amplitude and frequency of an RF modulating signal are not as influential on the LD coherence as compared to lower bias cases. For the MLM window LD, the coherence length was also decreased due to each individual linewidth broadening and due the boadening of overall spectrum.

4. Linearity Performances Under Optical Feedback

4.A Large Signal Two-tone Modulation

The linearity characteristics of a DFB-DC-PBH LD under large signal two-tone modulation is shown in curves (a)-(c) of Fig.6. The modulation signal power was +9 dBm. When the modulation frequencies were below 1 GHz, the measured carrier to third-order intermodulation ratio (C/ IM_3) is insensitive to the amount of feedback power. In curves (a) and (b) of Fig.6, the C/ IM_3 as a function of feedback power ratio (R_f) for two tones around 600 MHz is shown for bias levels of 55 mA and 65 mA, respectively. Both curves indicate the insensitivity to optical feedback. At a medium bias level of 55 mA with two tones around 1.5 or 2 GHz, the C/ IM_3 is also independent of R_f (the measured data coincides with curve(b)). As explained in sec.3.A, the insensitivity of linearity performance to R_f is a result of large-signal induced chirping. However, when the bias level is increased to about 65-70 mA, the CW laser light becomes more coherent, and the combined effect of

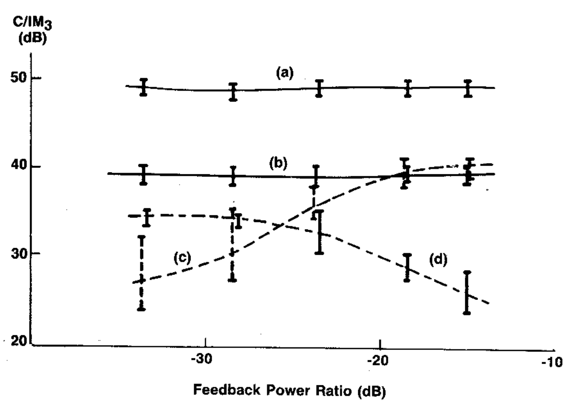

Figure 6 Ratio of fundamental carrier to third order intermodulation (C/IM_3) as a function of optical feedback power ratio R_f of the DFB-DC-PBH laser

optical feedback (between -40 dB and -20 dB) and large RF modulating signals make the laser spectrum a multivalued function of the feedback phase [9,12], which causes a 10 dB fluctuation in the C/ IM_3 . As the reflection level keep increasing, the LD linewidth is again broadened [8-12], and the measured C/ IM_3 was improved to about 41 ± 2 dB. The complete behavior of C/ IM_3 vs. R_f in this case is shown in curve (c) of Fig.6.

For the MLM window LD under large signal two-tone modulation, the C/ IM_3 vs. R_f performance is always a constant around 40 dB as long as the RF modulating frequencies are not too close to the RO region. Curve(a) of Fig.7 is a typical measured result. The MLM LD was biased at about 60 mA (so that RO occurred at 5 GHz), and the two tones are around 3 GHz. When the two tones move closer to the RO

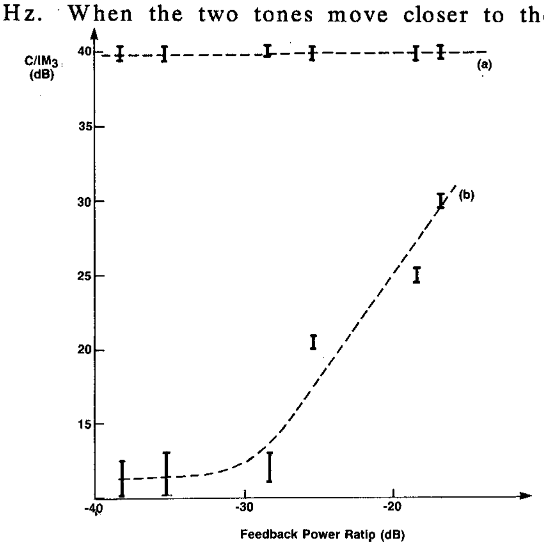

Figure 7 C/IM_3 versus R_f of the MLM window laser

region, e.g. around 4.5 GHz, the C/ IM_3 vs. R_f characteristic is shown in curve (b), Fig.7. When the reflection level is low, C/ IM_3 is as low as 13 ± 3 dB. As the feedback power ratio increases above ~ -25 dB, the C/ IM_3 improved proportionally. This is because strong optical feedback broadened both the overall spectrum and each individual line.

Large signal two-tone modulations in curve (a) and (b) in Fig.6 caused incoherent optical feedback. Therefore, the measured C/ IM_3 is not sensitive to the frequencies of two tones. Curve (c) in Fig.6 is the result of choosing optimum modulation frequencies.

4.B Small Signal Two-tone Modulation

Intermodulation products and induced intensity noise are the highest when the tone frequencies coincide with the peaks (Fig.8(b)) or valleys of undulations caused by optical feedback (the period is about 45 MHz). When the tone frequencies are randomly spaced, or at least one tone frequency does not concide with reflection-induced undulation

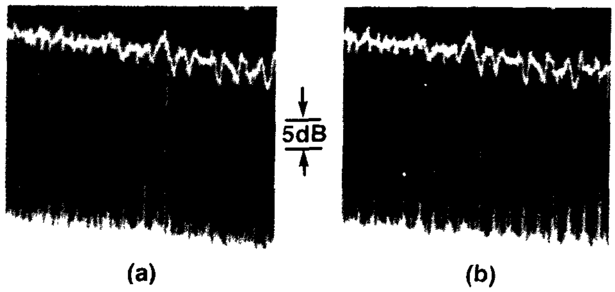

Figure 8 Dependence of intermodulation products on the frequencies of small modulating two-tones around 3 GHz (total microwave power 0 dBm) for the DFB-DC-PBH laser: (a) tones randomly spaced; (b) tones coincide with peaks of reflection-induced intensity undulations. The upper trace in each figure represents frquency response of the laser diode.

peaks/valleys, the intermodulation products and intensity noise levels are both lowered, as can be seen in Fig.8(a). The underline reasoning was explained in section 3.B.

For the DFB-DC-PBH LD biased at a very high level and modulated by small signals, the general C/IM_3 vs. R_f characteristics is shown in curve (d) of Fig.7. The LD was biased at 65 mA and modulated by two large signals outside the 3-dB bandwidth (around 4.5 GHz). It can be seen that higher feedback levels degrade the LD linearity.

Same phenomena were observed for two small tones with total power of 0 dBm and frequencies within the 3-dB bandwidth.

Conclusion

We have examined the relationship between coherent properties of LDs under optical feedback and their linearity performance up to frequency range of several gigahertz. Large signal modulations (current modulation depth 50 - 80%), in general decrease the coherent properties of both a 1.3μm SLM DFB-DC-PBH LD and a 1.3μm MLM window LD, and can make the optical feedback coming from a ~2 meter pigtail end out of phase with the light field inside the active region, therefore improve the linearity performance of both types of LDs. The exception is when the modulation tones coincide with the multiples of the inverse of reflection round trip time, at which case the optical feedback becomes coherent to the modulated light, and the linearity performance is degraded. But in practice, LDs in microwave fiber optic transmission systems carry signals of certain bandwidth, therefore degradations of linearity is unlikely to happen.

The linearity of a 1.3μm MLM LD is generally insensitive to optical feedback when the modulation frequencies are not too close to the RO region, even for a high feedback power ratio of about -18 dB. When the MLM LD was modulated by large microwave signals near the resonance frequency region (in which poor linearity are generally observed), high level optical feedback can improve its linearity performance by as high as 17 dB.

Despite the high coherency of a 1.3μm DFB-DC-PBH LD under CW operations, it is insensitive to high level of optical feedback provided that it is properly biased and is modulated by large signals.

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