Electrically Injection-Locked Intermodal Oscillation in a Long Optical Cavity Laser Diode

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***Abstract*—This paper presents frequency stabilization of intermodal oscillations observed in long optical cavity laser diodes. A 2170-μm-long optical cavity for a 1.5-μm laser experiences intermodal oscillation of ≈19.3 GHz. This optical oscillation is stabilized using electrical injection locking process by modulating the gain section. A significant improvement in frequency stability and phase-noise reduction is observed. Performance of the injection-locked intermodal oscillation is compared to the mode-locking experimental results in terms of modulation power and FM noise degradation level.**

I. Introduction

The physical limitations of laser diodes have restricted practical system applications of the directly modulated fiber optic links to few gigahertz. Since subcarrier-modulated fiber optic (FO) links require only a relatively narrow bandwidth about a high microwave carrier, Lau [1] has proposed a number of laser structure modifications to apply directly modulated FO links up to millimeter-wave frequencies. Most laser structure modification schemes are based on integration of a long external cavity with the gain section or elongating the gain section length. As a result of multiple reflection, a large number of modes could be supported under the gain curve, which are spaced by the round trip repetition frequency.

However, this intermodal oscillation frequency is unstable. Active mode locking is an attractive technique to synchronize the intermodal oscillations to an electrical reference. In this technique, either gain or loss of laser is 100% modulated, where a large (phase and frequency) locking range is attained. Both fundamental [2] and subharmonic [3] mode-locking have been demonstrated, resulting in generation of millimeter-wave frequency repetition rate. Another viable method of stabilization is based on electrical injection locking.

This technique is based on forced oscillation of intermodal oscillation using an optical modulation index much smaller than 100%. However, this phenomena occurs over a limited locking range and lacks phase locking. Recently subharmonic electrical injection locking of a monolithic laser diode has been demonstrated [4], [5]. Ni *et al.* [6] analyzed the residual FM noise of a subharmonically injection locked laser with external cavity. This paper compares experimental results of injection locking to the mode-locking results for a monolithic laser structure described in [7].

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II. Experimental Results

This monolithic laser [7] is composed of a 1970-μm-long gain section, a 50-μm-long high-resisitivity separation region, and a 150-μm-long multiple quantum-well electro-absorption (EA) modulator. The EA section is only employed for mode-locking experiments and otherwise is set at $V_m = 0$ V. The modulator section's facet is coated with high reflective film ($R \approx 85\%$), but the gain section's facet is cleaved. A threshold of 42 mA and differential efficiency of 0.09 mW/mA are measured for $V_m = 0$ V. The 2-Ω junction resistance of laser is resistively matched to 50 Ω using a thin-film resistor in one version of a high-frequency fixture and reactively matched at 19.3 GHz in another version.

The laser diode output is collimated to a single-mode optical fiber using a polarizing collimator with overall 12% coupling efficiency. The fiber output is connected to an integrated optical receiver and RF analyzer system (HP70004A). The displayed optical domain values of HP70004A system are converted to a relative electrical signal by multiplying the displayed results measured in dedibels by a factor of two. Throughout the reported experiments the laser diode's temperature is actively stabilized to 20 °C.

The measured optical spectra of a long optical cavity laser diode is shown in Fig. 1 for $I_b = 80$ mA. The optical modes are separated by an intermodal frequency of ≈19 GHz. The longitudinal mode separation is calculated as $\Delta f = c/2nL \approx 19.3$ GHz, where $c = 300$ mmGHz is speed of light in free space, the index of refraction of waveguide is $n \approx 3.5$, and the length of the F-P cavity is $L \approx 2.17$ mm. A similar optical modal separation is also observed for other bias currents.

The intermodal oscillation characteristics is measured on HP70004A as resonance peak in the frequency response of laser. Comparison of the intermodal oscillation peaks at $I_b = 80$ mA, $I_b = 110$ mA, and $I_b = 150$ mA is depicted in Fig. 2. A broad resonance is clearly observed for bias conditions of $I_b = 110$ mA and $I_b = 150$ mA. A close observation of the resonance peak at $I_b = 80$ mA indicates also two resonance peaks that are ≈1 MHz apart (see Fig. 3). The integrated frequency drift of the intermodal oscillation over 15 min is as high as 200 kHz. A frequency tuning sensitivity of ≈1 MHz/mA is measured at $I_b = 80$ mA.

This intermodal oscillation is not very stable hence not useful as a carrier signal in microwave applications, unless it is frequency and phase stabilized. As the gain section is

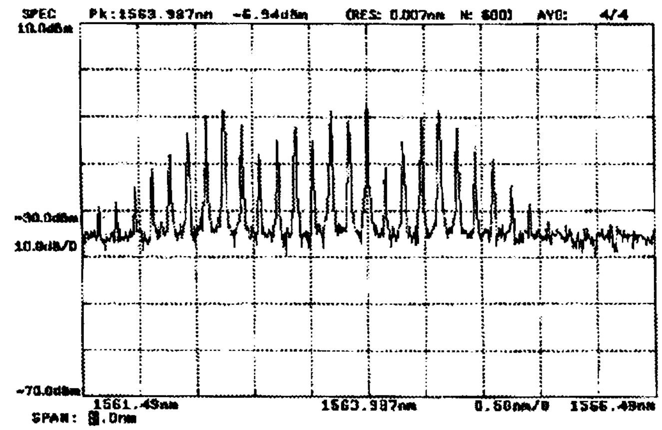

Fig. 1. Optical power spectra of a long F-P laser diode at $I_b = 80$ mA. Optical modes are separated by 0.15 nm at peak wavelength of 1563 nm.

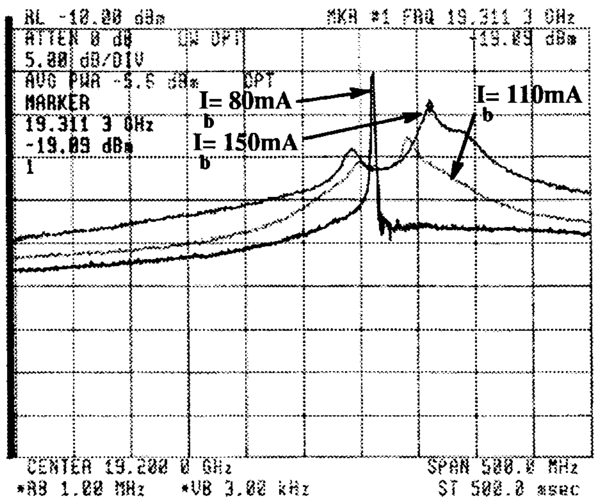

Fig. 2. Intermodal oscillation frequencies of the long optical cavity laser at bias current levels of $I_b = 80$ mA, $I_b = 110$ mA, and $I_b = 150$ mA (center frequency of 19.200 GHz, span of 500 MHz, and resolution bandwidth of 1 MHz).

modulated by a synthesized frequency reference (HP83640A) of $P_m \geq -1$ dBm at $f_m = 19.258$ GHz, a single oscillation peak appears, as shown in Fig. 3 for $I_b = 80$ mA. The familiar one-sided injection locking spectra is observed outside the injection locking range and the close-in to carrier phase noise is significantly reduced within the locking range. The measured close in to carrier phase-noise degradation at 100-Hz offset carrier is depicted in Fig. 4, where 31- and 6-dB degradation are measured for the injected power of $P_m = +0.5$ dBm in the resistively and reactively matched modules, respectively. However, for injected power level of +4.5 dBm, a close-in to carrier phase noise identical to the reference source is measured for the reactively matched case.

III. Discussions

The phase-noise degradation of the injection-locked signal is measured and depicted in Fig. 4. The FM noise degradation with respect to the synthesized reference signal at 19.258 GHz is only 9 dB for the injected power of +9 dBm in the case of the resistively matched module. Note that the attained locking range for this module at the $P_m = +9$ dBm is larger than 3 MHz as compared to the observed integrated frequency drift of 200 kHz. The degradation of 9 dB in close-in to carrier phase noise is primarily due to contribution of the free-running oscillator to the overall phase noise of the injection-locked oscillator, as evidenced by degradation of 19 dB for $P_m = +6$ dBm.

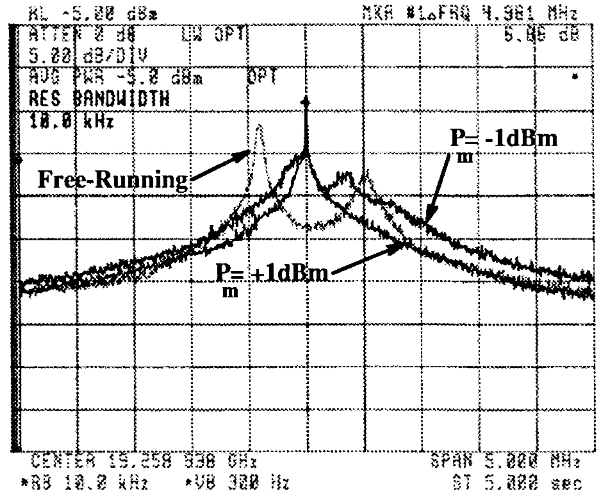

Fig. 3. Frequency stabilization of the optical oscillation in the long F-P laser diode for $I_b = 80$ mA. Note reduction of the frequency instability as the injection electrical power level, P_m, is increased from 0 mW to +1 dBm (center frequency of 19.258 GHz, span of 5 MHz, and resolution bandwidth of 10 kHz).

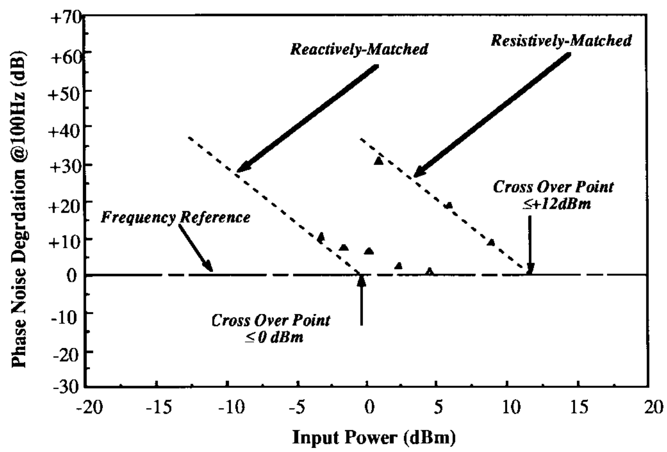

Fig. 4. Measured FM noise degradation at 100-Hz offset carrier for the injection-locked intermodal oscillation. The measured injection-locking power of the long F-P laser diode are also depicted at the cross-over point for the resistively (▲) and reactively matched (△) lasers.

Since the optical frequency response of this laser rolls off at 20 dB/decade above the relaxation oscillation of 2 GHz, the injected power level of +9 dBm at ≈19.3 GHz is corresponding to the detected optical power of ≈−27 dBm. However, the intermodal oscillation has an optical power level of −12 dBm (i.e., locking voltage gain of +15 dB). Therefore, the injection-locking power of $P_m = +9$ dBm is not sufficient to reach the cross-over point, where the phase noise of the injection-locked oscillator equals the frequency [8]. This cross-over power level is calculated to be $P_m \leq +12$ dBm. On the other hand, this cross-over power level is reduced to $P_m \approx 0$ dBm using the reactively matched module (cf. Fig. 4).

Attempts are also made to compare the measured phase-noise degradation to other injection-locking work. Unfortunately, the other reported works on monolithically integrated laser diodes [4], [5] do not show the close-in to carrier phase-noise characteristics of injection-locked optical oscillations closer than 1 MHz, where it is dominated by the noise floor of spectrum analyzer.

In comparison to the mode-locked results [9], at 100-Hz offset carrier for the $P_m \approx +15$ dBm and $V_m = -4.5$ V, a phase-noise degradation of 7 and 10 dB is measured at $I_b = 140$ mA and $I_b = 100$ mA, respectively, using an HP83640A as the reference source. Note also that the minimum electrical power required to achieve mode-locked pulses of 6 or 12 mW using EA modulation is ≈15 dBm at $V_m = -2.5$ V. On the other hand, estimated electrical power of $P_m \approx 12$ dBm and $+20$ dBm is required to generate mode-locked pulses of 6 and 12 mW using gain modulation for $V_m = 0$ V. Therefore, electrical injection locking provides a low-power-consuming alternative to the active mode-locking to stabilize the intermodal oscillations.

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