Large-Signal Analog Modulation Response of Monolithic Optical Injection-Locked DFB Lasers

Hyuk-Kee Sung, Erwin K. Lau and Ming C. Wu
Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720
hyukee92@icsl.ucla.edu

D. Tishinin, K.Y. Liou and W.T. Tsang
Multiplex Inc. 5000 Hadley Road, South Plainfield, NJ 07080

Abstract: A monolithic optical injection-locked distributed feedback laser with bent-waveguide is demonstrated to achieve large optical extinction ratio (> 12 dB) with DC to 2-GHz bandwidth. The extinction ratio is 6 dB higher than that of the free-running laser.

OCIS codes: (140.5960) Semiconductor lasers

Introduction

Strong optical injection locking has attracted a great deal of attention recently because they significantly improve the dynamic response of directly modulated semiconductor lasers, including enhancing the resonant frequencies, suppressing nonlinear distortions and relative intensity noise, and reducing chirp [1-3]. The enhanced performance is at the expense of the increased complexity: a single free-running laser is replaced by a master and a slave laser. Recently, we have reported a monolithic optical injection locked distributed feedback (DFB) laser [4]. Both the master and the slave lasers are integrated on the same chip. They are mutually injection locked. Suppression of nonlinear distortions and enhancement of resonant frequencies that are characteristic of injection locking have been observed. However, most of the previous studies focus on small signal modulations. Large signal modulation with high fidelity and large extinction ratio has applications in optical remote sensing and analog or multi-level optical communication systems.

In this paper, we report the large-signal analog modulation of monolithic optical injection locked DFB lasers. Both the master and the slave lasers are realized by bent-waveguide DFB lasers. The effective quarter-wave shift in bent-waveguide DFB increases the single mode yield and extends the effective injection locking range. Experimentally, we show that the large-signal analog extinction ratio at 2 GHz is improved from 6.8 dB to 12 dB by using monolithic optical injection locking.

Dynamic Response of Free-Running Lasers

Though extinction ratio > 20 dB is not uncommon in digitally modulated lasers, it is highly nonlinear and cannot be used for large-signal analog systems. Figure 1(a) and (b) show the temporal responses of a free-running laser under a large-signal sinusoidal modulation (RF power = 15 dBm) at 2 GHz when the laser is biased at 8.5 mA and 34.3 mA, respectively. At low bias (8.5 mA = 1.1 I_{th}), the measured waveform shows a non-sinusoidal, gain-switched

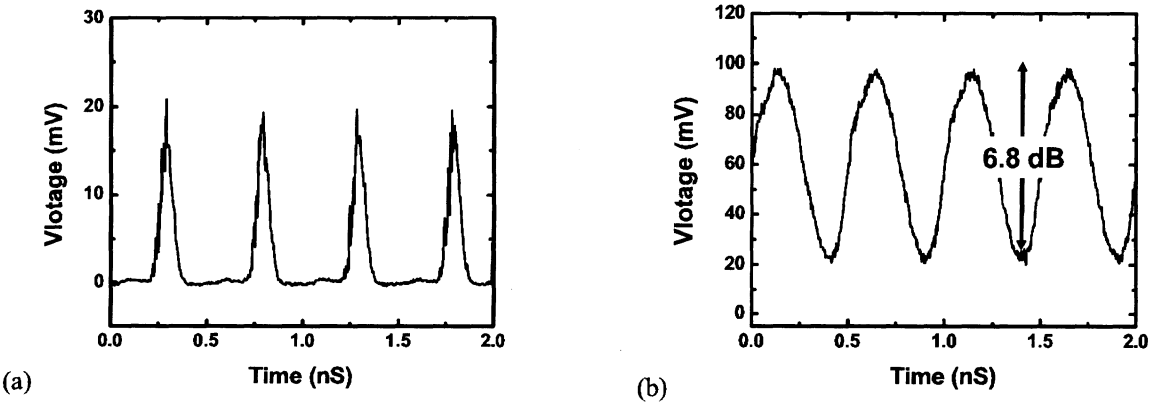

Fig. 1. Temporal response of a free-running laser when it is modulated by a large-signal sinusoidal waveform at 2 GHz when the dc bias of the laser is (a) 8.5 mA, and (b) 34.3 mA.

waveform because the large signal swings the laser below threshold and turn-on transients manifest as the laser attempts to swing above threshold. The frequency response below threshold is dramatically reduced due to a lack of photons within the slave laser. Though the extinction ratio is greater than 20 dB, the optical waveform is significantly distorted. To achieve a more linear response at high frequencies, the bias current on the slave section is increased to 34.3 mA so that the laser does not swing below threshold. The detected waveform is shown in Fig. 1(b). The measured waveform shows the increase of DC value due to the increase of DC current bias. The measured optimized extinction ratio for the free-running case is 6.8 dB.

Monolithic Optical Injection Locked Lasers

To improve the large-signal analog response of the laser, we employ monolithic optical injection-locked DFB lasers. The schematic of the laser is shown in Fig. 2. It consists of two back-to-back bent-waveguide DFB lasers. Strong DFB grating is employed to confine the photons locally in individual lasers. The κL product, where κ is the coupling coefficient of the grating and L is the device length, is approximately 4 for L = 500 μm. Typical DFB lasers without a phase shift have a low yield of single-mode lasing due to degeneracy. To overcome this issue, we have designed a bent waveguide with an equivalent quarter-wavelength shift [5]. By properly designing the waveguide bend, a 180° phase shift can be achieved without using sophisticated electron-beam lithography. The quarter-wave phase shift also helps extend the optical injection locking range before mode hopping occurs. Since the two lasers are mutually injection locked, there is no clear distinction on which laser is master or slave. For easy reference, we call the laser that we apply RF modulation (I_1) the slave laser, and the laser with dc bias master laser. The master laser is further partitioned into two sections so we can tune its waveguide by differential biasing (I_2 and I_3).

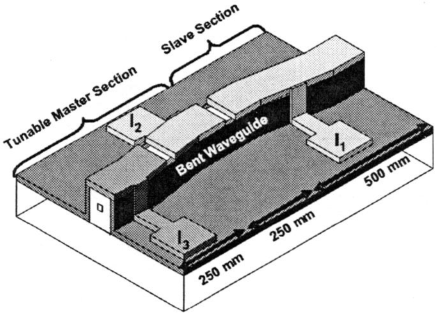

Fig. 2. Three-section DFB laser with bent wave-guide used for achieving high extinction ratio.

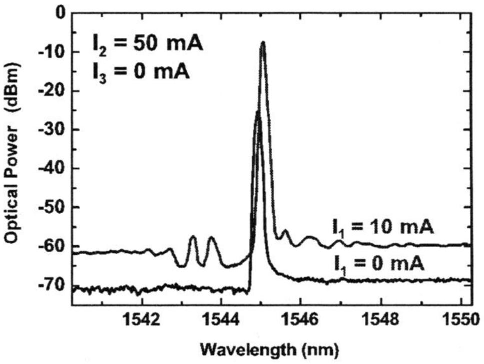

Fig. 3. Measured optical spectrum from the facet near the slave section.

Capped-mesa buried heterostructure (CMBH) is employed for the laser. It is grown by three-step metal-organic chemical vapor deposition (MOCVD) growth. Another mesa (~ 10 μm wide) is patterned around the active strip to reduce the parasitic capacitance. Typical lithography and waveguide etching processes are followed by an electrical isolation etch of 0.2-μm depth between sections. The top metal contact is split into multiple sections. After etching the p++ layer between the sections, over 3 kΩ of electrical isolation is achieved. In a two-section device, each section operates as an independent laser because of the distributed feedback nature of the device. By adjusting current bias on each section, it is possible to injection-lock two DFB lasers without an isolator between them. However, to achieve an optimum injection locking condition, it is necessary to adjust both the amplitude and detuning frequency of the injected signal. A tunable master laser with split contact is employed to control the detuning frequency.

Figure 3 shows measured optical spectrum from the mutually injection locked laser. An anti-reflection (AR) coating with a reflectivity of less than 0.1% is deposited on both facets to suppress the Fabry-Perot modes of the cavity. The output power is collected from the facet near the slave laser. When the bias current of the master section is set at I_2 = 50 mA (~ 6 I_{th}), the slave section current I_1 and wavelength tuning section current I_3 are set at 0 mA, the output power measured at the slave section is attenuated by the unbiased section closest to the output facet. When the slave section is biased slightly above the threshold (~ 1.3 I_{th}) at 10 mA with same bias current of I_2 = 50 mA, output power increases by 17 dB due to the current injection in the slave section. However, the optical spectrum still shows single-mode lasing because the mode from the slave section is locked to the output of the master section. The lasing wavelength changes slightly towards longer wavelengths due to thermal effect. Figure 4 shows the measured light-versus-current (L-I) curve when the bias current of the master section is maintained at 50-

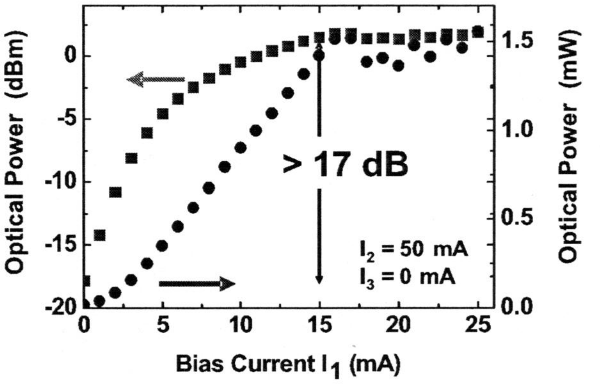

Fig. 4. Measured light-versus-current curve of the monolithic optical injection-locked DFB laser with bent waveguide in dB and linear scales. The master section current I_2 is maintained at 50 mA and tuning section current I_3 at 0 mA.

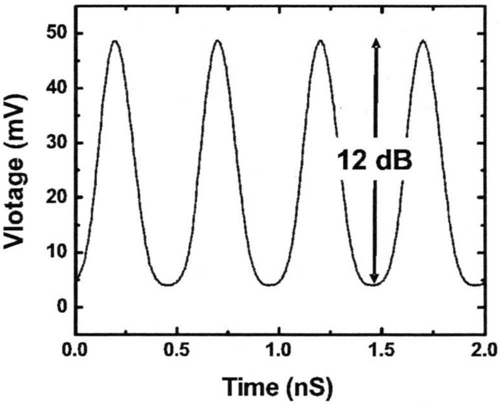

Fig. 5. Measured time domain waveform of the monolithic optical injection-locked DFB laser. I_1 = 8.5 mA, I_2 = 50 mA and I_1 = 0 mA. Modulation signal from the RF synthesizer is output power of 15 dBm at 2 GHz

mA. The output power of the slave section varies linearly from the bias current of 1 mA to 16 mA. As shown in the DC L-I curve, up to 17 dB of extinction ratio can be obtained by modulating the current of the slave section with a low frequency large signal. The abrupt power changing at I_1 = 17 mA is due to the multimode lasing.

The dynamic response of the mutually injection locked laser under large-signal RF modulation is shown in Fig. 5. The master section is biased at 50 mA and the slave section is biased at 8.5 mA with the same RF-modulation power (15 dBm) and frequency (2 GHz). As shown in the optical spectrum in Fig. 3, the output from the slave section is locked to the output of the master section at the bias current range of the slave section from 1 mA to 16 mA. The measured extinction ratio of the output waveform is increased to 12 dB, with improved linearity and less noise. It should be noted that the free-running laser used for the measurement in Fig. 1 is actually the slave laser with the master sections unbiased so the waveform in Fig. 5 can be directly compared with those in Fig. 1. The increased extinction ratio is achieved because the injected master section light provides a reservoir of photons to the slave section, allowing it to be modulated below its free-running threshold. Therefore, in the injection-locked state, the DC output can be deduced to achieve large extinction ratio while maintaining linearity.

Conclusion

The large-signal analog responses of monolithic optical injection-locked bent-waveguide distributed feedback (DFB) laser have been experimentally characterized. Optical injection locking improves the large-signal linearity and improves the extinction ratio by 6 dB at a bandwidth of 2 GHz. This laser has applications in optical remote sensing and multi-level optical communication systems.

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