Modulation Bandwidth Enhancement and Nonlinear Distortion Suppression in Directly Modulated Monolithic Injection-locked DFB Lasers

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Abstract—**We have experimentally investigated the dynamic performance and the suppression of nonlinear distortions of a monolithic optical injection-locked distributed feedback (DFB) laser. The master and the slave lasers are monolithically integrated in a single strip of strongly coupled DFB laser. Optical injection locking is achieved by current tuning. The resonant frequency of the laser is increased from 11 GHz to 23 GHz, and nonlinear distortions are suppressed by more than 15 dB.**

I. INTRODUCTION

The simplicity of directly modulated semiconductor lasers has attracted much attention in analog fiber-optic applications such as cable television (CATV) distribution systems, antenna remoting in cellular networks [1], and high-bit rate (40 Gbit/s) very-short-reach (VSR) optical links [2]. In this approach, the nonlinearity and low modulation bandwidth of semiconductor lasers limit the performance of the fiber-optic systems. In order to achieve high bandwidth and high fidelity, optical injection locking of semiconductor lasers has been widely investigated and found to be an effective method to improve the modulation characteristics. Such benefits include increased modulation bandwidth, increased linearity, lower chirp, and lower noise [3- 5].

The experimental setups used to achieve optical injection locking often require two light sources – an external cavity laser (ECL) or a wavelength-matched distributed feedback (DFB) laser as a master laser and another semiconductor laser as a slave laser. Since the frequency detuning and the power injection ratio between the master and the slave laser must be carefully matched to achieve stable injection-locked state, injection locking using an external master laser has been limited to laboratory use. In a typical injection locking system, the master laser is isolated from the slave laser using optical isolators. The isolation is on the order of 30-40 dB with an insertion loss of 1-3 dB. For strong injection locking, the output power from the master laser needs to be much higher than the slave laser. Often an optical amplifier is used to boost the master laser power to achieve a high injection ratio. To overcome these issues, we have proposed a monolithic injection-locked DFB laser with two separate gain sections. In two-section DFB laser with strong gratings, each section can lase by itself. Locking/unlocking phenomenon between the modes of individual sections was observed by tuning the bias current on each section [6]. When biased within the proper current range, the two sections operate at the same wavelength and exhibit a significant increase in the modulation bandwidth, similar to optical injection locking with external master lasers. In addition, the nonlinear distortions such as second harmonic and inter-modulation distortions are also suppressed.

II. DEVICE

A two-section DFB laser fabricated using an capped mesa buried heterostructure is shown in Fig. 1. The DFB laser has a very strong grating: the κL product is approximately 3 to 4 for a device length, L of 750 μm (κ is the coupling coefficient of the grating). The 1-μm-wide active region and the surrounding semi-insulating InP are covered by a p-

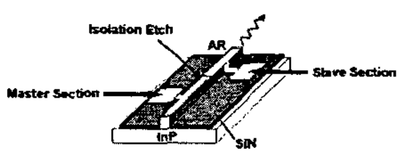

Fig. 1. Schematic of two-section DFB laser for monolithic injection locking

type InP top cladding layer and a heavily doped InGaAs contact layer. A mesa of 10-μm width is etched down to the semi-insulating InP to reduce parasitic capacitance. Silicon nitride is used as a passivation layer. Multiple p-metal contacts are formed using Ti/Pt/Au electrodes. Bottom n-contact is formed using Au/Sn/Au. The contact resistance obtained was typically less than 10Ω after annealing. The top metal contact is split into two sections. A gap of 0.2-μm depth is etched between sections to achieve electrical isolation. The resistance between sections is greater than 4 kΩ. An anti-reflection (AR) with a reflectivity of less than 0.1% is deposited on one facet to suppress the Fabry-Perot modes of the cavity.

To attain optical injection locking using a two-section DFB laser, each section must be able to operate independently. For each section to lase independently, a relatively strong grating is needed such that a shorter gain length is required to reach threshold. Increasing the distributed feedback is analogous to decreasing the mirror loss so that a short cavity can be used. For devices with small κL product, it was found that current tuning in each section did not achieve independent operation of two distinct wavelengths.

III. Experiment

The experimental setup used to measure the optical spectrum, modulation response, and nonlinear distortion of the monolithic injection- locked DFB laser with two gain sections is shown in Fig. 2. This setup is more compact than injection locking setups

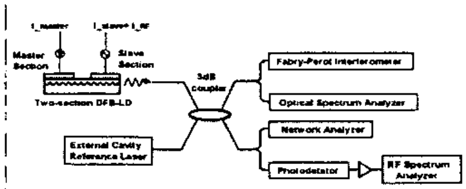

Fig. 2. Experimental Setup

using an external light source since polarization controllers, optical circulators (or isolators), and fiber to laser couplers are not required [4]. An external cavity laser is used as a stable wavelength reference for measuring the current tuning characteristics of each mode. For the device used in the measurement, the wavelength of one section is longer than the other section in the un- locked state. Therefore, the master and slave sections can be determined by the negative frequency de- tuning characteristic of the injection-locked laser [7]. A DC current and an RF signal are applied to the slave section through a bias tee, while another DC current is applied to the master section. The main difference between this optical injection locking system and the external injection locking system is that both lasers share a common waveguide and there is no optical isolation between them. The modulated output taken from slave section is coupled into a high-speed photodetector (34 GHz). The detected signal is amplified by low-noise RF amplifier with 20 dB gain and then observed by an RF spectrum analyzer.

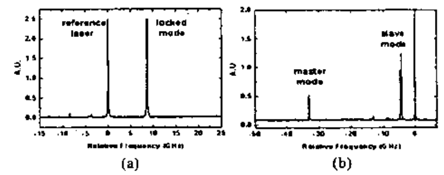

Fig. 3. Measured optical spectrum. (a) injection-locked (master section bias = 54mA, slave section bias= 45.2 mA) and, (b) unlocked (master section bias = 61mA, slave section bias= 45.2 mA)

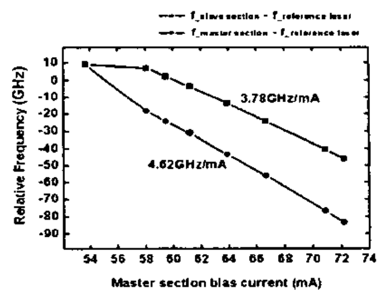

Fig. 4. Measured current tuning characteristic for each mode as the bias current of the master section is varied and slave section is biased at 45.2mA

Fig. 3 shows the high resolution optical spectra of the two-section laser in (a) injection-locked and (b) unlocked states measured by a scanning Fabry-Perot interferometer. In the injection-locked state, a single locked mode is observed at + 9 GHz (compared to the reference laser) and no other frequency components are observed. However, in the unlocked state, the master and the slave section lase at two distinct wavelengths that are approximately 28 GHz apart. Fig. 4 shows the relative wavelengths of the master and the slave sections versus the current of the master section. The slave section bias is fixed at 45.2 mA. As the master section bias current increases, both the master and the slave lasers move towards longer wavelengths due to heating effect. The wavelength tuning rate of the master laser is slightly larger than the slave laser. Therefore, as the master laser current decreases, the wavelength difference between the master and the slave lasers gradually reduces and eventually the slave laser enters the injection-locked state. The monolithic optical injection locking scheme is very robust. There is only one tuning parameter, namely the master section current. Unlike external injection locked lasers, the monolithic injection locked laser is much less sensitive to ambient temperature since the wavelengths of both master and slave lasers drift in the same direction and the frequency detuning remains constant.

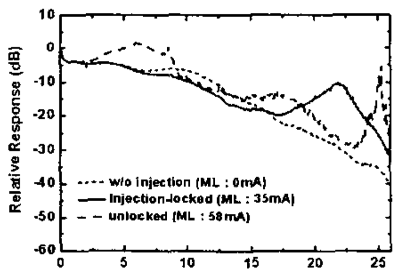

Fig. 5. Measured frequency response. Slave section bias is fixed at 45.2 mA

The modulation frequency response is shown in Fig. 5. The relaxation oscillation peak of the slave laser is 11 GHz in the free-running state, which is defined as no bias current into the master section. In the injection locked state, the resonance peak is increased to 23 GHz. The output power of the device under injection locking is slightly higher (by 0.2 dB) than that of the free-running state. This relatively small power increase indicates that the enhanced modulation bandwidth is due to optical injection locking and not simply due to the increased photon density. In general, the modulation bandwidth is proportion to the square root of the photon density. To double the modulation response would require a four-fold increase in photon density. The measured resonance frequency is consistent with the value obtained using external optical injection locking. The modulation bandwidth obtained using an ECL master laser was 21 GHz. In the unlocked state, the beating of the two modes generates a very sharp spike at the difference frequency of ~25 GHz in the frequency response. The Lorentzian peak is superimposed on the free-running modulation response.

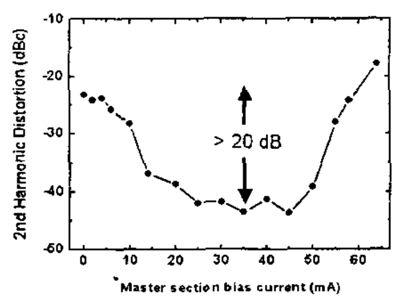

Fig. 6. Measured second harmonic distortion with master section bias current. Slave section is biased at 45.2 mA and modulated by 9GHz RF signal.

It is known that the nonlinear distortion becomes more severe as the modulating frequency approaches the relaxation oscillation frequency due to the nonlinear coupling between electrons and photons [8]. Hence, if the resonance frequency of the laser is increased, the nonlinear distortions can be reduced while the modulation bandwidth is increased. To measure the second-harmonic distortion (2HD), the slave section is modulated by a single tone RF signal (f = 9 GHz). The second harmonic product is at 18 GHz. To investigate the 2HD in both locked and unlocked states, the slave laser current is fixed at 45.2 mA and the master laser section current is varied from 0 mA to 65 mA. Stable optical injection is observed between 14 mA to 53 mA. The measured 2HD versus the master section bias current is shown in Fig. 6. At the injection locked state, the second harmonic RF power is reduced by more than 15 dB compared to the free-running and unlocked state.

Fig. 7 shows the received RF powers of the fundamental and third-order intermodulation products (IMP3) versus the input RF power for both the free- running and the injection-locked state. The measured noise floor is −140 dBm/Hz. Under the injection- locked state, the spurious-free dynamic

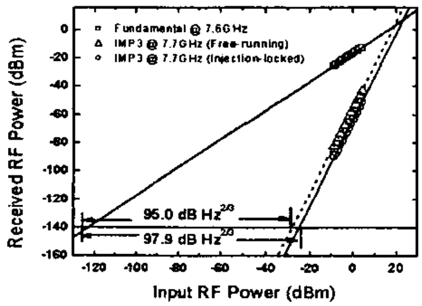

Fig. 7. The SFDR of the link with directly modulated two-section DFB laser at f_1=7.5 GHz and f_2=7.6GHz. For the free-running state, slave section is biased at 45.2 mA and master section is not biased. For injection-locked state, slave section is biased at 45.2 mA and master section is biased at 40mA.

range (SFDR) is increased by 2.9 dB, from 95 $dB \cdot Hz^{2/3}$ to 97.9 $dB \cdot Hz^{2/3}$.

IV. Conclusion

We have fabricated a monolithic injection-locked DFB lasers with two gain sections and experimentally investigated optical injection locking phenomena of the laser. A relatively strong grating is used to attain independent lasing between the maser and the slave lasers. By properly controlling the bias current of the individual sections, the slave laser wavelength is locked to that of the master laser. Under this injection-locked state, the resonance frequency of the laser was increased from 11 GHz to 23 GHz. Because of the increased bandwidth, the 2HD at 9 GHz range, which is slightly lower than the resonance frequency of free-running laser, was suppressed by 15 dB. A 3-dB improvement in SFDR was achieved. These results demonstrate a new approach for optical injection locking using a single chip laser. The monolithic injection-locked DFB laser is very promising for RF photonic links and high-speed fiber optic systems.

Acknowledgement

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