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# Dynamic Property Investigation of Optical Burst Injection Locking Lasers

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**Abstract**— The dynamic properties of DFB- and DML-based injection lock lasers are investigated by analyzing the instantaneous frequency of the master and slave lasers' beat signal. Around 10–20 ns locking time is measured by burst signal injection and a large injection ratio leads to longer unlocking time.

**Keywords**—Phase measurement; Lasers; Injection Locking

## I. INTRODUCTION

Optical injection locking (OIL) in semiconductor lasers have been widely studied since the beginning of the 1980s [1]. In OIL, the slave phase locks to that of the master under certain conditions. There are applications utilizing the OIL, such as colorless optical network unit for passive optical network [2], burst mode transceivers, all-optical switching and coherent carrier recovery. Some applications require short response time, which means very fast locking/unlocking. The locking/unlocking dynamics of Fabry-Pérot (FP) laser diodes have been characterized by the side modes power [3]. In this work, the burst dynamic properties of two single-mode OIL lasers, a distributed feedback (DFB) laser and a discrete mode laser (DML) [4], are investigated by analyzing the instantaneous frequency of the beating signal, which is generated by a coherent receiver (Co-Rx), between the master laser and the OIL laser under investigation.

## II. EXPERIMENTAL SETUP

The experimental setup for investigating the dynamic properties of the OIL lasers is illustrated in Fig. 1. An external cavity laser (ECL) with 100-kHz linewidth was split by a 10:90 coupler. The 90% arm was passed directly into the local oscillator (LO) port of the Co-Rx, while the 10% arm was modulated by a Mach-Zehnder modulator (MZM) and then injected into the OIL laser through a circulator. The OIL laser under test was either a DFB or a DML laser. The MZM with ~20-dB extinction ratio was driven by a continuous square wave from an arbitrary waveform generator (AWG) to simulate burst injection. The duty cycle of the square wave was 50% and its periodic length was 200 ns. The rising and falling time of the optical square wave was within 1 ns. The injection

power was adjusted by the modulator bias and the optical attenuator. For the time slots with higher injection power, the slave laser's frequency could be locked to the master's. The in-phase and quadrature components of the beating signal between the signal at LO and the output of the slave laser was recorded by a real-time oscilloscope (RTO) at 50 GSa/s. An example of the captured beating signal from the DFB laser is illustrated in Fig. 2. The occurrences of the oscillation in the waveform represent the unlocking state of the slave laser.

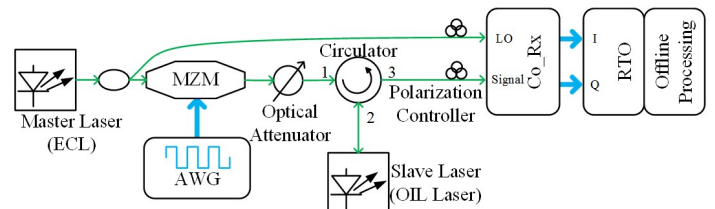


Fig. 1 Experimental setup for evaluating the injection locking properties

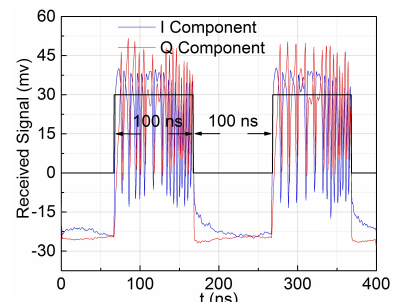


Fig. 2 Captured beating signal's I- and Q-component. The square wave indicates the modulation waveform.

## III. STATIC CHARACTERIZATION

The static properties of the OIL lasers are firstly investigated without externally modulating the injected signal. The injection-locking maps for the DFB and DML lasers are in Fig. 3(a) and 4(a), respectively. The initial frequency detuning is defined as the initial frequency difference between the master laser and free-running slave lasers, when injection is totally off. The initial frequency detuning is altered adjusting the frequency of the ECL. The injection ratio is defined as the ratio of the injecting optical power to that of the slave laser output. As the injection power gradually increases, the spectral peak of the beating signal gradually moves to zero-frequency, as shown in the RTO's spectrum measurement. When the slave

laser frequency is finally locked to the master laser's, the corresponding injection ratio is recorded. The relationship between the injection ratio and initial frequency detuning is plotted in Figs. 3(a) and 4(a). The fitted of the recorded data shows the locking range for a particular injection ratio. For example, the locking range of the DFB laser at the injection ratio of -40 dB is around 740 MHz. As the injection ratio increases, the measured locking range also increases. At low injection ratios, stable locking occurs over a narrow locking range symmetrical around the zero-frequency. Fig. 3(b-d) and 4(b-d) illustrate the frequency modulation (FM) noise spectrum of the beating signal at certain points in or out of the locking range. It is seen that the FM noise spectra of the beating signal contain severe low frequency  $1/f$  noise when the slave laser is not locked (at point A). When the slave laser is locked (at point B and C), the FM noise inside the locking range is suppressed.

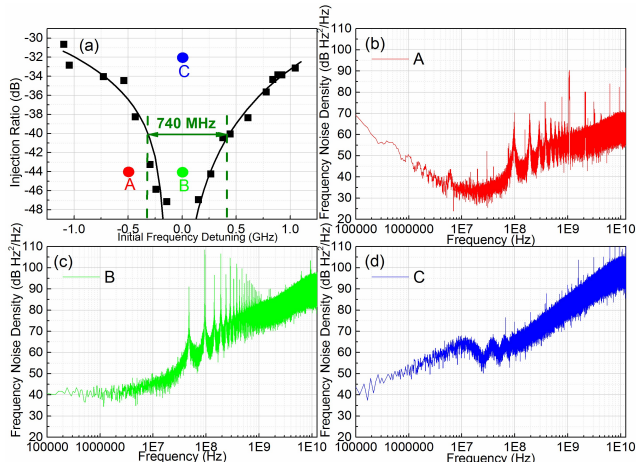


Fig. 3 (a) Locking range of the DFB laser. (b)-(d) FM noise spectrum of the beating signal when the initial frequency detuning and the injection ratio are (b) -500 MHz, -44 dB (c) 0 Hz, -44 dB (d) 0 Hz, -32 dB

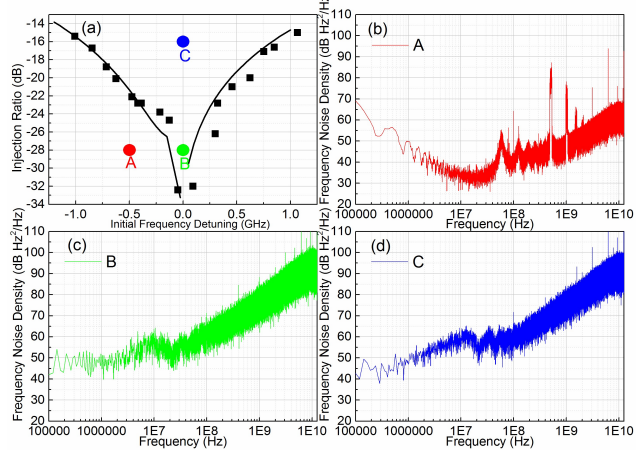


Fig. 4 (a) Locking range of the DML. (b)-(d) FM noise spectrum of the beating signal when the initial frequency detuning and the injection ratio are (b) -500 MHz, -28 dB (c) 0 Hz, -28 dB (d) 0 Hz, -16 dB

#### IV. DYNAMIC CHARACTERIZATION

To evaluate the dynamic properties, the master laser was intensity modulated periodically by a square wave to switch the slave lasers between the locking and unlocking states. The instantaneous frequency of the beating signal is analyzed with varied injection ratio and initial frequency detuning. To derive

the instantaneous frequencies of the beating signal, the Wigner-Ville (WV) distribution, a time-frequency analysis method, is used. The WV distribution of a time domain signal  $x(t)$  is

$$W(t, \Omega) = \int_{-\infty}^{+\infty} x(t + \tau/2) x^*(t - \tau/2) e^{-j\Omega\tau} d\tau \quad (1)$$

where  $\Omega$  is a frequency variable. The instantaneous frequency of  $x(t)$  can be obtained by

$$f(t) = \frac{\frac{1}{2\pi} \int_{-\infty}^{+\infty} \Omega W(t, \Omega) d\Omega}{\frac{1}{2\pi} \int_{-\infty}^{+\infty} W(t, \Omega) d\Omega} = \frac{\frac{1}{2\pi} \int_{-\infty}^{+\infty} \Omega W(t, \Omega) d\Omega}{|x(t)|^2} \quad (2)$$

Fig. 5 shows the derived instantaneous frequencies of the beating signal between the master laser and the slave laser with different initial frequency detuning and injection ratio. The injection ratio values, when the slave laser is locked during the “1” level period of the injecting signal, are given in Fig. 5. The modulation extinction ratio of the injecting signal into the slave laser is  $\sim 20$  dB. It is seen that even during the “0” level period of the injecting signal, the frequency offsets between the outputs of the slave laser and the master laser are not equal to the initial frequency detuning due to the pulling effect of the residual injecting power. As the injecting power increases, this residual power for the “0” level also increases and the frequencies of the slave lasers are pulled closer to that of the master. The rising and falling edges of the injecting signal are shown by the green dash lines. Observing from the curves near the injection rising edges (or falling edge) for negative (or positive) initial frequency detuning, the injection power has little impact on the locking time, during which the absolute values of frequency offset decrease from the maximum to zero. The locking time is around 10~20 ns for both lasers. However, the unlocking time increase with the injection ratio, varying from  $\sim 10$  ns to several tens of ns.

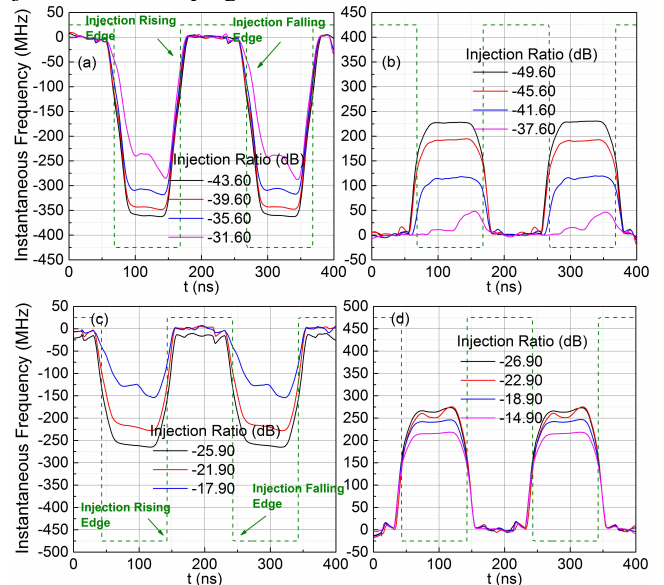


Fig. 5 Instantaneous frequency of beating signal for the DFB laser at the initial detuning of (a) -362MHz (b) 278MHz and for the DML laser at the initial detuning of (c) -278MHz (d) 292MHz. The injection ratio indicated is the ratio during “1” level only.

## V. CONCLUSION

The dynamics of DFB- and DML-based OIL lasers and their locking/unlocking time are experimentally investigated. The results show that the injection power has little impact on the locking time, and 10~20 ns locking time can be achieved with burst injection; It is also shown that a large injection power leads to longer unlocking time, varying from ~10 ns to several tens of ns.

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