Ultra-High, 72 GHz Resonance Frequency and 44 GHz Bandwidth of Injection-Locked 1.55-µm DFB Lasers

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Abstract: We demonstrate record high resonance frequency (72 GHz) and record broadband performance (44 GHz) for 1.55-µm direct-modulated distributed-feedback (DFB) lasers under strong optical injection locking. The frequency response above 50 GHz is measured directly using optical heterodyne detection.

OCIS codes: (320.7090) Ultrafast lasers; (060.4080) Modulation; (320.7100) Ultrafast measurements; (040.2840) Heterodyne; (140.3520) Lasers, injection-locked; (140.5960) Semiconductor lasers

1. Introduction

In a semiconductor laser, the resonance frequency is a figure-of-merit which determines the maximum direct modulation bandwidth. Optical injection-locking has been shown, experimentally and theoretically, to enhance the resonance frequency of semiconductor lasers [1, 2]. This enhancement can be achieved by increasing the injection power and adjusting the detuning frequency, Δf (frequency difference of the master laser to free-running slave laser). By tuning these parameters, we can optimize the laser frequency response to either maximize broadband performance or maximize resonance frequency. The previous 1.55-µm laser bandwidth record reports 37 GHz for a coupled-cavity-injection-grating distributed-Bragg reflector (DBR) laser [3]. By optimizing for maximum bandwidth, we report a 3-dB bandwidth of 44 GHz using optical injection-locking in DFB lasers. To our knowledge, this is the highest bandwidth for a 1.55-µm laser under direct modulation. The previous record for enhanced resonance frequency (50 GHz) in 1.55-µm vertical-cavity surface-emitting lasers (VCSELs) was reported by Chrostowski, *et al.* [4]. Additionally in this paper, we experimentally demonstrate a record resonance frequency of 72 GHz.

Direct measurement of laser frequency response is often limited by the bandwidth of photodetectors and network analyzers. In order to measure frequencies above our detection equipment limit (50 GHz), we develop a new optical heterodyne technique that can detect arbitrarily-high modulation frequencies. This technique, in contrast to previous heterodyne methods [5], does not require stable frequency solid-state lasers and can be used to test telecom-wavelength lasers.

2. Experimental Setup

The device under test is a 1.55-µm DFB InGaAsP laser [6] under strong optical injection locking, as shown in Fig. 1. The master laser (ML) is a tunable external cavity diode laser coupled to an Erbium-doped fiber amplifier (EDFA). The polarization is then manipulated to provide optimal coupling to the slave laser cavity using a polarization controller (PC). An optical circulator (Circ.) isolates the input and output beams to the slave laser (SL). The SL is biased at 29 mA ($3.5\times I_{th}$) at 16°C; its optical power is +1.2 dBm. The slave laser is directly modulated by a RF signal (f_m) from a 50-GHz signal generator (SG) and a W-band (50-75 GHz) 4x frequency multiplier. Hence, to take a complete frequency curve, two different frequency range measurements must be made. The injection-locked output is combined with a local oscillator (LO) via a 3-dB coupler (3dB), and then detected by a 10-pm resolution optical spectrum analyzer (OSA) and a 34-GHz photodetector (PD) with a 50-GHz electrical spectrum analyzer (ESA).

We employ a new optical heterodyne detection technique that will allow us to measure the laser frequency response well over 100 GHz (Fig. 1). In order to detect 50-75 GHz, we combine the optical frequency of the LO laser (f_{LO}) tuned to 50 GHz away from the injection-locked laser mode (f_S) so that $f_{LO}=f_S-50$ GHz. Thus, the photodetector will beat the 50-75 GHz modulation sideband (f_S-f_m) with the LO light and down-convert the modulated signal to 0-25 GHz ($|f_S-f_m-f_{LO}|=f_m-50$ GHz). Details of the optical heterodyne technique will be reported elsewhere.

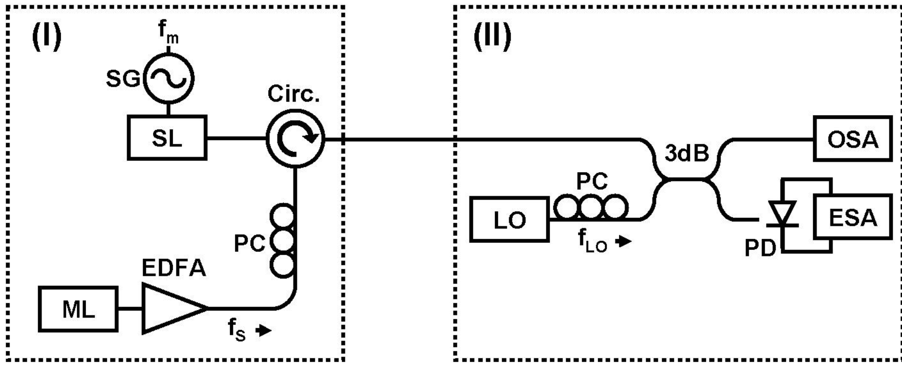

Fig 1. Experimental setup for (I) ultra-high frequency laser by strong optical injection locking with (II) high frequency measurement setup by optical heterodyne detection.

3. Results

Optical injection locking provides two main tuning parameters: injection power and detuning frequency. By tuning these parameters, we can significantly modify the frequency response of the laser. There are two major regimes for which to optimize: 1) maximum broadband performance and 2) maximum resonance frequency.

3.1 Maximum Broadband Performance

Telecom as well as broadband analog photonics applications demand maximum flat bandwidth ranges. By optimizing the detuning, we find the maximum broadband region lies in the negative detuning range. In general, as Δf decreases, the frequency response becomes flatter and more broadband but lower overall response. We achieved a 3-dB bandwidth of 44 GHz with a highly-damped resonance peak, as shown in Fig. 2. The highly-damped resonance peak additionally results in lower non-linearities that manifest with sharper resonance peaks. The master laser power is set to +25 dBm and Δf= -60.5 GHz. As shown in Fig. 4, the free-running DC response is -26 dBm, which is 18 dB greater than the DC response of the broadband result. Several previous works have quoted an intrinsic bandwidth enhancement, after compensating for laser parasitics [4, 7]. Our results are directly measured from the frequency response curve. All results are normalized for SG, ESA, RF cables, Bias-T, 3-dB coupler, and PD response only. Results do not compensate for laser electrical parasitics or RF probe parasitics.

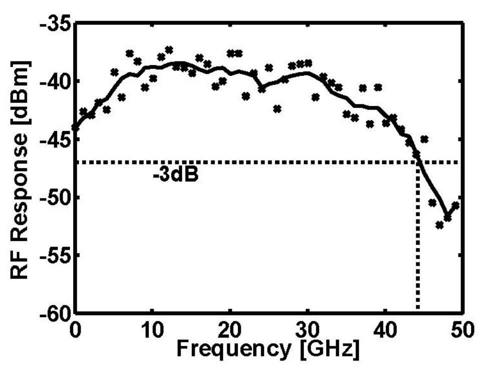

Fig. 2. Frequency response for optimized bandwidth = 44 GHz.

3.2 Maximum Resonance Frequency

In free-running semiconductor lasers, the resonance frequency is derived from the coupling between the carrier and photon densities. Modulation at or around this frequency will create symmetric sidebands on the longer and shorter wavelength sides of the main laser mode. In strong injection locking, the resonance frequency is dominated by the competition between the main locked mode, at the master laser frequency, and the preferred cavity mode of the slave laser, which is modified by the injection [8]. This cavity mode only appears on the negative frequency side of the locked mode and it is the frequency difference between the two that determines the resonance frequency. Physically, the modulated light is resonantly enhanced by the cavity mode. Hence, the modulation sidebands are asymmetric and the sideband on the cavity mode side will dominate. Fig. 3 shows the locked laser mode and cavity mode in the optical frequency domain, as well as the local oscillator used for heterodyne detection (solid). The free-running slave laser spectrum (dotted) is shown for comparison. Note the distance between the laser and cavity mode is 72 GHz, while the distance between laser mode and LO is ~50 GHz. This allows us to down-convert modulation from 50-75GHz to 0-25GHz, which allows us to overcome the limitation of the bandwidth of the PD and ESA.

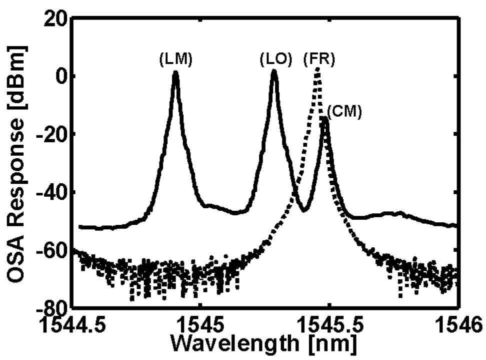

Fig. 3. Optical spectrum of injected laser, optimized for 72 GHz resonance, with local oscillator (solid). (LM) is the main locked mode. (CM) is the cavity mode. (LO) is the local oscillator. (FR) is the free-running SL mode (dotted).

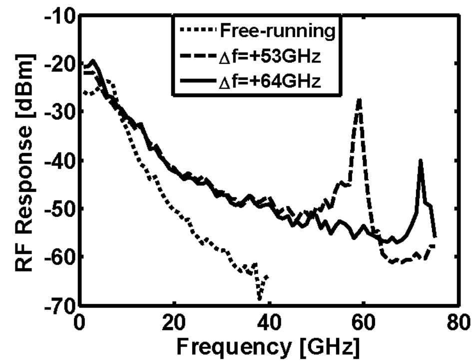

Fig. 4. Frequency response at different detuning frequencies. Dashed gives a resonance frequency of 59 GHz. Solid gives 72 GHz resonance frequency.

It has been shown in previous works that the resonance frequency increases with increased optical injection [2] and with positive detuning frequency [8]. Using a master laser power of +23 dBm and Δf of +53 GHz and +64 GHz, we demonstrate resonances at 59 GHz and 72 GHz respectively, as shown in Fig. 4. In general, as Δf increases, the injected mode pulls away from the cavity mode, resulting in a higher resonance frequency. Each of the two curves is composed of a 1-50 GHz and a 50-75 GHz response, down-converted by 50 GHz using optical heterodyning. The free-running response is shown for comparison. This resonance-enhanced modulation is different from biasing the system in the period-one oscillation regime, as described in [9], since the un-modulated optical beating is not detectable within the noise floor of the ESA (~-65 dBm). Only when modulation is applied on or near the resonance frequency is there a detectable enhancement. Additionally, by tuning the master laser parameters, we can tune the magnitude and frequency of the resonance for greater peak response or variable frequency.

4. Conclusion

Under strong optical injection locking, we have directly modulated 1.55-μm DFB lasers in two distinct regimes. Tuning the injection power and frequency detuning controls the shape of the frequency response. The first regime, favoring negative frequency detuning, exhibits extremely wide broadband response. Here, we report 44 GHz bandwidth. As the frequency detuning becomes more positive, the response enters the second regime. This regime trades a broadband response for increasingly-high resonance frequencies. We experimentally demonstrate up to 72 GHz resonance frequencies.

5. References

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