High Speed Modulation of Semiconductor Lasers

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Abstract We review the recent advances in optical injection-locked lasers, focusing on high resonance frequencies (> 100 GHz) and 3dB bandwidth (> 80 GHz). Physical parameters governing the dynamic performance will be discussed.

Introduction

To support the growing need for larger transmission speeds in tele- and data communications, much research has been devoted to increasing the direct modulation bandwidth of semiconductor lasers. The resonance frequency of directly-modulated lasers has been demonstrated up to ~30 GHz. Practical limitations, including laser heating and gain compression, limit the maximum resonance frequency. Furthermore, increased damping at higher resonance frequencies limit the maximum bandwidth to ~ 40 GHz. Optical injection locking (OIL) has been shown to enhance the resonance frequency of the directly-modulated injection-locked laser. In this paper, we review the current research directions in high-speed modulation of optical injection-locked lasers. By using strong optical injection locking, we report resonance frequency enhancement in excess of 100 GHz in semiconductor lasers.

Direct-modulated optical injection-locked lasers

In a conventional laser, as bias current is increased, both damping and resonance frequency increase, thereby limiting the maximum bandwidth. In injection-locked lasers, the damping may actually decrease as resonance frequency increases, allowing very efficient modulation response at extremely high frequencies. Because of these enhanced dynamics, we have been able to exceed the fundamental limits for direct-modulated laser resonance frequency. Fig. 1 shows the progression of resonance frequency reported over the past 25 years. Since 2000, research on OIL lasers has resulted in a markedly steeper increase in the highest resonance frequency, both in distributed feedback (DFB) [2] and vertical cavity surface emitting lasers (VCSELs) [3].

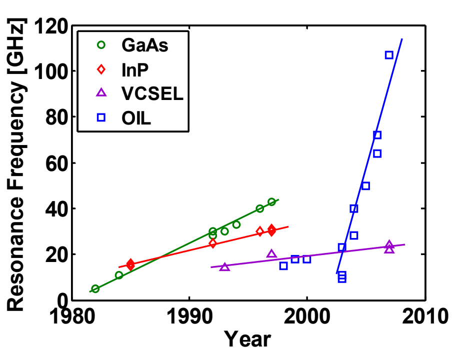

Fig. 1 Resonance frequency as a function of time, for conventional direct-modulated lasers (circles, diamonds, and triangles) and direct-modulated, injection-locked lasers (squares).

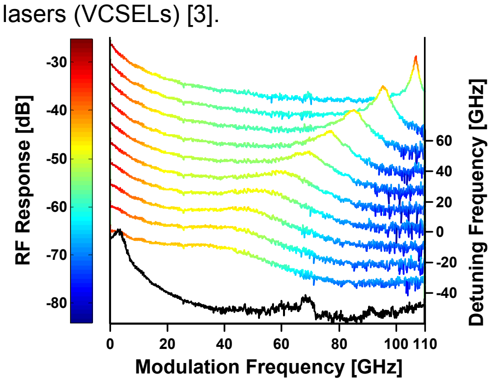

Fig. 2 Evolution of frequency response in optical injection-locked DFB laser across locking range for +14 dB injection ratio. The detuning frequencies are varied from -47 to +67 GHz, in 12.7 GHz increments. The solid black lines represent the freerunning case.

Figure 2 shows the frequency responses of optical injection-locked DFB laser across the locking range. The DFB is biased at 1.3× threshold with an output power of 1 dBm. The frequency response of the free-running DFB laser is shown by the black curve, having a free-running relaxation oscillation frequency of 3 GHz. Under strong optical injection, the frequency response exhibits significant enhancement. We inject the DFB with a master laser output power of 18 dBm. With the 50% coupling efficiency of the optical head and about 1 dB of insertion loss in other components, this results in an injection ratio of ~14 dB. The colored curves of Fig. 2 show the frequency response for the injection-locked DFB; holding the injection ratio constant, the detuning frequency was varied from -47 to +67 GHz,

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with a step size of ~12.7 GHz. This resulted in a resonance frequency increase from 45 to 107 GHz, respectively. These results are limited only by the 110-GHz source and detection equipment we used, and is not limited by the injection-locked laser itself. The migration of the resonance to higher frequencies and the decrease in damping is clearly shown as the detuning frequency is increased. The 107-GHz resonance frequency case represents a 34 times increase in the resonance frequency over the 3-GHz of the free-running laser. The DC levels of both free-running and 107-GHz case are equal. Similar results have also been achieved in VCSELs. Though the round-trip times of long (e.g., DFB) and short (e.g., VCSEL) cavities differ by as much as two orders of magnitude, we have shown that the maximum resonance frequency enhancement is only dependent on the quality factor (Q) of the lossless cavity and the external power injection ratio [5]. The time–bandwidth product (product of photon lifetime and maximum resonance frequency) is equal to one half the square root of the external power injection ratio [5].

To achieve a broadband 3-dB frequency, we need to minimize the impact of the additional low frequency pole in injection-locked lasers, which may be as low as ~1 GHz for high resonance frequency. The low-frequency damping between DC and the resonance peak in Fig. 2 is a result of this low frequency pole. We have shown that the low-frequency pole increases proportionally to the photon density [4]. Hence, by biasing the slave current higher, we can obtain bandwidths > 80 GHz. This new mechanism for bandwidth enhancement should allow us to far exceed the bandwidths of conventional direct modulated lasers.

Conclusions

We have shown that the resonance frequency of directly modulated semiconductor lasers can be significantly increase by strong optical injection locking. With a +14dB injection ratio, we have achieved record high resonance frequency of 107 GHz in both DFB lasers and VCSELs. Fundamental scaling law of the resonance frequency is derived. Broadband response can be obtained by biasing the slave laser at high current. A 3-dB bandwidth of 80 GHz has been demonstrated.

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