High-Speed Modulation of Optical Injection-Locked Semiconductor Lasers

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Abstract: We review the recent high-speed advances in optical injection-locked lasers, focusing on high resonance frequencies (> 70 GHz) and maximum bandwidth (> 40 GHz). Experimental and theoretical direct modulation and master amplitude and phase modulation are presented.

OCIS codes: (140.3520) Lasers, injection-locked; (060.4080) Modulation; (140.5960) Semiconductor lasers

1. Introduction

To support the growing need for larger transmission speeds in optical communications, much research has been devoted to increasing the direct modulation bandwidth of semiconductor lasers. In a typical laser, the resonance frequency, f_R, is a figure-of-merit that is a necessary but not sufficient condition for determining its maximum direct modulation bandwidth. The resonance frequency of directly-modulated lasers has been demonstrated up to ~30 GHz [1-3]. Practical limitations, including laser heating and gain compression [4], limit the maximum resonance frequency. Furthermore, increased damping at higher resonance frequencies limit the maximum bandwidth to 30-40 GHz. Optical injection locking (OIL) has been shown to enhance the resonance frequency of the directly-modulated injection-locked laser. 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, thereby 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 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) [5] and vertical cavity surface emitting lasers (VCSELs) [6]. As this research is on-going, the fundamental limit has not yet been reached.

In this paper, we review the current research directions in high-speed modulation of optical injection-locked lasers. The state-of-the art direct-modulated OIL resonance frequencies and novel insights to improving bandwidth are presented. In order to bypass the low-frequency roll-off as well as the slave laser parasitics, we cover bandwidth enhancement of amplitude and phase modulated signals via master modulation, showing bandwidths > 50 GHz.

2. Direct-modulated optical injection-locked lasers

It has been shown that the resonance frequency of injection-locked lasers is enhanced with increasing injection ratio, R, and detuning frequency, Δf [7, 8], as shown in Fig. 2. Fig. 3(a) shows a schematic and frequency response of direct-modulated OIL lasers. This mechanism shows no fundamental limit to resonance frequency enhancement, although practical limitations exist, such as frequency spacing of nearest-neighbor Fabry-Perot modes. Using this principle, we have experimentally shown a record resonance frequency of 72 GHz, shown in Fig. 4 [5]. Response above 50 GHz was measured by the heterodyne detection technique described in [9]. The responses include losses from laser parasitics and microwave probe, however photodetector and other electrical losses were calibrated. Optimizing for broadband performance, a 3-dB frequency of 44 GHz was also demonstrated, as shown in Fig. 5.

The frequency response of the direct-modulated OIL laser is proportional to a low-pass roll-off pole, f_P, that may be as low as ~1 GHz for high f_R and severely limits the laser bandwidth. In order to obtain higher modulation bandwidths, we have shown that f_P increases proportionally to the photon density [7]. Hence, by biasing the slave current higher, we can obtain bandwidths that exceed the resonance frequency, as simulations show in Fig. 6. With a f_R of 68 GHz, we can obtain > 80 GHz bandwidths simply by increasing the current. This new mechanism for bandwidth enhancement should allow us to far exceed the bandwidths of conventional direct modulated lasers.

3. Master amplitude modulated optical injection-locked lasers

The low-pass roll-off in direct-modulated OIL lasers is a result of the finite carrier modulation speeds, limited by the enhanced stimulated carrier recombination [7]. In order to bypass the carrier modulation, we can alternatively modulate the master light before injection. If the master light is amplitude modulated at high injection ratios, the

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slave will cause a resonant amplification of the modulation at the enhanced resonance frequency [10]. The schematic and theoretical frequency response is shown in Fig. 3(b). There is no longer a low-frequency roll-off; only a small DC-suppression appears that can be mitigated depending on bias. By initially using a 25-GHz electro-optic modulator (EOM) to modulate the master, we can enhance the response beyond 25 GHz so that the overall bandwidth is 59 GHz, shown in Fig. 7 [11]. The modulator exhibits a modulator-specific resonant dip at 55 GHz, which ultimately limits the 3-dB bandwidth, but is not a fundamental limit of the system. Disregarding the dip, we see a > 70 GHz flat response in Fig. 7. Additionally, by subtracting out the EOM response, we can observe the resonance of the OIL slave in Fig. 8. This shows a tunable resonance from 73 to 107 GHz. The source of initial modulation is general, and any amplitude modulator can be used. For example, we have also performed amplitude modulation on an electro-absorption modulator laser [12] and direct-modulated, cascaded VCSELs [13].

4. Master phase modulated optical injection-locked lasers

Following the same concept in the previous section, we can also phase modulate the master and measure the phase modulation enhancement (shown schematically in Fig. 3(c)) [11]. The response suffers no low-frequency roll-off; furthermore, the response is flat at DC and resembles that of a 2-pole classical laser. Here, we use a 20-GHz $LiNbO_3$ phase modulator (PM) to perform the master modulation. After injection, the modulation response is enhanced up to 53 GHz, as shown in Fig. 9.

In summary, for direct modulation of injection-locked lasers, we have shown that resonance frequency enhancement will increase simply by increasing the injection ratio, with resonance frequencies well above 100 GHz possible. By increasing the slave bias current, bandwidths on the order of 100 GHz is fundamentally possible. This far exceeds the bandwidths possible for conventional direct modulated lasers. For master-modulated injection-locked lasers, we have shown resonance frequencies > 100 GHz, and bandwidths exceeding 50 GHz, for both amplitude modulation and phase modulation. We expect to exceed these bandwidths with faster modulators.

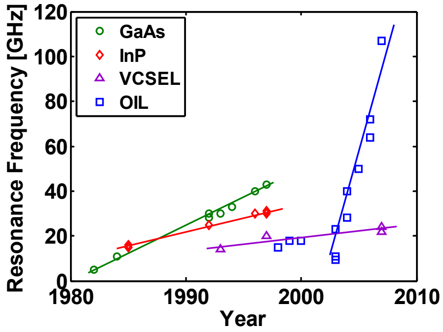


Fig. 1. Resonance frequency as a function of time, for conventional direct-modulated lasers (circles, diamonds, and triangles) and direct-modulated, injection-locked lasers (squares).

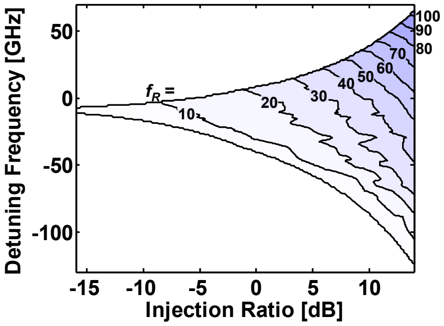
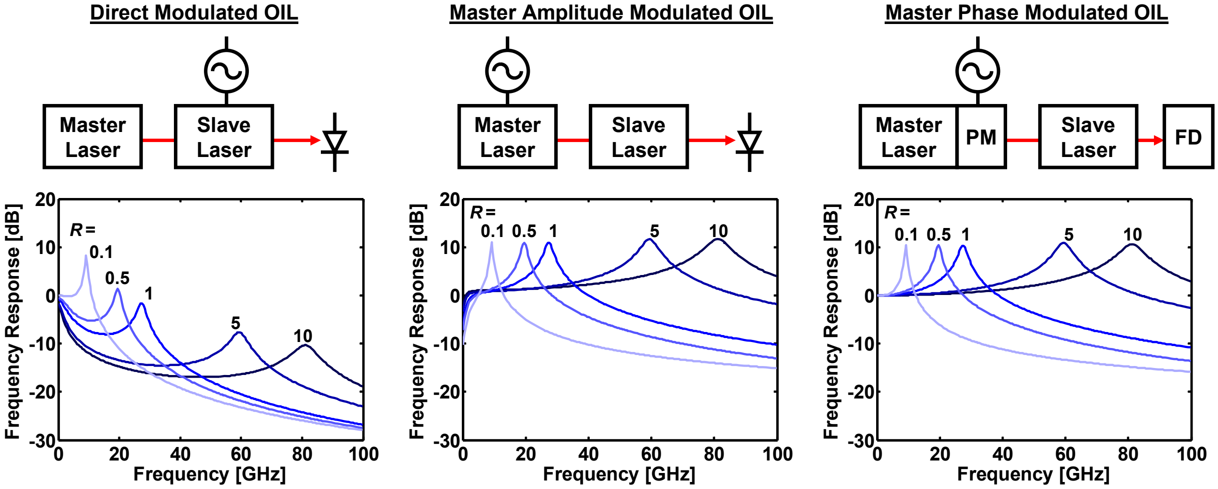


Fig. 2. Contour plot of experimental resonance frequency (GHz) as a function of detuning frequency and injection ratio.



(a) (b) (c)

Fig. 3. Schematics and corresponding frequency response simulations of the different optical injection locking modulation schemes, versus injection ratio, *R*: (a) direct modulation, (b) master amplitude modulation, (c) master phase modulation. FD = frequency discriminator necessary for phase detection.

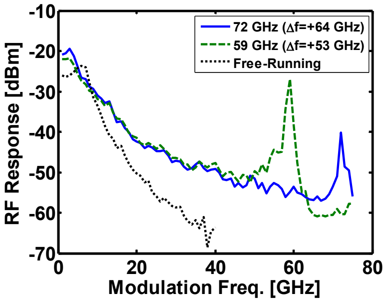


Fig. 4. Experimental frequency response curve showing resonance frequencies of 59 GHz and 72 GHz. R = 16 dB.

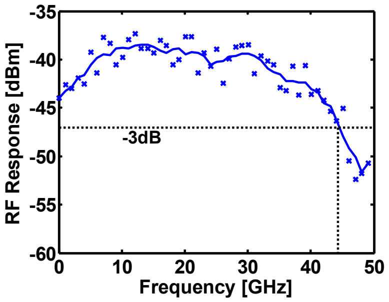


Fig. 5. Experimental frequency response curve showing a broadband, 3-dB response of 44 GHz. R = 18 dB, Δf = -60.5 GHz.

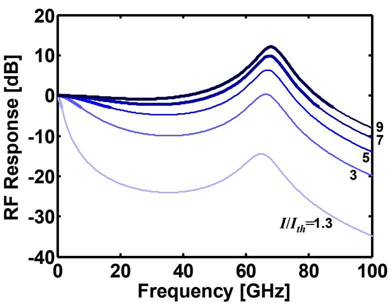


Fig. 6. Frequency response of OIL for various bias conditions, R = 4, f_R = 68 GHz. Bold lines indicate the 3-dB bandwidth.

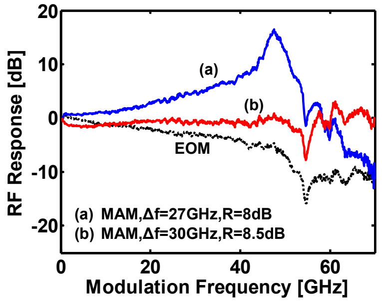


Fig. 7. Frequency response of EOM (f_{3dB} = 25 GHz) and MAM-OIL for different injection conditions: (a) maximum f_{3dB} (59 GHz) (b) >70 GHz flatness (aside from 55 GHz notch).

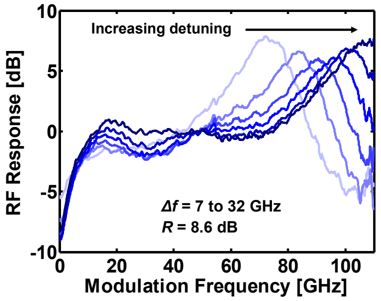


Fig. 8. Optical response of MAM-OIL (EOM response subtracted) for various detuning, showing resonance frequencies from 73 to 107 GHz.

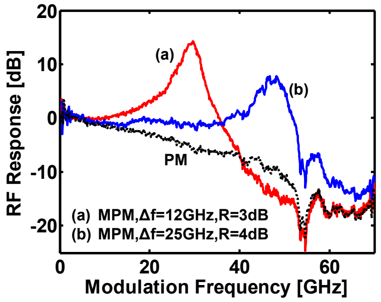


Fig. 9. Frequency response of PM (f_{3dB} = 20 GHz) and MPM-OIL for different injection conditions: The bandwidths for (a) and (b) are 36 and 53 GHz, respectively.

References

1. Y. Matsui, H. Murai, S. Arahira, S. Kutsuzawa, and Y. Ogawa, "30-GHz bandwidth 1.55-µm strain-compensated InGaAlAs-InGaAsP MQW laser," IEEE Photon. Technol. Lett. **9**, 25 (1997).
2. S. Weisser, E. C. Larkins, K. Czotscher, W. Benz, J. Daleiden, I. Esquivias, J. Fleissner, J. D. Ralston, B. Romero, R. E. Sah, A. Schonfelder, and J. Rosenzweig, "Damping-limited modulation bandwidths up to 40 GHz in undoped short-cavity $In_{0.35}Ga_{0.65}As$-GaAs multiple-quantum-well lasers," IEEE Photon. Technol. Lett. **8**, 608-610 (1996).
3. X. Zhang, A. Gutierrez-Aitken, D. Klotzkin, P. Bhattacharya, C. Caneau, and R. Bhat, "0.98-µm multiple-quantum-well tunneling injection laser with 98-GHz intrinsic modulation bandwidth," IEEE J. Sel. Top. Quantum Electron. **3**, 309-314 (1997).
4. R. S. Tucker, "High-speed modulation of semiconductor lasers," J. Lightwave Technol. **3**, 1180-1192 (1985).
5. E. K. Lau, H. K. Sung, and M. C. Wu, "Ultra-high, 72 GHz resonance frequency and 44 GHz bandwidth of injection-locked 1.55-µm DFB lasers," in *2006 Optical Fiber Commun. Conf.*, Tech. Dig. (IEEE, 2006), 1-3.
6. L. Chrostowski, X. Zhao, C. J. Chang-Hasnain, R. Shau, M. Ortsiefer, and M. C. Amann, "50-GHz Optically Injection-Locked 1.55-µm VCSELs," IEEE Photon. Technol. Lett. **18**, 367-369 (2006).
7. E. K. Lau, H. K. Sung, and M. C. Wu, "Frequency response enhancement of optical injection-locked lasers," IEEE J. Quantum Electron. (to be published, Jan. 2008).
8. C. H. Henry, N. A. Olsson, and N. K. Dutta, "Locking range and stability of injection locked 1.54 µm InGaAsP semiconductor lasers," IEEE J. Quantum Electron. **QE-21**, 1152-1156 (1985).
9. E. K. Lau, H. K. Sung, and M. C. Wu, "Frequency Response Measurement of Opto-Electronic Devices Using an Optical Heterodyne Down-Conversion Technique," (manuscript in progress).
10. E. K. Lau and M. C. Wu, "Amplitude and frequency modulation of the master laser in injection-locked laser systems," in *2004 IEEE Int. Topical Meeting on Microw. Photon.*, Technical Digest (IEEE, 2004), 142-145.
11. E. K. Lau, H.-K. Sung, X. Zhao, D. Parekh, C. J. Chang-Hasnain, and M. C. Wu, "Bandwidth enhancement by optical amplitude and phase modulation of injection-locked semiconductor lasers," presented at the 2007 IEEE Int. Topical Meeting on Microw. Photon., Victoria, BC, Canada, 4-6 Oct. 2007.
12. E. K. Lau, H. K. Sung, X. Zhao, D. Parekh, C. J. Chang-Hasnain, and M. C. Wu, "Bandwidth Enhancement of Electro-absorption Modulated Lasers by Optical Injection Locking," presented at the 2007 Annu. Meeting IEEE Lasers and Electro-Optics Soc., Lake Buena Vista, FL, 22-25 Oct. 2007.
13. X. Zhao, D. Parekh, E. K. Lau, H. K. Sung, M. C. Wu, and C. J. Chang-Hasnain, "Novel cascaded injection-locked 1.55-µm VCSELs with 66 GHz modulation bandwidth," Opt. Express **15**, 14810-14816 (2007).