REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE
Final Technical Report

3. DATES COVERED *(From - To)*
7/22/08-7/30/10

4. TITLE AND SUBTITLE
Novel Applications of High Speed Optical-Injection Locked Lasers

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-08-1-1181

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ming Wu (PI)
Costance Chang-Hasnain (Co-PI)
Young-Kai Chen (Co-PI)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, Berkeley
Sponsored Project Office
2150 Shattuck Ave RM 313
Berkeley, CA 94704-5940

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Kyoohui Beal
Contractor Support to Code 247, ADS Corporation
Office of Naval Research, Seattle Regional Office
300 Fifth Avenue, Suite 710
Seattle, WA 98104

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public releases, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In this project, we have developed a fundamental understanding of the dynamic response of semiconductor lasers under strong optical injection locking (OIL). We have derived a fundamental expression for the maximum achievable resonance frequency in OIL lasers, and shown that it is only related to the external injection ratio and the coupling quality factor. Experimentally, we have achieved a maximum resonance frequency of 107 GHz using both distributed feedback (DFB) lasers and vertical cavity surface-emitting lasers (VCSELs) under strong OIL. This is the highest frequency every achieved for all directly modulated lasers. Using these high speed lasers, we have shown we can generate millimeter-wave signals that can be used to probe the high frequency response of high speed phototransistors. We have also shown the OIL lasers can significantly extend the reach of optical communications, to 120km, for OIL VCSELs.

15. SUBJECT TERMS
Optical injection locking, high speed modulation, direct modulation, chirp reduction, optoelectronic network analysis, optical communication links

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			USARME
U	U	U	UU		**19b. TELEPHONE NUMBER** *(Include area code)*

20140530000

Final Technical Report

N00014-08-1-1181

Title:
Novel Applications of High Speed Optical-Injection Locked Lasers

Period of Performance:
07/22/2008 - 07/31/2010

PI: Ming C. Wu, University of California, Berkeley
Co-PI: Connie Chang-Hasnain, University of California, Berkeley
Co-PI: Young-Kai Chen, Alcatel-Lucent, Bell Laboratories

Introduction

Direct-modulated semiconductor lasers are compact and the most cost-effective optical sources for high-frequency modulations. Since the early 80s, there has been steady but slow progress in the modulation speed of semiconductor lasers. Their bandwidth scales with the relaxation oscillation frequency. Ultimately, the maximum bandwidth is limited to ~ 40 GHz due to nonlinear gain compression and heating [1]. Recently, strong optical injection locking (OIL) has been shown to overcome the relaxation oscillation limit [2][3]. Using OIL, the maximum resonance frequency has increased sharply in the past few years, as shown in Figure 1. Under a seedling program, the UCB contractor has demonstrated a record-high resonance frequency of 108 GHz in both edge-emitting distributed feedback (DFB) and vertical-cavity surface-emitting lasers (VCSELs) [4][5]. In addition, we have derived an analytical expression to achieve maximum 3-dB modulation bandwidth under strong OIL. Experimentally, we have demonstrated an intrinsic 3-dB bandwidth of 80 GHz in OIL VCSELs [5].

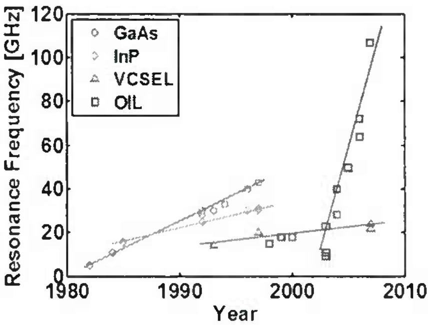


Figure 1. *The evolution of maximum resonance frequency of semiconductor lasers over time for GaAs-, InP-based edge-emitting lasers, vertical-cavity surface-emitting lasers (VCSELs), and optical-injection-locked (OIL) lasers. The OIL lasers exhibited a must steeper slope of advances.*

The goal of this program is to leverage the investigators' expertise in Optical Injection-Locked (OIL) lasers toward new applications in optoelectronic characterization and communications that rely on high frequency optical modulation. We aim to both develop technology built around the unique abilities of OIL lasers and further refine our scientific understanding of OIL. At this point in the program, we have demonstrated a 70-105 GHz millimeter-wave source using commercial-off-the-shelf (COTs) distributed feedback (DFB) lasers, which was used to characterize high-speed InP Heterojunction PhotoTransistors (HPTs).

HPT test wafers have been designed and taped out, consisting of single ended HPTs, transimpedance amplifiers (TIAs) and optical hybrids. We have also demonstrated digital communications on a 60 GHz optical subcarrier using directly modulated vertical-cavity surface-emitting lasers (VCSELs), which is a first step in constructing a wide-band subcarrier-multiplexed (SCM) link. A new analytical model for the VSCEL OIL has been developed and experimentally verified that explains phenomenon observed in the high-injection ratio, high reflectivity regime of OIL operation.

Fundamental Study of Optical Injection Locking

We have performed detailed study, both theoretically and experimentally on the properties and fundamental limit of semiconductor lasers under strong optical injection locking (OIL). We have published extensively on this subject [5]–[9]. In Ref. [8], we derived the expression for the maximum enhanced resonance frequency, $\Delta\omega_{R,\max}$, of OIL lasers, and found it to depend only on the optical quality factor of the coupling and the external injection ratio:

$$\Delta\omega_{R,\max} = \frac{\omega_0}{2Q_C}\sqrt{R_{inj}}$$

where ω_0 is the optical frequency (in radian), Q_C is the coupling quality factor, and R_{inj} is the external injection ratio. This is the most simple, and most fundamental expression of the maximum resonance frequency of OIL lasers that has ever been derived. It is *independent of the type of lasers*, and is applicable to both DFB lasers and VCSELs. The key theoretical result is show in Figure 2. It matches very well with the experimentally measured frequency response shown in Figure 3. The maximum resonance frequency of 107 GHz is the highest ever reported for any type of lasers. We have obtained that for both DFB lasers and VCSELs, and it is only limited by the frequency response of our network analyzers (110 GHz).

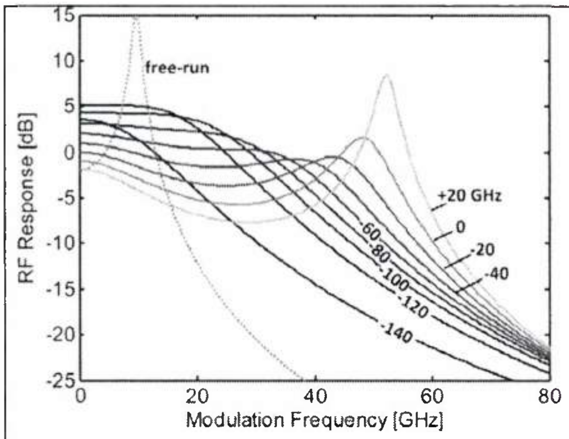


Figure 2. Calculated frequency response of OIL lasers under external injection ratio of 4dB.

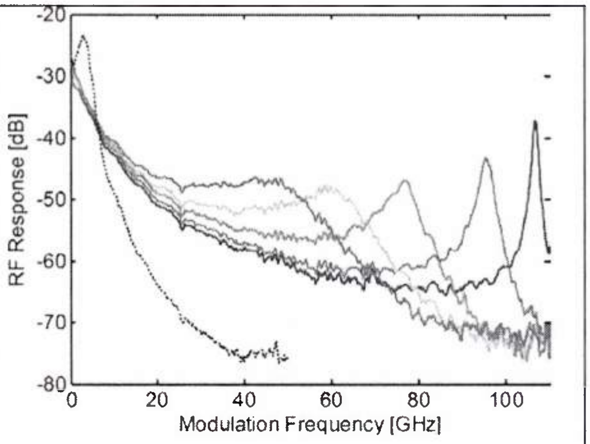


Figure 3. Experimentally measured frequency response of DFB lasers under external injection ratio of 14dB and various frequency detuning. The maximum resonance of 107 GHz is the highest ever reported.

Ultrawide Band Optoelectronic Network Analyzer

We are studying the application of optical injection locked (OIL) lasers to the characterization of high-speed active devices. Millimeter wave signals generated in the optical domain with OIL will be used to probe optoelectronic devices at frequencies much higher that of available optical modulators and microwave sources. The technique will obtain both amplitude and phase responses, important for optical receivers intended for proposed coherent optical communications schemes such as optical OFDM. Furthermore, it will probe fast electronic devices, such as heterojunction bipolar transistors, by optically injecting and modulating carrier concentrations at frequencies past that of available electronic measurement equipment and RC parasitic limitations.

During this project, we have completed setting-up a test-station to probe the electronic and optical characteristics of transistors and have constructed a system to optically generate millimeter-wave signals up to 105 GHz.

We have set up a test-station for probing the electronic and optical characteristics of transistors. The electronic part of the test-station consists of a semiconductor parameter analyzer, a vector network analyzer, and a wafer probe station. A low-frequency optoelectronic test is performed with the addition of a tunable laser, electro-optic modulator, and a lens fiber to couple modulated light into devices. Diagrams of the test-station are shown in Figure 4. Light modulated at higher frequencies will be provided in the future by the millimeter-wave source.

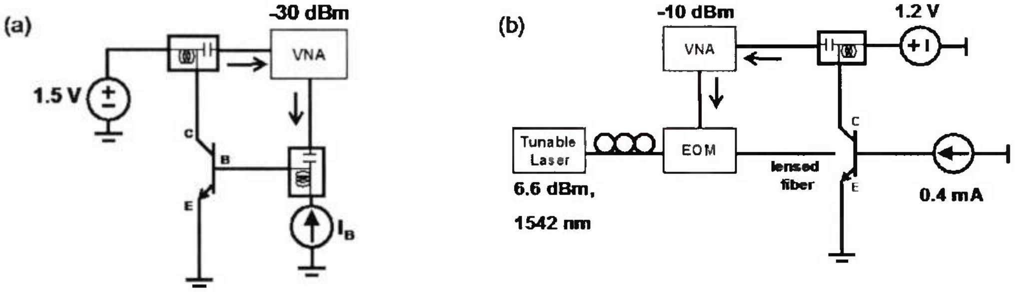
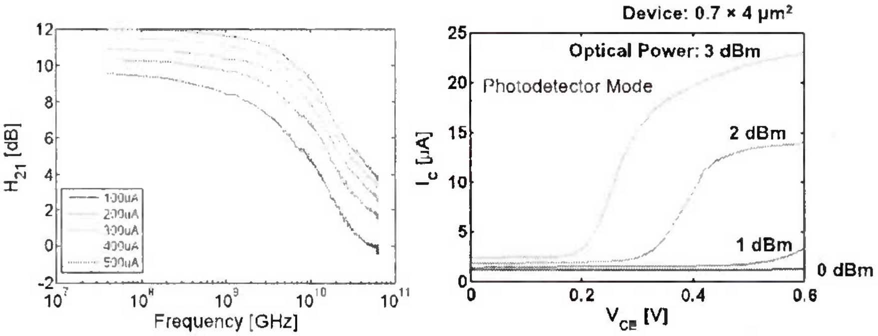


Figure 4 (a) Electronic test setup. (b) Optoelectronic test setup.

Alcatel-Lucent has provided test devices for the project, consisting of waveguide coupled InP heterojunction phototransistors. Light transmitted by the lens fiber and waveguide into the base of the transistor modulates the base current in the device. The transistors have cutoff frequencies estimated to be greater than 400 GHz. One motivation for optically characterizing the transistors is that high frequency non-idealities such as power-gain resonance effects can shift the response at lower frequencies, making interpolated estimates of the transistor cutoff inaccurate or ambiguous. We have measured the two port electrical response for transistors of different dimensions up to 40 GHz. We have also probed the optoelectronic response up to 40 GHz using EOM modulated light. Figure 5 shows sample response curves from a 0.7 x 4 micrometer device.



(a) Electrical Characterization

(b) Optoelectronic Characterization

Figure 5. (a) Electrical H21 response of HPTs. (b) DC optoelectronic response of HPTs

The optical millimeter-wave source works on the concept of frequency multiplication, as shown in Figure 6. Optical sidebands are generated on an optical carrier with an EOM. Because the EOM is a nonlinear device, it produces optical sidebands at multiples of the modulation frequency. An arrayed waveguide grating (AWG) is used to separate the optical power at each harmonic to a different optical fiber. Arbitrary channels can be recombined to produce beat tones at a desired frequency. The AWG's advantage in carrier suppression over null-biased EOMs is that both even and odd order sidebands can be selected, and spurious harmonics are suppressed 40 dB or more. Optical injection locking is used to coherently amplify sidebands that are selected by the arrayed waveguide grating. Each sideband can act as a master laser, to which a high-power slave laser will lock its optical frequency. As opposed to other amplification techniques, OIL contributes limited amplified spontaneous emission (ASE) noise, has fine control over the intensity of the amplified signal, and can suppress intensity noise in the modulation.

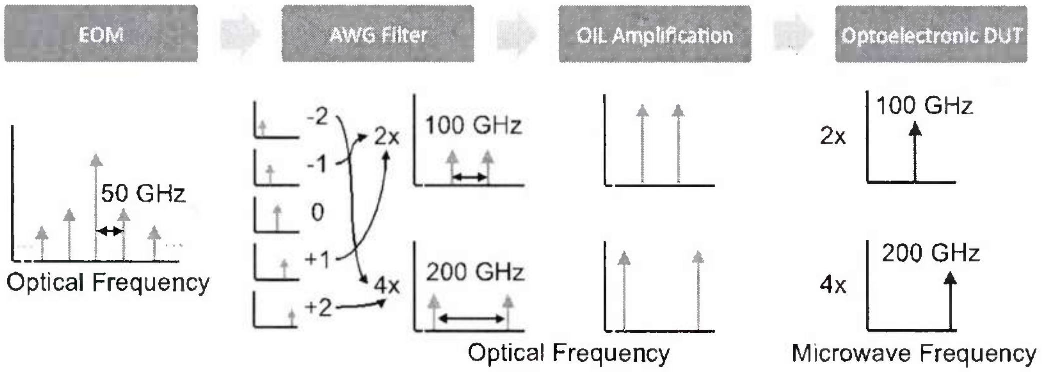


Figure 6. Millimeter wave generation using optical injection locking (OIL) and spectral filtering with array waveguide grating (AWG).

The optical millimeter-wave source is composed of commercial off-the-shelf (COTs) optical components used in WDM optical communications, which offers the potential for low-cost and widespread use of this technique. The system consists of an EM4 high power distributed feedback (DFB) laser used as the master laser, an EOSpace 40 GHz Mach Zehnder modulator, an NTT Electronics 50 GHz AWG and two EM4 isolator-free, ITU grid DFB lasers used as slave lasers. A diagram of the system is shown in Figure 7 as well as tones produced from 70-105 GHz.

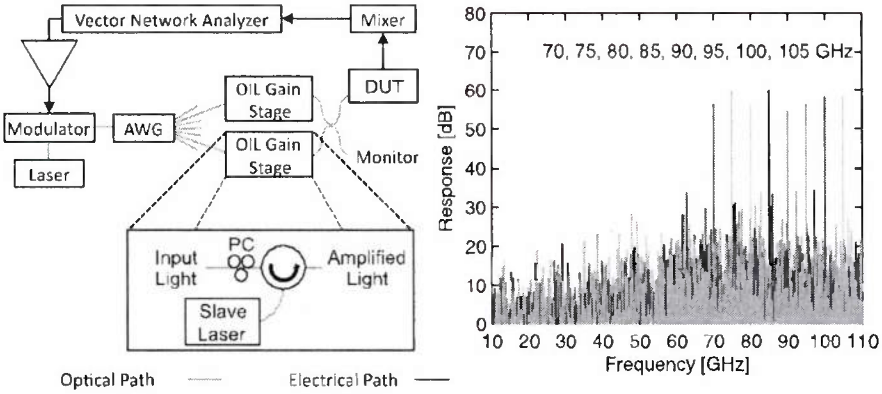
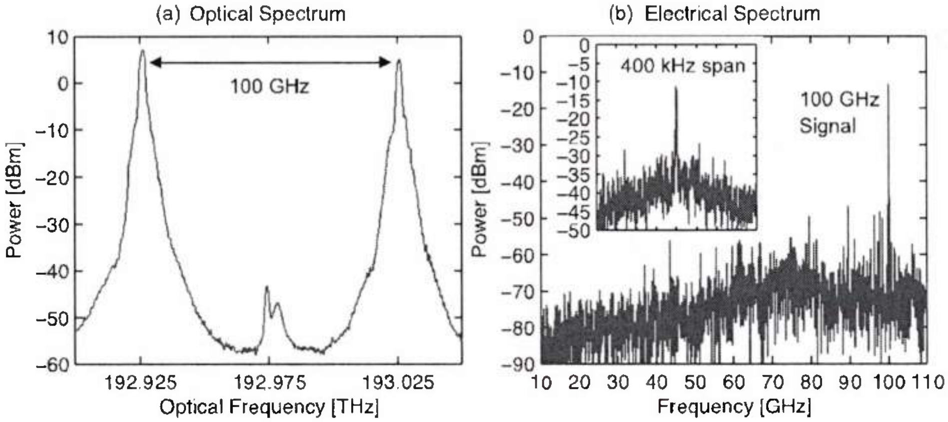


Figure 7. Optical millimeter-wave source and 70-105 GHz tones.

To produce 105 GHz signals, the EOM is modulated with a 52.5 GHz electrical signal, and the positive and negative first-order sidebands are selected. Higher order sidebands can be selected to produce higher frequency bands. The performance of the system has been tested with a high-speed photodetector. Figure 8 shows a 100 GHz signal produced by this technique, with the final millimeter wave signal with power of more than -13 dBm.


(a) Optical Spectrum

(b) Electrical Spectrum

Figure 8. 100 GHz coherent optical signals with high spectral purity.

Future work is to study the noise and dynamic range performance of the millimeter wave source. At this point, we have characterized the long-term (drift) stability of slave lasers, and their locking ranges. In order to measure the phase and amplitude response of devices, the source needs low amplitude and phase noise, and stable power. We need to stabilize our system to ensure repeatable measurements. In addition, we are creating an analytical model for the noise of the millimeter-wave generation system in order to compare it to other optical and electronic techniques.

Phototransistor Mask Layout

A mask has been taped out to evaluate the high frequency response of our InP Hetrojunction PhotoTransistors (HPTs). The mask contains of device test structures to characterize the optical performance (bandwidth) of the devices. Also included on the mask are both single ended as well as differential transimpedance amplifiers (TIAs). These circuits have a phototransistor as the input stage of the circuit that is fed optically by a ridge waveguide. This will eliminate the need for bondpads at the input of the circuit and will therefore increase the bandwidth of the circuits because of reduced bondpad parasitics. The TIA will convert the optical signal to an electrical one with gain and also provide a buffered 50 ohm electrical output, so it can be used in a 50 ohm environment. To demodulate a phase encoded signal for coherent optical communications schemes the differential TIAs are also integrated together with an optical multi-mode interference MMI device that will act as an optical hybrid. The optical hybrid will mix the incoming signal with the four quadratural states associated with the reference signal in the complex-field space. The optical hybrid would then deliver the four light signals to two pairs of differential TIAs for separate I and Q detection. Figure 9 shows the completed layout design.

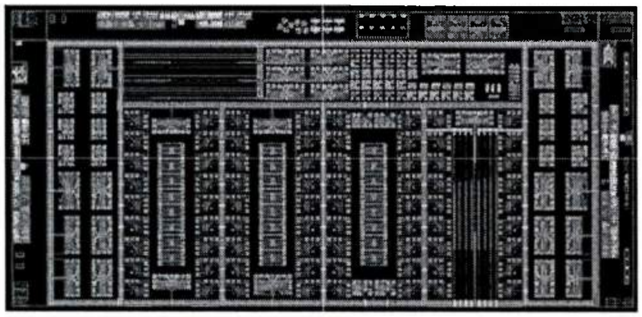


Figure 9. Mask layout of photo-transistors

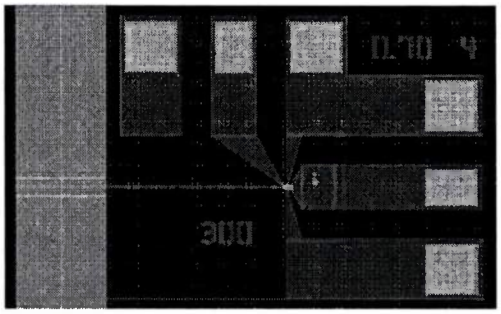


Figure 10. Layout of device test structure.

Device Simulations and Small-signal measurements

Test structures of single photo-transistors fed by an optical waveguide are put on the mask to be able to measure the high-frequency performance (bandwidth) of the photo-transistor. To evaluate the photo-response, a small signal electrical equivalent circuit (T-model) was developed for the HPTs. Because of the optical input, a phototransistor can be represented as a three-port network with the optical input modeled as a current controlled current source (see Figure 11(b)). We extrapolated a maximum optical gain cut-off frequency F_{opt} of 447 GHz at a base current of I_b=650 μA using A=0.7 x 4 μm^2 emitter devices and a $F_{t,opt}$ of 341 GHZ for our A=0.7 x 16 μm^2 devices at a base current of I_b=2400 μA.

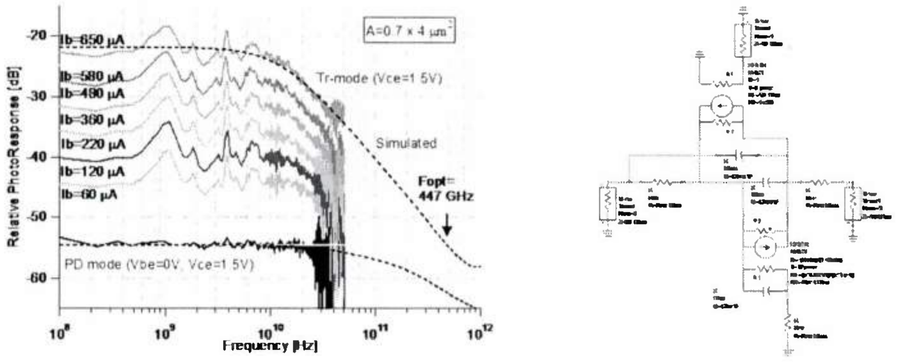


Figure 11. (a) Small signal device simulations and measurements. (b) Small signal phototransistor model.

Circuit simulations have been performed to optimize the performance of the transimpedance amplifiers with the photo-transistors as the input stage. Simulations predict a transimpedance bandwidth of 120 GHz for the single ended TIA and 70 GHz for the differential transimpedance amplifier with a transimpedance gain of over 49 and 55 dB-Ohm respectively (see Figure 12(b) and Figure 13(b)).

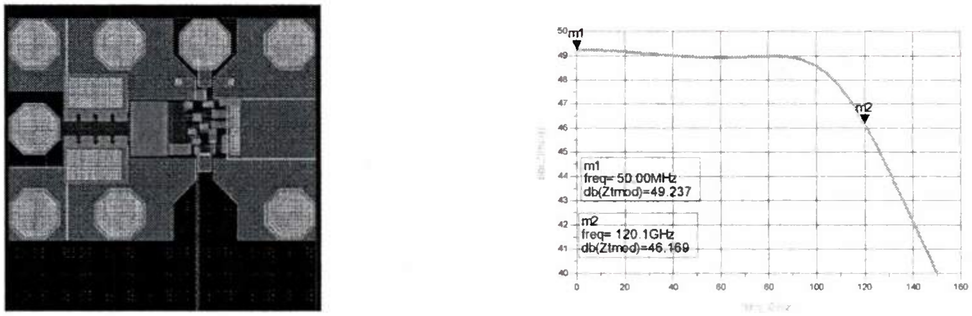


Figure 12. (a) Circuit layout of the completed single ended TIAs and (b) Simulated transimpedance frequency response.

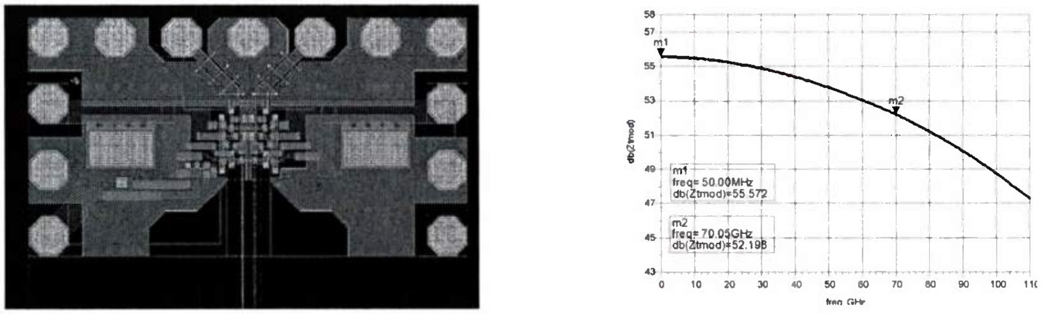


Figure 13. (a) Circuit layout of the completed differential TIAs and (b) Simulated transimpedance graph.

Broadband Communications Using OIL VCSELs

Directly modulated vertical-cavity surface-emitting laser (VCSELs) are attractive candidates as cost-effective optical transmitters for metro-area networks (MANs), local area networks (LANs) and high-speed Ethernet applications. A directly modulated VCSEL is desirable because it is compact, cost-effective and consumes a small amount of power. However, VCSELs have an intrinsic problem of frequency chirp, which significantly limits their transmission distance through standard single-mode fibers. Hence, in addition to the modulation bandwidth, chirp is a very important figure-of-merit to gauge transmitter performance. It has been demonstrated that optical injection locking (OIL) can greatly enhance the modulation bandwidth of a directly-modulated laser. Previously, we reported a factor of 10 increase of modulation bandwidth and resonance frequency in an OIL-VCSEL [5], [10]. In this project, we have developed several novel schemes of broadband optical communications using OIL lasers [10]–[13].

We have developed a completely new approach to achieve adjustable chirp in a directly modulated VCSEL using optical injection locking [14]. We show that OIL can be used to change the polarity of the chirp of a VCSEL, from a positive chirp for a standard VCSEL to a negative chirp. The resulting negative chirp compensates the chromatic dispersion of standard single-mode fiber (SSMF) at 1550 nm, and increases the 10 Gbps transmission distance up to ~120 km for a single mode VCSEL, more than 10X compared to a free-running VCSEL. Theoretical simulations are presented to explain the OIL conditions with which the negative chirp can be achieved. Excellent agreement is obtained between experimental and theoretical results. This all-optical approach will be widely applicable to various modulation formats, bandwidths, and fibers and can even be applied as a post-deployment enhancement for VCSEL-based transmission systems.

The experimental results are shown in Figure 14, which plots the power penalty versus SSMF transmission distance when the VCSEL is directly modulated by 10Gb/s pseudo-random bit sequence (PRBS). Error-free (BER $< 10^{-9}$) power penalty referenced to free-running back-to-back as a function of transmission distance is measured for both a free-running VCSEL and an OIL VCSEL with negative chirp. An optimal transmission appears at a distance (25 km in this case) where the error-free receiver power is minimal due to compensation between chromatic dispersion of the fiber and the negative chirp of an OIL VCSEL. The transmission distance and dispersion tolerance are significantly enhanced. In a practical system, the transmission distances for various experimental conditions are typically compared at a fixed power penalty, for example, 4 dB here. For a DM VCSEL, the power penalty rapidly increases with transmission distance due to chirp, and the 4 dB-distance is limited to less than 10 km. However, under OIL conditions in this paper, the power penalty decreases with distance for the first 25 km to 0-dB power penalty, and subsequently increases at a slower rate with fiber distance. The 4 dB-distance is enhanced by one-order-of-magnitude to ~120 km. This behavior suggests the existence of negative chirp, which compensates the fiber dispersion to result in an optimal transmission distance with minimal power penalty. Eye diagrams in back-to-back, 25-km transmission and 100-km transmission conditions are also shown, which clearly demonstrates pulse compression due to dispersion compensation.

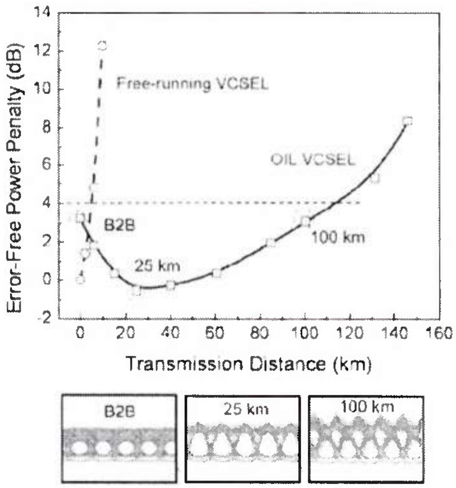


Figure 14. Transmission measurements demonstrating distance enhancement of a direct-modulated OIL VCSEL with negative chirp at 10 Gb/s. Eye diagrams for OIL VCSEL at back-to-back (B2B), after 25-km and 100-km transmission are shown.

Conclusion

In this project, we have developed a fundamental understanding of the dynamic response of semiconductor lasers under strong optical injection locking (OIL). We have derived a fundamental expression for the maximum achievable resonance frequency in OIL lasers, and shown that it is only related to the external injection ratio and the coupling quality factor. Experimentally, we have achieved a maximum resonance frequency of 107 GHz using both distributed feedback (DFB) lasers and vertical cavity surface-emitting lasers (VCSELs) under strong OIL. This is the highest frequency every achieved for all directly modulated lasers. Using these high speed lasers, we have shown we can generate millimeter-wave signals that can be used to probe the high frequency response of high speed phototransistors. We have also shown the OIL lasers can significantly extend the reach of optical communications, to 120km, for OIL VCSELs.

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