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# LARGE-SIGNAL MODULATION OF SEMICONDUCTOR LASERS WITH OPTICAL FEEDBACK FOR MILLIMETER WAVE APPLICATIONS

V. M. Contarino*, A. S. Daryoush+, and P. R. Herczfeld+

* Naval Air Development Center, Warminster, PA, 18974
+ Millimeter Wave & Lightwave Engineering Laboratory, Dept. E.C.E.
Drexel University, Philadelphia, PA, 19104

## ABSTRACT

Large-signal microwave modulation of laser diodes excite harmonics which have been exploited to achieve optical injection locking of multiple millimeter wave oscillators. Experimental results of large-signal modulation of laser diodes with optical feedback are presented. The external cavity increases the optical intensity modulation depth of both the fundamental (3.456GHz) and its harmonics by approximately 20dB.

## INTRODUCTION

High-speed fiber-optic links are gaining increasing interest in various microwave and millimeterwave applications. In particular, applications such as antenna remoting and optically controlled phased arrays [1, 2] are receiving the most attention. Key to these applications is the frequency and phase synchronization of the distributed, independent transmit/receive T/R modules. The frequency synchronization can be achieved by optical injection locking of independent and remotely located local oscillators. Indirect optical injection locking of a millimeter wave local oscillator (operating at 39 GHz) has been recently demonstrated[3]. A promising architecture which utilizes two high speed fiber optic links, one that carries only the frequency reference signal and one that carries the data or communication information has been reported.[4] In this configuration the extremely high frequency link, which synchronizes the distributed local oscillator, operates in a very narrow band. The data signal is mixed with the output of the local oscillator at the T/R module. The advantage of this architecture is that each of these two high speed links can be independently optimized to achieve higher frequency, better sensitivity and dynamic range. Our present research efforts on the high frequency link are concentrated on three aspects of the problem, namely:

i. synchronization of oscillators at 40GHz and above,
ii. extend the locking range,
iii. increase the number of local oscillators that are locked by a single laser diode.

The bandwidth of fiber-optic links are primarily limited by the optical modulators and it is not anticipated that laser diodes with bandwidths in excess of 20GHz will be available in the near future. Large-signal modulation of semiconductor lasers provides higher order harmonics of the modulating frequency and thereby extends the effective bandwidth of the fiber-optic links[5, 6]. The difficulty is that many harmonics are excited even though for optical injection locking only one of the harmonics is utilized. In addition the modulation amplitudes of the harmonics are small. The significance of these inadequacies are two fold. First, it means that the locking range of the local oscillators is smaller and therefore a fewer number of oscillators can be locked simultaneously to the same modulated laser diode. Second, the modulating power of the master source is not efficiently converted to the required harmonic. The goal of the reported research is i) to enhance the intensity modulation depth of the laser diode providing an increase in harmonic content, ii) enhance the level of desired harmonic frequency at the expense of the others.

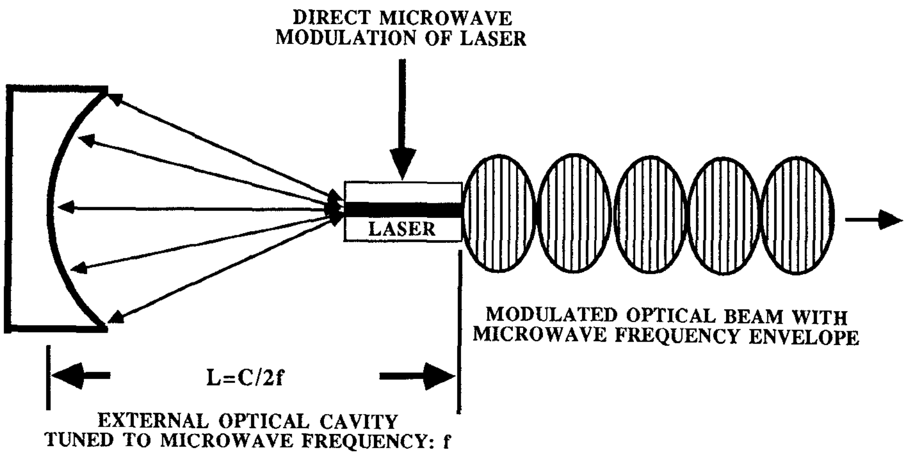


Fig. 1. Conceptual representation of large-signal modulation of semiconductor laser with optical feedback. The microwave cavity is a curved mirror.

## OBJECTIVE

The objective of this experiment was to selectively enhance the harmonic output of a laser diode by utilizing optical feedback. The use of optical feedback results in increased modulation depths even at frequencies above the normal direct modulation bandwidth. The conceptual diagram of this experiment is shown in Fig. 1. A semiconductor laser diode, with access to the rear facet, is imbeded into an external optical cavity. The length of the external cavity, L, is equal to a half wavelength of the desired output modulation frequency, which is in the microwave/millimeter wave region. If the laser is modulated in the large-signal mode at frequency $f_o$, it will excite the fundamental as well as higher order harmonics at $2f_o$, $3f_o$, $4f_o$,....[5, 7] However, the amplitude of the harmonics is small but may be enhanced if the external cavity is tuned to $f_o$. Furthermore, it is anticipated that a specific harmonic's amplitude (e.g. $4f_o$) may be increased if the external cavity length is tuned for that frequency (e.g. $L \approx c/4 f_o$).

## EXPERIMENTAL SETUP

The experimental set up is shown in Fig. 2. A buried hetero-junction (BH) GaAlAs laser diode mounted on a heat sink, is used in this experiment. The laser diode, manufactured by Ortel Corp., emits light at 850nm and has an output power of 15mW. The relaxation oscillation frequency of the laser diode is 3GHz at biasing level corresponding to 80% of maximum output power. The laser diode is biased by a current source, and is modulated by an rf sweeper through a bias-Tee. The modulated light output from the front facet of the laser diode is collimated using focusing lens from Melles Griot. The collimated light beam is reflected back by a flat mirror mounted on a micropositioner. The refelected light is focused back to the active region of the laser using the same focusing/collimating lens. The collimating lens and mirror combination provides for adjustment of the external cavity length. The output from the laser's back facet is coupled to a high-speed fiber pigtailed pin photodiode manufactured by Ortel Corp. The pin photodiode has a responsivity of 0.35mA/mW at 840nm for 20V reverse biasing. The detector has a 3dB bandwidth of 14GHz, and its output is monitored on a spectrum analyzer.

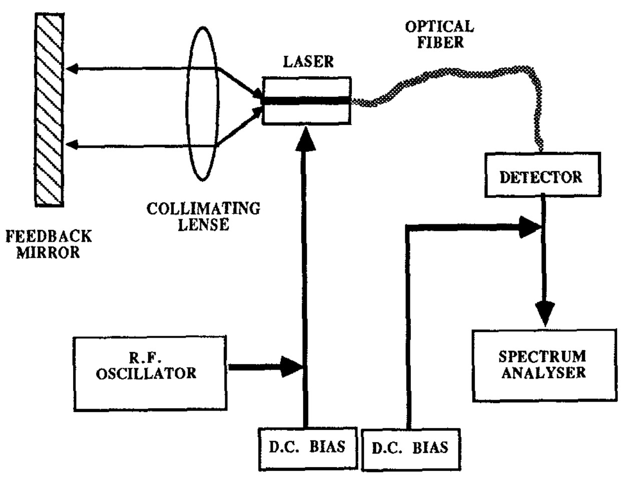


Fig. 2. Experimental setup for the measurement of optical feedback to a laser cavity.

## EXPERIMENTAL RESULTS

The effect of the optical feedback on the operation of the laser diode was investigated as a function of dc biasing and rf modulation. The influence of the external cavity on the performance of the laser diode with only dc biasing was studied first. For the case when no light is fed back to the laser, typical relative intensity noise (RIN) is observed. However, if the light is fed back into the active part of the laser, the noise floor level increases at the frequencies corresponding to the round trip time of light in the external cavity. When the external cavity is tuned such that the resonance is at 4.2GHz, indeed a peak at that frequency is observed as shown in Fig. 3. Furthermore, a similar peak occurs at the harmonics of this frequency, but with lower amplitude, as expected. The feedback noise peak, which corresponds to the external cavity resonance frequency, can be varied from 2 to 5GHz by adjusting the cavity length. Increase in the RIN of the laser in addition to changes in the threshold current were employed as a measure of light coupling from the external cavity back to the active region of the diode. The unloaded electrical quality factor of the feedback cavity was estimated to be 10.

The second set of experiments were performed on an Ortel SL600 laser, with 3dB bandwidth of 6GHz. The external cavity was tuned to 3.456GHz. The detected signal with no feedback, a reference condition, is shown in Fig. 4a. The modulated signal with the optical feedback from the external cavity showning a significant increse in its amplitude is depicted in Fig. 4b. The experiment was repeated with different rf input levels yielding a average increase of 20dB with respect to the established reference. No degradation of the signal quality (spectral purity of the modulating signal) was observed at a resolution of 30 Hz. The output of the second harmonic (6.912GHz) with and without feedback are shown in Fig. 5a and Fig. 5b, respectively. The feedback enhances the second harmonic by 30dB. The third harmonic, at 10.368GHz, produced approximately a 30dB increase in signal level with feedback (Figs. 6a and 6b). The fourth harmonic (13.824GHz) enhancement was also investigated. Fig. 7a indicates that the detected signal is submerged in the noise floor of the spectrum analyzer. However with the feedback the signal rises above the noise by 15dB, Fig.7b.

Direct modulation of the laser diode at the harmonic frequencies was also investigated. First the laser was modulated at 6.912GHz, with and without feedback. The feedback produced a 10dB gain at this frequency. When the laser was modulated at 3.456GHz, the second harmonic at 6.912GHz was enhanced by 20dB due to the feedback. This seems to suggest that the cavity is effective in increasing the harmonic output power and thereby demonstrates its utility in extending the modulation bandwidth of semiconductor lasers.

## DISCUSSION

Experimental results of a large-signal modulated laser diode with the optical feedback cavity was presented. The optical feedback increases the intensity modulation depth of the modulated laser diode. In particular, the RIN noise of a dc biased laser diode increased at the frequencies corresponding to the round trip time of the external cavity. Even in an external cavity with a low unloaded quality factor of 10, the effect has been as high as 20dB. For an rf modulated laser diode, enhancement of the second, third, and fourth harmonic was demonstrated. The detected fundamental signal increased by 20dB where as for the second harmonic an improvement of 30dB was observed. A

10dB increase in the intensity modulation depth implies that the number of LOs that can be synchronized by a single semiconductor laser are increased by an order of magnitude. This substantial improvement has major implications in large systems, such as MMIC based large aperture phased array antennas. The low Q for this experiment resulted from the difficulty in feeding back sufficient light into the active region of the laser diode. The mechanical alignment necessary for efficient coupling to the small active region of BH laser (typically 1μm by 5μm) is quite difficult. Furthermore, the commercially available high speed laser diodes were not designed for this kind of experimentation and their mounting in the external cavity proved to be difficult. However it is anticipated that with fabrication of the integrated optic version of this configuration, better coupling efficiencies will be observed. The use of an all fiber cavity is also a viable technique and should greatly improve the feedback efficiency. The improvement in the effective "Q" of the external cavity should provide substantial harmonic enhancement. This however would require a fixed fiber length which would preclude the flexibility desired for this experimentation.

Further work is presently being pursued to improve the optical feedback coupling efficiency, and optical and electrical characterization of the optical feedback's effect.

ACKNOWLEDMENT

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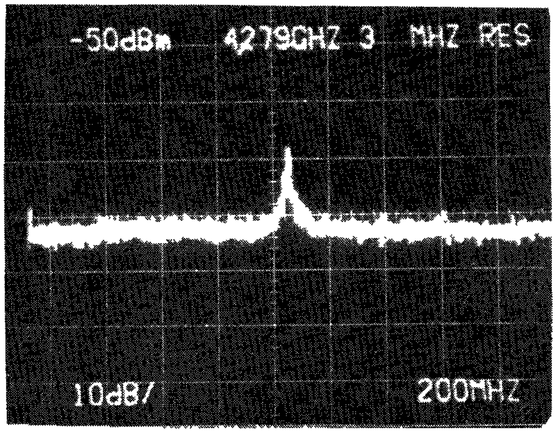
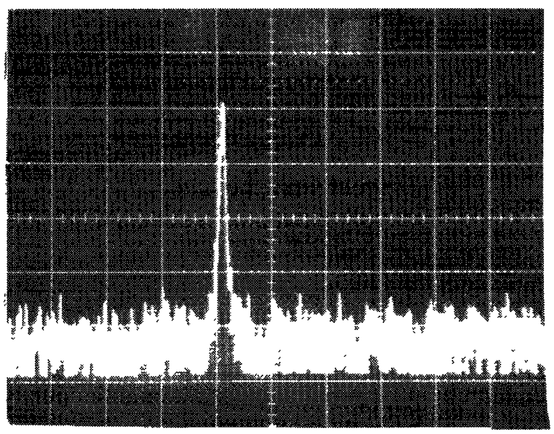
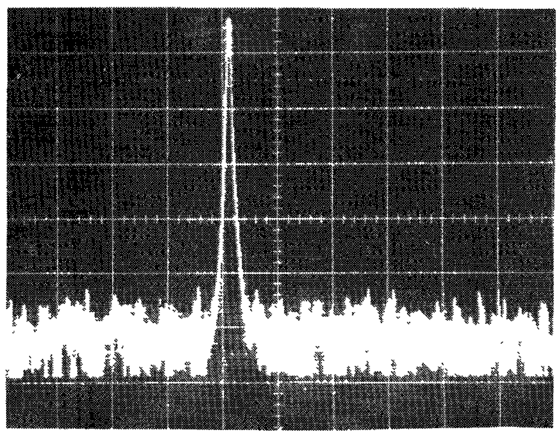



Fig. 3. The effect of light feedback to a dc biased BH laser diode. The external cavity is tuned for 4.2GHz. (Vertical scale is 10dB/div and horizontal scale is 200MHz/div. Center frequency is at 4.279GHz.)

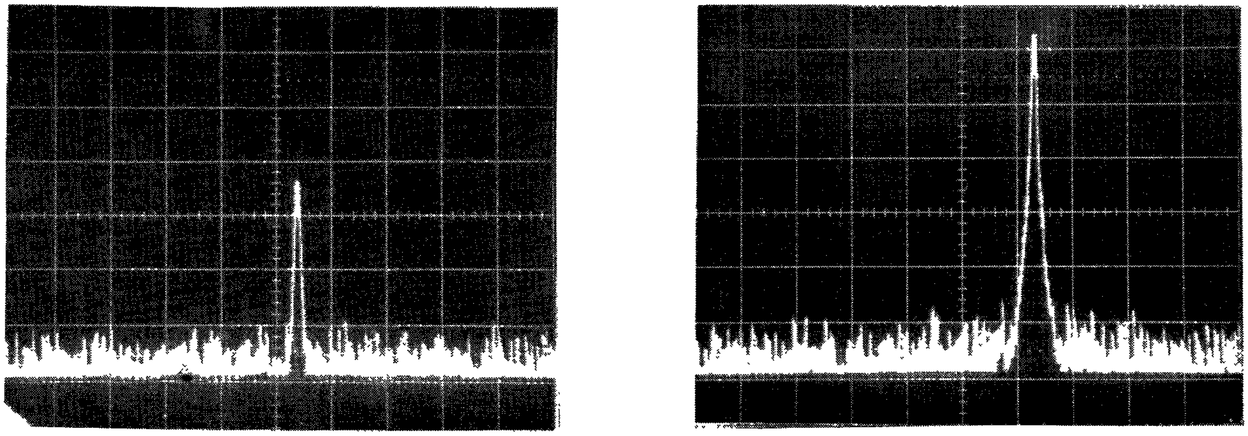


a)



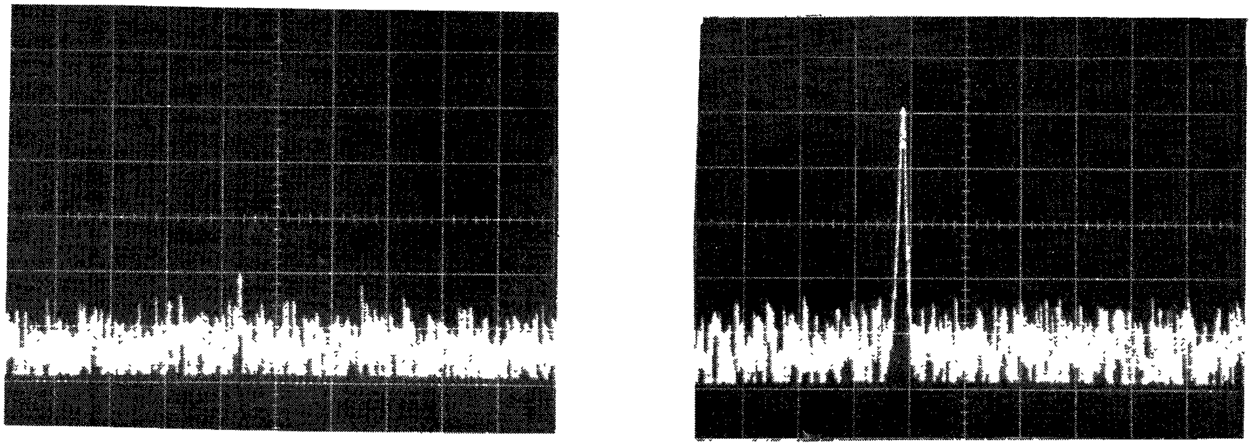
b)

Fig. 4. Detected fundamental signal for a large-signal modulated laser diode at 3.456GHz; a) without optical feedback; b) with optical feedback (The reference level is at -50dBm , and the vertical scale is 10dB/div. The horizontal scale is 0.5KHz/div with a resolution filter of 30Hz).



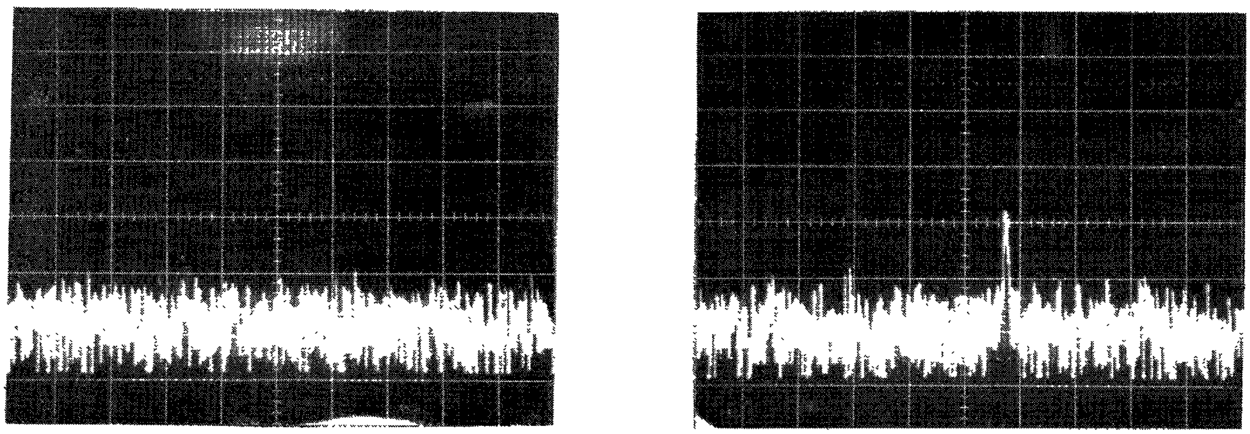
a) b)

Fig. 5. Detected second harmonic signal at 6.912GHz for a large-signal modulated laser diode at 3.456GHz; a) without optical feedback; b) with optical feedback. (The reference level is at -50dBm , and the vertical scale is 10dB/div. The horizontal scale is 0.5KHz/div with a resolution filter of 30Hz).



a) b)

Fig. 6. Detected third harmonic signal at 10.368GHz for a large-signal modulated laser diode at 3.456GHz; a) without optical feedback; b) with optical feedback. (The reference level is at -50dBm , and the vertical scale is 10dB/div. The horizontal scale is 0.5KHz/div with a resolution filter of 30Hz).



a) b)

Fig. 7. Detected fourth harmonic signal at 13.824GHz for a large-signal modulated laser diode at 3.456GHz; a) without optical feedback; b) with optical feedback. (The reference level is at -50dBm , and the vertical scale is 10dB/div. The horizontal scale is 0.5KHz/div with a resolution filter of 30Hz).