Harmonic Enhancement of Modulated Semiconductor Laser with Optical Feedback

Tsang-Der Ni, *Student Member, IEEE*, Xiangdong Zhang, *Member, IEEE*, and Afshin S. Daryoush, *Senior Member, IEEE*

***Abstract*— A harmonic conversion approach for the efficient transfer of power to the desired harmonic of a directly modulated semiconductor laser diode is presented. This approach will help to overcome the limitations of modulation bandwidth that are associated with semiconductor laser diodes. In particular, the transfer of power from the second harmonic to the fourth harmonic of the modulation signal by the establishment of an external cavity matching to the fourth harmonic frequency is shown. The fourth harmonic at 5 GHz is at least 14 dB higher than the fundamental signal level.**

I. Introduction

BECAUSE of the modulation bandwidth limitation of laser diodes, it is hard to realize the directly modulated fiber optic links at millimeter-wave (MMW) frequencies [1]. To solve this problem, various methods, such as large-signal modulation [1], mode-coupling [2] and mode-locking [3], have been tried. Daryoush [1] demonstrated harmonic generation by large-signal modulation of laser. However, this method is limited in bandwidth and conversion efficiency. Lau [2], [4] demonstrated a technique for achieving an ultra-high frequency response (at approximately 70 GHz) beyond the laser modulation bandwidth by taking advantage of intermodal coupling of small cavity laser diodes. This approach has led to a high FM noise level of the generated millimeter-wave signal. Derickson *et al.* [3] used the hybrid passive-active mode-locking technique to generate a short optical pulse which contains high frequency harmonics. While suitable for the optical distribution of the millimeter-wave frequency reference, this method has potentially low conversion efficiency since the spectral power is distributed among many unused harmonic components. In addition, an efficient mode-locking method requires a stringent anti-reflection coating (about 10^{-3} to 10^{-4}) on the laser diode [2], which would be difficult to manufacture.

To provide fiber optic distribution of a MMW carrier, an improvement in high frequency modulation depth [1], a reduction of the difficulty in fabricating devices [3], and low FM noise level of the generated carrier [4] will be required. This letter demonstrates a harmonic conversion method which takes advantage of a laser diode's nonlinearity in presence of an external cavity and which eliminates the need for complicated fabrication techniques.

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The authors are with the Center for Microwave/Lightwave Engineering, E.C.E. Department, Drexel University, Philadelphia, PA 19104.

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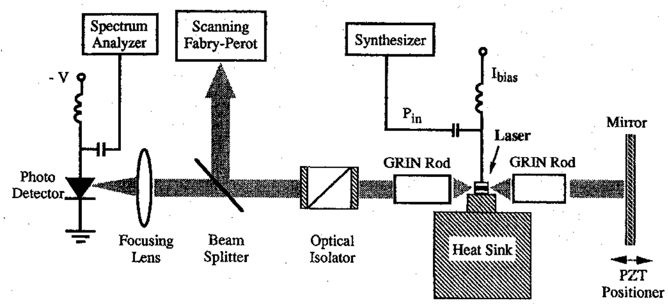

Fig. 1. Experimental setup for measuring the microwave harmonic content and optical spectra of a modulated semiconductor laser with external optical feedback.

This approach combines the ideas of mode locking and subharmonic large-signal modulation at higher frequency to improve the modulation efficiency. A semiconductor laser is modulated by a large-signal around the relaxation oscillation frequency, and an external optical feedback cavity is set up to match to the fourth harmonic frequency of the modulating signal. Therefore, this feedback will effectively enhance the modulated optical signal at fourth harmonic at the expense of the unwanted harmonic signals, such as the second harmonic.

II. Experimental Setup

The objective of the experiment is the selective enhancement of the harmonic components of a laser output through optical feedback. A symmetric InGaAsP BH laser diode ($R_1 = R_2 = 0.3$) manufactured by David Sarnoff Research Laboratory, with an active volume of 500 μm × 20 μm × 0.05 μm, operating at a wavelength of 1355 nm, was used in our experiment. As shown in Fig. 1, the output light from both facets was collimated by the GRIN rod; a mirror with 99% reflectivity, used as an external cavity, was mounted on a micro-positioner, so that external cavity lengths could be adjusted. Part of the outgoing light from the front facet was sampled through a beam splitter and focused on a scanning Fabry–Perot. The other path of the collimated light was focused on an ultra high-speed optical detector. The harmonic contents of the laser diode output were measured on the spectrum analyzer.

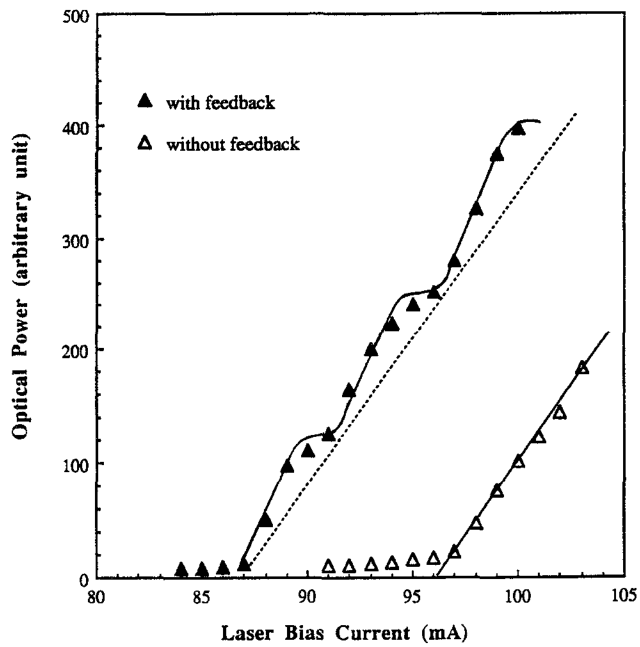

Fig. 2. Measured light output power versus bias current of the laser diode with and without optical feedback.

III. Results and Discussion

The measured threshold current for the laser without optical feedback was $I_{th} = 96$ mA, as shown in Fig. 2. When the external cavity was added, the optical power increased significantly and the threshold current reduced to 86 mA. This amount of decrease in the threshold current indicated a feedback level of −25 dB [5]. A short-period ripple was observed at higher bias current due to the mode competition between the diode cavity and the external cavity [6], [7].

The external cavity length was set ≈3 cm (i.e., $f_{\text{ext}} \approx n \times 5.0$ GHz) in this experiment. The frequency response of laser diode, biased at $I_b = 108$ mA, for the two cases of with and without optical feedback is shown in Fig. 3. The frequency response without the optical feedback indicates a relaxation oscillation frequency at 800 MHz. On the other hand, the one with the optical feedback shows a greatly broadened bandwidth and a sharp resonant peak at 5.08 GHz, corresponding to the reciprocal of the round-trip time along the feedback path. The enhancement at this frequency, clearly outside the relaxation oscillation frequency of the laser without feedback, is caused by coherent optical feedback from the external cavity instead of by an increase in the photon density. We verified this understanding by increasing bias current of the laser without feedback to 122 mA, so that the same laser optical power density was achieved when biased at 108 mA with the optical feedback. We found that the relaxation oscillation frequency increased to only 1.2 GHz, much less than the observed results of 5.08 GHz.

To examine the harmonic conversion process, we conducted experiments under large-signal modulation of the laser diode with feedback. The laser was modulated at a current modulation index of $m = I_{\text{RF}}/(I_b - I_{th}) = 1.45$ at frequency of $f = f_{\text{ext}}/4 \approx 1.298$ GHz. Comparison of the harmonic contents of the laser diode with and without optical feedback

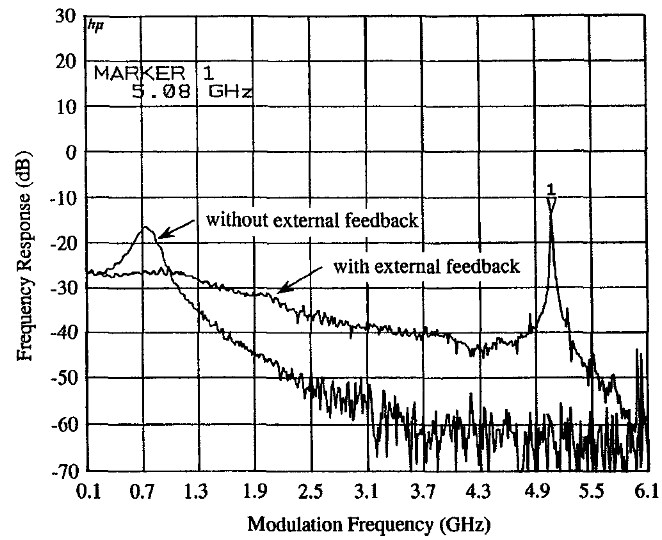

Fig. 3. Frequency responses of the laser diode with and without external feedback. A sharp peak at frequency of 5.08 GHz is clearly seen, corresponding to the external cavity's resonance frequency.

TABLE I
Comparison of the Measured Spectra Power and the Harmonic Contents of Semiconductor Laser with and without Optical Feedback

	Without Feedback	With Feedback	Feedback Phase	Enhancement
	RF Power (dBm)	RF Power (dBm)		Power Level (dB)
Fundamental	-23	-36	$\pi/2$	-13
2nd Harmonic	-33	-41	π	-8
3rd Harmonic	-46	-35	$3\pi/2$	11
4th Harmonic	-57	-22	2π	35
	Pwer Ratio (dB)	Pwer Ratio (dB)	Feedback Phase	Pwer Ratio (dB)
Fundamental	0	0	$\pi/2$	0
2nd Harmonic	-10	-5	π	-5
3rd Harmonic	-23	1	$3\pi/2$	24
4th Harmonic	-34	14	2π	48

The laser was modulated at current mudulation index of 1.45 at frequency of 1.298 GHz. The cable loss was calibrated out from the measured data. The feedback phase and the enhancement of power level are also compared.

are shown in Table I, where the fourth harmonic is enhanced by 35 dB with respect to the without case. Furthermore, the fourth harmonic is 14 dB higher than the fundamental signal with feedback. The second harmonic is reduced by 8 dB from the case of without feedback.

The enhancement for the fourth harmonic at the expense of other harmonics can be explained as follows. Since the external cavity introduces a 2π phase shift of the modulation envelope of light for the fourth harmonic, the fourth harmonic obtains the in-phase enhancement through the feedback optical signal; in contrast, the external cavity introduces a π phase shift to the second harmonic signal, so that this harmonic obtains the cancellation because of the out-of-phase feedback and results in the very low power ratio. For the same reason, the measured fundamental, and third harmonic levels occur in between the fourth and second harmonics due to the $\pi/2$, and $3\pi/2$ phase shifts introduced by external cavity.

IV. Conclusion

For the first time, laser bandwidth has been extended through the harmonic enhancement offered by the addition of an external cavity to an uncoated semiconductor laser. The new method of generating high frequency modulation signal for semiconductor laser diodes with optical feedback described in this letter combines two methods: large-signal modulation and external optical filtering. In this new method, external feedback effectively enhances the desired harmonic content generated by large-signal modulation, as the cavity filters out unwanted frequency components. The result is a desirable high modulation frequency and high RF power conversion efficiency. Through the use of commercial laser diodes with bandwidths exceeding 10 GHz, the advantages offered by this method could be extended to the generation of MMW modulated optical signals.

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