OPTICAL GENERATION OF MICROWAVE SIGNALS USING A DIRECTLY MODULATED SEMICONDUCTOR LASER UNDER MODULATED LIGHT INJECTION

Young-Kwang Seo,[1] **Ajung Kim,**[2] **Jung-Tae Kim,**[1] **and Woo-Young Choi**[1]
[1] Department of Electrical and Electronic Engineering
Yonsei University
Seoul 120-749, Korea
[2] Digital Communication Laboratory
Samsung Advanced Institute of Technology
Suwon 440-600, Korea

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ABSTRACT: *We have experimentally demonstrated a new optical microwave signal generation scheme using semiconductor lasers in a master–slave configuration, in which both lasers are directly modulated. The sidebands of the slave laser are locked to those of the master laser by the simple control of the applied modulation power.* © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 30: 369–370, 2001.

Key words: *optical microwave generation; injection locking; semiconductor lasers*

INTRODUCTION

The optical injection locking technique with semiconductor laser diodes (LDs) can be used in laser chirp and linewidth reduction [1], measurement of laser dynamics [2, 3], wavelength conversion [4], and optical microwave signal generation [5–7]. In particular, the technique of optical microwave signal generation with injection-locked lasers is quite promising for many applications because it can produce high-frequency signals with low phase noise and good stability. In the sideband injection-locking scheme [5–7], the master laser (ML) is electrically modulated, and two of the resulting sidebands having the desired frequency separation are injected into the slave lasers (SLs) and lock them. When these two injection-locked SLs beat each other in the photodiode (PD), the desired microwave signal is generated. The maximum achievable microwave frequency is, however, limited by the maximum sideband separation, which is typically several tens of gigahertz.

In order to overcome this limitation, we propose a new optical microwave signal generation method using two semiconductor LDs in the master–slave configuration. The lasing frequencies of two LDs are detuned so that injection locking does not occur when the light from one laser is injected into the other laser. In this state, two LDs are directly modulated using the same RF source. When the light from the ML is injected into the SL, the SL can be injection locked to the ML if any of the ML sidebands is placed within the locking range to any of the SL sidebands. This allows a wider separation of the locked sidebands since the sidebands of two lasers are used instead of one laser, as in the typical sideband injection-locking method; furthermore, the lasing frequencies of these two lasers can be significantly separated. In this paper, we report the experimental demonstration of this method.

EXPERIMENT

Figure 1 shows the experimental setup used for our investigation. Two commercially available DFB laser diodes are used that have an emission wavelength around 1550.6 nm. One DFB LD (Lucent D2570H) is used as the ML, and the other DFB LD with no internal isolator (Samsung SDL24) as the SL. The ML light is injected into the SL through a polarization controller and an optical circulator (isolation better than 40 dB). By controlling the ML operating temperature, the ML lasing frequency is set about 14 GHz higher than the SL frequency. The lasing frequency separation does not allow injection locking initially. Both lasers are then RF modulated by a single RF source (HP 83620A) whose power is divided by a 3 dB power splitter. The modulation frequency (f_M) is set at 3 GHz, which is the cutoff frequency of the bias-T used in our experiment. At the fixed f_M, the modulation power (P_m) ranging from -15 up to 10 dBm with increments of 0.5 dB is applied to each bias-T. The SL output is amplified by an erbium-doped fiber amplifier, and then divided into two paths. In one path, the signal is measured by a Fabry–Perot (F–P) interferometer (FSR = 75 GHz), and in the other path, the beat signals produced in a *p-i-n* detector (bandwidth = 45 GHz) are measured by an RF-spectrum analyzer. The occurrence of injection locking between sidebands of the ML and SL can be identified by observing the linewidth narrowing of the beat signal in the RF-spectrum analyzer at the frequency corresponding to the peak lasing frequency separation between the ML (f_{ML}) and SL (f_{SL}).

Figure 2(a), (b) shows the SL output under the ML light injection measured by the F–P interferometer and RF-spectrum analyzer, respectively. Figure 2(a, i) shows the SL output under the ML light injection when no electrical modulation is applied. The lasing frequency separation is about 14 GHz. Two peaks beside the ML and SL lasing peaks are the four-wave mixing (FWM) modes in which the ML and SL light work as a probe and pump, respectively. Typically, the FWM beat signals have very large linewidths, as can be seen in Figure 2(b, i), and they have limitations for practical applications [8]. In our experiment, the beat signal has a linewidth of about 4 MHz. The reason that the ML peak is smaller than the FWM peaks in Figure 2(b, i) is due to the interference effect between the back-reflected ML light and the SL output light.

When a P_m of -3 dBm is applied to each LD, the SL peak frequency (f_{SL}) becomes shifted to the lower frequency, as can be seen in Figure 2(a, ii). In the figure, the broad beat

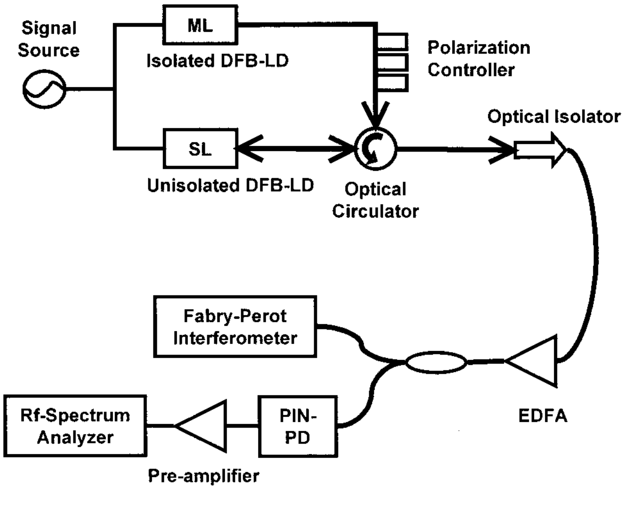

Figure 1 Experimental setup

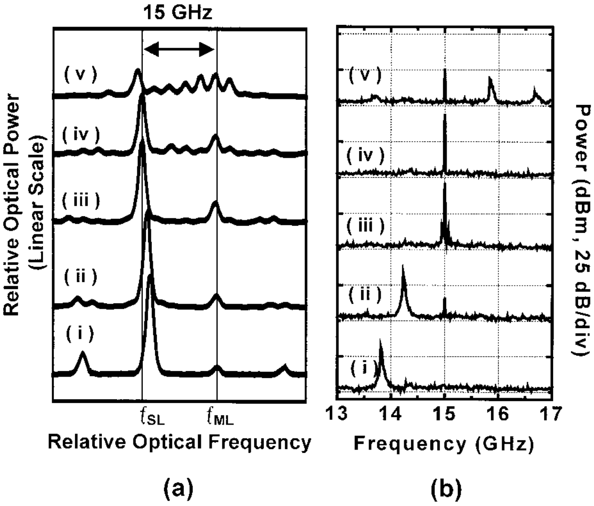

Figure 2 Optical spectra observed by the F–P interferometer (a) and beat signal spectra by RF-spectrum analyzer (b) for no modulation (i), and $P_m = -3$ dBm (ii), 2 dBm (iii), 4 dBm (iv), and 8 dBm (v)

signal in the RF spectrum indicates that locking has not occurred. The sharp peak at 15 GHz is the higher order harmonic response of the SL modulated at 3 GHz.

For a P_m of 2 dBm, the frequency separation between f_{ML} and f_{SL} becomes 15 GHz, and clear linewidth narrowing for the beat signal is observed as in Figure 2(a, iii) and (b, iii). Even if P_m is further increased to 4 dBm, the SL does not show any shift in f_{SL}, and maintains a sharp beat signal, as can be seen in Figure 2(a, iv) and (b, iv). This indicates that the SL remains locked. When P_m is further increased to 8 dBm, as seen in Figure 2(a, v) and (b, v), the SL shows an additional shift in f_{SL}, and the beat signal becomes broad again, indicating that the SL is now unlocked. The reason for the shift in f_{SL} with P_m is not identified, and is under investigation.

Figure 3 shows the single-sideband phase-noise measurement for the beat signal when the SL is locked [Fig. 2(b, iv)]. The measured phase noise is -96 dBc/Hz at an offset frequency of 100 kHz. This, compared with the unlocked linewidth of 4 MHz for the unlocked beat signal in Figure 2(b, i), shows a significant reduction in the beat signal linewidth. In our experiment, the locking condition is maintained for a range of P_m from 2 to 5.5 dBm.

CONCLUSION

We have experimentally demonstrated a new optical microwave signal generation scheme using semiconductor lasers in a master–slave configuration under electrical modulation. The SL sidebands are locked to those of the ML by the simple control of the applied modulation power. This allows a wider separation of the locked sidebands since the sidebands of two lasers are used instead of one laser, and the lasing frequencies of these two lasers can be significantly separated. We believe that this method is useful for generating low-phase-noise microwave signals with very high frequency.

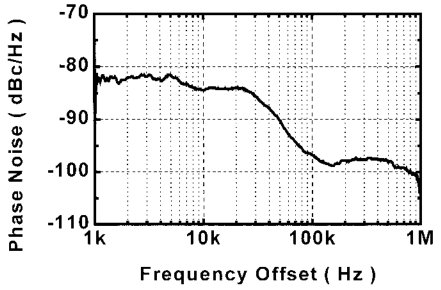

Figure 3 Single-sideband spectrum measurement of Figure 2(b, iv)

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COMPACT PENTAGON MICROSTRIP ANTENNA WITH CIRCULAR POLARIZATION

Horng-Dean Chen[1] **and Wen-Shyang Chen**[1]
[1] Department of Electronic Engineering
Cheng-Shiu Institute of Technology
Kaohsiung, Taiwan 833, R.O.C.

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ABSTRACT: *By embedding a group of four bent slots in the equilateral-pentagon patch and introducing a peripheral cut at the patch boundary, a compact pentagon microstrip antenna with circularly polarized (CP) operation can be implemented using a probe feed. Results have been obtained that, for a given operation frequency, the antenna size reduction of the proposed design can be as large as 41% as compared to the regular-size CP equilateral-pentagon microstrip antenna. Details of the design considerations are described, and measured CP characteristics are presented.* © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 30: 370–372, 2001.

Key words: *pentagon microstrip antenna; compact circularly polarized*