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Optoelectronic Phase-Tracking and Waveform Display of Microwave Signals up to 8 GHz Using Gain-Switched Laser Diodes

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We present a new, more versatile scheme for maintaining phase coherence between optical probe pulses and microwave signals under test in a laser-diode-based optoelectronic sampling system. This approach takes advantage of the relative ease of changing the repetition rate of the gain-switched laser diode (GSLD). The microwave signal to be sampled is used as the clock signal for phase-locking of a voltage controlled-oscillator (VCO) which drives the GSLD. Phase-tracking and display of waveforms at frequencies up to 8 GHz have been realized. It is also shown that lower phase noise sidebands for the phase-locked VCO can be realized by locking the higher harmonics of the laser pulse to the microwave clock.

KEYWORDS: laser and laser applications, electro-optic sampling, harmonic mixing, optoelectronic phase-locked loop, optical-microwave interactions

1. Introduction

During the past few years, optoelectronic sampling techniques[1,2] have been demonstrated to be powerful tools for characterization of high speed electronic devices and circuits. To make use of the sampling techniques, synchronization and signal averaging methods are required to achieve both high signal-to-noise ratio and satisfactory temporal resolution. In some experiments, the electrical waveform under study and the probing optical pulses are derived from the same source. As a result, synchronization is not a problem. For the measurement of high speed digital or microwave monolithic integrated circuits (MMICs), however, the circuit element under test is best examined by employing digital data sequences or microwave sinusoids originated from internal oscillators. In those cases, timing synchronization or phase coherence between electrical signals and optical probe pulses must first be established.

Previously, Rodwell *et al.*[3] employed two electronically phase-locked synthesizers for driving the device under test and the mode-locker of an actively mode-locked Nd:YAG laser, respectively. This approach requires the use of high quality signal generators and complicated feedback techniques to achieve extremely low phase jitter. Recently, we have reported compact laser-diode-based optoelectronic phase lock loops (OEPLL)[4-6] for this application. The key element of the OEPLL's can be either a laser-diode-activated photoconductive switch or an electro-optic sampler which functions as an optoelectronic harmonic mixer (OEHM) for intermixing microwave signal from the target voltage-controlled-oscillator (VCO) and the optical probe pulses. Similar techniques have first been reported with main-frame actively mode-locked laser systems by Li *et al.*[7] In practice, the microwave signal to be probed on a monolithic microwave integrated circuit (MMIC) might not be generated from a VCO. To solve this problem we take advantage of the relative ease of changing the repetition frequency of gain-switched laser diodes (GSLD). It is shown for the first time in this letter that synchronization and waveform measurement can be achieved by using the microwave signal to be probed as the clock to allow phase tracking of a VCO which drives the laser diode.

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2. Experimental Methods

The experimental apparatus is shown in Fig. 1. It is comprised of a microwave circuit under test, an electro-optic harmonic mixer (EOHM), phase lock loop (PLL) electronics, and a gain-switched laser diode (GSLD). In this experiment, the GSLD employed is a InGaAsP/InP laser diode (Oki, model OL303A-100, $\lambda=1.3\,\mu$m). A synthesized sweeper (HP 83620A) simulating the internal oscillator of an MMIC provides microwave signals which are fed to the EOHM and acts as the clock to be tracked. The EOHM used is a typical arrangement of reflection-mode electro-optic sampler (EOS) with a GaAs microstrip transmission line. The microwave clock signal at frequency f_m is mixed with the fundamental or higher harmonics of the optical

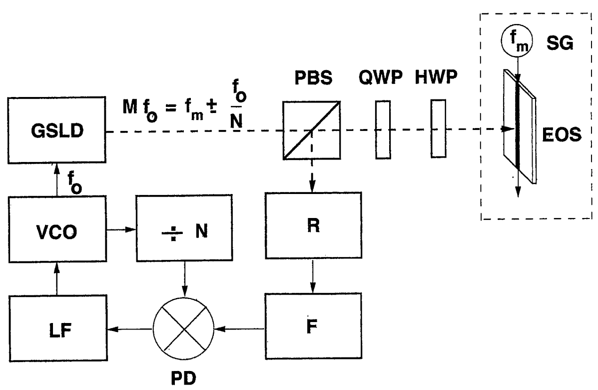


Fig. 1. Schematic of the experimental apparatus. GSLD: gain-switched laser diode, VCO: voltage-controlled oscillator, PBS: polarizing beam splitter, QWP: quarter wave plate, HWP: half wave plate, R: optical receiver, F: bandpass filter, ÷N: frequency devider, PD: phase detector, LF: loop filter, SG: signal generator, EOS: electrooptic sampler.

pulse train and down-converted to the offset or intermediate frequency (IF) at the output of an optical receiver. A bandpass filter then selects the desired IF signal for phase locking. The PLL consists of a reference IF with a prescaler (used for dividing the frequency of VCO by N), a phase detector, a loop filter, and the VCO (HP8640B). The GSLD is driven by the VCO. When the phase-locking condition is achieved, the repetition frequency of the optical pulse train should be $f_0=(f_m \pm f_{IF})/M$, where $f_{IF}=f_0/N$, M and N are integers.

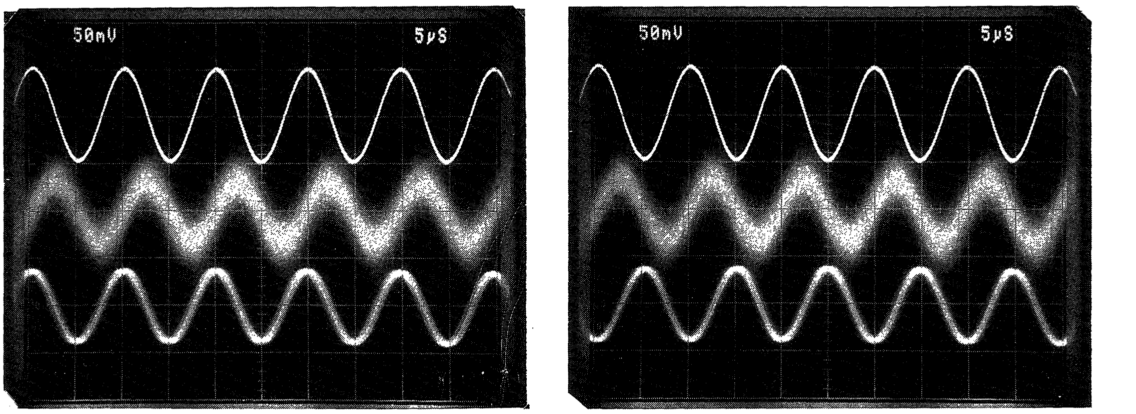
3. Results and Discussion

With the GSLD operating at $f_0 \approx 250$ MHz, a pulse duration of ≈ 50 ps and an average power of 0.73 mW, we find that the IF signal at 100 kHz is 2 mV_{rms} in response to a microwave signal power of 16 dBm at 250 MHz. The average detected photocurrent is 30 μA. This corresponds to a throughput from RF to IF of -57 dB. The IF signal decreases as the frequency of the microwave signal increases. This can be explained by the bandwidth limitation imposed by the laser pulses. To reduce phase noise, a bandpass filter of which the center frequency can auto-track that of the reference input is utilized. The passband (between 70% pass points) of the filter is chosen to be 1/5th that of the center frequency. With the filter operational, the rms noise drops to about 420 μV. The rms noise density for the IF signal is 3 $\mu V/\sqrt{Hz}$. A gain-variable amplification stage follows the filter before the IF signal is fed to the phase detector (PD). With this system, the phase of the microwave signal up to 8 GHz has been successfully tracked by tuning the repetition frequency of the GSLD. To sample its waveform, the microwave signal is sent to a photoconductive switch (PCS) and probed by optical pulses from another GSLD ($\lambda=0.8$ μm), driven by the same VCO in the OEPLL, via an optical delay line. A low-frequency oscilloscope can then be used to monitor the waveforms of the reference IF source, the output of the signal IF amplifier, and that of the 8 GHz microwave signal as displayed by the PCS via a low frequency replica.[8] The time base of the oscilloscope is triggered by the reference IF. If phase tracking is achieved, clean waveforms from these signals can be observed. This is illustrated in Fig. 2(a). Figure 2(b) displays the same waveforms except that the trace from the PCS is obtained by probe pulses optically delayed by 62.5 ps (one half the period of an 8 GHz sinusoid) with respect to that for lower trace in Fig. 2(a). From Fig. 2(a) and 2(b), we can determine that the frequency of the microwave signal under test is 8 GHz. This is in good agreement with the real signal applied. For the data in Fig. 2, SNR ≈ 1. The signal-to-noise ratio can be improved by increasing the average optical power or employing shorter optical pulses. Investigation of the sideband spectra for the VCO reveals that as the frequency of the microwave signal increases, the phase-locked VCO exhibits lower and broader phase noise spectrum. For example, the signal-to-sideband phase noise density of the phase-locked VCO at 250 MHz (Fig. 3(a)) is about -30 dBc/Hz at a frequency offset of 200 Hz. It is about -64 dBc/Hz at a frequency offset of 800 Hz for the microwave signal near the 32th harmonics, or 8 GHz (Fig. 3(b)). These results indicate that, to reduce phase noise, it is desirable to phase-lock the higher harmonics of the optical pulses generated by VCO-driven GSLD to the microwave signal.

We emphasize that, in the present scheme, phase-locking can be accomplished without requiring any electrical contacts between the microwave test circuit and other components of the sampling system. This is in contrast to conventional electro-optic sampling systems which employ electronic or optoelectronic phase-locking techniques. It is thus particularly useful for measurement of devices with internal oscillators.

4. Conclusions

We have demonstrated a novel laser-diode-based optoelectronic phase tracking scheme which can be applied for contactless electro-optic sampling of electrical signals within MMICs. Microwave signals up to 8 GHz are used as the clock signal to be tracked and sampled



(a) (b)

Fig. 2. (a) Waveforms of the reference IF (upper trace), signal IF down-converted from microwave signal at 8 GHz (middle trace), and sampled low-frequency replica of the IF from the PCS (lower trace). (b) the same waveforms as in (a) except that the sampled signal of the lower trace is probed by a pulse train optically delayed by 62.5 ps with respect to that of (a).

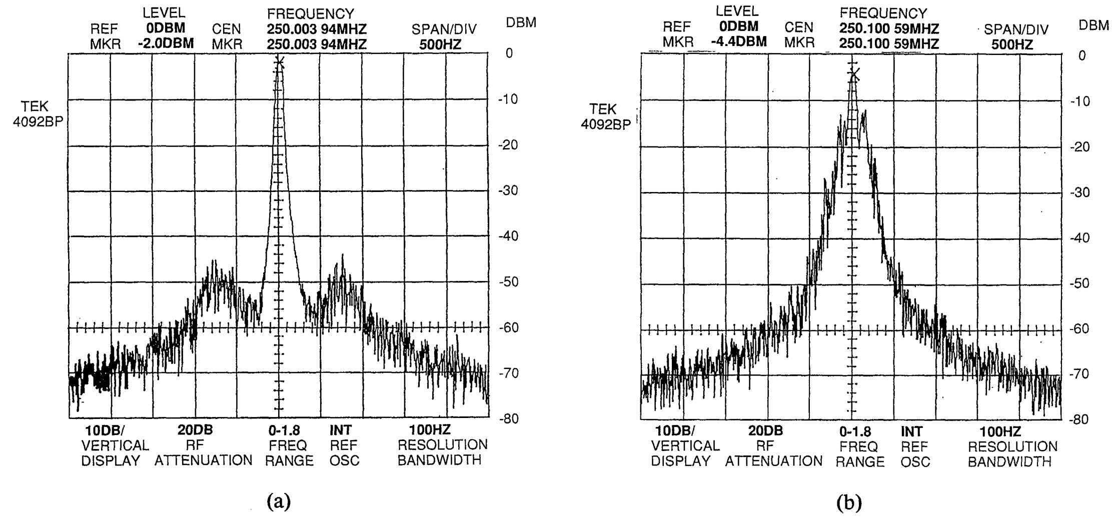


Fig. 3. Phase noise sideband spectra of the VCO phase-locked to microwave clock signals at (a) 250 MHz (b) 8 GHz.

by optical pulses generated from two GSLDs driven by the same VCO. Examination of the power spectra for the phase-locked VCO indicates that, for the same SNR, lower phase noise sideband is achieved by locking the higher harmonics of the laser pulse to the microwave signal in heterodyne phase lock system. With the availability of ultrashort optical pulse generated from GSLD, our approach is thus a promising method for tracking the phase of electrical signal beyond millimeter wave range.

Acknowledgment

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