Broadband and Real-Time Waveform Sampling Using Optic-Microwave Phase-Locking

S. L. Huang,* H-L. A. Hung,† and Chi. H. Lee*

* Electrical Engineering Department, University of Maryland, College Park, MD 20742
† COMSAT Laboratories, Clarksburg, MD 20871

Abstract

A real-time, 100-GHz, high-fidelity photoconductive sampling system has been demonstrated. The system provides a 4-ps time resolution, and $5\text{-}\mu V/\sqrt{Hz}$ sensitivity. Potential application of this technique is the real-time characterization of monolithic microwave/millimeter-wave integrated circuits with bandwidths higher than a conventional network analyzer.

I. Introduction

Optical sampling techniques offer a much higher measurement bandwidth than that obtained from a conventional electronic sampling scope and network analyzer [1],[2]. Real-time use of these optical techniques using electro-optic effect can be achieved through optic-microwave intermixing [3]. A new microwave waveform replica technique [4] has also been demonstrated which employs both optic-microwave phase-locking (OMPL) and photoconductive (PC) sampling. Using this technique, any free running microwave source can be phase-locked to the mode-locked laser, and its waveform can be displayed by a low-frequency replica on a conventional low-bandwidth oscilloscope. Fast PC response time and careful selection of intermediate frequency are essential in order to achieve high measurement bandwidth, precise time resolution, and low distortion in the waveform replica. In this paper, a real-time waveform sampling system with a bandwidth exceeding 100 GHz, a time resolution of 4 ps, and sensitivity of $5\text{-}\mu V/\sqrt{Hz}$ is described.

II. Experiment

The optical system used is a continuous wave mode-locked Nd:YLF laser which generates 50-ps pulses at a 76-MHz repetition rate. These laser pulses are compressed to 3 ps, followed by frequency-doubling to green light. The light is then split into two beams for phase-locking and waveform sampling.

Figure 1 is a schematic diagram of the optic-microwave waveform sampling system. The laser is applied to a PC switch in which the gallium arsenide (GaAs) substrate has been deliberately ion-damaged to reduce the carrier lifetime. Thirty V DC is superposed on a voltage-controlled oscillator (VCO) to bias the PC switch, and the intermixed signal is then amplified through an IF amplifier with a gain of 75 dB. The intermediate frequency phase is compared to a reference signal which is frequency divided from the laser mode-locker frequency (i.e. fixed frequency from a synthesizer). The error signal is then delivered through a loop filter to the VCO. This phase-locking scheme can be applied to any free-running oscillator.

The value of the intermediate frequency (f_{if}) is based on a tradeoff between time resolution and phase noise. Since time resolution is equal to $f_{if}/(f_{mw} \times f_l)$, the lower the f_{if}, the better the time resolution (f_{mw} is the frequency of microwave oscillator, and f_l is the laser pulse repetition frequency). However, when the f_{if} falls in the laser noise band, phase-locking of the source signal becomes more difficult, and the subsequently sampled waveform is noisy. Low distortion is also a consideration in selecting the intermediate frequency. In general, the following criterion should be

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satisfied to avoid interference from the laser mode-locker frequency ($f_l/2$) :

$$f_{if} < \frac{f_l}{2}\frac{f_{mw}}{f_{max}} \tag{1}$$

where f_{max} is the highest measurement bandwidth, which is 100 GHz in the present case.

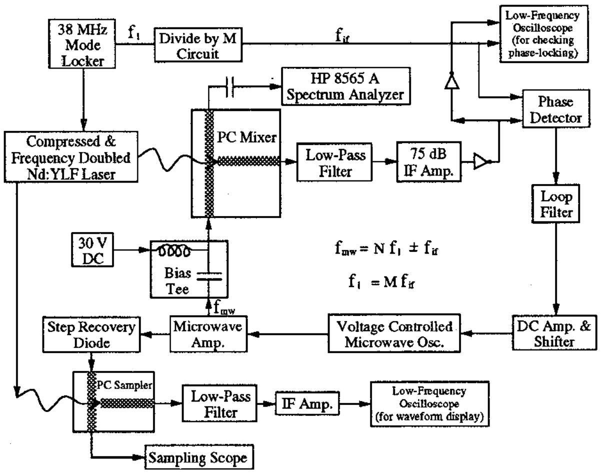


Fig. 1. *Schematic diagram of the optic-microwave waveform sampling system.*

Taking all the above considerations, the f_{if} was selected to be 300 kHz. This gives 4-ps time resolution. After the microwave source was phase-locked to the laser pulses, the output signal was delivered to another fast PC sampling switch for waveform display. The response of the PC switch measured by PC sampling is shown in Figure 2. The autocorrelated pulse width is measured to be 14.5 ps, which decreases to 10 ps after deconvolution. This electrical pulse contains frequency components up to about 100 GHz. Since the f_{mw} was selected to be 1 GHz, signals of up to the 100th harmonic of the intermediate frequency (which is 30 MHz) should be detected on a 100-GHz sampling system.

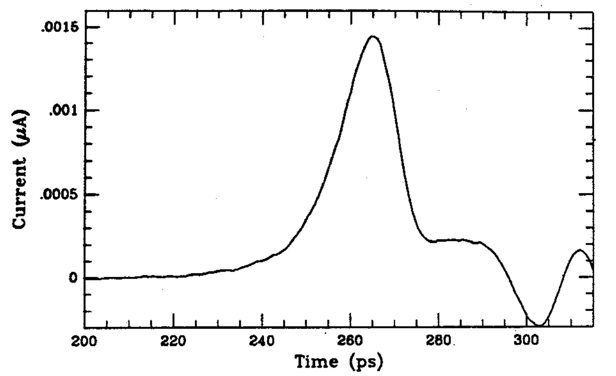


Fig. 2. *Autocorrelation measurement of response of the PC switch.*

III. Results and Discussion

The phase-locked 1-GHz signal is shown in Figure 3. To generate a signal of high frequency content, two approaches can be used. A step recovery diode or a nonlinear transmission line [5] can be driven by this 1-GHz signal to achieve ultrahigh frequency content. In this experiment, a step recovery diode was used, and the output waveform was detected by both a conventional sampling scope (TeK11802/SD-24, 20-GHz bandwidth) and the second PC switch for waveform sampling. Figure 4 depicts the waveforms sampled by both methods. The optical sampling system possesses a higher measurement bandwidth, as indicated by the inset in Figure 4. The measured pulse widths using both the optical sampling technique and a conventional sampling scope, were 40.2 ps and 54.8 ps, respectively.

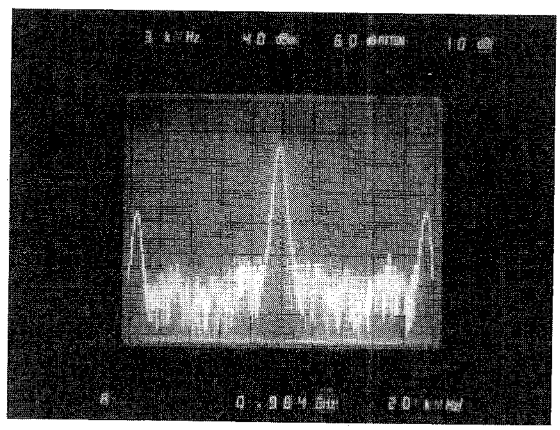


Fig. 3. *Phase locked 1-GHz signal with 300-kHz intermediate frequency.*

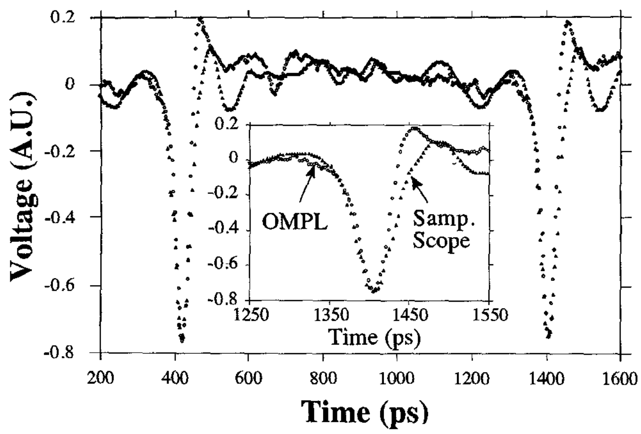


Fig. 4. *Sampled waveforms by optic- microwave phase-locking and electronic sampling scope.*

To further increase system sensitivity, noise sources should be identified. We first estimated the potential noise contribution in the optic-microwave phase-locked loop. The noise was determined to come from three sources as shown in Figure 5. The dependence of θ_0 on θ_{rn}, θ_{vcon}, and θ_{ln} is shown as the following equations. For a linear system, the superposition principle can be used to find the total θ_0.

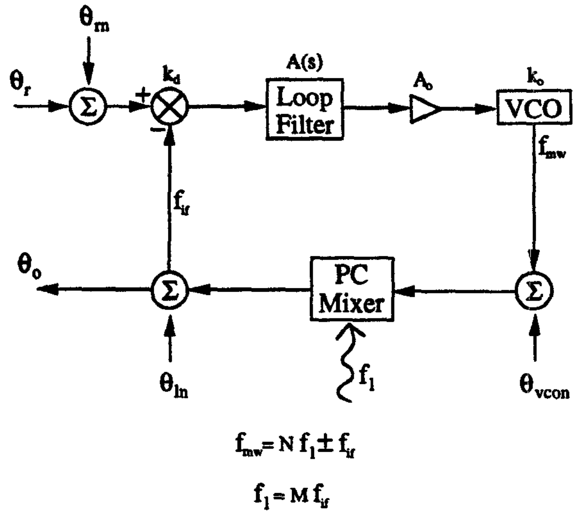
$$\left.\frac{\theta_0(s)}{\theta_{rn}(s)}\right|_{\theta_r=\theta_{vcon}=\theta_{ln}=0} = \frac{1}{1+\frac{MN\pm1}{k_d k_0 A_0 A(s)}s} \qquad (2)$$

$$\left.\frac{\theta_0(s)}{\theta_{vcon}(s)}\right|_{\theta_r=\theta_{rn}=\theta_{ln}=0} = \frac{1/(MN\pm1)}{1+\frac{k_d k_0 A_0 A(s)}{MN\pm1}\frac{1}{s}} \qquad (3)$$

$$\left.\frac{\theta_0(s)}{\theta_{ln}(s)}\right|_{\theta_r=\theta_{rn}=\theta_{vcon}=0} = \frac{1/M}{1+\frac{k_d k_0 A_0 A(s)}{MN\pm1}\frac{1}{s}} \qquad (4)$$

The measured phase noise of the mode locker, laser, and VCO at 10 kHz from their center frequencies is -96, -94, and -82 dBc/Hz, respectively. Therefore, phase noise of the laser comes mainly from the mode-locker. According to Eq. 3 and 4, the noise from the VCO should be divided by a factor of $(N \pm \frac{1}{m})$ to compare the relative effect of the VCO and the laser phase noises at the IF. The equivalent VCO phase noise becomes -102 dBc/Hz and is less than laser phase noise. Combining these two results, we note that the major noise source in the phase-locked loop is from the mode-locker. When the phase-locked signal is delivered to the second PC switch, laser intensity noise (below 1 MHz) may leak through the PC switch and interfere with the intermediate frequency. Depending on amplitude of the phase-locked microwave signal, the system noise may be dominated by either mode-locker or laser intensity noise on the second PC switch. In this experiment, the sensitivity of the PC switch was measured to be about 5 $\mu V/\sqrt{Hz}$, which is more than an order of magnitude better than electro-optic sampling.

Although it is difficult to eliminate low- frequency noise from the laser, a high-pass filter with a cutoff frequency set at 300 kHz can be used to filter out the major part of the laser intensity noise.



- θ_r : Input signal (phase of reference frequency)
- θ_o : Output signal (phase of intermediate frequency)
- θ_m : Phase noise of reference frequency
- θ_{vcon} : Phase noise of VCO
- θ_{ln} : Phase noise of laser repetition rate
- k_d : Phase comparator conversion gain (V/rad.)
- k_o : VCO conversion gain (rad./V-sec)
- A_o : Amplifier gain
- A(s) : Transfer function of loop filter

Fig. 5. *Signal flow diagram.*

IV. Conclusion

The interaction between ultrafast optics and a microwave signal offers a number of potential new applications. A 100-GHz bandwidth sampling system has been developed with low distortion, low noise, and high time resolution. This system is simple and economical, and could be further enhanced to perform network analysis with a measurement bandwidth higher than a conventional network analyzer. Phase control of the microwave signal is also possible, since the microwave oscillator is slaved to the laser pulses through phase-locking.

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