Ultrafast Optoelectronic Sample-and-Hold Using Low-Temperature-Grown GaAs MSM

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***Abstract*—We demonstrate 20-GHz input bandwidth of an optoelectronic sample-and-hold circuit using optically triggered metal–semiconductor–metal switches made of low-temperature-grown GaAs. Linearity $\geq$ 4 effective-number-of-bits and an estimated 3-dB bandwidth of up to $\sim$63 GHz are observed for the sample-and-hold process, making the device a potential candidate for moderate resolution, high-speed sampling applications.**

***Index Terms*—Analog-to-digital (A/D) conversion, low-temperature (LT)-grown GaAs, metal–semiconductor–metal (MSM) devices, optical data processing, sample-and-hold circuits.**

I. Introduction

CONVENTIONAL analog-to-digital (A/D) converter technology can not readily be scaled to applications requiring tens of giga-samples/second at even moderate numbers of bits, raising questions on the fundamental limitations of A/D conversion [1]. In such limits, timing jitter is a key parameter. This observation has, in part, led to the idea of combining the intelligence of electronics with the speed and timing precision of photonics to obtain superior performance in a hybrid photonic A/D conversion system [2]–[4].

Previously, we proposed a photonic A/D conversion system using a sample-and-hold scheme with low-temperature (LT)-grown GaAs metal–semiconductor–metal (MSM) switches [5]. The switch is attached to a transmission line and samples the input electrical signal onto a hold capacitor when optically triggered by a short-pulse laser. An electrical A/D converter then extracts this sampled data. By time-interleaving a number of these channels, the aggregate sampling rate is increased. Precision of the clocking mechanism is critical to the performance of high bandwidth time-interleaved A/D conversion systems, making the extraordinary timing accuracy of mode-locked laser pulses an enabling technology for such systems [2]. The short carrier trapping time and relatively high mobility of the LT GaAs material provide optically triggered broad-band sampling capability with good sensitivity [6]. In this way, the larger bandwidth requirements are placed on the first stage sample-and-hold, freeing the electrical A/D converter to operate at a much slower speed. Using a sample-and-hold test circuit, we previously demonstrated 5.7 effective-number-of-bits (ENOB) under dc input conditions, with a sampling gate width of less than 2 ps. In addition, we incorporated a differential device configuration, eliminating feedthrough noise on the hold capacitor.

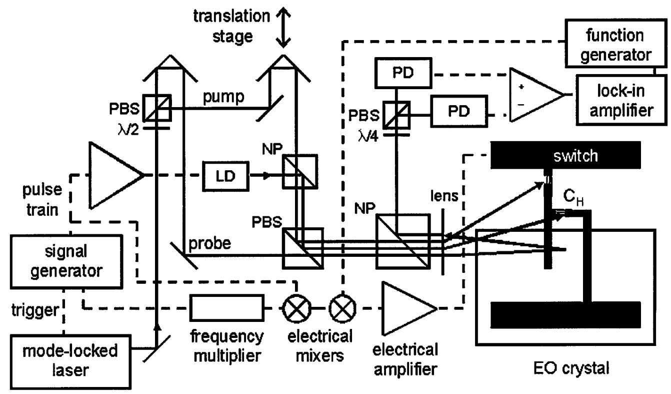

Fig. 1. Schematic of experimental setup. Solid lines represent optical beams, dotted lines represent electrical connections. Frequency multipliers create a harmonic of the laser trigger, which is used as the input to the sample-and-hold. PD—photodetector. PBS—polarizing beam splitter. NP—nonpolarizing beam splitter. LD—laser diode.

In this letter, we present high-speed characterization of the sample-and-hold circuit. We demonstrate $\geq$ 4 ENOB accurate sampling of 2-, 10-, and 20-GHz input sinusoids with an optical switching energy of 250 pJ. The frequency response of the sample-and-hold process was measured, exhibiting a switching-energy-dependent 3-dB bandwidth of up to $\sim$63 GHz.

II. Experimental Setup

The sample-and-hold structure was made by attaching two MSM devices in series across the signal and ground lines of a transmission line [Figs. 1 and 2(a)]. The first device serves as the switch, while the second serves as the hold capacitor (C_H). Both MSMs consist of a 1-μm finger spacing, 1-μm finger width, interdigitated structure covering a $\sim$20 $\times$ 20 μm area. MSM size was chosen such that the hold capacitance is $\sim$20 fF, the approximate size of the postsample-and-hold load of the eventual system. The switch MSM was chosen to be the same size. The entire structure was made by depositing titanium–gold contact metal for both MSM and transmission line patterns on an LT GaAs layer, grown on a semi-insulating GaAs substrate. The LT GaAs layer was grown at a substrate temperature of 250 °C and postgrowth annealed at 700 °C for 10 min using a rapid thermal annealer.

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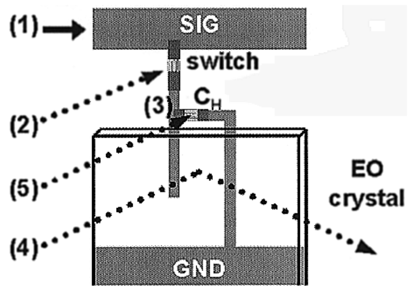
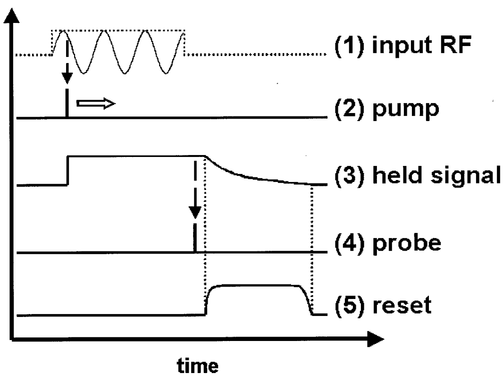


(a)



(b)

Fig. 2. Timing diagram for EO sampling measurement. The location of the appropriate signal is designated in (a) by the matching number of the corresponding trace in (b). All signals are phase-locked with relative phase of the pump pulse being changed. For simplicity, the held signal does not indicate feedthrough effects.

In order to minimize loading of the circuit, time-resolved electrooptic (EO) sampling [7] was used to measure the voltage across the hold capacitor. A schematic of the experimental setup is shown in Fig. 1. The titanium–sapphire mode-locked laser provided ~150-fs full-width at half-maximum pulses at an ~80-MHz repetition rate. A photodetector monitoring the laser output created an electrical trigger signal, which was fed into the trigger detection circuit of an electrical signal generator. An 80-MHz sinusoid from this signal generator was then fed into various frequency multipliers, which were used to generate the input 2-, 10-, and 20-GHz sinusoids (25th, 125th, and 250th harmonics) phase-locked to the optical pulse train. Electrical mixers (Marki Microwave M1-0420, hp 11665B) allowed windowing of the input signal and lock-in detection. Reset pulses were created by directly modulating a Fabry–Pérot semiconductor laser diode with a phase-locked electrical pulse train. The output optical pulses were ~5 ns wide with 190 pJ/pulse. The rest of the diagram shows a conventional pump–probe setup.

Fig. 2 shows a timing diagram for the measurement. The location of the appropriate signal is designated in Fig. 2(a) by the matching number of the corresponding trace in Fig. 2(b). The pump pulse closes the switch MSM, sampling the input radio frequency signal onto the hold capacitor. The probe pulse then samples the held voltage via the Lithium Tantalate EO crystal, placed across the ends of the hold capacitor. The reset pulse, positioned during the off period of the input signal, discharges the hold capacitor to ground by triggering the hold capacitor MSM, returning the circuit to initial conditions.

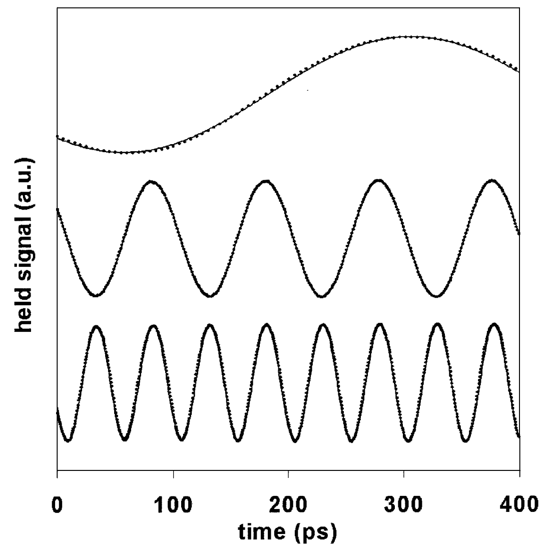


Fig. 3. Results of EO sampling measurement for a switching energy of 250 pJ. The top, middle, and bottom traces show the 2-, 10-, and 20-GHz results, respectively. Dots indicate sampled points with solid lines showing pure sinusoids matched to data using a minimum mean squared error fit. Each scan took several minutes to complete.

By varying the pump-pulse phase relative to all other inputs, different points of the input signal are sampled enabling a dynamic input sample-and-hold measurement. For simplicity, feedthrough effects are not included in this figure. Our previous work shows how such feedthrough noise can be cancelled [5].

III. Results and Discussion

Results of the EO sampling measurement are shown in Fig. 3 for a pump-switching energy of 250 pJ. Input signals for all frequencies were made approximately equal (3~4 V peak-to-peak) by measuring the input signals electrooptically above the sample-and-hold circuit and tuning the electrical signal generator. The top trace is 2 GHz, the middle trace 10 GHz, and the bottom trace 20 GHz. Dots indicate sampled points with solid lines showing pure sinusoids matched to data using a minimum mean squared error fit. The data exhibits 4.8, 5.5, and 4.0 ENOB, respectively, with the two lower values reflecting distortion of the input signals.

Good linearity of the sample-and-hold was also seen for lower switching energies, although an increase in distortion was observed as the energy was decreased. The inset of Fig. 4 shows results for the 10-GHz signal sampled with a pump energy of 62 pJ. The data exhibits 4.6 ENOB. The held signal amplitude as a function of pump energy is plotted in Fig. 4 for the 10-GHz input. The amplitude saturates to a value ~70% of the signal amplitude measured without reset. This indicates switch saturation not allowing the hold capacitor to charge to the full input voltage during sampling. Similar behavior was seen for the 20-GHz input.

Due to the short carrier lifetime of the LT GaAs material, only photogenerated carriers near the electrodes of the MSM contribute significantly to the held signal, the rest of the carriers being lost mainly to traps and recombination. With the near band-edge wavelength (850 nm) of the input pulse, large pulse

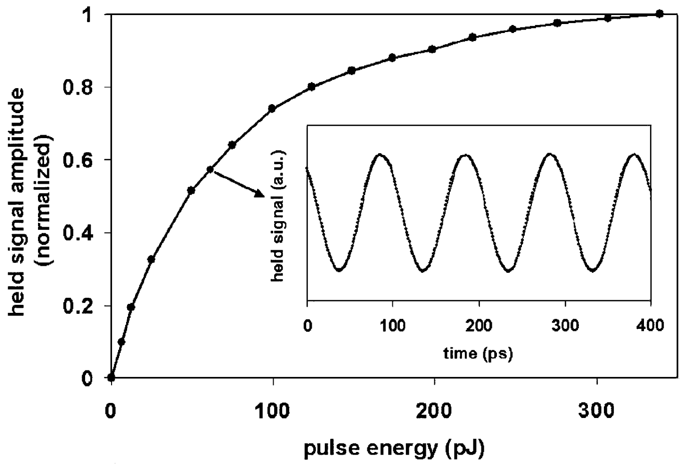


Fig. 4. Held signal amplitude versus pump-pulse energy for 10-GHz input. Inset shows held signal (dots) for a 62-pJ switching energy matched to a pure sinusoid (solid line). The good fit demonstrates the linearity of the sample-and-hold for a large range of pulse energies.

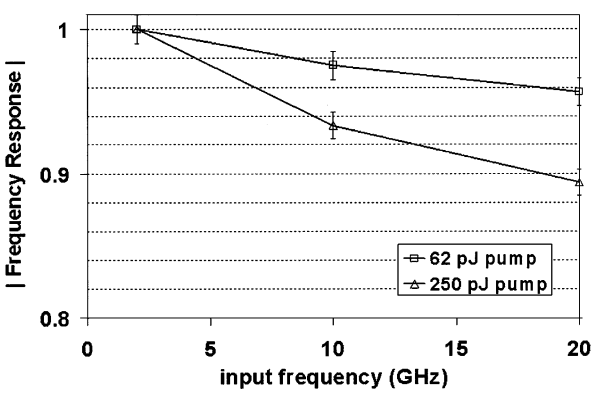


Fig. 5. Magnitude of sample-and-hold frequency response for 62- and 250-pJ pump energies. The 2-GHz points are normalized to unity for both plots.

energies cause significant bandfilling within the semiconductor volume close to the electrodes. Thus, the number of useful photogenerated carriers saturates as the pump energy increases. In addition, the field inside the switch decreases due both to the hold capacitor charging up and to field screening [8], making carrier sweep out more difficult. These effects combined cause the switch to saturate, leading to the behavior seen in Fig. 4.

To characterize the frequency response of the sample-and-hold process, the held signal amplitude at each input frequency was normalized by the corresponding input signal amplitude measured electrooptically above the sample-and-hold circuit. Results are shown in Fig. 5, with rolloff to 89.4% at 20 GHz for 250-pJ switching energy and 95.7% for 62-pJ switching energy. Due to the large expected bandwidth of the response, the 2-GHz points are normalized to unity for both plots. The energy dependence of the response is due to variation in sample-and-hold gating time as the pump energy changes. As the energy increases, a combination of trap saturation and carrier pile-up effects [9] most likely causes the turn off time of the switch to be longer, observed in previous switch response measurements [5]. Thus, as the switching energy is increased, the bandwidth of the sample-and-hold decreases. Assuming a linear, exponential-decay impulse response for the sample-and-hold process, 3-dB bandwidths of 38 ± 2 GHz and 63 ± 7 GHz are obtained for 250- and 62-pJ switching energies, respectively.

IV. Conclusion

We have demonstrated a linear, high-bandwidth sample-and-hold using LT GaAs MSM switches. We have shown $\geq$ 4 ENOB accurate sampling for a 20-GHz input bandwidth and a switching-energy-dependent 3-dB bandwidth estimated at $\sim$63 GHz for the sample-and-hold process.

Inability to charge the hold capacitor to the full input voltage leaves the sample-and-hold process prone to errors caused by pulse energy fluctuation and requires reset of the hold capacitor after every sampling event. Thus, full charge-up operation would be preferred, requiring improvements in the efficiency of the switch or a decrease in the hold capacitance. An increase in efficiency may be accomplished by improvement in material mobility through optimization of growth and anneal conditions.

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