Linear Electro-optic Conversion of Sampled Voltage Signals Using a Low-Temperature-Grown GaAs MSM and a Multiple Quantum Well Modulator

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Abstract: We present a low-temperature-grown GaAs metal-semiconductor-metal photo-conductive switch and GaAs SEED optical modulator, for sampling input voltages with potentially >40-GHz bandwidth and performing linear electro-optic conversion at a rate >500 megasamples/sec.

OCIS codes: (230.4110) Modulators; (999.9999) Photonic A/D Conversion

1. Introduction

In certain mixed-signal systems such as analog-to-digital converters (ADCs), carrying signals from one subsystem to another optically can yield important advantages. For example, one proposal for a 100 gigasample/second ADC calls for packets of charge that have been sampled on a capacitor by a high-speed sample-and-hold photoconductive switch to be relayed to a CMOS buffer and quantizer [1]. To show the feasibility of such an architecture, a 2-channel system with a resolution of 3.5 effective number of bits and an input signal bandwidth of 40 GHz has been previously demonstrated [2].

To take full advantage of this architecture, a large number of channels – on the order of 100 – is required. Certain obstacles could prevent the scaling of this system however. One issue is noise: the photoconductive switch could be vulnerable to noise generated by the digital signals from the CMOS quantizer, and vice versa. Crosstalk among the large number of channels is also a possibility. A second issue is the limited bandwidth and consequent attenuation of the electrical transmission line that carries the input analog signal. Finally, every optical sampling event creates transients on the transmission line that can distort the sampling on other channels [2]

One possible solution to these potential problems is to convert the electrical output of the sample-and-hold switch to an optical signal, and then to send this optical signal to quantizer circuits on a different chip. Such electrical isolation naturally alleviates many of the potential noise issues. Also, the use of compact electrical-to-optical converters allows a reduction in size of the input analog signal transmission line. The attenuation of the transmission line becomes less of an issue, and we add flexibility to the electrical network design so that the sampling of any spurious transients can be avoided.

For this kind of A/D system then, a method for linear, high-speed electro-optic conversion in a compact device is desired. We have previously demonstrated the potential of the self electro-optic effect device (SEED) optical modulator to perform this conversion [3,4]. In this paper we show for the first time the promising behavior of such devices when integrated with the actual photoconductive switch.

2. Device Principles

2.1 Metal-semiconductor-metal (MSM) photoconductive switch

The photoconductive switch used in our experiments is fabricated on low-temperature (LT) grown GaAs. Such material is grown at a lower substrate temperature (in our case 250 ^{o}C) than the normal ~600 ^{o}C. The wafer is subsequently annealed for 1 minute at 700 ^{o}C. The MSM structure consists of interdigitated titanium/gold fingers that have been evaporated on the LT GaAs wafer.

The growth of the material at low temperatures introduces excess arsenic into the carrier lattice, forming carrier-trapping sites. Subsequent annealing leads to the formation of arsenic precipitates. The final result is a material which has a fast recombination time on the order of a few picoseconds, but is still semi-insulating. When the device is hit with short (~200 fs) pulses from a mode-locked laser, we realize a switch that conducts for a few picoseconds and then turns off. The capability of a sampling front-end employing this device is discussed in detail in [1,2]. In particular, [2] discusses the potential of this device for sampling input signals with greater than 40-GHz bandwidth.

2.2 Multiple quantum well self-electrooptic effect device (SEED)

The SEED used in our experiments consists of multiple quantum wells formed from alternating layers of GaAs and AlGaAs. These quantum wells make up the intrinsic region of a p-i-n diode. Due to the quantum-confined Stark effect (QCSE), the bandgap of the device red-shifts with applied voltage. Hence, for a photon energy just below the bandgap of an unbiased quantum well, the absorption can be changed through an applied voltage bias.

Though this electroabsorption curve is nonlinear, in certain situations the absorption is linear with respect to the input current. In the steady-state case there are two principal limitations: (1) the device must be reverse-biased strongly enough so that there is essentially zero diode diffusion current and one electron of current results from each absorbed photon, and (2) the device must be operated in a region where the absorption rises with voltage [5].

Our previous work has demonstrated that this self-linearization also works even if the current is supplied in pulses rather than as a DC signal [3,4]. In the current work, the integrated switch and modulator enable a linear conversion of input *voltage* to optical energy.

2.3 The integrated device

A micrograph and schematic of the integrated device is shown in Fig. 1. We connect the photoconductive switch and SEED in series by solder-bonding modulators on a regular GaAs chip to the switches on an LT GaAs chip. The bond is formed between gold contacts using indium solder.

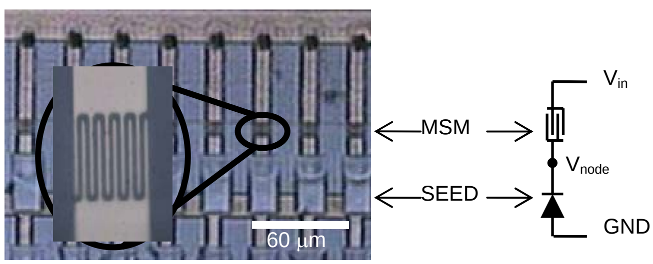

Fig. 1. Micrograph and schematic of the MSM photoconductive switch and SEED modulator in series. In normal operation, a short optical pulse triggers the sampling of an input signal V_{in} onto V_{node}. The SEED modulates a CW beam, producing an output beam whose integrated power over a sampling period is a linear representation of the sampled voltage.

During a typical operation, we introduce a CW beam on the SEED as well as an input voltage signal V_{in}. To sample the input voltage V_{in}, we excite the MSM with a short optical pulse, thus charging V_{node} towards V_{in}. The SEED then discharges the node by absorbing extra photons from the input CW beam. If the SEED has a strong enough reverse bias, then it will absorb one extra photon for each electron's worth of charge that was injected onto the center node. The net absorbed optical *energy* is hence linearly proportional to the input voltage. If the input voltage is a DC signal, then the average output optical power is representative of the optical energy per sampling event, and we can determine the linearity of the system by measuring the average absorbed power as a function of the DC input voltage.

3. Experimental Results

Figure 2(a) shows a typical response of the system with respect to time. The output power sharply dips at 2 ns when the optical pulse hits the MSM and quickly charges up the modulator. (The response shown here is limited by the 2.5 GHz bandwidth of the photodetector used in the experiment.) The output power then recovers back to its original level as the SEED discharges itself through the absorption process. Under a first order approximation, the recovery speed is governed by an exponential with a time constant of $\tau = \hbar\omega C/(e\gamma P_{in})$, where C is capacitance at V_{node}, e is the electron charge, P_{in} is the input CW power, and $\gamma = dA/dV$ is the absorption sensitivity with respect to voltage [6]. In our case the wavelength is 850 nm, the capacitance is ~30 fF, P_{in} is 1.13 mW, and γ is ~0.1, thus yielding a time constant of 0.4 ns. The fitted recovery time constant of 0.5 ns is hence in good agreement with this predicted value. Since from Fig. 2(a) we see that the SEED can fully recover within 2 ns under practical operating conditions, we believe this system has the potential for operating at sampling rates above 500 megasamples/sec.

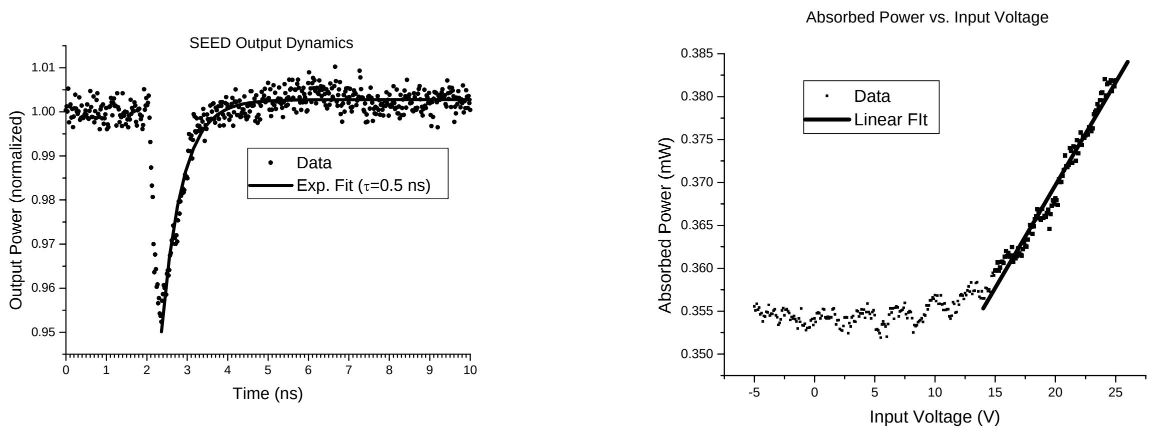

Fig. 2. (a) Modulated output power of SEED as a function of time. The power drops sharply after the sampling optical pulse hits the MSM switch, then recovers with a fitted exponential time constant of 0.5 ns as the SEED discharges itself through the absorption process. This is in good agreement with the predicted time constant of approximately 0.4 ns. (b) Absorbed power versus input voltage. The absorbed power (and hence output power) is linearly proportional to the input voltage when the input is large enough to keep the SEED out of forward bias.

Figure 2(b) shows how much power the modulator absorbs with respect to a DC input voltage. Note that two distinct regions can be seen: first the absorbed power remains relatively flat and then rises with increasing slope, and second the absorbed power rises linearly with respect to the input voltage.

When the input voltage is small, the SEED is not strongly reverse-biased and hence there is no linear charge-to-photon conversion as discussed in Sec. 2.2. This results in the behavior of the device below about 15 volts. Beyond this point however, the sampling system begins to linearly convert input voltage to output power. (The output power is simply the absorbed power subtracted from the input power.)

We expect to allow for conversion of signals at a range closer to 0 volts through a differential conversion in the future [4].

4. Conclusion

We have presented here an integrated system consisting of a very high-speed MSM photoconductive switch and a multiple quantum well optical modulator. Previous work on the switch has shown the capability for sampling signals with greater than 40 GHz bandwidth [2]. In the present work, we show linear conversion of DC voltage signals with a potential for sampling rates greater than 500 megasamples/sec. Possible applications for this device include a photonic-assisted A/D converter as well as any other system requiring high-bandwidth sampling and linear electro-optic conversion.

5. References

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