Linear differential electro-optic conversion of sampled voltage signals using a MSM and multiple quantum well modulators

Henry Chin, Ryohei Urata, Kai Ma, David A. B. Miller, and James S. Harris, Jr.
Department of Electrical Engineering, Stanford University, Stanford, CA 94305-4085, USA
henry.chin@stanford.edu

Abstract: We demonstrate a photoconductive switch hybridly integrated with quantum-well self-electrooptic effect devices, capable of sampling input voltages with potentially >40-GHz bandwidth and performing differential linear electro-optic conversion at a rate ~1 gigasample/sec.

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 or chips. 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 in a differential fashion [3]. We have also integrated the photoconductive switches with the SEED in a single-ended configuration [4]. In this paper we show for the first time differential conversion when integrated with the actual photoconductive switch, and clear potential for sampling at 1 gigasample/sec.

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.

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.

The SEEDs used in our experiments consist 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].

A micrograph and schematic of the integrated device is shown in Fig. 1. We tie the photoconductive switch's output to the node in between two totem-pole SEEDs by solder-bonding modulators on a regular GaAs chip to switches on an LT GaAs chip. The bond is formed between gold contacts using indium solder.

During typical operation, we introduce a CW beam on each of the two SEEDs ***A*** and ***B***. Initially, both devices will absorb a constant amount of power and generate a constant and equal amount of photocurrent. Suppose that V_{in} is greater than V_{node}. Now when an optical short pulse hits the MSM, V_{node} will be charged up towards V_{in}. If we have chosen the appropriate initial electrical and optical biases, this leads to a lower absorption and hence smaller photocurrent in device ***A***. Conversely, device ***B*** will have greater absorption and larger photocurrent. Both devices act to lower V_{node}, such that V_{node} eventually returns to its initial state.

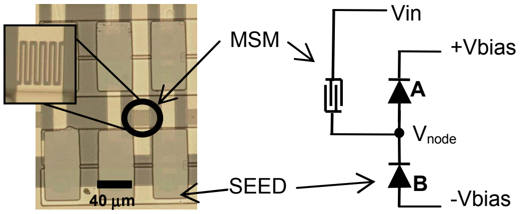

Fig. 1 The MSM samples input voltage V_{in} onto V_{node}. SEEDs A and B in a totem pole structure perform linear differential electro-optic conversion.

Assuming unity quantum efficiency, monitoring the momentary increase in the output power of ***A*** tells us exactly how much photocurrent ***A*** contributed towards lowering V_{node}. Measuring the decrease in the output power of ***B*** does the same thing. If we express the *difference* between the outputs of ***A*** and of ***B*** in numbers of photons, we can find the number of charges that were injected onto V_{node}. Assuming that the capacitance at V_{node} is relatively constant, then ultimately V_{in} has been linearly converted into optical energy

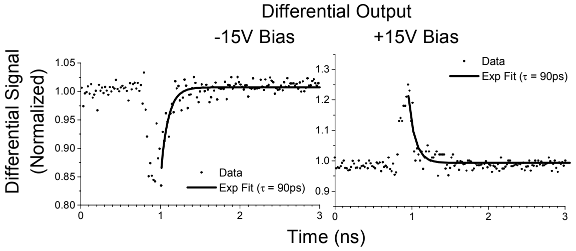

Fig. 2 Differential output power from the SEEDs for biases of -15V and of +15V.

Figure 2 shows $P_{out}(\mathbf{A}) - P_{out}(\mathbf{B})$ over time for two different input voltages. In both cases the leading edge of the signal is fast and corresponds to the short aperture window of the MSM. Then, to first order, the signal exponentially decays back to its initial value. The time constant is given by $\tau = \hbar\omega C/(e\gamma P_{in})$, where C is the 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 ~40 fF, the total P_{in} is 4.2 mW, and γ is ~0.1, thus yielding a time constant of ~0.1 ns, which is consistent with what is experimentally observed. Since from Fig. 2 we see that the SEED can fully recover within 1 ns under practical operating conditions, we believe this system has the potential for operating at sampling rates above 1 gigasample/sec.

Figure 3 shows the differential optical output averaged over time as a function of a DC input voltage. This measurement tells us whether the electro-optic conversion process is a linear one.

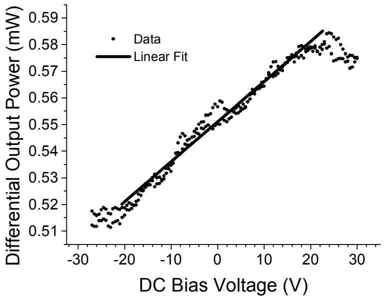

Fig. 3 The differential optical output is linearly proportional to the DC input voltage.

While some amount of noise is present in the experimental system, the device does appear to exhibit a linear conversion process. The device reaches the limits of its input range when one modulator has reached its peak absorption while the other is on the verge of forward bias.

In summary, we have presented an integrated system consisting of a very high-speed MSM photoconductive switch and multiple quantum well optical modulators. 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 into differential optical beams, with the potential for sampling at rates greater than 1 gigasamples/sec. With the differential scheme presented here, bipolar input signals are possible. 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.

References

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