Skew and Jitter Removal Using Short Optical Pulses for Optical Interconnection

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***Abstract*—We demonstrate data resynchronization in a multichannel chip-to-chip free-space optical interconnect for complementary metal–oxide–semiconductor (CMOS) using short optical pulses. Operation of the system is shown at speeds of 82 Mb/s per channel, limited by the repetition rate of the mode-locked laser used. We show explicitly the ability to resynchronize parallel channels and eliminate timing fluctuations; we remove up to ±3/8 of a bit period of interchannel skew and single channel jitter from the transmitted signals in a complete interconnect link that includes optical transmission, reception, and retransmission of digital data.**

***Index Terms*—CMOS integrated circuits, optical interconnections, optical pulses, quantum well devices, skew removal, synchronization, timing jitter, ultrafast optics.**

I. Introduction

OPTICAL interconnects offer numerous benefits over their electrical counterparts, including the potential for dense high-bandwidth interconnections, essentially no distance-dependent signal loss or degradation, and immunity to electromagnetic interference. Virtually all conventional optical interconnects use continuous wave (CW) lasers, either driven directly or externally modulated. The use of a short pulse laser with a modulator-based system can, however, provide additional advantages with respect to power requirements, system design, and timing issues.

Here, we define short pulse optical interconnects as those using a return-to-zero (RZ) data format with a very low duty cycle, i.e., pulses much shorter than a bit period. This format is easily attained by using external modulators to encode data onto the optical pulse trains of a mode-locked laser. Several aspects of such short optical pulses provide advantages over a system using modulated CW beams. First, the short pulse duration of an ultrafast laser can reduce the optical power requirements of an optical interconnect [1]. It has been shown that receiver sensitivity increases using impulsive coding [2], [3]. Also, since optical power is incident on the transmitters and receivers only during valid output states, the electrical power consumption is reduced because photocurrent is not generated during transitional periods.

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Second, the short pulse duration of an ultrafast laser results in a large spectral bandwidth. This enables system concepts such as a single-source implementation of wavelength-division multiplexed optical interconnects [4], [5], a technique that allows multiple channels to be transmitted down a single waveguide.

Finally, the low-jitter periodic pulse train from an actively mode-locked laser gives rise to many timing advantages. It can provide a high-quality signal for optical clock distribution [6]. Another clocking benefit could be gained by using short pulses to transmit data: the sharp rising edge of each bit would allow simplified clock recovery. Furthermore, the use of short pulses for both data transmission and clocking would enable large multichip systems to be run synchronously with a single laser.

Resynchronization is yet another timing benefit made possible by the use of short pulses. In this letter, we show the use of the low-jitter periodicity of the mode-locked laser, in combination with the extremely short pulse duration, to remove jitter and skew. In doing so, we demonstrate the operation of a multichannel modulator-based chip-to-chip optical interconnect using ∼1-ps optical pulses. Though some features of short pulse optical interconnects have been discussed previously [7], to our knowledge this represents the first demonstration of such a system.

II. Theory

To use the full bandwidth of multiple channels efficiently in a parallel interconnect, one must ensure good signal synchronization. Differences in parallel signal path lengths (due either to static differences or changes in the surrounding environments) introduce interchannel skew and timing jitter. Free-space optical interconnects can effectively remove such interconnect-introduced timing problems, since matching optical path lengths is reasonably easy for even highly parallel systems. However, signal timing uncertainty may be present at the transmitters of such a system due to process variations, clock skew, gate delays from dissimilar circuits, and changing local conditions on-chip. This uncertainty can limit the maximum data rate of parallel interconnects, and minimizing the problem with electrical techniques increases design complexity. Through the use of a short optical pulse-based interconnect, skew and jitter can essentially be removed.

To remove skew and jitter, we employ the following: a modulator-based system, a laser repetition rate matched to the chip clock frequency (obtainable with a phase-locked loop or optically distributed clock), and placement of the optical pulses at

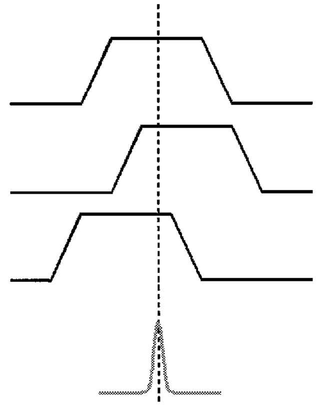


Fig. 1. Conceptual illustration of transmitter skew removal with short optical pulses.

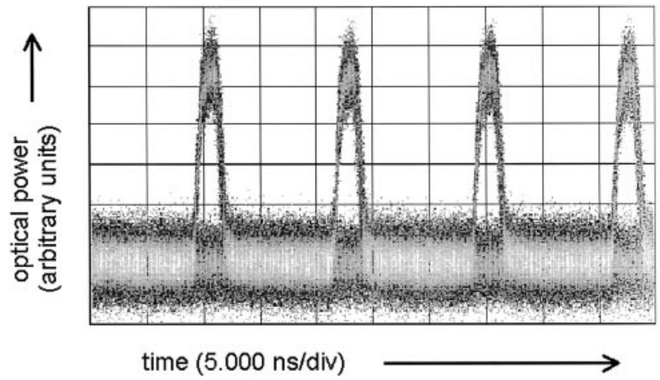


Fig. 2. Eye diagram from one channel of the short pulse interconnect, demonstrating transmission of data from an on-chip pseudorandom data generator. The signal is the optical readout of a modulator driven by the receiver output circuit.

the center of the bit in the timing reference frame of the transmitter chip. By using an array of beams generated from a single short pulse beam, each transmitter is simultaneously "sampled," removing interchannel skew as shown in Fig. 1. Similarly, since an actively mode-locked laser pulse train has very low jitter, the short pulse readout (incident on the modulators at the center of each bit period) removes jitter from each channel, theoretically up to $\pm 1/2$ of a bit.

III. Experiment

The chips used in this experiment were fabricated in 0.5-μm silicon complementary metal–oxide–semiconductor (CMOS) through MOSIS. The optical devices are GaAs multiple-quantum-well diodes, flip-chip bonded to the CMOS by Lucent Technologies using a well-established technique [8]. The diodes serve as both modulators and detectors, have a pitch of 62.5 μm, and are placed in a series of 1×20 arrays spaced by 125 μm. Channels are differential, an architecture allowing better system performance with low voltages. The modulators are operated with a 3.3-V swing, providing a contrast ratio of approximately 2:1. The nominal operating wavelength is 850 nm.

The optical layout is a free-space setup on milled stainless steel slotted baseplates that were first described by McCormick *et al.* [9]. The system is designed as follows: the incoming interconnect laser beam (either pulsed or CW for comparison) is split into a linear array of twenty beams using a diffractive optical element. The beams are focused to spots with diameters of a few microns onto the transmitter chip modulators, whose outputs are imaged onto the detectors of the receiver chip. The detectors are components of differential receiver circuits that were described previously by Woodward *et al.* [10]. The receiver circuits drive additional modulators, enabling high-speed optical readout of the received signal with a dedicated CW laser and optical detector(s).

The short pulse laser is a Spectra-Physics Tsunami mode-locked Ti:sapphire laser with a repetition rate of approximately 82 MHz. The transmitter chip is driven with electrical signals from a Hewlett-Packard 8133A pulse generator, frequency-locked to the laser pulse rate. This pulse generator can be used to provide data directly to the modulator drivers, or to generate a clock signal for an on-chip pseudorandom data generator.

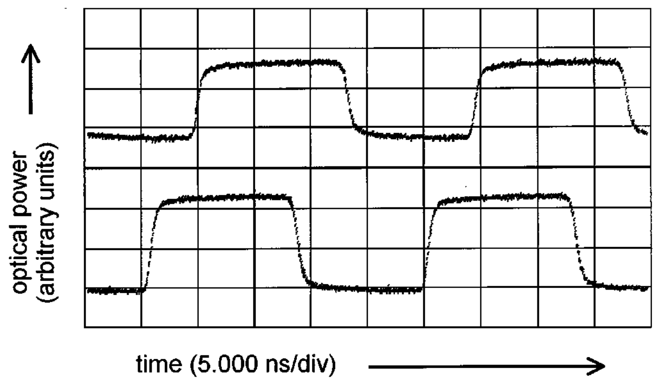
Thus, the results shown here correspond to data transmitted by modulators on one chip, reception by photodiodes and associated receivers on a second chip, followed by retransmission using modulators on the second chip with a CW readout beam. This final modulated beam is analyzed using a Tektronix P6701 detector with a signal bandwidth of 700 MHz, and the output is recorded using a digital oscilloscope. The short pulse interconnect allows comparisons between CW and RZ operation, and we use it to demonstrate benefits of the short pulse system, such as the removal of single channel jitter and interchannel skew.

IV. Results

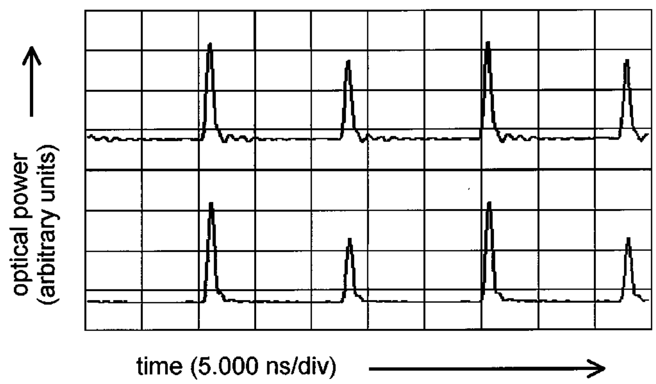
Individual testing of modulators and receiver circuits on a separate optical probe station with CW beams indicates good performance to data rates above 750 Mb/s. Using these components in the short pulse interconnect, we observe an open eye diagram at the maximum repetition rate of the mode-locked laser, 82 MHz. Fig. 2 shows the performance of a single channel at this rate (with an average received optical power of approximately 100 μW per beam), using a CW readout beam on the receiver optical output. The receiver is neither clocked nor latched, so its output state can be seen to relax to the off state with a characteristic time constant (chosen during circuit design to be compatible with a system running at 1 Gb/s).

Neighboring transmitter channels in the array can be simultaneously driven with different electrical data signals. Fig. 3 shows the modulator outputs from the transmitter chip for two of these channels. The inputs are intentionally skewed by 3/8 of a bit relative to one another. We monitor one reflected beam from each differential channel, first for the CW and then the short pulse interconnect. While the interchannel skew remains for the cw-based interconnect, the short pulses effectively remove all skew.

With the introduction of up to $\pm 3/8$ of a bit period of jitter (i.e., 3/4 of a bit peak-to-peak) on the electrical input of a single modulator channel, a CW laser-based interconnect transfers that jitter to the receiver. However, when we use a short pulse interconnect (with the pulses temporally centered with respect to the



(a)



(b)

Fig. 3. Transmitted signals from two channels operating at 82 Mb/s, whose electrical inputs are skewed by 3/8 of a bit period. Readout is performed with a (a) CW laser and (b) short pulse laser. Skew is removed by the use of the short optical pulses. The finite contrast ratio of the modulators is evident in the bottom part.

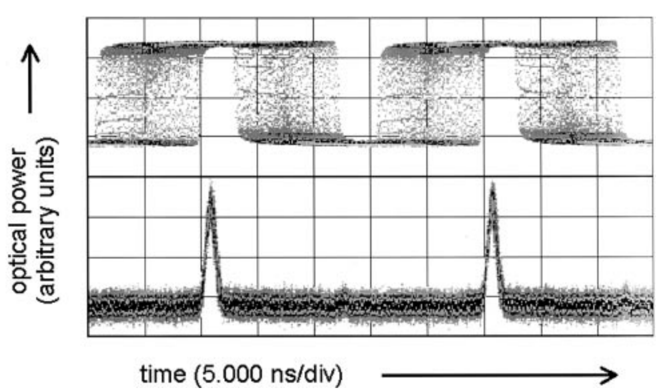


Fig. 4. Demonstration of jitter removal from a single interconnect channel at a data rate of 82 Mb/s. Upper trace shows the electrical input signal while the lower trace shows the optical readout of the receiver.

electrical bits), all the jitter is removed as expected. Jitter removal results are shown in Fig. 4.

V. Conclusion

We have used the low-jitter output and short pulse duration of a mode-locked laser to demonstrate the removal of up to $\pm 3/8$ bit of jitter and interchannel skew at 82 Mb/s. In doing so, we have demonstrated the operation of a multichannel optical interconnect using short optical pulses. The maximum speed of this system is currently limited by the repetition rate of the laser, but tests of the individual modulator and receiver circuits show significantly higher system speeds are possible. Advances in mode-locked laser diodes and fiber lasers suggest that commercialization of suitable high-repetition rate, compact, low-jitter short pulse sources is possible, making short pulse optical interconnects a feasible alternative to conventional CW interconnects.

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