A multichannel optical oscilloscope for sampling broadband, free-space, optoelectronic circuits

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Abstract

The advent of large-scale, free-space, opto-electronic interconnections, as demonstrated in recent system prototypes[1-4], requires new sampling methods to reveal diagnostic information. Several factors contribute to the difficulty of probing optical communications channels without disrupting their operation. High-speed electronic connections to the chip periphery are not available in sufficient number and would contribute an undesirable thermal load. Electronic and optical[5,6] physical contact probes would obscure many of the optical channels that are relayed to a common surface of the chip in current systems. Optical sampling provides the better method although many standard techniques are either too time consuming or complex to implement.

We will describe a tool we developed that delivers diagnostic information on a large number of high-speed, optical data channels simultaneously and operates analogously to the conventional sampling electronic oscilloscope. The optical oscilloscope is constructed using CCD cameras and video capture boards that are controlled by a software application resident in a personal computer. Sampling is based on a stroboscopic method of using short pulsed laser probe beam synchronized to a data stream to illuminate optical modulators within the opto-electronic circuit. We have demonstrated and will discuss the tool's capability of simultaneously monitoring arrays of broadband opto-electronic devices operating at speeds from several hundred Megabit/s to a few Gigabit/s.

Fundamental Operation

In current free-space photonic systems, data is transmitted optically between electronic processor cells by modulating the intensity of light beams. Arrays of light beams, externally generated by laser diodes and diffractive components, are focused by lenses onto small reflective windows underlying multiple-quantum-well (MQW) material. The optical absorption of the MQWs is electronically governed by attached processing circuitry. In this manner, the absorption of the MQW encodes data onto each optical channel. An optical infrastructure then routes the reflected modulated channels to the subsequent chip or fiber.

An optoelectronic chip may embody thousands of optical channels each operating at speeds of hundreds of Mbits/sec, thus posing a serious challenge in collecting diagnostic information. In present-day investigations, it is typically necessary to simultaneously monitor a large number of parallel channels to determine the optimal operation parameters. Rather than design a complex array of high-speed photodetectors that must be accurately aligned to a remote image of the modulator array, it is far simpler to sample the modulators' states using a repetitive, short duration light pulse and collect the image with an inexpensive CCD video camera. Thus in the same manner that a stroboscopic light source apparently freezes or slows the motion of rotating fan blades, the pulsed illuminator highlights the evolution of a periodic data stream for a large set of modulators.

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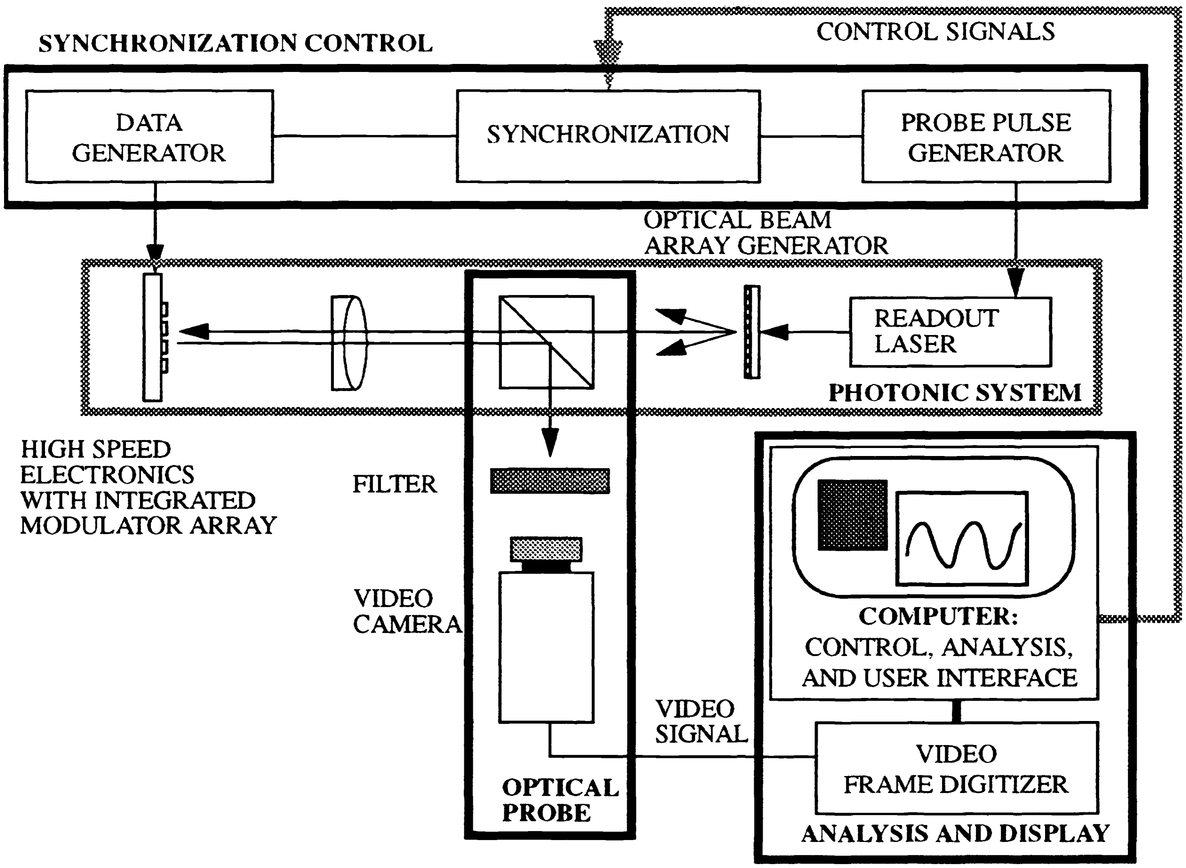

Figure 1. Schematic of test photonic system and optical oscilloscope modules.

Tool Design

A schematic of the multichannel, optical oscilloscope is shown in figure 1. The three primary functions of the oscilloscope hardware modules are:

- to generate pulses that create short duration readout light beam arrays for probing the modulator absorption and to synchronize these pulses with a periodic data stream (synchronization control module)
- to sample the readout light from several optical data channels in parallel and focus the individual channels separately onto a photosensor array, typically a CCD video camera (optical probe unit)
- to digitize and analyze the video signal and display the sampled waveforms in a format similar to that of an oscilloscope (analysis and display processor)

Currently, the separate modules have been only loosely integrated since the system to be investigated influences the design of the probe and synchronization units.

The synchronization control unit is typically custom designed to match the system. For example, generation of the short-duration readout light pulses can be performed by connecting new signal lines to the existing readout lasers in some systems, while in other cases a pulsed, broad-area illuminator can be integrated with the optical probe assembly. Since the readout pulse usually occurs repeatedly during the time sampling window of the photosensor, it must occur at the same point in the data stream throughout that window. In our demonstrations, we have maintained synchronization by using coupled data and pulse generators referenced to a common clock, but differing by about 1Hz at the bit frequency so that the pulse slowly scans the data pattern.

It is also possible to use a delay generator to scan the readout pulse through the data stream, although this would require control signals from the analysis unit to coordinate the process. The end result is that a multitude of samples are collected from a finite duration window of the data stream by a low speed photodetector.

The optical probe, also referred to as the viewport, extracts light from the system using a partially reflecting surface, such as a beam-splitter or pellicle. The deflector must be designed so that it does not seriously disturb the readout beams or other optical channels communicating information to the optoelectronic chip. The optical channels of systems we investigated operated at a wavelength of 850 nm which is within the sensitivity range of most CCD cameras. Filters are used to reduce the intensity level as necessary. Lenses form an appropriately sized image of the optoelectronic modulator array on the video camera. At this point, the user is able to watch the evolving intensity variation of the spots on a video monitor.

The analysis and display processor must digitize and store the video signal frame-by-frame. Enhanced multimedia computers are available with internal video cards that provide accessibility of the video memory to the processor. We have developed a custom written software application to coordinate the analysis, control, and display interface for the oscilloscope. Our implementation of the oscilloscope was produced for an Apple Macintosh 840AV and demonstrated on other compatible Macintosh platforms.

The location and sizes of the regions of interest (i.e., the modulator spots) are interactively defined by the user while examining either a live or captured video frame. During operation, the processor calculates the average intensity in a set of predetermined regions of interest and plots these intensities in a variety of possible waveform formats. Control of other display aspects, such as the scales of the intensity and time axis, are also provided to the user. In operation, our system collected and analyzed about 10 video frames/sec. The intensity resolution of the waveform is limited by video noise and the digitization accuracy of the A/D video signal convertor. The temporal resolution is effected by the width of readout pulse and the speed with which it scans through the data stream. The tool has proven capable of analyzing as many as 256 channels simultaneously without any degradation in performance.

One further advantage of collecting the data using a video camera is that the video signal can be recorded using video tape recorders. Thus, the performance can be archived and reanalyzed at a later time.

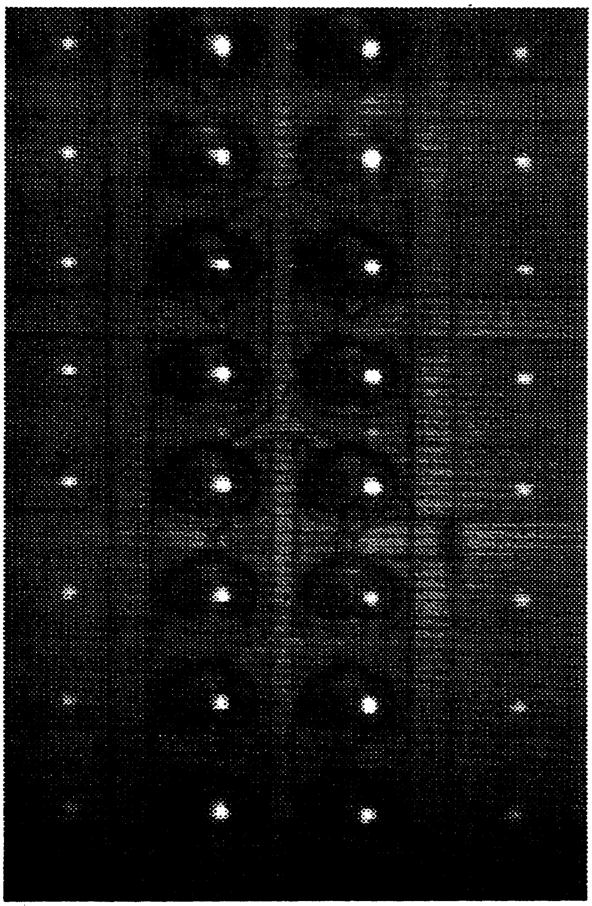

Figure 2. Readout light beams illuminating high-speed MQW modulator array.

High-speed system demonstration

To demonstrate the high-speed capability of the optical oscilloscope, an array of independent, electrically driven, differential multiple quantum well modulators[7] were monitored while operating at multi-Gbit/s speeds. The sixteen modulator windows are shown with their associated readout beams in figure 2.

The synchronization between the data stream and probe pulses were fixed by using two high-precision, frequency stabilized analog signal generators synchronized to a common clock to trigger digital data and pulse generators. The optical probe pulse was measured to have a width of about 200 ps as measured by an independent high-speed detector.

Two independent NRZ data waveforms and their complements were connected to four of the eight modulator pairs while a square waveform was connected to the remaining four pairs. Figure 3 shows the oscilloscope traces for data streams of 1 Gbits/s and square waves of 1GHz. All traces share a common time

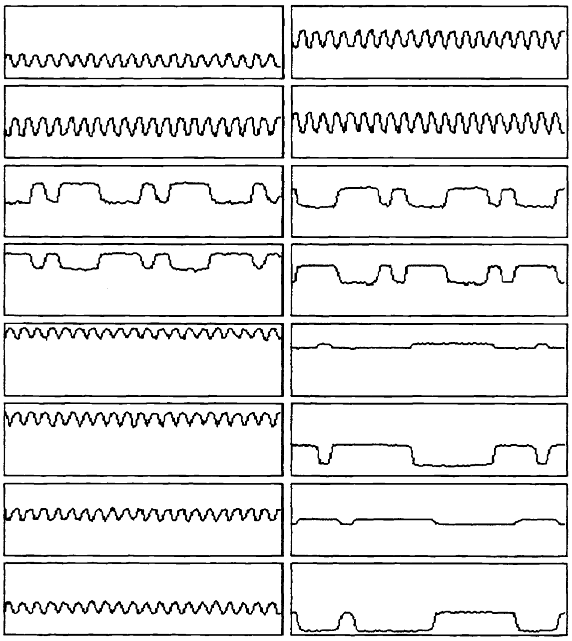

Figure 3. Optical oscilloscope traces from high-speed modulators for 1Gbit/s data and 1GHz square waves.

and intensity scale. The reduced intensity variation in certain channels is due to local heating, caused by termination of transmission lines, that shifts the operating characteristics of the modulator. Although the beams are well focused on the modulator windows in this test, we have demonstrated that equivalent oscilloscope performance is attained when the spots are defocused to illuminate a larger area.

Free-space photonic switch fabric

To demonstrate its operation in a practical system, the multichannel optical oscilloscope was used to examine the performance of the current free-space photonic switching demonstration[4]. This demonstration system is composed of one opto-electronic chip comprising sixteen independent 16x16 crossbar switches, and the optomechanical infrastructure to relay optical channels between the chip and a two-dimensional fiber bundle array. The opto-electronic chip is a hybrid combination of GaAs MQW modulators bonded to VLSI silicon processing circuitry and illustrates the potential for dramatically expanding data throughput. The fiber bundle serves to collect and concentrate the data streams for remote external transmitters and receivers. In addition, a small number of low-speed electronic connections supply control and switch configuration information to the chip. During operation, the switching fabric has been shown to route digitized video and ATM-like traffic.

In this demonstration, one 16x16 switching node was examined. Two independent optical input channels provided periodic 8-bit data streams for this node. The switch was configured to route each of the two input streams to separate output modulators. The system was operated at a channel data rate of 200 Mbits/s which, under normal operation, provides sufficient overhead to allow switch reconfiguration and data encoding and a net communications channel throughput of 155 Mbits/s.

The photonic switch required only minor adjustments to enable the oscilloscope to monitor operations. A low reflectivity fused silica substrate, that was also used for inspecting optical beam registration, was inserted near the system pupil to deflect a portion of the modulated light toward a video camera. Lenses and attenuators were then selected to produce an image of the 16 output modulators residing on the surface of the

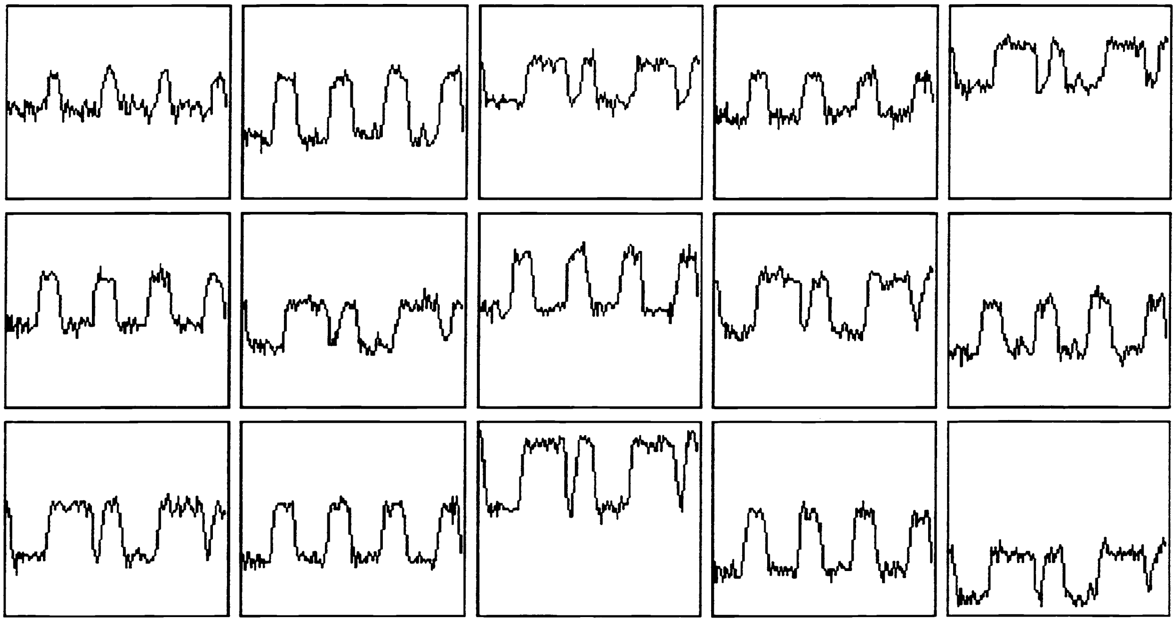

Figure 4. Fifteen traces obtained simultaneously from free-space photonic switch operating at a channel rate of 200 Mbits/sec. One of two separate input data channels is routed to each output modulator.

optoelectronic chip. This viewport assembly did not disrupt system operation as evidenced by the undisturbed routing of a separate video data stream.

In order to coordinate the data and readout signals, a common reference clock synchronized a data generator and pulse generator operating at 200,000,001 Hz and 25 MHz respectively. The data generator, a Tektronix HFS9000 stimulus generator, is part of the system hardware. The readout laser, usually operated as a CW source, was modulated by the 25 MHz signal with a pulse width of about 1 ns. Thus a series of eight data bits were scanned over a time interval of about 8 seconds.

Figure 4 shows oscilloscope traces that were obtained simultaneously from the active system. Only fifteen traces are displayed since only 15 of the 16 output modulators were illuminated by readout beams. This scheme is due to a design experiment where two alternate receiver designs, optimized for different power levels, were tested. The optimal configuration required shifting all spot arrays by one location so that the sparsely populated fiber array was aligned with the better performing circuitry leading to a more robust system demonstration.

During the diagnostics test, the multichannel oscilloscope provided the opportunity to investigate the full set of output channels that was inaccessible with the current, sparsely populated output fibers. In addition, it was possible to immediately discern the differing operating characteristics of the receiver designs as a function of the bias voltage.

Summary

Ongoing development of new opto-electronic interconnection architectures and technologies requires the invention of new diagnostic tools to investigate the performance of these novel photonic circuits. The application of stroboscope techniques using commercially available CCD cameras to probe optical absorption characteristics of modulator-based systems provides the basis for our high-speed, multi-channel, optical oscilloscope. We have demonstrated its capabilities by collecting diagnostics from parallel multi-Gbits/s data streams and from practical free-space photonic prototype systems.

Acknowledgments

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References

1. F. B. McCormick, T. J. Cloonan, F. A. P. Tooley, A. L. Lentine, J. M. Sasian, J. L. Brubaker, R. L. Morrison, S. L. Walker, R. J. Crisci, R. A. Novotny, S. J. Hinterlong, H. S. Hinton, E. Kerbis, "Six-stage digital free-space optical switching network using symmetric self-electro-optic-effect devices," Appl. Opt. **32**, no. 26, 5153-5171 (1993).

2. F. B. McCormick, T. J. Cloonan, A. L. Lentine, J. M. Sasian, R. L. Morrison, M. G. Beckman, S. L. Walker, M. J. Wojcik, S. J. Hinterlong, R. J. Crisci, R. A. Novotny, H. S. Hinton, "Five-stage free-space optical switching network with field-effect transistor self-electro-optic effect-device smart-pixel arrays" Appl. Optics **33**, no. 8, 1601-1618 (1994).

3. F. B. McCormick, A. L. Lentine, R. L. Morrison, J. M. Sasian, T. J. Cloonan, R. A. Novotny, M. G. Beckman, M. J. Wojcik, S. J. Hinterlong, and D. B. Buchholz, "155 Mb/s operation of a FET-SEED free-space switching network," Photon. Tech. Lett. **6**, no. 12, 1479-1481 (1994).

4. A.L. Lentine, D.J. Reiley, R.A. Novotny, R.L. Morrison, J.M. Sasian, M.G. Beckman, D.B. Buchholz, S.J. Hinterlong, T.J. Cloonan, G.W. Richards, and F.B. McCormick, "Optoelectronic ATM switch employing hybrid silicon CMOS/ GaAs FET-SEEDs", SPIE Proceedings conference #2692, 1996.

5. J. A. Valdmanis and G. Mourou, "Subpicosecond electrooptic sampling: principles and applications," J. Quant. Elect., QE-**22**, 69-78 (1986).

6. B. H. Kolner and D. M. Bloom, "Electrooptic sampling in GaAs integrated circuits," J. Quant. Elect., QE-**22**, 79-94 (1986).

7. A. L. Lentine, L. M. F. Chirovsky, L. A. D'Asaro, R. F. Kopf, and J. M. Kuo, "High speed 2x4 array of differential quantum well modulators," Phot. Tech. Lett. **2**, no. 7, 477-480(1990).