Design and demonstration of a high-speed, multichannel, optical-sampling oscilloscope

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Free-space digital optical systems have demonstrated the capability to provide thousands of optical connections between optoelectronic chips. This dense concentration of channels creates substantial challenges in monitoring individual connections for diagnostic purposes without compromising performance. From the concept of stroboscopic techniques, we have designed and constructed a multichannel optical diagnostic tool that operates analogously to an electronic-sampling oscilloscope. The tool is economically constructed by the use of commercially available video cameras and video-enhanced personal computers. An integrated software application operates the tool and displays multiple-channel waveforms. We demonstrate the oscilloscope-sampling optical waveforms of a two-dimensional optoelectronic modulator array operating at data rates from 0.5 to 4 Gbits/s.

1. Introduction

A series of system experiments has been performed to evaluate the potential and technical issues of free-space digital–optical interconnections. The basic premise is that free-space optical interconnections generated normal to the electronic component surface will provide a beneficial dense, parallel, high-speed information transfer at the chip-to-chip level. The great density of optical interconnections is achieved when the high spatial resolution of lenses that form the optical-relay framework is exploited. External electronic connectivity in these systems is generally limited to a small number of low-bandwidth signals.

The fundamental operation of one class of free-space optical systems[1–3] relies on the absorption of light within multiple-quantum-well (MQW) modulators in devices such as the self-electro-optic-effect device. Large arrays of laser beams are generated by diffractive elements and imaged onto arrays of modulators integrated on an optoelectronic chip. These readout beams are individually intensity modulated during reflection to encode information processed within the isolated smart-pixel cells. The modulated beams are collected and routed to the next optoelectronic chip by a link stage that defines an interconnection fabric. Because of this method of image relay, the optical channels are isolated from each other only in the vicinity of the modulators and the detectors.

The testing and the analysis of prototype optical systems are integral to characterizing the performance and reliability of free-space photonic technology. However, this technique of transmitting information poses a serious challenge to sampling diagnostic signals within large-scale digital–photonic systems. In this paper we present a novel tool, constructed from cost-effective video and computer platforms, that utilizes the inherent optical-channel format to simultaneously monitor a two-dimensional array operating at high data rates. We demonstrate the system's effectiveness by presenting results from an electrically addressed MQW array[4] operated at gigabits per second (Gb/s) data rates.

In Section 2 we outline the method that we implemented to monitor an array of optical channels encoded by modulator devices. Next, we describe the hardware that acts as the probe to collect and digitize the optical signals. Then we present the details of the software application developed to identify and display the waveforms. Finally, we discuss the results of a high data rate demonstration.

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Received 14 June 1995; revised manuscript received 30 October 1995.
0003-6935/96/081187-08$06.00/0

2. Diagnostic Method

Although information exists in both electronic and optical formats within the referenced photonic systems, the difficulty of attaining diagnostic signals becomes apparent if we examine a few schemes for data sampling. First, conventional electronic techniques are not appropriate in the typical free-space environment. Electronic contact probes must be excluded from the volume above the chip surface because they would obscure numerous optical channels. In addition, high-speed electronic test leads connected to the boundary of the electronic chip are limited in the number of sample points that can be accessed and would generate further undesired power consumption.

Although high-speed, electro-optic-sampling techniques have been developed to monitor individual electronic channels,[5,6] the use of fiber contact probes would likewise obscure optical channels. Thus the most promising means of optical sampling is to somehow extract an image of the modulator light destined for a subsequent chip. Streak cameras are one means available to record the intensity evolution of an individual optical source by functionally scanning the film or CCD array past the focused image. However, these systems tend to be specialized (i.e., expensive) and are not easily extensible to large arrays of spots.

Up to now, the typical procedure for monitoring optical-intensity waveforms was by sampling the light reflected from the output modulators with a removable system viewport and forming a remote magnified image of the device array. A high-sensitivity photodetector was then sequentially aligned with each spot associated with a modulator to transform the signal to an electronic waveform that could be monitored by an electronic oscilloscope. This sampling procedure is too time consuming when many signals must be actively monitored. Such situations, though, are the norm when system components are being aligned and electronic parameters are being adjusted for optimal performance. This procedure is inadequate even when the mechanical alignment is computer automated if the number of channels is large.

An alternative means of sampling the two-dimensional image would be to build either a two-dimensional fiber bundle array connected to a set of receivers or a customized photodetector and receiver array whose physical layout matched that of the modulators. This solution, unfortunately, would be system specific and would still require a rigorous alignment process for coupling light into the small photosensitive areas of high-speed detectors. Indeed, the photodetector array could still be limited in the number of electrical connections that could be made off chip.

Over the course of characterizing a number of free-space optical systems, it became apparent to us that a useful diagnostic tool should satisfy two basic criteria. Thus the objective of the project became to design and demonstrate a tool that

- simultaneously samples a two-dimensional array of high-speed optical channels in a cost-effective manner that requires a minimum of user attention either to align or to identify the regions to monitor,
- provides a user interface whose operation resembles that of a multichannel oscilloscope.

One potential technique of monitoring the device array is suggested by the process of aligning the optical channels during system construction. In the referenced systems,[1–3] an optical viewport option was provided so that a video camera could inspect the registration of beams to modulator windows at each optoelectronic chip. The entire electro-optic device array could be viewed and the intensity modulation directly observed during very low-speed (a few hertz) operation. Unfortunately, nominal system operating speeds are targeted toward hundreds of megabits per second per channel and even specialty CCD imagers are limited to a few kilohertz sampling rate. However, because video techniques offer the most suitable opportunity for sampling a two-dimensional array of optical channels, we have explored enhancements to this basic technique.

One method of increasing the temporal resolution is to shutter the CCD chip and thereby obtain brief time exposures. To provide sufficient diagnostic information, the exposure should be of the order of a fraction of a bit duration or less. Because this is of the order of a few hundred picoseconds at gigahertz operating speeds, mechanical shutters must be eliminated from consideration. Although high-speed electro-optical shutters are available, their exposures are usually no faster than a few nanoseconds, and light may not be sufficiently blocked during the off state. One further criterion is that the CCD sensor collect a sufficient amount of light for each system state. It is thus highly desirable to sample a periodic event repetitively to avoid photomultiplication techniques.

The solution to this challenging problem is indicated by analogous photographic procedures for studying high-speed mechanical systems. In these systems, the key is not to increase the shutter speed, but to provide a brilliant light source of exceedingly short duration to freeze the action. The sampling technique we have implemented is based on this concept of stroboscopic photography whereby the modulator is repeatedly illuminated for a brief interval by a high-intensity laser source, thus selectively capturing an image of a particular system state.

This basic sampling technique is illustrated in Fig. 1. At the top of the figure is a waveform that represents a periodic electronic signal used to modulate the absorption of a MQW device. It has a period of T_p and a bit width of T_b. Below this, an optical strobe pulse is synchronized to illuminate the

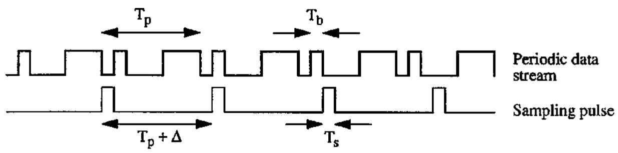

Fig. 1. General sampling scheme. The periodic electronic waveform modifies the absorption of the MQW modulator. An advancing optical-sampling pulse samples a slightly different time interval during each collection. In this example, the full waveform would be scanned in eight sampling pulses.

full device array about once per period. The reflected light is then imaged onto a low-speed CCD detector that in operation actually samples several strobe pulses. The period of the strobe is $n^*T_p + \Delta$, where n is an integer value, so that a waveform period is fully scanned during a time span of $n^*(T_p)^2/\Delta$. The strobe offset Δ is adjusted so that the advance of the strobe is typically T_b or less during a video frame. When T_s and Δ are selected to be $\ll T_b$, the strobe pulse is able to resolve the fine scale time evolution of the waveform.

This stroboscopic method is an ideal match for modulator-based photonic systems. Within the referenced systems, spot arrays are imaged onto modulators in which electronic signals modify the optical absorption to encode information for the subsequent optoelectronic device array. The time evolution of the modulators' absorption is investigated by the replacement of the normal readout beams with a set of synchronized pulsed readout beams (serving as strobes) to scan slowly through a repeated pattern embedded in the data stream. Light is then extracted by the viewport, and the resultant remote image is viewed by a video camera. Because the acquisition rate of a standard video system is ~30 frames per second, the intensity evolution of an array of waveforms can be captured in a time scale of seconds.

With the diagnostic information embedded in the video signal, it next becomes necessary to digitize and process each image. If the CCD camera generates a video signal compatible with commercial standards, video digitizing boards for personal computers can be used to analyze the image. Once the video frames are digitized and stored in computer memory, the user identifies regions of interest to track intensity variation. An application monitors the optical channels and displays the intensity change over time as an oscilloscope trace. One additional feature of using a standard video to monitor the system is that the signal can be stored by video tape recorders and later reanalyzed.

3. Hardware

The project hardware was designed so that connecting it to the free-space photonic system would disturb the system as little as possible. The key functions of the hardware for the multichannel optical oscilloscope are to

- ensure that periodic data streams modulate the optical absorption of the modulators arrays,
- synchronize short-duration stroboscopic pulses to scan the time evolution of the array slowly,
- extract and filter the reflected light and form a magnified image on a CCD camera,
- digitize the resultant video signal and store it in computer memory for analysis.

The primary components of the multichannel, optical oscilloscope are shown in Fig. 2. Typically, electronic components serve to synchronize the data stream and the stroboscopic pulse, although optomechanical methods may also be employed. Optical and video components are responsible for extracting and digitizing the image of each system state. The computer provides the platform for the software application that controls, analyzes, and displays the intensity waveforms. The nature of this application interface is discussed in Section 4.

The object to be examined is a high-speed, optoelectronic processing circuit with integrated MQW modulators. The modulators in the referenced systems have been designed to be interrogated at a wavelength of 850 nm and to operate at hundreds of megabits per second. Modulator windows in general can range in size from under 10 µm to several tens of micrometers on a side. The size is dependent on both optical and electronic performance considerations. A data generator module in the diagnostic system is either responsible for generating signals that are routed directly to the modulator or else coordinates the activity of each smart-pixel cell so that a periodic pattern persists.

The image of the modulator array is extracted by a viewport that is either added to the system as necessary or that forms part of the framework. In the referenced systems, the viewport's magnetized

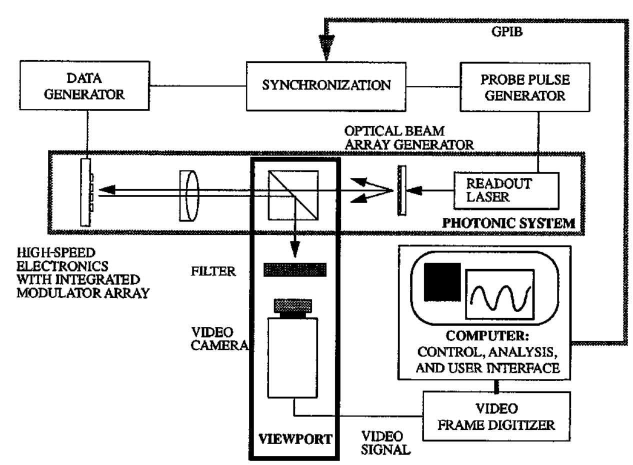

Fig. 2. Components of the optical oscilloscope: the photonic system under investigation, viewport, signal synchronization, and computer control and analysis. GPIB, general-purpose interface bus.

base allows it to be rigidly located in reserved areas of the system's steel baseplate, providing quick and easy insertion and removal. The viewport is composed of a mirror or partially reflecting beam splitter, the video camera, and potentially an illuminator. The camera's objective lens focal length determines the area of the device that will be monitored. Most monochrome video cameras are sensitive in the near infrared, although some cameras may require that a manufacturer's infrared filter placed near the focal plane be removed. To reduce the sensitivity of the camera to spontaneous laser emission between strobe pulses and light from secondary illumination, a narrow optical bandwidth filter can be employed during measurements. It is often necessary to provide additional neutral-density filters to reduce the light to a level tolerable by the CCD sensors.

Two methods can be used to produce the stroboscopic pulses. In the first method, the optical strobe pulse is generated by an external laser source linked with the viewport accessory. When the probe source is part of the viewport it is better if it provides either broad-area illumination or large spots so that only coarse registration of the illumination and modulators is required. Also, the broad-area illumination provides a simple means of identifying landmarks on the chip or of investigating local variations across large-area modulators. In this case the normal readout beams must be blocked or disabled. A light-emitting-diode source is generally not acceptable as a strobe source because of the restricted wavelength range of the quantum-well modulators and the difficulty of generating a pulse of sufficiently narrow time duration. The chief advantage of this method is that the diagnostic tool is independent of the photonic system except for the viewport tool and a clock signal shared with the system to synchronize the pulse. Also, the short-duration optical pulse may be generated by a laser more suitable for this task. In essence, this technique is suitable for all classes of electronic circuits wherein modulators are integrated solely as a means of obtaining diagnostic information.

A second method is to use the normal system readout laser to generate the probe optical pulse by supplying a new set of electronic pulse signals. Under normal system operation, this laser would generate an uninterrupted, intensity-modulated, square wave that is synchronized with each data bit as it is presented at the modulator. After modification, diagnostic readout is accomplished through disconnecting the normal clocking electronic signal and replacing it with the synchronized pulse signal. The advantages of this scheme are the ability to rely on the system's optical power sources and the ability to examine problems potentially associated with these lasers. Also, photocurrents produced in the modulators during testing may be more characteristic of those generated during normal system operation.

The low-speed responsivity of the CCD sensor has a directly impact on the operation of the diagnostic tool. Like the standard digital–electronic-sampling oscilloscope, the modulator's absorption waveform is selectively sampled for short intervals over the course of several repeated patterns. However, because the CCD camera acts as an integrator, collecting the light throughout a video frame of 1/30-s duration, waveforms can require several seconds for accumulating. In addition, because the CCD camera is susceptible to extraneous light sources and inherent electronic noise, it is desirable to collect several pulses throughout the video frame to maximize the signal strength. Because of this collection of multiple data points, the probe pulses must be exactly registered in time to the data throughout the video frame. In addition, the sampled points thus represent an average value for each time interval and are therefore unsuitable for determining a channel bit-error rate.

The pace of the strobe delay sequence is limited by the performance of the video acquisition and analysis system. In this implementation, the sampling speed is ~10 samples per second. Speeds of up to 30 frames/s would be expected in future advanced processing systems. Methods of electronically controlling the data and the strobe synchronization include using a computer-controlled delay generator triggered by a system timing signal, using a multichannel word generator that integrates pulse and data signal functions and features programmable delays, or using two signal generators that are highly synchronized but differ in the fundamental bit frequency by only a few hertz. An alternative optomechanical means of accurately delaying the optical pulse is to use a retroreflective optical relay whereby delay is introduced when a mirror is micropositioned along the beam path.

If the system data bit rate is given by $R = 1/T_b$, the synchronization is set so that a probe pulse is generated at a rate close to R/N, where N is the number of bits associated with the repeated bit pattern. The strobe duration should be the same as or smaller than the bit duration. The shorter the pulse duration and the slower the delay scan, the greater the information about the temporal evolution of the data waveform. If a delay generator is used, it may not be possible to generate the strobe pulse faster than a rate of a few megahertz. This is adequate, provided that the delay generator accurately triggers the pulse and so long as the number of pulses within each video frame does not vary significantly. This pulse is then slowly delayed such that it samples the entire data pattern over a period of a few seconds.

The time resolution of the optical oscilloscope is determined by three factors: the duration of the optical strobe pulse, the advance of the strobe pulse during a sampling interval, and the timing jitter of the pulse and the data signals with respect to each other. In the current demonstration discussed in Section 4, a semiconductor laser was used as a strobe source and was synchronized by two signal generators. The optical strobe width was ~200 ps and the pulse advanced at a rate of ~33 ps per video frame for 1-Gb/s data. Thus the strobe pulse duration had a dominant effect on temporal resolution. It is possible to reduce the effect of the strobe duration by performing a deconvolution of the measured pulse waveform with the data waveform.

The time resolution of the oscilloscope can be greatly improved by the use of a mode-locked laser as the strobe illumination. With a mode-locked laser it is possible to generate subpicosecond-duration optical pulses. The strobe delay can be controlled by retroreflection of the laser beam by a mirror mounted on micropositioning stages. In this manner, subpicosecond incremental delays can be added.

Finally, the electronic video signal is connected to video digitization hardware in which the image is stored in memory and becomes available to the computer processor. Rudimentary information is, of course, available to the user, who can directly view the intensity modulation on the video display. Computer-enhanced color mapping can be added to aid in distinguishing logic states. It is, however, the processing of the stored digital images that provides a more complete analysis of the waveforms.

The intensity resolution of this tool is primarily affected by the resolution of the video digitization system and the ratio of the strobe readout state energy relative to the off state. In general, the digitized video signal from current commercially available systems has an accuracy of less than 8 bits or 256 gray-scale levels. One can effectively reduce the level of video noise by integrating the spot intensity from a region of several pixels rather than by relying on a single pixel. In certain situations, this might require the image to be slightly defocused.

To monitor the spot intensities effectively, the background power of the strobe or other illumination during the off state must be considerably less than that of the readout pulse. An estimation of the required contrast ratio for the laser can be determined from

$$P_{\text{on}}/P_{\text{off}} = \text{SNR}^* T_{\text{off}}/T_{\text{on}},$$

where $P_{\text{on}}/P_{\text{off}}$ is the power contrast ratio of the strobe to the background, SNR is the desired signal-to-noise ratio of the waveform, and $T_{\text{on}} = T_s$ and $T_{\text{off}} \sim T_p + \Delta$ are the strobe duration and period respectively. As an example, in the demonstration presented in Section 4, $T_s = 200$ ps and $T_p + \Delta = 16$ ns. Thus for a desired signal-to-noise ratio of 1, the contrast ratio must be ~80. It is this contrast-ratio requirement that determined the need to use a narrow-band optical filter to reduce the spontaneous emission background of the semiconductor laser diode satisfactorily. It must be remembered that a large background signal will further reduce the limited contrast range of the 0 and the 1 states of the MQW modulators.

One of strongest secondary advantages of selecting video cameras to sample the optical waveform is the unparalleled ability to record the signal with conventional video tape recorders. In this manner, system operation can be reviewed or archived to provide comparisons against future performance.

In summary, the electronic module synchronizes the data stream and the strobe pulses. The module may be as simple as a delay generator triggered by the photonic system electronics or as elaborate as two matched signal generators whose base frequencies differ by ~1 Hz. The strobe itself may consist of the readout lasers integrated into the system or separate lasers that form part of the viewport. The optical channels are sampled by a viewport designed to form an image on a standard video camera. The video signal is then digitized by a video-enhanced personal computer for further analysis. Aside from the custom framework needed to attach the viewport to the system, all the diagnostic hardware are readily available and are economically priced.

4. Software Application

The duty of the software application is to

- control the synchronization of the probe pulse and high-speed data stream when necessary,
- manage the sampling and analysis of the video signal,
- allow the user to identify easily the pixel regions of the video frame to monitor,
- display the time sequential intensity evolution of an array of optical channels in a manner reminiscent of a standard electronic oscilloscope.

One project objective was to select a cost-effective personal computer platform for which video acquisition hardware and image analysis software could be easily integrated in a package that could be adapted to a broad class of systems. An Apple Macintosh Quadra 840AV served as the application platform for developing and running the software for the oscilloscope interface. This system was selected on the basis of the integrated video acquisition hardware and the QuickTime video event manager software toolkit. The QuickTime system standard allows the application to be easily transferred to similar systems that adhere to this standard. As proof, the optical oscilloscope has been demonstrated on the Power Macintosh AV platform without modification. In practice, alternative platforms will also provide a suitable environment for implementing this tool.

The application software can be viewed as three basic modules: the video acquisition and analysis module, the oscilloscope control and display module, and the signal synchronization module. Each module provides a user interface for adjusting parameters and options. The software for this project was coded with the Symantec ThinkC++ compiler and relied on the Think Class libraries. Visual Architect also aided in developing a code for the user interface. Both the video and oscilloscope module controls can be accessed through menu items permanently positioned at the top of the display screen and through popup dialogs to support individual functions interactively.

Figure 3 shows an example of the application software in operation. The leftmost window shows an image of the illuminated device array. The center video window shows the application's region selection interface. Sixteen modulator intensity waveforms obtained from the sampled video signal are shown in the rightmost window. For comparison, the intensity waveform of one modulator obtained from a high-speed photodetector is shown on the bottom left.

The synchronization of data stream and strobe pulse can be either controlled by the computer's communicating to a programmable delay generator by using the general-purpose interface bus or implemented by a tight coupling of the operation of the data and pulse generators. Under the computer-control scheme, a message would be sent to the delay generator after each frame capture, instructing the delay to be incremented by a fixed amount. Periodically, the generator would be instructed to restart the cycle. By allowing the computer to directly control the synchronization, the user can determine the degree of resolution or the speed of acquisition desired. We have not fully developed the synchronization control module in this project, as we were able to demonstrate the oscilloscope by using externally synchronized hardware.

The video module is responsible for digitizing, storing, and displaying video frames and extracting the intensity values from the designated regions of interest. The video digitization hardware and software are highly integrated with the workstation in this implementation. Apple QuickTime system software provided access to many features needed to control to these various functions. The Macintosh AV systems have video memory that is accessible by the video acquisition electronics, the central processor, and the graphics display controller, and thus intensity values are easily attainable by the analysis routines.

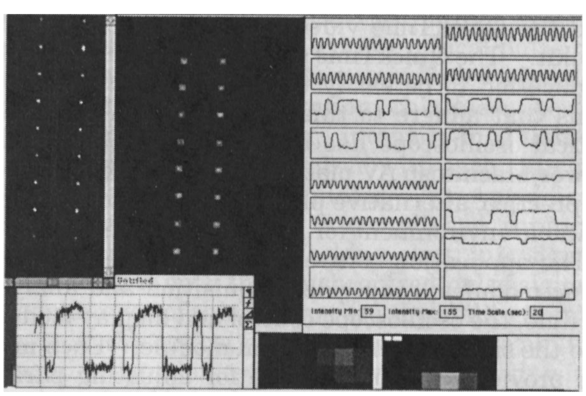

Fig. 3. Oscilloscope display interface showing an image of the illuminated modulator array, a video window for selecting the regions of interest, and the intensity traces for the designated devices.

The display sequence begins by opening the application tool that initializes the video acquisition hardware and displays a video window updated about once each second on the computer monitor. It may initially be necessary to provide broad-area illumination of the chip in order to identify the general location of specific modulators. Next, the illumination is reduced, and the pulsed light source is introduced (and aligned if necessary). It is not unusual to find that this light saturates the camera or video analog-to-digital converter so that a strong neutral-density filter must be inserted to reduce the intensity.

The video tool interface permits creation and manipulation of regions of interest in the video display window. The resizable video window will display either live video or a single captured image so that the user may identify the regions to monitor. A captured image is sometimes favored to avoid aligning during bits intervals when the intensity is low. The user selects the "Click Creates Region" item from the application menu to begin identifying areas to monitor. Using an interactive cursor, the user either selects an arbitrarily distributed set of regions by clicking on the center of each region or defines an array of regularly spaced regions by selecting three corners and providing the number of rows and columns. The region size can be adjusted from a single pixel to an arbitrarily sized rectangle of pixels. In the case of multiple-pixels regions, the average region intensity is calculated. The advantage of specifying a multipixel over a single-pixel region is that the alignment sensitivity is reduced and the averaging reduces some of the inherent video noise. To aid the user in accurately locating the region, a zoom feature will display a magnified region surrounding the selection point.

Another option provided is the ability to pause the video window update during analysis. By choosing to pause, the processor is able to devote a greater fraction of the time to the oscilloscope module and thereby increase its sample analysis rate. During operation, we have demonstrated the ability to analyze ~10 frames per second.

Once the regions are identified, the user selects the menu item "Graph Selected Regions" to create the oscilloscope traces. The oscilloscope interface is designed to present the intensity waveforms in a manner similar to that of a high-speed, multichannel oscilloscope. The waveforms can be displayed as an array of scan plots or overlaid on a common graph. Figures 3 and 4 show an example of an array of scan plots. All scans are simultaneously updated at ~10 points per second per channel. Once the trace has traveled across the plot, it is erased and a new trace is started. The user may choose to stop the scan at any point to examine the waveforms more closely and store the data in a file. Color is also used to

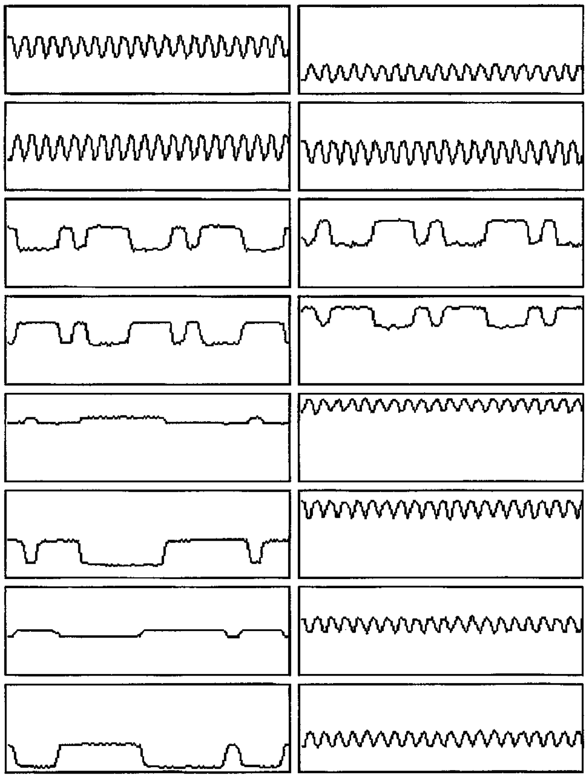

Fig. 4. Array of scope traces taken from 16 modulators. Vertical pairs of scans show complementary data. The data scans are 1-Gb/s nonreturn-to-zero data patterns. The high-frequency scans are 1-GHz square waves.

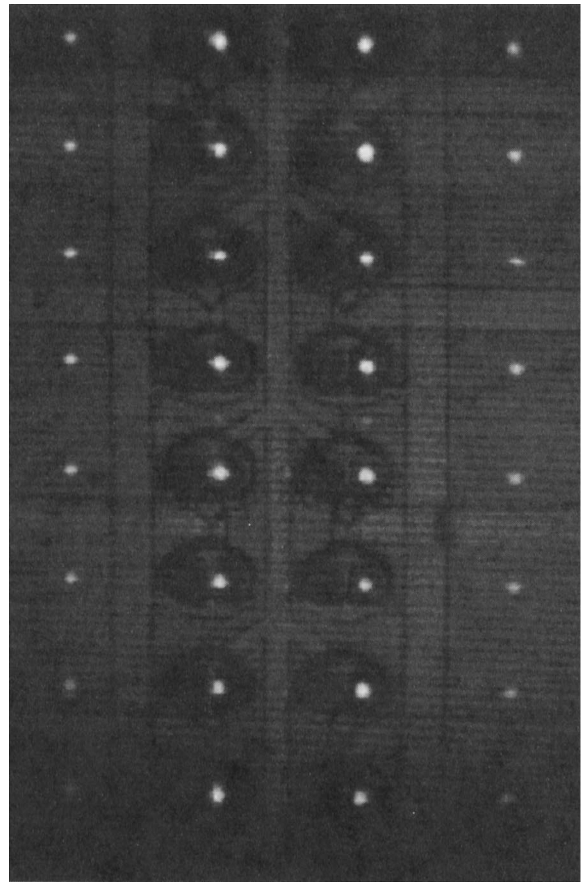

Fig. 5. Image of MQW modulator array illuminated by a beam array captured by video camera.

identify waveforms in the overlay plots, and a single waveform, on being selected, can be correlated with its region in the video window. The time scale and the intensity axis of the scan region are user adjustable. Autoscaling, triggering, and data storage functions are also provided. The user is also provided with a means of defining a signal mask and selecting a specific channel for triggering the scan event.

A video signal of the operating system was collected by a video tape recorder and analyzed by the optical oscilloscope, illustrating a means of storing diagnostics for later analysis. In this mode, the synchronization module is unnecessary.

5. Demonstration

To demonstrate the capabilities of the multichannel optical sampling oscilloscope, a 2 × 4 array of independent electrically driven, differential modulators[4] was monitored while operating at Gb/s data rates. Figure 5 shows an image of the modulator array in which the readout beams have been aligned to a set of the circular modulator windows. The synchronization between the data signals and the probe pulse was fixed by two high-precision, frequency-stabilized analog signal generators synchronized to a common clock to trigger digital data and pulse generators. The frequency of one generator could be adjusted to 1 part in 10^9.

For the data collected in Fig. 4, the data generator was triggered at a rate of 1,000,000,001 Hz, while the probe pulse operated at frequency of 62,500,000 Hz such that the probe pulse monitored every 16th bit. Four of the differential modulators were driven by a data generator (16-bit patterns) at 1 Gb/s, and four were driven by 1-GHz square waves (i.e., a 2-Gb/s 1010 bit pattern). The voltage on the modulators was set to a 3.3-V swing that, coupled with the shift in operating wavelength caused by heating from nearby 50-Ω terminating resistors, led to a poor contrast ratio between on and off states. When the probe pulse is scanned through the data pattern at a rate of ~1 bit per second and sampled ~10 times per second, the sample spacing on the optical oscilloscope is ~100 ps.

Signals were collected to illustrate the similarity of the waveforms obtained by a conventional high-speed photodetector and the optical oscilloscope. Figure 6 is the intensity trace from a high-speed photodetector sampled by an electronic oscilloscope for the data pattern of 10111000 operating at a 1-Gb/s data rate. The resolution of the optical oscilloscope is limited by the optical strobe pulse. Figure 7 shows the strobe pulse intensity profile with a width of ~200 ps as measured by a high-speed photodetector.

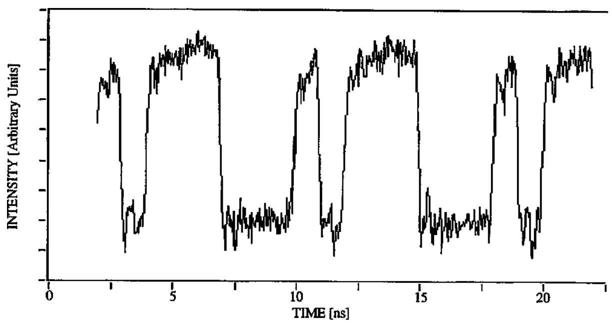

Fig. 6. Data pattern of 10111000 at 1 Gb/s sampled with a conventional high-speed photodetector.

The modulators were operated at data rates from 0.5 to 4 Gb/s. The upper limit was set by the available signal generator. Throughout these data rates, the relative characteristics of the oscilloscope traces remained unchanged. The 1- and 2-Gb/s data have been presented in Fig. 4 because they show more sharply defined edges than the higher rate waveforms do. In each of the 16 traces in the figure, a common intensity and time scale was used. On close observation, it can be seen that scans can be paired vertically as a data stream and its complement. This is as expected because the electronic signal drove the center connection of the serially connected biased self-electro-optic-effect-device modulator pair. The 1-GHz square waves represent an effective 2-Gb/s bit stream that has a 1010 · · · pattern. The patterns in the top half are 1-Gb/s 16-bit nonreturn-to-zero data streams of 1011100010111000, whereas the patterns in the bottom half are 1-Gb/s streams of 1000000111111000. The reduced size of the two signals in the right-hand column appears to be related to the modulator and not to the diagnostic tool.

The strobe spots were also severely defocused to determine whether the oscilloscope performed equivalently when a broad-area illumination was provided. Again the appearance of the traces closely resembled those of Fig. 4. The system also demonstrated the ability to analyze a recorded video signal, although the trace appearance was slightly degraded. This appears to be due to the addition of video noise during the recording and a less stable horizontal and vertical frame-to-frame synchronization. Although only 16 modulators were available for this test, it was demonstrated that the tool could successfully monitor and analyze a 16 × 16 region without degrading performance.

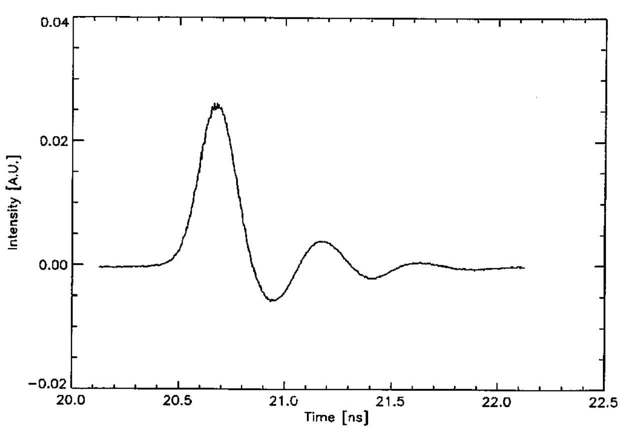

Fig. 7. Intensity evolution of optical strobe pulse as measured by a high-speed photodetector.

6. Summary

The high concentration and overlap of information channels transmitted through a digital free-space photonic architecture preclude the use of local electronic and optoelectronic diagnostic probes. It is, however, possible to insert a viewport into the system to form a remote image of the optoelectronic device array. Through the use of stroboscopic light pulses synchronized to the data stream, it has been shown that high-speed modulator absorption can be monitored by cost-effective video cameras. The high-speed operation of free-space photonic systems is easily monitored with this novel diagnostic tool. Its chief advantage is the ability to process several optically sampled channels operating at multigigahertz rates in parallel. We have demonstrated its operation by simultaneously monitoring 16 modulators operating at data rates ranging from 0.5 to 4 Gb/s.

This work was partially sponsored by the Advanced Research Project Agency under the U.S. Air Force Rome Laboratory contract number F30602-93-C-0166.

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, and E. Kerbis, "Six-stage digital free-space optical switching network using symmetric self-electro-optic-effect devices," Appl. Opt. **32,** 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, and 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,** 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. Technol. Lett. **6,** 1479–1481 (1994).
4. A. L. Lentine, L. M. F. Chirovsky, L. A. D'Asaro, R. F. Kopf, and J. M. Kuo, "High speed 2 × 4 array of differential quantum well modulators," Photon. Technol. Lett. **2,** 477–480 (1990).
5. J. A. Valdmanis and G. Mourou, "Subpicosecond electrooptic sampling: principles and applications," IEEE J. Quantum Electron. **QE-22,** 69–78 (1986).
6. B. H. Kolner and D. M. Bloom, "Electrooptic sampling in GaAs integrated circuits," IEEE J. Quantum Electron. **QE-22,** 79–94 (1986).