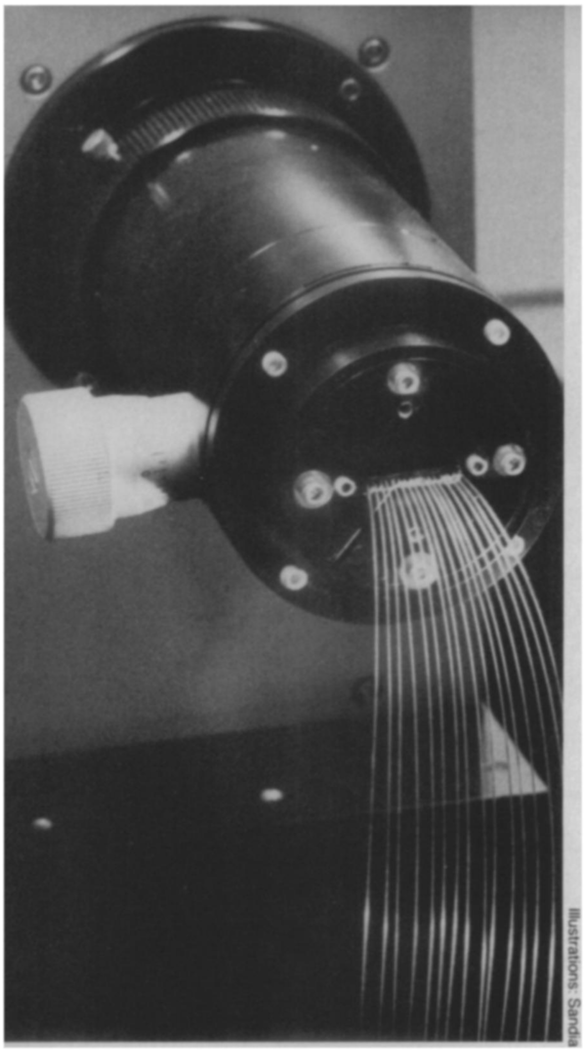
Throwing Light on Data-Taking

Electronic data-taking just isn't fast enough for some kinds of experiments. Starting from those applications, a new technique, photonics, could challenge electronics across the board.


Illustrations: Sandia

Array of data-carrying optical transmission fibers enters a streak camera.

By DIETRICK E. THOMSEN

Oscilloscopes are everywhere: in laboratories, factories, hospitals, repair shops. In a slightly different incarnation, as television picture tubes, they appear at least once in almost every household. They are used to monitor particle physics experiments, the beating of injured hearts, the pit stops of racing motors and the landings of airplanes. Our age is an electronic age — no fooling — and oscilloscopes are the most visible link in a common technology that senses, transmits, displays and records information by manipulating electrons.

Yet this ubiquitous technology lacks the speed and versatility desirable for certain scientific applications: those where a large variety of physical measurables change over extremely short times (billionths or trillionths of a second), such as the pulsed power devices of the Sandia National Laboratories in Albuquerque, N.M., and related installations. In these areas, a new technology, photonics, is finding its niche. Photonics uses photons — that is, particles of light — to do what electronics does with electrons.

In the opinion of James Chang of Sandia, a leading researcher in the development of photonics, such a new technology needs a niche, an application where the standard technology just can't cut it, in order to show what it can do and to begin to compete with the entrenched technology. From this niche photonics is likely to spread, he believes, replacing electronics in other applications. Today the oscilloscope and the technology connected to it is the tool of scientists, engineers, technicians and intensive-care-unit physicians, as it was 30 years ago. However, 30 years ago the slide rule was also a favorite tool of most of those people. Where is the slide rule now?

Photonics uses optical sensors, light pulses in glass fibers and streak cameras or other optical display devices in place of electrical sensors, electrical pulses in coaxial cables and oscilloscopes. Its development was driven, Chang says, by the requirements of such experimental devices as Sandia's Particle Beam Fusion Accelerator I (PBFA-I). PBFA-I stores up electrical energy and then releases it in extremely short high-power bursts. These high-power pulses are used in experiments relating to controlled thermonuclear fusion, weapons development and development of X-ray and gamma-ray lasers and other devices.

The shots are transient events — lasting a few nanoseconds or even less than a nanosecond — and in this ultrashort period a large number of important physical measurables are changing in complicated ways. The shots are expensive, about $100,000 apiece, and they can run three or four times a week. With such amounts of money in play the experimenters want to find out as much as they can about whatever happens during each shot. It is there that electronics hampers them, Chang says. It is just too slow.

Electronics today, like electronics 35 years ago, is limited to a signal bandwidth of 1 gigahertz, Chang says; that seems to be a "stone wall" limitation. In this matter bandwidth translates into time duration, and 1 gigahertz means time periods no shorter than about 335 picoseconds. During a 2-nanosecond event, experimenters want to be able to measure occurrences as short as 30 nanoseconds or so, Chang says.

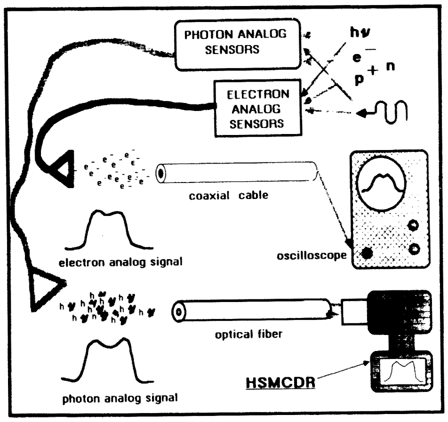
Circumstances also limit the feasible number of separate electronic measurement channels — and each measurable quantity requires a separate channel. Each such channel needs a separate coaxial cable and a separate oscilloscope. Oscilloscopes sensitive enough for these functions cost something like $30,000 to $35,000, Chang says. If an experiment requires 77 channels, that means 77 oscilloscopes or about $2 million for them alone.

That's not even adequate, Chang says. Experimenters would like 200 channels, or even more. PBFA-I has 36 transmission lines bringing electrical power to a concentration in a single central diode. Each line has 10 diagnostic points; that's 360 channels.

The result, says Chang, is that you can either do the experiment or do the instrumentation. As experimenters are naturally oriented toward doing experiments, "therefore we're always underdiagnosed." Thinking about it, he says, Chang's group realized that electrons are the cause of the problem: "You're always pushing electrons through a conductor," which is a resistive path. They asked themselves: Why not use something that has no mass — that is, a photon — and push it through an optical fiber, which is virtually nonresistive? Turns out that it works.

The fiber is the key to it, Chang says. The fiber allows them to send the photons along any arbitrary path. If the fibers did not exist, and the photons had to be guided along straight lines by mirrors, it would be totally impractical.

The photonic procedure shows other advantages as well. A very important one is electrical isolation. Light pulses in fibers are not affected by electric and magnetic fields that may exist in the neighborhood; electronic signals are. (And in the neighborhood of PBFA-I there are very strong electric and magnetic fields.) Photonics takes up less space — a single coaxial cable is as thick as a whole array of optical fibers. Photonics is cheaper and has a larger signal bandwidth than electronics. Finally, says Chang, there's "a very subtle advantage" — an end to limitations on signal dynamics.



Schematic comparison of photonic and electronic data gathering.

Chang points to computer-integrated display of amplitude versus time information from one of 11 channels recorded in a typical application of photonics. The screen on the left images streaks produced by all 11 channels in a single view.

Dynamics measures how strong a signal is. To use the electronic analog, says Chang, you can measure the strength of a happening in two ways. You can put a sensor in the presence of the measurable quantity, and, as that quantity changes, the sensor puts out an analog signal, whose electronic amplitude matches the strength of the observable quantity at any given moment. There is a limiting amplitude in any such system, the maximum electronic signal that the system will carry. If the strength of the observable passes that maximum, the signal will go no higher than the maximum, which is misleading, or it will blow out the system, which sends everything kaput.

The way around this is to use phase-modulation measuring. The strength of the observable quantity is made to alter the phase of a passing electronic signal, a carrier wave. In principle such a system has no dynamic limitations: The strength of the observable quantity is read by counting the number of cycles of the carrier wave that bear the phase alteration; the signal strength never exceeds the capacity of the transmission lines.

Electronic phase modulation of this kind will work well with fairly long-term processes, but electronic carrier waves have fairly low frequencies. This means that for events that occur quickly they may not have enough cycles available in time to measure changes accurately.

"You can do it electronically for low bandwidth," says Chang. "How do you do it when you have a high-speed single-shot phenomenon, which occurs in a few nanoseconds?" You need a high carrier frequency. Light waves have it. Their frequencies are 10^{13} to 10^{15} hertz. "That is a really subtle breakthrough as far as measurement technology is concerned. We can now make measurements that previously were limited to 15 or 20 percent accuracy with 2 percent accuracy. . . . A phenomenal improvement . . . revolutionary."

Photonic transmission has all these advantages. To do away with the limitations of oscilloscopes – where again "you have to wiggle electrons around" – Chang and his collaborators developed what they call a High-Speed Multichannel Data Recorder (HSMCDR, pronounced "husmucder"). The output of an array of optical fibers is imaged on the phosphor screen of a cathode ray tube. Each fiber produces a dot on the screen. The screen is monitored by a streak camera, a camera with a moving frame. In the streak camera, each dot produces a streak.

The streak camera gives three-dimensions of information: time (location along a given streak), intensity (the brightness at any point on the streak) and channel (which streak it is). An oscilloscope can give only two dimensions: time and intensity. Each separate channel requires its own oscilloscope. A streak camera can cost $100,000, but in the first version of the HSMCDR, it accounted for 22 separate channels, thus delivering information for about $5,000 per channel rather than $30,000. Another version will record 50 to 70 fibers for about $120,000.

Beyond the HSMCDR is a recorder that does away with the cathode ray tube and the streak camera. It puts the output of the fibers into an electro-optic crystal, a substance whose refractive properties change as a voltage applied across it changes. As the voltage changes the crystal deflects the light, and the output of each fiber is scanned across a charge-coupled device array. A charge-coupled device is a checkerboard arrangement of photoelectric sensors. Each element in the array senses the fiber's output at a certain instant and transforms that into a pulse of electrons, which it sends to a computer memory. (We have as yet no optical computers, so at some point the information gathered and transmitted optically must be converted to electronics for storage and computation, but that, with the necessary slowing to accommodate the speed limitations of electronics, is best done at the far end of the procedure, Chang says.)

Where the signals start out, optical sensors can replace electronic ones. Some occurrences produce light pulses directly. That is what happens when a subatomic particle strikes a scintillation detector. All that is required then is a fiber coupled to the detector to pick up the scintillation.

Sensors for various electrical quantities, such as electric field, voltage and current, depend on the effects of these phenomena on the light transmission properties of certain substances. Generally the substance alters the polarization of light passing through it as the quantity to be measured changes. When the light exits from the substance (usually some crystal, although in the case of a voltage detector it happens to be the water dielectric that separates capacitor plates in the power transmission line), it is passed through a cross polarizer. The cross polarizer lets a blip of light through if the original polarization of the light has been changed by such-and-such an amount, cancels it for a further change, lets it through again for yet a further change, and so on. To get the total change, count the blips.

Chang says the first sensor they made was to sense the radiation from a very strong source of microwave radio waves vibrating in the hundreds of megahertz. The vibration of these waves is sensed through the wiggle of their electric field, which affects the polarization of the light signal. The blips let through by the cross polarizer were coming out at a rate of 3 gigahertz. To this Chang exclaims: "My God, I made a 3-gigahertz measurement in real time!"

Photonics, Chang emphasizes, is a new technology from beginning to end, not a variation or an improvement on an old technology. As such, he figures, it would have a hard time getting started without this pulsed power niche where the older technology falls short. It will also have a hard time competing against an entrenched technology and extending itself beyond its little niche without a capacity for retrofitting, for building pieces of photonic systems into existing electronic ones *ad interim*. This need was foreseen by the people who are building photonic information transmission lines into the world's telecommunications networks. In both cases photonic-to-electronic and vice versa transducers exist or are being developed for retrofitting.

"To change technologies," Chang says, "you really have to wait for people to retire," so strong is most people's attachment to what they know and have invested their lives in. But with that caveat he expects a bright future for photonics. ☐