Timing Subpicosecond Electronic Processes

Using the same ultrashort light pulse from a laser to generate and then detect an electrical signal is the key to high-speed measurement

The fastest transistor reported so far switches in only 12 picoseconds. But no oscilloscope, the usual tool for recording electrical signals that change rapidly with time, has circuits fast enough to keep up with this. Researchers partly solved the problem by measuring the delay when a signal propagated through several transistors in series, thereby obtaining an average switching time.

While better than nothing, an average does not give the kind of information a researcher needs to characterize adequately a transistor and perhaps point the way to even better performance. Moreover, other kinds of electronic devices, such as high-speed photodetectors that can respond to light pulses in a picosecond or less, do not lend themselves to this approach at all.

Lasers provide a way out of the dilemma. The rise and decay of light from ultrahigh-speed pulsed lasers, which have pulses as short as 16 femtoseconds, the current speed record, are faster by far than any electrical device. With lasers, researchers at the Laboratory for Laser Energetics of the University of Rochester and at AT&T Bell Laboratories have been able to obtain time traces of electrical pulses lasting less than 0.5 picosecond. At least one company is working on a commercial version of the Rochester scheme.

A sampling oscilloscope, which can resolve repetitive signals down to 25 picoseconds, is the fastest type of oscilloscope. A high-speed circuit acts like a gate that lets in the signal only during a brief time interval, during which it is measured. To reconstruct the signal trace, the time interval is incremented so that successive segments are sampled as the signal repeats.

Synchronization is the major timing problem. The gate circuit needs to know when the signal is arriving and has to wait the prescibed period before opening for each sample. State-of-the-art circuitry limits how reproducibly this can be done. The laser-based methods overcome this difficulty because light from the same laser pulse triggers the signal generation and gate opening processes.

Researchers call the laser equivalent of sampling "pump and probe," which is now a venerable technique for looking at the kinetics of very fast optical processes. A partially reflecting mirror splits the laser pulse into two parts. Both pulses proceed to the sample but by different paths. The path length of one is adjusted by placing a mirror on a movable stage whose position can be accurately set. Each micrometer added to the path delays the pulse by 3 femtoseconds.

As described, pump and probe is an entirely optical affair. For the measurement of electrical signals, some way to tie optical and electronic effects together is needed. Four years ago, David Auston, Peter Smith, and John Bean of Bell Labs together with Anthony Johnson of the City College of the City University of New York, devised a way to use high-speed photoconductors for this purpose.

A photoconductor can act as a light-activated switch that turns current on and off in a circuit.

Photoconductors are semiconductors whose conductivity increases when exposed to light. If the difference between its conductivity in the dark and in the light is very high, a photoconductor can act as a light-activated switch that turns the current on and off in a circuit with a voltage source.

The Bell Labs method required two photoconductors. A laser pulse irradiating the first device launched a current pulse in a high-speed circuit. But between the current pulse and a detector was the second photoconductor, which played the role of the gate in the sampling oscilloscope. The second photoconductor let the pulse pass only when it was also irradiated. By varying the time delay between the two laser pulses, the researchers mapped out the shape of the electrical pulse, in this case the response of the photoconductor.

Short electrical pulses smear out quickly as they travel down a wire, but do much better in a transmission line, where signals propagate as electromagnetic waves at nearly the speed of light. The photoconducting switches made use of the microstrip transmission lines that are familiar in microwave circuits. These consist of two parallel electrically conducting strips, one above the other on the top and bottom surfaces of a dielectric substrate. The circuit elements (photoconductors in this case) sit in gaps in the upper conductor, while the lower is grounded.

For the method to work it is essential that the photoconductors respond to the laser light pulses very rapidly. The 1980 experiments at Bell Labs used amorphous (noncrystalline) silicon, which had a response time of less than 10 picoseconds. Subsequently, Smith, Auston, and Walter Augustyniak of Bell Labs used thin films of silicon on insulating substrates as even faster photoconductors to measure the switching time of a gallium arsenide transistor. The current pulse launched by the first photoconductor switched the transistor on and off, while the second photoconductor served as the sampling gate.

To get below 1 picosecond, Janis Valdmanis (now at Bell Labs), Gerard Mourou, and Conger Gabel of Rochester turned to an electro-optic effect for the sampling gate. The Pockels effect changes the birefringence of materials such as lithium niobate when an electric field is present. Birefringent means that the index of refraction or the speed of light in the material depends on the polarization of the light wave with respect to the material's "optical axis."

In 1982, the Rochester group reported a temporal resolution of 4 picoseconds. One part of a split laser pulse irradiated a gallium arsenide photoconductor that launched a current pulse down a microstrip transmission line on a lithium niobate crystal. The other part of the pulse passed through a polarizer and through the lithium niobate between the conductors of the transmission line to a polarization analyzer with a light detector behind it. With a current in the transmission line, there is an electric field between the conductors that affects the lithium niobate birefringence and therefore the polarization of the light pulse. This changes slightly the intensity of the light passed by the analyzer. By varying the time delay between the two laser pulses and observing the change in intensity, one maps out the shape of the electrical pulse.

The improved time resolution comes from the rapid speed of the transition to the birefringent state, which occurs in a few femtoseconds. The practical limitations are geometrical, the time it takes the laser pulse to pass through the lithium niobate between the conductors of the transmission line and for the electrical pulse to pass through the focused laser beam.

Last year, the same group used a smaller lithium tantalate crystal with transmission line conductors only 300 micrometers wide and focused the laser beam to 20 micrometers diameter to achieve a time resolution of 850 femtoseconds. The time resolution also improved as the thickness of the lithium tantalate crystal and hence the separation between the transmission line conductors decreased, the thinnest being 100 micrometers.

To further reduce the geometry, Kevin Meyer of Rochester and Mourou have adopted a so-called coplanar strip line in which the two conductors lie side by side on the top surface of the crystal. In this way, the methods used in delineating the patterns of microcircuits can be used to miniaturize the transmission line. In a first attempt with conductors 50 micrometers wide and 50 micrometers apart, Meyer and Mourou obtained a 460 picosecond time resolution.

Meyer and Mourou are also working on a more practical geometry for measuring waveforms in circuits. Princeton Applied Research has licensed the Rochester technology for possible commercialization.

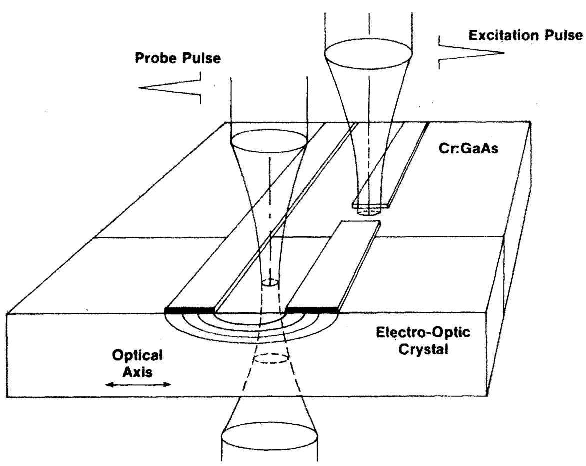
At Stanford University, Brian Kolner and David Bloom are applying electrooptic sampling to the problem of generating test signals for transistors in integrated circuits and recording the transistors' responses. Ideally, the test circuitry would be part of the chip, but no integrated circuits are made on lithium niobate or tantalate. Very fortunately, gallium arsenide, which is a candidate for very high speed integrated circuits, also exhibits the Pockels effect.

In their first demonstration, Kolner and Bloom tested the response of a high-speed gallium arsenide photodetector (photodiode) of the type developed by Bloom and his colleagues when he was at Hewlett-Packard Laboratories. On-chip testing requires a reflection geometry. One part of a laser pulse irradiated the photodiode, initiating an electrical pulse that entered a transmission line on a gallium arsenide substrate in the usual way. But the second part of the laser pulse was focused onto the gallium arsenide adjacent to the top conductor of the transmission line, where it entered the gallium arsenide, reflected from the bottom surface, and exited through the top near the entry point.

At Bell Labs, researchers have been taking another tack to achieving higher speed. Transmission lines have a property called dispersion that degrades time resolution. A short pulse represented by a Fourier series contains terms with a wide range of frequencies, each of which propagates through the transmission line at a different speed, so that the pulse spreads out. One approach is to eliminate the transmission line altogether and let the pulse travel as a wave through a nonconductor.

Coplanar sampler

A 100-femtosecond laser pulse excites the gallium arsenide photoconductor, launching a signal in the microstrip transmission line. After a controlled delay, a second 100-femtosecond pulse passes through the electro-optic crystal between the conductors of the transmission line, where the signal has changed the crystal's birefringence. [Source: K. E. Meyer and G. A. Mourou, Laboratory for Laser Energetics]



Last month, Auston, Kin Ping Cheung of Bell Labs, and Smith reported on this method. They prepared two silicon photoconductor films on opposite sides of an alumina slab 1.1 millimeters thick. One part of a laser pulse of 100 femtoseconds duration was focused on a gap in the metal electrode that covered most of one photoconductor surface. With a voltage source on one side of the electrode, this caused a current pulse in the photoconductor that, by Maxwell's equations of electromagnetism, generated a pulse of radiation in the alumina.

The other part of the laser pulse was focused on a gap in the electrode covering most of the second photoconductor. With no voltage source for this photoconductor, no current ordinarily flows. However, the electric field of the radiated pulse can drive the photocurrent. By varying the delay between the two laser pulses and measuring the photocurrent in the receiving photoconductor, the researchers mapped out the current pulse in the sending photoconductor. The time resolution was 1.6 picoseconds, as compared to 12 picoseconds when the same photoconductors were in the microstrip transmission line configuration.

Auston, Cheung, Valdmanis, and David Kleinman of Bell Labs have just reported a second approach to doing away with microstrip transmission lines. When a laser light travels through a material like lithium tantalate that is electro-optically active, it polarizes the material; that is, there is an electric dipole moment. If the light is a short pulse, the effect is that of a "particle" with a dipole moment shooting through the material. Once again, by Maxwell's equations, the transient dipole generates a pulse of radiation.

The speed of the "particle" with the dipole moment (the laser pulse) is faster than that of the lower frequency radiation it generates. The situation is analogous to that holding for Cherenkov radiation, which is created when an electrically charged particle travels faster than the speed of light in a material. All the light intensity lies on a shock-wave cone that trails behind the fast moving particle.

The Bell Labs group adapted the electro-optic sampling technique developed at Rochester to detect this radiation. A second, probe laser pulse travels through the lithium tantalate on a path parallel to but some distance away from that of the generating pulse. The polarization of the probe pulse light changes when it passes through the cone of radiation. The measured duration of the radiation pulse was 225 femtoseconds.

One way to use this radiation is in a novel kind of time-domain spectroscopy. The short pulse contains a broad band of frequencies up to 4 terahertz, which is in the far infrared, where there are not at present good tunable sources. By measuring the time trace of the pulse reflected from a material bonded to the lithium tantalate and using Fourier analysis, one can obtain the frequency dependence of the real and imaginary parts of the dielectric constant. With a third laser pulse, it is possible to do this kind of spectroscopy on short-lived species. The third laser could excite free electrons in a semiconductor, for example, which then relax. Experiments to demonstrate this capability are under way now at Bell Labs.—**Arthur L. Robinson**