Ultrashort Light Pulses

Peter W. Smith and Andrew M. Weiner

Abstract

In the past few years, there have been dramatic improvements in the ability to generate and control ultrashort light pulses. Researchers are now exploring ways in which such pulses may be used in future ultra-high capacity communications networks. This paper is a tutorial review of the field of ultrashort pulse generation and use. It is a revised version of an article that appeared in Bell Communications Research Exchange *magazine.*

Before the invention of the laser 25 years ago, the shortest pulses of light that could be generated were the strobe light flashes used for "stop-action" photography. Today, using lasers, researchers are able to generate light pulses 100,000 times shorter than these strobe light flashes and are using these ultrashort pulses to explore new frontiers in science and technology.

Light pulses under a picosecond in duration (see box: "What's a Picosecond?") were first observed 15 years ago. Since then, short pulse technology has advanced to the point where it is now possible to generate light pulses under 10 fsec long, Fig. 1. A 10-fsec pulse only lasts for about five periods of optical oscillation (cycles). Thus, we are rapidly approaching the fundamental limit of one optical oscillation cycle (about 2 fsec for visible light).

Researchers are working on the generation and control of ultrashort light pulses and are using these pulses to study new ultrafast optical switching elements. There are several motivations for this work.

First, ultrashort light pulses are a potential signal source in future high-bit-rate optical communication systems. The shorter the pulses, the more can be packed into a given time interval and the higher the data transmission rate. The use of ultrashort light pulses combined with all-optical switching and signal processing will allow future lightwave systems to take advantage of the tremendous bandwidth capacity of optical fiber transmission.

Second, ultrashort light pulses are opening up new areas in optoelectronics; for example, they may be used to generate, switch, and sample short electrical pulses. Thus, optical techniques can be used to measure the performance of very fast electronic structures and devices.

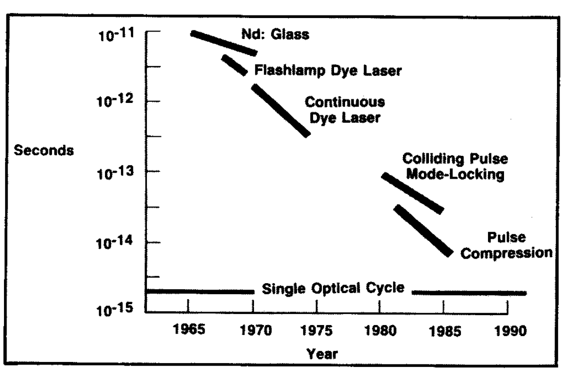

Fig. 1 Progress in short pulse generation.

Third, short optical pulses provide scientists with a tool for studying ultrafast processes in physics, chemistry, and biology. An analogy is strobe photography. Short bursts of light on the order of tens of microseconds in duration can "freeze" mechanical motions for stop-action photographs. By this method, we can photograph a bullet as it is shot through an apple or see a golf club hit and initially compress a golf ball. Strobe photography works because the light flashes occur so fast that no noticeable mechanical movement occurs during the flash. On a pico- or femtosecond time scale, the microscopic world is alive with motion. Atoms and molecules are vibrating; electrons are colliding with and scattering from the crystal lattice in metals and semiconductors; and rhodopsin molecules in the eye are undergoing complex photochemical changes in the process of converting incident light into a perceived image. Sophisticated measurement techniques using ultrashort light pulses make it possible to study this microscopic world.

To understand how short pulses are created, it helps to visualize how a laser operates. A typical laser consists of two essential elements: gain and feedback. The gain, or amplifying medium, is prepared by pumping its molecules up to a high energy level using an external power source such as an electrical discharge, a flashlamp, or another laser. A beam of light passing through such a material stimulates the molecules to release their extra energy in the form of additional light that adds to, or amplifies, the beam. Feedback is achieved by placing the amplifying medium within a resonator (a set of mirrors that reflects the beam back and forth, again and again, through the gain material). Each passage results in further amplification. As a result of this cumulative process, an intense, coherent beam of light (a laser beam) is produced.

Laser output occurs at a number of discrete wavelengths corresponding to different resonant frequencies (modes) of the resonator, Fig. 2a. If there is no fixed phase relationship between these modes, the various frequencies will interfere with each other, and the output will fluctuate over time, Fig. 2b. Mode-locking—fixing the relative phases of these modes—forces the laser to emit a train of narrow light pulses, Fig. 2c. The larger the band of frequencies over which the laser oscillates, the shorter the duration of the mode-locked pulses that can be produced. Mode-locking can be accomplished by placing a modulating element, either active or passive, within the laser resonator.

In active mode-locking, the modulator is driven by an external power source. The loss modulator that is commonly used may be pictured as a shutter that periodically opens and closes. When the modulation frequency is correctly adjusted, the shutter period is exactly synchronized to the resonator round trip time; a short pulse traveling back and forth within the laser may pass through the shutter, without loss, again and again. Pulses under 100 psec in duration have been obtained with this method.

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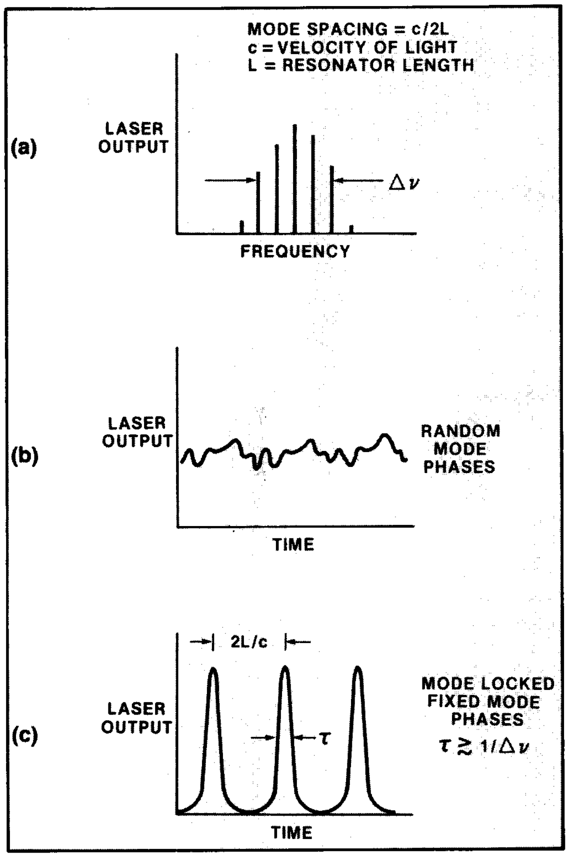


Fig. 2 Laser output—(a) Typical laser output as a function of frequency showing oscillating modes over frequency bandwidth $\Delta\nu$. (b) Laser output with randomly phased modes. (c) Mode-locked laser output with pulse duration $\tau \sim 1/\Delta\nu$.

Even shorter pulses have been produced using passive mode-locking, which requires no outside power source for its modulator. The modulator used in passive mode-locking is usually a saturable absorber dye. The absorption of such a dye decreases with increasing light intensity; i.e., the fraction of light transmitted by the dye increases with increasing intensity. When a pulse of light traveling back and forth within a laser passes through a saturable absorber, the absorber is bleached; hence, the transmission function of the absorber is modulated by the optical pulse. The saturable absorber in a laser that is mode-locked in this way produces a modulation that is automatically synchronized with the round trip time of the resonator.

This process of passive mode-locking is best exploited using a ring-shaped laser called a *colliding-pulse-mode-locked (CPM) ring dye laser*, Fig. 3. The ring geometry allows two pulses to exist in the laser at the same time; one travels around the ring in a clockwise direction, the other counterclockwise. The two pulses meet or "collide" in the saturable absorber. This collision leads to enhanced bleaching of the absorber, resulting in shorter pulses than those obtained with conventional mode-locking. With additional refinements that compensate for intracavity pulse broadening, such a laser has generated pulses as short as 27 fsec.

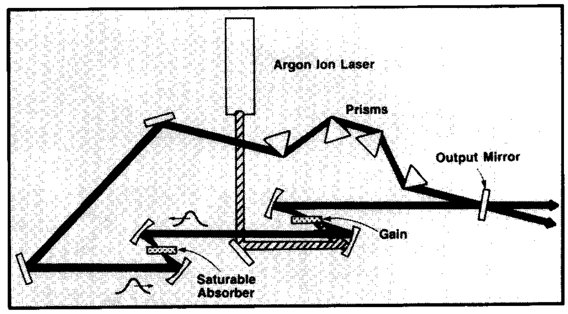


Fig. 3 Colliding-pulse-mode-locked (CPM) ring dye laser. Pulses "collide" in the saturable absorber but arrive singly in the gain medium, which uses an external argon ion laser as a power source. Femtosecond pulses are obtained through the partially transmitting output mirror.

Even shorter pulses can be produced when mode-locking is combined with a technique called *pulse compression*. Although this technique has roots in the radar technology of the 1950s, in the last several years, it has achieved new vitality in the optical field. The shortest optical pulses achieved to date—only 6 fsec long—have been obtained by applying pulse compression to the already very short pulses produced by a CPM ring dye laser. Relatively long pulses from actively mode-locked lasers may now also be compressed to durations previously accessible only with passively mode-locked lasers. For example, researchers have compressed neodymium:yttrium aluminum garnet (Nd:YAG) laser pulses by nearly two orders of magnitude: from 75 psec to only 0.8 psec (see box: "Pulse Compression").

Measuring the duration of ultrashort light pulses is no easy task. The shortest optical pulses today are more than three orders of magnitude shorter than the response of the fastest photodetectors and electronic sampling oscilloscopes. Thus, conventional electronic methods cannot be used to measure picosecond and femtosecond optical pulses. The pulses can be measured, however, using new optical techniques, which have been developed for this purpose. These techniques, known as autocorrelation techniques, use two synchronized, ultrafast pulses to sample each other (see box: "Measuring Ultrashort Light Pulses").

The ability to generate and control ultrashort light pulses has exciting implications for the design of future communications networks. We will mention briefly, here, two potential applications that appear to show great promise: high-speed signal processing and parallel processing.

In optical communications systems, the characteristics of large bandwidth, high speed, and the ability to process signals already in the form of light should be particularly useful. It should be possible, for example, to make an all-optical multiplexer, Fig. 4, that would take several optical data streams, each with the maximum data rate compatible with electronic devices, and multiplex them into a single data stream for transmission down an optical fiber at a much higher bit rate. At the other end, a similar all-optical device could demultiplex to get back to data rates that can be handled with electronic components.

Many optical devices are especially suited for parallel processing application, where many individual operations must be performed at the same time. One type of optical

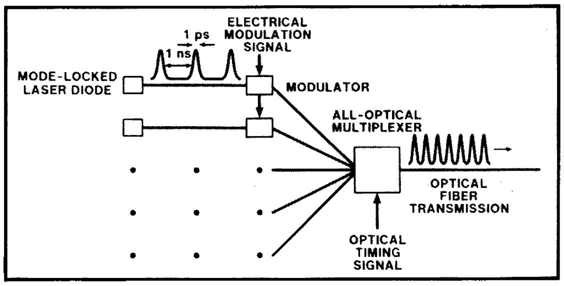


Fig. 4 A possible scheme for optically multiplexing signals from a number of mode-locked laser diodes using a fast all-optical multiplexer.

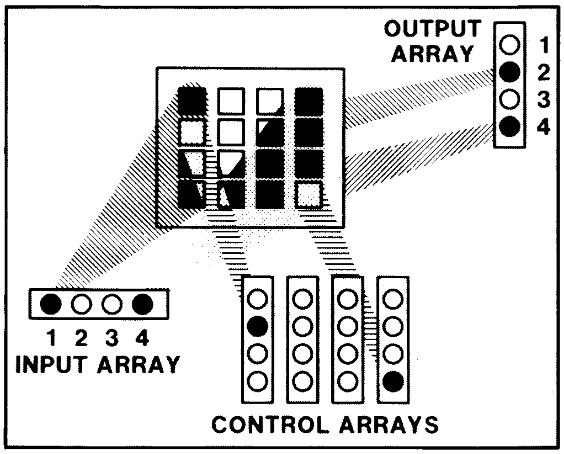


Fig. 5 A possible scheme for an optical crossbar switch array. The array is shown switched so that input 1 is connected to output 2, and input 4 is connected to output 4.

device that could be developed for this purpose is an optical "crossbar," Fig. 5, in which each crosspoint is an all-optical switching element that can be switched from "transmitting" to "not transmitting" by a light beam from a control array. Each input beam illuminates one of the columns, and each output beam collects the light from one of the rows. By switching the crosspoints to the "transmitting" state, it is possible to connect any input to any output. This could, in principle, be done very rapidly and with very large bandwidth channels.

Before such applications can become a reality, however, further research is needed to develop ultrafast materials and devices that are compact and efficient. We mention below three examples of current research that will help lay the groundwork for telecommunications applications of ultrashort light pulse technology: mode-locking of semiconductor diode lasers, manipulation of picosecond and subpicosecond pulse shapes, and measurements of ultrafast semiconductor dynamics.

For ultrashort pulses to find widespread use outside of the laboratory, a simple, compact, and reliable pulse source is needed. Although the shortest pulses have been generated with dye lasers, such systems are large, costly, and inefficient. For this reason, researchers have been studying ways to mode-lock a semiconductor diode laser in order to produce a compact and efficient solid-state source of picosecond pulses. They have found that diode laser mode-locking can be achieved with the aid of a thin semiconductor wafer composed of many alternating layers of material, each of which is only a few atomic layers thick. This semiconductor structure, called *multiple quantum well (MQW) material*, has unique electrical and optical properties. The optical properties of MQW material make it potentially useful as a saturable absorber for passive mode-locking of diode lasers. By bombarding the MQW material with protons, researchers can tailor its absorption characteristics to produce optimum mode-locking.

Recently, Bellcore researchers reported a new record for the shortest pulses ever obtained in continuous train from a mode-locked diode laser: 0.8 psec.[1] This is an important step toward the practical application of picosecond light pulses in high-bit-rate communications systems.

Manipulating the shape of ultrashort light pulses is an area of research that grew out of pulse compression studies. Scientists have invented a way to produce arbitrarily shaped optical pulses, with picosecond or even subpicosecond features. This ability to synthesize arbitrary pulse shapes may well have important applications for optical communications systems, optical radar systems, and picosecond studies of optical interactions in nonlinear materials.

Pulses are shaped using a modified pulse compressor apparatus. Within this apparatus, the various frequency components (colors), which constitute the pulse, are separated in space. The amplitude and phase of the various spatially dispersed frequency components can be individually controlled. Since the temporal pulse shape is determined by the frequency spectrum, pulse shapes may be tailored by adjusting the spectrum. In this fashion, a wide variety of ultrashort optical pulse shapes have been generated.

Bellcore researchers have been successful in producing the world's first picosecond optical "square" pulse, Fig. 6. The rise and fall times of the square pulse are limited only by the available optical bandwidth. Such a shaped pulse should be useful in connection with digital optical signal-processing systems.

Other research has focused on studying the solid-state physics of semiconductor materials on a picosecond scale.

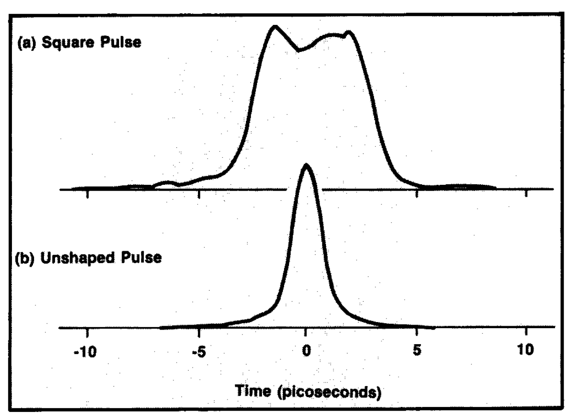


Fig. 6 A picosecond optical square pulse. An unshaped pulse is shown for comparison.

Specifically, researchers are investigating the dynamics of "hot" charge carriers in semiconductors. Carriers are said to be hot when they are driven out of thermal equilibrium with the surrounding crystal lattice to higher energy states.

In one type of experiment, picosecond light pulses from a mode-locked dye laser are used to produce the hot carriers within the semiconductor. The subsequent luminescence from the carriers provides information about their energy distribution. The electron temperature may be monitored by tracing out the time history of the luminescence spectrum. In other words, one can determine the way in which the carriers return to equilibrium. An understanding of carrier cooling mechanisms is important not only from a fundamental physical viewpoint but also because of its relevance to the design of high-speed optical and electronic switching devices using semiconductor materials.

Many challenges still face researchers before picosecond and femtosecond optics can be moved out of the laboratory and into telecommunications and signal-processing systems. Improved techniques for generating and controlling ultrashort light pulses are still being studied, and efficient solid-state materials for optical signal-processing devices are being developed. Parallel advances in other disciplines, such as microfabrication techniques, integrated optics, and network design, are rapidly taking place. Just as the research of a few years ago has led to today's technology, so will today's laboratory studies of ultrashort light pulses lead to tomorrow's ultrahigh capacity communications networks.

BOX 1 - What's a Picosecond?

In 1 sec, light travels 186,000 mi., so a 1-sec pulse would stretch three-quarters of the distance from the earth to the moon. Picoseconds and femtoseconds are miniscule fractions of 1 sec.

A picosecond is one trillionth of a second, or 10^{-12} sec. A light pulse of a picosecond duration has a length of about one-third of a millimeter—about the thickness of a business card.

A femtosecond is one quadrillionth of a second, or 10^{-15} sec. There are as many femtoseconds in 1 sec as there are seconds in 30 million years. One femtosecond is the time it takes for light to travel approximately 3000 Å, which is less than 1 percent of the thickness of a human hair.

BOX 2 - Pulse Compression

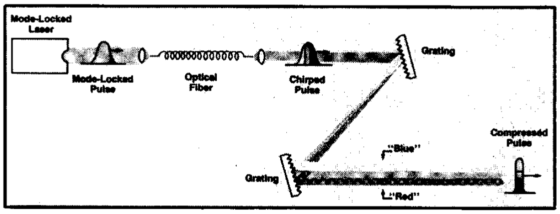
The technique of pulse compression exploits a nonlinear optical interaction that occurs naturally within single-mode glass fiber—the same sort of fiber now being used in optical communications systems. This interaction, known as self-phase modulation, occurs because the refractive index of the glass is modulated by the presence of an intense optical pulse. The change in refractive index in turn affects the optical phase. As a result of this process, the bandwidth of the optical pulse emerging from the fiber is increased dramatically. Since the minimum achievable pulse-width is limited by the bandwidth, the spectrally broadened pulses have the potential to be compressed by a substantial amount.

The additional bandwidth of the pulse emerging from the fiber is caused by a "chirp"—the instantaneous frequency increases with time. The leading edge of the pulse contains red-shifted frequency components, and the latter part of the pulse contains blue-shifted components. This chirped pulse is then directed through a pair of parallel diffraction gratings. The higher frequencies ("blue") travel through the grating pair faster than the lower frequencies ("red"). When the grating separation is properly adjusted, the "blue" catches up to the "red," and the pulse is compressed down to the bandwidth limit.

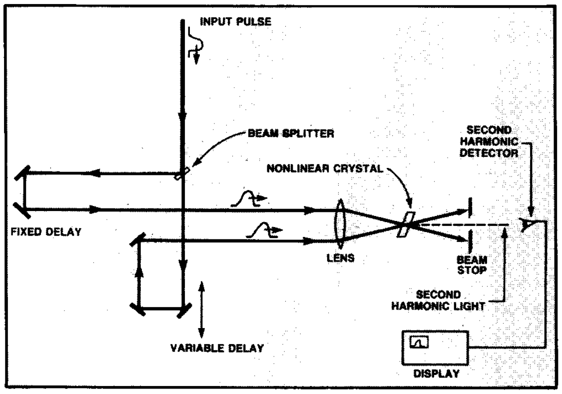
BOX 3 - Measuring Ultrashort Light Pulses

An autocorrelator is a device used to measure the duration of ultrashort pulses. In the autocorrelator, a single pulse is first split using a beam splitter (a partially transmitting, partially reflecting mirror) into two identical pulses. By causing each pulse to travel to different path lengths, the relative delay between these two pulses can be adjusted. (For example, a difference of 0.3 mm of path length in air generates a time delay of 1 psec.)

The two pulses are focused by a lens to a common spot in a nonlinear crystal, such as potassium dihydrogen phosphate, where second-harmonic generation takes place. This is a nonlinear optical process that produces output light at twice the frequency of the original light. Because the second-harmonic intensity is proportional to the square of the incident light intensity, more second-harmonic light is generated when both pulses are coincident than when the two pulses are separated in time. Thus, by measuring the amount of second-harmonic light as a function of the delay between the two pulses, researchers can infer the pulse durations.



Sidebar 2 Pulse compression apparatus. Pulses from a mode-locked laser are spectrally broadened (chirped) in an optical fiber and then compressed with a pair of diffraction gratings.



Sidebar 3 Autocorrelation apparatus used to measure the width of ultrashort light pulses.

For Further Reading

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2. R. R. Alfano and S. L. Shapiro, "Ultrafast Phenomena in Liquids and Solids," *Scientific American*, June 1973, pp. 42–60. Discusses early measurements of picosecond phenomena in liquids and solids. Also an interesting discussion of short light pulses before the advent of lasers back through several hundred years.
3. S. L. Shapiro, Ed., *Ultrashort Light Pulses: Picosecond Techniques and Applications* (Springer Verlag, Berlin, 1977). This gives the background for the field and reviews the state of the art ca. 1977.
4. C. V. Shank and D. H. Auston, "Ultrafast Phenomena in Semiconductor Devices," *Science*, vol. 215, pp. 797–801, Feb. 12, 1982. Discusses application of ultrashort light pulses to the measurement of fast phenomena in semiconductor structures and devices.
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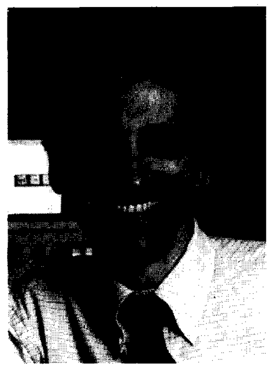
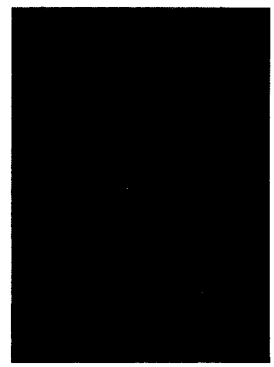
6. G. R. Fleming and A. E. Siegman, Eds., *Ultrafast Phenomena V* (Springer Verlag, Berlin, 1986). This is a conference proceedings, which covers nearly every topic of current ultrashort light pulse research.
7. *Lasers and Applications*, pp. 79–82, Jan. 1985, and pp. 91–94, Feb. 1985. Covers the basic principles of active, passive, and synchronous mode-locking.

1 A mode-locked diode laser with pulse widths below 0.6 psec was reported at the 1988 Conference on Lasers and Electro-optics by researchers from the University of California at Santa Barbara.



Peter W. Smith



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Dr. Smith is a Fellow of the IEEE and a Fellow of the Optical Society of America. He is a member of the American Physical Society and the American Association for the Advancement of Science.

Andrew M. Weiner received the S.B., S.M., and Sc.D. degrees in electrical engineering from MIT in 1979, 1981, and 1984, respectively. From 1979 through 1984, he was a Fannie and John Hertz Foundation Graduate Fellow. Since 1984, Dr. Weiner has been a member of the technical staff at Bell Communications Research in Red Bank, New Jersey. His research interests include picosecond and femtosecond pulse generation, optical probing of high-speed electronics, femtosecond spectroscopy, and nonlinear optics in fibers. He is an Associate Editor of the *IEEE Journal of Quantum Electronics* and a 1988-1989 IEEE Lasers and Electro-optics Society Traveling Lecturer.