THE ▸ DECADE ▸ IN OPTICS

By R. L. Fork

The technology for producing femtosecond optical pulses was first realized in 1981 and improved to produce pulse durations as short as 6 fs by the end of the decade. In addition to the rapid reduction in pulse duration and close approach to the fundamental limits on optical pulse duration, the pulses were produced in highly stable pulse trains at repetition rates as large as 10 kHz. The direct observation of a broad range of previously inaccessible time dependent phenomena made possible by this progress has stimulated research in a number of fields. This work culminates some 25 years of progress that has resulted in reducing the duration of optical pulses by a factor of more than 100,000.[1]

It is unusual to have such a large advance in a technical capability in any field in such a short period. In this case, the sudden advance was triggered by invention of the laser—in particular, by invention of the modelocked laser, which combines nonlinear elements within the laser resonator to enable, in effect, light to shape light into short pulses. This large magnitude of improvement—combined with the inherent potential that optical phenomena offer for research, information processing, and education—create extraordinary opportunities.

Based on the rapid advances of the '80s, the issue for the '90s is not so much, "How much shorter can we make optical pulses?" but rather, "How well can we use ultrashort optical pulses to access their enormous potential?" While the latter question will only be answered by time, this review discusses some of the strategies by which advances in femtosecond technology came about in the '80s, as well as the current impact of those advances. It is hoped that this information will provide some guidance in formulating technological and research strategies related to ultrashort pulse work in the coming decade.

A historical perspective

A historical perspective on the progress made in generating short optical pulses can be gained by comparing the improvement in temporal resolution of optical phenomena during the last few decades with improvements in spatial resolution of optical phenomena achieved with the invention of the microscope and telescope in the early 17th century. In the 1600s, those inventions caused a similarly sudden increase in the resolution with which optical phenomena could be observed. The impact on the technology and society of that time was similar in the comparative rapidity with which new potentials were translated into instruments and commercial products permitting a variety of observations and measurements not previously accessible.

Improvement in the resolution of optical phenomena made possible by the microscope was a little less than three orders of magnitude. The impact on the science, technology, and society of that time was, however, dramatic and literally reshaped man's perception of his universe. The present increase in temporal resolution of optical phenomena has been over five orders of magnitude over the past 25 years, with the two most difficult of those orders of magnitude achieved in the last decade. It seems reasonable to conclude that the current improvement in temporal resolution of optical phenomena is extraordinary. Not only will it significantly impact our present science and technology, but it is also likely to influence the very nature of our society.

Current impact

The initial impact of the advances in femtosecond technology has been principally in the area of basic research, where the capacity to create femtosecond pulses immediately opened a previously inaccessible time domain. One of the most important areas of research has been the dynamics of semiconductor materials and semiconductor microstructures. Key experiments have dealt with the transport and relaxation of carriers in bulk material and microstructures, the motion and localization of carriers in amorphous semiconductors, the melting of surfaces, and the dynamics of virtual excitations. Most of these studies were performed using pump probe techniques to perform time resolved transmission spectroscopy. However, other techniques have been developed. In studies of photoluminescence by Shah,[2] for example, upconversion in nonlinear crystals provides time dependent grating with femtosecond time resolution.

The dynamics of conductors have been difficult to observe because of the extremely short time scale on which much of the important phenomena take place. Schoenlein's[3] use of femtosecond technology to study of the dynamics of the image potential at metal surfaces, however, demonstrates access to some of these phenomena. Other areas of active work are in the

Femtosecond Technology in the '80s

dynamics of thermomodulation of metals and scattering by dielectric particles.

The short time behavior of optically excited molecules, in particular, has provided an important testing ground for the newly developed femtosecond techniques. Direct observation of changes in the transmission spectrum of molecules excited and probed by femtosecond pulses has provided specific evidence of vibronic relaxation, spectral hole burning, and extremely rapid dephasing processes. The dephasing processes occur with time constants as short as a few femtoseconds and were studied using four wave mixing and photon echo techniques. Time resolved studies of photosynthesis, proton transfer, and photodissociation have also been examined using related techniques.

One of the most dramatic experiments involving time resolved molecular dynamics has been the observation of nuclear vibrational motion in the molecules Nile blue and malachite green impulsively excited by compressed femtosecond pulses. These observations were achieved using pulses of 6 fs duration for both pump and probe in flowing solutions of the dyes (see Fragnito, *et al.* in Ref. 1). The quality of the initial data achieved in that experiment and the explicit information about the extremely short time dynamics of the excited molecules suggests that, as higher repetition rates are achieved and more sophisticated data processing techniques developed, it will not be unusual to obtain displays of molecular dynamics with femtosecond resolution where the parameters of the experiment can be varied and the consequences observed on the scale of human response time. I anticipate that this will be a research and educational tool of great power.

The optical generation and study of electrical pulses does not typically require the extremely high time resolution available from femtosecond pulses. Nonetheless, those problems are of important practical and fundamental interest and can be effectively addressed using femtosecond optical pulses. Electrical pulse generation and propagation of those pulses on striplines fabricated of high temperature superconductors provide an interesting example of two technologies created during the '80s that have been combined to mutual advantage. Grischkowsky and co-workers' terahertz bandwidth pulses generated using femtosecond pulses also explore another interesting aspect of this class of phenomena.[4]

A novel technique that is of special interest from an educational and analytical point of view is that of three-dimensional holography performed with femtosecond time resolution. Abramson and others[5] have demonstrated the evolution in the spatial distribution of the energy in femtosecond optical pulses as the pulses propagate through a lens systems or are reflected from complex objects. This technique provides an unusually explicit means of viewing optical pulse propagation under conditions normally inaccessible to conventional perception. These techniques should be of great advantage in teaching students a visual intuition for the properties of femtosecond optical pulses. Work using the time resolved scattering of femtosecond pulses to probe the macroscopic structure of biological samples is also being undertaken, as by Alfano and coworkers.[6] The use of these techniques, possibly in combination, to study structures of medical or technological interest could provide diagnostic tools with capabilities unlike any previously available.

Evolution of short pulse technology

The area of short pulse generation and shaping has itself become something of a distinct area of research. Some of the more intellectually interesting problems that have arisen in the course of creating the femtosecond technology occur because the combined action of self phase modulation and group velocity dispersion can produce a soliton-like contribution to the pulse shaping within a laser oscillator, even in the absence of optical fibers. When combined with the more conventional processes of amplitude shaping by saturable gain and saturable absorption, this soliton-like phase shaping mechanism causes a rich variety of phenomena within the laser oscillator. Properly managed, these conditions can be used to produce some of the shortest pulses and most stable pulse trains from a laser oscillator. At the moment, the shortest pulses from a oscillator have durations of 27 femtoseconds; there is a good reason to believe that shorter pulse durations are possible by optimal use of the combined action of amplitude shaping, phase shaping, and spectral filtering.

Looking back on the '80s, it is possible to see that the strategy of creating femtosecond technology was largely the result of one simple concept implemented via five different techniques. The concept was that of balancing shaping mechanisms in pairs. The five techniques that illustrate this strategy were:

- Enhancement of pulse shaping in a saturable absorber by means of the collision of two counterpropagating pulses.
- Balancing the negative group velocity dispersion, due to geometric factors, and the positive group velocity dispersion, due to material dispersion, for prism pairs.
- Adjusting self phase modulation and group velocity dispersion within a laser oscillator to produce a strong soliton-like phase shaping contribution to the pulse shaping.
- Balancing strong phase shaping and strong amplitude shaping within a laser oscillator to produce pulses shorter than could be obtained by either technique alone.
- Using the opposite signs of the cubic phase distortion from prisms and gratings to reduce cubic phase distortion of pulses compressed external to the laser oscillator.

The combination of the techniques described above was adequate to reduce the duration of optical pulses to 6 fs, or only three cycles of the optical field close to the fundamental limits of the duration of pulses formed of visible light. Among the many workers who contributed to these advances, I would single out J.D. Kafka, the first to communicate the possibility of using the techniques for correcting cubic phase distortion mentioned above.[7] In this vein, it also seems appropriate here to recognize C.C. Cutler, who pointed out in an unpublished communication almost immediately after invention of the actively modelocked laser, the strategy—which eventually proved essential to realization of femtosecond technology—of including a saturable optical absorber in the laser resonator.[8]

Perhaps the single technological advance most important in making femtosecond technology possible was the discovery that prisms—in particular, a four prism sequence—could be used not only to produce group velocity dispersion correction, but also to do so with low loss in a manner that allowed the net dispersion to be adjusted smoothly from positive through negative values. This advance permitted introduction of easily adjusted group velocity dispersion within laser oscillators, provided means of higher order group velocity dispersion correction outside of laser oscillators, and also provided a simple means of implementing spectral filtering within or outside of laser oscillators.

If there was a single conceptual advance that made femtosecond technology possible, aside from the general strategy of balancing pairs of shaping mechanisms, it was probably the understanding that angular dispersion and group velocity dispersion are intimately related and that the controlled introduction of angular dispersion is essential to the process of creating short pulses of light. It was this understanding, for example, that made it particularly clear why four prisms, as opposed to one or two, were necessary to obtain the most effective control of group velocity dispersion in the devices that made femtosecond technology possible. O.E. Martinez and J.P. Gordon played particularly important roles in this advance.

Further improvements

There are relatively obvious directions in which further improvements can be made. One is the extension of femtosecond technology to a wider range of wavelengths, particularly in the near ultraviolet and the near infrared. Another is to increase the repetition rate of the pulses, the energy of the pulses, or both, while maintaining good spatial mode quality and pulse train stability and expending as little pump energy as possible. Some of the technologies likely to be important in this regard are those of feedback techniques for stabilizing beam direction and resonator length and those of increasing the ease with which semiconductor and solid state lasers can be used as sources of femtosecond pulses.

Additive pulse mode locking, which uses the addition of two pulses within the laser resonator that have experienced different phase modulation while traversing different paths, is a rapidly developing area of considerable importance. This method owes an intellectual debt to Mollenauer and his pioneering work on soliton shaping within a laser oscillator produced by including an optical fiber in one part of a resonator. This latter work, incidentally, has provided an important source of femtosecond pulses in the infrared.

Optical and optoelectronic information processing are other areas rich in potential where further advances in femtosecond technology can play an important role. However, just as the advances in femtosecond technology stemmed from a deeper understanding of the underlying scientific principles, so to will significant advances in optical information processing depend on similar strides in our understanding. One area of particular interest is the formation of images of femtosecond pulses. Such matrix arrays of femtosecond optical pulses should facilitate strategies for better using the potential for parallel computing inherent in optical phenomena.

Whichever strategy succeeds, it will be important for those involved in working with the technology of ultrashort pulses to respect the lessons history teaches. We should work hard to translate the advances of the 80's into useful tools and, at the same time, take responsibility for guiding the social impact those tools will inevitably produce along positive directions.

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Optical Neural Networks

By Demitri Psaltis and Yong Quio

The optical implementation of artificial neural networks is a subject that combines optics and neural networks. The notion that links the two fields is connectionism. In optical computers, photons are used instead of electrons as the carriers of information. The advantage of doing this derives from the fact that photons do not directly interact with one another. This makes it easier to establish a communication network connecting a large number of processing elements. Therefore, the design of optical computers is naturally guided toward architectures that require many connections.

Neural computers, on the other hand, are computing structures whose design is motivated, at least partially, by the nervous system. One of the most striking features of the brain is its dense connectivity. Each neuron typically receives input from several thousand other units. Accordingly, artificial neural network architectures require very dense connectivity and optics is a device technology that is well suited for providing it.

A similar history of development is another common feature of optical and neural computers. Both topics became popular in the late 1950s and early 1960s and both fell out of favor soon thereafter, until recently. The difficulty that both approaches ran into was that they could not provide competitive, practical solutions to interesting problems, despite their promise for superior capabilities. This remains true today.

Nevertheless, there is renewed optimism and the level of interest in these two fields is more intense now