Ultrafast-Laser Technology from the 1990s to Present

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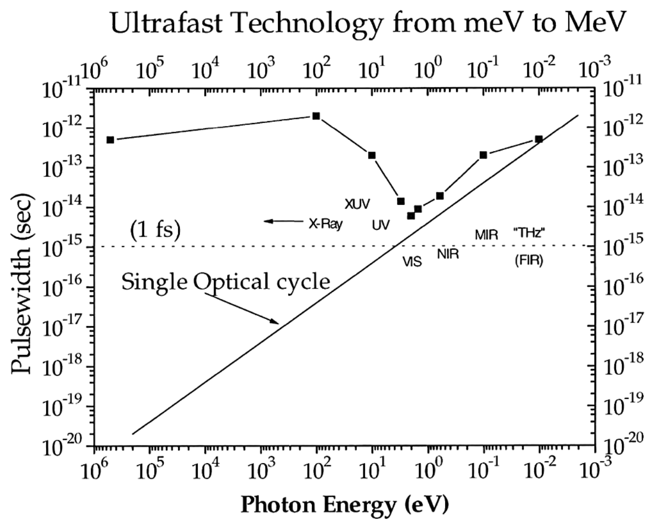
The field of femtosecond lasers was in a difficult state in January 1984. Lasers that generated pulses of 100 fs or less in duration were few and far between, but there were a growing number of research applications they could be applied to. For example, at Bell Laboratories in Holmdel, New Jersey, David A. B. Miller and Daniel S. Chemla were very interested in studying the excitonic nonlinear optical response and electro-optic properties of GaAs-based quantum wells, which were rather new back then. The author was a post-doc with that group and was able to take advantage of the magnificent femtosecond laser labs that had been developed by Richard L. Fork and Charles V. Shank to work on the generation of infrared femtosecond pulses, which were perfect to use to study the dynamics of GaAs-based quantum wells. A few years before, Chuck Shank's group had developed the first colliding pulse mode-locked laser that reliably gave pulses of great stability and always shorter than 100 fs around 625 nm wavelength [1]. They had built a multi-stage dye-cell amplifier system pumped by a frequency-doubled Q-switched Nd:YAG laser at 10 Hz rate, producing millijoule pulse energies that were more than intense enough to generate a beautiful white-light continuum. Pumped by an argon laser with a few watts of green light, the dye laser produced average powers of a few tens of milliwatts in a train of femtosecond pulses as long as the dye jets were behaving well. Bad behavior included clogging, popping hoses squirting dye all over the lab. And, of course, the dye would eventually turn bad and have to be changed. So, given that the laser was generating only one color of light in the visible at low power and was running on 40 kW of electrical line power, while using five gallons per minute of chilled water, it was very difficult to imagine how such a laser technology could be useful in the world someday.

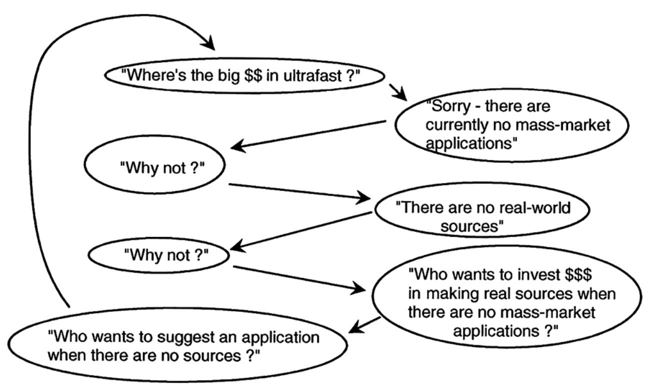
The development of Ti:sapphire lasers by Peter Moulton while at MIT Lincoln Labs and subsequent demonstration of Kerr-lens mode locking by Wilson Sibbett's group [2, 3] were a tremendous advance for the field, offering much higher powers and near-infrared tunability as well. Chirped-pulse amplification, by Gerard Mourou's group at the University of Rochester in 1985 [4], led to widely scalable oscillator-amplifier systems of great variety and complexity. Simultaneously, development of erbium and then later ytterbium fiber gain media together with the development of cheap high-power laser diode pump sources were driven strongly by demand during the telecommunications bubble that peaked in March 2000 with the NASDAQ briefly hitting 5000. Combining these advances in solid-state as well as fiber technologies now has made possible a new generation of practical ultrafast compact laser sources that are offered by more than 30 commercial suppliers, many of which are still in search of their "killer application." Figure 1 shows the state of the ultrafast-laser field in 1995, plotting shortest pulse width as a function of photon energy. We can see that the attosecond short-wavelength frontier had been identified, but not explored yet, and note the tremendous advances in that field have been driven by science and technology developments in many fields since then.

The Optical Society (OSA) has been at the forefront in promoting ultrafast laser technology through its various journals and conferences. In 1995 a CLEO (Conference on Lasers and Electro-Optics) tutorial entitled "Ultrafast Optical Power Supplies" was given by the author [5], which reviewed the progress of the field and laid out some of the challenges for laser developers. Figure 2 shows an "Ultrafast Catch-22" that seemed to exist then and still seems to be true today. With the rapid developments in source technologies and materials in the late 1990s, it appeared that it would be possible to develop compact reliable sources of femtosecond pulses covering a variety of parameter ranges; however, few commercial applications had been developed, and therefore there were few incentives to invest in those technologies. Figure 3 shows that a wide range of applications require a wide range of versatile sources, and no single laser can satisfy all of them; therefore, individual unit volumes remain low. In 1996 a plenary talk was given by the author at CLEO titled "Ultrafast Epiphany: The Rise of Ultrafast Science and Technology in the Real World" [6]. *The Epiphany was that ultrafast lasers could actually be useful for things beyond the obvious ones in high-speed measurements.* This is indeed the most important consideration about the use of ultrafast laser technology. In some cases, there may be absolute value in the use of ultrafast laser technology. In such a case, there is simply no other way to carry out a certain application without the use of femtosecond lasers. Those cases may not be very numerous. But in most of the other cases, there is competing technology, and then femtosecond laser technology has to offer enhanced value but at a price that is commensurate with the increased value that it offers. Most ultrafast laser oscillators still cost \$50–\$150K today, so they need to add a lot of value to justify that expense.

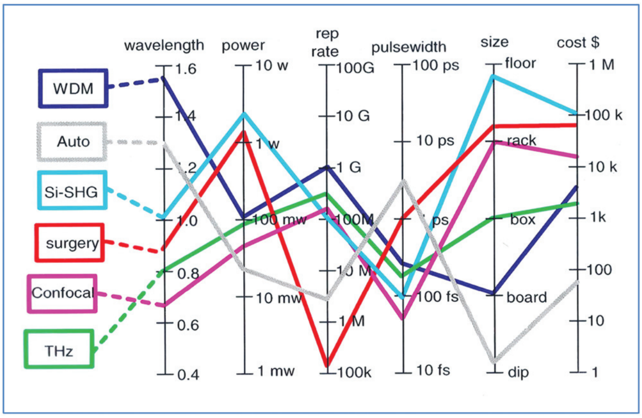


▲**Fig. 1.** Survey of the ultrafast laser field in 1994. The short-wavelength attosecond frontier had been identified, but not explored.

A number of applications for femtosecond technology were predicted by the author in 1995 and 1996; it might be interesting to see how those predictions have come out. The first known commercial application of femtosecond technology was coherent phonon generation and detection for multilayer thin film metrology, by Rudolph Instruments in New Jersey. For this, an OEM laser source was developed by Coherent, Inc. In 1995, the author predicted that a high-power chirp-pulse amplified femtosecond laser would be mounted on a truck and used by the military forces. Today, indeed such a truck has been developed and sold by Applied Energetics for detection and detonation of IEDs (improvised explosive devices). The TeraMobile project has taken atmospheric propagation of femtosecond pulses truly throughout the globe in search of applications. In 1995, the author predicted that ultrafast electro-optic sampling systems would be commercially available, and indeed such systems are available from Ando and others. In 1996, the author predicted that ultrafast sources would power new generations of two-photon microscopes, and several companies now offer these, including Zeiss/IMRA and BioRad/Spectra-Physics, but they are not yet widely used in clinical practice. In 1995, the author predicted that someday there would be commercial terahertz radiation spectrometers. Indeed, this area has advanced tremendously, with commercial systems available from seventeen companies [7]. Applications for



▲**Fig. 2.** The incentive to invest in development of practical "real-world" femtosecond lasers comes from the applications. Lasers and applications must be developed in parallel.



▲Fig. 3. The various needs for ultrafast optical laser systems identified in 1995. A wide range of applications requires a wide range of laser technology options.

terahertz measurements have exploded, including at least the following: insulating foam analysis, chemical analysis, explosive detection, concealed weapons detection, moisture content, coating thickness, basis weight measurement, product uniformity, and structural integrity. In 1996, however, the author certainly did not predict that ultrashort lasers spanning greater than one octave range would produce a revolution in high-precision frequency measurements, yet that has emerged as an important new area, and there are now at least three companies supplying femtosecond lasers with 6-fs or shorter pulses. In 1985, such an experiment was worthy of the *Guinness Book of World Records*, but now it is commercially available. Micromachining in many materials using femtosecond pulses has developed into a significant commercial area. In 1996, although there was research in that area, the author did not predict that it would become commercially significant. Several companies, including Clark-MXR, now offer commercial versions of ultrafast manufacturing systems. It should be pointed out that terahertz systems that are based on femtosecond lasers are currently offered by four companies; however, thirteen other companies offer terahertz systems based on continuous-wave sources [7]. Similarly, ultrafast manufacturing systems have to compete with excimer lasers and other conventional types of advanced manufacturing approaches. Both of these examples illustrate that while ultrafast laser technology may offer enhanced value to certain applications, the extra cost involved puts it on a par with competing technologies.

And this leads us to the most important application of femtosecond laser technology to date. One outgrowth of femtosecond material-damage studies occurred at the University of Michigan in the 1990s [8]. A very well-developed technology for excimer laser ablation of the human cornea (LASIK) had been developed, but it required the creation of a corneal flap. A technique was developed using a rapidly vibrating razor blade to create a corneal incision and horizontal flap that could be lifted off to expose the middle part of the stroma, which is the tough structural part of the cornea. Ophthalmologists got used to using the razor blade system, which cost them about $30,000. But it turns out that a new approach developed involving the use of focused femtosecond light pulses could create a dense array of microbubbles that, once interconnected, could be lifted like a "flap." With this new approach, patients would not have to worry about their corneas being cut with a razor blade. This technique gained excellent market acceptance, and with additional benefits in enhanced precision of the corneal flap thickness and positioning, it was found that patients greatly preferred this technology. Over time, during 2000 and up to the present, it has been firmly established that femtosecond-laser flap cutting is the one preferred by patients. Ophthalmologists have been able to work out successful business plans involving the new systems (which cost over $500,000 and have expensive annual maintenance plans). So, it is clear that one application has risen far above all others in economic value and market acceptance, and this was unpredictable back in 1996.

Looking to the future of vision correction, a new approach is being developed that does not involve cutting of the cornea. This technology creates a controlled index of refraction change [9–11] using high-repetition-rate femtosecond lasers. It is hoped that this approach will replace much if not all of currently used refractive correction technologies; however, much work to do remains to be done.

It is expected that many new areas of application will continue to emerge for femtosecond lasers in the future. In each case, there will be a definitive test of the value of the new technology, and each one will be an interesting story. Will we be writing about applications of attosecond technology some day? Surely we will!

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