CLINICAL IMPLICATIONS OF BASIC RESEARCH

Elizabeth G. Phimister, Ph.D., *Editor*

Femtosecond Lasers for Ophthalmic Surgery Enabled by Chirped-Pulse Amplification

Daniel Palanker, Ph.D.

This year's Nobel Prize in Physics was awarded to Donna Strickland (currently at the University of Waterloo, Canada) and Gérard Mourou (now at École Polytechnique in France) for chirped-pulse amplification, an invention that enabled the development of powerful femtosecond lasers. These lasers have revolutionized ophthalmic surgery by providing cellular-scale precision, deep inside transparent ocular tissues.

In a tight focus of a short-pulsed (i.e., a nanosecond or less) laser beam, irradiance can reach extremely high levels (exceeding 10^8 watts per square centimeter), producing such a strong electric field that outer electrons can be stripped from atoms. This results in the formation of plasma (ionized matter), which in turn absorbs the laser light. This process, called dielectric breakdown, enables highly localized energy deposition at the focal point of the laser beam inside a transparent medium. Rapid heating of the tissue above its vaporization threshold leads to an explosive formation of cavitation bubbles (on a micrometer scale), which collectively dissect tissue.

Since the mid-1970s, this process has been used to fragment the opacified posterior lens capsule (secondary cataract). A relatively high threshold energy (millijoules) of the dielectric breakdown with nanosecond pulses results in the formation of rather large cavitation bubbles, which are good enough for blowing a millimeter-wide hole in the posterior lens capsule but are too crude for other surgical applications in the eye.

The threshold energy of dielectric breakdown decreases with shorter pulses, reaching a minimum at pulse durations of approximately 100 fsec.[1] Ultrashort (subpicosecond) pulsed lasers with energy sufficiently high for surgical applications (in the range of microjoules) were not feasible because the amplification of the pulse energy at such short durations results in ultrahigh peak power, which causes saturation and even damage to the lasing material itself. In 1985, Strickland and Mourou (at that time both at the University of Rochester) developed a clever solution to this problem.[2] Basically, they lowered the power of the laser pulse before amplification by spreading the pulse over a longer duration (Fig. 1). To do this, they used a kilometer-long optical fiber: since red light propagates faster than blue in glass and in many other materials, different spectral components along the continuum of wavelengths in the low-energy picosecond pulse arrived at the optical amplifier at slightly different times, stretched over a few hundred picoseconds. A similar phenomenon with sound waves produces the characteristic chirping sound made by birds — in which the pulse starts at a high frequency and ends at lower frequencies — hence the name "chirped pulse." Modern versions of this process typically use gratings, which direct various wavelengths in different directions, resulting in different path lengths for various spectral components of the beam (Fig. 1). After amplification of the chirped pulse, the reverse process — again using gratings — can recombine these spectral components back into an ultrashort pulse. This chirped-pulse amplification technique enabled the generation of high-energy (up to millijoules) ultrashort laser pulses and led to a wide range of new applications in imaging, surgery, material processing, and other areas of science and engineering.

Because of the dramatic reduction in the threshold energy (by a factor of more than 100) of the dielectric breakdown with a femtosecond pulse, as compared with that of the previous nanosecond limit,[1] lasers could now be used to perform much more precise intraocular dissection — for

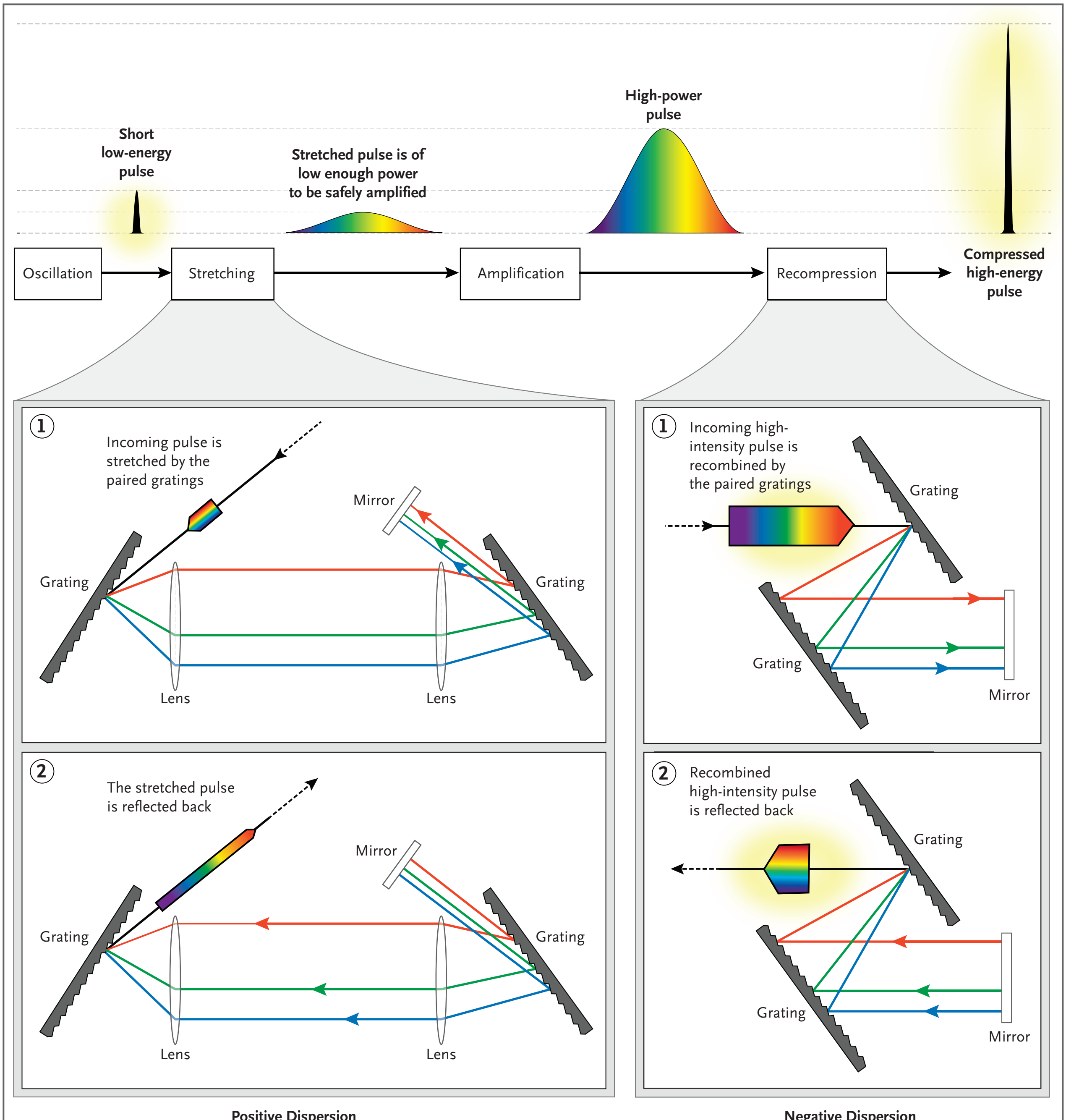

Figure 1. Chirped-Pulse Amplification for Ultrashort-Pulse Lasers.

An ultrashort pulse of low energy is stretched to reduce its peak power, amplified, and then recompressed back to an ultrashort duration. Both stretching and compression can be achieved with the use of pairs of gratings, with one pair configured to have positive dispersion and the other configured to have negative dispersion.

example, in cutting a corneal flap in laser-assisted in situ keratomileusis (LASIK) surgery, which improved the precision and reproducibility of the refractive outcomes. Later developments enabled refractive surgery using a femtosecond laser only, eliminating the need for an open flap, improving biomechanical stability, and permitting more rapid corneal reinnervation.[3] Similarly, precise intrastromal cutting facilitated full- and partial-thickness corneal transplantation, including transplantation of the corneal endothelium (a process known as Descemet's stripping endothelial keratoplasty).[4]

For cataract surgery, femtosecond lasers have enabled precise capsulotomy (Fig. 2) and lens segmentation,[5] ensuring perfect centration of the intraocular lens and accurate overlap of the capsular bag with the implant. Segmentation and softening of the lens simplify its subsequent ultrasonic emulsification, thereby reducing the collateral damage to the corneal endothelium during lens removal. Femtosecond lasers have also been applied for exact placement of the limbal relaxing incisions to reduce residual astigmatism.

A potential future site for the application of ultrafast lasers lies beyond the anterior chamber of the eye: the dissection of vitreous floaters. Here, a pattern-scanning laser would need to be guided by three-dimensional imaging, as it is in cataract surgery, to avoid collateral damage to surrounding tissues.

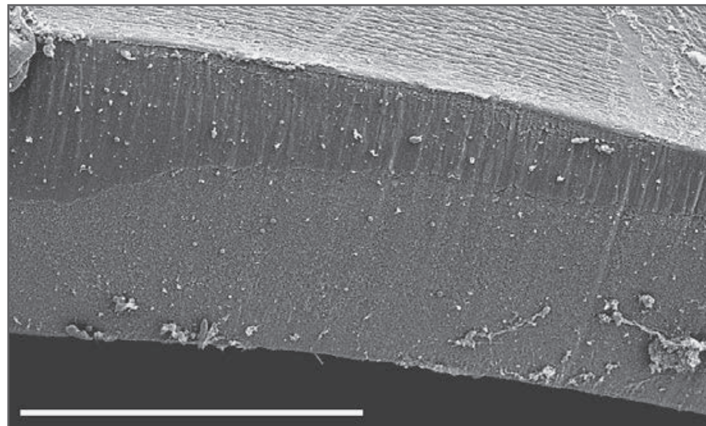

Figure 2. Edge of a Porcine Lens Capsule Cut with a 150-fsec Laser at a Wavelength of 400 nm.
The scale bar indicates 50 μm.

Disclosure forms provided by the author are available with the full text of this article at NEJM.org.

From the Department of Ophthalmology and Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA.

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