Femtosecond Lasers

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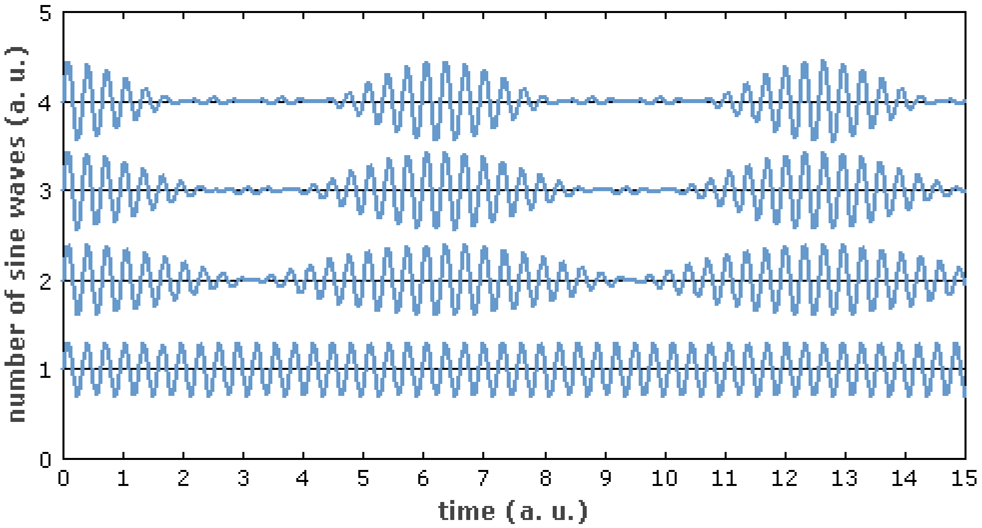
Achieving pulse widths on the order of femtoseconds even further restricts already complicated laser cavities and often requires extra components beside the laser itself. For many applications of the femtosecond pulse, high repetition rates are desirable, leading to especially particular kind of cavities. This paper presents the history of the femtosecond pulse, along with the developments and their limitations. In addition, the stereotypical modern Ti:Sapphire femtosecond laser system will be presented.

High repetition rate femtosecond pulses are not the last step in ultrashort pulses, but were certainly were not the first. After it was noted that oscillating output could be obtained perturbations of the cavity, “giant” pulses followed quickly. While useful in their own right, these pulses offered widths on the scale of the cavity lifetime or nanoseconds, not femtoseconds. It was not until researchers found good methods of mode locking, a way of linking the multiple longitudinal mode’s phase together, that truly short pulses flourished. Many different methods of mode locking, broadly classified into active and passive mode locking, brought the pulsed laser’s width into to the order of femtoseconds. Forcing the laser to repeat these pulses became the next order of research in reaching the femtosecond pulse. Many laser systems make suitable systems for ultra short pulses, but the one most often used is Ti:Sapphire for a host of considerations.

The phenomena most responsible for ultra short pulses is certainly mode locking. For the average laser cavity regime, there are many stable longitudinal modes available to the laser. If the gain profile of the medium is very broad, then there are correspondingly a large number of oscillating modes. Drawing an analogy from Fourier analysis, one knows that a delta function can be constructed only by adding an infinite number of sine and cosine functions, and thus similarly, a sharp pulse requires many oscillating modes. It seems then that to get sharp modes, “spectral purity” is actually less desirable. This is demonstrated in the figure.



[http://www.rp-photonics.com/mode_locking.html]

Thus, the minimum pulse width is inversely proportional to the number of oscillating modes involved in the pulse. In fact, using a Fourier transform, it can be shown that there is actually a theoretical limit for the width based on shape of the pulse and number of oscillating modes, this minimum is called the time-bandwidth product. If the phase relationship created by mode-locking is perfect, then the laser will produce a pulse of this width. If there are many modes that have started oscillating independently of each other with no definite phase relationship, then the output will have non-time varying intensity. There are two ways to modulate the phases: passive and active.

Active mode locking utilizes a device placed inside the cavity, usually and acoustico-optical modulator. This is driven by signal at a frequency of f, which introduces a frequency shift in some of the laser light inside the cavity. Assume that the modulator is being driven while a laser is powered up, then the longitudinal mode nearest (in frequency) to the gain profile’s peak will begin oscillating, let its frequency be denoted as v. Thus as it passes through the cavity it will develop sidebands at v + f and v – f due to the modulator. If the driven frequency is the longitudinal mode spacing, then these sidebands correspond to the adjacent longitudinal modes. The result on one pass is 3 modes all oscillating in phase. Thus as the light makes many passes, the other longitudinal modes will also be shifted, but all resulting oscillations will remain in phase. This will create interference in such a way as to make a sharp pulse that is transmitted once per roundtrip of the cavity. This method is very sensitive and thus difficult to make stable. Its advantage to passive mode locking, which is more prevalent, is that active mode locking does not rely on loss to create the mode locking.

Passive mode locking instead relies on filtering out small intensity portions of the light in the cavity. Take for example, one of the most classic passive mode locking methods, a saturable absorber. This tool relies on a non-linear effect, where higher intensity sections of the beam are allowed to pass, while lower intensity sections are absorbed. Thus a saturable absorber is placed in the beam, if an intense section of the beam exists; the absorber will leave it alone to make multiple passes through gain medium while muting all other light. The intense pulse will become more and more intense; this will allow modes oscillating in a way as to increase the pulse's intensity to remain oscillating. Those modes that are not oscillating in this way will be absorbed.

A very notable method of passive mode locking, called Kerr-lens modelocking, is the one most often used in femtosecond lasers today. It relies on a non-linear response of the medium to intensity of light. As an intense pulse propagates through the medium, the Gaussian pulse "feels" a different index of refraction for different intensities. Thus the medium becomes a kind of lens to the light. This effect in itself is referred to as "self-focusing". In particular this gives rise to a difference in beam waist of the continuous wave part of light in the cavity and the high intensity "pulsed" part at the mirrors. With the creative use of mirror sizes as apertures, a cavity can be made to favor a pulsed behavior in the presence of a Kerr-lens. For example, small mirrors large enough to reflect the high intensity pulse, but not large enough to accommodate the larger continuous wave beam spot would favor pulsed nature since continuous wave light would be lost. One of the biggest problems with Kerr-lens mode locking is that it leaves the beam with dispersion, that is, there is a phase difference in the middle of the beam and the outer. For extremely narrow pulses, this dispersion must be accounted for. This requires that another optical instrument be inserted into the cavity or incorporated into the mirrors that correct the dispersion. Additionally, the feedback from the Kerr-lens effect towards pulsed behavior is enough to sustain pulsed behavior but often not enough to start it. So in most setups, the Kerr-effect is used in conjuction with semiconductor saturable absorber mirrors, or SESAMs. These saturable absorbers are also the cavity mirrors. These special mirrors can also have dispersion correction built in as well. If the laser can then begin mode locked behavior on its own, it is known as self-mode locked.

For many of the applications of a femtosecond laser, the repetition rate needs to be high. In the first pulsed lasers, the pulse repetition rate generally corresponded to the roundtrip time of the cavity. This would imply that there was only one pulse circulating in the cavity. A general lesson to take from this implication is that repetition rate is inversely proportionate to the cavity length. So making a smaller cavity increases the repetition rate; but it also decreases the gain medium length. It is of course possible to include more than one pulse circulating in the cavity through delicate design of the cavity, such as using a ring cavity with counter propagating pulses that meet at a saturable absorber. However, as more pulses are included in the cavity, they will draw on the inversion more and more. For even reliable output from the laser, all pulses must remain above certain intensity or they will be repressed by any passive mode-locking mechanism present. Thus max repetition rates are related strongly to the rise time of the gain medium. These considerations of course are related to intracavity considerations. There a number of methods that causes the higher repetition rates of pulses out of the laser. The most used commonly used methods are the optical parametric oscillators. This is essentially another laser cavity that "resonates" at harmonic frequencies of its pumping beam. It does not have a traditional medium, but instead a special non-linear crystal. These have been shown to increase repetition rates by up to 10-20 times.

The most common regime for producing femtosecond pulses is the Titanium Sapphire laser. It is extremely versatile as a pulsed laser, and thus the specifications change drastically depending on what repetition rates or pulse width the laser was designed to support. Because of its broad gain profile, it has produced pulses on the order of a femtosecond. Additionally, its gain properties allow for an extremely high repetition rate on the order of tens of gigahertz. At these high repetition rates the average power output is around 10 mW, small for this regime. For the average pulsed Ti:Sapphire the pulse width will be on the order of 100s of femtoseconds with a repetition rate of about100 megahertz. The lasers average power output will be around a watt. If even this average Ti:Sapphire pulse rate is used as the pump source for a synchronously pumped optical parametric oscillator, then repetition rates can again reach tens of gigahertz.

Applications from the femtosecond laser abound. Since they have such a short time scale, these pulses would be ideal for studying time dependant molecular/atomic interactions. Additionally, just used as a cutting tool, a high repetition femtosecond laser offers huge advantages to continuous wave ablation. Because all the energy is squeezed into a tiny time period, there is rapid conversion of the medium being cut into plasma with little heat transfer to the surrounding material. This means a perfectly smooth edge, be it precision tools being laser machined, or biological material. Also since these pulses can be amplified by chirped amplification, they represent the first step in producing the Petawatt pulse. These huge intensity pulses create an opportunity to study physics in limits here unto unstudied.

Femtosecond pulses have become a reality in lasers today, through an ever increasing library of materials available to laser designers; maybe attosecond lasers will also be realized in the future. Even so, these new lasers will still probably utilize current methods of mode locking, passive and active. Any laser capable of femtosecond pulses or better will lead to amazing advances of physics.

References

Esteban-Martin, A. “ High-harmonic-repetition-rate, 1 GHz femtosecond optical parametric oscillator pumped by a 76 MHz Ti:sapphire laser.” Optics Letters 34.4 (2009): 428-430.

Ouellette, J. “Femtosecond lasers prepare to break out of the laboratory.” Physics Today Jan. 2008: 36-38

Paschotta, Rudiger. “Mode Locking.” Encyclopedia of Laser Physics and Technology. 2008. 22 April. 2009 <http://www.rp-photonics.com/mode_locking.html>

Stormont, B. “Low-threshold, multi-gigahertz repetition-rate femtosecond Ti:sapphire laser.” Electronic Letters 39.25 (2003): 1-2.

Steinmeyer, G.. “ Frontiers in Ultrashort Pulse Generation: Pushing the Limits in Linear and Nonlinear Optics.” Science 286.5444 (1999): 1507-1512.