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Femtosecond pulsed laser technology and applications

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Abstract. This paper describes femtosecond pulsed laser technology and related applications. The focus is on two core femtosecond pulsed laser technologies: femtosecond pulsed laser generation and amplification. In the generation of femtosecond pulsed lasers, mode-locking techniques, Kerr-lens mode-locking, and semiconductor saturable absorber mirrors are presented; in the amplification of femtosecond pulsed lasers, chirped-pulse amplification and coherent synthesis techniques are presented. This paper analyses the applications of femtosecond pulsed lasers in both the biomedical and manufacturing sectors and gives the development trends as well as the challenges of femtosecond laser technology. Femtosecond lasers are now used in a wide range of applications. Femtosecond pulsed lasers will develop in the directions of high power, miniaturisation, intelligence and precision. Laser tweezers will become the new direction of development in the future.

Keywords: femtosecond pulsed laser, generation, amplification, application.

1. Introduction

Since the introduction of mode-locking technique in the early 1970s, the era of ultrashort pulses has begun. The era of ultra-short pulses began. After just over 20 years of development, active mode-locking, passive mode-locking, collision pulse mode-locking, and coupled cavity mode-locking have emerged, using these mode-locking techniques to shorten laser pulses to the picosecond or even femtosecond level. In the mid-1980s, with the discovery of broadband laser gain crystals and the emergence of self-mode locking and chirped pulse amplification due to non-linear effects, we entered the world of ultrashort and ultra-short laser pulses. With this technology, the pulse width of the output laser can be as short as the femtosecond. The pulse power can be as high as 10^12W, 10^15W, and the power density after focusing can reach 10^21 W/cm^2 [1].

Femtosecond pulsed lasers have the advantages of high precision, weak thermal effects, and a wide processing range due to their extremely short pulse times and high peak power. For more than 40 years, femtosecond laser technology has been used in high-precision machinery manufacturing, which has greatly contributed to the improvement of the technology level of the manufacturing industry. In addition to the manufacturing sector, femtosecond lasers are also used in biomedical fields, such as vision correction and medical imaging. In the future, femtosecond laser technology will penetrate various fields in various industries. Therefore, this paper will analyse the applications of femtosecond pulsed lasers in both the biomedical and manufacturing sectors and gives the development trends as well as the challenges of femtosecond laser technology.

2. Femtosecond pulsed laser technology

Femtosecond pulsed laser generation and amplification is the core of femtosecond laser technology, which is associated with phase stabilisation technology, pulse width measurement technology, spectral broadening technology, etc. The aim is to obtain a wider spectrum, shorter pulses, higher signal-to-noise ratio and peak pulse power, etc.

2.1. Femtosecond pulsed laser generation

Femtosecond pulsed lasers are generated from mode-locking technology. Typically, a laser has several longitudinal modes that are oscillating, and their superposition causes the laser output intensity to fluctuate irregularly with time. If these longitudinal modes are kept at a certain frequency interval and have a defined phase relationship, the laser can output a series of ultrashort pulses.

Mode-locking techniques are generally divided into active and passive mode-locking. The former modulates the gain or loss of the laser periodically by feeding a signal to the laser from outside to achieve mode locking, while the latter uses a saturable absorber to lock the relative phase using its non-linear absorption to produce an ultrashort pulse output.

2.1.1. Kerr lens mode-locking. In 1990, the advent of Kerr lens mode locking opened the door to a revolution in ultrafast laser technology and led to the first titanium-doped sapphire Kerr lens mode-locking laser, marking the beginning of a new phase of solid-state femtosecond lasers with ultra-high peak power [2]. The basic structure of the Kerr lens mode locking is shown in Figure 1. The most basic structure of the KLM is the addition of an optical diaphragm in front of a Kerr non-linear gain medium. Since the Kerr medium has an intensity-dependent refractive index:

$$n = n_0 + n_2 I \tag{1}$$

where n_0 is the linear refractive index, I is the light intensity and n_2 is the non-linear refractive index coefficient (positive number).

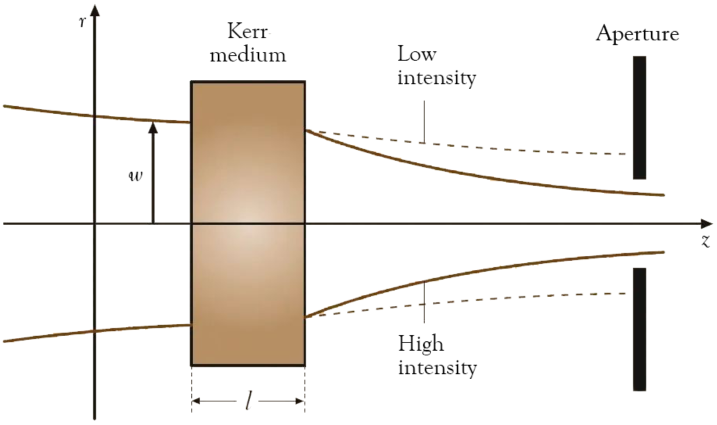

Figure 1. The structure of Kerr lens mode locking [3].

Therefore, the higher the light intensity, the greater the refractive index and the slower the speed. For Gaussian beams, the central light intensity is the highest, so the edge light speed is faster than the centre, similar to a beam passing through a plano-convex lens to form a self-focus. If a diaphragm is added at a suitable distance in front of the Kerr medium, the high-intensity beam will be tightly focused and pass through the diaphragm. Essentially, the Kerr gain medium plus diaphragm modulates the loss like a fast saturable absorber, reducing the loss as the intensity of the transient pulse increases, thus enabling mode-locking.

The advantages of Kerr lens mode locking include being very fast, so the pulse is the shortest, and very broadband, so the tuning range is wider. However, there are also disadvantages, such as the inability to self-start; severe resonant cavity tuning (close to the stability limit of operation); and saturable absorbers associated with the cavity design (limited applications) [4].

2.1.2. Semiconductor saturable absorber mirrors. In the same year, Swiss physicist U. Keller prepared a semiconductor saturable absorber mirror by epitaxially growing GaAs semiconductor saturable absorbers on a Bragg reflector and applied it to a titanium gem laser to obtain 2ps pulses [5].

The basic structure of a semiconductor saturable absorber mirror is the combination of a reflector and a semiconductor saturable absorber. The bottom layer is typically a semiconductor mirror on which a thin film of the semiconductor saturable absorber is grown, and the top layer may grow a reflector or use the semiconductor-air interface directly as a reflector so that the top and bottom mirrors form a Fabry-Perot cavity.

As shown in Figure 2, the absorption of a semiconductor contains two characteristic relaxation times: the intraband thermalisation process, which occurs at 100 to 200 fs and is essentially unchangeable, and the interband leap process, which occurs relatively slowly at a few picoseconds to several hundred picoseconds and will vary with the temperature at the time of growth. Achieving mode-locking primarily exploits the response to intraband thermalisation, but also requires the interband relaxation time to be much less than the round-trip time of the pulse in the oscillator cavity.

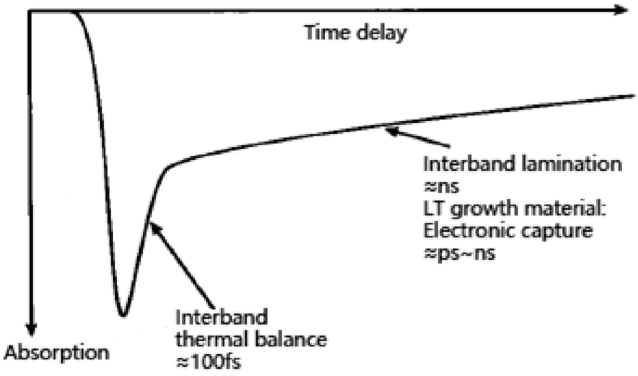

Figure 2. Temporal properties and physical mechanisms of semiconductor saturable absorbers [6].

During SESAM mode-locking, the long response time inter-band leap provides the self-start mechanism for mode-locking, while the short response time intraband thermal balance effectively compresses the pulse width and maintains mode-locking [7].

The SESAM is used as a mode-locked initiation and stabilisation element in mode-locked lasers, overcoming the drawbacks of the Kerr clamping mode itself, reducing the difficulty of designing mode-locked lasers and the requirements for laser material performance, and greatly improving system stability. The invention of this laser marks a new stage in the development of ultrafast solid-state lasers.

2.2. Femtosecond pulsed lasers amplification

Since the invention of the laser, technologies such as higher pulse energies, greater average power, and shorter pulse durations have evolved and continue to create new applications and even open up entirely new fields. For example, chirped pulse amplification in 1985, double-clad fibre technology in 1988, the introduction of the large mode field fibre concept in 1997, and techniques such as split-pulse amplification, multi-channel coherent ensemble amplification, pre-chirped managed amplification and coherent pulse stacking have all had a profound impact on the development of ultrafast fibre lasers.

2.2.1. Chirped pulse amplification. The laser was introduced in 1960. Over the next five years, tabletop lasers reached a power of 10^9 watts through a series of technical improvements. Not much progress was made in the next 20 years, the only way to increase the power of lasers was to develop larger lasers. After Mr. Gérard Mourou and his student Professor Donna Strickland introduced a technique called Chirped Pulse Amplification, the laser power was increased by a factor of 1000 to the TW level and has been steadily increasing ever since.

When amplifying a pulse by chirping, the first step is to generate a short light pulse from a laser and stretch it, usually by a factor of 10^3 to 10^5. This process reduces the intensity of the pulse by a factor of the same magnitude. This pulse can then be amplified using standard laser amplification methods. The final step is to use a compressor to compress the pulse back to its original length, thus increasing its power by a factor of 10^3 to 10^5 beyond the power limit of the amplifier [8].

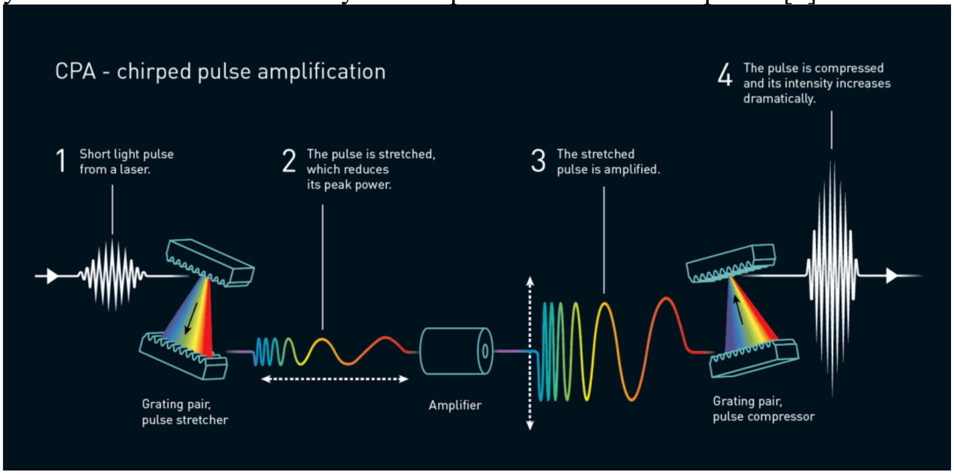

Figure 3. Chirped pulse amplification [9].

2.2.2. Coherent synthesis. The three main types of methods for implementing coherent synthesis of ultrashort laser pulses are spatially coherent synthesis, divided-pulse amplification, and pulse stacking [10]. Two or three of these methods can also be used simultaneously in a single laser system.

(a) Spatially coherent synthesis

The basic principle of the spatially coherent synthesis of ultrashort laser pulses is shown in the Figure 4: the seed laser passes through a pulse stretcher and a beam splitter into multiple paths, each path passes through a phase modulator (Δφ) and a power amplifier, and then uses a spatial combiner to combine the amplified lasers into a single beam.

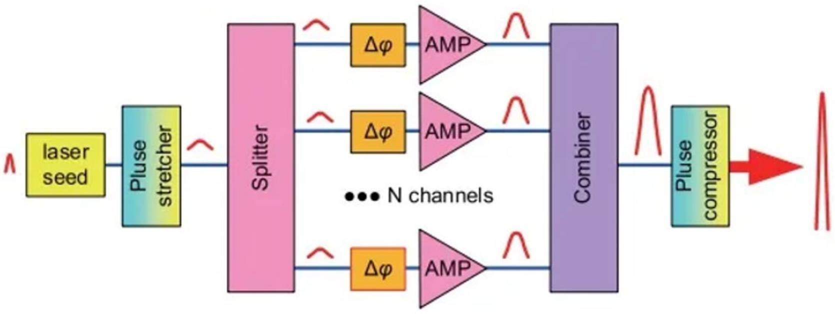

Figure 4. Spatially coherent synthesis [11].

(b) Divided-pulse amplification

Divided-pulse amplification is the process of splitting a laser pulse into a sequence of sub-pulses, which are separated from each other in terms of pulse timing, then amplified by the same amplifier, and finally, the pulse sequence is recombined into a single laser pulse, thus increasing the peak power of the output pulse [12].

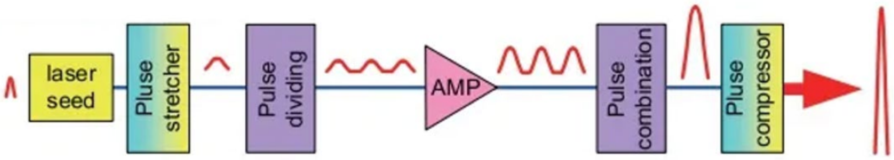

Figure 5. Divided-pulse amplification [11].

(c) Pulse Stacking

Pulse stacking is generally the superposition of multiple pulses into a single pulse using a toroidal enhancement cavity [13]. The two main types of ring cavities used for pulse stacking are the Gillet-Turnauer interferometer resonance cavity (GTI) and the stack-and-dump cavity (SnD).

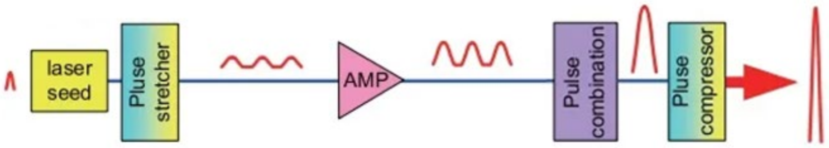

Figure 6. Pulse Stacking [11].

GTI cavity: The cavity consists of a beamsplitter and multiple all-reflective mirrors, with the pulse sequence entering the annular cavity through the beamsplitter. The previous pulse travels around the cavity for one revolution before meeting the next incoming pulse at the beamsplitter, coherently phasing out in the direction of the output GTI cavity and coherently growing in the direction of the input GTI cavity, with energy stacked into the cavity. When the last pulse of the pulse train meets the previous stacked pulse at the beam splitter, it is coherently phased out in the direction of the output GTI cavity, and the pulse sequence is synthesised into one pulse and output out of the cavity.

SnD cavity: The cavity consists of a coupling mirror and multiple all-reflective mirrors, with the pulse sequence passing through the coupling mirror into the annular cavity. The previous pulse meets the next pulse at the coupling mirror, each time with a coherent phase length in the direction of transmission within the cavity. The cavity contains a switch device, which is transmissive during the energy stacking process. A moment after completing the pulse stacking of the pulse sequence, the device causes a change in the direction of laser transmission of the pulse, and the energy is exported out of the cavity.

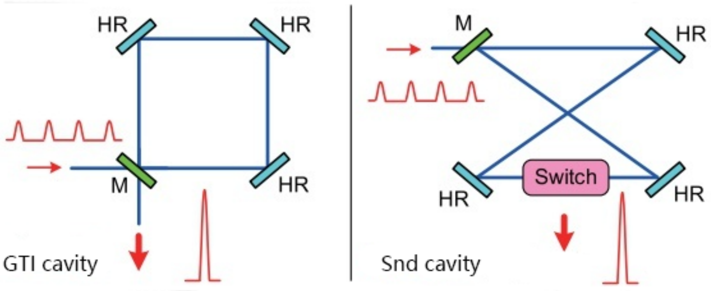

Figure 7. GTI cavity & SnD cavity [14].

3. Applications of femtosecond pulsed lasers

Femtosecond laser technology has been around for more than 40 years and has been awarded the Nobel Prize twice. It is the most accurate measurement technology in the world today and is widely used in various fields. Femtosecond laser technology is gradually being used in high-end industrial manufacturing, as well as in cutting-edge fields such as chips, flexible electronics, medical imaging, and vision correction.

3.1. Femtosecond pulsed laser for biomedical applications

The advantages of the femtosecond laser are the narrow pulse width, the fast repetition rate, and the low energy of the pulse. Most importantly, the femtosecond laser is not absorbed by localised light-absorbing tissue, so the laser can be precisely distributed to different depths of tissue. The shorter the pulse length, the lower the final energy output, reducing the damage to the patient's tissues.

3.1.1. Vision correction. Full Femtosecond laser surgery is done entirely with a femtosecond laser. The procedure uses a femtosecond laser to scan twice through the corneal layers to create a lens. The lens is removed through a lateral corneal incision to correct myopia. Full Femtosecond laser surgery has the advantage of short duration and high patient comfort. In addition, the procedure allows for greater individualisation of the patient for excimer laser surgery. The surgeon can make a plan for the patient based on the data collected before surgery, ensuring that the flap is of uniform thickness and stable, thus improving the accuracy and repeatability of the procedure, reducing the incidence of postoperative complications such as dry eye and infection, and improving the healing of the flap.

3.1.2. Medical imaging. Optical coherence tomography (OCT) is widely used in medical research in the fields of dermatology, ophthalmology, and neurology [15]. The basic structure of the experimental setup for OCT is a fibre optic Michelson interferometer. The light source is a low-coherence light-emitting diode, a femtosecond laser, or white light. OCT uses the coherent part of the reflected or scattered light from the internal structural cross-section of the sample to interfere with the reference light, select the signal light and then image the sample laminarly, precisely determining the position of the measured point along the optical axis by the light range of the reference light.

Femtosecond lasers are also used in time-selective gate-scanning imaging [16, 17]. The device uses a femtosecond laser as the light source and a second harmonic intensity correlation as a time-selective gate to separate the ballistic light and part of the serpentine light from the diffuse light as the signal light for imaging. Because the femtosecond laser is used as the light source, the longitudinal resolution is less than 30μm and the lateral resolution is about a dozen μm.

3.2. Femtosecond pulsed lasers for manufacturing applications

3.2.1. Drilling. In the manufacturing industry, drilling is a very common but delicate task. Oil holes, positioning holes, and fastening holes are some of the more common types of holes machined. Femtosecond laser technology has a very short processing time in a single pass, much shorter than the time required for heat diffusion or heat conduction, so using femtosecond laser technology for drilling can avoid the problems associated with conventional laser drilling and result in clean, very high-quality holes [18].

Femtosecond laser technology for punching holes has three characteristics.

(1) High accuracy and precision. In femtosecond laser technology punching, hole surface roughness R_a is not more than 0.1m, which is what traditional mechanical drilling and ordinary laser punching can not achieve. The accuracy and precision of femtosecond laser technology are more than 10 times higher compared to ordinary laser drilling and more than 100 times higher compared to mechanical hole making.

(2) No heat-affected zone. With femtosecond laser technology, the processing interface is a heat-damage-free surface, thus greatly improving the surface properties of the hole wall.

(3) Good consistency. Femtosecond laser technology can achieve a high degree of consistency in the accuracy of the holes, including roundness, taper, cylindricity, etc. When processing multiple holes simultaneously, the deviation in position can be less than 1%. A high degree of consistency in accuracy cannot be achieved by other processing methods.

3.2.2. Super smooth surface processing. Femtosecond laser technology can induce changes in the surface properties of material structures, such as frictional properties. Femtosecond laser technology enables ultra-slick surfaces to be machined and the surface roughness of materials to be altered. Femtosecond laser technology is a solution to the problem that the service life of many structural components in the manufacturing industry is limited by the frictional forces involved in the working process.

3.2.3. Etching and cutting. Femtosecond laser technology for etching and cutting is more commonly used in the automotive industry, the construction machinery industry, and the aerospace industry, mainly for the treatment of metallic materials such as steel, aluminium alloys, and titanium alloys. Femtosecond laser etching and cutting do not cause mechanical deformation problems and have little effect on the material, with negligible thermal effects during the irradiation process [19].

4. Development trends and outlook of femtosecond pulsed laser

In medicine, the future of lasers for treatment will develop in the directions of high power, miniaturisation, intelligence, and precision. The femtosecond laser is considered to be the ideal ultra-precise surgical scalpel due to its high precision. Nowadays, femtosecond lasers are mainly used for laser vision correction, and research on the use of femtosecond lasers for glaucoma treatment has been successful. Femtosecond lasers can also be used to cut fragile polymers without altering their important biochemical properties, which means that they have great value in scientific fields such as molecular biology and gene therapy.

Recent developments in optical technology, particularly femtosecond lasers, and nanotechnology have opened up new avenues for selective therapy at the cellular and subcellular levels. Lasers can be used to influence the function of cells, and laser-based cell surgery enables higher spatial and temporal resolution of the treatment area. Laser optical tweezer technology will be a new direction for future development.

In manufacturing, femtosecond laser technology is a manufacturing tool that is at the heart of the future of high-precision manufacturing. The ability to process any material, high precision, and no need for tooling are the three main manufacturing characteristics of femtosecond laser technology. Femtosecond laser technology also offers the advantages of contactless, impact-free, one-shot processing, making it the ideal technology for future advanced manufacturing.

However, there are still many challenges to overcome. For example, the interaction mechanism between the femtosecond laser and matter is very complex and requires different physical models to explain the common and individual scientific problems in the processing of different materials; the progress of femtosecond laser processing technology also relies on the continuous development of the laser light source; there is a constant conflict between processing accuracy, processing efficiency, and processing scale for femtosecond laser processing.

In recent years, the accuracy of femtosecond laser processing has increased to the nanometre scale. New technologies, represented by parallel processing strategies, have also improved the efficiency of the process. In contrast, the processing scale of femtosecond lasers has yet to be improved and is often small due to the limitations of high-precision 3D moving platforms and optical systems. This severely limits its practical applications. The expansion of processing scales from the micron and millimetre scale to macroscopic large areas (centimetres and metres) is one of the future directions for femtosecond laser processing technology; this heavily relies on more advanced femtosecond laser processing systems. The future of femtosecond laser technology in the manufacturing industry is very promising and deserves continuous exploration and research by technical personnel.

5. Conclusion

The paper provides an in-depth explanation of femtosecond pulse laser technology by focusing on the generation and amplification of femtosecond lasers. Based on the short pulse duration, high peak power, and fast repetition rate of femtosecond pulsed lasers, they are widely used in biomedical and manufacturing applications. Finally, this paper shows the future development trend of femtosecond pulsed lasers and presents the challenges between femtosecond laser processing accuracy, processing efficiency, and processing scale. And there is a new research direction on laser optical tweezers technology, which are worthy of further study by researchers.

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