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Ultrafast lasers: A new frontier for optical materials processing

Javier R. Vázquez de Aldana [a], Pablo Moreno [a,*], Luis Roso [b]

[a] Grupo de Investigación en Microprocesado de Materiales con Láser, Universidad de Salamanca, Plaza de la Merced s/n, 37008 Salamanca, Spain
[b] Centro de Láseres Pulsados, CLPU, Patio de Escuelas 1, 37008 Salamanca, Spain

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ABSTRACT

In the last years, ultrashort laser pulses have gone through the laboratory walls to burst into the industrial arena as a tool for material micro- and nanoprocessing. The number of industrial fields and specific applications is steadily growing, reaching the nanotechnology applications. Now, we celebrate the 25th anniversary of the CPA (chirped pulse amplification) technique which made available intense ultrashort (subpicosecond) pulses able to induce ablation of any material. This contribution tries to review the fundamentals of ultrafast lasers as well as some of their applications, emphasizing the processing of optical materials.

1. Introduction

Theodore Maiman built the first laser in 1960 [1]. Fifty years later, lasers have decisively contributed to the development of many scientific and technological fields and are present all over in our lives. The development of laser technology itself is far from being over. Ultrafast lasers technology is one of the most active branches. The achievement of extremely intense ultrashort laser sources constitutes a ground-breaking milestone that will foster scientific and technological research in fields such as particle acceleration, soft X-ray generation, nuclear physics, and materials science as well.

The paper contents are divided in two main sections. In Section 2, we review the technology of current ultrashort laser sources and identify the trends of future development of this technology. In Section 3, we point out the fundamentals of the interaction of ultrashort pulses with matter, focusing on the mechanisms that lead to the modification or ablation of optical materials. Some examples of the application of ultrashort pulses to the fabrication of photonic devices are shown.

2. Ultrafast laser technology

The needs of telecommunications industry were probably the main driving force for the development of pulsed light technology. The earliest technique to attain pulsed light was inserting a mechanical chopper into the beam path of a continuum laser source. It was soon discovered that some solid state materials emit pulsed coherent light in the range of hundreds of nanoseconds but in a rather uncontrollable way. The fast development of electronics and non-linear optics provided the means to act within the laser cavity in order to handle the level of population inversion in the active material and losses in the cavity. This technique is known as Q-switching [2]. The fundamentals are simple. A fast attenuator induces a high level of radiation losses in the cavity (low Q-factor) whereas the population inversion is growing as a result of pumping. If the attenuator is suddenly switched off, the cavity rapidly increases its Q-factor leading to the release of all the stored energy as a short pulse. The output is typically some nanoseconds with power up to kW.

2.1. Mode-locked lasers

Generation of extremely short pulses (picosecond or less) is out of reach for Q-switching techniques. Already in the 1960s, a new technique was proposed to break the limitations of Q-switching. The name, mode-locking, refers to the key mechanism of the technique [3], which basically consists in establishing a fixed phase relationship among the modes of the laser's resonant cavity.

An ordinary laser cavity supports a lot of resonant modes since the optical wavelengths are much smaller than the cavity length [4]. The frequency difference between two consecutive modes is inversely proportional to the length of the cavity. These modes are independent each other, what means that the cavity emits coherent radiation at slightly different wavelengths at the same time. The phase of the light waves in each mode is not fixed since the cavities are not stable (as a result of thermal load of the materials, for instance). Since all these modes share the same cavity, interference effects arise leading to random or uniform intensity output depending on the number of modes. However, if we could

* Corresponding author.
E-mail address: pmoreno@usal.es (P. Moreno).

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fix the relative phase among all these modes, constructive interference would periodically give rise to the release of intense and very short laser pulses. The pulses generated under mode-locking or phase-locking conditions are separated the time they take to complete a round trip of the cavity which corresponds to a frequency equal to the frequency difference between consecutive modes. The duration of the pulses depends inversely on the mode-locked bandwidth, i.e. the product of the number of locked modes and their frequency difference. Some other effects limit the minimal duration of the pulses, essentially the pulse temporal shape and the dispersion of the cavity.

Concerning the methods to produce mode-locking, there are two families, active and passive ones [5]. Any of them modulates the light by an intracavity optical element, either triggered by an external signal (acousto-optic or electro-optic modulators) or directly induced by the radiation in the cavity (Kerr lens, saturable absorbers). As time goes by, a great number of design arrangements have been developed to increase the stability and reliability of these lasers (Fig. 1). At the same time new techniques and materials have been explored in order to reduce the pulse duration and increase the output peak power.

2.2. The titanium:sapphire revolution

For many years, most of the mode-locked lasers used Nd:YAG or similar materials as active media. This hegemony changed dramatically in the 1980s when the outstanding properties of Ti:Sapphire crystals put this material on the stage as the best candidate ever to generate ultrashort pulses [6,7]. The key property is the Kerr nonlinearity of the active medium which makes unnecessary the use of any other element to induce phase locking within the cavity. The gain bandwidth is very large which allows the generation of very short pulses and at the same time a wide range of wavelength tunability (650–1100 nm). The thermal and mechanical properties of the crystal allow high powers and intensities within the active medium and therefore output powers as high as some watts for pulses shorter than 100 fs. The laser emission cross sections are relatively high reducing the probability of pulse energy instabilities. All these properties have contributed to generate a new class of reliable and robust, high-average power, femtosecond lasers.

Ti:Sapphire allows a wide range of pumping wavelengths in the green spectral region. Initially, Ti:Sapphire lasers were pumped with Argon ion lasers which are bulky and inefficient as a pumping source. The reason is that the fluorescence lifetime for Ti:Sapphire is very short (3.2 ms) and the saturation power is very high. Therefore a high pumping intensity is required, precluding continuous wave lasers. Unfortunately, powerful diode lasers are not available in this region [8]. Q-switched frequency-doubled solid state lasers based on Nd doped crystals (Nd:YAG, Nd:YVO, Nd:YLF and some others) meet the requirements for pumping Ti:Sapphire. Nd:glass is the most suitable choice when high pumping power and low repetition rates are required. On the other hand, for low pumping power and high repetition rates, diode-pumped Nd-doped crystals are a reasonable choice.

The most significant advance in Ti:Sapphire lasers design since its original demonstration has been a dramatic reduction in the pulse duration [9]. Nowadays, companies offer extremely stable and reliable Ti:Sapphire lasers providing even 10 fs pulses at repetition rates around 100 MHz and pulse energies of approximately 10 nJ. Regardless other applications of these lasers, they are often used as front-end sources for high power, ultrafast, amplifier systems.

Shortening the pulse duration below 10 fs means a huge technological challenge since any optical component may introduce a dispersion that increases significantly the pulse length. Thus, achieving pulses as short as 5 fs require an extremely precise dispersion compensation in the cavity.

Up to now, Ti:Sapphire has a prevailing role in the field of high intensity ultrashort pulse generation. However, intensive research is being carried out to find out other materials that could improve the performance of Ti:Sapphire. The ideal material should exhibit very good optomechanical properties, very long fluorescence time (at least milliseconds) and a proper pumping band. Pumping with longer wavelengths will open the door to high power diode pumping lasers and lasing wavelengths beyond 800 nm will not constitute a problem.

2.3. Chirped pulse amplification (CPA) technology

For many applications, Ti:Sapphire oscillators delivering pulses with few nanojoules are enough. Femtochemistry has found in such lasers the main tool for research purposes. However, other applications require huge intensities that can only be accomplished by increasing the energy per pulse. In fact, as the intensity of ultrashort pulses has increased, new phenomena, physical effects and applications have been made accessible.

The simplest amplification technique uses a second active medium, in this case, another Ti:Sapphire crystal which is optically pumped with an external source (Fig. 2). Despite the high saturation power and the excellent thermal and mechanical properties of Ti:Sapphire, there is a limit for the amplification laid down by the huge increase of intensity inside the crystal as a result of non-linear processes such as self-focusing. These intensities above

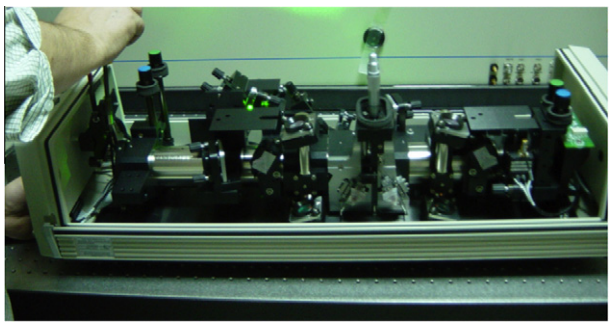

Fig. 1. A typical Ti:Sapphire mode locked oscillator.

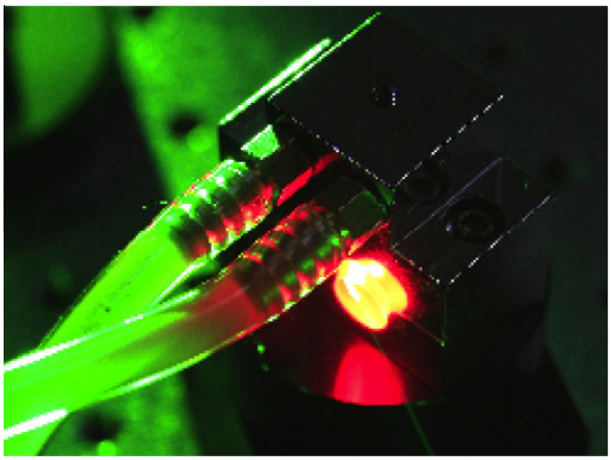

Fig. 2. Ti:Sapphire crystal pumped with green light. The red emission is the fluorescence of the crystal. The crystal needs cooling during the process (tubes on the left). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

GW/cm^2 cause irreversible damage to the crystal or other optical elements within the cavity.

A first attempt to overcome this drawback was to expand the beam section and insert crystals big enough to avoid reaching the damage threshold inside. This led in the 1980s to the first Terawatt laser (NOVA) in the Lawrence Livermore National Laboratory. This was a giant system with an extremely low repetition rate, not affordable for the vast majority of labs in the world.

A new and amazing approach for increasing ultrashort laser power output was proposed in the 1980s by a group of researchers in the Laser Laboratory at the University of Rochester (Rochester, NY), headed by Gérard Mourou. The technique, previously used in the 1960s for increasing radar power, was named chirped pulse amplification or simply CPA [10]. The development of this technique meant the starting point of ultraintense laser technology.

The basic idea behind CPA is quite simple. An ultrashort pulse is stretched out in time, then amplified to increase its energy but avoiding peak powers that could damage the laser components. Finally, the pulse is compressed back to pulse widths similar to the original one achieving peak powers orders of magnitude higher than the pulses delivered by the Ti:Sapphire oscillator.

The "seed" pulses have widths in the subpicosecond range what means that their frequency spectrum is really broad, at least some nanometers. They are stretched to pulse widths of hundreds of picoseconds or even nanoseconds and, at the same time, chirped to compensate the different paths that low and high frequency components have to travel during the amplification procedure. This is attained by means of strongly dispersive elements, normally a pair of gratings. With this pulse width and chirping, the pulse energy is increased six or more orders of magnitude by optical pumping. To recover the temporal and spectral features of the original pulses, the amplified pulses are driven to a second pair of gratings such that the chirping is compensated and the pulse width is reduced back to the range of femtoseconds [10–12].

Amplification stage may follow different strategies. Since the gain must be huge in most of these systems, multiple pass is usually needed. The most common setup to obtain very high gains is a regenerative amplifier (Fig. 3). In this scheme, a Ti:Sapphire crystal is placed within an optical resonator. Initially, the crystal is pumped in order to store energy. Then, the seed pulse is injected with an electro-optic or acousto-optic switch, undergoing many round trips across the resonator and the corresponding amplification. Finally, the pulse is released using again a fast switch. Petawatt powers may be achieved following a combined scheme of regenerative and multipass bulk amplifiers. For these very high powers, the amplifying stage becomes more complicated since vacuum technology is needed.

To achieve extremely large peak powers, a development of CPA technique, called optical parametric CPA (OPCPA) [13], is becoming the standard among laser facilities. In optical parametric amplification [14], the signal beam propagates through the crystal together with a pump beam of shorter wavelength. Photons of the pump wave are converted into signal photons and the same number of idler photons; the photon energy of the idler wave is the difference between the photon energies of pump and signal wave. Since all the pumping energy is transferred to the signal and idler beams, the crystal does not undergo significant thermal load, allowing high power operation. The cavity does not store energy, and therefore the contrast of intensity between amplified and non amplified pulses is very high. The gain in a single pass is huge what makes complicated multipass setups unnecessary. Finally, parametric amplification is possible in a wide range of wavelengths, although an ultrabroad gain bandwidth is achieved only under certain phase-matching conditions [15]. So far, few femtosecond high energy pulses may be generated with this technique. As compared to conventional CPA techniques, OPCPA has some technical challenges, such as the synchronization of seed and pumping lasers, the required high quality of the pumping beam and all the issues connected to phase matching.

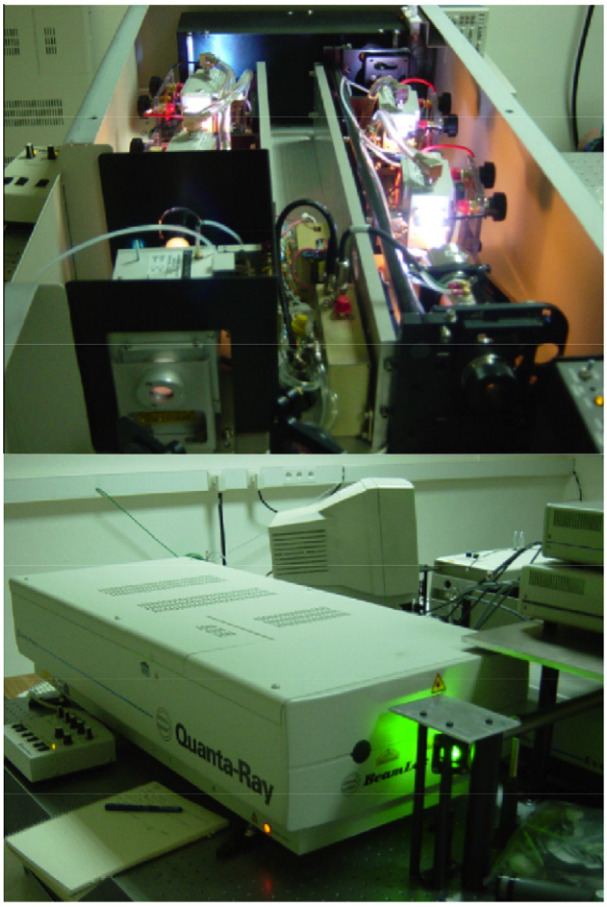

Fig. 3. Nd:YAG doubled pumping laser (bottom) and the amplifier of a Ti:Sapphire CPA system (up).

An excellent review of the ultra-short high-intensity laser pulse generation and amplification can be found in [16]. The landmarks of the 30-year evolution of ultrashort-pulse laser physics and technology culminating in the generation of intense few-cycle light pulses can be found in [17].

2.4. Limits of the cpa technology and new developments

2.4.1. Pulse duration

OPCPA technique has made possible to produce high-power ultra-short (few optical cycles) pulses overcoming the bandwidth limitation by making the pump and signal pulses to interact in certain non-collinear geometries [15,18]. However, the high complexity of OPCPA is leading to the search for alternatives. One of the most promising techniques is the so-called "post-compression".

Post-compression techniques are based on the phenomenon of filamentation [19]. When a high power ultrashort pulse is focused in media with third-order non-linear susceptibility (gases, liquids, amorphous solids), a light channel (filament) – much longer than the Rayleigh length – can be created. Filamentation process is a consequence of the balance between two competing non-linear processes: on one hand, optical Kerr effect which increases locally the refractive index of the medium that behaves as a converging lens; on the other hand, a dense electronic plasma produced by the ionization of the material acts as a defocusing medium. Under

certain conditions, both processes are balanced resulting in the creation of a long filament. The pulses emerging from the filament exhibit a strong spectral broadening due to both self-phase modulation and interaction with the plasma. Such spectrally broadened pulses can be recompressed and shortened with regard to original pulses. In fact, ultrashort pulses have been obtained using filamentation and chirped mirrors for the phase compensation [20]. The main drawback of post-compression techniques is that the output energy is typically less than 1 mJ. The limiting factor at this point is that higher pulse energies give rise to several filaments at random positions, and thus the spatial beam quality is lost. However, some new methods are in progress to increase the pulse energy into a single filament.

Many research is being carried out in this topic. For instance, it is important to unveil the effect of the input pulse polarization in the filamentation process. When circular polarization is used, higher input energies may come into play and higher output energies are achieved as well [21,22]. Increasing the polarization ellipticity allows simultaneously the decrease of the target ionization rate and the increase of the critical power for self-focusing. With this technique, output pulse energies above 1 mJ have been obtained, with ultra-broadband spectra supporting 7 fs pulses. Control of the chirp (spectral phase) of the incident pulses is another important issue: when certain chirped pulses are used as input, the threshold energy for multi-filamentation increases and thus higher pulse energies may be obtained. These and other issues now under investigation will hopefully contribute to push the energy limit of post-compression generated pulses to the multi-millijoule level.

2.4.2. Repetition rate

Concerning the use of ultrashort pulses for materials microprocessing, in particular optical crystals or glasses, very high peak powers are not required [23,24]. In most of the practical applications, focusing the beam in order to reduce the irradiated area for a high resolution material structuring is mandatory. For pulse durations around 100 fs, peak powers in the range of 1–10 GW (pulse energy of 0.1–1 mJ) are enough for most practical applications. Such pulse parameters are usually obtained with just a regenerative amplifier. However, there is another parameter that is crucial for efficient microprocessing: the repetition rate. Low repetition rates preclude the use of ultrafast lasers since the process would become never-ending. Nowadays, regenerative amplifiers of standard commercial femtosecond systems allow repetition rates up to 5–10 kHz preserving a pulse energy level close to the millijoule. Thermal load of the amplifying crystal remains the bottleneck. Fortunately, the use of cryogenically cooled crystals allows increasing the mean power to several tens of Watts [25], but at the expense of losing the simplicity and robustness of the system.

2.4.3. Peak intensity

Many of the applications of high-power femtosecond lasers come from the non-linear effects [26] that they are able to induce in the interaction with matter. The phenomenology of the interaction of high-power lasers with matter in terms of the intensity is very rich and surprising [27]. The standard Einstein's photoelectric effect gives way to multiphoton effects above 10^{10} W/cm^2. Multiphoton ionization – ionization of atoms and molecules by the simultaneous absorption of several photons – is the dominant effect in laser–matter interaction up to 10^{15}–10^{16} W/cm^2. Beyond these intensities, the laser electric field becomes comparable to the Coulomb field that binds the electrons to the atomic nuclei. At 10^{18} W/cm^2 the ionized electrons undergo relativistic dynamics [28], and so the ions at 10^{21} W/cm^2 [29]. Electron beams have already been accelerated to keV with ultrashort pulsed lasers.

These non-linear effects depend mainly on the peak intensity of the electromagnetic radiation. A high peak power laser is not enough, it is necessary to strongly concentrate such power in space by using a focusing system. The limiting factor that prevents the achievement of an ideal focal spot (given by the diffraction limit) is the spatial quality of the beam. The operation at high pumping levels worsens the beam quality of the amplified pulses. For this reason, the record intensities [30] are not comparable to the corresponding peak power lasers. A lot of research is still needed to optimize focusing of high power pulses.

3. Ultrafast processing of optical materials

3.1. Fundamentals of interaction

Optical materials are usually transparent to visible and near infrared light since their linear absorption rate for these wavelengths is extremely low. This is a consequence of their large bandgap which prevents the electrons in the valence band to be promoted to the conduction band by absorbing a single photon [31]. As a matter of fact, laser micro-structuring of these materials becomes a huge or even an impossible task with conventional pulsed lasers.

A promising pathway to struggle with this issue was found almost two decades ago when intense ultrashort laser pulses were used for the first time to modify the surface of silica [32]. The interaction of such short pulses with dielectrics is no longer determined by the rules of linear absorption. Multiphoton absorption allows a number of electrons to be detached from their parent atoms [33]. It is interesting to point out that multiphoton ionization rate depends on the intensity as I^m, where m is the minimum number of photons needed to overcome the bandgap of the material. Since the bandgap is material dependent, the threshold intensity to trigger the process may be quite different as well.

Permanent modification of the material requires massive carrier generation, much larger than what we can achieve exclusively through multiphoton ionization. Once some seed electrons are released they can absorb more energy from the laser pulse in the presence of the ions through inverse bremsstrahlung, quivering with increasing amplitude. This electron motion may induce further release of bound electrons via collisions in the process known as avalanche ionization [34,35]. A density of electrons as large as the solid state density (10^{23} cm^{-3}) can be achieved within a small volume of the material during the pulse duration. This dense plasma absorbs the remainder of the pulse energy what will induce further plasma heating. The thermalization of this plasma is very fast as a result of electron–electron scattering (in the order of some fs). At the time the pulse is over, the thermal coupling of electrons and ions is almost negligible since the typical time scale for this process ranges from one to hundreds of picoseconds depending on the material and the pulse duration and energy. Summarizing, after irradiation with a single infrared femtosecond laser pulse, a small volume of the material consists of a hot dense electronic plasma and a lattice of ions.

Obviously, the magnitude and relevance of the processes taking place after the pulse is over will depend on the pulse energy and duration. Following the irradiation, the material undergoes a number of different physical processes that will determine the final morphology and properties of the irradiated zone and the surroundings. The effects are different if the dense plasma is created on the surface of the material or inside the bulk.

Moderate intensities lead to a dense plasma but still under the threshold for dielectric breakdown of the material (in the order of 10^{21} cm^{-3}). In this case, thermal load is able to disorder the lattice and the subsequent reorganization may result in densification, rarefaction or defect formation [36]. The most representative perma-

nent effect for these intensities is a change in the refraction index of optical materials in the focal volume.

For intensities above the threshold, charge separation give rise to a sort of "quasistatic" electric field between electrons and ions that may overcome the binding energy within the ion lattice and induce the ejection of the ions. The process is known as Coulomb explosion and is the leading ablation mechanism for intensities slightly above the threshold, taking place in the range of some picoseconds after the pulse is over [37,38]. The trace of Coulomb explosion is a shallow crater on the surface or a void inside the bulk [39].

For higher intensities, a huge amount of energy is absorbed by the dense electronic plasma and then transferred to the lattice in a period of time as long as tens of nanoseconds. Depending on the level of lattice heating, the material may undergo extremely fast fusion, vaporization and ejection of the material. This process is known as phase explosion [40,41]. On the surface, a deeper crater will be generated leaving some traces of its thermal nature on the surroundings whereas inside the bulk, voids are generated together with cracks, resolidified material, phase transformations leading to changes in the optical properties in the surroundings of the focal volume. Mechanical waves are responsible for some of these pernicious effects. Estimations of the temperature within the focal volume show that it is overheated even orders of magnitude above the thermodynamical critical temperature of the materials [42]. This means an enormous pressure that will be released through adiabatic expansion. Shock waves are generated and propagate through the material and, in the case of surface ablation, in the ambient gas [42,43]. The material undergoes compression stresses as high as thousands of GPa as the mechanical wave propagates, producing distortion or even the fracture of the adjacent zones (Fig. 4).

It is also important to point out that the presence of a dense plasma alters significantly the propagation of the laser pulses which is no longer linear (optical Kerr effect). This leads to a modification of the focal volume which affects the morphology of the changes induced in the material [36].

3.2. Fabrication of photonic devices

One of the most impressive capabilities of infrared femtosecond lasers is the possibility to perform three dimensional processing of transparent dielectrics. Since the central wavelength of Ti:Sapphire based femtosecond laser systems (around 800 nm) lies in the transparency range of most crystals and optical glasses, the pulses can be focused at any point inside the dielectric leading to the localized modification of some physical properties of the material. By setting accurately the irradiation conditions, the nature and size of the induced modifications can be controlled to some extent. This property has been applied to high-precission micro-fabrication of a number of optical devices: optical waveguides [44–52], photonic crystals [53], three-dimensional optical storage systems [54], or diffractive elements embedded in glasses or crystals [55–62], among many others (for a recent review, see [63]).

3.2.1. Optical waveguides

Since the first demonstration of optical waveguide fabrication with a femtosecond laser [44], this topic has focused lots of research efforts. The technique is simple: the laser is focused inside the material while a motorized stage moves the sample according to the desired geometry, producing some local increase in the refractive index of the material. Therefore, the writing procedure presents many advantages when compared to standard fabrication techniques: it is a single-step process (no need for either a mask or post-development processing), any waveguide geometry can be written and the processing can be done at an arbitrary depth of the sample.

The mechanisms for waveguide formation, as well as the optical properties of the waveguide, strongly depend on the material and on the irradiation conditions: pulse duration, intensity at focus, repetition rate, polarization and, focusing optics. All these parameters can be optimized in order to achieve, for instance, the desired type of waveguide (mono/multi-mode) [45], the refractive-index profile or to minimize the optical losses.

There exist two main approaches to waveguide fabrication with femtosecond lasers. In the first one (single scan technique, Fig. 4a), the refractive index increase is created just at the focal volume of the incident laser beam. This approach was the first one in being investigated and, in general, it requires the use of low pulse energies (as low as a few nJ) in order to avoid or minimize the laser-damage of the sample: in fact, only a laser oscillator is enough [46]. Such kind of waveguide is particularly interesting in the fabrication of complex devices such as arrays of coupled waveguides [47], where the damage of the sample would modify the extension of the evanescent wave, or waveguide Bragg gratings [48].

The second approach involves the use of higher pulse energy (typically mJ) in order to produce a severe damage track along the focal volume. In this case, in the surrounding area of the damage, a local increase in the refractive index appears that can be further increased and shaped by making a second irradiation at some distance of the first one (double scan technique, Fig. 5b). This technique is particularly suitable for the fabrication of active devices [49] provided that the spectral [50] and anisotropy [51] properties

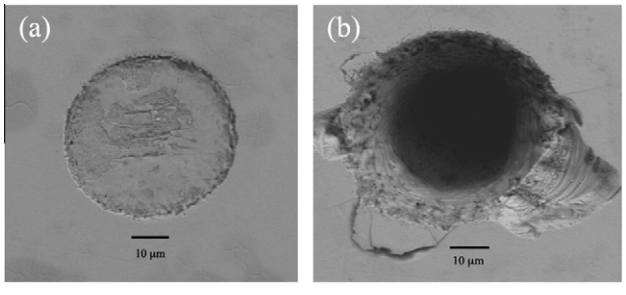

Fig. 4. The effect of mechanical waves on the surface of $KLu(WO_4)_2$ is clearly visible in the regime of strong ablation. Left, after 5 pulses; right, after 100 pulses.

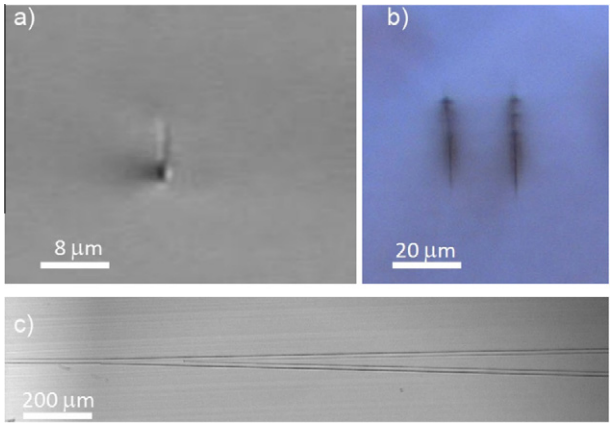

Fig. 5. (a) Transverse section of a waveguide recorded in fused silica by the single scan technique. (b) Transverse section of a waveguide recorded in Nd:YVO_4 by the double scan technique. (c) Beam-splitter written in Nd:YAG by the double scan technique. Pictures taken with an optical microscope in transmission mode.

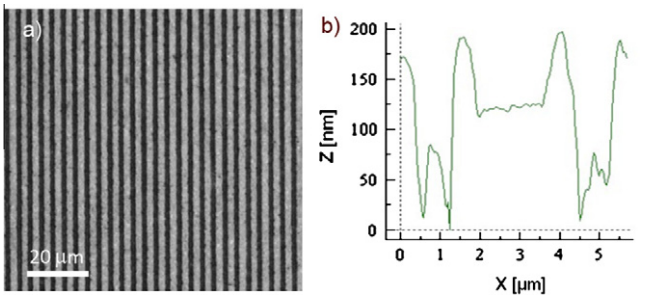

Fig. 6. One-dimensional diffraction grating written in the surface of a β-BaB_2O_4 crystal by ultrafast laser ablation. Irradiation parameters were selected to minimize the damage of the crystal. The grating period was 3.5 mm. (a) Optical microscope picture taken in reflection mode. (b) Atomic force microscope profile.

in the waveguide can be well preserved, they resist very high temperatures [52] and both TE and TM polarizations can be confined.

3.2.2. Diffractive elements integrated in crystals

Both ultrafast ablation, as the local refractive index modification that can be produced with femtosecond lasers, have been applied to the fabrication of diffractive elements integrated in transparent dielectrics. In the first case, the laser is focused in the surface while the sample is scanned following the desired geometry. The result is a micro-patterning of the surface that acts like a binary (amplitude) mask [55–59]. In the second case, the structure is written at some depth inside the sample, and consists of a phase mask in which high diffraction efficiencies can be achieved [60–62].

Concerning the applications of such devices to high-power femtosecond lasers, diffractive elements have been used for triggering some non-linear optical processes. The first demonstration of this use consisted of the integration of a two-dimensional relief grating in the surface of a KH_2PO_4 crystal [55]. When the micro-structured crystal was irradiated with an intense femtosecond beam, some diffraction orders generated at the entrance surface of the crystal satisfying non-collinear phase-matching conditions, were converted into the blue. Slight variations of the crystal tilt, lead to the generation of different patterns of second-harmonic femtosecond pulses: the device behaves as an active non-linear beam splitter for high power lasers. The same principle of operation has been extended to other crystals with more interest for ultra-short pulse applications as β-BaB_2O_4 [59].

Another interesting application of the diffractive elements concerns the sum-frequency generation of two intense femtosecond beams with different wavelengths [56]. In this case it is possible to design a grating that achieves the effective matching of both the phase as the group velocities of the interacting wavelengths. Such effect results in the strengthening of the generated pulsed beam. Moreover, the suppression of group velocity mismatch allows the use of these micro-structured crystals for the temporal measurement of ultrashort pulses by cross-correlation. In particular, it was demonstrated in a β-BaB_2O_4 crystal (see Fig. 6) for the characterization of 398 nm femtosecond pulses.

4. Conclusions

Ultrashort pulsed laser technology has provided a new and powerful tool both for industrial applications and scientific research. In this paper, we have provided a review of the origin and evolution of ultrafast laser technology, pointing out some of the current and future developments of the technology focusing on those related to materials processing applications. These include new lasing materials, a research field which is experiencing a rapid growth in the last years [64,65].

We have described a number of applications to optical materials processing. Fabrication of waveguides or diffractive elements within optical materials require very high precision and minimum mechanical and chemical changes on the surroundings of the processed area. Ultrashort pulses offer the chance to induce such microstructures inside practically any material with high geometrical precision. A huge number of innovative applications are expected for the upcoming years in this field.

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