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Femtosecond laser micromachining with extended depth of focus by using diffractive lenses

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ABSTRACT

We show that a simple diffraction focusing element can alleviate mechanical tolerances in ultrafast laser microprocessing. In particular, we experimentally demonstrate that, in comparison with a conventional refractive lens (RL), focusing light pulses of 30 fs onto a stainless steel sample with a diffractive lens (DL) can increase twice the useful axial ablation region. This is thanks to the combination of the broadband spectrum of ultrashort pulses, and the huge longitudinal chromatic aberration associated with DLs. We believe that our results might be useful for reducing the complexity and cost of ultrafast microprocessing systems.

1. Introduction

The use of ultrafast lasers in material processing has grown rapidly in recent years thanks in large part to the high precision surface or tridimensional microstructuring that these lasers provide. In the low fluence regime, the different mechanisms of ablation depend, among other factors, on the type of materials. For instance, the dominant mechanism of ablation in dielectrics is the multiphoton surface ionization process (also called Coulomb Explosion) [1]. In contrast, for metals, the prevailing ablation mechanisms seem to be spallation and melting [2]. The ablation processes due to the above mechanisms occur with minimal thermal or mechanical damages in the surrounding of the processed area. Excellent results [3] in cutting, drilling, as well as marking of metals [4], dielectrics [5], polymers [6], ceramics [7] or glasses [8] with femtosecond lasers have been shown.

In order to generate feature size with high quality and small dimensions the most widely adopted method is to focus the light with a RL. It allows concentrate the energy of the beam onto a small area whose minimum size is restricted by the diffraction limit and the beam aberrations. In addition, precision micromachining is highly susceptible to minor displacements caused by e.g., environmental disturbances such as temperature variation or system vibration. This may be a bottleneck for the fabrication of nanostructures, microprocessing of rough samples or large areas where active compensation of sample tilt would be required. Hence, the depth of focus (DOF) is a relevant parameter in micromachining.

Sophisticated monitoring and control of the focal position not only slow the speed of the material processing due to the continuous realignment, but also increase the cost of the beam delivery system. Intense efforts have been undertaken to obtain stable laser modules with high mechanical tolerances. One alternative is to use an axicon as a focusing element. The axicon produces a diffraction-free beam lying along the propagation axis of light. As a result, axicons have a huge Rayleigh range at the expense of the decreasing of beam power and contrast in the workpiece. The applications of axicons for material processing [9] range from laser micro-drilling [10] to the fabrication of high aspect ratio channels for micro/nanofluidics [11] or 2D photonic crystals [12].

A less explored method to increase the DOF of femtosecond laser beams comes from the use of a DL as a focusing element [13]. Within the paraxial approximation, the focusing of a continuous-wave (cw) with a RL or a DL of the same NA should give similar ablation region. However, for a femtosecond pulse, strong differences appear due to its large spectral bandwidth. For instance, the irradiance distribution in the focal region of a RL is different from that of a DL [14,15]. Note that, the focal length of the DL, f, is related to the wavelength of light, λ, by the expression $\lambda f=\lambda_0 f_0$, where f_0 is the focal length for λ_0. From the above relation, it is apparent that the focal region of a DL is elongated along the propagation direction of the incident femtosecond pulse. Such a different behavior has been also explored in other branches of ultrafast science i.e., to tailor the spectral features of second harmonic [16] and supercontinuum [17,18] pulses, and for the construction of pulse shapers [19,20]. In this manuscript we experimentally demonstrate that DLs can be

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used in ultrafast micromachining to increase the ablation region by defocusing.

2. Theory

In this section we provide a heuristic reasoning on the main parameters related to ultrafast micromachining with RL or DL, including some approximate expressions to estimate their contributions. The term ablation region is referred as the volume around the focus of the lens where the beam intensity is greater than the fluence threshold for the material removal. Then, within such an ablation region the workpiece is affected by the laser-matter interaction. In this context, when a laser beam is focused by a lens, the axial ablation region depends on both the fluence threshold of the exposed material, and how rapidly the light diverges near the focus [21]. An estimation of this divergence is given by the DOF. Out of the DOF the beam size expands, and the density of energy decreases quickly.

In order to consider the effect a polychromatic illumination on the axial focal elongation, we estimate the DOF as the Full-Width-at-Half-Maximum (FWHM) of the resulted normalized axial irradiance obtained from the incoherent addition of the axial irradiance contributions corresponding to the different wavelengths of light. Using the generalized Huygens–Fresnel diffraction integral, the axial irradiance $I(z, \omega)$ due to the pass of a plane wave with frequency ω through a truncated DL can be expressed as follows:

$$I(z,\omega)=\frac{a^4\omega^2}{4z^2c^2}\left\{\mathrm{Sinc}\left[\frac{a^2\omega}{4zc}\left(1-\frac{z\omega}{f_0\omega_0}\right)\right]\right\}^2 \tag{1}$$

In Eq. (1) the focal length of the DL is given by the expression $f=\lambda_0 f_0/\lambda$, the term $\mathrm{Sinc}(\xi)=\sin\xi/\xi$ represents the Sinc function of argument ξ, the parameter a holds for the radius of the circular iris used to truncate the beam, and $\omega_0=2\pi c/\lambda_0$, whereas c is the speed of light in vacuum. Owing to the same behavior of refractive and diffractive lenses under cw illumination, the DOF of the RL is equal to that of the DL for the same wavelength ($\lambda=\lambda_0$). In accordance with the above definition and Eq. (1), the monochromatic $\mathrm{DOF_M}$ can be determined from the expression:

$$\mathrm{DOF_M}=2f_0\frac{\gamma}{1+\gamma} \tag{2}$$

In Eq. (2), the term $\gamma=2f_0\lambda_0 N/\pi a^2$, where the constant $N=1.39$ is numerically determined from the condition $\mathrm{Sinc}^2(N)=1/2$. Note that, for many practical situations $\gamma\ll 1$, and consequently $\mathrm{DOF_M}\cong 2f_0\gamma$. In the case of having a DL illuminated by a broadband source, the inverse dependence of its focal lens with the wavelength of light lets to strong longitudinal chromatic aberrations that significant increase the DOF. Then, the polychromatic $\mathrm{DOF_P}$ can be numerically evaluated (because there is not simple analytical expression) by taking into account the different wavelength contributions of the light source to the Eq. (1).

On the other hand, for non-thermal micromachining we should care about the temporal duration of the pulse in the focus of the DL. For a lens with chromatic aberrations, and focal length f_0, the maximum group delay, ΔT, is given by the expression [22]

$$\Delta T\approx\frac{a^2}{2cf_0^2}\lambda_0\left.\frac{df}{d\lambda}\right|_{\lambda_0}. \tag{3}$$

The Eq. (3) allows us to determine the geometrical difference in the time of arrival to the focus among pulses passing through the lens at the transverse locations $r=a$ and $r=0$, respectively. Within the paraxial approximation, for the case of a DL, Eq. (3) is reduced to

$$\Delta T\approx\frac{a^2}{2f_0c}. \tag{4}$$

When the square modulus of the amplitude of the input pulse $u_{in}(\tau)$ is much shorter than ΔT, Eq. (4) provides a good estimation of the on-axis temporal window. If the assumption $|u_{in}(\tau)|\ll\Delta T$ is no longer valid, $u_{in}(\tau)$ should be included in the analysis. In this case, the amplitude of the output waveform $u_{out}(\tau)$ is approximately assessed by the following convolution expression [19]

$$u_{out}(\tau)\approx u_{in}(\tau)\otimes\left[circ\left(\frac{\tau}{\Delta T}\right)\exp\left(\frac{-i2\pi c\tau}{\lambda_0}\right)\right] \tag{5}$$

In Eq. (5), $circ(\xi)$ denotes the circle function of argument ξ. It takes into account that the lens has a finite circular shape.

3. Experimental setup

In order to experimentally show the different behavior of refractive and diffractive focusing elements for broadband micromachining purposes, we carried out a laser processing of a stainless steel sample. The processing consists of making a set of blind holes over the sample at two different light regimes by using RLs and DLs of similar focal lengths. In the first regime the light can be regarded as a quasi-monochromatic source with a relative-low bandwidth of 10 nm. In the second regime the light consist of ultrashort pulses with spectral bandwidth of 40 nm FWHM. In particular, we will study the laser ablation region.

The optical setup is show in Fig. 1. For the experiments we used a femtosecond Ti:Sapphire laser (Femtosource, Femtolaser) that delivers pulses with intensity FWHM of 30 fs centered at $\lambda=800$ nm, and 1 kHz repetition rate. The output mean power of the laser was 500 mW. Before exit the ultrashort pulses pass through a user-adjustable post-compression stage based on fused silica Brewster prisms which allow us to introduce negative dispersion in the beam delivery path. The energy of the pulses was measured with an analogy power-meter (Spectra Physics, Model 407-A) and controlled by using a set of calibrated neutral density filters. The cross-section of the pulsed beam was slightly elliptical, and the beam propagation factor is less than two. To reduce optical aberrations and increase the spatial uniformity, the beam passes through a 2× all-mirror beam expander. In addition, an iris of 4.5 mm of diameter is placed before the focusing optics (RL or DL). To adjust the duration of the ablation process, an electronically controlled shutter was utilized. The light was focused with an achromatic doublet RL of focal length of 100 mm (Linos, G063144525) or a kinoform DL (Institute of Automatics and Electrometry, Russia) of focal length of 150 mm (for the design wavelength of $\lambda_0=565$ nm). Note that, for $\lambda=800$ nm the focal length $f=f_0\lambda_0/\lambda$ of the DL is $f\cong 106$ mm, which is approximately equal to the above focal length of the RL. The positive material dispersion introduced by the RL was compensated with the help of the above-mentioned post compression stage. The estimated temporal window given by the DL lens due to the PTD is about 35 fs. From Eq. (5), such temporal window yields a maximum temporal duration over the sample less than 65 fs (assuming an input pulse of 30 fs). To make holes over different spatial regions of the sample, the stainless steel sheet was mounted on a *XYZ* translation stage which allows for the displacement of it across the focused pulse. The results are shown and discussed in the following sections.

4. Results

4.1. Fluence threshold

Before going further, the fluence ablation threshold of stainless steel for pulses of 30 fs and 120 fs focused with a RL was calculated by using the Liu's method [23]. That is, a series of blind holes were drilled with different energy per pulse over the stainless steel sample. The average fluence was determined by the ratio between