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Geometrical profile of material surface ablated with high-power, short-pulse lasers in ambient gas media

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Abstract. Finer and cleaner features are expected in micro-machining with high power, ultra-short pulse lasers as the melt and evaporation phases are considerably reduced. However, a high-intensity optical beam propagating through a gaseous medium can cause its breakdown generating plasma, which is enhanced further by the self-focusing effect of the medium. Photon-plasma scattering compensates somewhat for the self-focusing, but it also distorts the beam profile with consequent impact on the fabricated surface. Plasma also continues to supply heat beyond the pulse duration, which may cause melting and thus distort the features further. In the present article, we show that suitable parameters can be determined to reduce the distortion to the beam profile and balance self-focusing and plasma defocusing resulting in plasma filamentation. Well-shaped beam and plasma filaments, both have favourable impact on the fabricated features. The calculated surface features are compared with the experimentally machined crater profiles with good agreement.

1. Introduction
Material removal by low power, long-pulse lasers proceeds through melting and evaporating the material, which yields distorted surface features and debris. With short pulse lasers, the pulse duration is too short to establish the thermal equilibrium necessary to melt the material. Therefore, ablation proceeds with photo-ionization creating an imbalance of the electromagnetic forces in the lattice, which expels the material. High power is needed to transfer sufficient energy during the pulse for material removal. The consequent plasma emanating from the material also acquires high energy by collision transfer preventing it from re-settling and thus, reducing debris. Thus, cleaner fabricated features with less debris can be expected. For this reason, ultra-short pulse laser processing of materials is becoming a preferred technique for various applications such as drilling, cutting, fabrication of complex features and property modification [1]. However, this requires a well-shaped beam as the fabricated surface profile conforms closely to the incident intensity distribution.

At high intensities the optical beam propagating through a gaseous medium such as air, He and Ne, suffers the self-focusing Kerr effect, which increases the intensity further causing gas breakdown. The scattering effects due to the generated plasma compensate for self-focusing to some extent but they also distort the beam profile with consequent distortion of the surface features [2]. Intensity is still sufficiently high to ablate and generate material plasma [3]. Addition of plasma increases the distortion to the beam profile. Plasma also acts as an energy source supplying heat to the material beyond the pulse duration, which may result in melting offsetting benefits further [4]. Thus, material
processing with high power ultra-short pulse lasers involves complex phenomena with both, favorable and unfavorable impact on the machined surface quality.

Balance of the competing Kerr effect and the photon-plasma scattering can result in plasma filamentation [3-5]. Although fragile, plasma filaments can exist in case of material processing in a sufficiently large energy range. Proper modeling can be used to optimize the parameters to create hot plasma filaments. This reduces distortion to the beam profile as well as generates well-shaped plasma energy source, which participates in material removal and prevents it from resettling.

In the present article, we use a numerical scheme based on the path-integral representation of the propagator [6] to solve the non-linear Schrödinger equation, which describes the optical beam propagation in a gaseous medium [2]. The method of the fast Fourier transforms is used to obtain the propagator and thus, the beam profile [7]. Calculated intensities are used to determine the profile of the fabricated surface by a geometrical method [8]. Results are compared with the experimental observations with good agreement.

2. Numerical procedure

Propagation of an optical beam in a gaseous medium is described by the nonlinear Schrödinger equation [2]

\[
i \frac{\partial A}{\partial \xi} + \frac{1}{2k} \nabla^2 A - [n_2 ki - (2\pi e^2 N_e(I)/km_e c^2)]A = 0, \]

for slowly varying amplitude \(A\) with intensity \(I = |A|^2\). The Laplacian is in the plane orthogonal to the beam axis \(\xi\) and \(k\) is the wave number. The first term describes the self-focusing effect in terms of the Kerr coefficient \(n_2\). The second term describes the generation and effect of plasma resulting from the gas breakdown in terms of the electron charge \(e\), electron mass \(m_e\) and the speed of light \(c\). Free electron density \(N_e\) induced by the laser pulse by field ionization is determined by the rate equation \(N_e' = N_0 R_{ion}(I(t))\), where prime denotes the time derivative, \(N_0\) is the number density of the gas molecules and \(R_{ion}\) is the ionization rate, which can be determined from the basic principles or from the experimental data [9].

Equation (1) can be solved efficiently by evaluating the path-integral propagator [6] by the fast Fourier transform routines [7] from the amplitude at the lens location, which is determined by the pulse energy [4,7,8,10]. The calculated intensities \(I(r,t)\) can be used to calculate the depth \(z(r)\) at the radial distance \(r\) on the surface in terms of the absorption coefficient \(a_0\) and the heat \(E_H\) required to remove unit volume of the material, by solving [8]

\[
\frac{\partial z(r)}{\partial t} = - \frac{a_0 I(r,t)}{E_H} \left[1 + \left(\frac{\partial z(r)}{\partial r}\right)\right]^{-1/2},
\]

We have assumed radial symmetry. Eq. (2) can be solved accurately and efficiently by the forward Euler method. An adequate approximation to \(E_H\) is given by the energy required to melt and evaporate the unit volume of the material even in the present case of direct material removal [4, 10].

3. Results and discussion

Calculated profile was compared with the surface of the craters fabricated with a short-pulse laser on thin sheets of copper. The system used was a Clark-MXR CPA 2010 femtosecond laser, which consists of a 35 MHz SErF fiber oscillator and a chirped-pulse-amplification, Ti: Sapphire regenerative amplifier, delivering 150 fs pulses of wavelength centered at 775 nm with average power of 1 W corresponding to the maximum pulse energy of 1 mJ, at repetition rate of 1 kHz. A set of ND
filters was used to control the pulse energy. The laser beam was collimated with a beam expander and focused with a chromatic objective (CVI Laser Co.) with NA = 0.23 and focal length of 21 mm. In order to ensure that each laser ablated crater on the material surface be produced by a single pulse, the motion system translated at a speed of 750 mm/min, while the laser fired at a pulse repetition rate of 500 Hz. Experiments were conducted at the pulse energy of 200 µJ. The depth at various locations of each crater was measured by an optical interferometric WYKO surface profiler (model NT-2000), which provides a 1 nm resolution in its vertical-scanning mode. Fabrication was conducted in air with the Kerr coefficient of $5.0 \times 10^{-23} \text{ m}^2/\text{W}$ and the rate $R_{nm}$ was calculated from a polynomial fit to the experimental values for $O_2$ (20%) and $N_2$ (80%) [9]. All figures correspond to these input parameters.

The craters produced were not identical to each other due to noticeable random variations. The observations selected for comparison with the calculated profile were deemed to represent the observed profiles adequately. For comparison with the theoretical values calculated for a radially symmetric system, the depths along X and Y-axes were averaged to obtain the profile with respect to the radial distances and measured data was also averaged over a number of craters to minimize the effects of the statistical variations. Since the representative experimental profile was obtained by averaging, it is radially symmetric and due to cancellations of the statistical variations, it is smoother than the individual craters. Since random, statistical variations are not included in the model, this provides a better test of its adequacy.

Figure 1 shows the self-focusing effect of air and consequent impact of the plasma generated on a Gaussian signal at a spot radius corresponding to a high intensity. Fluence is normalized in units of peak input fluence. Intensities for a beam propagating through vacuum are high enough to cause some air breakdown but with little impact on the beam profile. However, the intensity is increased substantially by self-focusing, to cause commensurate distortion to the beam profile. Figure 2 investigates the onset of this distortion. With the indicated parameter values, noticeable distortion is observed as the spot radius is decreased below 2.5 µm. Thus, clean fabrication can be expected for spot radii of greater than 2.5 µm, with some margin allowed for the material plasma, which is not included in the present model. Major effects are included in the present model. The complexity of the phenomena describing the formation of the material plasma exceeds by far the value of the information as the expected impact on the beam profile and the surface features is estimated to be small in comparison. A better strategy is to develop an on-line monitoring system to make minor adjustments to the calculated parameters if desired [11].

Figure 1. Normalized fluence in vacuum (dashed line) with self-focusing (dotted line) and with consequent plasma effects included (solid line) at the focal radius of 1.5 µm.

Figure 2. Calculated intensity profile of the optical beam propagating in air with spot radius of 2.5 µm (dashed line), 2.0 µm (dotted line) and 1.5 µm (solid line).
Figure 3 shows a comparison of the calculated and the averaged experimentally observed depth profiles at a spot radius of about 5 \( \mu m \), which is sufficiently large to eliminate distortions from the air and the material plasma. Intensity is still sufficiently high for an effective ablation.

4. Concluding remarks
Present article illustrates a method to calculate the profile of an optical beam propagating through a gaseous medium and to determine the features of the surface processed by a high-intensity, short-pulse laser. The procedure provides an adequate estimate of the experimentally adjustable parameters to obtain a clean machined surface. Close agreement between the calculated and experimentally observed surface features indicate the adequacy of the model.

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