Array of femtosecond plasma channels in fused silica

O.G. Kosareva a,*, T. Nguyen b, N.A. Panov a, W. Liu b, A. Salimina b, V.P. Kandidov a, N. Akozbek c, M. Scalora d, R. Vallee b, S.L. Chin b

a International Laser Center, Physics Department, M.V. Lomonosov Moscow State University, Moscow 119992, Russia
b Centre d’Optique, Photonique et Laser (COPL) et Département de Physique, de Génie Physique et d’Optique, Université Laval, Québec, QC, Canada G1K 7P4
c Time Domain Corporation, Cummings Research Park, 7057 Old Madison Pike, Huntsville, AL 35806, USA
d Charles M. Bowden Research Center, AMSRD-AMR-WS-ST, RDECOM, Redstone Arsenal, AL 35898-5000, USA

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Abstract

We have shown experimentally and confirmed by means of full dimensional (3D + 1) numerical simulations, the possibility to create an array of refractive index modification zones inside a fused silica sample using a 43 fs, 2 mJ, 800 nm laser pulse and a periodic mesh introduced in front of the sample. Robust filaments and the corresponding refractive index modification zones preserve their transverse positions for more than 10 Rayleigh lengths (~500 μm). Numerical simulations prove that each mesh unit is an independent source of the background energy for a filament formed within this unit. The effect of the simultaneous formation of many extended periodically spaced filaments can be used to accelerate the fabrication of microoptics devices.

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1. Introduction

Structural modifications of transparent solids made by femtosecond laser pulses have important advantages as compared to the case of longer pulses. Filamentary tracks formed inside glass by means of focused 1 MW 55 ns laser pulses were represented by a sequence of damage spots along the pulse propagation direction [1]. Short pulse duration allows one to avoid material damage and to create the regions with increased refractive index inside the bulk of the solid sample [2,3]. It was demonstrated that using a Ti:Sapphire laser pulse with a duration of 50–100 fs centered at 800 nm it is possible to write directly 3D structures such as waveguides, couplers, gratings, phase-type diffractive lenses [see, e.g. 4–7] inside different kinds of transparent glasses by translating the sample through the focal point of the beam.

The key issue concerning waveguide writing is its controlled quality. The waveguide quality depends on the initial pulse energy, pulse duration and central wavelength, as well as focusing condition, and translation speed of the sample. Material modification remaining after each single-shot pulse is associated with the deposition of energy into the sample. This deposition is directly related to the spatial distribution of laser-produced plasma at the end of a femtosecond pulse. Indeed, during a femtosecond pulse the plasma remains relatively “cold” and at the end of the pulse the electrons almost preserve the positions of their original formation. Free electrons return back to the valence band through radiative and non-radiative transitions and through the formation of excitons followed by...
exciton self-trapping [8]. The relaxation of a self-trapped exciton leads to the formation of an intrinsic structural defect. Both non-radiative and radiative transitions through re-absorption lead to a local heating of the glass material. It was observed that such heating leads to the melting of glass [9]. Depending on the total amount of free electrons after the pulse has gone, the result of plasma recombination might be local melting or micro explosions and voids, which develop with increasing plasma density caused by avalanche process. Cooling the locally melted material down results in a homogeneous region of refractive index modifications and good quality waveguides. Instead, the zones with voids deteriorate waveguide properties [10,11]. Thus, by varying the plasma density produced in the bulk of condensed matter, one can control the waveguide quality.

At fixed femtosecond pulse duration the amount of free electrons in the interaction zone of condensed medium can be controlled by the combination of input pulse energy and geometrical focusing. Comparatively loose geometrical focusing and the pulse peak power slightly higher than the critical power for self-focusing in the medium results in a geometrical focusing. Comparatively loose geometrical focusing might be local melting or micro explosions and voids, which develop with increasing plasma density caused by avalanche process. Cooling the locally melted material down results in a homogeneous region of refractive index modifications and good quality waveguides. Instead, the zones with voids deteriorate waveguide properties [10,11]. Thus, by varying the plasma density produced in the bulk of condensed matter, one can control the waveguide quality.

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Additional difficulty is represented by multiple filament formation, which might lead to a multimode output, as it was observed in [15]. The authors of [15] noticed that for 150 fs pulses at 775 nm with a 250-kHz repetition rate the waveguide fabricated in the Nd-doped sodium-alumino-borosilicate glass becomes multimode if input pulse energy is higher than 4 μJ. The seeds for multiple filaments arise from initial imperfections, which are always present in the laser beam profile at the laser system output.

Several possible ways for suppression of stochastic multifilamentation in a high-power femtosecond laser pulse were suggested in [16–20]. Masks of different shapes were used to organize filaments in [17]. The authors of [18,20] used the whole beam squeezing in order to decrease the spacing between the initial perturbations on the beam profile and to increase the backscattered fluorescence signal in air. The authors of [16] aligned stochastic filaments by imposing the degree of the beam ellipticity to larger than 2. In [19] it was shown both experimentally and numerically that the introduction of a periodic mesh into a propagation path of 42 fs 810 nm pulse with random spatial intensity fluctuations in the transverse plane leads to systematically more regular spatial distribution of multiple filaments produced in the laser pulse. The formation of regularly spaced filaments are initiated nearly simultaneously and at the same propagation distance, which is determined by the ratio of power contained within a single mesh unit to the critical power for self-focusing. Our numerical predictions of stochastic and regularized filamentation were experimentally observed in a liquid cell. The distribution of multiple filaments, in the plane perpendicular to the pulse propagation direction, was observed by means of a blue filter, positioned at the liquid cell output and in front of the CCD objective. Thus, white-light continuum generation due to the pulse self-transformation in the medium with Kerr nonlinearity and laser-produced plasma was a direct indication of filamentation.

In this paper, we show both experimentally and by means of numerical simulations, a new way to simultaneously induce regularly spaced refractive index modification zones within the bulk of a fused silica sample. These
zones, originate from the regularly spaced filaments formed by a metallic wire mesh positioned in front of the lens, which focuses a 43 fs Ti:Sapphire femtosecond laser pulse inside the sample. Our results may have important implications for waveguide writing applications in transparent optical media where the processing time could be significantly reduced. This approach would particularly be beneficial for diffraction gratings and other micro optical devices, which require the fabrication of multiple equally spaced structural modifications in the medium.

2. Experiment

A Spectra Physics chirped-pulse-amplification (CPA) Ti:sapphire laser system consisting of a mode-locked oscillator (Tsunami: 500 mW, 80 MHz, FWHM ~ 40 nm) and a 2 W Spitfire regenerative amplifier, was used to generate pulses at a central wavelength of 810 nm (bandwidth: 30 nm at FWHM) with 1 kHz repetition rate. The sample was a polished bulk of pure 6 mm long or 20 mm long fused silica. The laser beam diameter was 5.7 mm FWHM corresponding to 6.8 mm at e⁻¹ intensity level with an initial energy 2 mJ per a pulse. The temporal width of the transform-limited pulses was measured by an optical autocorrelator (Positive Light SSA) to be approximately 43 fs before the focusing lens. A shutter was used to control the number of pulses incident onto the sample.

The schematic layout of the experimental setup is shown in Fig. 1a and b. The beam was focused using the lens with the focal length f = 20 mm (Fig. 1a) or f = 70 mm (Fig. 1b) so that the geometrical focus was almost behind the output surface of the sample. Before falling onto the lens, the beam was transmitted through a metallic mesh. The mesh period was d = 240 μm and the width of opaque part was 40 μm. The optimum distance between the mesh and the sample entrance surface was ≈100 mm for both setups shown in Fig. 1a (short 6 mm sample) and in Fig. 1b (long 20 mm sample). Change of the mesh position in the longitudinal direction means that the propagation distance in air before the sample will constitute different fractions of the Talbot distance [19]. Therefore, different diffraction patterns will be produced on the sample entrance surface. As estimated further in Section 3, the peak power per a single mesh unit is about seven critical powers for self-focusing in fused silica. The simulations published elsewhere [21] show that for the case of a square mesh unit only one filament per a unit can be produced with this peak power. However depending on the particular size of the transverse spatial

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Fig. 1. Schematic layout of the experimental setup to observe the filaments and create refractive index modifications in a fused silica sample (a) in the transverse plane relative to the propagation direction, GF is a green filter, NDF is a neutral density filter. (b) in the longitudinal direction. The mesh is fixed at a distance of 100 mm from the sample. The beam transmitted through the mesh falls onto the lens, which has the geometrical focus near the exit surface of the sample. The sample length is either (a) 6 mm or (b) 20 mm.
perturbations in the diffraction pattern on the sample entrance surface this single filament can be developed earlier in the propagation and give more white light. Therefore, in the experiment we varied the longitudinal position of the mesh in order to find that optimum position (≈100 mm from the sample entrance surface), which gives us earlier formation of filaments and more white light coming out from the sample. The direct consequence of this optimization procedure is increasing number of peripheral mesh units generating filaments with observable amount of white light. Thus, in total, the optimum longitudinal position of the mesh results in more filaments and white light in the whole beam. At the same time, the number of filaments per a single unit and their transverse positions are preserved as we move the mesh along the propagation direction.

To indicate the positions of the filaments the light coming out of the sample was imaged onto a CCD through a green filter with a bandwidth of 330–620 nm and peak transmission at 515 nm. Thus, only the developed filaments, i.e., the streaks of light, where the intensity is high enough to produce plasma column and generate white light were registered. In transverse plane the spacing of the local maxima corresponding to the developed filaments is regular (Fig. 2a and b). This is the indication of the spatial control introduced by the metallic mesh [19, 23]. Another direct indication of multiple filament control in the plane perpendicular to the propagation direction is the local refractive index modification on the entrance surface of the sample (Fig. 3). After inspection of the sample entrance surface with the phase-contrast microscope, we have found that the regularly spaced “dots” correspond to the simulated spatially arranged local zones with the intensity higher than the ionization threshold (see the details in Section 3 and Fig. 3).

The second configuration of the experimental setup is shown in Fig. 1b. In this case we choose the longer 20 mm sample and the lens with the focal length of 70 mm or 100 mm. The filaments inside the sample were imaged to the CCD from aside, so that 1 mm of longitudinal pulse propagation inside the fused silica could be observed. The measurable value is scattering at 800 nm and plasma emission around 450 nm, similar to what was done in a single filament regime in Ref. [10].

In Fig. 2c we show 30 s exposure time images of filaments along the propagation direction. The geometrical focusing distance of the lens is 100 mm, which is much larger than the sample length. Therefore, the filaments are almost parallel and equally spaced in the transverse direction. In addition, three of them in the central part, have the same length of 500 μm. The registered longitudinal distribution is a direct evidence for the fact that the metallic mesh suppresses the chaotic merging and splitting of filaments. This is the case when the pulse has natural imperfec-

Fig. 2. (a) Digital camera image of the filaments obtained at the exit surface of a fused silica sample in the experimental setup shown in Fig. 1a. (b) Fluence distribution obtained with a green filter on a CCD camera at the exit surface of a fused silica sample in the experimental setup shown in Fig. 1a. The filter bandwidth is 330–620 nm and the peak transmission is at 515 nm. (c) Side image of multiple filaments taken by 10× microscope objective in the setup configuration shown in Fig. 1b. The exposure time is 30 s (30,000 laser shots).
tions on the transverse spatial profile and its peak power is much larger than the critical power for self-focusing in the medium [24].

3. Numerical simulations

Analysis of the experimental data reveals that the insertion of the metallic mesh into the beam results in nearly a 54% transmission loss. In addition, reflection and scattering losses from the lens and sample surface, result in an additional energy loss of about 4%. Thus we assume in the numerical simulations that the energy falling on the sample is 0.8 mJ per pulse. The resulting ratio of the pulse peak power to the critical power for self-focusing in fused silica $P_{\text{peak}}/P_{\text{cr}} = 6500$ and the number of critical powers per a mesh unit is $P_{\text{unit}} = 7P_{\text{cr}}$. The black arrow indicates the direction of the light field intensity and phase cross sections shown in Fig. 4. (b) Image from the phase-contrast microscope obtained with 400 time magnification taken in the transverse plane near the entrance surface of the fused silica sample in the experiment. The experimental setup is in the configuration shown in Fig. 1a. (c) Magnified region of the simulated transverse intensity distribution indicated by a rectangle ABCD in panel (a).

Fig. 3. (a) Simulated transverse intensity distribution at a distance of $z \approx 200 \mu m$ from the sample entrance surface. The ratio of the peak power to the critical power for self-focusing in fused silica is $P_{\text{peak}}/P_{\text{cr}} \approx 6500$ and the number of critical powers per a mesh unit is $P_{\text{unit}} \approx 7P_{\text{cr}}$. The black arrow indicates the direction of the light field intensity and phase cross sections shown in Fig. 4. (b) Image from the phase-contrast microscope obtained with 400 time magnification taken in the transverse plane near the entrance surface of the fused silica sample in the experiment. The experimental setup is in the configuration shown in Fig. 1a. (c) Magnified region of the simulated transverse intensity distribution indicated by a rectangle ABCD in panel (a).
Thus, even after significant transmission losses through the metallic mesh and optical components the peak power transmitted through the sample remains high enough to generate multiple filaments. Estimation of a peak power per a single mesh unit yields $P_{\text{unit}} = P_{\text{peak}}/N_{\text{unit}} \approx 7P_{\text{cr}}$, where $N_{\text{unit}} \approx 900$ is the number of mesh units within a beam diameter $2a_0 = 6.8$ mm at $e^{-1}$ intensity level. (The actual value $P_{\text{unit}}$ may be larger than $7P_{\text{cr}}$ in the beam center and smaller than $7P_{\text{cr}}$ in the periphery due to transverse intensity gradient in the initial beam.) Hence, most of the mesh units located within the beam radius can generate at least a single filament and successfully overcome stochastic filamentation induced by initial random intensity fluctuations in the beam with the noise variance less or equal to $\sigma^2 = 0.01$ [19].

In order to model the experiment with these initial parameters we used the equation for the light field complex amplitude $E(x, y, z, t)$ in the slowly varying envelope approximation:

$$2i k \left( \frac{\partial}{\partial z} + \frac{1}{v_g} \frac{\partial}{\partial t} \right) E(x, y, z, t) = \Delta_1 E(x, y, z, t) - \frac{\partial^2}{\partial t^2} E(x, y, z, t) + \frac{2k^2}{n_0} \Delta n(x, y, z, t) E(x, y, z, t) - i k x E(x, y, z, t),$$

where $\Delta_1 = \partial^2 / \partial x^2 + \partial^2 / \partial y^2$ is the transverse Laplacian, $k = n_0 2\pi / \lambda$ is a wavenumber corresponding to the fundamental laser wavelength $\lambda = 800$ nm, $n_0 = 1.45$ is the refractive index and $v_g$ is the group velocity in fused silica at the wavelength $\lambda$. The first term on the right-hand side of the Eq. (1) describes diffraction, the second term describes group velocity dispersion with the coefficient $k''_n = 390$ fs$^2$/cm calculated from the data taken from Ref. [26]. The third term on the right-hand side of the Eq. (1) is responsible for nonlinear refraction. The nonlinear contribution to the refractive index $\Delta n$ originates from both Kerr and plasma nonlinearities and takes the form:

$$\Delta n = \Delta n_k + \Delta n_p,$$

where the Kerr nonlinear contribution was considered as instantaneous: $\Delta n_k = 0.5n_0^2|E|^2$ and corresponding to the measured critical power $P_{\text{cr}} = 2.7$ MW, which effectively takes into account both instantaneous and delayed nonlinear response. We also note that, the delayed Raman contribution into the Kerr effect in fused silica constitutes 0.18 of the total Kerr nonlinear contribution [27]. Since the delayed response time is 32 fs, then, by the end of the pulse the critical power for self-focusing will be decreased by approximately 20% of the initial instantaneous value. In this paper, we do not make an exact quantitative comparison between the simulation and experimental results, therefore this variation in the critical power is not critical to the results discussed here.

The nonlinear contribution $\Delta n_p$ from the laser-produced plasma is defined by the elastic electron collision frequency and the plasma frequency:

$$v_e = N_0v_a \sigma_c,$$

$$\omega_p = \sqrt{4\pi e^2 N_e / m_e},$$

$$\Delta n_p = -\frac{\alpha_p^2}{2n_0 (\omega^2 + \omega_p^2)} \left( 1 + i \frac{v_e}{\omega} \right),$$

where $e$, $m_e$ are electron charge and mass, respectively, $N_0 = 2.1 \times 10^{22}$ cm$^{-3}$ is the density of neutrals, $v_e = \frac{eE}{m_e}$ is the electron velocity in the laser field, $N_e$ is free electron density. The root-mean-square free electron velocity $v_e$ is self-consistently calculated at each spatial position and time moment as a function of the light field $|E|$. To define the elastic electron collision cross section in fused silica we use the recently measured collision time $\tau_c = 1/v_e = 1.7$ fs [28] obtained at the intensity of about $10^{15}$ W/cm$^2$. From Eq. (3a) we find the cross section $\sigma_c = 0.52 \times 10^{-15}$ cm$^2$.

The electron density $N_e$ is calculated according to the kinetic equation:

$$\frac{\partial N_e}{\partial t} = R(|E|^2) (N_e - N_e) + \nu_N N_e - \frac{N_e}{\tau_e},$$

where $R(|E|^2)$ is the optical-field-induced ionization rate [29]. We choose this rate for the description of the time dependent growth of electrons, because the simulated spatial distribution of electron density contours obtained using this rate in [13] shows good agreement with inspected damage tracks under the microscope in the bulk of a fused silica sample. The avalanche ionization frequency $\nu_i$ is given by

$$\nu_i = \frac{1}{W_e} \frac{e^2 E}{2m (\omega^2 + v_e^2)} v_e,$$

where $W_e = 9$ eV is the band-gap energy in fused silica. As the characteristic recombination constant $\tau_e = 170$ fs we chose the electron plasma lifetime measured after the propagation of a femtosecond pulse in fused silica [28].

The last term on the right-hand side of the Eq. (1) describes optical-field-induced ionization energy loss:

$$\alpha = r^{-1} \nu_{\text{ph}} \tau_0 \frac{\partial N_e}{\partial t},$$

where $\nu_{\text{ph}} = \left\{ \frac{n_p}{n_{\text{th}}} \right\} + 1 = 6$ is the number of photons necessary for the electron transfer to the conduction band.

As an initial condition for the regularization of stochastic multifilamentation, we take a Gaussian pulse with Gaussian transverse intensity distribution. One of our objectives is to show that the array of filaments can be formed from the pulse in spite of natural imperfections on the beam transverse profile. To model these random imperfections we use the additive noise $\xi(x, y)$:

$$\tilde{E}_i(x, y, z = 0, t) = E_0 (1 + \xi_i(x, y)) \exp \left( -\frac{x^2 + y^2}{2a_0^2} - \frac{t^2}{\tau_0^2} \right),$$

where $\tau = t - z/v_g$ is the time in the co-moving coordinate system, $v_g$ is the group velocity of the pulse, $a_0$ and $\tau_0$ are the initial beam radius and half pulse duration at $e^{-1}$ intensity level. $E_0$ is the amplitude of the random light field $\tilde{E}$. 
One realization of the random field $\tilde{E}$ corresponds to a single laser shot.

A random function $\xi(x, y)$ obeys the normal distribution law with zero mean value and the variance $\sigma^2$. Spatial correlation of the perturbations in the transverse section is given by the Gaussian correlation function:

$$B(r) = \sigma^2 \exp \left(-\frac{r^2}{R_{\text{cor}}^2}\right)$$  \hspace{1cm} (9)

The radius $R_{\text{cor}}$ is chosen so that the power contained in the perturbation with this radius exceeds the critical power for self-focusing $P_{\text{cr}}$:

$$\pi R_{\text{cor}}^2 I_0 \geq P_{\text{cr}}$$  \hspace{1cm} (10)

where, $I_0 = c\eta_0/\pi|E_0|^2$ is the initial peak pulse intensity. In this case, a perturbation with the radius $R_{\text{cor}}$ can produce a separate filament in the course of self-focusing [30].

The wire mesh located in the experiment was modeled by the regular intensity perturbations introduced into the beam. Each mesh unit was represented by a square with the side $d$. The transmittance coefficient of the mesh $T_{\text{mesh}}$ is unity within each unit and zero on the boundaries with the width $b \ll d$:

$$T_{\text{mesh}}(x, y) = \frac{\pi a_0}{N} \exp \left\{ -\frac{(x - (k + 1/2)d)^2}{(d - h/2)} \right\} \times \exp \left\{ -\frac{(y - (l + 1/2)d)^2}{(d - h/2)} \right\}$$  \hspace{1cm} (11)

where $s = 6$ is the degree of the supergaussian function, $2N \times 2N$ is the total number of mesh units and the aggregate $(k, l)$ corresponds to an individual unit in the mesh.

Due to the tremendous excess of the pulse power over the critical power for self-focusing in fused silica $P_{\text{peak}}/P_{\text{cr}} \approx 6500$, two sets of the simulations were performed. In the first set, we preserved the spatial dimensions and the pulse peak power used in the experiment. Following the experimental data, in the simulations we have preserved the ratio of the beam power to the critical power for self-focusing $P_{\text{peak}}/P_{\text{cr}} \approx 6500$, the power transmitted through a single mesh unit $P_{\text{unit}} \approx 7P_{\text{cr}}$, the ratio of the beam radius to the mesh period $a_0/d = 0.34 \text{cm}/0.0240 \text{cm} = 14.2$ and the ratio of the opaque part of the mesh $h$ to the mesh period $d$: $h/d = 40 \mu\text{m}/240 \mu\text{m} = 0.167$. The variance of the random noise $\xi(x, y)$ in Eq. (9) was $\sigma^2 = 0.01$ and the correlation radius $R_{\text{cor}} = 0.16a_0$. This random noise variance was chosen to be larger than the value of $\sigma^2 \approx 0.0025$ estimated from the analysis of the initial beam distribution in the experiment. In this way we make sure that the lower level of noise in the experiment does not lead to random filamentation if the simulated higher-level noise is suppressed successfully.

Preservation of the spatial relations and high peak power requires simultaneous treatment of a large beam size and small transverse spatial scales of the order or less than the opaque part of the mesh. In total, around 900 mesh units should be considered within the beam diameter region. In order to handle this large variety of spatial scales in our first set of numerical simulations we used the reduced version of Eq. (1):

$$2i\kappa E_{x, y, z} = \Delta t \Delta n_{x, y, z} E(x, y, z)$$  \hspace{1cm} (12)

The initial condition is given by the Eq. (8) multiplied by the transmittance coefficient of the mesh $T_{\text{mesh}}(x, y)$ (11):

$$E(x, y, z = 0) = T_{\text{mesh}}(x, y) \times E_0(1 + \tilde{\xi}(x, y)) \exp \left(-\frac{x^2 + y^2}{2a_0^2}\right)$$  \hspace{1cm} (13)

The time $t$ in co-moving coordinate system is $t = \tau$, so that only the pulse central slice containing the peak power is considered. This stationary approach to our nonstationary problem allows us to follow the intensity growth till the plasma is formed and time-dependent dynamics comes into effect. The simulations were performed on $7000 \times 7000$ spatial grid in $(x, y)$ transverse plane. In the propagation direction $z$ the grid steps were varied adaptively with increasing peak intensity.

In the simulations we considered that the parallel beam was transmitted through the mesh and entered the nonlinear medium at $z = 0$. The coordinate $z = 0$ corresponds to the position of the fused silica entrance surface. According to the experimental data, the beam radius on the sample entrance surface was $0.5 \text{mm}$ (FWHM), which corresponds to $a_{\text{surface}} = 0.3 \text{mm}$ at $e^{-1}$ intensity level. We remind that on the lens the beam radius was $a_0 = 3.4 \text{ mm}$ and the mesh period $d = 240 \mu\text{m}$. For the calculations the ratio $a_0/d$ on the lens is preserved on the entrance to the sample: $a_0/d = d_{\text{surface}}/a_{\text{surface}}$, where $a_{\text{surface}} = 21 \mu\text{m}$ is the period of the diffraction pattern corresponding to the mesh period. Thus, in the initial conditions (11), (13) we substitute the values $a_0$ and $d$ by their scaled counterparts $a_{\text{surface}}$ and $d_{\text{surface}}$. The number of mesh units $N \times N$ located on the whole transverse region used in the simulations was $12,544$.

In the simulations we put the mesh right in front of the sample at the position $z = 0$ according to the initial condition given by Eq. (13). Although there is a discrepancy in the mesh position in the experiment and the simulations, the major role of the mesh is preserved as it is in the experiment: (i) the number of filaments (i.e. single) generated per a mesh unit and (ii) the relative transverse position of filaments. Therefore, based on these initial conditions qualitative comparison between the experimental and the simulation results can be performed.

In the experiment the peak intensity on the sample entrance surface was estimated as $1.4 \times 10^{12} \text{ W/cm}^2$. The ten-time increase in this value is enough to cause ionization inside the fused silica sample. In the simulations we followed the peak intensity growth up to 50 times as compared with the peak intensity $I_0$ at $z = 0$. The 50-time increase is reached very near to the sample entrance surface.
at $z \approx 200 \mu m$. Therefore, in the experiment we can expect the refractive index changes due to the plasma production also very near to the entrance surface.

The simulated transverse intensity distribution at the propagation distance $z \approx 200 \mu m$ where the ionization threshold is reached, is plotted in Fig. 3a. Each mesh unit produces a single developed filament, which ionizes the sample. The seed for each filament comes from the perturbation arising within a mesh unit as a consequence of the diffraction on a 2D periodic structure, represented by our mesh. Spatial location of the high-intensity peaks corresponds to the mesh unit centers. In Fig. 3b we show the image from the microscope taken in the transverse direction near the entrance surface of a fused silica sample in the experiment. The mesh of the metallic wires is indicated by the dashed black line and the distance between the modification zones corresponds to the mesh period $d_{\text{surface}}$. In parallel, Fig. 3c shows the magnified region of the simulated intensity distribution indicated by the rectangle ABCD in Fig. 3a. White dashed square in Fig. 3c corresponds to a single mesh unit. Note that in the experiment the angle between the mesh wire direction and the $y$-axis of the beam is $\approx 45^\circ$.

Comparison between the simulated spatial positions of the filaments (Fig. 3a and c) and experimentally observed refractive index modification zones (Fig. 3b) allows us to conclude that both in the experiment and in the simulations one filament is produced per a single mesh unit. The plasma, produced in the filament, recombines and deposits the energy into the material, resulting in the local melting and subsequent refractive index modification [9]. The spacing between the modification zones in Fig. 3b is in agreement with the filament-to-filament spacing in Fig. 3c. Thus, the mesh introduced into the beam profile leads to the formation of an array of filaments and the corresponding array of refractive index modification zones.

Formation of a single filament per a mesh unit can be interpreted in terms of the beam wavefront shape formed due to the joint effect of the mesh and the nonlinear medium. The wavefront shape is characterized by the spatial phase distribution $\phi(x,y)$ extracted from the light field complex amplitude $E(x,y,z)$ at a given propagation distance $z$. The cross section of this phase distribution and the corresponding light field intensity made along the direction indicated by the arrow in Fig. 3a, is shown in Fig. 4a and b. The propagation distance $z$ corresponds to slightly earlier position $z \approx 180 \mu m$ from the sample entrance surface than the intensity distribution in Fig. 3a. However, at this shorter distance the peak intensity already reached $18I_0$ (Fig. 4a). Each period of the intensity and phase structures corresponds to the mesh unit as indicated by the two dashed lines in Fig. 4. Within each period a local focusing is created. The phase barriers between the neighboring intensity spikes are larger than 1.5 rad, which is enough to fully separate the filaments and suppress the energy exchange among them [20]. Thus, the array of regularized filaments is created and we can expect that each filament and the corresponding plasma channel will preserve its transverse position while propagating in the bulk of the sample. To check this assumption the second set of the simulations was performed.

4. Regularized plasma channels

In the second set of simulations we used the system of equations (1), (2), (3a), (4)–(7) to follow the time-dependent evolution of multiple filaments inside the fused silica sample. Stochastic filamentation was described by the initial condition (8) with the radius $a_0$ substituted by the radius on the sample $a_{\text{surface}}$, while the filamentation controlled by the mesh was described by the following equation:

$$\tilde{E}_i(x,y,z = 0, t) = T_{\text{mesh}}(x,y) 	imes E_0(1 + \tilde{\xi}_i(x,y)) \times \exp \left( -\frac{x^2 + y^2}{2a_{\text{surface}}^2} - \frac{z^2}{r_0^2} \right)$$

Unlike Eq. (13) in Eq. (14) the temporal profile of the pulse was taken into account. In three-dimensional nonstationary simulations we are not able to consider the actual beam radius and the actual number of mesh units per this beam radius due to the limitations of our computer resources. Indeed, the simulations in our experimental conditions would require the complex array with the minimum size of $M_x \times M_y \times M_z = 4096 \times 4096 \times 1024 = 17.2 \times 10^9$ elements. Here $M_x$, $M_y$, and $M_z$ are the number of grid steps in the transverse plane $(x,y)$ and in the temporal domain, respectively. The memory required to allocate such complex array.

Fig. 4. Cross sections of the simulated transverse intensity (a) and phase (b) distributions. The cross sections are made along the line indicated by the arrow in Fig. 3a at the propagations distance $z \approx 180 \mu m$ from the sample entrance surface. The dashed lines indicate the period of mesh-produced controlled filaments and the corresponding phase wells.
is 137 Gb, while for the simulations we used two-processor computer based on Intel Xeon™ 2.8 GHz with 2Gb RAM per a processor. Therefore, we reduced the initial pulse energy and beam radius but preserved the main characteristics, which determine the control of stochastic filamentation. By these main characteristics we mean the number of critical powers per a single mesh unit \( P_{\text{unit}} \approx 7 \) \( P_{\text{cr}} \) and the ratio of the opaque to the transparent part of the mesh as \( h/d = 40 \mu m/240 \mu m = 0.167 \). We remind that the amount of power contained in a single mesh unit is an important parameter because it defines the number of filaments formed per a mesh period.

In order to satisfy these parameters, we have chosen the input pulse energy equal to 6.5 \( \mu J \), the initial beam radius on the sample surface \( d_{\text{surface}} = 60 \mu m \), pulse duration \( \tau_0 = 25 \) fs corresponding to 43 fs FWHM. The mesh period was \( d_{\text{surface}} = 40 \mu m \) and the width of opaque part of the mesh was \( h = 6.7 \mu m \). The number of critical powers per a single mesh unit was \( P_{\text{unit}} \approx 7 \) \( P_{\text{cr}} \). Stochastic filamentation was characterized by the correlation function of the noise \( \xi_i \) with the variance \( \sigma^2 = 0.01 \) and the correlation radius \( R_{\text{cor}} \approx 10 \mu m \). We started the simulations from the entrance surface of fused silica \( (z = 0) \) and considered parallel beam. The peak pulse intensity was \( \approx 10^{12} \) W/cm\(^2\) similar to the one in the experiment. We can neglect beam convergence because the geometrical focus of the lens is located behind the output surface of the sample. Indeed, in the experiment the effect of external focusing cannot be revealed by eye as seen in Fig. 2c in the side view of filaments (the corresponding configuration of the setup is shown in Fig. 1b). Merging of these filaments due to geometrical focusing was not observed.

The fluence distribution obtained at a distance \( z \approx 1000 \mu m \) from the entrance to the medium is shown in Fig. 5a in the random beam \( (\sigma^2 = 0.01, \text{no mesh}) \) and in the random beam transmitted through the mesh (Fig. 5b). The good regularization of random filamentation is provided by a comparatively large number of mesh units (\(~12\) per a beam area and sufficiently large number of critical powers for self-focusing in each unit \( (\sim 7 \) \( P_{\text{cr}} \)). This leads to the formation of one filament per a unit, especially in the beam center. The analysis of the spatial phase distribution (Fig. 6a and b) in the central slice of the pulse at the filament starting position \( z \approx 500 \mu m \) shows that the transverse phase has four well-pronounced local minima separated by the distance of the order of the mesh unit period \( d_{\text{surface}} \) (Fig. 6a) In the cross section shown in Fig. 6b we can see that the phase barrier between these minima is of the order of 1.3 rad. It keeps the filaments within the spatial regions corresponding to the mesh units. Thus, even much smaller number of mesh units considered in the three-dimensional nonstationary simulations as compared to the case of 900 cells per the beam area described in Section 3, gives good qualitative description of the mesh-induced filament formation. We observe from the simulations that a single mesh unit is an energy reservoir [31] or a source of the background energy [32] for a filament born within it. The phase barrier prevents essential energy flow between the neighboring units and keeps the filament transverse position constant. This is in contrast to the case of a bunch of stochastic filaments [20], when the filaments share their background energy and create their children.

Separated energy reservoirs make the filaments evolve independently along the propagation direction. To demonstrate this we plot the three-dimensional \((x,y,z)\) distribution of plasma channels formed by the end of the pulse \( \tau_{\text{end}} \) inside the fused silica sample. Mesh-induced filamentation is shown in Figs. 7a–c, while stochastic filamentation is shown in Figs. 7d–f. In all panels of Fig. 7 the longitudinal direction corresponds to the propagation distance inside the sample \( (z = 0) \) is the sample entrance surface) and the transverse directions correspond to \((x,y)\) plane in the initial beam. Fig. 7b,c,e and f shows the projections of the 3D picture in Figs. 7a and d on either \((x,y)\) or \((x,z)\) plane. In the
channels the electron density $N_e(x, y, z, \tau = \tau_{\text{mod}})$ is above the level $3 \times 10^{-3}N_0$, where $N_0$ is the density of neutrals in the sample before the femtosecond pulse. This density is enough to produce refractive index modifications as shown in Ref. [13].

In the regular case (Fig. 7a–c) the filaments and the respective plasma channels are formed within the four central mesh units at $z \approx 500 \mu m$. They persist without an interruption for $\approx 500 \mu m$, then stop and afterwards recover at $z \approx 1200 \mu m$ for another $\approx 150 \mu m$. Later in the propagation ($z \approx 1800 \mu m$) the four filaments merge into a single filament, which persists for $500 \mu m$. In the stochastic case (Fig. 7d–f) the filaments are formed later in the propagation at $z \approx 700 \mu m$. They are born from the beam with random initial intensity and phase distribution given by Eq. (8). Thus, they are distributed randomly in the transverse plane (Fig. 7f). From Fig. 7d and e one can follow the formation of independent filaments, birth of child filaments, and their merging and dying off.

The interruption and recovery of filaments is mainly due to the material dispersion in fused silica. The time-resolved intensity distributions at a distances $z \approx 730 \mu m$ and $z \approx 1200 \mu m$ are shown in Fig. 8a and b. They show the time evolution in the filaments in the transverse section along the $x$-axis ($y = \text{const}$). The intensity in Fig. 8a is “registered” within the first region of propagation, $500 \mu m < z < 1000 \mu m$, i.e. before the interruption. In the central mesh units the intensity peak is reached in the pulse front, while the tail is defocused in the laser-produced plasma as it should be in the developed filament [see, e.g., 33]. Note the increased intensity in the center of remote (peripheral) mesh units ($x \approx \pm 60 \mu m$). At these peripheral units the ionization threshold is not reached, therefore no plasma channels are created as seen in Fig. 7a–c. However, if the initial pulse energy were increased these intensity peaks would reach the ionization threshold and develop into filaments. Later in the propagation the pulse splits and the intensity peak moves towards the trailing part of the pulse at $z \approx 1200 \mu m$. This second peak is the product of the joint effects of refocusing and material dispersion [31,33,34]. Later on, at $z \approx 1800 \mu m$ (Fig. 7a and b) all the filaments merge into a single one. This merging is a consequence of essential energy loss due to the radiation absorption in the plasma ($\approx 20\%$ by this distance). The pulse peak power in a mesh unit falls below the critical one and a single unit can no longer feed a filament.

Before going to Fig. 9 showing the relation between the simulated plasma zones and refractive index modification regions, let us point out to the mechanisms involved in refractive index changes in fused silica. The detailed study of these mechanisms with the similar silica samples [35] shows that the origin of the refractive index increase is mainly due to material densification, when the generated microplasma transfers its energy back to the sample. Indeed, the experiments have shown that the intensity of Raman lines 490 cm$^{-1}$ and 605 cm$^{-1}$, emitted by the modification zones, increases if this modification has been produced at higher fluence. These Raman peaks are related to the oscillation modes of three- and four-membered ring structures in silica [36]. Taking into account that in silica glass structure most frequent rings are six-membered rings, we note that the increase in the number of the three- and four-membered structures indicates the decrease in the average bond angle and densification of the material. According to our previous analysis [34] color centers are also present in the modified index zone. However, they are erased after annealing at 400 $^\circ$C, while refractive index change is observed till 800 $^\circ$C.

Fig. 9a shows the plasma-induced refractive index change inside the sample obtained in the experiment in the long focusing geometry $f = 70$ cm (Fig. 1b). Each zone of refractive index modification follows the plasma channel corresponding to a single mesh unit. The channels initiated by the central mesh units are formed earlier in the propagation. Later on the channels from the peripheral units are initiated. The later start of the peripheral plasma channels is associated with the decrease of peak power per a mesh unit as we move towards the edge of the beam. At a dis-
tance of $z \sim 400 \mu m$ from the left edge of the image in Fig. 9a an array of more than 100 equally spaced zones of refractive index modification can be observed. Qualitatively the same picture is observed in numerical simulations (Fig. 9b and c). In Fig. 9b one can see the longitudinal projection of the simulated fluence distribution. The transverse size of the projection corresponds to four mesh periods. Similar to the distribution of refractive index modification zones in the experiment, the development of the zones with the increased fluence starts from the central units and proceeds towards the peripheral units later in the propagation. However, the generation of plasma is observed only in the central mesh units (Fig. 9c). The transverse size of this projection corresponds to two mesh periods and both longitudinal and transverse scale is the same as in Fig. 9b. The extension of the plasma channels in Fig. 9c is $\approx 500 \mu m$ or 10 Rayleigh lengths, taking into account that the radius of the channel is $\approx 2 \mu m$. We note that with increased initial pulse energy the plasma would also be generated in the peripheral units, following the fluence distribution in...
Therefore, the experimentally obtained refractive index modifications in the longitudinal direction in Fig. 9a are qualitatively well explained by the simulation results in Figs. 9b and c. Based on the presented experimental and simulation results, let us try to estimate the diameter of plasma channels and the corresponding refractive index change. According to Fig. 3b, the transverse size of each of the zones, where the material experienced plasma-induced modification, is 1.6–3.2 μm. The diameter of the plasma channel can be found from the simulation results. In Fig. 7 (see panels b and e) the width of the plasma strings varies in the range 1–3 μm at the level 3 × 10⁻³ of the neutral density N₀. In the regular case (Fig. 7e) the maximum plasma diameter at the level 3 × 10⁻³ × N₀ is 2.14 μm.

In both the experiment and the simulations the transverse position of plasma channels is remarkably stable and does not change with the propagation distance. Thus, the mesh introduced before the transparent solid sample is a good tool to produce an array of filaments with prescribed and stable positions in the transverse plane and longitudinal extensions for at least 10 Rayleigh lengths. One of the possible applications of such a mesh technique is accelerating the process of writing the volume gratings in the bulk of fused silica. Direct writing of the grating with the size 300 μm × 300 μm and the thickness of around 150 μm takes from 5 to 8 h [37] because of translating the sample with the speed 1 μm/s. The 10 time acceleration of this process can be achieved by: (1) choosing the ratio between the beam radius and mesh period in such a way that at least 10 mesh units are located in the central almost flat part of the beam, (2) adjustment of the peak power flowing through a single mesh unit. The first condition is necessary for making the initial intensity almost the same in ten mesh units, the second condition is needed to make sure that exactly one filament per a unit is formed. If the sample were translated with the same speed of 1 μm/s, the grating of the similar size might be produced ten times faster due to the simultaneous formation of the ten equally-spaced filaments instead of one.

5. Conclusions

We have shown both experimentally and by means of numerical simulations the possibility to create a controlled array of refractive index modification zones inside a fused silica sample. In the experimental conditions, the pulse peak power is many times larger than the critical power for self-focusing in fused silica. Therefore, almost each of 900 mesh units within a beam diameter produces a robust filament. The corresponding plasma channel gives rise to the local refractive index modification zone as seen under the microscope both in the perpendicular to the propagation and longitudinal directions.

By numerical analysis of the light field phase dependence on the transverse coordinates (x, y) we have found that mesh units are separated from one another by phase barriers of the order of one radian. These barriers define the energy reservoirs for filaments formed within a unit and
prevent the energy exchange with the filaments from the neighboring units. As a result, the filaments and the corresponding plasma channels preserve their transverse positions for more than 10 Rayleigh length (or more than 500 µm). Merging of filaments occurs only due to the energy absorption and decrease of the peak power per a mesh unit below the critical power for self-focusing in the medium. In contrast to the mesh-induced filaments, stochastic filaments produced from the same pulse without the mesh can split, produce child filaments and merge at arbitrary positions along the propagation direction.

The most important controlling parameter of the mesh-produced array of filaments is the amount of pulse peak powers flowing through a single mesh unit. By optimizing this parameter we can obtain the closest to the sample entrance surface formation of the regular array of filaments. Besides, the increase/decrease of the pulse peak power with the simultaneous proportional decrease/increase of the mesh unit area controls the spacing between the filaments in the transverse plane. The results of this optimization are being prepared for the publication now.

Longitudinal inspection of structural changes in the laser-irradiated fused silica sample reveals equally-spaced elongated zones of refractive index modifications. This is in qualitative agreement with the simulated fluence distribution and plasma channels obtained with the mesh inserted into the beam. Thus, the usage of the mesh can essentially accelerate the fabrication of microoptics devices due to the simultaneous formation of multiple periodically spaced filaments in a single-shot pulse.

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