Discrete Damage Traces from Filamentation of Bessel-Gauss Pulses

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Filamentation of Bessel-Gauss pulses propagating in borosilicate glass is found to produce damage lines extending over hundreds of micrometers and consisting of discrete, equidistant damage spots. These discrete damage traces are explained by self-regeneration of Gauss-Bessel beams during the propagation and are potentially applicable in laser microfabrication of transparent materials.

Light filaments formed by laser beams propagating in transparent media present an interesting case of spatial, and possibly, temporal localization of electromagnetic radiation at extremely high power densities sustainable over significant propagation lengths. The potential areas of applications of such light channeling range from remote sensing and LIDAR to laser microscopy and microfabrication. Generation and dynamics of light filaments is explained using a wide range of physical models. Some of them adopt moving focus model [1] which implies that filamentation is merely an optical illusion occurring when time-integrated detection is used. Others describe filaments as self-channelled beams [2, 3] whose stationarity is supported by a balance between Kerr-induced self-focusing and plasma-induced defocusing; a genuine soliton-like propagation, however, is destroyed by additional physical effects [4]. The dynamic spatial replenishment model [5] treats filamentation as a cyclic defocusing and focusing due to the dynamic interplay between the Kerr and plasma effects. According to the recently proposed "filamentation without self-channelling" model [6, 7], multiphoton absorption alone can dynamically balance the self-focusing, thus leading to filamentation. It was shown numerically [8] that the absorption transforms the initial Gaussian beam toward the Gauss-Bessel (GB) beam, which is a modified solution of the free-space Helmholz equation [9]. Consequently, filament represents a narrow, high-intensity central part of a GB beam, whose propagation losses are replenished from the low-intensity side lobes containing the main part of the beam's energy. This model is strongly supported by recent experimental and theoretical results [7, 10, 11] demonstrating extreme robustness (self-healing) of the filaments in reconstructing their intensity after encountering microscopic obstacles.

In most of the studies reported so far filamentation was seeded using laser beams with Gaussian transverse profiles. Having in mind the GB nature of filaments, the possibility of directly launching a powerful Bessel beam into the material and thus circumventing the internal transformation from Gaussian toward GB beam, is intriguing. The internal transformation is governed by the materials' nonlinear response, which may limit the obtainable peak intensity of the GB beam. An external GB beam (e.g., generated using an axicon) may have power sufficient for inducing and sustaining extensive damage along its entire propagation path. The possibility to fabricate extended lines in transparent solids almost instantaneously is beneficial for laser microfabrication. Here we show that a GB beam, delivering femtosecond laser pulses with central wavelength of 800 nm, and power exceeding the self-focusing threshold of a Gaussian beam, can propagate in bulk borosilicate glass over tens of micrometers leaving a line of periodic discrete damage spots. The spots represent refocusing of the central part of the GB beam, whose absorptive losses at each focus cause the damage, but are quickly replenished due to the self-healing. These findings are explained by a simple theoretical model, which yields, in particular, the value of 8.6 μm for the distance between the damage spots, close to the experimentally obtained value of 9 μm.

Our theoretical predictions are based on numerical simulations of the propagation of a linearly polarized laser pulse along the $z-$axis. The electric field of the initial GB beam is expressed in cylindrical coordinates as $A(r,z,t) \propto J_0(k_\perp r)\exp(-r^2/w_G^2 - t^2/t_p^2)\exp(ik_z z)$, where J_0 is the zeroth order Bessel function of the first kind, $k_\perp$ and k_z are the radial and longitudinal components of the wavevector k, respectively. The wave packet with Gaussian beam waist $w_G = 100\,\mu$m, duration $t_p = 130$ fs assumed to have the diameter of $w_B \simeq 2\,\mu$m in its central part (at $z = 0$), whereas the maximum power (at the temporal peak) exceeds the critical self-focusing power by twelve times, in accordance with the experimental situation (to be described later).

The evolution of the complex scalar envelope of the wave-packet, $A(r,z,t)$, was deduced from the nonlinear Schroedinger equation assuming cylindrical symmetry. The latter equation included terms describing diffraction, dispersion, self-focusing, nonlinear losses (due to the five-photon absorption at the photon energy of ≈ 1.4 eV in borosilicate glass with effective gap $\simeq 5.8$ eV), and time-dependent (dispersive) terms up to the third order. The nonlinear losses were accounted for by the coefficient $\beta^{(5)} = 10^{-47}\mathrm{cm}^7/\mathrm{W}^4$. Since self-healing can only occur due to the non-linear losses, possible defocusing due to

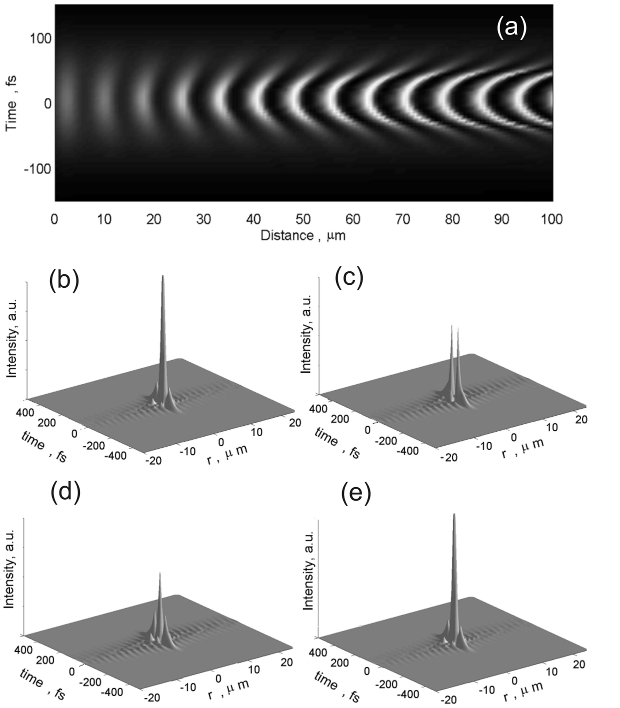

FIG. 1: Calculated *zt*- image of the on-axis pulse intensity in the moving coordinate frame (above); Below: space-time resolved energy fluence profiles of the wave packets at the distances between $z = 50$ μm and $z = 58.5$ μm, representing refocusing cycle of the GB beam in glass.

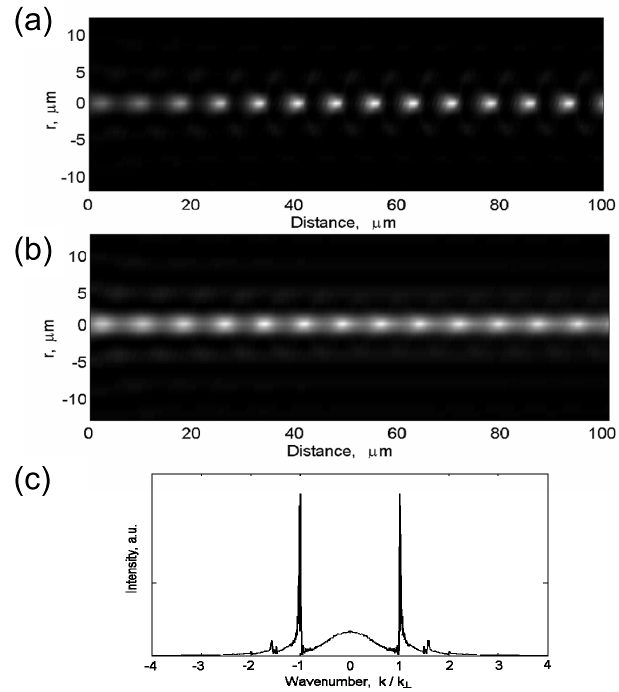

FIG. 2: Instantaneous (at $t = 0$ in the moving coordinate frame) intensity (a), fluence (b) and the angular spectrum (c) calculated for the GB wave-packet propagating for 100 μm in glass.

the photogenerated plasma was neglected.

The beam propagation resulting under the above assumptions is illustrated by the data in Fig.1. The spatiotemporal intensity map shown in Fig.1 (a) indicates that central part of the beam propagates without visible loss of intensity, simultaneously oscillating with period of $8.6\,\mu$m (twelve cycles fit into the $100\,\mu$m length). These oscillations can be understood as periodic focusing of the central part during the propagation. This behavior is further illustrated by the wave packet structures in Fig.1 (b-e) corresponding to various stages of focusing within single period at $z = 50,\ 53, 55$ and $58\,\mu$m. Similar periodicity, albeit with smaller period, was observed earlier for low intensity beams, and explained by the interference between the initial GB beam and the Gaussian constituent generated during the four-wave mixing process [12, 13]. However, we have verified that neither Gaussian, nor GB beam would exhibit such behavior in this case, when the intensity strongly exceeds the self-focusing threshold of the Gaussian beam, and when mechanisms which arrest the beam's collapse (e.g., dispersion and nonlinear losses) are active. It is helpful to note here that at this intensity the self-focusing length of a Gaussian beam having waist of $2\,\mu$m is less than $3.5\,\mu$m.

The spatial distributions of the intensity and fluence shown in Fig. 2 (a,b) indicate that high power density, possibly sufficient for inducing significant optical damage, might be achievable at the intensity maxima. Optical losses resulting from scattering or absorption by the damaged regions should not inhibit the beam's propagation owing to its self-regeneration capability. This effect can be qualitatively explained using the spectrum shown in Fig. 2 (c). By taking into account on-axis interference between the input beam $k_\perp$ and the secondary Gaussian and Bessel beams, generated during the nonlinear interaction at $k_{\perp 0} = 0$ and $k_{\perp 1} = 1.5 \times k_\perp$ respectively, the condition for constructive interference is $(k_{zj} - k_z)z = \pi$, where k_{zj}, $\quad (j = 0, 1)$ are $z-$components of the wavevectors of the secondary beams. This infers the distances between the interference maxima to be as large as $10.5\,\mu$m and $12.8\,\mu$m.

The above evaluation hints that the expected distance between the damage points falls into the interval between 3.5μm (due to the arrest of the collapse) and $10.5\,\mu$m (due to the influence of the nonlinear change of the refractive index on the interference).

These predictions were verified experimentally by launching a GB beam into a block of borosilicate glass. The initial Gaussian beam was generated by a femtosecond Ti:sapphire laser with pulse duration $t_p = 150$ fs, central wavelength $\lambda_p = 800$ nm, and repetition rate of 1 kHz. The Gaussian beam was transformed into the GB beam by an axicon [14] with wedge angle $\gamma =$

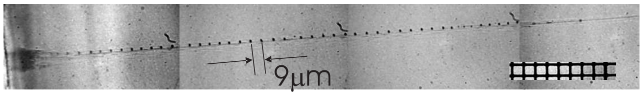

FIG. 3: Side image of the trace recorded by 8000 shots of 0.4 mJ each (the image was obtained by combining four separately taken images). The entrance (on the left side) has ablation marks. The pitch of the scale grid is 10 μm.

0.175 rad [15]. The radial distance between the neighboring intensity maxima of the GB beam was approximately 55 μm. The beam was imaged onto the sample using a telescope with demagnification factor of 3.3. At the entrance to the sample the time-integrated GB beam power was 8.0 MW, much higher than the self-focusing threshold for an equivalent Gaussian beam (1.8 MW) even if about 25% Fresnel power loss is accounted for. Its central maximum had diameter of 2.1 μm, and power of 0.069 MW. This power density was well below the white light continuum generation threshold, and correspondingly, no spectral broadening could be detected in the filaments. Although pulse duration in the sample was not measured experimentally, a considerable broadening can be expected after the propagation in glass over tens of micrometers.

After the irradiation for the time interval from few to tens of seconds, the sample was examined by optical microscopy. Figure 3 shows the image of the region after 8 s exposure (8000 pulses). As expected from the theory, the exposure produces a line consisting of periodically arranged light-induced damage dots with period of approximately 9 μm. The dots are seen as dark spots having nearly uniform contrast against the background within almost the entire length of the line. This feature indicates that self-blocking of the beam's central part was indeed compensated by self-healing. In addition, after exposures longer than 20 s (which helped increase the visibility of the dotted lines), large surface ablation areas (up to 20 μm in diameter) developed on the sample at the beam's entrance (see Fig. 3). However, this did not stop further augmentation of the dotted lines' contrast, illustrating that accumulation of the damage, either at the entrance or along the lines did not lead to self-blocking. Interestingly, the observed self-action of the beam manifests itself in a manner characteristic to the Talbot effect, which is a linear, lens-like self-imaging of propagating diffracted fields. Our observations, due to the crucial role of nonlinear absorption and refraction, may indicate the presence of "non-linear Talbot effect".

In conclusion, we have studied propagation and self-action of powerful GB beams in borosilicate glass. It was demonstrated that formation of the dotted light damage traces left by these beams is in accordance with the "filamentation without self-channelling" model. GB beams were previously found useful in various fields, like optical tweezers [16], cold atom guiding [17], and in nonlinear optics [18]. Our findings may further extend their versatility to large-scale rapid laser microstructuring of borosilicate glass and similar materials. For example, when translated laterally, BG beams might act as optical dicing tools.

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