# Discrete damage traces from filamentation of Gauss–Bessel pulses

**Eugenijus Gaižauskas**

*Vilnius University, Saulėtekio 9, 2040 Vilnius, Lithuania*

**Egidijus Vanagas**

*Laser Systems, Inc., Sapporo Marumasu Building, N7-W4, Sapporo, 060-0807, Japan*

**Vygandas Jarutis, Saulius Juodkazis, Vygantas Mizeikis, and Hiroaki Misawa**

*CREST-JST and Research Institute for Electronic Science, Hokkaido University, Sapporo 001-0021, Japan*

Received June 17, 2005; revised manuscript received August 18, 2005; accepted August 26, 2005

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 propagation and are potentially applicable in laser microfabrication of transparent materials. © 2006 Optical Society of America

*OCIS codes:* 190.5940, 220.4000, 350.3390.

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. The generation and dynamics of light filaments are explained by using a wide range of physical models. Some adopt a 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-channeled beams[2,3] whose stationarity is supported by a balance between Kerr-induced self-focusing and plasma-induced defocusing; genuine solitonlike propagation, however, is prevented by additional physical effects.[4] The dynamic spatial replenishment model[5] treats filamentation as cyclic defocusing and focusing due to the dynamic interplay between Kerr and plasma effects. According to the recently proposed model of filamentation without self-channeling,[6,7] multiphoton absorption alone can dynamically balance self-focusing, thus leading to filamentation. It was shown numerically[8] that 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 sidelobes 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 by 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 a 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 by using an axicon) may have power sufficient for inducing and sustaining extensive damage along its entire propagation path. The possibility of fabricating extended lines in transparent solids almost instantaneously is beneficial for laser microfabrication. Here we show that a GB beam, delivering femtosecond laser pulses with a 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 by self-healing. These findings are explained by a simple theoretical model, which yields, in particular, the value of 8.6 $\mu$m for the distance between the damage spots, close to the experimentally obtained value of 9 $\mu$m.

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 $A(r,z,t)\propto J_0(k_\perp r)\exp(-r^2/w_G^2-t^2/t_p^2)\times\exp(ik_z z)$, where $J_0$ is the zeroth-order Bessel function of the first kind and $k_\perp$ and $k_z$ are the radial and longitudinal components of the wave vector $k$, respectively. The wave packet with Gaussian beam waist $w_G=100$ $\mu$m and duration $t_p=130$ fs is assumed to have a 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 12 times, in accordance with the experimental situation (described below).

0146-9592/06/010080-3/$0.00 

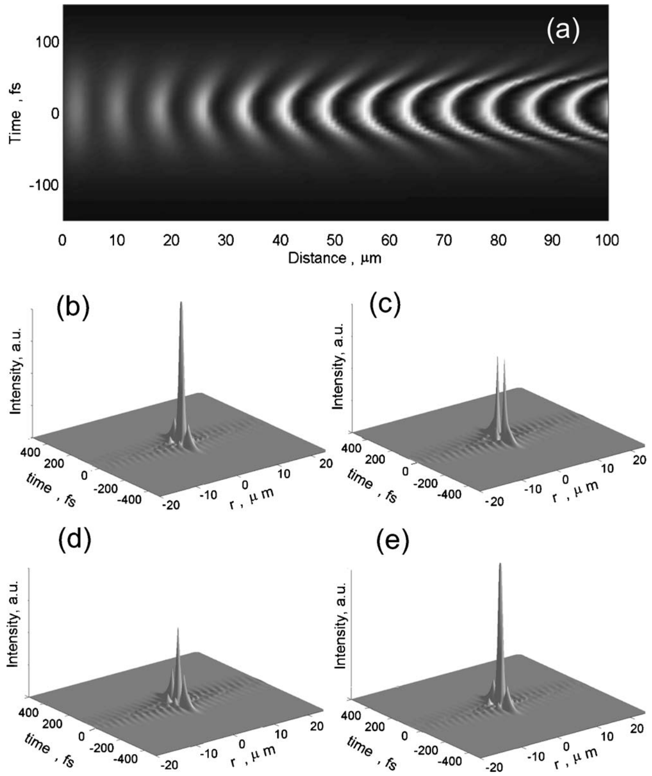


Fig. 1. (a) Calculated $zt$ image of the on-axis pulse intensity in the moving coordinate frame. (b)–(e) Space–time-resolved energy fluence profiles of the wave packets at distances between $z=50$ $\mu$m and $z=58.5$ $\mu$m, representing the refocusing cycle of the GB beam in glass.

The evolution of the complex scalar envelope of the wave packet, $A(r,z,t)$, was deduced from the nonlinear Schrödinger 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 $\approx$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 $\beta^{(5)}=10^{-47}$ cm$^7$/W$^4$. Since self-healing can only occur as a result of the nonlinear losses, possible defocusing due to 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 the central part of the beam propagates without visible loss of intensity, simultaneously oscillating with a period of 8.6 $\mu$m (12 cycles fit into the 100 $\mu$m length). These oscillations can be understood as periodic focusing of the central part during propagation. This behavior is further illustrated by the wave-packet structures in Figs. 1(b)–1(e), corresponding to various stages of focusing within single period at $z=50,53,55,58$ $\mu$m. Similar periodicity, albeit with a 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 a Gaussian nor a 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 that 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 a waist of 2 $\mu$m is less than 3.5 $\mu$m.

The spatial distributions of the intensity and fluence shown in Figs. 2(a) and 2(b) indicate that a 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 by 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 $k_{zj}$ $(j=0,1)$ are $z$ components of the wave vectors of the secondary beams. This implies the distances between the interference maxima to be as large as 10.5 and 12.8 $\mu$m.

The above evaluation hints that the expected distance between the damage points falls into the interval between 3.5 $\mu$m (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

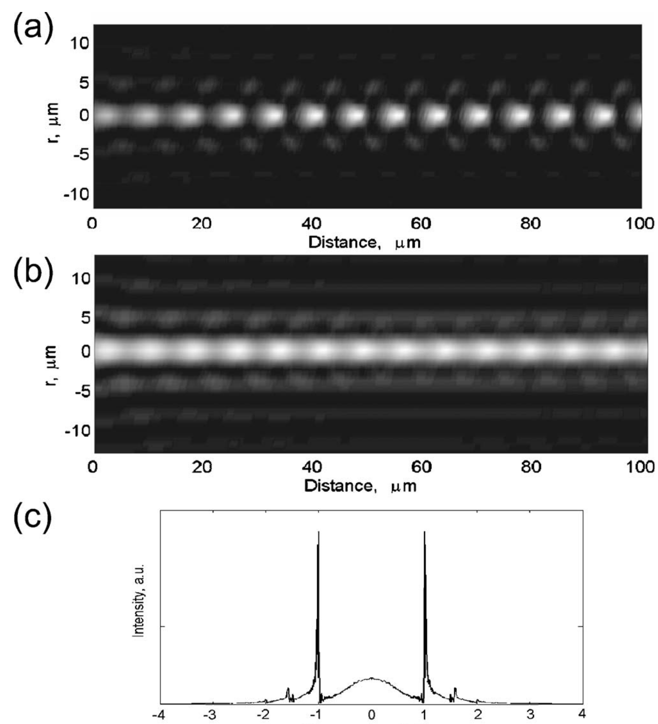


Fig. 2. (a) Instantaneous (at $t=0$ in the moving coordinate frame) intensity, (b) fluence, and (c) the angular spectrum calculated for the GB wave packet propagating for 100 $\mu$m in glass.

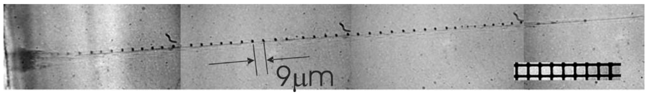


Fig. 3. Side image of the trace recorded by 8000 shots of 0.4 mJ each (the image was obtained by combining four separately taken images). The entrance (on the left side) has ablation marks. The pitch of the scale grid is 10 $\mu$m.

femtosecond Ti:sapphire laser with pulse duration $t_p = 150$ fs, central wavelength $\lambda_p = 800$ nm, and a repetition rate of 1 kHz. The Gaussian beam was transformed into the GB beam by an axicon[14] with wedge angle $\gamma = 0.175$ rad.[15] The radial distance between the neighboring intensity maxima of the GB beam was approximately 55 $\mu$m. The beam was imaged onto the sample by using a telescope with a 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 a diameter of 2.1 $\mu$m 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, considerable broadening can be expected after propagation in glass over tens of micrometers.

After the irradiation for the time interval from a 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 a period of approximately 9 $\mu$m. The dots are seen as dark spots having nearly uniform contrast against the background for 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 $\mu$m 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 of the Talbot effect, which is a linear, lens-like self-imaging of propagating diffracted fields. Our observations, because of the crucial role of nonlinear absorption and refraction, may indicate the presence of a nonlinear "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 model of filamentation without self-channeling. GB beams were previously found useful in various fields, such as optical tweezers,[16] cold atom guiding,[17] and nonlinear optics.[18] Our findings may further extend their versatility to large-scale rapid laser microstructuring of borosilicate glass and transparent dielectric materials. For example, when translated laterally, BG beams might act as optical dicing tools.

E. Gaižauskas is thankful to the Satellite Venture Business Laboratory (SVBL) of the University of Tokushima for a travel grant. H. Misawa's e-mail address is misawa@es.hokudai.ac.jp.

## References

1. A. Brodeur, C. Y. Chien, F. A. Ilkov, S. L. Chin, O. G. Kosareva, and V. P. Kandidov, Opt. Lett. **22**, 304 (1997).
2. H. R. Lange, G. Grillon, J.-F. Ripoche, M. Franco, B. Lamouroux, B. Prade, A. Mysyrowicz, E. T. J. Nibbering, and A. Chiron, Opt. Lett. **23**, 120 (1998).
3. A. Braun, G. Kornand, X. Liu, D. Du, J. Squir, and G. Mourou, Opt. Lett. **20**, 73 (1995).
4. L. Berge and A. Couairon, Phys. Rev. Lett. **86**, 1003 (2001).
5. M. Mlejnek, E. M. Wright, and J. V. Moloney, Opt. Lett. **23**, 382 (1998).
6. V. Sirutkaitis, E. Gaižauskas, V. Kudriasov, M. Barkauskas, R. Grigonis, V. Vaicaitis, and A. Piskarskas, in Proc. SPIE **4932**, 346 (2003).
7. A. Dubietis, E. Gaižauskas, G. Tamošauskas, and P. di Trapani, Phys. Rev. Lett. **92**, 253903 (2004).
8. M. Mlejnek, M. Kolesik, E. M. Wright, and J. V. Moloney, Phys. Rev. Lett. **83**, 2938 (1999).
9. J. Durnin, J. Miceli, and J. H. Eberly, Phys. Rev. Lett. **58**, 1499 (1987).
10. M. Kolesik and J. V. Moloney, Opt. Lett. **29**, 590 (2004).
11. A. Dubietis, G. Tamošauskas, E. Kučinskas, E. Gaižauskas, and P. Trapani, Opt. Lett. **29**, 1126 (2004).
12. V. Jarutis, R. Paškauskas, and A. Stabinis, Opt. Commun. **184**, 105 (2000).
13. R. Gadonas, V. Jarutis, R. Paškauskas, V. Smilgevičius, A. Stabinis, and V. Vaičaitis, Opt. Commun. **196**, 309 (2000).
14. R. M. Herman and T. A. Wiggins, J. Opt. Soc. Am. A **8**, 932 (1991).
15. A. Marcinkevicius, S. Juodkazis, S. Matsuo, V. Mizeikis, and H. Misawa, Jpn. J. Appl. Phys., Part 2 **40**, L1197 (2001).
16. V. Garcés-Cháves, D. McGloin, H. Melville, W. Sibbett, and K. Dholakia, Nature **419**, 145 (2002).
17. J. Arlt, T. Hitomi, and K. Dholakia, Appl. Phys. B **71**, 549 (2000).
18. D. Ding and J. Lu, J. Acoust. Soc. Am. **107**, 1212 (2000).