Quantum Electronics **34** (10) 879 – 880 (2004) ©2004 Kvantovaya Elektronika and Turpion Ltd

LETTERS

PACS numbers: 42.60.Jf; 42.65.Jx; 42.65.Re
DOI: 10.1070/QE2004v034n10ABEH002870

A method for spatial regularisation of a bunch of filaments in a femtosecond laser pulse

V.P. Kandidov, N. Akozbek, M. Scalora, O.G. Kosareva,
A.V. Nyakk, Q. Luo, S.A. Hosseini, S.L. Chin

Abstract. **A method for spatial regularisation of chaotically located filaments, which appear in a high-power femtosecond laser pulse, is proposed, numerically substantiated, and experimentally tested. This method is based on the introduction of regular light-field perturbations into the femtosecond-pulse cross section.**

Keywords: *filamentation, femtosecond pulses, spatial structures.*

1. Due to a spatial instability of an intense light field under self-focusing in gases and condensed media, high-power pulses decompose into a large number of chaotically located filaments [1]. The stochastic character of the filamentation, which is determined by perturbations of the light field at the output of the laser system and fluctuations of the optical parameters of the medium, leads to an unstable backscattering signal, for example, in femtosecond lidars [2, 3]. The possibility of obtaining a bunch of filaments regularly arranged in the form of a ring in the pulse cross section using strong spatial gradients of the light field was considered in [4].

In this work, we propose a method for spatial regularisation of a bunch of filaments in a laser pulse by modulating the intensity in the pulse cross section.

2. Extended filaments (with a length of several hundred metres) are formed due to a dynamic redistribution of the power density in the pulse cross section, which occurs because of the Kerr self-focusing in the medium and a nonlinear refraction in the laser plasma [5]. The appearance of the filaments is determined by the small-scale self-focusing of the light-field intensity. The concept of the method proposed for regularising the chaotically located filaments is to produce in the pulse cross section a system of preset intensity perturbations, at which filaments are initiated despite pulse fluctuations associated with both the quality of the laser output radiation and random inhomogeneities of the medium.

3. To substantiate this method, we studied numerically stationary small-scale self-focusing of a plane wave with random and regular intensity perturbations. A stochastic filamentation is considered for a light field $\tilde{\boldsymbol{E}}(x, y, z = 0)$ for random additive perturbations of the amplitude $\xi(x, y)$ distributed according to the normal law with a zero mean and a variance σ^2. The correlation radius of $\xi(x, y)$ was chosen equal to the spatial scale at which the perturbations of a plane wave with the intensity $I_0 = [cn_0/(8\pi)]|\langle\tilde{\boldsymbol{E}}\rangle|^2$ have the largest increment in the Kerr medium [1]. In the case of a periodic filamentation, regular light-field perturbations were specified by introducing a periodic mesh with a square unit of a period d and nontransparent lines with a width $h \ll d$ into the pulse cross section. The spatial regularisation was achieved by a multiplicative superposition of the mesh-produced regular perturbations on the stochastic light field $\tilde{\boldsymbol{E}}(x, y, z = 0)$. In numerical studies, it was assumed that a power eight times higher than the critical self-focusing power was transferred through a single mesh unit of size $d \times d$.

Statistical tests performed with a sample of 50 independent realisations of a random field $\xi(x, y)$ have shown that, for $\sigma^2 = 0.01$, the regularisation of the light field by a mesh leads to the systematic arrangement of filaments in the plane of the pulse cross section. The average distance to the filamentation onset simultaneously decreases, and the average density of filaments increases by $> 30\,\%$. When σ^2 increases to 0.09, this mesh does not virtually lead to a spatial regularisation of filaments. A detailed numerical study of this method will be published in 'Applied Physics B'.

4. The method for spatial regularisation of the filamentation was demonstrated experimentally on the setup at the Laval University (Canada). Radiation of a 810-nm Ti-sapphire laser with a pulse repetition rate of 10 Hz, a pulse duration of 42 fs, an energy of < 15 mJ, and a beam radius of 4 mm propagated in a 1-cm long cell filled with methanol. Filaments were detected with a CCD camera, in front of which we installed a selective narrow-band dielectric mirror reflecting the radiation at the laser wavelength and a BG18 green filter for selecting the short-wavelength branch of directed supercontinuum radiation that accompanies the filamentation [6]. To obtain random intensity perturbations, a polyethylene-film mask with a randomly distributed transmission coefficient was

---

V.P. Kandidov, O.G. Kosareva, A.V. Nyakk Department of Physics, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119992 Moscow, Russia; e-mail: kandidov@msuilc.phys.msu.su; nyakk@mail.ru;
N. Akozbek Time Domain Corporation, 7057 Old Madison Pike, Huntsville, AL 35 806, USA;
M. Scalora US Army Aviation and Missile Command, AMSAM-WS-RD-ST, Huntsville, AL 35 898-5000, USA;
Q. Luo, S.A. Hosseini, S.L. Chin Department de Physique, de Genie Physique et d'Optique and Centre d'Optique, Photonique et Laser, Universite Laval, Quebec GIK 7P4, Canada;
e-mail: slchin@phy.ulaval.ca

Received 13 September 2004
Kvantovaya Elektronika **34** (10) 879 – 880 (2004)
Translated by A.S. Seferov

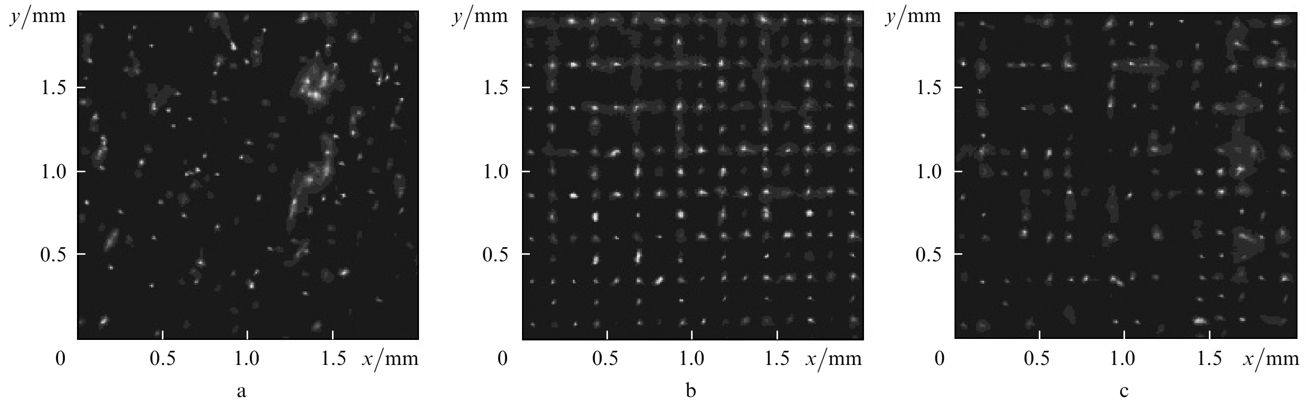

Figure 1. Pictures of the arrangement of filaments in the cross section of a 2-mJ, 42-fs pulse recorded in green light on the output window of the methanol-filled cell: (a) stochastic filamentation with the mask located at a distance of 102 mm from the cell entrance, (b) periodic filamentation with the mesh located at a distance of 13.5 mm from the cell, and (c) regularised filamentation with the mask and mesh placed at the aforementioned distances.

placed in front of the cell entrance window at a distance of 102 – 120 mm from it. The relative intensity fluctuations behind the mask were on average as high as 60 %, while their spatial scale was 25 – 140 μm. The filamentation was spatially regularised by a mesh with a period of 240 μm including 220 μm of transparent part and 20-μm wire. The distance between the grid and the cell entrance window was varied from 5.5 to 43 mm with a pitch of 2 mm.

The pulse energy in the experiments was 2 mJ and the peak intensity I_0 on the axis was 9×10^{10} W cm^{-2}; in this case, a peak power ten times higher than the critical self-focusing power in methanol was transmitted through a single grid mesh. A typical picture recorded on the cell output window is shown in Fig. 1 for a near-axial region with a size of 7 × 7 mesh units. For a stochastic filamentation achieved when only the mask was located in front of the cell entrance window, filaments were arranged chaotically in the pulse cross section. For a periodic filamentation when only the grid was in front of the cell, a regular system of filaments was formed. When both the mask and the grid transparency were placed in front of the cell entrance window, an ordered spatial arrangement of filaments is observed in contrast to a stochastic filamentation. A spatial regularisation was observed under changes in the pulse energy and the distances from the mask and mesh to the cell entrance window. Statistical processing of a set of data obtained upon shifting the mask in its plane has shown that, as a result of regularisation, the density of filaments increases on average by a factor of 1.5 – 2.

5. In this method for controlling the filamentation process, the introduction of either regular intensity or regular phase perturbations into a femtosecond-pulse cross section can be used. Optimising the geometry of the regularising perturbations allows one to increase the efficiency of the proposed method. This method can be applied in femtosecond lidar systems operating under conditions of atmospheric turbulence.

Acknowledgements. V.P. Kandidov, O.G. Kosareva, and A.V. Nyakk are grateful for the support from the Russian Foundation for Basic Research (Grant No. 03-02-16939) and European Office for Research of US Army (Contract No. 62558-04-P-6051). Q. Luo, S.A. Hosseini, and S.L. Chin are grateful to the CFI, NSERC, CIPI, DRDC-Valcartier Research Foundations of Canada, and also to Spectra Physics and FQRNT.

References

1. Bespalov V.I., Litvak A.G., Talanov V.I., in *Nelineinaya optika* (Nonlinear Optics) (Novosibirsk: Nauka, 1968) p. 428.
2. Kasparian J., Rodriguez M., Méjean G., Yu J., Salmon E., Wille H., Bourayou R., Frey S., André Y.-B., Mysyrowicz A., Sauerbrey R., Wolf J.-P., Wöste L. *Science*, **301**, 61 (2003).
3. Hosseini S.A., Luo Q., Ferland B., Liu W., Akozbek N., Roy G., Chin S.L. *Appl. Phys. B*, **77**, 697 (2003).
4. Mechain G., Couairon A., Franco M., Prade B., Mysyrowicz A. *Phys. Rev. Lett.*, **93**, 035003 (2004).
5. Kandidov V.P., Kosareva O.G., Koltun A.A. *Kvantovaya Elektron.*, **33**, 69 (2003) [*Quantum Electron.*, **33**, 69 (2003)].
6. Kandidov V.P., Kosareva O.G., Golubtsov I.S., Liu W., Becker A., Akozbek N., Bowden C.M., Chin S.L. *Appl. Phys. B*, **77**, 149 (2003).