

# On the problem of the initial conditions for tightly-focused ultrashort laser pulses in the modeling of laser beam propagation in transparent solids

V.P. Zhukov<sup>1,2,3</sup>, N.M. Bulgakova<sup>1</sup>

1- HiLASE Centre, Institute of Physics of the Czech Academy of Sciences, Za Radnici 828, 25241 Dolní Břežany, Czech Republic

2- Institute of Computational Technologies SB RAS, 6 Lavrentyev Ave., 630090 Novosibirsk, Russia

3- Novosibirsk State Technical University, 20 Karl Marx ave., 630073, Novosibirsk, Russia

zhukov@ict.nsc.ru

For fabrication of high-precision structures inside bandgap materials for photonics and optoelectronics applications, tightly-focused laser beams with ultrashort pulse duration are preferable in order to minimize the intensity clamping effect and, hence, to avoid delocalization of the absorbed laser energy [1,2]. Sophisticated numerical modeling of different stages of laser-materials interactions, from the laser excitation of the electronic sub-system of a solid to its thermal and mechanical response to the laser energy deposition, offers a great potential for the fundamental understanding the laser-induced processes and optimizing the irradiation regimes for specific applications. However, in the case of tightly-focused beams, mathematical modeling faces the problem on how to set up the correct initial conditions for the laser field.

Usually, in numerical models, the shape of the incoming laser beam at the sample surface is taken in the Gaussian form, which is a solution of the non-linear Schrödinger equation for the monochromatic case [2,3]. For tightly focused laser beams, such initial conditions lead to unphysical results while the validity of a ‘smoothed’ initial conditions is still not well-proven [2]. For achieving the adequate modeling results, it is necessary to elaborate the initial conditions for the incoming tightly-focused beam, which would correspond to the real focusing systems. In this regard, the “parabolic mirror” initial condition is seemingly one of the most reasonable approaches [4]. In the presented work, we investigate the “parabolic mirror” initial condition in applications to the problems of propagation of tightly-focused laser beams in transparent dielectrics. For these aims, we are applying the technique of the Stratton-Chu integral [5]. It is also shown that using the temporal Gaussian shape to describe tightly-focused ultrashort laser pulse propagation yields unphysical results. For obtaining the physically meaningful solutions, it is necessary to calculate temporal evolution of the beam in a special way. To do this, the generalization of the Stratton-Chu integral for the time dependence of the propagating laser pulse has been proposed. We have developed a numerical code enabling efficient calculations of the generalized Stratton-Chu integral.

[1] V.V. Kononenko, V.V. Konov, E.M. Dianov, Delocalization of femtosecond radiation in silicon, *Opt. Lett.*, vol. 37, pp. 3369-3371 (2012).

[2] N.M. Bulgakova, V.P. Zhukov, Y.P. Meshcheryakov, L. Gemini, J. Brajer, D. Rostohar, T. Mocek, Pulsed laser modification of transparent dielectrics: what can be foreseen and predicted by numerical simulations? *J. Opt. Soc. Am. B*, vol. 31, pp. C8-C14 (2014).

[3] V.P. Zhukov, N.M. Bulgakova, M.P. Fedoruk, Nonlinear Maxwell’s and Schrödinger equations for describing the volumetric interaction of femtosecond laser pulses with transparent solid dielectrics: effect of the boundary conditions, *J. Opt. Technol.*, vol. 84, pp. 439-4467, (2017).

[4] K.I. Popov, C. McElcheran, K. Briggs, S. Mack, L. Ramunno, Morphology of femtosecond laser modification of bulk dielectrics, *Opt. Express*, vol. 19, pp. 271–282 (2010).

[5] J.A. Stratton and L.J. Chu, Diffraction theory of electromagnetic waves, *Phys. Rev.*, vol. 56, pp. 99–107 (1939).