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Numerical simulation of interaction of few-cycle pulses counter-propagating in the optical fiber

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Abstract. Interaction of few-cycle pulses counter-propagating in an optical fiber is studied numerically via solution of equations for bi-directional fields that are equivalent to the full scalar wave equation. It is simulated how 3-cycle optical pulse of the Ti:Sa laser is gained as it propagates through the field of the pulse on the second harmonic with higher intensity in the telecommunication type single-mode optical fiber. Rise of sixths harmonic is also observable under considered conditions.

1. Introduction

Qualitative and quantitative description of a few-cycle pulse evolution is one of the most relevant challenges for the modern nonlinear optics. Extremely short durations of such pulses allow for concentration of high peak intensities with a lower amount of the input power, which in turn leads to gain in efficiency of nonlinear light-matter interactions boosting all sorts of nonlinear phenomena. In the linear regime low-intensity pulses propagate independently from each other, so that the resulting field is simply the superposition of those pulses. High-intensity pulses affect each other via nonlinear response of the propagation medium so that the resulting field differs from the simple superposition of electromagnetic waves at the given point in space and time. Some investigations on characteristics of these differences are presented in [1, 2]. However the articles imply quite a few analytical simplifications and do not contain straightforward numerical solution for the equations describing evolution of the counter-propagating pulses.

2. Set of equations

A set of equations for forward and backward waves can be utilized for description of evolution of few-cycle pulses counter-propagating in the optical fiber [3]:

$$\partial_z G_\pm = \pm ik(\omega)G_\pm \pm \frac{1}{2} ik(\omega)N_\omega(E_+ + E_-)\,, \tag{1}$$

$$N_\omega(E) = 4\pi F[P_{NL}(E)]/n^2(\omega)\,, \tag{2}$$

where z is the coordinate along the axis of the fiber, $G_\pm = F[E_\pm]$ is the spectral density of the fields of the forward and backward waves $E_\pm$, F is Fourier transform, t is time, ω is frequency, i is the imaginary unit, $k(\omega) = \omega n(\omega)/c$ is the wavenumber, $n(\omega)$ is the refractive

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index, c is the speed of light, N_ω is the nonlinear operator in the frequency domain and P_{NL} is the nonlinear response of the medium.

3. Medium parameters

Frequency dependency of refractive index of the silica glass within the range of transparency can be expressed as power series of frequency [4]:

$$n(\omega) = N_0 + ac\omega^2 - \frac{bc}{\omega^2}, \tag{3}$$

where $N_0 = 1.4508$, $a = 2.7401 \cdot 10^{-44}$ $s^3 \cdot cm^{-1}$, $b = 3.9437 \cdot 10^{17}$ $s^{-1} \cdot cm^{-1}$.

Nonlinear response can be described with phenomenological model suggested by Platonenko and Khokhlov [5]:

$$\begin{cases} P_{NL} = \chi_3^e E^3 + \chi_3^{ev} RE \\ \dfrac{\partial^2 R}{\partial t^2} + \dfrac{1}{T_v}\dfrac{\partial R}{\partial t} + \omega_v^2 R = \gamma E^2 \end{cases}, \tag{4}$$

where χ_3^e and χ_3^{ev} are the cubic nonlinear susceptibility of electronic and electronic-vibrational nature, respectively, R is the amplitude of the molecular oscillations, T_v is the relaxation time, ω_v is the Stokes frequency and γ is the damping coefficient.

4. Results of simulations

Equations (1) allow us to represent two counter-propagating pulses as forward and backward waves, respectively. Therefore it seems convenient to investigate how a high-intense pulse influences the field of counter-propagating pulse with lower intensity by numerical solution of equations (1). Within such approach initial field distribution of the high-intensity pulse was represented as the field of the backward wave with Gaussian profile and central frequency of 390 nm (the second harmonic of Ti:Sa laser) and duration 7.8 fs (6 field cycles), and pulse with the lower intensity was represented as the field of the forward wave of Gaussian form with central frequency 780 nm (the first harmonic of Ti:Sa laser) and duration of 7.8 fs (3 field cycles). If initial time delay between the pulses is 50 fs, then the distance in optical waveguide, which is enough for the pulses to propagate through each other with interaction and even accumulate some time delay is about 10 μm.

Since the forward and backward waves are interrelated via the nonlinear term in equations (1), a non-zero forward wave gives rise to non-zero backward and vice versa. Such behavior is independent of initial conditions, hence to exclude peculiarities of the directional fields separation it is worth considering the total field $E = E_+ + E_-$ and compare it between linear and nonlinear regimes. In order to do this comparison we run three numerical experiments. For the first it was assumed that the forward wave is absent, but the intensity of the backward wave is $I = 2 \cdot 10^{13}$ W/cm^2. For the second the initial field of the backward wave was set to zero, while the initial amplitude of the forward wave was 5 times lower than that of the backward wave in the first experiment. And finally we considered the initial distributions with both waves presented and amplitudes of backward and forward waves taken from the first and second experiments, respectively. The sum of resulting fields from the first and second experiments $E_1 + E_2$ corresponds to independent propagation of pulses, while the total field E_3 of the third experiment is the result of their interaction. The spectral density of the difference of these fields $G^{diff} = G_3 - (G_1 + G_2)$ depicted in figure 1 illustrates the effect of nonlinear interaction between counter-propagating pulses.

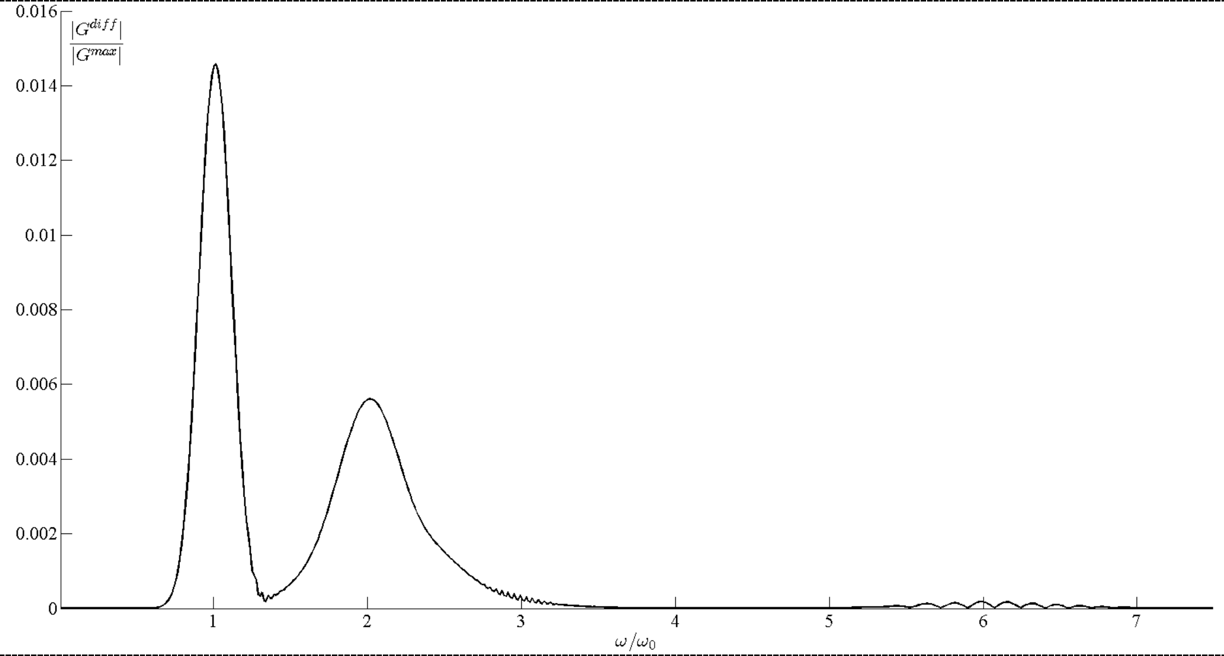

Figure 1. The spectral density of the difference of the resulting fields in non-linear and linear regimes.

It is seen that the interaction leads to the gain of waves on basic frequencies, and the wave on the first harmonic of Ti:Sa laser corresponding to the pulse with the lower intensity is affected more than the one on the second harmonic corresponding to the pulse with the higher intensity. Higher impact of the more intense pulse on the weaker seems justified. Besides one can observe the gain of the sixths harmonic, which corresponds to the triple frequency of the intense backward wave on the second harmonic. The amplitude of the spectral density G^{diff} is in the order of 0.015 of the initial amplitude of the intense pulse.

5. References

[1] Buyanovskaya E M and Kozlov S A 2007 *JETP Lett* **86** 349
[2] Buyanovskaya E M and Kozlov S A 2010 *Sci. and Tech. Journ. of Inf. Tech., Mech. And Opt.* **66** 23
[3] Kinsler P, Radnor S B P and New G H C 2005 *Phys. Rev. A* **72** 063807
[4] Bespalov V G, Kozlov S A, Shpolyanskiy Yu A and Walmsley I A 2002 *Phys. Rev. A* **66** 013811
[5] Platonenko V T, Stamenov K V and Khokhlov R V 1966 *Sov. Phys. JEPT* **22** 827