Effect of Raman nonlinearity on forward and backward waves of intense few-cycle laser field in optical fibre

Leonid Konev, Yuri Shpolyanskiy
Department of Photonics and Optoinformatics
Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics
Saint-Petersburg, Russia

Abstract—Bidirectional equations for forward and backward waves of intense few-cycle femtosecond pulses are solved numerically for single-mode optical fibre with dispersion and cubic nonlinearity including Raman mechanism. Appearance of a weak backward wave which was absent in the initial distribution is shown. The role of Raman nonlinearity on the amplitude and profile of forward and backward waves is investigated.

Keywords—bidirectional propagation; Raman nonlinearity; few-cycled pulses; femtosecond pulses

I. INTRODUCTION

We consider propagation of intense few-cycle femtosecond optical pulses in telecommunication-type single-mode optical fibres. For simulation of propagation of optical pulses in transparent media approach based on bidirectional propagation equations is used. In our earlier research [1] we described results of bidirectional approach considering only instantaneous cubic nonlinearity of the fibre, and the impact of Raman nonlinearity was beyond consideration. In this paper we show how to include Raman nonlinearity into the model and investigate its effect on forward and backward waves.

II. BIDIRECTIONAL PROPAGATION EQUATIONS

Mathematical model of the process can be represented by the set of bidirectional equations for counter-propagating forward and backward waves [2]. The set is analogous to the full second-order scalar wave equation for the total field. In the spectral domain it can be written in the form:

\[ \partial_z G_\pm = \pm ik(\omega)G_\pm \pm \frac{1}{2}ik(\omega)N_\alpha(E_+ + E_-), \]

where \( z \) is coordinate along the propagation axis, \( E_\pm \) are fields with energy fluxes in forward and backward directions, respectively, and \( G_\pm \) are their spectral densities, \( \omega \) is frequency, \( k(\omega)=\omega n(\omega)/c \) is wavenumber, \( n \) is refractive index, \( c \) is velocity of light, \( N_\alpha \) is nonlinear operator in frequency domain, \( P_{NL} \) is nonlinear response of the medium, \( F \) is Fourier transform.

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

where \( \chi_3^e \) is cubic nonlinear susceptibility related to electronic nonlinearity and \( n_2^e \) in CGS units as \( n_2^e = 3\pi\chi_3^e / n(\omega_0) \), \( R \) is the amplitude of molecular oscillations, \( T_e \) is relaxation time, \( \omega_0 \) is Stokes frequency, coefficient \( \gamma \) relates electronic-vibrational (Raman) cubic susceptibility \( \chi_3^v \) and respective coefficient \( n_2^v \) in the following way: \( n_2^v = 2\pi\gamma\chi_3^v / \omega_0 n(\omega_0) \).

Two main non-resonant nonlinear mechanisms of fused silica for intense femtosecond optical pulses are instantaneous cubic nonlinearity and Raman nonlinearity [3]:

\[
\begin{cases}
P_{NL} = \chi_3^e E^3 + \chi_3^v R E \\
\frac{\partial^2 R}{\partial t^2} + \frac{1}{T_e} \frac{\partial R}{\partial t} + \omega_0^2 R = \gamma E^2
\end{cases}
\]

where \( \chi_3^e \) is cubic nonlinear susceptibility related to electronic nonlinearity, \( n_2^e \) in CGS units as

\( n_2^e = 3\pi\chi_3^e / n(\omega_0) \), \( R \) is the amplitude of molecular oscillations, \( T_e \) is relaxation time, \( \omega_0 \) is Stokes frequency, coefficient \( \gamma \) relates electronic-vibrational (Raman) cubic susceptibility \( \chi_3^v \) and respective coefficient \( n_2^v \) in the following way: \( n_2^v = 2\pi\gamma\chi_3^v / \omega_0 n(\omega_0) \).

III. NUMERICAL RESULTS

Simulation of 50-fs pulse with central wavelength \( \lambda_0 = 1500 \text{ nm} \) propagation over the distance of 100-\( \lambda_0 \) in the fibre with the assumption that the backward wave was absent initially shows that the latter consists of two counter-propagating parts. The third harmonic is generated in both forward and backward waves. Formal addition of Raman nonlinearity gives rise to the total nonlinear response. Backward wave is generated via nonlinearity hence one of the most noticeable effects introduced by such addition is increase in the amplitude of the backward wave. At longer distances the low-frequency part of the spectrum acquires specific modulation due to Raman nonlinearity.

REFERENCES