<table>
<thead>
<tr>
<th>Instructions for use</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of delayed nonlinear response on femtosecond optical pulse compression by use of an organic crystal-cored fiber in the normal dispersion region</td>
<td>Morita, Ryuji; Yamashita, Mikio</td>
</tr>
<tr>
<td>Citation</td>
<td>Optics Letters, 19(18): 1459-1461</td>
</tr>
<tr>
<td>Issue Date</td>
<td>1994-09-15</td>
</tr>
<tr>
<td>Doc URL</td>
<td><a href="http://hdl.handle.net/2115/45325">http://hdl.handle.net/2115/45325</a></td>
</tr>
<tr>
<td>Rights</td>
<td>© 1994 Optical Society of America</td>
</tr>
<tr>
<td>Type</td>
<td>article</td>
</tr>
<tr>
<td>File Information</td>
<td>OL19-18_1459-1461.pdf</td>
</tr>
</tbody>
</table>
Effect of delayed nonlinear response on femtosecond optical pulse compression by use of an organic crystal-cored fiber in the normal dispersion region

Ryuji Morita and Mikio Yamashita

Department of Engineering Science, Hokkaido University, Kita-13, Nishi-6, Kita-ku, Sapporo 060, Japan

Received March 22, 1994

We investigate the effect of delayed nonlinear response on pulse compression, using an organic crystal-cored fiber in the normal dispersion region. With up to third-order phase compensation, a 100-W, 100-fs hyperbolic-sescent pulse is compressed to ~10 fs with a delayed nonlinear response time as well as without it. It is shown that third-order phase adjustment can compensate for the phase asymmetry in the frequency domain that is induced by the effect of the delayed nonlinear response.

Organic materials are attractive for potential applications in electro-optical switching and frequency conversion because of their large optical nonlinearities. Organic materials are also used for optical pulse compression. For example, efficient compression of femtosecond laser pulses by use of a fiber cored with the organic material 4-(N,N-dimethylamino)-3-acetamidonitrobenzene (DAN) was demonstrated.1

Most analyses of pulse compression in the normal dispersion regime are performed without taking into account the delayed nonlinear response, whereas in the soliton-effect compression regime this delayed response is taken into account.2,3 This is because fused-silica fibers are usually utilized for pulse compression, and in many cases their response time, which was evaluated to be 2–4 fs, is much shorter than the input pulse widths. However, when pulse widths are comparable with the response time the nonlinear response time becomes significant.

From our recent experiment on nonlinear femtosecond optical pulse propagation the response time of DAN was evaluated to be several tens of femtoseconds,4 causing us to consider the effect of the response time for femtosecond optical pulse compression with a DAN fiber.

In this Letter we investigate numerically the effect of the delayed nonlinear response time on pulse compression, using a DAN fiber in the normal dispersion region, as well as those of second- and third-order dispersion, self-steepening, initial frequency chirping, and propagation loss.

The modified nonlinear Schrödinger equation that we use here is

\[
\frac{\partial u}{\partial z} + i \frac{\Gamma}{2} u + \frac{\beta_4}{\sigma_1} |u|^2 u - \frac{\delta}{\sigma_4} \frac{\partial^3 u}{\partial r^3} = i \frac{\partial}{\partial r} \left( u J(\tau; \tau_R) + i \frac{\partial}{\partial \tau} \left[ u J(\tau; \tau_R) \right] \right),
\]

(1a)

\[
J(\tau; \tau_R) = \int_0^\infty d\tau' \exp(-\tau'/\tau_R) |u(\tau - \tau')|^2,
\]

(1b)

where \( u \) is the normalized complex amplitude of the pulse envelope and

\[
J(\tau; \tau_R) = \int_0^\infty d\tau' \exp(-\tau'/\tau_R) |u(\tau - \tau')|^2,
\]

(1b)

\[
\xi = |\beta_2 z/T_0^2|, \quad \tau = (t - z/u_0)/T_0,
\]

\[
\delta = \beta_3/6|\beta_2|^2 T_0, \quad \tau_0 = 2/\omega_0 T_0, \quad \tau_R = T_R/T_0,
\]

\[
\Gamma = \alpha L_D/2, \quad L_D = T_0^2/|\beta_2| \quad (\beta_2 > 0).
\]

We investigate numerically the effect of the delayed nonlinear response time on pulse compression, using an organic crystal-cored fiber in the normal dispersion region. With up to third-order phase compensation, a 100-W, 100-fs hyperbolic-sescent pulse is compressed to ~10 fs with a delayed nonlinear response time as well as without it. It is shown that third-order phase adjustment can compensate for the phase asymmetry in the frequency domain that is induced by the effect of the delayed nonlinear response.

\[
\xi = |\beta_2 z/T_0^2|, \quad \tau = (t - z/u_0)/T_0,
\]

\[
\delta = \beta_3/6|\beta_2|^2 T_0, \quad \tau_0 = 2/\omega_0 T_0, \quad \tau_R = T_R/T_0,
\]

\[
\Gamma = \alpha L_D/2, \quad L_D = T_0^2/|\beta_2| \quad (\beta_2 > 0).
\]

z is the distance along the fiber, \( \tau \) is the normalized retarded time measured in a frame of reference moving along the fiber at the group velocity \( v_g \), \( \omega_0 \) is the central frequency, \( T_0 \) is the initial pulse-width parameter [FWHM \( T_p = 2 \ln(1 + \sqrt{2}) T_0 = 1.763 T_0 \)], \( \alpha \) is the propagation loss, and \( \beta_2 \) and \( \beta_3 \) are the second- and third-order dispersions, respectively. The nonlinear refractive index \( n_2 \) is included in the definition of the normalized amplitude \( u \). Here the response function is assumed to be an exponential form specified by a response time \( T_R \) in Eq. (1b), and the instantaneous-response part of the nonlinear refractive index is assumed to be negligible.

If \( T_R \ll T_p \) (i.e., \( \tau_R \ll \tau_p = T_p/T_0 \)), then \( J(\tau; \tau_R) \) can be approximated by the form of the Taylor expansion, and the right-hand side of Eq. (1a) becomes

\[
i \left( u(\tau) \left[ |u(\tau)|^2 - \tau_R \frac{\partial}{\partial \tau} |u(\tau)|^2 + \tau_R^2 \frac{\partial^2}{\partial \tau^2} |u(\tau)|^2 - \ldots \right] + i \frac{\partial}{\partial \tau} \left[ u(\tau) |u(\tau)|^2 - \tau_R u(\tau) \frac{\partial}{\partial \tau} |u(\tau)|^2 + \ldots \right] \right),
\]

(2)

where the first term represents the self-phase modulation, the second term represents the self-frequency shift, and the fourth term represents the self-steepening. This approximated form is usually applied in most analyses of nonlinear pulse propagation; however, this approximation is no longer valid when \( T_R \approx T_p \) or \( T_R > T_p \). Therefore we use Eqs. (1a) and (1b) in our calculation of a DAN fiber, which has a large delayed response time.

The fiber input pulses are assumed to have an amplitude shape given by

\[
u(\xi = 0, \tau) = \text{sech}(\tau) \exp(-iC \tau^2/2),
\]

(3)

where \( C \) is the parameter representing initial linear frequency chirp.
The parameters that we used for a DAN crystal-cored fiber are central wavelength $\lambda_0 = 630$ nm, core diameter $= 2.5 \text{ mm}$, $n_2 = 2.1 \times 10^{-18} \text{ m}^2/\text{W}^2$, $\beta_0 = 1.85 \times 10^{-24} \text{ s}^4/\text{W}$, $\beta_3 = 3.79 \times 10^{-29} \text{ s}^6/\text{W}^3$, $\alpha = 14 \text{ dB/cm} (\delta = 6.0 \times 10^{-3}, \Gamma = 2.8 \times 10^{-1})$, and input pulse width $\Delta t_0 = 100 \text{ fs} (T_0 = 56.7 \text{ fs})$.

After solving relations (1) by using the split-step Fourier method, we carry out the calculation of up to third-order phase compensation for output pulses from fibers to obtain compressed pulses. That is, we determine the compensated phase $\phi_c$ in the frequency domain

$$\phi_c = \phi(\omega) - [a_2(\omega - \omega_0)^2 + a_3(\omega - \omega_0)^3],$$

where $\phi(\omega)$ is the precompensated phase of the fiber output pulses, so that the compensated pulse widths are minimized by the adjustment of parameters $a_2$ and $a_3$. This adjustment is usually performed with prism and grating pairs in a practical experiment.

Table 1 shows the dependence of the compressed pulse width $\Delta t_c$ and the optimum propagation length $z_{opt}$ on the response time $T_R$ and the Chirp Parameter $C$.

<table>
<thead>
<tr>
<th>Compressed Pulse Width $\Delta t_c$ (fs)</th>
<th>Optimum Propagation Length $z_{opt}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t_c$</td>
<td>$z_{opt}$</td>
</tr>
<tr>
<td>$T_R$ (fs)</td>
<td>$T_R$ (fs)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$C$</td>
<td>$C$</td>
</tr>
<tr>
<td>$-2$</td>
<td>$-2$</td>
</tr>
<tr>
<td>$-1$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$+1$</td>
<td>$+1$</td>
</tr>
<tr>
<td>$+2$</td>
<td>$+2$</td>
</tr>
</tbody>
</table>

The parameters that we used for a DAN crystal-cored fiber are central wavelength $\lambda_0 = 630$ nm, core diameter $= 2.5 \text{ mm}$, $n_2 = 2.1 \times 10^{-18} \text{ m}^2/\text{W}^2$, $\beta_0 = 1.85 \times 10^{-24} \text{ s}^4/\text{W}$, $\beta_3 = 3.79 \times 10^{-29} \text{ s}^6/\text{W}^3$, $\alpha = 14 \text{ dB/cm} (\delta = 6.0 \times 10^{-3}, \Gamma = 2.8 \times 10^{-1})$, and input pulse width $\Delta t_0 = 100 \text{ fs} (T_0 = 56.7 \text{ fs})$.

After solving relations (1) by using the split-step Fourier method, we carry out the calculation of up to third-order phase compensation for output pulses from fibers to obtain compressed pulses. That is, we determine the compensated phase $\phi_c$ in the frequency domain

$$\phi_c = \phi(\omega) - [a_2(\omega - \omega_0)^2 + a_3(\omega - \omega_0)^3],$$

where $\phi(\omega)$ is the precompensated phase of the fiber output pulses, so that the compensated pulse widths are minimized by the adjustment of parameters $a_2$ and $a_3$. This adjustment is usually performed with prism and grating pairs in a practical experiment.

Table 1 shows the dependence of the compressed pulse width $\Delta t_c$ and the optimum propagation length $z_{opt}$ on the response time $T_R$ for the DAN crystal-cored fiber (the input peak power $P_0 = 100 \text{ W}$, the input pulse width $\Delta t_0 = 100 \text{ fs}$, and the chirp coefficient $C = 0, \pm 0.4, \pm 1, \pm 2$). It is found that, even with the delayed response, a 100-W 100-fs hyperbolic-secant pulse is compressed to $\sim 10 \text{ fs}$. The same compression is also seen without the delayed response, in the range of $|C| \leq 2$. As Table 1 shows, the optimum propagation lengths $z_{opt}$ are $\sim 0.5 \text{ mm}$, for which the propagation loss is low enough.

Figure 1(a) shows output spectra from the fiber at $T_R = 0$ and 30 fs, along with an input spectrum. The blue-side broadening in the spectrum that is due to self-steepening is clearly seen at $T_R = 0$ fs, whereas the frequency down shift (corresponding to the red shift) occurs as a result of the delayed response effect and suppresses the blue-side broadening at $T_R = 30$ fs. In addition, the effect of third-order dispersion may result in the spectral asymmetry for both $T_R$ values. Figure 1(b) shows one of the typical compressed pulse profiles ($T_R = 30$ fs) with fiber input and output pulses ($T_R = 0$ and 30 fs) in the time domain. The precompensated pulse at $T_R = 30$ fs has a small peak in the leading edge as a result of the delayed response. This behavior is explained as follows: since the red components travel faster than the blue components in the normal dispersion regime, the red shift that is due to the delayed response corresponds to the forming of a small peak in the leading edge in the time domain. The compressed pulse shape is slightly asymmetric, and the compressed pulse quality $Q_c$ (the ratio of compressed pulse energy to precompensated energy) is $\sim 0.73$.

Figure 2 depicts the precompensated phase $\phi(\omega)$ of the fiber output pulse in the frequency domain at $C = 0$ with or without the delayed response ($T_R = 0, 10, 20$, and $30$ fs). It is clearly seen that the shape of $\phi(\omega)$ becomes more asymmetric with increasing $T_R$. Therefore efficient pulse compression with the delayed response requires third-order phase compensation. By sufficient adjustment of third-order phase compensation, pulses are efficiently compressed with the delayed response, as shown in Table 1, confirm-
Fig. 2. Fiber output phase $\phi(\omega)$ in the frequency domain at the optimum propagation lengths $z_{\text{opt}}$. The parameters are $P_0 = 100$ W, $T_{\text{p,in}} = 100$ fs, and $C = 0$.

Fig. 3. Dependence of (a) the compressed pulse width $T_{\text{pc}}$ and (b) the optimum propagation length $z_{\text{opt}}$ (filled circles) and the pulse quality $Q_c$ (open circles) on the input power $P_0$. The parameters are $T_{\text{p,in}} = 100$ fs, $T_R = 0$ fs, and $C = 0$.

The authors are grateful to H. Sone for his help in the computations. This study was partially supported by a Grant-in-Aid for Scientific Research on Priority Areas, Ultrafast and Ultraparallel Optoelectronics from the Ministry of Education, Science and Culture of Japan.

References