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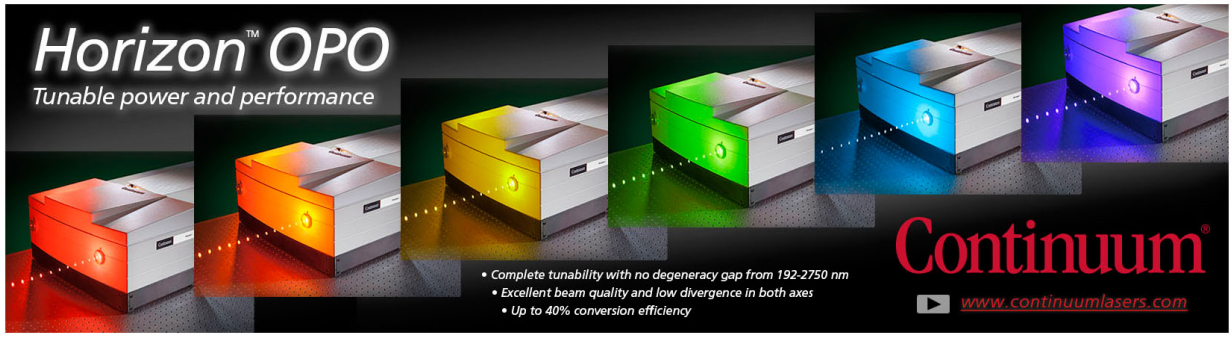

Special narrowing of ultrashort laser pulses by self-phase modulation in optical fibers

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We demonstrate experimentally and theoretically that frequency-modulated femtosecond laser pulses can be spectrally narrowed by self-phase modulation in optical fibers. We obtain a reduction of the spectral linewidth from 10.6 down to 2.7 nm, limited only by the laser power in the fiber. Applications for extracavity conversion of femtosecond lasers to narrow-linewidth picosecond sources are discussed.

Spectral broadening of transform-limited laser pulses through self-phase modulation (SPM) in an optical fiber is a well-known process, and widely applied for optical pulse compression.[1] This effect was used to produce the shortest optical pulses with a duration of 6 fs.[2] If the laser pulse entering the fiber is frequency modulated ("chirped"), the effect of SPM on the spectra and pulse shape will be different for up- and down-chirped pulses. In the latter case the initial frequency modulation should be compensated by the frequency modulation arising from the SPM. This should lead to a narrowing of the spectral width, accompanied by a temporal broadening in comparison to the original transform-limited laser pulse. In this letter we will present experimental evidence and quantitative theoretical explanation for strong spectral narrowing of femtosecond laser pulses from a mode-locked Ti:sapphire laser in a quartz glass fiber.

For our experiments we used a passively mode-locked Ti:sapphire laser, pumped by an argon ion laser, giving a pulse duration of ~ 100 fs (FWHM of sech pulses) around 800 nm and a mean power of up to 2 W (repetition rate 76 MHz). The setup is schematically shown in Fig. 1. The output beam was collimated by two $10\times$ microscope objectives. The spectral narrowing by SPM in the fiber depends on the initial chirp and peak power of the fiber-input pulse as well as the length of the fiber. In order to get the strongest spectral narrowing for our experimental parameters we calculated the necessary frequency modulation of the input pulse, giving a necessary phase shift, as defined in Eq. (2), of about $\phi_2=(1\text{–}15)\times 10^{-26}$ s^2. The necessary frequency modulation was realized by a prism configuration as proposed by Fork *et al.*[3] with SF10 prisms and a distance of $L_P=3$ m, giving a calculated phase shift of $\phi_2=1.2\times 10^{-26}$ s^2. We used two prisms with a mirror (M1) which is slightly tilted so that the reflected beam strikes mirror M2, which is situated about 1 cm above the output beam of the laser. The chirped laser pulses were coupled into a polarization preserving monomode glass fiber with a $10\times$ microscope objective.

We characterize the laser pulses by measuring the spectrum with a CCD spectrometer and the pulse duration with an intensity autocorrelator (AC) using 0.3 mm of KDP. Pulse formation and spectra of the Ti:sapphire laser were not disturbed by the backscattered light of the glass fiber, what was verified by observing the spectrum and autocorrelation of the input pulses during all experiments. After the prism configuration we measured the spectrum to make sure that no spectral filtering had occurred. The frequency modulation caused by the prism configuration was determined by measuring the pulse duration between prism sequence and fiber input. Finally, as shown in Fig. 1, the spectrum and autocorrelation of the fiber output pulses were measured.

For our first experiment we chose a 48-cm-long fiber and varied the intensity in the fiber by attenuating the input beam with neutral density filters. The results are shown in Fig. 2. The bottom curve titled input represents the spectrum after the prism configuration with a spectral width (FWHM) of 10.6 nm. If the power is low enough, one will get quasilinear propagation with no observable spectral changes (Fig. 2, curve $0.003P_{\max}$). As the peak power increases, the spectrum narrows gradually down to 3.1 nm (FWHM). This dependence shows clearly, that *the spectral narrowing is produced by nonlinear interaction in the fiber and is not a spectral filtering effect.* The shape of the spectrum evolves into an asymmetrical one with oscillating features on the short wavelength side. This behavior will be explained later by the cubic phase distortion introduced by the prism configuration.

We measured the output spectra for four different fiber lengths, the results are plotted in Fig. 3. The solid line represents the spectral width (FWHM) according to the theoretical calculations described later, the experimental results are indicated with the symbol ●. The spectral width decreases down to 2.7 nm for a fiber length of 28 cm. For longer fiber lengths the reduction of the linewidth is less pronounced.

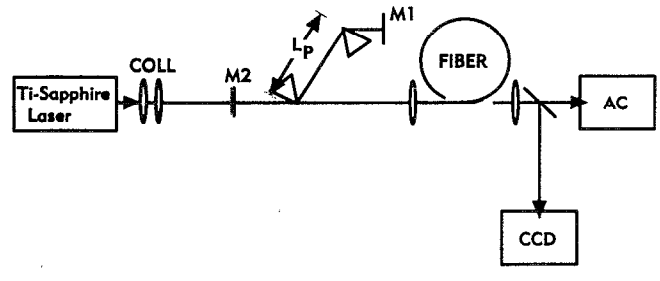

FIG. 1. Schematical experimental arrangement for frequency modulation and subsequent nonlinear fiber propagation of femtosecond laser pulses.

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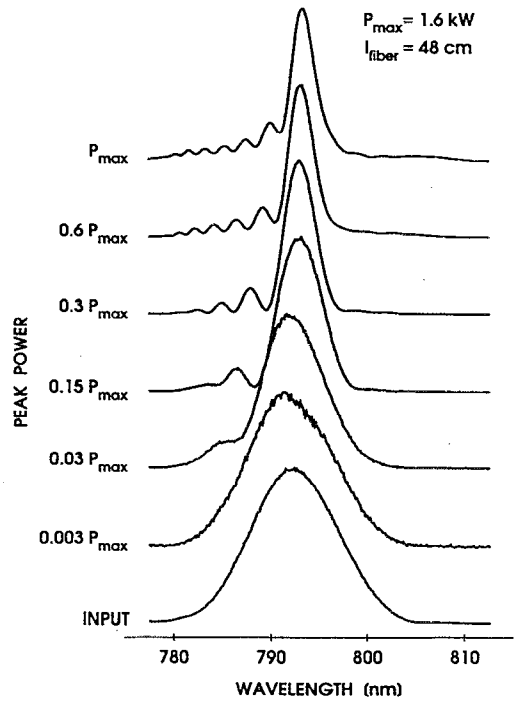

FIG. 2. Experimental spectra for different peak powers in a glass fiber for a constant fiber length of 48 cm.

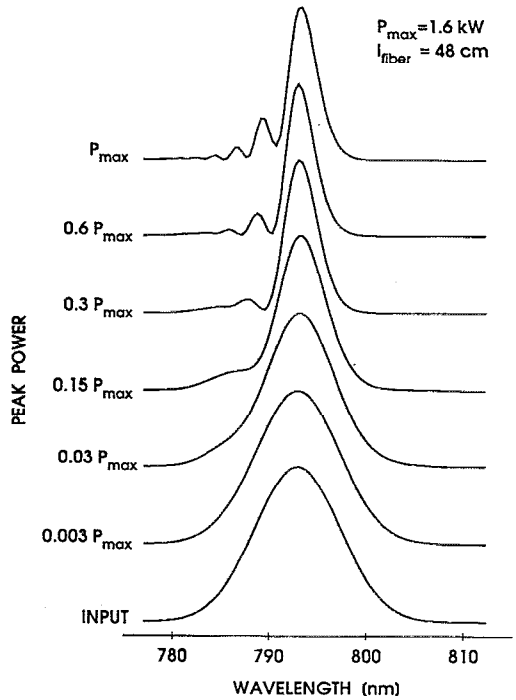

FIG. 4. Theoretical spectra for different peak powers in a glass fiber for a fixed fiber length of 48 cm.

The theory describing nonlinear propagation in a fiber is well known and different solution methods were applied.[4–6] We used the total field formulation in the frequency domain of the nonlinear Schrödinger equation demonstrated by François.[6] The used differential equation is the following:

$$\frac{\partial A(z,\Omega)}{\partial z} \equiv -i\left(\sum_{k=2}^{3} \frac{\Omega^k}{k!}\frac{d^k\beta}{d\omega^k}(\omega_0)\right)A(z,\Omega) - i\left(1+\frac{\Omega}{\omega_0}\right) \times Q_{\mathrm{Kerr}}\mathrm{FT}_{\Omega}[A(z,\tau)\,|A(z,\tau)\,|^2]. \quad (1)$$

$\beta(\omega_0)$ is the absolute value of the wave vector at the center wavelength ω_0, Ω is the frequency difference to ω_0, $A(z,\Omega)$ is the Fourier component of the laser pulse with the electromagnetic field envelope function $A(z,\tau)$ at the frequency $\omega=\Omega+\omega_0$. Q_{Kerr} represents the nonlinear coupling factor[6] and FT stands for Fourier transformation. This method describes the dispersion directly in the frequency domain, but for every integration step the nonlinear interaction is calculated in the time domain and is transformed through fast FT into the frequency domain. In our calculations we took into account chromatic dispersion (second and third order) within the first term in Eq. (1) and the Kerr effect with shock term [second term in Eq. (1)].[6] The third-order dispersion and shock term influence the spectral evolution insignificantly, because we use a maximum fiber length of about 1 m.

The spectral narrowing arises from the phase shift compensation through the SPM caused by the optical Kerr effect. Therefore, it is necessary to describe the fiber input pulse with the envelope function *and* phase of the electromagnetic field. The ratio of second order to third order dispersion $\rho=\phi_2/\phi_3$ was calculated according to Ref. 2, giving $\rho\simeq 8\times10^{-15}$ s. The fiber input pulse is described by

$$A(z=0,\Omega)=\sqrt{I(\Omega)}\,\exp i(\phi_2\Omega^2+\rho\phi_2\Omega^3). \quad (2)$$

The theoretical results for the fiber length of 48 cm are plotted in Fig. 4. The reduction of the spectral linewidth and also the shape of the spectra agree very well with the

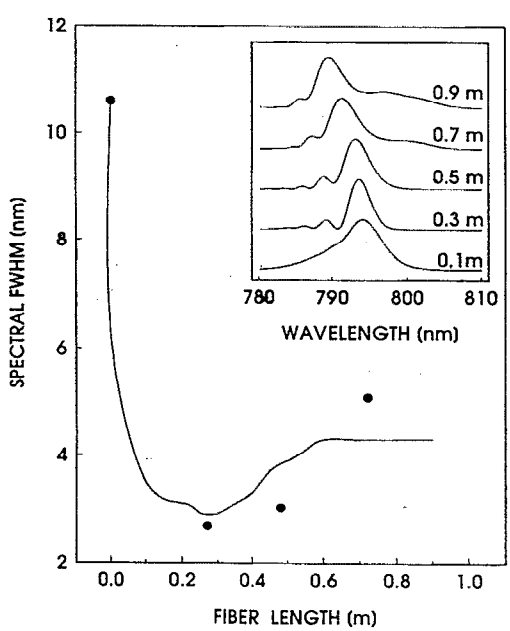

FIG. 3. Spectral width (FWHM) for different fiber lengths with fixed peak power of about 1 kW. Theoretical results are plotted as a solid curve and the experimental data are represented by (●). Insert: calculated spectra for different fiber lengths.

experimentally observed behavior (Fig. 2). The oscillating and asymmetric spectral shape arises from the third-order phase distortion introduced by the prism configuration.[7] Boyer *et al.*[8] calculated the influence of the input pulse shape on the spectral evolution and report similar asymmetric behavior. The theoretical spectral shapes for different fiber lengths are plotted in Fig. 4 (inset), the evolution of a low energy tail can be clearly seen. This is the reason that for fiber lengths above 70 cm the FWHM of the spectra does not increase further, as it is obvious from the theoretical curve in Fig. 3. Both experiment and theory show that there is an optimum fiber length for a given frequency modulation and peak power.

We have calculated the expected spectral width for a realistic achievable power in the fiber of 30% of the laser power and got for a fiber length of 20 cm, an initial frequency modulation of $\phi_2 = 5 \times 10^{-26}$ s^2 and $\phi_3 = 0$ a spectral width of 0.36 nm (!). This corresponds to a transform-limited pulse of a duration of 1.8 ps. The advantage of this method as opposed to spectral filtering[9] is the energy transfer from the short and long wavelengths sides into the center region of the spectra, which results in a higher intensity of the spectrally narrowed pulse. Spectral filtering down to 0.36 nm would lead to an output intensity of less than 4% of the input intensity. The method described in our work is only limited by the efficiency of fiber coupling. Applications are promising especially for the passively mode-locked Ti:sapphire laser system, because the femtosecond version of this system is much simpler and more stable than the picosecond version with complex spectral filtering techniques that allow linewidths below 0.5 nm.

In conclusion, spectral narrowing through SPM of frequency modulated laser pulses has been observed in a single-mode polarization-preserving glass fiber. The calculated spectra are in good agreement with the measured ones. The good agreement leads us to the further conclusion, that the "anomalous spectral narrowing" previously reported[10] is due to the SPM as described here. The results point to a new method to produce picosecond laser pulses with narrow linewidths externally from the easily producable and stable femtosecond laser pulses in Ti:sapphire lasers.

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