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SPECTRAL FILTERING OF PHASE-MODULATED LASER LIGHT; FORMATION OF TUNABLE, SPECTRALLY LIMITED, HIGH-CONTRAST LIGHT PULSES

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Spectral filtering of phase-modulated laser light; formation of tunable, spectrally limited, high-contrast light pulses

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A nonlinear-optics method for controlling the length and frequency of laser pulses is proposed. An implementation is reported. This method can produce high-contrast, tunable, ultrashort light pulses, either single pulses or temporally synchronized pairs.

The nonlinear dependence of the refractive index of a single-mode glass optical fiber on the light intensity, $n(I) = n_0 + n_2 I$ (n_0 is the refractive index in the linear approximation, and n_2 is the nonlinear refractive index), can be exploited to achieve effective control over the frequency-time envelope of laser light. The resulting phase modulation of the light is uniform along the cross section of the laser beam, and the beam remains a spatially single-mode beam.[1]

Laser-pulse compressors have been developed. These compressors make use of a phase self-modulation of the pulses in an optical waveguide and then compress the pulses either in an external dispersive delay line[2,3] or by making use of a negative dispersion of the group velocities of the waveguides themselves at wavelengths[4,5] $\lambda > 1.3\ \mu m$.

In the present letter we wish to propose a method for forming tunable, spectrally limited, ultrashort light pulses on the basis of the spectral filtering of phase-modulated light in an optical waveguide. During the propagation of a laser pulse $I(t)$ along a waveguide of length L, the different parts of the pulse undergo different additional phase shifts:

$$\Delta\Phi(t) = \frac{2\pi}{\lambda}\tilde{n}_2 L I(t)\,. \tag{1}$$

The pulse becomes spectrally broader, and it acquires a frequency modulation[6]

$$\Delta\omega(t) = -\frac{d\Delta\Phi(t)}{dt} = -\frac{2\pi}{\lambda}n_2 L\frac{dI(t)}{dt}\,. \tag{2}$$

It follows from (2) that the maximum frequency shift $\Delta\omega(t)$ in the Stokes and anti-Stokes regions is achieved at the inflection points of the envelope of the pulse $I(t)$ on, respectively, its leading and trailing edges. Furthermore, there is no frequency modulation $[d\Delta\omega(t)/dt = 0]$ at the inflection points of the pulse. The method consists of spectrally selecting the extreme Stokes or anti-Stokes frequency components; this selection should lead to the formation of pulses without a frequency modulation at a frequency shifted from the pump frequency. To determine the optimum parameters of

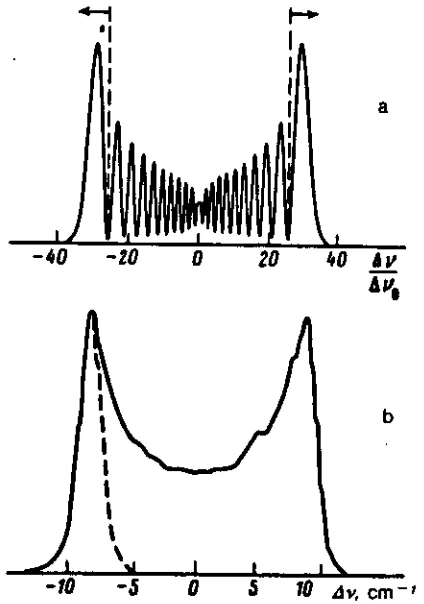

FIG. 1. a—Computer-generated spectrum of a phase-modulated Gaussian pulse for $\Delta\Phi = 66$. The parts of the spectrum selected during the optimum spectral filtering in the Stokes and anti-Stokes regions are shown ($\Delta\nu_0$ is the initial spectral width of the pulse); b—spectrum of the light emerging from the fiber at an input power $P = 20$ kW ($\tau_0 = 50$ ps). The dashed line is the part of the spectrum selected during the spectral filtering.

this spectral filtering, we have carried out numerical simulations of the process. The spectrum of a Gaussian pulse $I(t)$, phase-modulated as in (1), was determined (Fig. 1a). The spectral filter is approximated by a step function; i.e., one part of the spectrum is set equal to zero, and the rest is left unchanged. Inverse Fourier transforms are then calculated; they determine the shape of the pulse after the spectral filtering. Over the entire range of the parameter $\Delta\Phi \equiv \Delta\Phi(0)$, from 5 to 250 in these particular calculations, the optimum selection is the selection of the extreme Stokes (or anti-Stokes) peak in the spectrum (Fig. 1a). In this case, after a spectral filtering, a short, spectrally limited pulse is formed at the leading (or trailing) edge of the original pulse. The power of this new pulse is equal to the power of the original pulse (Fig. 2). When the width of the spectral slit deviates from the optimum, the pulse which is selected becomes broader temporally. A temporal substructure appears in the pulse when the slit is wider, while the pulse remains spectrally limited if the slit is narrower.

The length (τ) of the pulse which is formed in the case of the optimum filtering decreases with increasing $\Delta\Phi$: The values of τ_0/τ are 1.8, 4.7, and 7.5 for $\Delta\Phi$ of 5, 60, and 250, respectively.

The experimental apparatus consists of a cw-pumped Nd:YAG laser with active mode locking and Q switching ($\lambda = 1.064\ \mu m$; $\tau_0 = 50$ ps; the pulse repetition period in the train is 4 ns; and the repetition frequency of the Q-switching trains is 400 Hz). The output from this laser is coupled into a single-mode optical fiber with a length $L = 50$ cm. The spectral filtering is performed by a diffraction grating with 600 lines/mm; this grating resolves the light emerging from the fiber into a spectrum. A right-

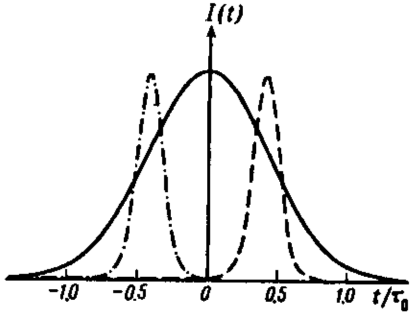

FIG. 2. Solid line—The pulse $I(t)$ before the spectral filtering; dot-dashed line—the Stokes pulse produced during the spectral filtering; dashed line—the anti-Stokes pulse produced during the spectral filtering, for $\Delta\Phi = 66$.

angle prism cap then returns the light to the grating to restore the parallel orientation of the rays in the different spectral components. The spectrum is then selected by a slit. The distortion caused in the shape of the pulse, which is formed by the group-velocity dispersion of the grating-prism system, is negligible. The pulse length is measured by a zero-background autocorrelation method involving second-harmonic generation in a nonlinear crystal.[3] The spectra are measured with a monochromator with a spectral resolution of 1 cm^{-1}. In the spectral and temporal measurements, we use a strobe integrator (the strobe width is 10 ns) to select signals from the maximum of the train of ultrashort pulses. The light power coupled into the fiber in these experiments is $P \leqslant 20$ kW, corresponding to $\Delta\Phi \leqslant 66$ (at a higher pump power, stimulated Raman scattering and stimulated four wave processes would occur in the fiber). The experimental results agree well with theoretical predictions. Figure 1b illustrates the results with the spectrum at the exit from the fiber at $P = 20$ kW. The dashed line shows the part of the spectrum in the Stokes region selected in the spectral filtering. Before the spectral filtering, the pulse length remains constant at $\tau_0 = 50$ ps; after the filtering, a high-contrast pulse with a length $\tau = 10.5$ ps is formed at the Stokes frequency. This pulse length agrees with that calculated for the value $\Delta\Phi = 66$. As predicted theoretically, the pulse which is formed becomes broader as the spectral slit is either increased or reduced from its optimum value. Similar results were found in the formation of pulses in the anti-Stokes region.

For the pulses which are formed, the frequency shift $\Delta\nu$ from the frequency of the original pulse is $\Delta\nu \simeq \frac{1}{2}\Delta\nu_0\Delta\Phi$. Tuning is achieved by varying $\Delta\Phi$, i.e., by varying either the power coupled into the fiber or the length of the fiber. The tuning interval $2\Delta\nu$ for the given length of the input pulse, $\tau_0 \sim 1/\Delta\nu_0$, is limited by the maximum value of $\Delta\Phi$ attainable in the experiments. The maximum attainable value of $\Delta\Phi$—the limitation is imposed by the onset of stimulated Raman scattering—is ~ 60 for quartz fibers (under the assumption that the dispersion of the fiber is slight and that the loss at the Stokes frequency of the stimulated Raman scattering is small). This value is essentially independent of the length of the fiber, the profile of the refractive index in the fiber, and the wavelength of the light.[7] At $\tau_0 = 50$ ps in our experiments, the tuning interval is 20 cm^{-1}, while at $\tau_0 = 5$ ps it is 200 cm^{-1}.

During spectral filtering with a simultaneous selection of the Stokes and anti-Stokes frequency components, Stokes and anti-Stokes pulses are formed at, respectively, the leading and trailing edges of the original pulse (Fig. 2). The method thus makes it possible to form a pair of temporally synchronized ultrashort pulses, and the frequency shift between the pulses is continuously tunable.

The method proposed here can also be used to increase the contrast of the output of mode-locked lasers, since the formation of the pulses occurs at a frequency shifted from the pump frequency, and the background radiation which is characteristic of certain types of these lasers is effectively filtered out.

Finally, we note that in the production of second-harmonic pulses, the role of the spectral slit which selects the spectral components can be played by the width of the phase matching of the second-harmonic crystal. The diffraction grating can therefore be eliminated, so that the experimental implementation of the method can be simplified considerably.

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Plasma-induced broadening of atomic levels of shifted terms lying below the ionization boundary

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The broadening of the levels of shifted terms in the VV and TiIV ions below the ionization boundary has been derived theoretically and observed experimentally in the plasma of a vacuum arc. The results are evidence that a new manifestation of a configurational interaction has been observed in atomic spectra.

The crossing of the $3d^{10}$ ionization boundary by the doubly excited $3d^9 4p^2$ configuration in ions of the copper isoelectronic sequence, BrVII–AsV, was studied in Ref. 1. An autoionization width appeared beyond the ionization boundary for several of the levels, in accordance with the selection rules. It was also found, however, that

