

Spectral windowing of frequency-modulated optical pulses in a grating compressor

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Spectral windowing or apodization of the spatially dispersed frequency components within a grating compressor has been used to control the temporal shape of compressed optical pulses. Windowing of undesirable high and low-frequency components, which are not linearly chirped, results in nearly complete elimination of the energy in the wings of the compressed pulse. We have applied this technique to improve the quality of pulses from a mode-locked neodymium: yttrium aluminum garnet laser compressed to less than 2 ps using a fiber and double-pass grating pair with an internal aperture.

The technique for compression of chirped optical pulses using a grating-pair compressor has enjoyed wide use since the introduction of a single-mode fiber, in the place of bulk Kerr media, to produce the chirp. The guided optical waves propagating in a single-mode fiber experience a uniform self-phase modulation,¹ thus eliminating transverse variations. Fiber group velocity dispersion can, in addition, favorably redistribute² the spectral energy of the self-modulated pulse resulting in efficient compression of the input pulse. This effect occurs for an optimum fiber length³ which depends upon the magnitude of the fiber group velocity dispersion (GVD) and the input pulse length. At the optimum length the GVD has produced a nearly linear chirp over the entire pulse. Unfortunately, at near infrared wavelengths ($< 1.3 \mu\text{m}$) the GVD is small, and practical fiber lengths are necessarily much less than optimum. This leads to deviations from linearity of the chirp and to wings or sidelobes on the compressed pulse.

In this letter we present a purely passive filtering technique that effectively eliminates most of the undesired side lobes and wings while broadening the pulse only slightly. A bonus feature of this technique is that fluctuations can be reduced. Our technique employs spectral windowing of the spatially dispersed frequency components within the grating compressor to manipulate the temporal features of the pulse.⁴ The windowing technique cleans up the pulse structure because most of the deviation from linearity of the chirp occurs near the maximum excursions of the instantaneous frequency.

Our experiments are performed with pulses from a cw mode-locked Nd:YAG laser operating at the fundamental period with second harmonic mode locking, a fiber, and a double-pass grating pair, in a configuration (Fig. 1) similar to that introduced by Johnson *et al.*⁵ We have obtained pulses as short as 60 ps from this laser, but in these experiments feedback effects (no special isolation was employed) limit the pulse width to 80 ps. The pulse train is coupled into a silica core (diameter $7.3 \mu\text{m}$, $n = 0.0054$, 2 dB/km loss) single-mode polarization preserving fiber of approximately 400-m length.⁶ The cladding structure is designed to suppress higher order modes. Our fiber is short compared to the calculated length of 1800 m for optimum compression for 80-ps pulses

of 70-W peak power.³ (For this pulse width stimulated Raman scattering begins to become important in this fiber for peak powers above 90 W.) The self-phase modulated output pulse diffracts off of a grating (1200/mm), and is reflected back to a different location on the same grating from mirror pair M_1 - M_2 . The mirror M provides for a double pass through the pair. The spatial dispersion of the spectrum is maximum at mirror M , and it is here that a variable aperture window is placed. The fiber output spot is imaged by lens L onto the plane at mirror M , producing the least smearing of the spatial resolution by the finite beam diameter. The second pass through the grating pair yields a collimated beam without spectral spreading and twice the dispersive delay of a single pass.

The compressed pulse widths we obtain without windowing typically range between 1 and 3 ps depending upon the peak power in the fiber. These results are in reasonable agreement with the expected pulse width³ for a fiber short enough that fiber group velocity dispersion is negligible and are similar to the results reported by Kafka *et al.*⁷ A total measured compressor path length of 3 m was required to optimally compress the pulses with approximately 70-W

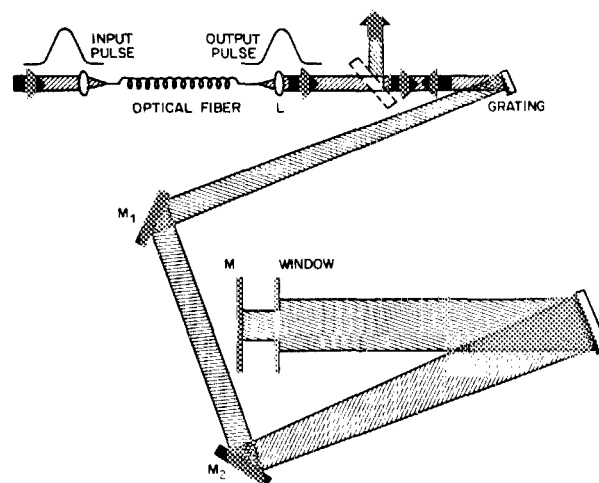


FIG. 1. Experimental arrangement for spectral windowing of compressed pulses. An adjustable width opaque window is inserted at the return mirror M , which is also the focal plane of lens L .

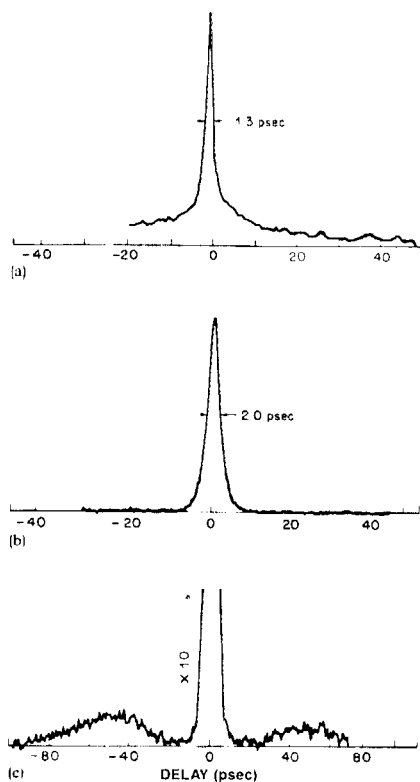


FIG. 2. Experimental autocorrelation traces of compressed 80-ps 1.06- μ m pulses. (a) Without windowing. (b) With spectral windowing. The reduction in energy in the wings is evident. (c) Extended view of (b) with vertical sensitivity $\times 10$ and wider time scale.

peak fiber power, in good agreement with the expected length.³

We present in Fig. 2(a) an autocorrelation obtained without spectral windowing. While the deconvolved pulse width of 1.3-ps FWHM (hyperbolic secant squared) is impressive, it should be noted that the wings of the pulse are extensive, extending over the entire input pulse width. The wings are a consequence of the fact that the linearly chirped portion of the pulse does not extend over the entire pulse width. The details of the sidelobe structure and wings are observed to vary dramatically with fractional changes of the compressor delay line length. The sidelobes and wings never disappear although the sidelobes in Fig. 2(a) have been experimentally minimized.

Figure 3(a) shows a compressed pulse intensity profile calculated for a hyperbolic secant amplitude profile, zero group velocity dispersion, and a quadratic compressor, using the method described in Ref. 3. This profile was chosen because it is representative of our experimental pulse shapes.

In order to demonstrate the spectral windowing technique we blocked the upper and lower frequency extremes of the spectrum of a compressed pulse similar to Fig. 2(a) with an aperture of variable width. While monitoring the compressed pulse width on a real-time autocorrelator, we simultaneously monitored the apertured spectrum with a scanning diode array mounted just behind the return mirror in the grating compressor. As the spectrum is narrowed, a reduction in the sidelobe strength relative to the peak becomes evident. Further narrowing of the spectrum dramatically eliminates the sidelobes. At this point pulse broadening

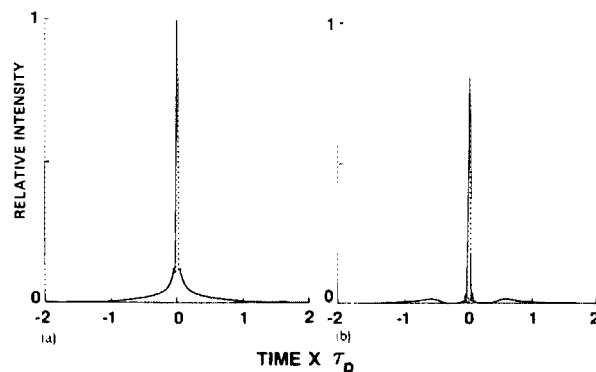


FIG. 3. Calculated compressed pulse intensity profiles. The time scale is normalized with respect to the input pulse FWHM, (a) Without windowing; (b) with windowing. Reduction in energy in the wings is effective out to approximately the input pulse half-width.

starts to become evident and the autocorrelation peak reduces in amplitude. Finally, as the window severely restricts the bandwidth the pulses broaden and lose energy as more spectral content is blocked. The suppression of the sidelobes is accompanied by a reduction in fluctuation of the autocorrelation amplitude from as much as 30% to less than 10%. This observation is in qualitative agreement with the numerical calculations, which indicate that the sidelobe structure of the compressed pulses is sensitive to fluctuations in the input pulse parameters.

In order to accurately record the pulse autocorrelations and to monitor the vanishing sidelobes and wings, we employed a stepper motor driven delay line with chopper and lock-in amplifier. Each of Figs. 2(a)–2(c) was recorded with this setup; special care was taken to establish true zero base lines. Figure 2(b) displays an autocorrelation of a spectrally windowed pulse experimentally optimized for greatest sidelobe reduction consistent with minimum pulse broadening. In this measurement the sidelobes were reduced to less than 0.1% of the peak height of the autocorrelation while the pulse width was broadened by only 50%. A typical spectrum was reduced in width from 26 to 18 Å while progressing from an unwindowed to a windowed pulse as in Figs. 2(a) and 2(b). The average power is typically reduced by a factor of 2. For this case, much of the loss comes from the sidelobes and wings.

Figure 3(b) displays a calculated pulse shape including the influence of spectral windowing. We modeled the filtering effect of the window by attenuating the highest and lowest frequency components of the calculated power spectrum of a self-phase modulated pulse. The quadratic compressor then compensates the region of linear chirp, producing the compressed, windowed pulse spectrum from which the pulse temporal profile is calculated. We employ a rectangular window with error function edges in order to model the finite spatial extent of the beam diameter. High spectral resolution requires that the beam diameter be much less than the spatial extent of the spectrum. In our experiments the beam diameter is approximately one-tenth of the spectral spreading. Note that our calculation ignores diffraction effects which will ultimately place limits on the type of temporal shaping that may be realized.

The reduction in energy in the near wings and sidelobes

is evident for both experiment and calculation. Note the appearance of sidelobes which peak in amplitude approximately one input pulse width away from the compressed pulse. These sidelobes are also observed experimentally as shown in Fig. 2(c) where the vertical scale is ten times more sensitive than in 2(b) and the time scan is doubled. The lobes peak 50 ps ahead and behind the pulse with an amplitude of 1.5% of the autocorrelation peak. We emphasize that these lobes are not caused by the presence of the window but rather are present in the leading and trailing edges of the input pulse where self-phase modulation is negligible. A slight peak at the center of the self-phase modulated spectrum, at the optical carrier frequency, is a result of this effect. These frequency components are not accessible to external windowing. In a preliminary experiment, we have flattened the spectrum at the optical frequency with a thin fiber (thickness 250 μm) placed in the center of the windowed spectrum. This strategy eliminated the far out lobes, but at the cost of some pulse broadening.

We anticipate that spectral windowing will be useful for elimination of sidelobes and wings of compressed pulses also in cases where group velocity dispersion is large enough to

allow one to realize the optimum fiber length. These results are tantalizing indication of the possibilities for shaping of initially frequency chirped pulses with spatial apodization in a grating compressor.

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Array mode selection utilizing an external cavity configuration

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We report operation of a ten-stripe, gain-guided, phase-locked diode laser in an external cavity configuration. The laser radiates in a single narrow (1°) lobe. Such lasers generally lase in the highest order array mode, $L = 10$, which radiates in a twin-lobe far-field pattern. With one antireflection-coated facet and a slit spatial filter, the laser has been operated in the $L = 1, 2, 3$ or 10 array modes. A theoretical explanation of the spatial filter function is included.

We report pulsed operation (200 ns at 1 kHz) of a gain-guided, phase-locked semiconductor laser array in an external cavity which radiates into a single-lobe far-field pattern. Lasers of this type without antireflection (AR) coated facets generally operate in the highest order array mode, with a twin-lobe far-field pattern.¹ That array mode has the lowest threshold gain and therefore lases preferentially.^{2,3} By antireflection coating the front diode laser facet and placing the laser in an external cavity with a suitable spatial filter, we were able to reduce the $L = 1$ array mode threshold relative to the other array modes so as to favor its operation. Moreover, adjustments to the cavity-spatial filter geometry permitted observation of several other array modes. Similar results obtained with an external grating have been reported previously.⁴

The laser employed in the experiment was a standard

multi-quantum well (MQW), ten-stripe, gain-guided array⁵ with a high reflectivity rear facet coating exceeding 90% and an Al_2O_3 quarter-wavelength AR front facet coating. The facet-coated laser threshold was measured to be ≈ 370 mA although the onset of lasing was so gradual that the threshold was difficult to define. Such lasers without AR coatings have approximately 200 mA thresholds and, as noted above, lase in the $L = 10$ array mode, which emits a dual far-field lobe.⁵ The device under study was placed in the external cavity illustrated in Fig. 1(a). The spatial filter is shown in Fig. 1(b), where we observe that both the slit width s and the position of its upper edge are adjustable. The latter adjustment permits intercepting any desired fraction of the laser beam. The laser is positioned with its AR-coated facet very close to the rear focal point of the lens. The partially reflecting mirror is adjusted angularly and longitudinally while observing near-field and far-field patterns of the laser chip on TV monitors. The amount of optical feedback from the