

Compression of optical pulses spectrally broadened by self-phase modulation with a fiber Bragg grating in transmission

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We demonstrate experimentally the compression of optical pulses, spectrally broadened by self-phase modulation occurring in the rod of a mode-locked *Q*-switched YLF laser, with an unchirped, apodized fiber Bragg grating in transmission. The compression is due to the strong dispersion of the Bragg grating at frequencies close to the edge of the photonic bandgap, in the passband, where the transmission is high. With the systems investigated, an 80-ps pulse, which is spectrally broadened, owing to self-phase modulation, with a peak nonlinear phase shift of $\Delta\Phi = 7$, is compressed to approximately 15 ps, in good agreement with theory and numerical simulations. The results demonstrate that photonic bandgap structures are promising devices for efficient pulse compression. © 1998 Optical Society of America

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1. Introduction

Pulse propagation through periodic media such as photonic bandgap structures has attracted much attention, owing to the enormous dispersion that exists in and around the stop band.^{1–5} In the case of one-dimensional photonic crystals, such as fiber Bragg gratings, the dispersion can be 5–6 orders of magnitude larger than the dispersion of standard fiber, thus providing for pulse-chirp compensation and pulse compression over short distances. Dispersion in a fiber grating exists both in reflection—inside the stop band, particularly when the Bragg wavelength is made to vary with axial position, along the length of the grating^{2,3}—and in transmission—in the pass band, owing to the strong frequency dependence of the group velocity of light propagating through the grating.^{4,5} Chirped Bragg gratings, which operate in reflection, have become promising candidates for dispersion-compensating devices in wavelength-division-multiplexing optical-fiber networks. How-

ever, they suffer the drawback of requiring a circulator or a 3-dB coupler in order to retrieve the reflected signal, which can be undesirable for many applications. In transmission, however, the requirement for an optical circulator or 3-dB coupler is avoided. Experimental results on using a fiber grating in transmission for dispersion compensation of a 10 Gbit s⁻¹ signal over a 100-km fiber link have been reported.⁶ Subsequent analysis has shown that by careful arrangement of the grating parameters, namely, by apodizing the profile of the grating and by increasing the length and strength of the grating, it is possible to achieve almost perfect recompression of dispersed optical pulses.⁵

There has also been interest in using fiber Bragg gratings for the compression of pulses spectrally broadened by self-phase modulation (SPM). In this scheme a transform-limited pulse propagated through a nonlinear medium is spectrally broadened and acquires a frequency sweep, owing to SPM. A dispersion-compensating element, such as a diffraction grating pair or a prism pair, can then be used to compress the pulse, resulting in a shorter transform-limited pulse.⁷ In an experiment by Williams *et al.*, a 2-ps pulse was spectrally broadened by transmission through a length of fiber and was subsequently compressed by a factor of 10, on reflection off a chirped fiber grating.⁸ To avoid the losses associated with the use of a circulator, a transmission device would be desirable in this case. In an earlier paper Peter *et al.* considered using a uniform Bragg

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grating in transmission for compressing pulses spectrally broadened by SPM; however, they concluded that the maximum achievable compression is of order 2 (Ref. 9). Typically, the nonlinear element is a length of fiber; however, in many cases spectral broadening can occur in a laser cavity, owing to the high peak intensities achieved in the cavity combined with the multiple round trips. In this case the pulse acquires a nonlinear phase shift in the laser cavity and thus is inherently chirped.

In this paper we demonstrate experimentally the compression of spectrally broadened 80-ps pulses, generated by a mode-locked Q -switched YLF laser, down to approximately 15 ps, with an unchirped (apodized) Bragg grating operating in transmission. The compression factor of 5 is in good agreement with theory and with numerical simulations and is close to the compression that could have been achieved with an ideal compressor. More generally, we show, in contrast to the results of Peter *et al.*,⁹ that a suitably unchirped (apodized) Bragg grating can compress spectrally broadened pulses by much greater than 2 and that the compression ratio, for a given nonlinear phase shift, is limited only by the strength and length of the grating. In the present experiments the spectral broadening occurs as a result of SPM in the rod of the mode-locked Q -switched YLF laser, where the peak nonlinear phase shift can be as large as $\Delta\Phi = 7$. A one-dimensional photonic crystal, such as a fiber grating operating in transmission, may serve as an efficient scheme for producing shorter pulses from such systems. The paper is organized as follows: In Section 2 we present a simple analytic model for the compression of spectrally broadened pulses by transmission through an unchirped (apodized) Bragg grating. In Section 3 we describe the details of the experiment and present experimental results for compressing spectrally broadened pulses. Finally, we conclude with some general considerations of using photonic bandgap structures for efficient pulse compression.

2. Analysis

The key to this compression scheme is that an intense pulse propagating through a nonlinear medium spectrally broadens and acquires a frequency sweep. In contrast to the chirp acquired by a linear pulse propagating in a dispersive medium, the chirp is intensity dependent and is approximately linear only over the central portion of the pulse. In spite of the nonlinear chirp, the spectrally broadened pulse can be compressed with a dispersive element, which exhibits negative dispersion.⁷ The compression is not perfect, owing to the residual noncompressible nonlinear chirp. The chirp can be linearized through normal dispersion, which can be provided by an optical fiber⁷ or, as was proposed by Lenz *et al.*, through the use of an apodized Bragg grating.¹⁰ Here we are concerned with the second part of the compressor, and we emphasize that the propagation through the Bragg grating is linear. The Bragg grating possesses strong dispersion at frequencies close to the

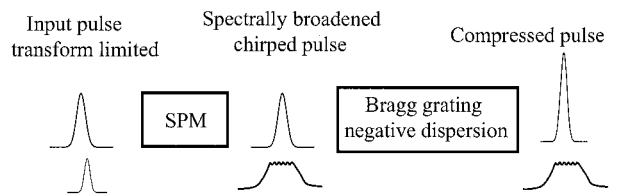


Fig. 1. Schematic diagram of compressor. The first section (SPM) is for bandwidth generation, and the second section (Bragg grating) is for chirp compensation.

edge of the photonic bandgap, in the passband where the transmission is high, thus allowing for efficient pulse compression of chirped optical pulses in short distances. This is illustrated schematically in Fig. 1; note that the spectral width of the pulse is increased in the nonlinear medium, and thus the chirp compensation results in a compressed pulse, which is shorter than the original pulse.

Consider a transform-limited Gaussian pulse with a $(1/e)$ half-width of T_0 , which is chirped by SPM, and let $\Delta\Phi = (2\pi/\lambda) n_2 IL$ denote the peak SPM-induced phase shift, where λ is the free-space wavelength, n_2 is the Kerr coefficient, I is the peak intensity of the pulse, and L is the optical path length. With a derivation similar to that outlined in Refs. 9 and 11, the necessary dispersion for optimum pulse compression can be shown to be given by

$$|\beta_2|z \approx \frac{T_0^2}{2\Delta\Phi}, \quad (1)$$

where β_2 is the value of the group-velocity dispersion in units of $\text{ps}^2 \text{cm}^{-1}$ and z is the length of the dispersion-compensating element in centimeters. For large nonlinear phase shifts ($\Delta\Phi > 2$), the resulting compression ratio can then be approximated by¹¹

$$Q = T_0/T_c \approx 0.75\Delta\Phi, \quad (2)$$

where T_c is the duration ($1/e$ half-width) of the compressed pulse. Ultimately, the degree of compression is limited by the bandwidth over which the dispersion is constant. If we assume that the dispersion of the compressor is constant over the bandwidth of the spectrally broadened pulse ($\Delta\omega_s = 1/T_c$), then it is trivial to show that the compression factor is determined only by the dispersive properties of the grating and is given by

$$Q \approx 2|\beta_2|z\Delta\omega_s^2. \quad (3)$$

Note however that for $\Delta\Phi \geq 3/2\pi$ zeros are introduced in the spectrum,¹¹ which cannot be restored by any linear system.

In a Bragg grating the dispersion bandwidth is usually of the order of the stop band of the grating. The limiting factor is the significant higher-order dispersion close to the edges of the stop band. In the case of an apodized fiber grating it was shown previ-

ously^{5,10} that the quadratic dispersion can be well approximated by

$$\beta_2 = -\left(\frac{n}{c}\right)^2 \frac{1}{\delta} \frac{(\kappa/\delta)^2}{\left[1 - \left(\frac{\kappa}{\delta}\right)^2\right]^{3/2}}, \quad (4)$$

where n is the refractive index; c is the speed of light; and $\kappa = \pi\Delta n\eta/\lambda_B$ is the coupling coefficient with Δn the index modulation, η the fraction of energy in the core, and λ_B the Bragg wavelength. Here $\delta = (n/c)(\omega - \omega_B)$ is the detuning parameter, where ω_B is the Bragg frequency: The wavelength detuning from the center of the stop band is then given by $\Delta\lambda = -(\lambda_B^2/2\pi n)\delta$. Note that the sign of the dispersion depends on the side of the stop band; in this case we are interested in the frequency range above the photonic bandgap ($\delta > \kappa$), where the dispersion is negative (anomalous dispersion). The third-order dispersion can be similarly written^{5,10}:

$$\beta_3 = 3\left(\frac{n}{c}\right)^3 \frac{1}{\delta^2} \frac{(\kappa/\delta)^2}{\left[1 - \left(\frac{\kappa}{\delta}\right)^2\right]^{5/2}}, \quad (5)$$

which is the key parameter in ensuring efficient compression. Third-order dispersion results in asymmetry in the compressed pulse and energy in the trailing edge, which is clearly undesirable and thus limits the bandwidth ($\Delta\omega_s$) over which the dispersion can be assumed to be constant. Thus the cubic dispersion ultimately limits the compression factor given by Eq. (3). We thus compare the relative importance of the second- and third-order terms, arriving at a figure of merit,^{5,10}

$$M = \frac{\beta_3\Delta\omega_s}{\beta_2} = 3\Delta\omega_s \frac{n}{c} \frac{1}{|\delta|} \frac{1}{1 - (\kappa/\delta)^2}. \quad (6)$$

We now look at parameters required for pulse compression of a spectrally broadened pulse with an apodized (unchirped) fiber grating. Consider a 80-ps (FWHM), giving $T_0 = 48$ ps, transform-limited Gaussian pulse, spectrally broadened by propagation through a nonlinear media, with a maximum nonlinear phase shift of $\Delta\Phi = 7$. From Eq. (2) we would expect a compression factor of $Q = 5.25$, limited by residual nonlinear chirp and by the higher-order dispersion of the grating. Consider also a grating in which $\kappa = 21.5 \text{ cm}^{-1}$, with a total length of 6.5 cm, which corresponds to the strength of the grating described in Section 3. The grating is also suitably apodized to reduce out-of-band reflections; the effective length of each of the apodized regions is approximately 0.75 cm, and thus the length of uniform grating is 5.0 cm. Implicit in this model is the assumption that the apodized regions of the grating are sufficiently small to be ignored. The apodization profile used in the numerical simulations and in the experiments described in Section 3 is a raised cosine profile, which is typical of profiles used in designing gratings for wavelength-division-multiplexing light-

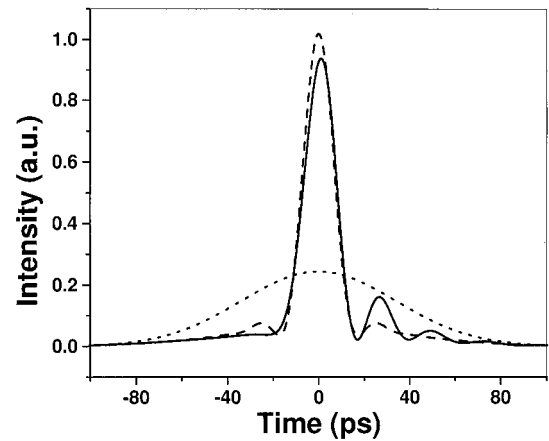


Fig. 2. Pulse compression according to numerical simulation of coupled-mode equations. Grating parameters: $\kappa = 21.5 \text{ cm}^{-1}$ and $L = 5 \text{ cm}$ (apodized). Short-dashed curve, spectrally broadened input pulse (FWHM = 80 ps, $\Delta\Phi = 7$, $\delta = 39 \text{ cm}^{-1}$, $\Delta\lambda = -0.47 \text{ nm}$); solid curve, pulse compressed by the grating; dashed curve, pulse compressed by the ideal compressor, with only quadratic dispersion.

wave applications.¹² Recently, Sipe *et al.*¹² showed that the dispersion of a Bragg grating operating in transmission depends on the integrated properties of the grating profile, and thus the details of the apodization profile are not important. Using Eq. (1) and given the length of the grating, we determine that the dispersion of the grating should be $\beta_2 = -33 \text{ ps}^2 \text{ cm}^{-1}$. We can now solve Eq. (4) to find the detuning parameter that gives maximum compression, giving $\delta = 39.0 \text{ cm}^{-1}$ ($\Delta\lambda = -0.47 \text{ nm}$).

Figure 2 shows the numerically simulated compression for the above example; the short-dashed curve shows the input spectrally broadened pulse (FWHM = 80 ps), and the solid curve shows the pulse on transmission through the grating. The transmitted pulse is compressed to a FWHM of approximately 15 ps, representing a compression factor of $Q \cong 5.2$, in good agreement with that predicted from Eq. (2). Note the structure on the trailing edge of the compressed pulse, which contains approximately 10%–15% of the total pulse energy. It is not surprising that the compression is not perfect, because in this example the figure of merit, given by Eq. (6), is $M \cong 0.35$, and thus the third-order dispersion is significant.^{5,10} In previous papers it was shown that a reasonable value of M , to minimize the effects of third-order dispersion, was $M < 0.1$, which can be achieved by means of making the grating stronger or longer.^{5,10} The dashed curve in Fig. 2 shows the calculated compressed pulse obtained by assuming only quadratic dispersion in the compressor. Note that the pulse is not entirely compressed, even in the case of the ideal quadratic compressor, owing to the nonlinear nature of the chirp associated with SPM.

3. Experiment

The experimental setup is shown in Fig. 3. The light source was an actively mode-locked YLF laser oper-

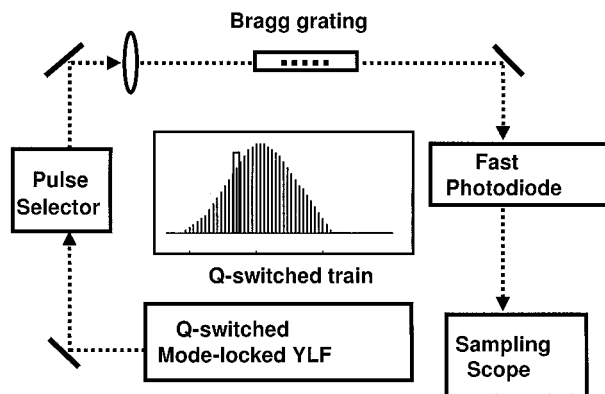


Fig. 3. Experimental setup. The inset shows the mode-locked pulse train, in the Q -switched envelope, consisting of approximately 100 mode-locked pulses.

ating at 1052.6 nm. With continuous-wave mode-locking the laser produced 80 ps approximately Gaussian transform-limited pulses, with a bandwidth of 0.02 nm, at a repetition rate of 82 MHz. This laser was used in recent experiments in which high peak intensities of order ($\sim 10 \text{ GW cm}^{-2}$) were coupled into fiber gratings.¹³ We achieved the high intensities by simultaneously Q -switching the laser at 500 Hz.¹⁴ Under these operating conditions, every 2 ms the laser emits a train of approximately 100 mode-locked pulses, whose peak power varies between zero and 1 MW. To avoid thermal effects in the nonlinear grating experiments, an electro-optic pulse picker was used to select one pulse in each train of mode-locked pulses, within the Q -switched envelope (see Fig. 3).

In addition to minimizing the thermal effects in these experiments,¹³ we selected a pulse in the leading edge of the Q -switched envelope. This was motivated by our observation that pulses close to the peak of the Q -switched envelope were significantly chirped as a result of SPM occurring in the laser rod and in intracavity glass elements; similar observations were reported in Ref. 15. By selecting an appropriate pulse in the train, we were able to maximize the intensity in the grating but avoid nonlinear effects occurring in the YLF laser, which result in spectral broadening. Here, however, we are interested in exploiting the large chirp for pulses near the peak of the Q -switched envelope to achieve pulse compression with a Bragg grating.

We can determine the amount of spectral broadening in the YLF rod on the basis of estimates of all the relevant parameters. At the peak of the Q -switched envelope the energy per pulse is measured to be 100 μJ . For pulsewidths of 100 ps this corresponds to peak powers of 1 MW, and, given that the output coupler of the YLF cavity has a reflectivity of 80%, the peak power in the cavity is 5 MW. The beam diameter is approximately 1 mm at the rod, and thus the peak intensity in the YLF rod is $\sim 0.6 \text{ GW cm}^{-2}$. To determine the actual nonlinear phase shift, we must include the multiple round trips in the cavity. A

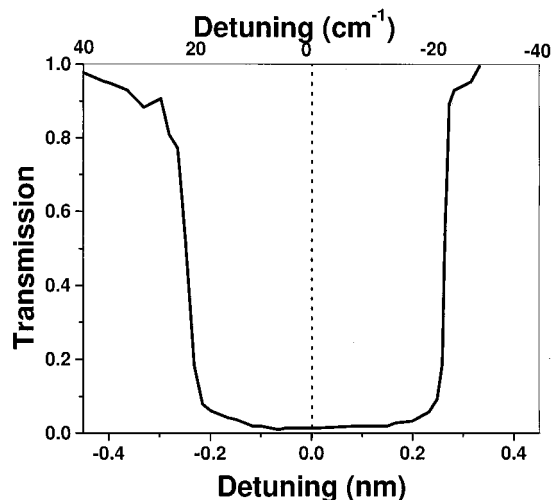


Fig. 4. Measured transmission spectrum of apodized Bragg grating as a function of wavelength (bottom axis) and detuning (top axis).

pulse at the peak of the Q -switched envelope has undergone roughly 50 round trips. Given that the YLF rod is 20 cm in length, the effective path length is approximately 20 m. If we assume that the nonlinear refractive index of YLF is approximately $1.0 \times 10^{-16} \text{ cm}^2 \text{ W}^{-1}$ (Ref. 15), the nonlinear phase shift that is due to spectral broadening in the YLF rod is estimated to be $\Delta\Phi = 7$, which is consistent with that reported in Ref. 15. Here we neglect the effect of SPM that occurs in other optical components (which are shorter than the YLF rod) in the laser cavity, where the beam diameter is larger. The pulse generated by the laser, under these conditions, is thus equivalent to a transform-limited 80-ps (FWHM) pulse propagated through a nonlinear medium with a peak nonlinear phase shift of $\Delta\Phi = 7$; the analysis in Section 2 thus applies.

The grating, which was fabricated with the phase-mask scanning technique,¹⁶ was mounted on a precision translation stage, which allowed tuning of the central wavelength, with respect to the fixed wavelength of the YLF laser. The transmission spectrum of the grating, as a function of detuning from the center of the stop band, is shown in Fig. 4; it is approximately 0.50 nm wide, corresponding to $\kappa = 21.5 \text{ cm}^{-1}$, with a total length of 6.5 cm, including 0.75-cm apodized regions on each end of the grating. The uniform region of the grating is thus 5 cm long. As mentioned above, the apodization ensures efficient coupling into the grating and removes oscillations in the grating dispersion associated with grating end reflections.⁵ The length of fiber before the grating was less than 2 cm, thus ensuring negligible SPM in the pigtail.

The peak intensity of light in the core of the fiber for these experiments was kept below 0.1 GW cm^{-2} (corresponding to a negligible $\Delta\Phi \sim 0.01$ in the grating) to avoid any nonlinear effects occurring in the grating. The optical pulses were coupled into the

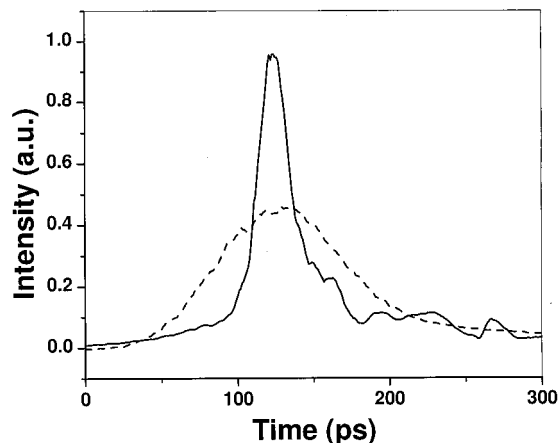


Fig. 5. Experimentally measured transmitted intensity as a function of time. Dashed curve, spectrally broadened input pulse (FWHM = 80 ps, $\Delta\Phi = 7$, $\Delta\lambda = -0.45$ nm); solid curve, compressed pulse.

fiber grating with a $10\times$ objective, and the emerging light was then recollimated and detected with a fast photodiode and a sampling scope with a net resolution of 20 ps.

Figure 5 shows a typical result of the compression with the apodized fiber grating. In this example we estimate that the nonlinear phase shift is $\Delta\Phi = 7$, corresponding to a pulse close to the peak of the Q -switched envelope, and the detuning of the input pulse is adjusted to maximize the compression, where the detuning is $\Delta\lambda = -0.45$ nm ($\delta = 38$ cm $^{-1}$), corresponding approximately to the parameters in Fig. 2. The dashed curve represents the input pulse, with a FWHM of 80 ps, and the solid curve represents the compressed pulse, with a measured FWHM of 25 ps. Since the detection system has a total response time of 20 ps, we conclude that the compressed pulsewidth is approximately 15 ps, thus representing a compression factor of greater than 5. Comparing

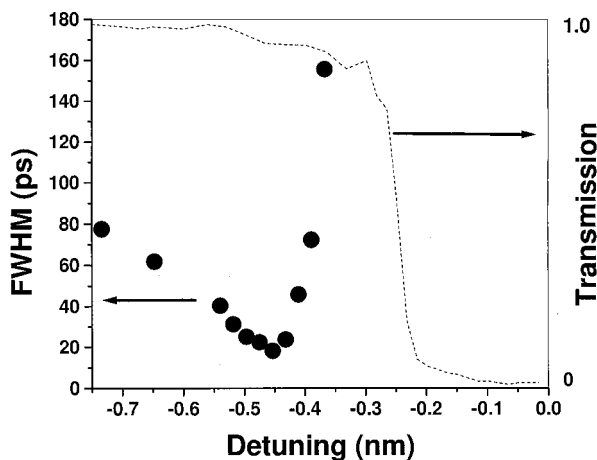


Fig. 6. Deconvolved pulsewidth (FWHM) of transmitted pulse as a function of wavelength detuning ($\Delta\lambda$). Transmission spectrum of apodized Bragg grating is superimposed.

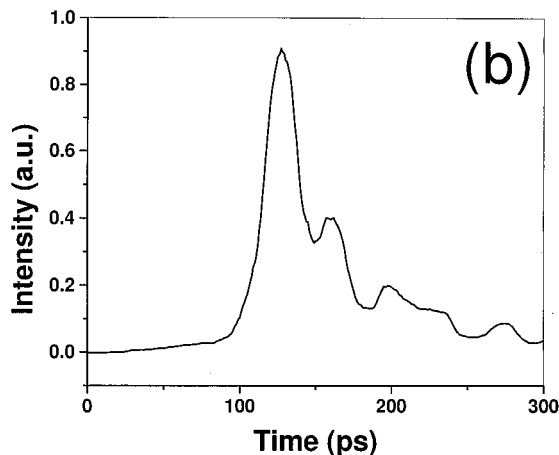
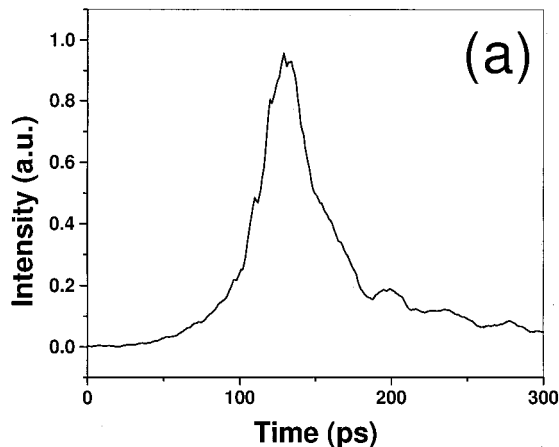


Fig. 7. Transmitted intensities for detunings of (a) $\Delta\lambda = -0.54$ nm and (b) $\Delta\lambda = -0.41$ nm.

Fig. 5 with Fig. 2, we note that the agreement is quite good. In fact the compression ratio predicted from theory and numerics is $Q \cong 5.25$, which is in good agreement with that of the experiment. Note that there is some structure on the trailing edge containing approximately 15%–20% of the total pulse energy. This is clearly associated with higher-order dispersion in the grating and the nonlinear chirp. We note that there is little spectral truncation owing to spectral overlap of the spectrally broadened pulse with the grating spectrum, and in fact the transmission for the pulse is greater than 95%, owing to the apodization. This is determined by measurement of the transmitted power versus detuning, for the nonlinear phase shift of $\Delta\Phi = 7$, and of the detuning of $\Delta\lambda = -0.45$ nm.

Figure 6 shows the measured deconvolved pulsewidth (FWHM), for a fixed nonlinear phase shift of $\Delta\Phi = 7$, as we vary the strain on the grating, which effectively corresponds to changing the detuning of the input pulse. At detunings far from the stop band, the dispersion is small and the pulse shape is mostly unaffected. The transmitted pulse reaches a minimum pulsewidth for a detuning of $\Delta\lambda = -0.45$ nm ($\delta = 38$ cm $^{-1}$), which corresponds to the case shown in Fig. 5. Close to the stop band, the disper-

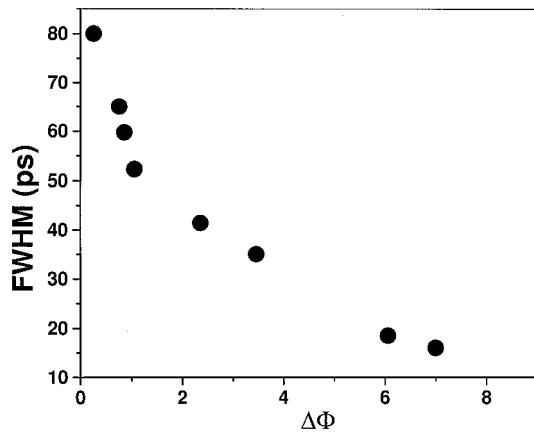


Fig. 8. Deconvolved pulsewidth (FWHM) of transmitted pulse as a function of nonlinear phase shift ($\Delta\Phi$).

sion is too large to recompress the spectrally broadened pulse and higher-order dispersion becomes significant. Figures 7(a) and 7(b) shows the transmitted intensity for detunings of $\Delta\lambda = -0.54$ nm, on the short-wavelength side of the optimum detuning, where the pulse is undercompressed, and $\Delta\lambda = -0.41$ nm, on the long-wavelength side of the optimum detuning, respectively, which illustrates the effects of the higher-order dispersion close to the stop band.

We also investigated the effects of selecting different pulses in the Q -switched envelope, which corresponds to selecting different amounts of spectral broadening. Figure 8 shows the measured deconvolved pulsewidth (FWHM) of the transmitted pulse for different values of the estimated nonlinear phase shift in the laser cavity. In this example the detuning is fixed to $\Delta\lambda = -0.45$ nm ($\delta = 38.0$ cm⁻¹) from the center of the stop band. It is worth noting that for nonlinear phase shifts of $\Delta\Phi < 0.2$ the transmitted pulse is mostly unaffected. This corresponds roughly to the regime of recent experiments by Eggleton *et al.*¹³ For nonlinear phase shifts of $\Delta\Phi > 7$ (for this detuning), numerical simulations reveal that the compression is incomplete and that the transmitted pulse is significantly distorted.

4. Conclusion

In summary, we have demonstrated the compression of spectrally broadened optical pulses with an unchirped (apodized) Bragg grating in transmission. The experimentally observed compression from 80 ps to approximately 15 ps, representing a compression factor of 5, is in good agreement with theory and with numerical simulations. Numerical simulations indicate that for this grating the compression factor is close to that which would have been achieved with an ideal quadratic compressor. The pulse compression is not perfect, owing to the nonlinear chirp and to the higher-order dispersion of the grating. More generally, we have shown that, in contrast to the results of Peter *et al.*,⁹ compression ratios of much greater than 2 can be achieved by means of choosing a suitably apodized fiber grating. We note that one can im-

prove the quality of the compression by increasing the grating strength and length, which can reduce cubic dispersion^{5,10}; linearizing the chirp of the spectrally broadened pulse by the effects of normal dispersion^{7,10}; or through the use of a saturable absorber, which can attenuate the wings of the pulse.

The spectral broadening occurs as a result of SPM in the rod of a mode-locked Q -switched YLF laser. We note that this effect is known to occur in a wider class of high-power mode-locked Q -switched lasers.¹⁵ By carefully selecting a particular pulse with an electro-optic pulse selector we can reduce the effects of the SPM. In the experiments described in this paper we select a pulse near the maximum of the Q -switched envelope, where the SPM is largest and the nonlinear phase shift is $\Delta\Phi = 7$. In contrast, in our nonlinear fiber grating experiment we select a pulse near the front of the Q -switched envelope, where the nonlinear phase shift is relatively small ($\Delta\Phi \leq 0.2$) (Ref. 13).

A transmission grating, as described in this paper, could be a valuable component for compressing chirped pulses generated by high-power lasers or, for example, chirped pulses generated by gain-switched semiconductor lasers.¹⁷ For the compression of high-power pulses, nonlinearities in the grating can complicate the compression process. In a scheme recently proposed by Galvanauskas *et al.*¹⁸ a chirped Bragg grating was imprinted in bulk glass, allowing for the compression of high-power pulses. Such a scheme based on a transmissive Bragg grating could provide for efficient compression of chirped high-power optical pulses. We note that the compression scheme is probably not suitable for compressing short optical pulses (<1 ps), as the cubic dispersion of the grating would dominate and the figure of merit would be quite poor. However, by use of stronger gratings, such as the photonic bandgap structures as discussed in Ref. 1, efficient compression of ultrashort pulses could be feasible.

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