Spectral features associated with nonlinear pulse compression in Bragg gratings

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We report, for the first time to our knowledge, direct spectral measurements of nonlinear spectral broadening caused by nonlinear propagation through Bragg gratings written on integrated AlGaAs waveguides. The spectral broadening is associated with pulse compression from 400 to 80 ps. The high nonlinearity of AlGaAs enables high-repetition-rate, low-peak-power sources to be used, facilitating easy spectral measurements.

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Nonlinear Bragg gratings are rapidly emerging as one of the most rewarding areas in nonlinear optics. The main advantage of Bragg gratings is that both the grating dispersion and the reflectivity can be engineered to match experimental requirements. In previous experimental reports of nonlinear effects in Bragg gratings,[1–4] only the temporal shaping of the input pulse was described, and to our knowledge no results concerning the spectral evolution of the pulses have been reported. This experimental bias follows the trend in the theoretical literature, which has concentrated exclusively on the temporal reshaping of pulses in a nonlinear Bragg grating.[5,6]

The spectral features of the transmitted pulse in the nonlinear regime are crucial to an understanding of the pulse-formation processes that are involved in the creation of a compressed output pulse. Obviously, in the experiments of both Eggleton *et al.*[2] and Taverner *et al.*[3] spectral broadening must have occurred, because an initially nearly transform-limited pulse was compressed by a significant factor in each case. It has also been shown theoretically that because of modulational instability an intense cw beam incident upon a nonlinear Bragg grating breaks up into a periodic train of solitons.[7] It is clear that here again spectral broadening must occur, but again little or no attention has been paid to the spectral features of the resultant pulse train. Here we redress this imbalance by presenting our observations of spectral features associated with nonlinear pulse compression in AlGaAs Bragg gratings.

In our earlier experiments on switching fiber Bragg gratings[3] we used narrow Bragg gratings with a spectral width of 30 pm to reduce the power needed for observing nonlinear effects. To observe significant switching it was necessary to use pulses with bandwidths narrower than that of the Bragg grating, and the end result was that neither our pulses nor our grating could be resolved with a conventional spectrum analyzer. Because of the scaling of the nonlinear coupled-mode equations that govern this system[8] it is possible to use stronger, and hence wider, gratings to observe the same effects but at the expense of higher powers. To interrogate such stronger gratings, one can use shorter pulses whose features can be resolved with a conventional spectrum analyzer. These considerations point the way toward using a semiconductor geometry for spectral experiments. A semiconductor such as AlGaAs has two main advantages compared with fibers: Most importantly, the nonlinearity is much larger. Second, with a semiconductor it is possible to obtain bigger index differences and hence to write stronger gratings. We recently reported what we believe was the first demonstration of nonlinear propagation through an AlGaAs Bragg grating at powers of a few hundred watts and repetition rates of 100 kHz.[4] These high repetition rates and the short pulses used (500 ps) makes it a simple matter to resolve the spectral details on a high-resolution commercial spectrum analyzer.

As we demonstrate below, the spectral measurements show considerable detail and, unlike simple self-phase modulation, the resultant spectra are markedly asymmetric, with most of the broadening occurring on the short-wavelength side (i.e., away from the Bragg resonance).

We used a high-quality molecular beam epitaxy–grown AlGaAs wafer to fabricate the integrated grating filters. The lower cladding layer was 4 μm thick and contained 24% Al, the guiding layer was 1.5 μm thick with 18% Al, and the upper cladding layer was 1 μm thick with 24% Al. AlGaAs was chosen as the device material because it has an enhanced nonresonant nonlinearity when operating at a wavelength below the half-bandgap region that can be tailored to lie within the 1.55-μm low-loss telecommunications window. At this wavelength the detrimental effects of two- and three-photon absorption can be minimized through wafer design. AlGaAs waveguides provide good optical power confinement over long interaction lengths with sufficient power handling capabilities for this type of nonlinear experiment. For example, in

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this experiment as much as 1.2 kW of power (660 W launched) was coupled onto the guides without optical damage occurring. The nonlinear refractive index of this material was measured to be $\sim 1.5 \times 10^{-13}$ cm^2/W. The grating filters were based on a weak grating on a strip-loaded waveguide to minimize excess scattering loss. A one-step electron beam lithography process was used to define the grating and the ridge guides simultaneously. Gratings 8-mm long were written on 1-cm-long, 5-μm-wide single-moded waveguides. We selected a grating period of 235 nm to position the grating stop band near the maximum gain of the amplifier near 1533 nm. The waveguides were reactive-ion etched to a depth of 0.9 μm. Because of the reactive-ion etching lag, the grating etch depth was approximately 0.3 μm, resulting in an effective index modulation of 4.4×10^{-4}.

The experimental setup is as described in Ref. 4. High-repetition-rate transform-limited pulses from an externally modulated tunable diode were amplified to kilowatt peak powers in a sequence of cascaded erbium fiber amplifiers.[9] The pulse repetition rate was chosen to be 100 kHz, and the pulse duration was 415 ps with a peak power of 1.4 kW. The initial spectral width was measured to be ~2 GHz, which is less than the resolution limit of the spectrum analyzer. At the output, 10% of the light was coupled into a spectrum analyzer, while the rest was coupled into a fast photodetector and a sampling oscilloscope that had a temporal resolution of ~50 ps.

The grating's reflection spectrum is shown in Fig. 1 (dashed curve), which shows a strong stop band of 0.2-nm width over which the grating is approximately 99% reflecting. This spectrum was taken by use of the amplified spontaneous emission from the amplifier with the input pulse blocked. This case accounts for most of the asymmetry in the spectrum on the long-wavelength side. The periodic ripples in the spectrum are Fabry–Perot resonances from the wafer itself; because of the high refractive index of AlGaAs there is a 30% reflection from the end facets.

At low peak powers the input and output pulse spectra were, as expected, identical.[4] In addition, no temporal compression was observed. As the input power was increased, temporal compression and associated spectral broadening were observed. Figure 1 shows the output spectrum (solid curve) and pulse-shape data (inset) for an incident power of 380 W. Note that in Fig. 1 the input pulse was centered at 1533.873 nm, which is well inside the grating's bandgap. From Fig. 1 it is obvious that strong nonlinear pulse shaping and spectral broadening are taking place; to determine whether they are caused by the grating we tuned the pulse's wavelength to 1534.429 nm, which is well outside the grating's stop band, and repeated the measurements. In this case the pulse's width went from 415 ps at low powers to 420 ps at high powers while the spectral width increased from 0.02 to 0.04 nm, changes that are not nearly so dramatic as the changes seen at wavelengths close to the Bragg resonance.

The most obvious feature of the high-power spectrum in Fig. 1 is that it is double peaked, with one peak corresponding to the original wavelength and the new peak shifted toward the short-wavelength edge of the grating. Indeed, a significant fraction of the pulse's energy now lies outside the grating's stop band. The two peaks are separated by 0.07 nm, which is roughly the distance between the input wavelength and the edge of the stop band. Two other features are apparent from Fig. 1: First, the output pulse has been compressed from 415 to 80 ps, and second, there is now a delay of 250 ps between the two components of the high-power transmitted pulse. Finally, as the power increases, the pulse exits the grating earlier: by as much as 155 ps compared with a medium-powered pulse.

The explanation for the time differences among the various features is complicated by the fact that the transit time of the grating is ~90 ps, whereas the input pulse width is 415 ps. Thus the time delay can arise either from the transmitted pulses' being formed from different portions of the input pulse or from the different pulses' having different group velocities. As is well known, the group velocity approaches zero at the edge of the photonic bandgap and increases rapidly as the frequency moves away from the band edge. In the high-power case the nonlinear detuning would move the pulse farther from the band edge; hence one would expect that its velocity would increase.

To ensure the repeatability of this effect we examined a second, nominally identical, grating on the same wafer and observed similar results. For an input wavelength of 1533.900 nm and a launched power of 660 W (i.e., greater than that used for the spectrum in Fig. 1) the resultant spectrum is as shown in Fig. 2. Here again can be seen multiple peaks on the short-wavelength side, which are widely separated, whereas there is almost no sign of spectral broadening on the

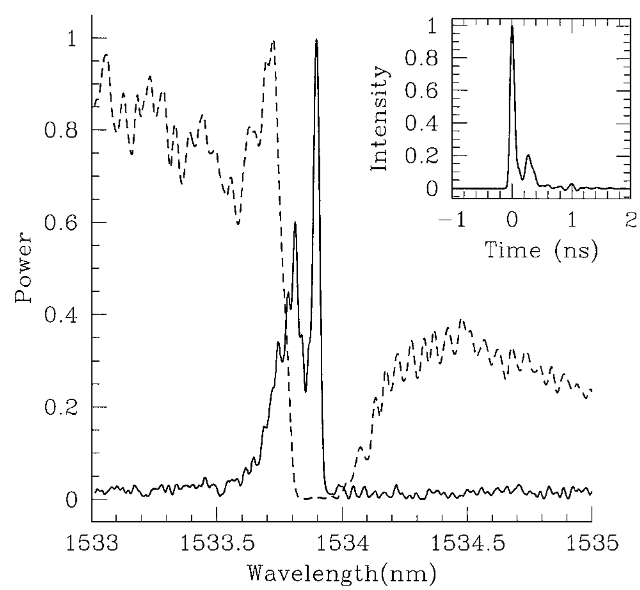

Fig. 1. Output pulse spectrum at high powers (solid curve) superimposed upon the linear grating reflection spectrum (dashed curve). Inset, the corresponding temporal pulse shape with a FWHM of 80 ps. The input pulse was a 415-ps Gaussian pulse.

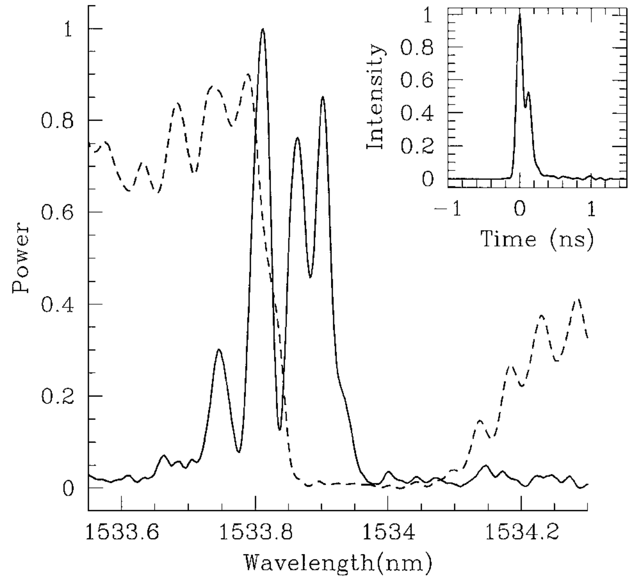

Fig. 2. Observation of multiple spectral peaks at high powers in which a substantial fraction of the power is outside the bandgap.

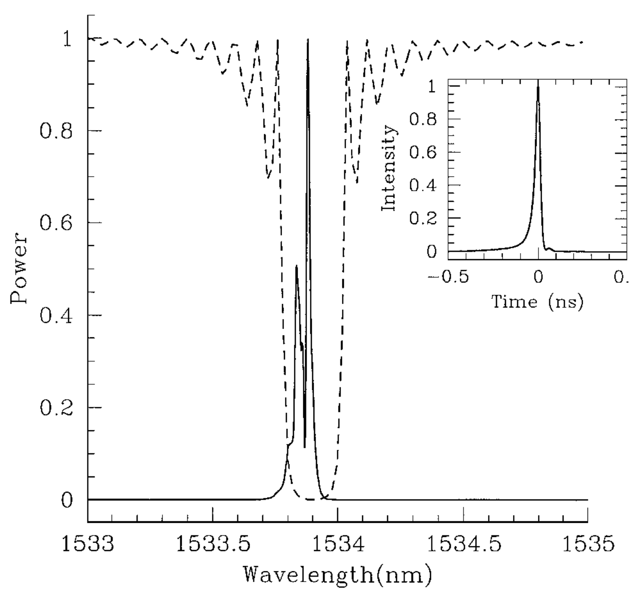

Fig. 3. Results from a numerical simulation of the experiments. The peak powers and detuning correspond to those in Fig. 1.

long-wavelength side. Note also that in this case the power in the new spectral peaks is higher than the power left at the original wavelength. The inset in Fig. 2 shows the transmitted pulse shape.

To better understand spectral shaping, we modeled the nonlinear grating by using standard nonlinear coupled-mode equations,[8] and our initial results are shown in Fig. 3. Here we show the computed transmission spectrum in the nonlinear regime for an input super-Gaussian pulse of width 415 ps tuned to lie in the center of the bandgap. As can be seen, the agreement between Fig. 3 and the experimental spectrum in Fig. 1 is very good, with the theoretical trace reproducing all the main features observed experimentally. In particular, it reproduces the distinct spectral features seen in the experimental trace. The modeling needs to be refined further to yield a better agreement between the theoretical and the experimental pulse shapes. In particular, we used an ideal uniform grating for the theoretical trace, whereas the actual grating is clearly nonuniform. In addition, the effects of both one- and two photon-loss should be included in the model (which is a relatively straightforward change).

In conclusion, we have presented what is to our knowledge the first spectral characterization of nonlinear transmission through a Bragg grating. These results show that during propagation the spectrum becomes significantly asymmetric, with the majority of the power lying near the short-wavelength edge of the grating. In the time domain this spectral broadening is associated with nonlinear pulse compression from 415 to 80 ps (detector limited). The results of our numerical simulations agree well with the experimental result and reproduce the main spectral features. An understanding of the spectral reshaping in a nonlinear Bragg grating is essential if such devices are to be used as all-optical elements for switching purposes, and this research is a first step in that direction.

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References

1. U. Mohideen, R. E. Slusher, V. Mizrahi, T. Erdogan, J. E. Sipe, M. Gonokami, P. J. Lemaire, C. M. de Sterke, and N. G. R. Broderick, Opt. Lett. **20,** 1674 (1995).
2. B. J. Eggleton, R. E. Slusher, C. M. de Sterke, P. A. Krug, and J. E. Sipe, Phys. Rev. Lett. **76,** 1627 (1996).
3. D. Taverner, N. G. R. Broderick, D. J. Richardson, R. I. Laming, and M. Isben, Opt. Lett. **23,** 328 (1998).
4. P. Millar, R. M. D. L. Rue, T. F. Krauss, J. S. Aitchson, N. G. R. Broderick, and D. J. Richardson, Opt. Lett. **24,** 685 (1999).
5. C. M. de Sterke and J. E. Sipe, Opt. Lett. **18,** 269 (1993).
6. N. Broderick, C. M. de Sterke, and J. E. Sipe, Opt. Commun. **113,** 118 (1994).
7. C. M. de Sterke, J. Opt. Soc. Am. B **15,** 2660 (1998).
8. C. M. de Sterke and J. E. Sipe, in *Progress in Optics*, E. Wolf, ed. (North-Holland, Amsterdam, 1994), Vol. XXXIII, Chap. III, pp. 203–260.
9. D. Taverner, D. J. Richardson, L. Dong, J. E. Caplen, K. Williams, and R. V. Penty, Opt. Lett. **22,** 378 (1997).