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Supercontinuum generation in a fiber grating

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We show that supercontinuum generation in a fiber containing a Bragg grating exhibits $>10\times$ enhancement near the Bragg resonance wavelength. We also show that the grating dispersion exceeds the waveguide dispersion over a bandwidth far in excess of its photonic band gap. The observed enhancement is consistent with nonlinear Schrödinger equation simulations of the supercontinuum formation that combine grating and waveguide dispersion. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1818740]

Supercontinuum generation[1] has been demonstrated over very large bandwidths in both germanosilicate highly nonlinear fibers[2] and air–silica fiber waveguides.[3,4] Such sources exhibit record spectral densities over more than an octave of optical spectrum, and many applications, such as frequency metrology,[5] optical coherence tomography,[6] and telecommunications[7,8] have been impacted by these unique light sources. However, fiber supercontina have limitations, such as bandwidth and power distribution, that are dictated by the fiber dispersion. In particular, enhancing specific wavelengths within a supercontinuum frequency comb is difficult with fiber design alone. Such local enhancements are potentially very beneficial for frequency locking schemes that reference only a narrow portion of a comb with light stabilized to an atomic resonance.[9]

It is known that supercontinuum generation in optical waveguides depends on an interplay between the χ_3 optical nonlinearity and the dispersion of the waveguide. Except in the case of fiber tapers,[4] control of the waveguide dispersion is usually achieved through careful design and fabrication of an appropriate fiber waveguide,[10,11] typically with very low dispersion and carefully chosen dispersion zero, in order to maintain narrow pulse shape and provide appropriate phase matching for nonlinear processes. While they often require meters of fiber, supercontinua have also been generated in centimeters of fiber.[3,12] Such short lengths readily allow for UV inscription of fiber Bragg gratings,[13] resonant structures composed of periodic modulations of the core refractive index. The entire supercontinuum generation process may then occur in the presence of such a grating. Fiber Bragg gratings are known to exhibit large dispersion in transmission,[14] and this altered propagation constant near the photonic band gap at the Bragg wavelength will change the phase matching of nonlinear processes giving rise to the supercontinuum. The use of modified effective index near photonic band gaps to enhance nonlinear interactions was suggested as early as 1970.[15] Here we report the effect of one-dimensional photonic bandgap dispersion on fiber supercontinuum generation.

Nonlinear pulse propagation in fiber Bragg gratings, including Bragg soliton formation, has been studied theoretically and experimentally,[16–18] however, these studies had a pulse spectrum whose bandwidth (<few nm) was similar to the grating bandwidth and was centered very near the grating band gap. Moreover, these studies considered only the self-phase modulation portion of the χ_3 nonlinearity in silica. In contrast, we consider femtosecond pulses, whose spectrum can begin hundreds of nanometers from the Bragg resonance, growing rapidly in the grating, and always much larger than the grating band gap of a few nm. Description of such pulses and supercontinuum generation requires inclusion of χ_3 optical shock and delayed Raman terms in addition to self-phase modulation.[19] In this regime of nonlinear propagation, we anticipate supercontinuum phenomena governed by the grating (as opposed to the waveguide) dispersion. These include grating tuned supercontinua, amplification of an arbitrary portion of a frequency comb for improved frequency metrology, and the possibility of exciting Bragg solitons in a supercontinuum.

In this work, we propagate 35 femtosecond pulses down short optical fibers containing gratings (period$\leqslant 1\ \mu$m) and observe that the supercontinuum can be enhanced by more than a factor of 10 near the Bragg gratings' resonant wavelength. We also measure the grating dispersion over >500 nm and show that it is much larger than the fiber dispersion over a bandwidth (>100 nm) far in excess of its photonic band gap (4 nm). We consider an approximate model of the nonlinear propagation within the grating, using the nonlinear Schrödinger equation (NLSE) and neglecting the weak grating reflected light. We solve the NLSE with a dispersion operator modified to include the dispersion of an ideal one-dimensional photonic band gap to represent the Bragg grating. The qualitative agreement of our model indicates strongly that the grating enhancement arises from the effect of grating dispersion on the supercontinuum formation.

The experimental setup is shown in Fig. 1. The pump source was an amplified, mode-locked Er-doped fiber laser[20] with a repetition rate of 46 MHz, pulse duration of 35 fs, center wavelength of 1580 nm, and average power of 0.5 W at the end of the standard single-mode fiber (SSMF) pigtail after the amplifier. Gratings were inscribed in OFS Fitel highly nonlinear fiber (HNLF).[11] See the fiber image in Fig. 1. Before grating inscription, the HNLF had dispersion zero at 1478 nm, and dispersion and effective area at 1550 nm of

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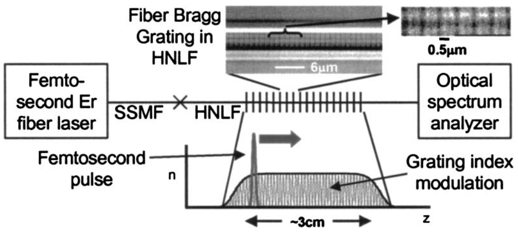

FIG. 1. Experimental setup: Amplified femtosecond fiber laser (1580 nm; 0.5 W; 46 MHz rep rate; 35 fs pulse width) spliced (at *X*) to a UV-written Bragg grating in HNLF. The supercontinuum generation is observed with an optical spectrum analyzer. Large image shows core and surrounding low index region of HNLF. Scale bar is approximate pulse length. Small image shows 1 μm and 0.5 μm grating periods.

1.19 ps/(nm km) and 13 μm^2. Several identical gratings were fabricated. The fiber was first photosensitised in high pressure D_2. The grating was inscribed by scanning a ~1 cm Gaussian beam (242 nm pulsed) over 22 mm of fiber at uniform velocity through a phase mask with period 0.672 μm. One of the gratings' spectra after inscription is shown in Fig. 2(a). The Bragg resonance was centered at 990 nm and 4 nm in width.

These gratings were cleaved to a length containing only the 32 mm grating, <2 cm of unexposed fiber between the input cleave and the grating, and 10–20 cm of fiber after the grating to connect to an optical spectrum analyzer to record the supercontinuum. They were then fusion spliced onto the SSMF output of the fs fiber laser of Fig. 1. The resulting supercontinuum spectrum is shown in Figs. 2(a) and 2(b). For comparison, we include in Fig. 2(b) the supercontinuum from a UV exposed HNLF. This fiber was 20 cm long and had 10 cm exposed to uniform UV radiation with the same average dosage used to write the gratings. The supercontinuum in the uniform UV exposed HNLF is significantly broader than that in unexposed HNLF.[12] The HNLF grating showed an enhancement of the supercontinuum >10 times stronger than the HNLF with only uniform UV exposure. The grating feature was observed just outside the grating band gap, on the long wavelength side of the resonance. Figure 2(a) shows the enhancement on a smaller wavelength scale and compares it to the linear transmission of the grating. For this measurement, ~1 m of HNLF was after the grating.

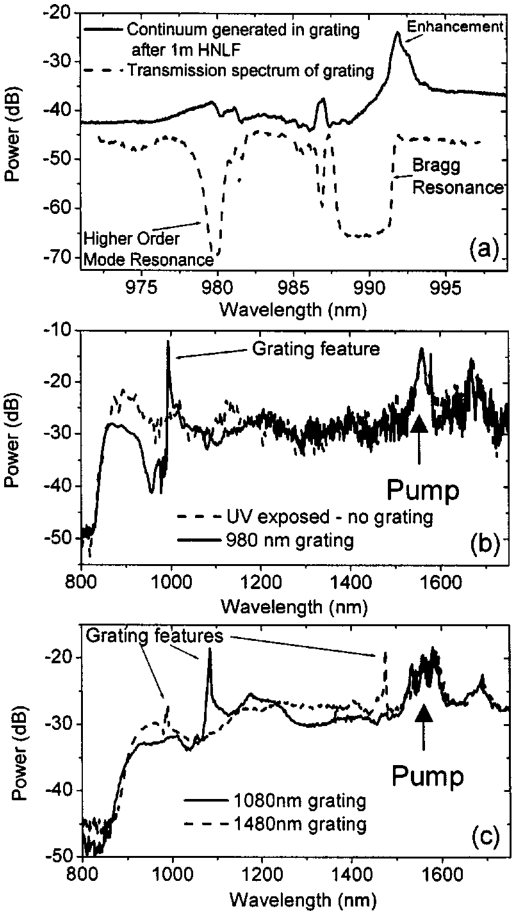

FIG. 2. Supercontinua observed in HNLF Bragg gratings. (a) Linear and nonlinear response near 990 nm grating resonance. (b) Comparison of a 990 nm grating with UV exposed fiber having same average core refractive index. (c) Supercontinua in fibers with gratings near 1480 and 1080 nm. Feature near 1 μm is a higher-order resonance from the 1480 nm grating.

We then inscribed gratings with periods of 505.5 and 367 nm. These also showed ~10× enhancements near the grating resonances of 1473 and 1080 nm [Fig. 2(c)]. The strength and width of the enhancement was dependent on the length of fiber grating used. A typical length that gave good enhancement was ~3 cm of grating with <2 cm of HNLF before it. Figure 2(a) shows that the grating peak can survive even after ~1 m of HNLF. The enhancement was on the long-wavelength side of the grating resonance for all the measured gratings.

A complete description of these experiments requires solution of nonlinear coupled mode equations which include both the Bragg reflected wave and the full χ_3 nonlinearty giving rise to the supercontinuum.[19] However, the enhancement occurs outside the band gap where the back reflected wave is small. Moreover, the band gap (~4 nm) is much smaller than the supercontinuum (>30 nm), so that the reflected light is weak. We therefore neglect backreflected frequencies in the band gap and simulate the effect of the Bragg resonance by using an NLSE with a modified dispersion operator that includes the grating. The grating dispersion is approximated as an ideal one-dimensional photonic band gap,[21] while the propagation constant of the guided mode, $\beta_{\text{Fiber}}(\lambda)$, is computed from the measured radial profile of the fiber refractive index. The propagation constant of fiber + grating, $\beta_{\text{Fiber+Grating}}$, is then

$$\beta_{\text{Fiber+Grating}}(\lambda) = \begin{cases} \beta_{\text{Fiber}}(\lambda_B) - \sqrt{\{\beta_{\text{Fiber}}(\lambda) - \beta_{\text{Fiber}}(\lambda_B)\}^2 - \kappa^2} & \lambda < \lambda_B \\ \beta_{\text{Fiber}}(\lambda_B) + \sqrt{\{\beta_{\text{Fiber}}(\lambda) - \beta_{\text{Fiber}}(\lambda_B)\}^2 - \kappa^2} & \lambda > \lambda_B \end{cases} \quad (1)$$

where $\kappa = \pi \delta n \eta / \lambda_B$, δn is the amplitude of the index modulation, η is the radial overlap of the mode with the grating, and λ_B is the vacuum Bragg wavelength. For weak gratings, Eq. (1) is equivalent to adding grating dispersion to the fiber dispersion. We neglect the frequency dependence of κ and the effect of nonresonant grating dispersion far from the Bragg wavelength.[22] Our approximation is not useful for frequencies in the band gap, since no reflected wave is computed. The transmission was simply assumed to be zero in the grating band gap and 1.0 elsewhere. Cladding modes were ignored. The dispersion (second derivative) of Eq. (1) was used in a split-step NLSE simulation of the light propagation that included optical shock and time-delayed Raman

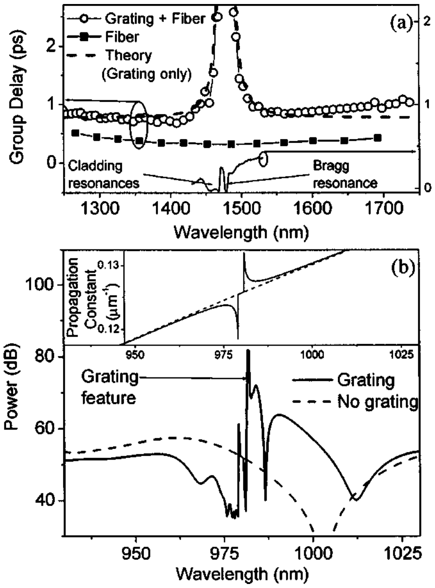

FIG. 3. (a) Theoretical grating group delay compared to measured group delay and transmission of fiber grating, as well as fiber dispersion before grating inscription. Curves offsets for clarity. (b) Top inset: Waveguide propagation constant used in simulations with and without the grating; bottom: NLSE simulations reproducing the observed enhancement.

terms with parameters similar to that of Ref. 23.

The value of δn was determined from a rough fit to the measured dispersion of the HNLF grating. The group delay (integral of dispersion) of a 10 cm Bragg grating (in a 26 cm length of fiber), similar in strength to the experimental gratings, was measured using spectral interferometry. The measured group delay compared to a theoretical grating dispersion with $\delta n = 0.003$, $\eta = 0.8$, and $\lambda_{\mathrm{Bragg}} = 1479$ nm is shown in Fig. 3(a). Figure 3(a) also shows the unexposed HNLF group delay (fiber length of 21 cm). The group delay of the grating exceeds the waveguide over a wavelength range greater than 100 nm, far in excess of the 4 nm photonic band gap. The fiber dispersion (β_{Fiber}) used in Eq. (1) was simulated using the measured radial refractive index profile of UV exposed HNLF. Previously, this value was used to accurately determine the extended continuum bandwidth in UV exposed HNLF.[12]

The simulation results are shown in Fig. 3(b). The top inset of Fig. 3(b) shows the propagation constant used in the simulations and below this the resultant continuum from the HNLF with a 980 nm grating, compared to a simulation without a grating. In agreement with our experiments, a strong enhancement is observed on the long-wavelength side of the grating resonance. The simulations were repeated for other wavelengths and grating parameters, giving a similar enhancement. An important finding of these simulations, also in agreement with experiment, is that the enhancement depends on the length of the grating, with typically a few centimeters giving the highest enhancement.

In the time domain, the simulations show that the enhancement peak corresponds to a weak ps pedestal that forms under the main femtosecond pulse, which remains in the femtosecond regime throughout the supercontinuum generation. If the picosecond wave was strong enough to undergo nonlinear propagation within the grating, there might exist conditions under which Bragg solitons could be excited by the continuum. These would have the advantage of being excited within the grating, much like Raman gap solitons.[24] The picosecond pulses associated with our enhancement, though, are not likely to be in the Bragg soliton regime, since their power is too low and the grating dispersion on the long wavelength side of the Bragg wavelength has the wrong sign for soliton formation.[18]

We have shown that supercontinuum generation in a fiber may be significantly enhanced (10×) near a fiber Bragg resonance. Our results with different Bragg wavelengths strongly indicate that enhancement is possible over a large wavelength range within the continuum. We have also measured the dispersion of a fiber Bragg grating on a wavelength scale broad enough to observe fiber dispersion, and found that the grating dispersion dominates the fiber dispersion over more than ten times its photonic band gap. The interaction of resonant dispersion with supercontinuum generation promises to extend the range of applications and nonlinear effects that exploit supercontinuum sources.

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