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Experimental demonstration of nonlinear pulse propagation in a fiber Bragg grating written in a fiber amplifier

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We study experimentally nonlinear propagation of sub-nanosecond optical pulses in a fiber Bragg grating written in a Ytterbium-doped fiber amplifier (YD-FBG). The magnitude and the sign of group velocity dispersion (GVD) in YD-FBG can be controlled by adjusting the fiber tension. In the case of anomalous GVD, pulse breakup was observed due to modulation instability. However, for the same input pulse power in the normal GVD regime, the output pulse duration was increased, and pulse breakup was not observed. The deterioration of pulse spectrum due to Raman and four-wave mixing effect was also reduced in the normal GVD regime. Since GVD in YD-FBG is six orders of magnitude higher than in standard fibers, the advantages of normal GVD in fiber amplifiers that were demonstrated in previous works for femtosecond and picosecond pulses can be exploited for amplifying sub-nanosecond pulses. The experimental results are in good agreement with numerical simulations. We have also demonstrated a gain coefficient enhancement by a factor of 1.7 due to slow-light propagation in the YD-FBG.

OCIS codes: (050.2770) Gratings; (060.3735) Fiber Bragg gratings; (060.4370) Nonlinear optics, fibers; (060.5530) Pulse propagation and temporal solitons; (060.2320) Fiber optics amplifiers and oscillators.

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High power optical fiber amplifiers (FAs) and lasers have become important for several important applications. The maximal pulse power and energy that can be obtained from FAs is often limited by nonlinear effects that cause a degradation of the temporal and spectral properties of the amplified pulses [1]. In the anomalous group velocity dispersion (GVD) regime, modulation instability (MI) can cause breakup of pulses [2]. However, in the case of normal GVD, the interaction between dispersion and nonlinearity can be used to avoid pulse breakup by causing the amplified pulses to converge into stable parabolic, linearly chirped pulses called similaritons [3]. Due to the limited dispersion in fibers and FAs, self-similar amplification is obtained for short pulses with a temporal duration on the order of picoseconds (ps) or femtoseconds (fs) [1,3].

Recently, we have shown theoretically that the high GVD obtained in fiber Bragg gratings (FBGs) is sufficient to affect the propagation of nanosecond (ns) pulses over a length scale on the order of centimeters [4]. In this Letter, we experimentally study nonlinear propagation of pulses with duration of 370 ps in a FBG written directly into Ytterbium-doped fiber amplifier (YD-FBG). The measured GVD of the YD-FBG was six orders of magnitude higher compared to that of standard fibers. The sign and the magnitude of the GVD could be adjusted by a controllable stretching of the FBG. In the anomalous GVD regime pulse breakup was observed due to modulation instability. However, for the same input power, pulse breakup was not observed in the case of normal GVD. Hence, the advantages of normal GVD in FAs that were demonstrated in previous works for amplifying fs and ps pulses can be exploited for amplifying sub-ns pulses by using FBGs. In previous works it was also shown that the amplification of sub-ns pulses is often limited by four-wave mixing (FWM) and stimulated Raman scattering (SRS) [5,6]. We show that the high normal GVD obtained in YD-FBG also helps to reduce these effects for sub-ns pulses.

A uniform grating with a length of $L_{\mathrm{FBG}} = 10$ cm was written in Yb-doped fiber (Yb118) manufactured by CorActive, using a pulsed picosecond laser source [7]. The effective mode area of this fiber equals $A_{\mathrm{eff}} = 11.4\ \mu\mathrm{m}^2$ and the measured small signal gain coefficient at 1064 nm equals $g_0 = 2.5\ \mathrm{m}^{-1}$. The grating strength, $\kappa = 350\ \mathrm{m}^{-1}$, was estimated by matching the measured bandwidth to the theoretical bandwidth for a uniform 10 cm long grating [8]. The measured loss induced by writing the grating was about 10 dB/m. In the case that a similar grating is written by using a CW laser, the loss can be only 2 dB/m [9]. The setup (Fig. 1) allowed us tuning the YD-FBG spectrum with respect to the laser wavelength by accurately stretching the grating with a high-precision translation stage as performed in [10]. The input pulses were generated by a *Q*-switched YAG laser that operates at a wavelength of 1064 nm and generates pulses with a full-width at half-maximum (FWHM) duration of 370 ps at a repetition rate of 50 Hz,

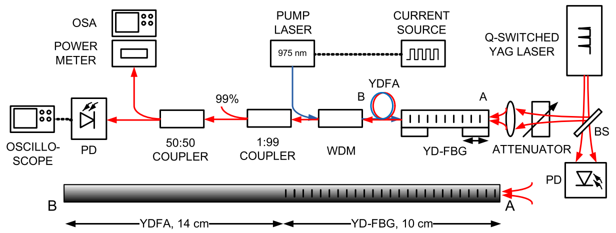

Fig. 1. Schematic drawing of the setup and the YD-FBG fiber structure used in our experiments. PD is a photodetector; OSA is an optical spectrum analyzer; and BS is a beam-splitter. The 10 cm long grating is written in a 24 cm long Ytterbium doped fiber amplifier (YDFA). Side A of the YD-FBG is placed in a precise mechanical stage that allows stretching the YD-FBG. Side B of the YDFA is spliced to a wavelength division multiplexer (WDM).

and a peak power of 12 kW. The pulses were attenuated by a tunable attenuator and coupled into side A of the YD-FBG. The measured coupling efficiency was about 27%, and the maximum attainable input pulse power was 3.2 kW. The relatively small coupling efficiency is caused due to the small numerical aperture of the fiber. The optical damage threshold was about 2.8 kW. This damage threshold is more than an order of magnitude lower than reported in previous work [6], probably due to defects created during the writing of the grating. The output and the input pulses were measured by a photodetector and a sampling oscilloscope with a bandwidth of 20 GHz. The output end of the YD-FBG was connected to an optical spectrum analyzer through a passive fiber (Corning, HI1060) and couplers with a total length of 1.2 m. The propagation through this fiber added some nonlinear effects to the output pulses.

The pumping was performed by a laser diode that operates at a wavelength of 975 nm. In order to reduce the refractive index change (RIC) due to pumping [7], the current source of the pump laser generated pulses with a repetition rate of 50 Hz and a pulse duration of 2 ms. The optical pump peak power was equal to 62 mW and the average pump power was 6 mW.

We measured the grating spectrum with a spectral resolution of 1 pm by accurately stretching the YD-FBG and measuring the output power for low-intensity input pulses. Figure 2(a) shows the transmission spectrum T and the normalized group velocity ν in the device. The group velocity was obtained by measuring the change in the propagation time of the pulses in the YD-FBG as a function of the wavelength by using a sampling oscilloscope. The GVD was calculated from the measured group velocity change by using the relation

$$\beta_2 = \frac{d^2k}{d\omega^2} \cong -\frac{\lambda_0^2}{2\pi n_{\mathrm{eff}} V_g^2}\frac{d}{d\lambda}(\nu^{-1}), \tag{1}$$

where ω is the angular frequency, $\lambda_0 = 1064$ nm, k is the wavenumber, and $n_{\mathrm{eff}} = 1.46$ is the effective refractive index of the fiber.

The effective gain coefficient of the signal changes due to the decrease in the propagation velocity of the pulses in the YD-FBG. In Ref. [11] we have shown that the effective gain coefficient approximately equals $g_{\mathrm{eff}} \cong g_0/\nu$. To verify this relation, we have calculated at several wavelengths the effective gain coefficient g_{eff} by measuring the ratio between the pulse transmission with and without the pumping. The theoretical and the measured values of g_{eff} are presented in Fig. 2(b). The minimum group velocity obtained in our experiments was $\nu = 0.6$. The gain coefficient at this point was enhanced by the factor of 1.7 as predicted by theory. However, we note that as the group velocity is decreased the grating transmission also decreases. For example, in the case of $\nu = 0.6$ the unpumped grating transmission was 26%. Nevertheless, we have shown theoretically in [4] that by using very long apodized gratings with a length of about 1 m, it is possible to obtain a group velocity as low as $\nu = 0.35$ while maintaining transmission close to 1. The writing of a grating with a length of 1 m has been demonstrated in previous work [12].

We measured the output pulses at four operating points marked by vertical blue and red dashed lines in Fig. 2(a). The four operating points, denoted by $\Delta\lambda_{a1}$, $\Delta\lambda_{a2}$, $\Delta\lambda_{n1}$, and $\Delta\lambda_{n2}$, correspond to measured GVD of −210, −640, +200, and +430 $\mathrm{ps^2\,cm^{-1}}$, respectively. Blue lines in Fig. 2(a) correspond to operating points with anomalous GVD and red lines correspond to operating points with normal GVD. Higher absolute values of GVD are obtained at wavelength that are closer to the bandgap. The measured GVD values are more than six orders of magnitude higher than GVD of standard fibers, such as Corning HI1060, in which $\beta_2 = 33\ \mathrm{ps^2\,km^{-1}}$ at 1060 nm. All operating points are outside the grating bandgap and hence the transmission of the grating is above 80%.

Figure 3 shows the measured transmitted pulse profiles at the four operating points, for low input pulse energy of $E_{\mathrm{in}} =$ 46 nJ and a peak power of 110 W and for high energy of 363 nJ and a peak power of 870 W. All the pulse profiles shown in Figs. 3 are normalized to the corresponding input pulse peak power. The transmitted pulses are shown by a blue solid line in the case that the pump was switched off, and by a dashed green line in the case that the pump was switched on. Left sub-figures show the experimental results and right sub-figures show the corresponding theoretical results. The input profile is shown in the insert of Fig. 3(a). In all 12 cases presented in Fig. 3 the transmission change due pumping was 1.7–1.95.

Figure 3(a) shows the output pulses for operating points $\Delta\lambda_{a1}$ and $\Delta\lambda_{a2}$ where the GVD of the YD-FBG is anomalous. In the case that $E_{\mathrm{in}} = 46$ nJ, nonlinear Kerr effect can be neglected and the transmitted pulse profiles does not significantly depend on dispersion. However, at higher energy of 363 nJ, the combination of nonlinear effect and anomalous GVD causes

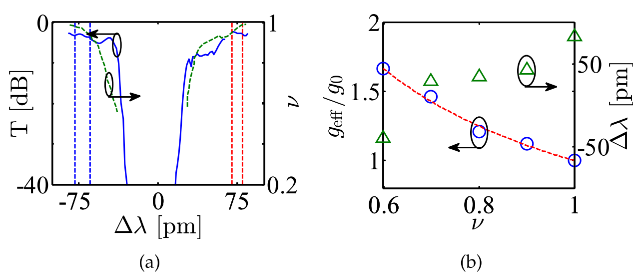

Fig. 2. (a) Transmission spectrum of the unpumped YD-FBG measured with a resolution of 1 pm by a controllable stretching of the grating. The blue solid line shows the transmitted spectrum amplitude, and the green dashed–dotted line shows the measured normalized group velocity in the grating $\nu \times V_g$, where V_g is the group velocity in the fiber. Dashed vertical lines indicate the four operating points used in our experiments. (b) Theoretical (red dashed line) and experimental (blue circles) effective gain coefficient g_{eff} that was measured at several wavelength offsets (green triangles).

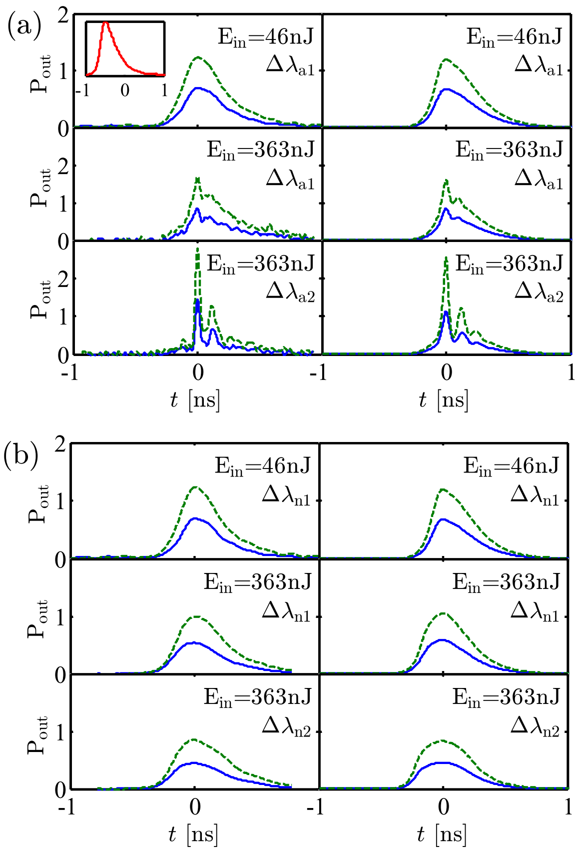

Fig. 3. Measured transmitted pulse (left sub-figures) that is compared to the result of a numerical simulation (right sub-figures) in the case that the pump was turned off (blue solid line) and in the case that the pump was turned on (green dashed line) for four operating points: (a) $\Delta\lambda_{a1}$ and $\Delta\lambda_{a2}$ that correspond to anomalous GVD of −210 and −640 $\mathrm{ps}^2\,\mathrm{cm}^{-1}$, respectively; and (b) $\Delta\lambda_{n1}$ and $\Delta\lambda_{n2}$ that correspond to normal GVD of +200 and +430 $\mathrm{ps}^2\,\mathrm{cm}^{-1}$, respectively. The results are given for two input pulse energies: 46 and 363 nJ that correspond to peak powers of 110 and 870 W, respectively. The time profiles are normalized to the corresponding input pulse peak power. The insert shows the measured profile of the input pulse.

breakup of the pulse and the amplifier gain enhances the effect. Such behavior that is caused by modulation instability has been previously observed in standard fibers [2] and in unpumped FBGs [13]. Figure 3(b) shows the output pulses for operating points $\Delta\lambda_{n1}$ and $\Delta\lambda_{n2}$ where the GVD of the YD-FBG is normal. In these cases, pulse breakup is not observed for the high energy pulses even when the pump was turned on. Instead, the output pulse duration increases, compared to the input pulse duration, by a factor of 1.2 and 1.3 in the case of $\Delta\lambda_{n1}$ and $\Delta\lambda_{n2}$, respectively. The pulse broadening is obtained only at high power. In this case, nonlinear Kerr effect broadens the pulse spectrum and hence the GVD effect is enhanced and broadens the pulse duration. Such broadening was obtained for short pulses during the buildup of similaritons [3].

To compare the experimental results with theory we modeled the pulse propagation by numerically solving the nonlinear coupled-mode equations with gain saturation (NLCME + G) [11]. The results are shown in the right sub-figures in Figs. 3(a) and 3(b). The fiber parameters we used in the simulation were provided to us by the fiber manufacturer: nonlinear coefficient $\Gamma = 17\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$, saturation signal power $P_{\mathrm{sat}} = 12.2$ mW, and relaxation time $\tau = 1$ ms. The calculated saturation energy equals $E_{\mathrm{sat}} = 12.2$ μJ and the maximal signal energy obtained in our experiments equals 3 μJ. Hence, we assumed that the small signal gain coefficient $g_0 = 2.5\ \mathrm{m}^{-1}$ is uniform along the amplifier. In the simulations, the wavelength offsets with respect to the Bragg wavelength were chosen to obtain the same GVD as was measured in the corresponding experiment. The theoretical results are in good quantitative agreement with the experiments. In particular, for high power pulses the pulse duration increases in the normal GVD regime as obtained in the experiments.

In previous works, the main nonlinear effects that limited the amplification of sub-ns pulses in FA were FWM and SRS [5,6]. These effects caused deterioration of the pulse spectrum, saturation of the amplified pulse energy, and pulse breakup. We measured the spectrum deterioration in the case that the power is sufficiently low such that nonlinear effects only slightly affect the output pulses. To eliminate noise caused by amplified spontaneous emission (ASE) we turned off the pump in this experiment. First, we reduced the GVD effect by increasing the relative wavelength $\Delta\lambda$, defined in Fig. 2(a), by +100 pm compared to operating point $\Delta\lambda_{n1}$. At this new operating point, denoted by $\Delta\lambda_f$, the GVD was two orders of magnitude lower than in $\Delta\lambda_{n1}$. Figure 4(b) [blue solid line] shows the spectrum of the pulses with output energy of 817 nJ. A clear deformation of the spectrum is observed compared to the spectrum measured at lower power. The spectrum contains two symmetrical peaks at both sides of the laser wavelength and a broad peak at around 1115 nm. Similar spectral features were reported in [5,6] and were attributed to a combination of FWM and SRS. Figure 4(b) [green dashed line] shows the measured output spectrum at operating point $\Delta\lambda_{n1}$ for the same output pulse energy used in operating point $\Delta\lambda_f$ (817 nJ). The figure shows that the output spectrum is similar to the input spectrum. The high normal GVD added by the FBG in operating point $\Delta\lambda_{n1}$ combined with Kerr effect caused a decrease in the peak power of the pulse, as shown in Fig. 4(a) and, hence, the pulse deterioration due to FWM and SRS is decreased. In addition, the large magnitude of the GVD may decrease the phase-matching condition that is required to obtain efficient FWM effect. These results indicate that by writing a relatively short FBG at the entrance of the amplifier, the maximum pulse energy can be increased by a factor that is approximately equal to the broadening ratio of the pulse duration. We have numerically calculated that in the case that a 35 cm length FBG is written at the fiber entrance, with 2.5 cm long sine-apodized sections at both ends, for a 200 ps (FWHM) 700 W peak-power input pulse, the theoretical output pulse peak-power is reduced by a factor of 10 while its transmitted energy exceeds 75%.

We note that pulse deterioration was observed in [5] for pulse energies above ~150 μJ which is significantly higher than in our experiments, 0.82 μJ. However, in [5] the fiber amplifier was a large mode area (LMA) fiber with an effective mode area $A_{\mathrm{eff}} = 511.4\ \mu\mathrm{m}^2$ and a nonlinear coefficient $\Gamma = 0.3\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$. The corresponding parameters in our experiment were $A_{\mathrm{eff}} = 11.4\ \mu\mathrm{m}^2$ and $\Gamma = 17\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$ along YD-FBG and $\Gamma = 3.7\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$ along the 1.5 m HI1060 fiber that connects the YD-FBG to the spectrum analyzer. To compare two experiments we choose, as a figure of merit, the accumulated nonlinear phase $\phi_{\mathrm{NL}} = \Gamma \times \int_0^L P_{\max}(z)\mathrm{d}z$, where $P_{\max}(z)$ is the pulse peak power along the fiber. The pulse duration in [5]

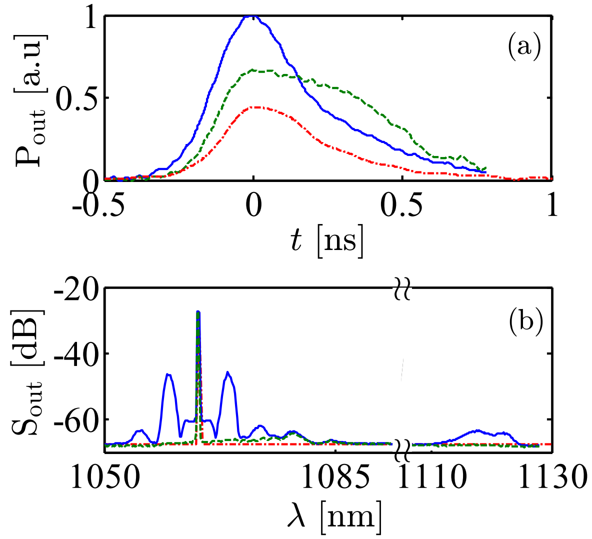

Fig. 4. (a) Temporal profiles P_{out} and (b) optical spectra S_{out} of the transmitted pulses in an unpumped amplifier, measured at operating point $\Delta\lambda_{n1}$ (green dashed line) and at operating point $\Delta\lambda_f$ (blue solid line). In both operating points, the output pulse energy was $E_{\text{out}} = 817$ nJ. For the comparison, the transmitted pulse profile at operating point $\Delta\lambda_f$ that was measured at lower output pulse energy of $E = 363$ nJ is also shown by the red dashed–dotted line. The high GVD added by the grating at operating point $\Delta\lambda_{n1}$ eliminates pulse deterioration at the higher energy.

was 1 ns and the fiber amplifier length was $L = 3.5$ m. Based on the input and output pulse energies (1.5 μJ and 150 μJ, respectively), we estimate that the gain coefficient was 5.6 dB/m in [5]. In our experiments, since the pump was turned off during the experiment presented in Fig. 4, the gain coefficient was about −10 dB/m along the YD-FBG. The nonlinear effect becomes significant in [5] at about $\phi_{\text{NL}} = 34$ compared to $\phi_{\text{NL}} = 17$ in our experiments. The similar figure of merits in both experiments indicates that the reduction of the nonlinear effect by a FBG that is demonstrated in this Letter may be important for amplifying high energy pulses in LMA fibers.

To verify that the high GVD induced by the FBG can increase the maximum amplified pulse energy, we measured the amplification in a 55 cm long FA with a 10 cm long YD-FBG written at the FA input. The grating strength was $\kappa \simeq 1200\ \text{m}^{-1}$. We measured (Fig. 5) the input and the corresponding output pulse energies for two operating points: $\Delta\lambda_f$ where the GVD effect was negligible and at the operating point with high normal GVD that caused a broadening of the FWHM pulse duration from 370 to 450 ps at input pulse energy of 1.2 μJ. The output energy was measured by using a silicon photodiode with a cutoff wavelength of about 1100 nm. At operating point $\Delta\lambda_f$, the maximum pulse energy was 2.45 μJ. Further increase in the input pulse energy caused pulse splitting in the time domain and a reduction of the measured output pulse energy, as was also obtained in [5]. However, at the second operating point with high normal GVD, the maximum output energy was increased by 23%.

In the design of the FBG-FAs, lasing of the structure should be eliminated. For a uniform 10 cm long grating with $\kappa = 350\ \text{m}^{-1}$, the threshold gain is only 0.7 dB/m [14]. In our experiments, lasing was not obtained since the loss induced by the grating was similar to the fiber gain. However, our

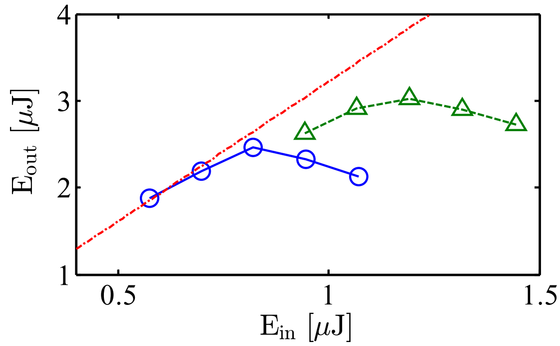

Fig. 5. Output pulse energy, measured with a silicon photodetector, in the case that the pump was turned on as a function of the input pulse energy for operating point $\Delta\lambda_f$ (blue solid line), and for operating point $\Delta\lambda_{n1}$ (green dashed line). The red dashed–dotted line corresponds to a small signal gain of 3.2.

simulations show that if the grating is apodized by sufficiently long apodization sections, lasing can be prevented even when the loss is negligible.

In conclusion, we have experimentally demonstrated nonlinear pulse propagation in FBG written in YD-FBG. The GVD added by the grating could be adjusted by stretching the fiber, and it was six orders of magnitude higher than obtained in standard fibers. In the case of anomalous GVD, pulse breakup was observed. By changing the sign of the GVD, pulse breakup was avoided and, instead, the pulse duration was increased by a factor of 1.3 due to the combination of GVD and nonlinear effect. The high normal GVD in YD-FBGs also helps in decreasing the effect of FWM and SRS. Normal GVD was used in previous works to overcome limitations in amplifying fs and ps pulses in fiber amplifiers. We believe that YD-FBG may enable exploiting the advantages of normal GVD in fiber amplifiers to amplify high power sub-ns pulses.

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