Tunable narrow-band spectral peak imposed onto a soliton with an acoustic long-period grating

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ABSTRACT

We demonstrate a method of local spectral enhancement of an ultrafast soliton pulse. We use an in-line acoustic long-period grating (LPG), a periodic structure modifying both the phase and the loss of the propagating light, and which is readily tuned by simple adjustment of an applied electrical signal. The soliton perturbed by this narrow-band filter evolves with nonlinear propagation into an intense localised spectral peak. Our setup consists of creation of a red-shifted optical soliton by propagation of pulses from a fibre laser in standard single-mode optical fibre, followed by imposition of a spectrally narrow LPG near to the soliton peak, and then continuing propagation. The wavelength and the peak value of the resulting local enhancement can be tuned by adjustment of the applied acoustic frequency and amplitude. The physics of the observed local spectral enhancement will be discussed in detail here.

Keywords: Pulse propagation, solitons, ultrafast processes in fibers, nonlinear optics.

1. INTRODUCTION

Enhancement of narrow regions of the spectrum of an ultrafast pulse is of interest in frequency-comb metrology[1] and in spectrally sliced wavelength division multiplexing applications[2]. Westbrook *et al.*[3, 4] used an in-line fiber Bragg grating (FBG) to create a narrow spectral peak at a pre-selected wavelength in a supercontinuum. This spectral enhancement is caused by local modification of the phase and amplitude of the optical wave, followed by nonlinear propagation. An increase of the signal-to-noise ratio was demonstrated in a self-referenced frequency comb stabilization scheme for optical metrology[1]. FBG's have also been used for spectral enhancement to improve the signal in a coherent optical link comprising a frequency comb[5].

We recently demonstrated a more flexible type of local spectral enhancement by using an in-line long-period grating (LPG)[6], a structure with periodic modulation of the refractive index which modifies both the phase and the loss in a spectral region. This gives rise to a spectral enhancement which can be tuned thermally or extinguished by immersion in a high refractive-index fluid.

In this paper we extend this by demonstrating spectral enhancement in a soliton using an acoustic LPG[7]. The key advantage is that the acoustic LPG is easily and rapidly tuned by adjustment of an external radio frequency (RF) source. In addition, by adjusting the RF power the grating strength, and thus the enhancement, can be tuned at a fixed wavelength. We first present theoretical considerations that explain how an acoustic LPG resonance, coinciding with the soliton centre wavelength, leads, with nonlinear propagation, to a pulse that possesses a distinctive spectral signature exhibiting a periodic cycle between enhancement and suppression. We then present experimental results that show considerable local enhancement of the spectrum, and compare these results to numerical simulations. We discuss the potential to develop tunable supercontinuum sources.

2. PRINCIPLE

We earlier showed [8] that an intense optical pulse modified by a narrow spectral phase filter evolves in the presence of Kerr nonlinearity into a local spectral enhancement. To understand this we note that the spectrum of the pulse immediately after a filter can be considered as a superposition of two pulses: a pulse similar to the original one, and a spectrally narrow dispersive pulse. Upon further propagation these pulses interfere with each other, leading to enhancement of the local spectral intensity. A pulse modified by an amplitude filter evolves to display enhancement of

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up to a factor 4 (6 dB), relative to the intensity in absence of the filter [9, 10]. A phase filtered pulse can display even greater enhancement, depending on the magnitude of the phase deviation.

When an ordinary dispersive pulse is used for spectral enhancement the picture is complicated by the fact that the unperturbed pulse exhibits self-phase modulation (SPM) [11]. SPM removes power from the center of the spectrum and redistributes it at other frequencies. The spectral enhancement is then measured against a lower background than it would be without SPM. Applying a filter instead to a soliton allows clearer demonstration of the mechanism of spectral enhancement, since the soliton spectrum is unchanged during propagation. In this case the wave number of the soliton is $\eta=\gamma P_s/2$, where Ps is its temporal peak power and γ is the effective Kerr coefficient. The spectrally narrow dispersive pulse induced by the filter has a low amplitude, so it follows the linear dispersion relation, $\beta(\Omega)=\beta_2\Omega^2/2$ where $\Omega = \omega - \omega s$ is the deviation of the frequency ω from the soliton center frequency ωs, and $\beta 2 < 0$ is the group velocity dispersion at ωs. Thus the phase difference between the pulses, $\Delta\varphi(\Omega,z)\cong(\gamma P_s-\beta_2\Omega^2)z/2$, depends on the propagation distance z. The spectrum exhibits a periodic cycle between enhancement, when the two pulses are in phase, $\Delta\varphi(\Omega,z)=2\pi m$, and suppression, when they are in anti-phase, $\Delta\varphi(\Omega,z)=\pi m$ (m is an integer).

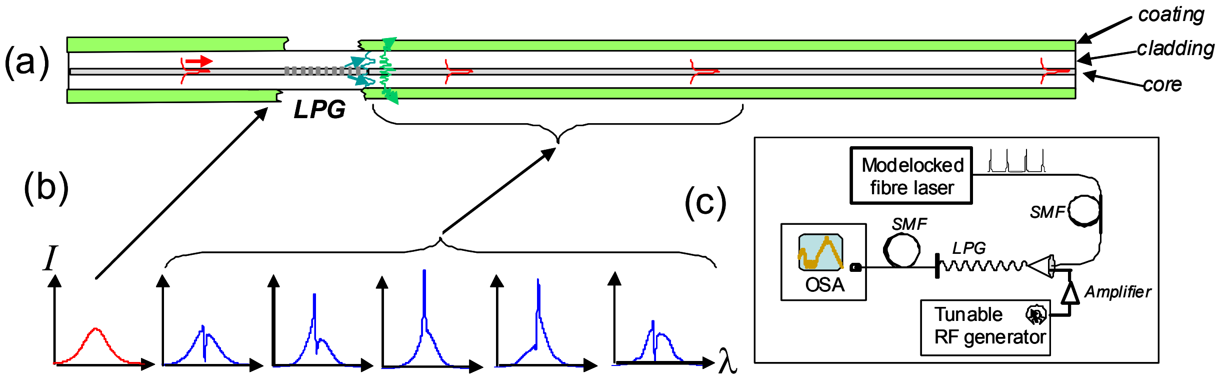


Fig. 1(a) A pulse propagating in uniform fiber encounters an LPG. During further propagation the phase and loss response transform the pulse spectrum. The diagrams in (b) are slices through the spectral intensity of the pulse at various stages during propagation, showing a distinctive periodic spectral profile (one period is illustrated). The experimental arrangement is shown schematically in (c).

The principle of tunable spectral enhancement of a soliton with a LPG is summarized in Fig. 1. Briefly (see Fig. 1(a)), a soliton interacts with a LPG and local changes to the transmission and phase occur. The result can again be viewed as a superposition of a broadband soliton and a narrowband dispersive pulse. In the case of the LPG we expect at least 6 dB enhancement of the pulse spectrum since the LPG is a combined phase-and-loss filter. The interaction of the soliton with different parts of the LPG-induced dispersive wave, containing phase and loss components, and produces a spectrum with a distinctive periodic signature (see Fig 1(b)).

3. EXPERIMENT

Our experiment (see Fig. 1 (c)) employs a mode-locked fiber laser, emitting 1550 nm pulses with peak power 10 kW and pulse width (FWHM) of 80 fs. This laser is attached to 40 m of Corning SMF28 fiber, which has anomalous dispersion at 1550 nm, thus supporting soliton evolution, and has a modal beat length suitable for creation of an acoustic LPG. The laser pulse evolves at the end of the 40 m patch cord into a transform-limited soliton, with width 180 fs. The peak power is $P_s\sim 2.5$ kW. The output is spliced to a further 30 cm length of SMF28 fiber, which has been stripped and fitted with a piezo-electric acoustic transducer. A high-energy RF wave at a frequency of ~1.9 MHz and with amplitude up to 26 Vpp is applied to the acoustic transducer via an external electrical drive. The transducer induces a traveling acoustic wave in the fiber, creating periodic micro-bends. This in turn produces a sharp LPG resonance of width 1.5-2.5 nm, the depth and position of which can be varied by manipulation of the RF power and frequency, respectively. The depth of the LPG of 14 dB, as measured from the transmission spectrum at low laser powers, shows approximately full coupling with a peak phase change up to $\pi/2$. Finally an acoustic dampener is used to terminate the acoustic LPG, and the output end is spliced to a further length of SMF fiber, where nonlinear propagation occurs.

4. RESULTS

Figs. 2(a) and 3(b) show measured spectra recorded under various conditions at the output of 7 m of SMF28 fiber after the LPG. Fig. 2(a) is the spectrum measured with the laser power attenuated before further propagation. A sharp LPG loss feature is observed, superimposed onto a Raman shifted soliton at 1620 nm, as well as a broad component of dispersive radiation around the original laser wavelength at 1550 nm[12]. The solid curve in Fig. 2(b) shows the corresponding spectral output at high power. The spectral region around the LPG resonance at 1618 nm has transformed into an enhanced spectral peak approximately 6 dB higher than in the absence of the LPG (dashed curve). Figs. 2(c) and 2(d) show the corresponding calculated spectra. In the simulation the LPG is treated as a sequence of short mode-coupling T-matrix[13] sections interleaved with nonlinear propagation. This approach is used to account for the nonlinear pulse propagation within the LPG. For a large number of sections it becomes equivalent to the full solution of the nonlinear coupled mode equations for the LPG[14]. Good agreement can be seen between the experimental spectra and those predicted from the approximate numerical model.

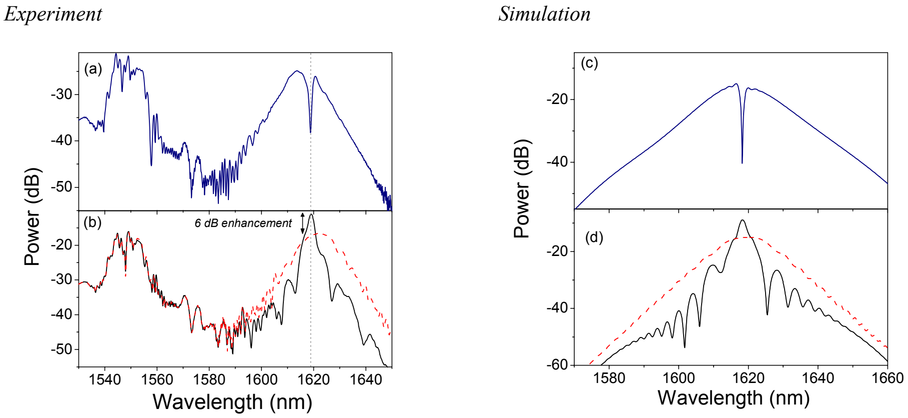
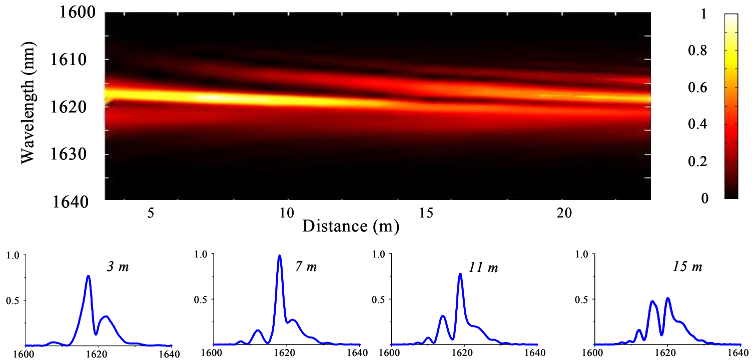


Fig. 2. Spectra at output of 7 m of fiber (a) when power is attenuated before LPG; (b) with no LPG present (red dashed curve); and when high laser power passes through LPG (black solid curve). (c) Simulated spectral response directly after the LPG; (d) Result of simulation showing spectrum of pulse after propagation through a LPG and 7 m of SMF fiber.

In order to map the spectral profile as a function of propagation distance we conducted a series of measurements in which the final fiber was cut back in 1 m increments. The upper diagram in Fig. 3(a) shows a color surface plot of the spectral intensity versus propagation distance, assembled from the experimental data, while below is a selected sequence of plots of the spectrum at various lengths, as indicated. The color surface plot has a distinctive striated shape caused by the different initial phases and different rates of evolution of the enhancement across the soliton. At the cut-back length of 7 m (second spectral snapshot in Fig. 3(a)) the pulse has transformed into a dramatically narrower and sharper profile, with peak spectral intensity enhanced four-fold.

Fig. 3(b) shows simulated results corresponding to Fig. 3(a). Again the data is presented both as a color surface plot, and as representative spectral snapshots. The color surface plot has a striated shape similar to that observed experimentally. The first 0.3 m of the sample contains the LPG, centered at 1618 nm, and the first two spectral snapshots show, respectively, the spectrum of the core mode directly before and after the LPG, demonstrating the sharp loss imposed by the LPG. The succeeding four diagrams are simulated spectral profiles at four positions matching those in Fig. 3(a). They exhibit enhancement and then attenuation in a signature given by the phase and loss response of the LPG. Good agreement can be seen between the experimental results and the simulation.

(a) Experiment



(b) Simulation

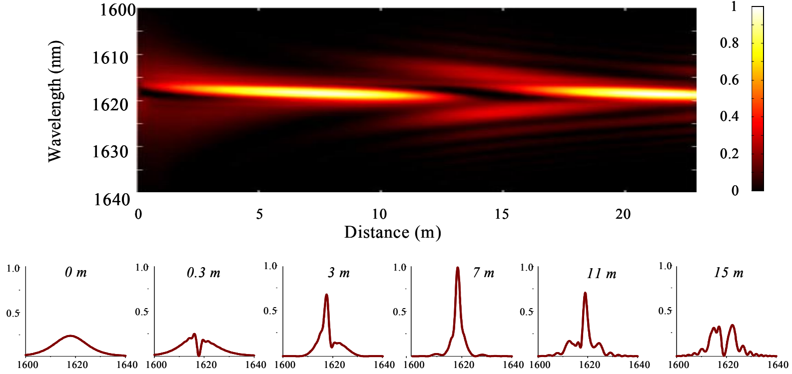


Fig 3. Evolution of LPG enhancement along fiber length for LPG at 1618 nm. (a) Experimental data showing spectral evolution. Top: colour surface plot, bottom: spectral slices at positions as marked. (b) Simulated evolution of spectrum. Top: colour surface plot, bottom: spectral slices at positions as marked.

The temporal characteristic of the spectral enhancement peak is explored in Fig. 4, which shows autocorrelation traces recorded with the LPG turned off (Fig. 4(a)), and with 7 m of propagation after an LPG, which is placed at 1618 nm (Fig. 4(b)). With no LPG present the autocorrelation width is 190 fs, indicating a pulse of FWHM of 225 fs. When the LPG is turned on, the pulse length broadens to produce an autocorrelation width of 880 fs, indicating a near transform-limited pulse of width 560 fs (with a spectral width of approximately 5 nm).

5. DISCUSSION AND SUMMARY

A large local spectral enhancement in excess of 20 dB has been reported by applying a FBG filter to a supercontinuum[3,15]. When spectral filtering is applied to a supercontinuum the local spectral increase can be against a very low background, leading to much greater relative enhancement. Additionally, supercontinuum evolution processes can serve to trap light within a filter singularity (depending on the temporal walk-off of different components of the supercontinuum), thereby leading to more energy gain within the enhancement peak[15]. We have conducted modeling which shows that a strong LPG (producing a phase shift of several π) could produce a comparable enhancement of up to 18 - 20 dB in a geometry using the high power levels and supercontinuum generation of Westbrook *et al.*[15].

Our method of widely tunable enhancement offers the potential to concentrate energy into selected narrow regions of the spectrum of an ultrafast pulse train. In future work we plan to extend our use of LPGs to produce large tunable spectral enhancement in an infrared supercontinuum. Such a tunable supercontinuum source is expected to provide considerable advantage in both frequency comb and spectral slicing applications.

In summary, we have demonstrated a tunable spectral enhancement of a soliton created during nonlinear propagation, by application of an acoustically generated LPG. The spectrum of the soliton can be modified by external adjustment of the RF drive unit creating the LPG.

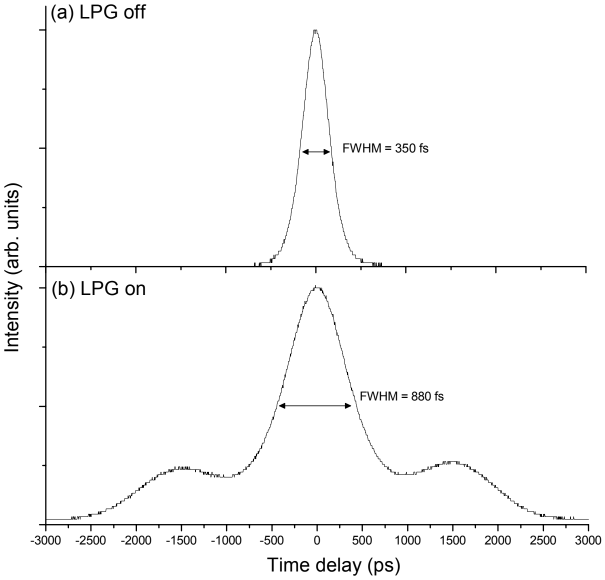


Fig 4. Autocorrelation of pulses at end of fibre propagation (a) with LPG off and (b) with LPG centred at 1618 nm. The pulse with the LPG switched on is seen to be substantially broadened, by a factor of approximately 2.5.

6. ACKNOWLEDGEMENTS

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