Tunable enhancement of a soliton spectrum using an acoustic long-period grating

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Abstract: We demonstrate a scheme for tunable shaping of a soliton spectrum. Specifically, we show a local enhancement of 6 dB in the pulse spectrum by propagating the pulse through a fiber containing micro-bends generated by a flexural acoustic wave – an acoustic long-period grating (LPG) – followed by nonlinear propagation through uniform fiber. The location of the enhancement peak can be tuned by external control of the acoustic frequency of the LPG. We discuss the potential application of this scheme to tunable supercontinuum sources.

OCIS codes: (060.5530) Pulse propagation and solitons; (060.7140) Ultrafast processes in fibers; (060.4370) Nonlinear optics, fibers.

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1. Introduction

Supercontinuum generation is a dramatic phenomenon arising from the interaction of ultrafast optical pulses with condensed media. It is of fundamental interest, and has also generated a number of engineering applications, in frequency metrology, optical tomography and optical communications. Tuning the characteristics of supercontinuum can facilitate many of these applications, and there have been a number of methods described for broad-band tuning, through the use, for example of adaptive pulse shaping [1], or UV post-processing [2]. Local enhancement of an ultrafast pulse spectrum is also of interest. Westbrook *et al.* [3] used an in-line fiber Bragg grating (FBG) to create a narrow spectral peak in a supercontinuum. They demonstrated an increase of the signal-to-noise ratio in frequency comb stabilization for optical metrology [4]. FBGs creating local spectral enhancement have also been used to improve the signal in a coherent optical link comprising a frequency comb [5].

In a recent paper, Li *et al*. [6] investigated the modification of the spectrum of a soliton with a fixed FBG, and observed the growth of narrow dispersive waves as the soliton was swept across the FBG by changing the power. We have shown [7] that a UV-laser written long-period grating (LPG) can be used to produce a more flexible method of local spectral enhancement of an ultrafast pulse spectrum, giving rise to a spectral peak which could be readily tuned or extinguished.

In this paper we demonstrate spectral enhancement using an acoustic LPG [8]. The key advantage is that the acoustic LPG is easily tuned by adjustment of an external radio frequency (RF) source. In addition, by adjusting the RF power the strength of the enhancement can be tuned. We first present theoretical considerations that explain how an acoustic LPG resonance leads, with nonlinear propagation, to a modified pulse exhibiting a periodic cycle between enhancement and suppression. We then present experimental results that show 6 dB of local enhancement, and compare these results to numerical simulations. The method is a novel means for electronic control of the bandwidth of an ultrafast pulse, producing a spectrally narrower pulse which remains close to transform limited. We also discuss the potential of our technique for development of tunable supercontinuum sources.

2. Principle of spectral enhancement

We earlier showed [9] that an intense optical pulse modified by a narrow spectral phase filter evolves in the presence of Kerr nonlinearity into a local spectral enhancement. An amplitude filter can also be used to create spectral enhancement [10]. To understand the mechanism for spectral enhancement caused by a narrow filter [10] 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. Fig. 1(a) schematically illustrates this construction in the cases of phase and amplitude filtering. 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 up to a factor 4 (6 dB), relative to the intensity in absence of the filter [11]. A phase filtered pulse can display even greater enhancement, depending on the magnitude of the phase deviation.

When a dispersive pulse is used for spectral enhancement the picture is complicated by the fact that the unperturbed pulse exhibits self-phase modulation (SPM) [12]. 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 to a soliton allows clearer demonstration of the mechanism of spectral enhancement. The wave number of the soliton is $\eta = \gamma P_{sol}/2$, where P_{sol} is its temporal peak power and γ is the effective Kerr coefficient. The 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 $\omega_{s,}$ and $\beta_2< 0$ is the group velocity dispersion at ω_s. Thus the phase difference between the pulses, $\Delta\varphi(\Omega,z) \cong (\gamma P_{sol}-\beta_2\Omega^2)z/2+\Delta\varphi_0(\Omega)$, where $\Delta\varphi_0(\Omega)$ is the initial phase difference, depends on the propagation distance z. The spectrum exhibits a periodic cycle between enhancement, when

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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). When the filter is offset from the center frequency of the soliton our formula estimates the change in periodicity. For example, when the filter frequency is changed by half of the spectral width then $\beta/\eta \sim 0.3$.

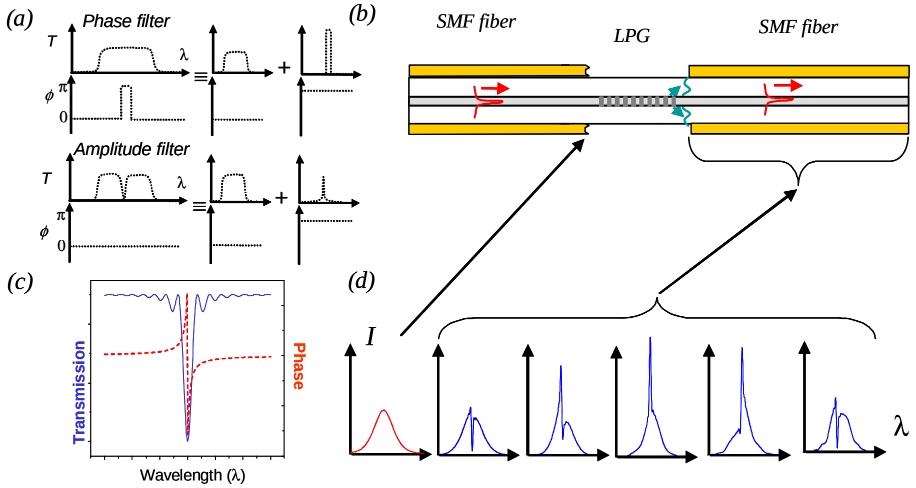

Fig. 1. (a) A pulse modified by either a phase or an amplitude filter can be represented as a superposition of pulses with different initial phases. (b). A pulse propagating in uniform fiber encounters an LPG, which imposes the filter response indicated in (c), where the filter transmission is indicated as a blue curve, and the phase is indicated as a dashed red curve. During further propagation the phase and loss response transform the pulse spectrum. The diagrams in (d) 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 principle of tunable spectral enhancement of a soliton with a LPG is summarized in Fig. 1(b)-(d). Briefly (see Fig. 1(b)), a soliton interacts with a LPG and local changes to the transmission and phase occur, as shown in Fig. 1(c). The result can again be viewed as a superposition of a broadband soliton and a narrowband dispersive pulse. In the case of an optimally coupled LPG, creating 100 % loss at the resonance, we expect to be able to generate at least 6 dB of enhancement of the pulse spectrum from the amplitude component of the filter response, and also a contribution from the phase part. The interaction of the soliton with different parts of the LPG-induced dispersive wave, containing phase and loss components as indicated in Fig. 1(c), produces a spectrum with a distinctive periodic signature (see Fig 1(d)).

3. Experimental setup

In our experiments (see Fig. 2) we use a mode-locked fiber laser emitting 1550 nm pulses with peak power 10 kW and pulse width (FWHM) 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, and peak power of $P_s \sim 2.5$ kW.

The output is spliced to a further 30 cm length of SMF28 fiber, which has been stripped and glued into a cylindrical piezo-electric acoustic horn 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. 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 π/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.

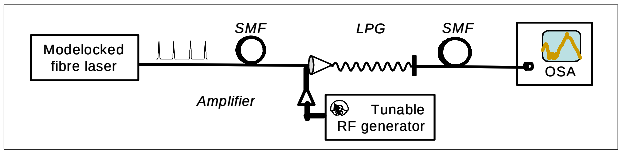

Fig. 2. Experimental layout: SMF = single mode fiber; LPG=long-period grating; OSA=optical spectrum analyzer.

4. Results

Figures 3(a) and 3(b) show spectra measured under various conditions at the output of 7 m of SMF28 fiber after the LPG. Figure 3(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 [13]. The solid curve in Fig. 3(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). Due to the small residual birefringence of the fiber the output spectrum is quite sensitive to polarization. However in our experiment we optimized the input polarization, then kept it constant. Therefore we do not believe the observed spectral changes can be attributed to variation of the polarization state.

Figures 3(c) and 3(d) show the corresponding simulated spectra. In the simulation the LPG is treated as a sequence of short linear mode-coupling sections interleaved with nonlinear propagation, to account for the nonlinear pulse propagation within the LPG. For a large number of sections this method asymptotes 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.

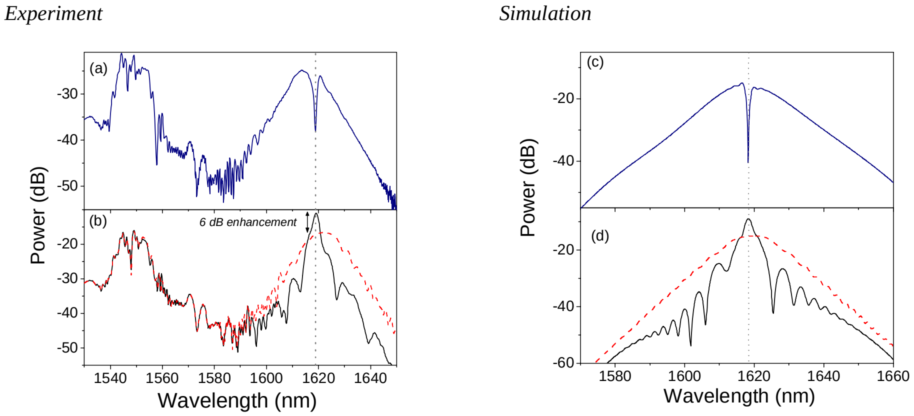

Fig. 3. Spectra at output of 7 m of fiber (a) when power is attenuated before LPG; (b) with no LPG present (red dashed curve); and when high laser power passes through LPG (black solid curve). (c) Simulated spectral response directly after the LPG; (d) Result of simulation showing spectrum of pulse after 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. 4(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 of the enhancement across the soliton. At the cut-

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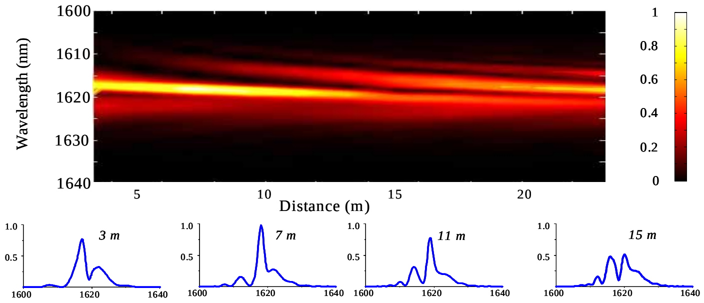
back length of 7 m (second spectral snapshot in Fig. 4(a)) the pulse has transformed into a dramatically narrower profile, with peak spectral intensity enhanced four-fold.

Figure 4(b) shows simulated results corresponding to Fig. 4(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 positions matching those in Fig. 4(a). Good agreement can be seen between the experimental results and the simulation.

The width of the resonance of the LPG used in the experiments is 0.1-0.2 of the initial pulse spectrum. Our estimate based on the discussion in Sec. 3 shows, that for an amplitude filter with such a width, the peak power P_e of the emerging soliton is $P_e \sim$ 0.3-0.6 P_s. Since the energy of a soliton is proportional to the square root of its peak power [12], the emerging soliton contains 0.6-0.8 of the initial energy. The oscillation period is estimated to be $4\pi/(\gamma P_e) \sim$ 8-16 m, consistent with the experimental and numerical results.

(a) Experiment



(b) Simulation

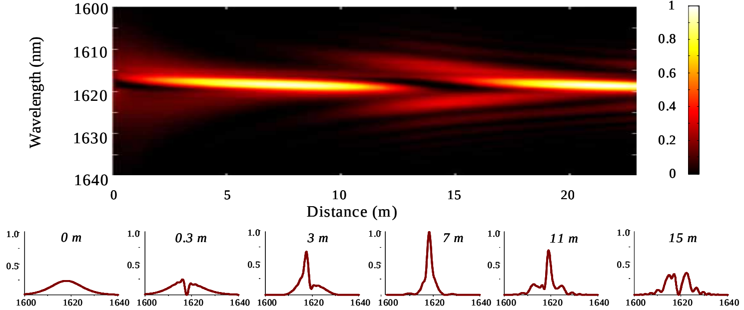


Fig 4. Evolution of LPG enhancement along fiber length for LPG at 1618 nm. (a) Experimental data showing spectral evolution. Top: colour surface plot, bottom: spectral slices at positions as marked. (b) Simulated evolution of spectrum. Top: colour surface plot, bottom: spectral slices at positions as marked.

Figure 5 shows experimental spectra when the RF frequency has been tuned over a 100 kHz range. The diagrams in Fig. 5(a) are when the power is attenuated before the acoustic LPG by applying a tight bend directly ahead of the LPG, thus monitoring the linear LPG response. The individual diagrams show the spectra at different RF drive frequencies showing how the LPG loss is tuned across the soliton by 25 nm with 100 kHz tuning of the RF frequency. In each diagram the corresponding spectrum with no LPG present is shown in grey. The curves in Fig. 5(b) show the corresponding results when a high laser power is permitted to pass through the LPG, followed by two meters of further propagation. Again the successive diagrams are with different RF drive frequencies, while the corresponding spectrum with no LPG present is shown in grey on each diagram. The RF-induced LPG loss is seen to result in an increase in the local spectral intensity in each of the curves of Fig. 5(b).

The range of tuning of 25 nm of the enhancement is limited by the bandwidth of the soliton. The LPG resonance itself can be tuned over 100 nm, however the soliton and the LPG interact only when the soliton coincides spectrally with the LPG filter. A similar issue was discussed by Li *et al*. for FBG-based spectral enhancement [6]. In these measurements we kept the propagation length after the LPG small enough to prevent the soliton walking off the filter position, which has limited the peak enhancement to a factor of 2 in Fig. 5.

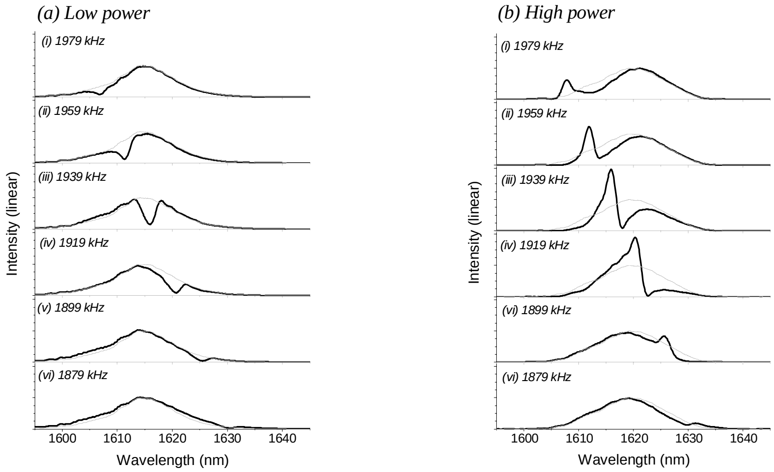


Fig. 5. Measured spectra, plotted on linear scale, at output of 2 m of fiber after LPG as RF frequency is varied, as marked on individual curves: (a) at low power (wave is attenuated before LPG); (b) At high power. The grey curve in each figure shows the spectrum with no RF power applied.

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), leaving more energy 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 regions of the spectrum of an ultrafast pulse, which could be useful for optimizing the channel power in a spectrally sliced wavelength division multiplexing application [16]. 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 wave creating the LPG.

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