Numerical study of Parabolic Pulse Generation in Microstructured Fibre Raman Amplifiers

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Abstract: Numerical simulations are used to demonstrate parabolic pulse generation in a highly nonlinear, normally dispersive microstructured fibre Raman amplifier. The results show that the output pulse shape depends on the sign of the third order dispersion.

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1 Introduction

In recent years self-similar parabolic pulses have generated considerable interest due to their ability to propagate in highly nonlinear media without suffering the usual deleterious pulse distortions whilst maintaining their linear chirp [1, 2]. Parabolic pulses thus offer themselves to a wide range of applications in many areas of optical technology and particularly, as their linear chirp facilitates efficient pulse compression, to the field of high-powered short pulse generation. Initial studies of parabolic pulse generation only considered their formation in optical fibre amplifiers with normal dispersion [3, 2, 4], and recently this work has been extended to examine the effects of the finite width of the gain spectrum [5]. This work has shown that the most efficient parabolic pulse generation occurs when the nonlinear effects are large enough so that the nonlinear propagation dominates over the dispersive propagation which requires a gain medium with a large gain bandwidth to support their growing spectral width.

In this paper we revisit the problem of parabolic pulse generation but this time employing a fibre Raman amplifier in order to exploit the broad Raman gain bandwidth [6]. Furthermore, as these amplifiers are not confined to any particular wavelength, this opens up the possibility for the use of parabolic pulses in optical communication systems which operate around 1.5 μm. Commercial Raman amplifiers based on standard fibre are available and are typically pumped via continuous wave sources operating at several watt power levels. In such a regime we expect that propagation lengths of the order of kilometers would be required for the pulse to become parabolic due to the small gain. As a result, it is questionable whether the nonlinear effects will be sufficiently large, and the dispersive effects sufficiently small, to generate parabolic pulses efficiently. To overcome this problem here we consider using a high power pulsed pump source and, to further enhance the nonlinear effects, a microstructured fibre with a large effective nonlinearity [7]. This has the added advantage that the dispersion properties of microstructured fibres can be tailored such that they operate in the normal dispersion regime, necessary for parabolic pulse propagation, at 1.5 μm. The results of our numerical simulations presented here show that parabolic pulse generation is indeed possible via Raman amplification and that these pulses can be efficiently compressed to the sub picosecond regime.

2 Numerical Model and Simulations

The refractive index profile of the microstructured fibre we used is shown in Fig 1(a) in which the core diameter is 1.1 μm, leading to an effective mode area of 2.5 μm² and and the dispersion profile shown in Fig. 1(b). Such a fibre is similar to that used previously as a Raman amplifier [7] and although no-one has yet demonstrated microstructured fibres with normal dispersion at 1.5 μm it should be possible to fabricate such fibres in the near future. Given the modal properties of the microstructured fibre, pulse propagation can be described by the standard NLSE. Including the effects of Raman amplification the evolution of the
Fig. 1. (a) Fibre profile used in the simulations and (b) associated dispersion parameter $D$ as a function of wavelength.

Pulses in our system can then be described by a modified form of the NLSE [8]:

$$i \frac{\partial \Psi}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 \Psi}{\partial T^2} + \frac{i \beta_3}{6} \frac{\partial^3 \Psi}{\partial T^3} - \gamma \left( 1 + \frac{1}{\omega_0 \partial T} \right) \Psi \int_0^\infty R(T') |\Phi(z, T - T')|^2 dT',$$

(1)

where $\beta_2$ is the GVD parameter, $\beta_3$ is the third order dispersion parameter and $\gamma$ is the effective nonlinearity of the microstructured fibre. We write the nonlinear response function as $R(T) = (1 - f_R)\delta(T) + f_R \delta_R(T)$, assuming that the electronic contribution $\delta(T)$ is nearly instantaneous and that the relative size of the vibrational (Raman) contribution $\delta_R(T)$ is determined by $f_R$ [6]. The field $\Psi$, in comoving coordinates, can be expressed in terms of the amplitude $A_j$ and the phase $\Phi_j$, $j = p, s$, of the pump and the signal beams as:

$$\Psi(z, T) = A_p(z, T) \exp[i\Phi_p(z, T)] + A_s(z, T) \exp[i\Phi_s(z, T)].$$

(2)

where the signal field is downshifted in frequency by 13.2 THz from the pump beam corresponding to the peak of the Raman gain spectrum. An important feature of Eq. (1) is the inclusion of the time-derivative operator in the nonlinear term which is necessary to ensure that the photon number is conserved, and not the optical energy, so that the Raman interaction is described correctly.

Our simulations consider the injection of a Gaussian signal pulse at 1.55 $\mu$m with a 1 ps duration (fwhm), and a peak power of 5 W together with a 315 ps (fwhm), 20 W super-Gaussian pump pulse at 1.45 $\mu$m. The fibre parameters which were calculated from the refractive index profile shown in Fig. 1 are: $\beta_2 = 0.126 \text{ps}^2\text{m}^{-1}$, $\beta_3 = -0.001 \text{ps}^3\text{m}^{-1}$, $\gamma = 0.041 \text{W}^{-1}\text{m}^{-1}$, and the fractional contribution of the delayed Raman response $f_R = 0.18$ [6]. The output signal pulse and spectrum are plotted in Fig. 2(a) after 20 m of propagation corresponding to a total pulse gain of $\sim 25 \text{dB}$. The top curves show the intensity profile, plotted on a log scale, together with the chirp, plotted on a linear scale, (solid lines), whilst the bottom curve shows the pulse spectrum. Despite the asymmetry in the output pulse, it is clear that this pulse displays the characteristic features of a parabolic pulse with a linear chirp including both the low intensity exponentially decaying wings and the oscillations on the spectrum [9]. Further confirmation is provided by the good agreement between the output pulse and the parabolic and linear fits to the intensity profile and the chirp, respectively (circles).

Although some of the asymmetry in the output pulse can be attributed to the shape of the gain spectrum [6] it is, in fact, primarily due to pump depletion where the leading edge of the pulse experiences more gain than the trailing edge. This effect is significant because the signal intensity eventually exceeds that of the pump intensity and, due to the large gains necessary to amplify a pulse to the parabolic regime, it is a difficult problem to avoid. An important consequence of the effects of the pump depletion is that the formation of a parabolic pulse is highly dependent on the sign of the third order dispersion. We have found that when $\beta_2 < 0$ then the asymmetry induced by the third order dispersion acts in the opposite direction to that induced by the pump depletion and thus can actually improve the quality of the output pulse. However, when $\beta_2 > 0$ the effects of the asymmetries combine which destroy the linearity of the chirp and can lead to the pulse developing oscillations on a long sloping training edge. Such effects can be seen in Fig. 2(b) where the top curves show the intensity profile and chirp, plotted on linear scales, and the bottom curve shows the spectrum of the output pulse generated under the same conditions as that in Fig. 2(a) but this time with
$\beta_3 = 0.001 \text{ps}^3\text{m}^{-1}$. Although in standard single-mode fibres $\beta_3$ is typically positive this is not necessarily the case in microstructured fibres. Fig. 1 shows a plot of $D (= d\beta_3 / d\lambda)$ as a function of wavelength for a theoretical model of the fibre on which the fibre parameters used in Fig. 2 were based. Clearly both the condition that $\beta_2 > 0$ (necessary for parabolic pulse formation) and $\beta_3 < 0$ are satisfied.

To demonstrate the potential use of Raman amplified parabolic pulses for high-powered short pulse generation we considered the compression of the pulse in Fig. 2(a) via a simple linear grating pair. As a result of the asymmetry in the pulse we found that the compressed pulse develops a long pedestal on the trailing edge. Nonetheless, this still yields a pulse with a fwhm of 700 fs and a peak power of 1.4 kW and we expect that these results can be improved with the inclusion of third order dispersion compensation in the compression stage.

3 Conclusions

In conclusion, we have used numerical simulations to demonstrate parabolic pulse formation in a microstructured fibre Raman amplifier. The results have shown that the effects of pump depletion can be reduced with the appropriate sign of the third order dispersion and that such values of $\beta_3$ are currently available in microstructured fibres. The case with which these pulses can be compressed suggests that Raman amplified parabolic pulses offer an efficient source of high-powered short pulses unrestricted by wavelength. We expect that they will find wide application in many areas of optical technology.

References