Optics Communications 389 (2017) 197–202

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Impact of amplitude jitter and signal-to-noise ratio on the nonlinear spectral compression in optical fibres

Sonia Boscolo[a], Julien Fatome[b], Christophe Finot[b,*]

[a] Aston Institute of Photonic Technologies, School of Engineering and Applied Science, Aston University, Birmingham B4 7ET United Kingdom
[b] Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR 6303 CNRS-Université de Bourgogne-Franche-Comté, 9 avenue Alain Savary, BP 47870, 21078 Dijon Cedex, Franceí

ARTICLE INFO

Keywords:
Nonlinear spectral compression
Optical regeneration
Nonlinear fibre optics

ABSTRACT

We numerically study the effects of amplitude fluctuations and signal-to-noise ratio degradation of the seed pulses on the spectral compression process arising from nonlinear propagation in an optical fibre. The unveiled quite good stability of the process against these pulse degradation factors is assessed in the context of optical regeneration of intensity-modulated signals, by combining nonlinear spectral compression with centered bandpass optical filtering. The results show that the proposed nonlinear processing scheme indeed achieves mitigation of the signal's amplitude noise. However, in the presence of a jitter of the temporal duration of the pulses, the performance of the device deteriorates.

1. Introduction

Self-phase modulation (SPM) in optical fibre is ordinarily associated with spectral broadening of an ultra-short optical pulse. However, for appropriate initial conditions of the input pulse, SPM can result in significant spectral compression [1]. Indeed, SPM causes spectral compression or broadening depending on the initial frequency modulation (chirp) of the pulse electric field. Specifically, a pulse with a negative chirp, such as that imparted by an anomalously dispersive element, is compressed by the effects of SPM [2–4]. This method of spectral compression has been implemented using various types of fibres [5–7] and has also been theoretically investigated in centimeter-long nonlinear waveguides [8]. It is suitable for a very large range of wavelengths including Ti: sapphire wavelengths [5], the widely used 1-μm [7,9,10] and 1.55-μm [11] windows and the emerging 2-μm band [12]. The process can also sustain simultaneous amplification of the pulse [9,10,12], thereby providing an attractive solution to convert ultra-short pulses delivered by femtosecond oscillators into high-power, near-transform-limited picosecond pulses, and to counteract the spectrum expansion that usually occurs with the direct amplification of picosecond structures. The concept can be extended to cascade amplifier systems in which pulse spectrum narrowing allows its efficient amplification in the subsequent stages [13], and fibre laser cavities where spectral compression components have been employed in the model of an efficient similariton laser [14].

Several recent theoretical and experimental studies [7,11,15–17] have been concerned with the reduction of the intensity level of the residual side lobes in the compressed spectrum that, in the nonlinearity-dominant regime of propagation, result from the mismatch between the initial linear chirp of the pulse and the SPM-induced nonlinear chirp. However, to date, the problem of the stability of the spectral compression process against various forms of quality degradation of the initial pulses, such as amplitude fluctuations or broadband noise, has not been yet considered to our knowledge. In this paper, after recalling the principle of SPM-driven spectral compression and describing the operational parameters of the system, we analyze the impact of amplitude jitter and degraded optical signal-to-noise ratio (OSNR) of the seed pulses on the compression process by means of extensive numerical simulations. Remarkably, our results show that the spectral compression is rather stable against these pulse degradation factors, thereby revealing its potential for use in the context of all-optical regeneration. The computed intensity transfer function (TF) associated with the process is indeed shown to achieve both reduction of the amplitude fluctuations and improvement of the extinction ratio of an intensity modulated signal. However, the amplitude noise rejection ability of the device diminishes for operation at degraded OSNR.

* Corresponding author.
E-mail address: christophe.finot@u-bourgogne.fr (C. Finot).

http://dx.doi.org/10.1016/j.optcom.2016.12.033
Received 10 November 2016; Received in revised form 13 December 2016; Accepted 14 December 2016
0030-4018/

2. Model and situation being investigated

Our numerical simulations of the spectral compression process in a fibre system are based on the standard nonlinear Schrödinger equation (NLSE) [18]:

$$i\frac{\partial\psi}{\partial z} + \gamma|\psi|^2\psi - \frac{1}{2}\beta_2\frac{\partial^2\psi}{\partial t^2} = 0, \qquad (1)$$

where $\psi(z,t)$ is the complex electric field envelope, z is the propagation distance, t is the reduced time, β_2 is the group-velocity dispersion (GVD) parameter and γ is the coefficient of cubic nonlinearity of the fibre. This equation neglects the effect of fibre loss, as well as higher-order linear and nonlinear effects. Although these effects can have noticeable impact on pulses shorter than 1 ps, here we neglect them as the leading-order behavior is well approximated by Eq. (1).

Contrary to some recent studies of spectral compression in fibre that have used incoherent initial conditions [19,20], we consider a transform-limited pulse with a Gaussian intensity profile $\psi_0(t) = \sqrt{P_0}\exp(-t^2/2T_0^2)$ as the initial condition for our study. The parameters T_0 and P_0 are a characteristic temporal value (the half-width at $1/e$-intensity point in the case of a Gaussian-shaped pulse) and the peak power of the initial pulse, respectively, and can be used to normalize the problem being studied [16]. The linear negative temporal chirp required for spectral compression to take place can be imprinted onto the initial pulse by stretching the pulse in the temporal domain in an anomalously dispersive medium, such as a pair of diffraction gratings [21,22], a prism pair [3,5], a fibre Bragg grating, or a segment of hollow core [9] or standard [11] fibre with anomalous GVD (and very low nonlinearity). As a result of GVD (described by Eq. (1) with γ=0), the different spectral components of the pulse acquire a frequency dependent delay. Even though such phase changes do not affect the pulse spectrum, they lead to temporal broadening of the pulse and a time dependence of the pulse phase. If A denotes the temporal broadening factor, the peak power of the pulse will drop by the same factor ($P_1 = P_0/A$) owing to the conservation of energy. Moreover, in the far-field regime (i.e., when $A >> 1$) the temporal phase becomes parabolic. The so obtained negatively linearly chirped pulse is then spectrally compressed in a nonlinear fibre.

For the purpose of illustration, we consider here an initial pulse with a full-width at half maximum (FWHM) duration of 2 ps at the wavelength 1550 nm. After dispersive propagation, the pulse is stretched by a factor of A =20 and has a peak power of P_1 =2 W. Nonlinear spectral compression of the pulse is then achieved through propagation in a highly nonlinear fibre (HNLF) with the Kerr coefficient γ=10 W^{-1}.km^{-1} and a low GVD coefficient of β_2 =1 ps^2 km^{-1}. With such parameters that are typical of various demonstrations of spectral compression due to SPM in fibre [11], the nonlinearity-dominant regime of propagation is applicable [16].

Fig. 1 illustrates the pulse evolution over a fibre length of 1250 m. Significant spectral compression occurs in the fibre, followed by splitting of the pulse spectrum into an increasing number of substructures (Fig. 1(a)). The narrowing of the pulse spectrum is quantified with the spectral compression factor C_{fwhm} (Fig. 1(b1)) defined as the ratio between the spectral FWHM width at some distance in the fibre and the entrance of the fibre. We also assessed the quality of the pulse spectrum by computing the spectral brilliance of the pulse at its central frequency (Fig. 1(b2)). The highest brilliance in the central region of the pulse spectrum is achieved at the propagation distance z_C =750 m, featuring a close to eightfold increase with respect to its value at the fibre entrance. The corresponding compressed spectrum is plotted in Fig. 2(a). The spectral compression factor is above 10 at z_C. The optimum propagation distance z_C in terms of spectrum quality differs from both the distance z_F at which the temporal phase of the pulse becomes flat near the pulse center [16], and the distance of maximum spectral compression factor where the compressed spectrum is impaired by significant pedestals containing a non-negligible part of the pulse energy. The abrupt drop of C_{fwhm} after the distance at which it is at its maximum is due to an increase in the intensity level of spectral satellites above the −3 dB threshold used for its computation. The pulse spectrum splits up shortly after the distance of maximum C_{fwhm} and, at a distance of around 1100 m energy is no longer present in the vicinity of the central frequency.

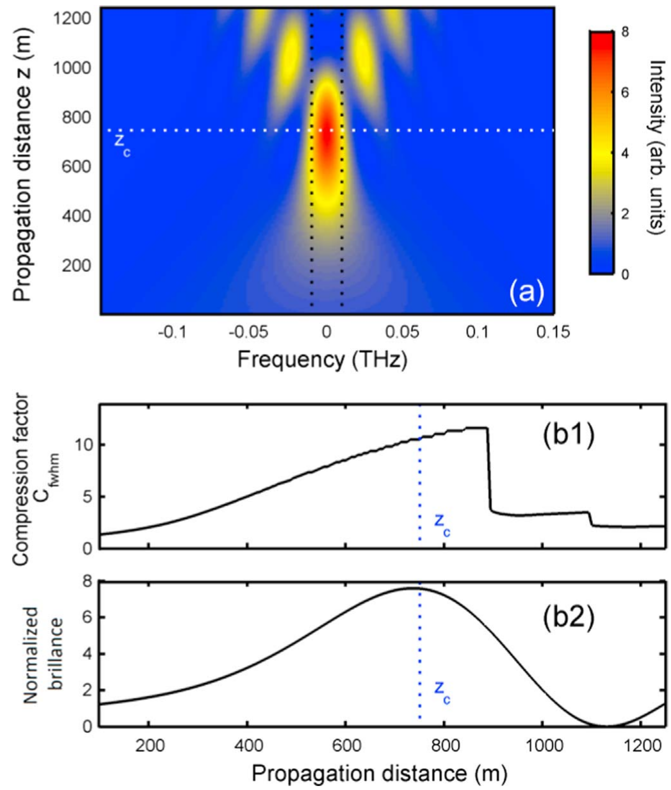

Fig. 1. Spectral compression of an initial picosecond Gaussian pulse with the stretching factor A=20 in a HNLF. Longitudinal evolution of: (a) the spectral intensity profile, (b) the FWHM spectral compression factor and the spectral brilliance at the central frequency. The spectral brilliance is normalized to its initial value.

3. Impact of initial amplitude jitter and OSNR

In this section, we describe how the spectral compression process is affected by factors that may deteriorate an initial train of pulses. Hereafter, we will consider the optical spectrum obtained at the propagation distance of optimum compression z_C. First, we studied the effect of fluctuations in pulse peak power. To this end, we considered 1000 individual input pulses with the peak power P_1, and we superimposed a random independent peak power fluctuation to each of them governed by the n-th extraction of a Gaussian random variable with a relative standard deviation (or root-mean-square (rms) variation) of 8%. In Fig. 2(a), we compare the average spectrum with the spectrum obtained in the absence of input fluctuations. We can see that the results are very close to each other, indicating that amplitude jitter does not heavily impact the average spectral behavior. However, when the spectra of individual pulses are overlapped together (Figs. 2(b1) and 2(c)), it appears that the different regions of the spectrum are not equally affected by the initial jitter of the pulses: while the central part of the spectrum turns up to be very stable, the spectral wings suffer from high fluctuations. The relative standard deviation of the output spectral intensity varies from 8% in the central lobe up to 120% in the side lobes. Such frequency dependence of a nonlinearly reshaped spectrum in normally dispersive fibres has been described in the context of super-continuum generation for wavelength-division multiplexed pulse sources [23], but it has never been discussed in connection with the process of spectral narrowing. We ascribe the high