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Limit for Pulse Compression by Pulse Splitting

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Abstract

We have detected a fundamental pulse-compression limit for high-nonlinear fibers in the normal dispersion regime near the zero-dispersion wavelength. The desired generation of a broadband continuum by self-phase modulation is limited by already small amounts of third-order dispersion, which results in pulse splitting above a critical pulse power. We investigate the critical fiber length in dependence on pulse- and fiber parameters.

1 Introduction

For typical semiconductor laser based pulse sources are still limited to approximately 1 ps in duration, an external compression scheme must be employed to generate femtosecond optical pulse trains with GHz repetition rate [1]. An effective method for pulse compression is the pulse evolution in a high-nonlinear fiber with normal group-velocity dispersion (GVD) followed by an anomalous dispersive medium [2]. The key step in this technique is to take advantage of the wider bandwidth generated by self-phase modulation (SPM) which enables support for shorter pulses. This bandwidth can be much enhanced close to the zero-dispersion wavelength (ZDW), where β_2 is small, but with the drawback, that in particular third-order dispersion (TOD) gains influence. We show that even a small amount of TOD can lead to a pulse break-up above a certain pulse power, which represents a fundamental limit to this compression technique.

2 Numerical modeling

We have simulated the pulse compression by numerically solving the generalized nonlinear Schrödinger equation (GNLSE) for the slowly varying complex envelope $A(z, \tau)$ of a pulse:

$$\frac{\partial A}{\partial z} = -\frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial \tau^2} + \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial \tau^3} - \frac{\alpha}{2} A + i\gamma |A|^2 A \tag{1}$$

The linear terms on the right-hand side represent the GVD, namely second-order (SOD), and third-order (TOD) dispersion, and the attenuation due to the fiber loss α. The nonlinear term represents the SPM. For the numerical solution of Eq. (1) we use a standard de-aliased pseudo-spectral method. The integration is performed by an eighth-order Runge-Kutta integration scheme using adaptive stepsize control [3].

3 Pulse compression

According to the compression scheme in [4], a pulse with an initial envelope

$$A(0,t) = \sqrt{P_0} sech(t/T_0) \tag{2}$$

propagates through a high-nonlinear fiber (HNLF) near the ZDW in the normal dispersion regime (β_2 small, but positive) and gets spectrally broadened and chirped. Afterwards, the chirped pulse is launched into a standard single mode fiber (SMF) for a subsequent recombination of its frequency components which leads to the desired compression.

The efficiency of the compression scheme is determined by the input pulse parameters and by the propagation through the HNLF. At the leading edge of the pulse, the SPM causes a red shift. The trailing edge of the pulse experiences a corresponding blue shift. The GVD tends to decrease the spectral width and in turn increases the temporal width of the pulse. The condition for optimum pulse compression was determined theoretically in [2]. There, the two important fiber parameters determining the performance of a fiber compressor are the nonlinear length $L_{NL} = 1/(\gamma P_0)$ and the dispersion length $L_D = T_0^2/|\beta_2|$. The optimum compression factor $F_c = T_0/T_c$, where T_c is the width of the compressed pulse, was found to be [2]

$$F_c = 0.63\sqrt{\frac{L_D}{L_{NL}}} = 0.63 T_0 \sqrt{\frac{\gamma P_0}{|\beta_2|}}\,. \tag{3}$$

According to (3) high compression factors can be reached by using a high nonlinearity γP_0 and small $|\beta_2|$, i.e. by operating near the ZDW. However, in practice this

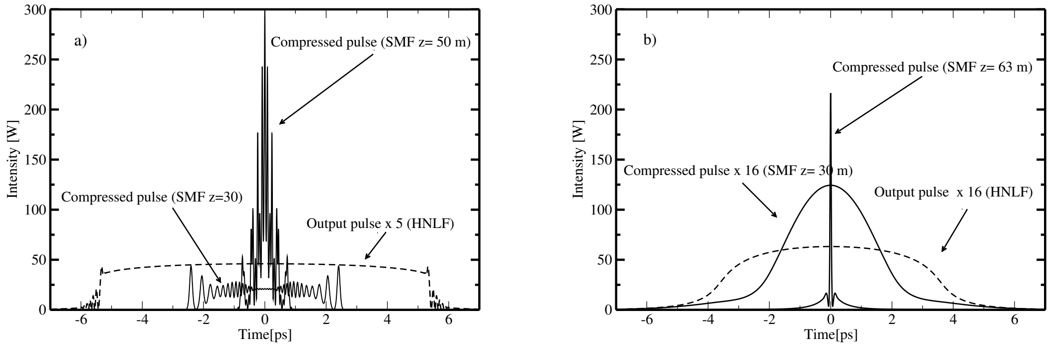

Figure 1: Pulse shapes after the HNLF (dashed) and in the dispersion compensating SMF (full lines). a) above crtitical power for optical wave-breaking, which is visible by the oscillations at the steep edges of the pulse. b) moderate power, no optical wave-breaking occurs.

compression scheme is limited by the optical wave-breaking which occurs for high input powers and long propagation distances, and which we illustrate in Fig. 1a) for an overcritical pulse power. Due to the dominating SPM increasingly frequency components are generated, which cause the rectangular shape of the pulse after the HNLF. In turn, the steep edges at the leading and trailing part of the pulse lead to optical wave breaking, which then reduces the spectral broadening. After the onset of optical wavebreaking the pulses can still be compressed, see Fig. 1a), but the generation of even shorter pulses is prevented. Other effects will occur, which are not of interest here.

We will from now restrict to powers below the critical value for optical wavebreaking, where pulse compression should work properly as drawn in Fig. 1b). However, in this regime the first relevant higher-order effect is TOD, especially evocated for small $|\beta_2|$, which in turn can also degrade the optimal compression ratio, as we will show now.

4 Pulse Splitting

We study now the impact of TOD on our pulse compression scheme by a practical example. A sech-pulse with $T_0 = 2.1$ps is launched into the HNLF with $\beta_2 =$

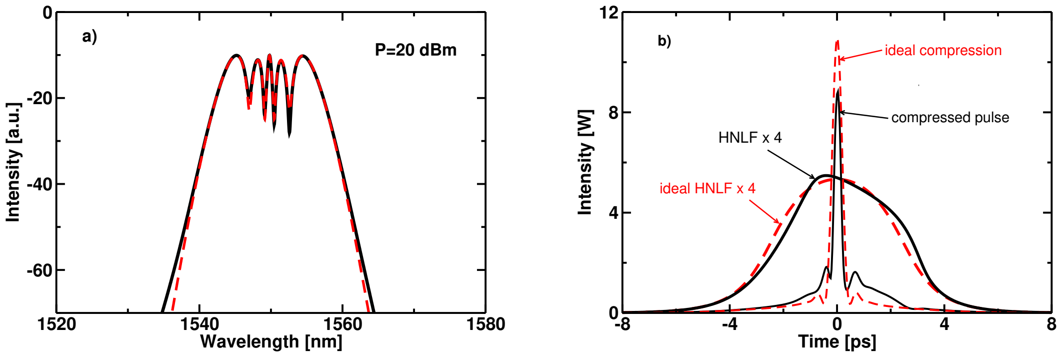

Figure 2: Nearly ideal compression for a pulse with $P_{av} = 20$ dBm and $T_0 = 2.1$ ps. a) spectrum, mainly determined by SPM. b) temporal shape. Higher-order terms are unimportant and the compression is close to the optimum (dashed).

$0.13 ps^2/km$, close to the zero dispersion wavelength (ZDW), centered at $\lambda = 1555$ nm. The fiber is 789 m long and has a nonlinear coefficient of $\gamma = 10.5\, W^{-1}km^{-1}$, with a fiber loss of $0.84\, dB/km$. Figs. (2),(3) show the calculated pulse shapes and spectra after the spectral broadening in the HNLF and the subsequent pulse compression in the SMF. [1] The pulses are compared with the ideal case, where TOD is excluded. For moderate power (Fig. 2) the structure of the resultant spectrum is

[1] The length of the compensation SMF was numerically optimized.

mainly determined by SPM and shows the typical multi-peak structure characteristics. The compression is close to optimum, but already a small asymmetry induced by TOD can be observed, although unimportant. The contribution of TOD appears with increasing bandwidth, achieved by a further increase of the power, c.f. Fig. 3. The pulse shape then experiences an asymmetric temporal developement with an enhanced transfer of power from the trailing portion of the pulse to the leading one. Hence, a narrow peak forms at the front of the pulse which would grow with further propagation through the HNLF. At a certain threshold ($P_{IN} = 23.75$ dBm, Fig. 3), the evolution of the pulse changes dramatically, because SPM is no longer dominant for the characteristics of the spectrum. The transmitted pulse in the HNLF exhibits

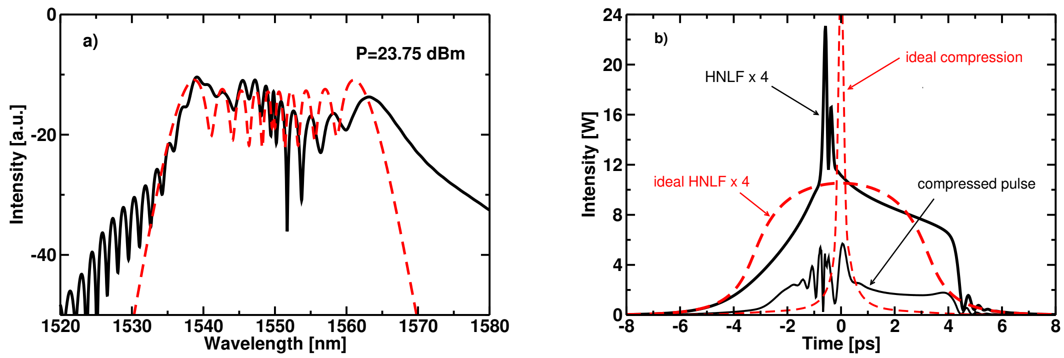

Figure 3: Pulse-breakup ($P_{av} = 23.75$ dBm). a) spectrum, with strong asymmetry to the blue side and complicated non-SPM characteristics. b) temporal shape. Increase of the peak intensity on the leading side and asymmetric splitting of the pulse. Full lines: with TOD, dashed: without TOD.

an asymmetric splitting and the injection into the SMF leads not to the desired compression behavior anymore, such that from here the compression scheme fails completely. Further increase of power causes pulse shapes with multiple sub-pulse signature. Thus, this splitting represents a fundamental limit for pulse compression and suggests that operation below a critical power is necessary for optimal compression. We notice here that this pulse splitting has been verified also experimentally in [4]. The HNLF used in the experiments exhibits a strong impact of TOD at the ZDW and has normal dispersion below $\lambda_0 = 1555$ nm, but has anomalous dispersion above this wavelength. To exclude the impact of possible anomalous dispersion on the pulse splitting we have numerically checked similar constellations of fiber coefficients with completely normal dispersion over the whole spectral range, which revealed the same compression limit behavior. Fig. 4 shows an example for pulse splitting of a sech-pulse with $T_0 = 2.1ps$ and $P_0 = 10W$ for normal dispersion over the whole wavelength range, which we managed by switching on a small β_4.

We have also investigated the dependence of the pulse splitting on the input parameters. The pulse splitting depends on L_{NL} and on the ratio $L_D/L'_D(= |\beta_3/\beta_2|/T_0)$,

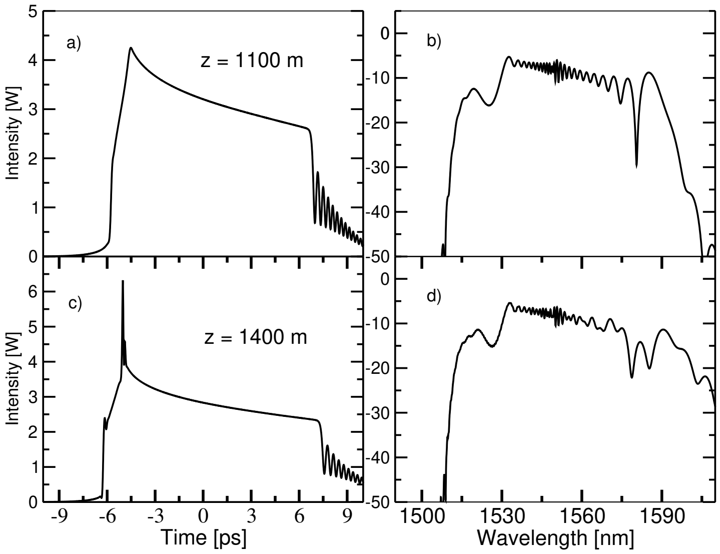

Figure 4: Simulated initial *sech*-pulse propagating down a HNLF with normal dispersion over the whole spectral range: $\beta_2 = 0.2ps^2/km$, $\beta_3 = 0.01ps^3/km$ and $\beta_4 = 1.7 \cdot 10^{-4}ps^4/km$. Evolution of shape (left) and spectrum (right).

where $L'_D = T_0^3/|\beta_3|$ is the dispersion length associated with TOD. This dependence is illustrated in Fig. 5. For fixed ratio L_D/L'_D the critical distance z_{cr}, where the pulse splitting sets in, is proportional to L_{NL}, as shown in Fig. 5a). In Fig. 5b) the dependence of z_{cr} on the ratio L_D/L'_D for fixed L_{NL} is shown. For example, for given dispersion β_2 and β_3 a decrease of T_0 leads to an increase of the ratio L_D/L'_D and hence reduces the critical length. In turn the critical peak power for pulse splitting decreases with a decrease of the temporal width of the injected pulse.

5 Conclusion

We have analyzed the pulse-compression scheme for high-nonlinear fibers in the normal dispersion regime followed by anomalous dispersive single mode fibers. After confining to optical nonlinearities below the onset of hindering optical wavebreaking we detected another fundamental compression limit near the zero-dispersion wavelength, which is caused by third order dispersion (TOD). The desired generation of a broadband continuum by SPM is perturbated by already small TOD, which results in pulse splitting above a critical pulse power and which can not be compensated after its appearance. We showed, that the critical length decreases with increasing pulse power and decreasing pulse width, and decreases with increasing ratio $|\beta_3/\beta_2|$ as well.

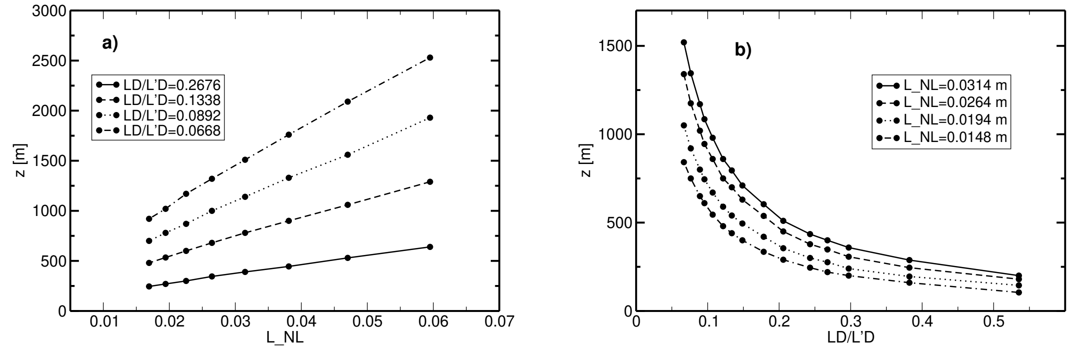

Figure 5: Critical distance z_{cr}, where the pulse splitting sets in, in dependence of a) the nonlinear length L_{NL} for different fixed ratio L_D/L'_D and b) in dependence of L_D/L'_D for diffferent L_{NL}.

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