# Similariton Generation in Fibre Optic Amplifiers and Lasers

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## Abstract

Self similar solutions of nonlinear partial differential equations have been found with applications in many areas of Physics. The techniques used to find these solutions have been recently been applied to develop solutions of the Nonlinear Schrodinger Equation (NLSE) governing optical pulse propagation, where they are known as similaritons. This talk will discuss not only the well known parabolic and hyperbolic similaritons but also self similar solutions appropriate to amplifiers with gain saturation, together with their applications in high power amplifiers, and similariton lasers.

## 1. Introduction

Self similar solutions of nonlinear partial differential equations are chirped solutions which maintain their mathematical form, whilst being scaled in time or amplitude. Standard techniques for finding such solutions have been developed with applications in nonlinear acoustics, plasma physics and other areas. Recently these techniques have been applied to locate new solutions of the NLSE, which are finding increasing applications in high power amplifiers and mode locked fibre lasers.

Of particular interest are the solitary pulse solutions which are known as similaritons. The various different similariton solutions applying to pulse propagation under the influence of the NLSE and the LSE provide a route to the development of stable pulsed lasers, with the potential to generate much power pulse energies than are available through soliton laser systems. Several research groups have recently reported the development of similariton lasers. In our laboratories the design of these lasers has benefited materially from the development of a full theoretical model of their operation.

## 2. Similariton Solutions

There are three different experimental regimes areas where self similar propagation is important. These include linear propagation, and nonlinear propagation in the normal and the anomalous dispersion regimes.

### 2.1 Linear Propagation

The best known example of self similar propagation is the propagation of a Gaussian pulse in a single mode fibre under the influence of dispersion alone. In this case the pulse always remains a Gaussian but its width increases and it develops a linear chirp on the underlying electric field as it propagates (Agrawal 2001). This example is well known, but it is also possible to show that any linearly chirped pulse of arbitrary shape, will propagate self similarly to a high degree of approximation, except in particular regions of propagation which can be readily identified mathematically.

### 2.2 Nonlinear propagation in the normal dispersion regime

Anderson first showed that a linearly chirped parabolic shaped pulse was a solution to the NLSE in the normal dispersion regime in the absence of gain or loss (Anderson et al. 1993). More recently it has been shown that in the presence of gain, any arbitrary input pulse will evolve to a parabolic shape with a linear chirp (Kruglov et al. 2002). This is an asymptotic similariton solution, and the speed with which the pulse evolves to this shape depends on a number of conditions. These include the initial pulse shape and chirp, and dispersion and nonlinearity coefficients of the fibre. The final pulse shape and chirp however, depend only on the initial pulse energy.

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### 2.3 Nonlinear propagation in the anomalous dispersion regime

In contrast to the asymptotic solutions which apply in the normal dispersion regime, the anomalous dispersion regime supports exact chirped solutions with a hyperbolic secant shape, which correspond to steadily compressing solutions. In the limit, these pulses are predicted to compress to an arbitrary degree, but in practice the NLSE becomes an inadequate description of the pulse propagation, as the pulses become very short. Our theoretical investigations have shown that these similariton solutions apply down to a pulse duration of about 200fs in typical optical fibres at communications wavelengths. Below this duration, the effects of Raman gain, third order dispersion and other effects perturb the exact self similar evolution.

Our experimental work has verified the compression of these similaritons down to around 250fs. It is important to note the qualitative difference between this sort of compression, which is mediated by the NLSE directly, and adiabatic soliton compression which typically involves much longer fibres, to ensure the adiabatic approximation is met. Indeed the main challenge with building a fibre compressor using similariton compression is generally with developing the required dispersion profile in a short fibre length.

## 3. Similariton Lasers

The first demonstration of the existence of parabolic pulses was made using a high power amplifier at 1micron wavelength, using a seed pulse of about 200fs duration (Fermann et al, 2000). The development of the seed pulse was challenging, and thus the possibility of constructing a laser which self consistently developed a parabolic shaped chirped output pulse was attractive, and several groups have pursued this. This has led to the development of similariton lasers of different designs, where the operating regimes have often been found by trial and error.

In our laboratory we have concentrated on developing a full mathematical model of the operation of a fibre based laser in which a parabolic similariton develops in a gain section which exhibits normal dispersion, and a selected spectral portion of the resulting pulse is recompressed in the anomalous dispersion regime. The laser also includes a mode locking mechanism to ensure the development of pulsed solutions. We have discovered various regions of operation of such lasers including a bistable operating regime where the laser outputs a stream of pulses of alternating characteristics.

Practical lasers have been constructed using the mathematical model, and a typical output from one of these lasers is shown in Figure 1. It exhibits the characteristic parabolic shape of the normal dispersion similariton in both the time and the spectral domain, accompanied by a linear chirp which can be measured using FROG based pulse characterisation equipment(Arguergaray et al, 2010).

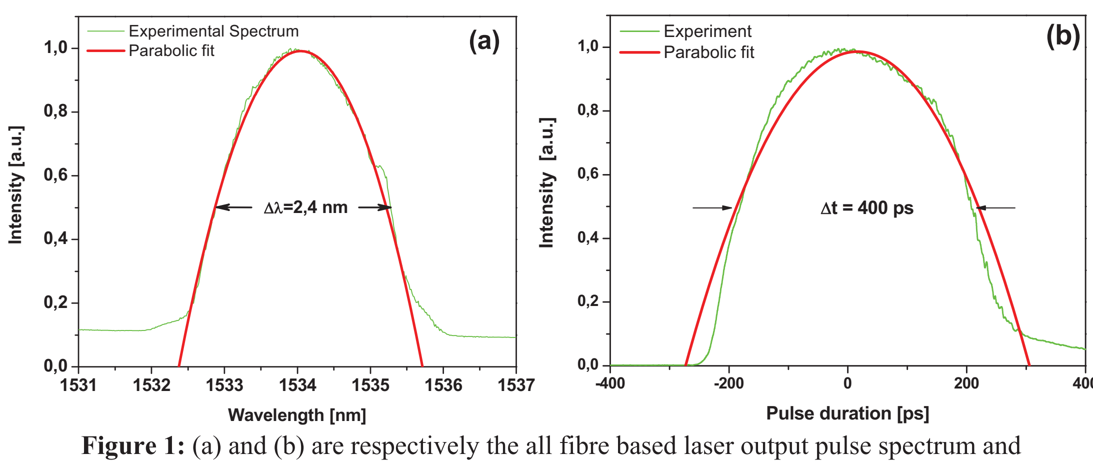


**Figure 1:** (a) and (b) are respectively the all fibre based laser output pulse spectrum and temporal shape with a parabolic fit.

Whilst the firWhilst parabolic pulse systems were based on Yb doped fibre amplifiers, and thus operated at about 1 micron wavelength, the laser which yielded the results shown in Figure 1 operated at in the C band, and was based on a Raman amplifier gain section with normal dispersion. The output pulse can linearly compressed down to 6 ps near to the Fourier Limit in 12.8 km of single mode fibre (SMF 28) by taking advantage of its linear chirp. The use of a Raman gain section ensures that the laser could be operated at any other wavelength, subject only to the availability of suitable pumps and fibres.

## 4. Amplifiers with gain saturation

We have recently investigated the case of a pulse propagating in a high power amplifier under the influence of gain saturation in the normal dispersion regime. It is important to include gain saturation when modelling practical high power amplifiers, and we have recently investigated theoretically, and confirmed numerically the shape of the self similar solutions which develop in amplifiers subject to gain saturation. These solutions are qualitatively different for low and high saturation energies. At high saturation energies, the pulses evolve into the well known parabolic shape, but at low saturation energies where self phase modulation effects do not dominate, the propagation is more characteristic of the LSE regime. An example is shown in Figure 2 where the pulse shape is well fitted by a parametric product of a Gaussian and a Super-Gaussian shape whilst the chirp on the pulse remains linear.

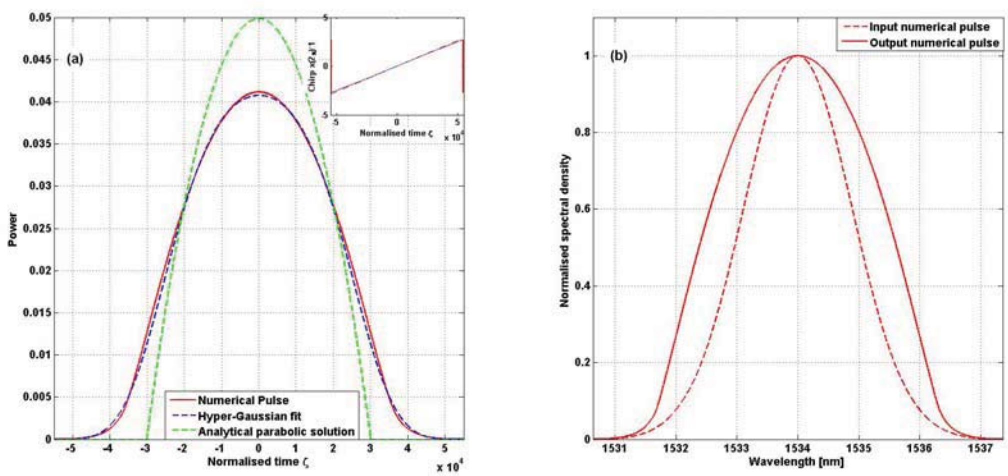


**Figure 2:** (a) and (b) are respectively the output pulse temporal shape and spectrum after propagation in an amplifier with a low saturation energy.

## 5. Conclusions

The study of self similar pulse propagation in optical fibre based lasers and amplifiers has led to the development of high power pulse sources and similariton lasers. The self similar analysis techniques are powerful methods of finding solutions to the NLSE and related differential equations. The theoretical techniques which have been developed to describe these systems also leads to a better understanding of their operation, and further development of these similariton systems could lead to a range of new applications for these pulse sources.

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