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Research Papers

Similariton Compression in a Comb like Dispersion Decreasing Fibre

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Abstract

Optical pulse compression using similariton propagation in an optical fibre with decreasing dispersion has been demonstrated for the first time. This compression scheme is a practical application of the sech-similariton solution to the generalized nonlinear Schrodinger equation (NLSE) with distributed coefficients recently found using the self-similarity technique. The sech-similariton solution exhibits a characteristic positive linear frequency chirp, which increases in slope as the pulse compresses. The solution does not develop any side pedestals or deformation in pulse shape as it propagates, making it a promising candidate for a new compression technique. Unlike the adiabatic compression technique, rapid compression can be achieved in a fibre with a specifically designed decreasing group velocity dispersion profile since the sech-similariton is an exact solution to the NLSE.

A cost-effective and effcient method of realizing decreasing dispersion in a fibre has been developed using a comb-like dispersion profiling technique and its feasibility has been experimentally demonstrated.

Introduction:

Optical pulse compression using similariton propagation in an optical fibre with decreasing dispersion has been demonstrated for the first time. This compression scheme is a practical application of the sech-similariton solution to the generalized nonlinear Schrodinger equation (NLSE) with distributed coefficients recently found using the self-similarity technique. The sech-similariton solution exhibits a characteristic positive linear frequency chirp, which increases in slope as the pulse compresses. The solution does not develop any side pedestals or deformation in pulse shape as it propagates, making it a promising candidate for a new compression technique.

The fibre with a decreasing dispersion profile is constructed using the comb-profile approximation technique and different variations of the technique have been developed to improve the accuracy of the approximation. The linearly chirped input pulse is generated using a Dispersion Compensating Fibre (DCF) and the influence of the DCF length on the performance of similariton compressor is numerically studied.

Similariton Compression:

The sech-similariton compresses in temporal width and increases in peak power and pulse energy during propagation in the dispersion tailored fibre. Thus the sech-similariton solution can be used as the basis of a new compression technique appropriately named as the similariton compression. Under ideal conditions, similariton compression does not induce any side pedestals unlike the SPM-induced compression or the higher-order soliton compression. The spectral broadening induced by similariton compression places no limit to the amount of compression achievable unlike the linear compression where the maximum compression is governed by the fixed spectral bandwidth. Sech-similariton propagation is an exact solution to the NLSE, meaning that there is no energy lost during its compressive propagation. This is an important property of the similariton compression as all of the other compression techniques lose energy when compressing sech-shaped pulses. Similariton compression is distinctly different to adiabatic compression as they have completely different compressive mechanisms. Adiabatic compression results from the breakage of balance between GVD and SPM. The soliton order oscillate about one as the pulse tries to asymptotically recover the balance by changing its width. The similariton compression is driven by the presence of linear positive chirp. As the pulse propagates in anomalous dispersion regime, the positive chirp induces compression. Its soliton order stays at one throughout the propagation, again emphasizing the fact that it is an exact solution to the NLSE. Similariton compression exhibits a set of desirable properties that other existing compression techniques fail to provide.

The compressive property of the sech-similariton solution has been used as the basis of a new compression technique: similariton compression. Taking the practical considerations into account, similariton compression realized in a fibre with decreasing dispersion and constant nonlinearity have been studied mathematically, physically and numerically.

The experimental realisation of the similariton compression suffers from the inevitable experimental errors in the values of the similariton parameters. The influence of these errors in each of the similariton parameters has been investigated by numerically propagating a similariton with values of a similariton parameter different to that used to design the DDF.

In order to design an experimental similariton compressor, the intensity and phase distributions of the input pulse need to be known. Short optical pulses in the order of picoseconds cannot be measured using electronic detectors due to their slow time-response (~10 ps). Optical intensity auto-correlation is commonly used to measure temporal intensity characteristics of short pulses, but it can only provide an estimate of the pulse width and exact information about the temporal intensity profile cannot be retrieved.

Under the conditions of exponentially decreasing gain and constant fibre non-linearity, the magnitude of the GVD profile yields a form that, although may increase in the beginning, eventually decreases as a function of fibre length. In this thesis, the term Dispersion Decreasing Fibre (DDF) is used to refer to optical fibre with a tailored GVD profile. As pointed out earlier, such profile is dependent on input pulse characteristics and a constructed DDF can only support similariton compression of the specific input pulse it was designed for. Thus it is important to be able to manufacture custom designed DDFs in a practical and cost effective way.

In some cases, the necessary GVD profile may be approximated in a step like DDF, where different types of fibre with different $\beta 2$ values are spliced together in a sequence to yield a variation in GVD (Chernikov, et al, 1994). However, it is difficult to accurately approximate the varying GVD using this technique, as it requires many different fibre types with different $\beta 2$ values.

Another method of constructing a DDF in a laboratory environment is to build a comb-like fibre. A comb-like fibre consists of two different types of fibre spliced in an alternating sequence to achieve a given dispersion profile by exploiting the different characteristics of the two fibre types. The name comb-like is given to reflect the shape of the GVD profile consisting of alternating high and low values, which resembles a comb when plotted on a graph. Previously, such comb-like arrangements have been used with highly dispersive fibre and highly nonlinear fibre to apply the effects of dispersion and nonlinearity separately at different spatial points along the fibre [Chernikov, et al, 1994B; Igarashi, et al, 2005). The comb-like arrangement can also be used to create a nonlinearity de- creasing fibre, by using two fibre types with similar $\beta 2$ values and different γ values.

Comb-Like DDF $\beta 2$ Profile:

In a CDDF, the total fibre length is divided into many segments. Each segment consists of a piece of high $\beta 2$ fibre and a piece of low- $\beta 2$ fibre. Since the GVD is a linear process, the total amount of GVD experienced by a pulse in a segment is the weighted average of the two $\beta 2$ values of the pair of fibre used in the segment. Hence the desired GVD profile can be approximated by varying the proportion of each type of fibre within a segment to make the weighted average of $\beta 2$ equate to the desired value for that segment. The accuracy of the comb-profile approximation depends on the number of steps used for a given length of CDDF. Using more steps will increase the accuracy of the comb-profile approximation, but it will come at the expense of increased attenuation due to a greater number of splice losses. This increase in loss affects the gain profile g(z) and results in a decrease in the compressive performance.

Accuracy of the Comb-Profile Approximation:

The number of steps used in a CDDF should be determined to keep the error resulting from the comb-profile approximation within an acceptable range. To demonstrate the relationship between the accuracy of the comb-profile approximation and the number of steps used in a CDDF, an ideal input pulse has been numerically propagated through CDDFs designed with the number of steps varying from 3 to 13. The pulse propagating in a CDDF has been compared against the pulse propagating in a theoretical profile to give a quantitative measure of the accuracy of the comb-profile approximation. The difference between the two pulses is presented in terms of the normalized RMS error of the temporal intensity, weighted RMS error of the frequency chirp, the final pulse width and the final chirp parameter.

DDF with Experimental β2 Boundaries

The comb-like DDF manufacturing techniques place a restriction on the range of β2 values that the GVD profile can span across. The upper and lower (absolute magnitude) limits of the range are determined by the two β2 values of the fibre types used in the CDDF. This experimental constraint reduces the degrees of freedom associated with the calculation of the GVD profile that maximises the compression for an input pulse with a given value of the chirp parameter.

Raman Experimental Gain through Pump Depletion:

The expression for the distributed optical gain used in the theoretical similariton propagation assumes that the Raman pump power is only reduced by fibre losses. In reality, the Raman pump wave experiences a further reduction in power as it provides gain to the optical pulse via Stimulated Raman Scattering (SRS). As the peak power of the similariton propagating in an experimental DDF can easily exceed the pump power, the effect of pump depletion has to be taken into account.

In the present study, the experimental similariton compressor is designed for an input pulse with the centre wavelength of 1532nm and its gain is provided by the CW Raman pump operating at 1445nm. Due to the large difference in their operating wavelengths, the optical pulse and the pump wave travel at different group velocities, exhibiting the walk-off effect.

The reduction in Raman pump power is dependent on the power of the Stokes wave or the similariton pulse. For a similariton propagating in an experimental DDF, the peak power can reach a value as high as 200W as the width gets very short (~200 fs). It has been numerically confirmed that even in such cases the effect of walk-off prevents any significant depletion in pump power. This can be explained by the fact that as the pulse gets shorter, the distance required for the pulse to walk past the partially depleted pump gets shorter. In the presence of the walk-off, the reduction in compressive performance and degradation in pulse quality caused by the depletion of the pump power is prevented and the condition of the non-depleting pump assumed in the theoretical similariton propagation is satisfied.

Conclusion:

In the present study, the techniques and methods employed in the experimental realisation of the similariton compression and the optimisation of the compressor have been presented. The decreasing dispersion has been realized in a Comb-like Dispersion Decreasing Fibre (CDDF) which consists of varying lengths of conventional single-mode fibre and large effective area fibre fusion spliced in an alternating sequence, referred to as the comb-profile approximation. The source of error of this approximation has been physically explained by considering the difference in the amounts of dispersive and nonlinear effects arising from the use of this design. The physical analysis of the error has led to the development of the improved CDDF step-size distribution scheme, where the step-sizes are determined such that the pulse accumulates the same amount of the maximum nonlinear phase shift in each step. This scheme achieves a higher efficiency of the comb-profile approximation than the two preceding schemes; the constant step-sizing scheme and the linearly varying step-sizing scheme.

Following the experimental realisation and optimisation of the DDF the experimental realisation of a linearly chirped sech input pulse was presented. In this input generation technique, a near-transform limited pulse is propagated in a DCF. Using the CDDF optimisation algorithm, the relationship between the performance of the similariton compressor and the DCF length was numerically investigated. The outcome of this investigation was used to decide the length of DCF used for the experimental similariton input generation.

Here, the theory of similariton compression has been demonstrated in an experimental similariton compressor system. To achieve a high accuracy in the experimental results, the values of the fibre parameters have been measured experimentally. Quick overviews of the techniques used for the measurements were presented along with the experimentally measured values. The experimental set-up of the similariton compressor system was presented and specific placements and purposes of its components were explained. The experimental result was compared against the theoretical and numerical results and the sources of error responsible for the small discrepancies in these results were addressed. To achieve further compression, a second-stage CDDF was constructed and added to the compressor system in a cascaded structure. The experimental set-up of the two-stage similariton compressor was presented with its experimental results and analysis.

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