SOLITON GENERATION THROUGH RAMAN AMPLIFICATION OF PULSES WITH SUB FUNDAMENTAL SOLITON POWERS

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Stimulated Raman scattering has been used to provide rapid gain over relatively short fibre lengths, to pulses with powers below the critical fundamental soliton power, giving rise to soliton formation.

Considerable interest has been directed towards the application of solitons in optical communication systems [1–3], since the first successful demonstration of soliton generation in optical fibres [4], following the earlier predictions of Hasegawa and Tappert [5]. This has further been enhanced by the recent demonstration of soliton transmission over more than 6000 km by Mollenauer and Smith [6]. In propagating over considerable fibre lengths, the fibre loss can measurably distort the initial soliton envelope and amplification schemes have been proposed to compensate for the propagation loss. Primarily, these schemes have been based on stimulated Raman processes in the host material of the fibre [7–10] and this technique operating in a counter propagating pump geometry has been successfully implemented [5,11]. In these previous demonstrations, the systems were operated in the small gain regime with \(\alpha_c z_a<0.05\), where \(\alpha_c\) is the effective or overall gain coefficient and \(z_a\) the defined soliton period. This condition arose since the gain supplied to the system was only required to overcome the small propagation losses of the launched single soliton, consequently \(\alpha_c z_a\) was low.

In this communication we describe the situation where \(\alpha_c z_a \gg 0.05\) and Raman gain is used to regenerate solitons from pulses launched into fibres with powers below the fundamental soliton power, consequently substantially larger gains and much greater perturbations on the initial pulse occurred. However, solitons with durations similar to that of the input pulse can be formed.

The experimental scheme is shown in fig. 1. A CW pumped mode locked Nd:YAG laser operating at 1.32 \(\mu\)m was used as the source of pump pulses to provide synchronous Raman gain, and was also used as the pump source for a dispersion compensated fibre Raman ring laser which acted as the signal source. Typically the Nd:YAG laser generated pulses of the order of 100 ps at a 100 MHz repetition rate and an average power of around 1.8 W.

Beamsplitter \(BS_1\) was used to divide the 1.32 \(\mu\)m pump beam, approximately in the ratio 2:1. In transmission, 1.2 W was used to synchronously pump

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a dispersion compensated fibre Raman ring laser, which has been described in detail previously [12]. This laser was broadly tunable around 1.4 µm with output pulse widths of around 1.8 ps and optimized average powers of up to 40 mW (~200 W peak power at 100 MHz repetition rate). The spectral bandwidth associated with the pulses was 2 nm, indicating that operation was just above the transform limit, however, the laser provided a useful source of pulse for soliton studies.

In order to examine the evolution of solitons, the output from the dispersion compensated fibre Raman ring laser was simply launched into a suitable length of single mode fibre using a standard times ten, uncoated microscope objective (MO). The collimated output, using an identical objective MO, was directed to the detectors comprising of a scanning autocorrelator, with 20 fs temporal resolution, and a 1/2 m spectrometer.

The initial test fibre was 140 m long, with a dispersion minimum at 1.27 µm and a group delay dispersion of 15 ps/nm km at 1.4 µm. For the effective core area of 98 µm², the calculated fundamental soliton power [4] was 8 W, which corresponded to an average power of ~1.5 mW in the 1.8 ps input pulses at the 100 MHz repetition rate and the soliton period was 105 m.

Fig. 2(a) shows a background free autocorrelation trace of the 1.8 ps pulses generated by the dispersion compensated fibre Raman ring laser. By simply varying the position of the input microscope objective, the power launched into the test fibre hence the soliton power (number) was varied. Fig. 2(b) shows the autocorrelation traces of the input pulse (outer profile) and the output pulse (inner profile) from the test fibre at a measured average launched power of 12 mW. As can be seen, the output pulse width was reduced from that of the input to 1.3 ps, which can be explained by the expected pulse narrowing [4] of the multisoliton (N=4) launched at this power level into the fibre.

At lower launched power levels approaching that of the N=1 soliton, the input and output pulses had similar halfwidths. This can be seen in fig. 2(c) for an average power of 2.5 mW where the input and output pulse halfwidths were identical. Some slight disparity occurred in the wings of the pulses primarily due to the input pulse shapes not being true sech profiles, while the generated solitons had this pulse shape and experienced a corresponding intensity reduction in the wings of the pulse compared to the input. For average powers down to 1.5 mW the input and output pulselengths were similar, to within the accuracies of the experimental measurement.

To investigate the launch of pulses with power lev-
els below the fundamental soliton power and their subsequent amplification. A 600 m long test fibre was used. This had a dispersion minimum at 1.38 µm and at 1.4 µm a group delay dispersion of 3 ps/nm km. The calculated fundamental soliton power was 1.97 W, which corresponded to a required average power of 330 µW in the input 1.8 ps pulses. The corresponding soliton period was 535 m.

In order to provide synchronic amplification, the reflected 1.32 µm pump beam off splitter BS1, was directed through a variable optical delay line and reflected off beam splitter BS2, which was nominally 100% reflecting at 1.32 µm, 80% transmitting at 1.4 µm, and focussed into the test fibre. The time synchronism of the pump and signal beams was adjusted to give the greatest amplification factor for the signal beam.

Fig. 3(b) shows an autocorrelation trace of the output from the test fibre at an average launch power of 250 µW from the 1.8 ps input pulses. A distinct broadening in the measured pulse half-width to 5.5 ps took place, which could be accounted for by the linear dispersive broadening.

Theoretical considerations by Blow et al. [13] of the generation of solitons in the amplified Schrödinger equation have shown that in the simplest form pulses in the anomalous dispersion regime temporally compress as they increase in energy and tend to the solitary wave of the equation. With increasing pump power the soliton will continually narrow, however saturation of the gain will tend to limit the temporal narrowing.

Fig. 3(b) shows an autocorrelation of the output pulse obtained for an average launched signal power level 250 µW with a synchronous 80 mW average pump power at 1.32 µm. A clear pump compression to 0.7 ps was recorded and on spectral selection, the average power in the amplified 1.4 µm beam was measured to be 3.5 mW, indicating an overall average power gain of times fourteen.

For an average pump power of 20 mW, the output signal pulse durations were measured as 1.5 ps, with an amplified average power of 500 µW. This corresponded to a peak power of 3.3 W in fair agreement with the theoretical value of 2.8 W. The soliton property of this pulse was further verified by re-launch into considerably longer fibre lengths (~3 km) where the slight pulse broadening which took place was simply accounted for by the coupling and propagation losses and no evidence of severe temporal broadening, such as that in fig. 3(a) was present.

In conclusion we have shown that it is possible to reconstruct or generate solitons through synchronous Raman gain and that soliton evolution will take place operating in the large gain regime. This technique could be readily applied to the amplification of pulses from semiconductor lasers to soliton power levels, and we have taken initial measurements using this scheme.

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