Soliton reconstruction through synchronous amplification

A. Gouveia-Neto,* A. S. L. Gomes,† and J. R. Taylor
Imperial College, London SW7 2BZ, UK

K. J. Blow
British Telecom Research Laboratories, Martlesham Heath, Ipswich, IP5 7RE, UK

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When pulses are launched with insufficient energy to create a soliton, they broaden as they propagate in optical fibers. We show that by synchronous Raman amplification this process can be reversed. Also, we show that it is not necessary to work in the limit of small gain. These results are in agreement with a theory of pulse generation and compression, which is discussed.

Since the theoretical prediction

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and experimental verification

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of the generation of optical solitons in fibers,

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many aspects of soliton behavior were investigated both theoretically

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and experimentally.

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One of the major reasons for the interest, apart from the basic science, is in the potential of solitons in optical communication systems, which has been discussed by several authors.

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However, over the long lengths of fiber to be used in practice, propagation losses can be considerable, and the effect on the soliton pulse shape plays an important role.

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As a result, several theoretical analyses have been presented relating to soliton amplification processes in fibers.

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The use of stimulated Raman scattering in fibers was proposed as an efficient amplification process for solitons

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and permits reasonably large amplifier separation. The first demonstration

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used a counterpropagating cw pump to provide the Raman gain. This system was operated in the small-gain regime with \( \alpha_{\text{eff}a} < 0.05 \), where \( \alpha_{\text{ef}} \) is the soliton period and \( \alpha_{\text{sg}} \) is the effective gain coefficient. Because the compensation was for propagation loss, the required gain was consequently small.

In this paper we describe experimental and theoretical results on the synchronous amplification of pulses obtained by using stimulated Raman amplification in a high-gain regime.

We show that the method can be used to reconstruct solitons from pulses that are launched with insufficient energy to create a soliton. We work with a larger gain than in previous experiments, \( \alpha_{\text{gg}} \sim 0.3 \).

The experimental scheme used is shown in Fig. 1. A cw mode-locked Nd:YAG laser operating at 1.32 \( \mu \)m and generating 100-psec pulses with an average power of 2 W (200-W peak) was used as the source. The laser output was split into two parts by using the 50–50 beam splitter BS1. One beam was used to generate a signal pulse through propagation in 1.5 km of single-mode fiber (fiber 1), which had a minimum dispersion at approximately 1.32 \( \mu \)m. The second beam was used, after transmission through a variable-delay line, to provide the pump pulse for the synchronous amplification.

The generation of solitons during stimulated Raman scattering was first shown theoretically.

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Recently

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solitons were shown to be quite generally produced when pulses are amplified. We also demonstrated experimentally the simplicity of this single-pass generation technique.

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Here we launched 400 mW of average power in 1.5 km of fiber to generate a nondispersive, high-intensity pulse, which we refer to as a soliton. Figure 2 shows a background-free autocorrelation trace of this pulse taken at the output of fiber 1. (In all the measurements that we report, a 100-\( \mu \)-thick LiIO3 crystal was used in the autocorrelator, and sech2 pulse shapes are assumed in the deconvolved pulse widths.) The soliton pulse sits on a pedestal that is due to the nonsoliton parts of the Stokes wave. The soliton, with a FWHM pulse width of about 240 fsec, and the pedestal are contained in the first Stokes band at 1.4 \( \mu \)m and are not transform limited. The pedestal was \( \leq 2\% \) of the peak autocorrelation intensity and about 200 psec wide, implying that 25\% of the total energy was contained in the soliton pulse. This percentage would correspond to a peak power of 4 kW. This soliton was used as the signal pulse after transmission through a dichroic beam splitter BS2 (100\% reflecting at 1.32 \( \mu \)m, 5\% reflecting above 1.35 \( \mu \)m) to remove the pump wave.

The pump pulse for the amplification was obtained from BS1 and was passed through a retroreflecting achromatic corner-cube delay line and then off BS2 into the second fiber. Synchronism of the pump radiation with the signal pulse was set coarsely, with picosecond resolution, by monitoring the fundamental and Raman pulses simultaneously with a synchroscan streak camera. The delay line was mounted on a precision translation stage to obtain fine adjustment. An in-line neutral-density filter permitted control of the synchronous pump power.

We then observed, by using the autocorrelator, the pulse temporal profile at the output of the second fiber (with identical properties to fiber 1) as a function of synchronous pump power and relative delay between pump and signal pulses. In Fig. 3 we show autocorrelation traces with no amplification and with maximum amplification for two lengths of fiber. The coupling from fiber 1 to fiber 2 results in a loss of energy. Thus the signal pulse power was lower than that required for the generation of a fundamental soliton. In the absence of amplification, dispersive broadening
Fig. 1. Experimental arrangement for investigating the synchronous amplification of solitons.

Fig. 2. Typical noncollinear autocorrelation trace of solitonlike pulses generated in a single pass of fiber at an average pump power of 400 mW.

of the pulse width occurs in the second fiber. Also, because the soliton Raman pulse is not transform limited, the non-soliton parts will disperse. This effect can be seen in Fig. 3a, in which the signal pulse has broadened considerably and sunk into the pedestal formed by all the non-soliton components. When the maximum amplification (60 mW of average power) is applied to this pulse, we obtain the output shown in Fig. 3b. A 390-fsec pulse was recovered with a considerable increase in the peak power relative to the pedestal. The pedestal was also larger, relative to the input, accounting for 8% of the autocorrelation intensity.

The original soliton pulse width of 240 fsec was not reached in our experiment because of the lack of available pump power, as can be seen in Fig. 4. This figure shows the output pulse width as a function of the average pump power and was obtained by introducing a neutral-density wedge filter into the pump beam arm. The pulse width decreases with pump power but has clearly not saturated at the highest available power. We therefore believe that we can reconstruct the 240-fsec pulse with sufficient pump power.

Figures 3c and 3d show results for a shorter second fiber (500 m). In Fig. 3c the amplified (inner) and unamplified (outer) traces are on a common baseline normalized to the same peak power. The decrease of pulse width and the increase of contrast between peak and pedestal can be seen. In Fig. 3d these pulses are shown on the same vertical scale, showing the relative enhancement of the peak-to-pedestal ratio.

The pulse compression shown in Figs. 3 and 4 depends strongly on the relative delay between pump and signal pulses. The results in these figures were all obtained at zero effective delay, which we defined to be the delay at which maximum pulse compression occurred. In Fig. 5 we show the effect on the pulse compression of the relative delay for various lengths of the second fiber. The average pump power was fixed at 60 mW. The recompression is plotted as the ratio of the amplified pulse width $\tau_{\text{out}}$ to the input pulse width $\tau_{\text{in}}$ from the first-stage fiber. The recompression is asymmetric about the minimum output pulse width (i.e., about the point of zero effective delay). This characteristic is as expected and is due to the group-velocity dispersion of the fiber. The group velocity of the Stokes wave is lower than that of the pump. Thus when the pump arrives before the signal (negative delay) the gain is reduced as the pump moves farther ahead in the fiber. When the delay is positive the signal pulse moves back through the pump pulse, thereby increasing the effective gain.

To examine the length dependence of the amplification process we performed a cutback measurement of the output pulse widths. The pump power was 100 mW throughout the experiment, and the pulse was amplified synchronously as described previously. The results are shown in Fig. 6. After 85 m of fiber, the soliton pulse width was 1.7 psec. The exponential nature of the gain process is evident between 80 and 140 m; the pulse width decreases from 1.7 psec to approximately 450 fsec. Beyond this length the pulse width saturates slowly and reaches 320 fsec at 300 m.

Fig. 3. Autocorrelation traces of a, 1.4-\mu m pulses on exit from fiber 2 (1.5 km long) after experiencing coupling loss; b, the same pulses after 60-mW (1.32-\mu m) average amplification power; c, the pulse compression experienced through synchronous amplification with fiber 2500 m long (the outer trace is unamplified and the inner trace is amplified); d, as in a except that the pulses now share a common baseline (the more intense trace is the amplified soliton).
Fig. 4. Variation of the Raman-amplified soliton pulse width with average fundamental pump power for a 1.5-km length of fiber: solid curve, theory; +'s, experiment.

Thus \( \Gamma \) depends on distance through the depletion of the pump field, which we model in a simple way by using the equations

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\frac{dP_p}{dz} = -\gamma P_s P_p, \\
\frac{dP_s}{dz} = \gamma P_s P_p, 
\]

where \( P_p \) is the average pump power and \( P_s \) is the average Stokes power. The coefficient, \( \gamma \), was estimated, from measurements taken under conditions similar to those here,\(^7\) to be \( 5 \times 10^{-4} \). Equations (2) can be solved analytically for \( P_p \), and this result is used in Eq. (1), together with the relation \( \Gamma = \gamma P_p \), to obtain an approximate description of the pulse evolution. Because the theory only predicts the compression ratio, we must choose a scale arbitrarily. The asymptotic value of 320 fsec was chosen, as these pulses had no pedestal and were therefore the most reliable measurement of the width. The initial Stokes power was chosen, as these pulses had no pedestal and were therefore the most reliable measurement of the width. The initial Stokes power was used as a parameter to obtain the best fit to these results. The value obtained was 2 mW and is rather lower than our estimate of 15 mW. The estimate is an upper bound since propagation in the first 85 m of fiber leads to the shedding of excess bandwidth and pulse broadening.\(^5\) However, the qualitative picture given by these equations is quite good. The initial deviation between theory and experiment, in Fig. 6, may indeed be due to the more complicated dynamics that occur during the early stages of evolution. Broadly speaking, the pulse initially acquires more energy than the soliton of the same width and then compensates by compressing faster than the perturbative prediction of Eq. (1).

To test our theory further, we used the parameter obtained from the fit to Fig. 6 to examine the power dependence of the output pulse width at fixed fiber length. The theoretical curve is shown as the solid line in Fig. 4 and is an extremely good fit to the experimental data.
In conclusion, we have demonstrated the reconstruction of solitons through Raman gain. We did not observe any frequency shifts that are associated with short-pulse propagation. This is consistent with the results of soliton Raman pulse generation and is due to the two-beam configuration. We showed that it is not necessary to use weak gain or to ensure that the initial pulse is not too perturbed from a single soliton. The results were compared with a recent theory of the effects of gain on soliton propagation, and good agreement was obtained.

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* On leave from Departamento de Fisica, Universidade Federal de Alagoas, Maceio, 57000, AL, Brazil.

† Permanent address, Departamento de Fisica Universidade Federal de Pernambuco, Recife, 50000, PE, Brazil.

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