TEMPORAL AND SPECTRAL EVOLUTION OF FEMTOSECOND SOLITONS IN THE REGION OF THE ZERO GROUP VELOCITY DISPERSION OF A SINGLE MODE OPTICAL FIBRE

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Femtosecond soliton generation in the region of the zero group velocity dispersion wavelength of a single-mode dispersion shifted optical fibre has been experimentally studied, both spectrally and temporally, for the first time. Spectral splitting followed by the formation of solitonic and dispersive waves was observed when the input pulses had their central wavelength straddling the zero dispersion of a single-mode fibre, in good agreement with reported theoretical predictions.

1. Introduction

The possibility of an all-optical, high transmission rate communication system based on soliton propagation in optical fibres has attracted much attention recently and its realisation has been analysed by several authors [1–3]. In pure silica based fibres, the maximum bit rate achievable for operation at wavelengths around the region of the minimum loss wavelength (1.55 μm) is of the order of 10 Gbits over ~30 km of fibre. However, by operating the system in the region of the zero of the second order group velocity dispersion, this bit rate increases considerably, reaching values of up to ~300 Gbits. Another advantage of operation in the region of zero second order dispersion is that the power required to establish a fundamental soliton [4] is much lower than that for operation in the anomalous regime where the dispersion is higher.

In the region of the zero of the second order dispersion, the effect of third order dispersion becomes important and plays a role in determining the required soliton power levels and in limiting the bandwidths of the system [5]. The effects of high order dispersion on soliton propagation in the region of the minimum dispersion were first examined by Blow et al. [6], with pulse broadening and break-up in the time domain being predicted, as has also been recently shown by Wai et al. [7].

In this work a temporal and spectral investigation of femtosecond soliton pulse generation in the region of the zero group velocity dispersion wavelength of a single mode dispersion shifted optical fibre was carried out. Spectral fragmentation and evolution of solitary (180 fs at 1.41 μm) and dispersive (1.5 ps) waves in a 50 m length of single-mode fibre (λo = 1.38 μm) were observed, in good qualitative agreement with the predictions of Wai et al. [8].

2. Experimental

The experimental scheme used is shown in fig. 1. The fundamental source of femtosecond tunable soliton pulses was a Nd:YAG laser pumped soliton self-filamentation

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frequency shifter. This system has already been described in detail elsewhere [9], it suffice to mention that throughout this work it generated continuously tunable 170 fs, pedestal-free soliton pulses in the spectral region of 1.32–1.45 μm.

The source of soliton pulses was then used to examine the spectral and temporal behaviour of pump pulses launched straddling the minimum dispersion wavelength of fibre F. This fibre was 50 m long, single-mode at 1.32 μm, with a loss of less than 1 dB/km at 1.3 μm, and a minimum group velocity dispersion wavelength of ~1.38 μm. The output of the soliton self-frequency shifter was coupled into the fibre F using a standard ×20 microscope objective. The radiation emerging from the fibre was collected and collimated using an identical microscope objective to the input, and the spectral and temporal characteristics were recorded on a 1m scanning spectograph in conjunction with a Ge photodetector and a noncollinear scanning autocorrelator incorporating a 2.0 mm thick LiIO₃ crystal with resolutions of 0.1 nm and <20 fs, respectively.

3. Results and discussion

Fig. 2a shows a typical output spectrum from the soliton self-frequency shifter incident on the dispersion shifted fibre F. The output spectrum, for 25 mW total average power coupled into the fibre F is shown in fig. 2b, where the splitting and shift of the spectral components are clearly apparent. The formation of the two distinct fragments, one in the anomalously dispersive regime (solitary wave) and another in the normal dispersion region (dispersive wave) is in very good qualitative agreement with the theoretical predictions of ref. 8. Integration of the relevant spectral regions above and below the minimum dispersion revealed that approximately 45% of the total average power resided in the dispersive wave component of the split spectrum.

Due to the distinct spectral splitting of the generated components around the dispersion minimum, wavelength selection of the solitary wave and the dispersive wave was feasible. Fig. 3 shows the background-free autocorrelation traces recorded for the respective regions, together with an inset of the spectral region examined. In fig. 3(a) a distinctive pedestal due to the dispersive broadening was in evidence, on the top of which was a 1.4 ps pulse which corresponded to the remnant of the dispersed input fundamental pulse at 1.32 μm from the soliton self-frequency shifter. In the time domain, the low level pedestal was apparent for up to 50 ps. On the other hand, in the anomalously dispersive regime the spectrum which evolved (see inset in fig. 3b) had a corresponding temporal profile of 180 fs duration with no apparent pedestal, to within the limits of our detection system.

The 15.5 nm bandwidth of the solitary wave spectral component was supportive of 140 fs pulses at 1.41 μm assuming a hyperbolic secant pulse shape, which would possibly indicate a small degree of chirp present in the measured pulse. Accounting for only third order dispersion, the fundamental soliton power is ~60 W (peak) for 170 fs pulses at 1.38 μm, well below the ~400 W (peak) power launched into the fibre spanning 1.38 μm. From the measured power and the behaviour of the pulse generated at 1.41 μm, it was most probable that a single soliton was formed through the splitting process.

The dependence of the wavelength shift of the solitary and dispersive waves on the amplitude of the pump pulses was also investigated and the results are
wavelength of the dispersive wave component showed a very linear shift with pump amplitude towards high frequencies. The solitary wave component exhibited a similar behaviour with a linear frequency downshift for high amplitudes of the pump pulses. The rate of wavelength shift of the dispersive and solitary waves components from the minimum dispersion wavelength with pump amplitude was different, with the dispersive wave branch presenting a 1.3 times larger slope than that of the solitary wave branch. It is important to point out that a factor of 1.7 times was predicted theoretically in ref. [8] and our lower value may be possible due to some contribution from Raman self-induced frequency shift [10,11].

The bandwidth of the ultrashort pulses is such that the high frequency (short wavelength) components can provide Raman gain to the low frequency region and consequently the pulses will experience a continuous shift to longer wavelengths. This shift which increases with pump power and distance down the fibre has been shown [12] to be proportional to $r^{-4}$, where $r$ is the pulsewidth. This self-frequency shift in addition to the spectral splitting for operation near the minimum dispersion wavelength, would give rise to a larger wavelength shift than that predicted theoretically in ref. [8], consequently reducing the 1.7 times factor of the shift in the dispersive wave to that of the solitary wave.

We have also analysed temporally and spectrally the formation of femtosecond solitons for input pump pulses with the central wavelength slightly above the minimum group velocity dispersion wavelength of the fibre F. Shown in fig. 5 are the input (a) and output (b) soliton pulse spectra for an average power of 50 mW in the fibre F. From the central wavelength of the input pulse ~20 nm into the region of anomalous dispersion, a distinct wavelength shift (~20 nm) or the long wavelength component in the anomalously dispersive regime was observed, caused by the soliton self-frequency shift, which was more apparent in this case, than for launch around the minimum dispersion.

The background-free autocorrelation traces of the input (170 fs (a)) and the output soliton pulses (200 fs (b)) are shown as insets in fig. 5. The soliton formed at ~1.42 μm presented a longer duration (~18%) compared to the ones formed from input
pulses straddling the minimum dispersion wavelength of the fibre. By fixing the input wavelength and varying the power into the test fibre (5–30 mW), no noticeable change in the spectral position of the central frequency of the soliton pulses was observed, within the limits of our detection system. Expected shifts of these fibre lengths would be of the order of a THz.

For input pulses launched with the central wavelength below (~20 nm) the minimum group velocity dispersion wavelength of the test fibre, only the expected dispersive behaviour was observed with the generation of a dispersive wave of ~1.5 ps duration and a spectrum characteristic of self-phase modulation broadening.

4. Conclusions

In conclusion we have presented experimentally for the first time, the generation of femtosecond optical solitons in the region of the zero group-velocity dispersion wavelength of a single-mode dispersion shifted optical fibre. Spectral splitting followed by the formation of a solitary wave frequency downshifted into the anomalous dispersion regime and a dispersive frequency upshifted wave was observed in good qualitative agreement with reported theoretical predictions. Temporally the solitary wave presented a pedestal-free pulse of 180 fs duration and the dispersive wave pulse of ~1.5 ps duration riding on the top of ~30 ps duration pedestal. The degree of spectral shift of the solitary wave to that of the dispersive wave was greater than theoretically predicted, most likely due to a contribution from the soliton self-frequency shift.

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