957

Dark soliton generation and propagation using a normally dispersive, dispersion decreasing fiber.

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The generation and propagation of bright and dark soliton pulses is an area of great scientific interest with relevance to many futuristic telecommunication and optical-processing applications. Bright solitons have been the subject of intense experimental investigation; however, the experimental study of dark soliton behaviour has been limited. This situation is in no small part due to the difficulty of generating and measuring such pulse forms [1,2,3] (for review see Ref .[4] and references within).

In this work we describe an extremely simple, all-fiber source of 100 GHz, 1.6 ps dark solitons. Unlike all previous schemes for dark soliton generation the pulses are formed on a true cw background rather than on a slowly broadening short pulse. In addition, we demonstrate the stable propagation of such trains over a distance of 2.2 km (≈ 2 soliton periods). The technique is based on the principle of nonlinear conversion of a high-frequency beat-signal into a soliton train through nonlinear propagation in a fiber of slowly decreasing normal dispersion [5,6]. Similar techniques have been successfully applied to the generation of high frequency bright soliton trains [7], however, the results presented here constitute the first experimental demonstration of the method applied to the dark case. Note that dark pulse formation from a beat signal by propagation in a fiber of uniform, low + ve GVD has already been demonstrated, however, in this instance the trains are not stable evolving and decaying periodically with propagation [8,9].

The experimental configuration is illustrated in Fig.1. Two single frequency DFB lasers operating around 1548 nm were combined using a 50:50 coupler. The resulting beat-signal (temperature tuned to 100 GHz) was then passed through a two stage 1064nm pumped Er^{3+}/Yb^{3+}-doped fiber amplifier incorporating a band pass filter. Upto 400 mW of average signal power was available at the amplifier output. In order to reduce gain saturation effects within the amplifier and increase the signal power to a level suitable for dark soliton formation the diodes could be synchronously square-wave modulated. Mark Space Ratios (MS Rs) as high as 10: 1 could be used at little expense in average signal output power. A diode pulse duration of 50 ns was used. Note that for 100 GHz pulse generation each 50 ns diode pulse contains ≈5000 pulses. Peak powers as high as 4 W were therefore available at the + ve GVD Dispersion Decreasing Fiber (+ DDF) input.

The +DDF had a length of 1.5 km and loss of 2.1 dB and was fabricated at Southampton University using conventional fiber tapering technology developed for -ve GVD DDF fabrication. The dispersion followed a hyperbolic profile along the fiber length, ranging from -8 ps/(nm.km) at the input to -1 ps/(nm.km) at the output (corresponding to a diameter taper along the length from 75 μm at the input to 93 μm at the output). For convenience, a WDM coupler was spliced to the +DDF output to enable the pulse trains to be monitored both in the temporal (with an autocorrelator) and in the spectral domain.

Pulse train formation was examined for a wide range of input beat-signal powers and repetition frequencies. Optimum performance was found at a repetition rate of ≈100 GHz for an input beat-signal power of ≈1.2W (diodes driven at MSR=4:1). A typical background-free autocorrelation function (ACF) trace of the dark pulse train so obtained at the +DDF output is shown in Fig.2 and the corresponding optical spectrum in Fig.3. The input beat signal power was 1.17 W and beat frequency = 103 GHz. The ACF exhibits small peaks on a large background as expected for a dark pulse train. The period of the peaks 9.6 ps agrees well with the spectral periodicity (0.82 nm = 103 GHz) observed in Fig.3. A close up of the ACF indicates that the dark pulses are well separated and have a good $Sech^2$ form. The pulse duration as measured from the ACF peaks is estimated at 1.6(±0.1) ps, corresponding to an MSR= 6.0(±0.4):1. The ACF shoulder between adjacent pulses is also extremely flat indicating that a high-quality dark pulse train has indeed formed. The peak to shoulder ratio for the ACF is measured to be 1.14(±0.01), in reasonable agreement with the theoretical value of 1.20(±0.02) expected for a perfect soliton train of the observed MSR. The optical spectrum shown in Fig.3 is also in good agreement with that expected for such a dark soliton train. In addition, the peak power for a fundamental soliton of 1.6 ps duration in a fiber of D ≐ -1 ps/(nm.km) and A = 60(±10) μm^2 is 0.75(±0.13) W. This value is in good agreement with the measured output peak power 0.88 (±0.04) W indicating that the optical powers are indeed within the soliton regime.

In order to confirm that the pulses were indeed solitonic and to examine the stability of the trains we performed pulse propagation measurements. A 2.2 km section of Dispersion Shifted Fiber (DSF) with D=-1 ps/(nm.km) and loss 0.28 dB/km was spliced directly to the +DDF output. The length of the DSF section corresponded to ≈2 soliton periods for 1.6 ps pulses. As can be seen in Fig.4 the pulses were found to propagate stably with no distortion to either the ACF or optical spectrum. The pulse duration was measured to be 1.55(±0.10) ps and the peak to shoulder ratio 1.15(±0.01). The output peak power 0.62 W is once again consistent with the expected soliton power for the fiber.

The results presented here constitute the first demonstration of dark soliton generation through beat signal conversion in a +DDF fiber. Simple spectral, autocorrelation and power measurements indicate the generation of 100 GHz, cw trains of dark soliton pulses. The soliton nature and high quality of the pulse train is confirmed by demonstration of stable pulse propagation of the trains through a further 2.2 km of +GVD DSF (≈2 soliton periods). Note that techniques for cross-correlation measurements of such high frequency dark pulse trains have already been developed [9] and should enable the practical use of the dark soliton source demonstrated here for the detailed study of dark soliton propagation and interactions.

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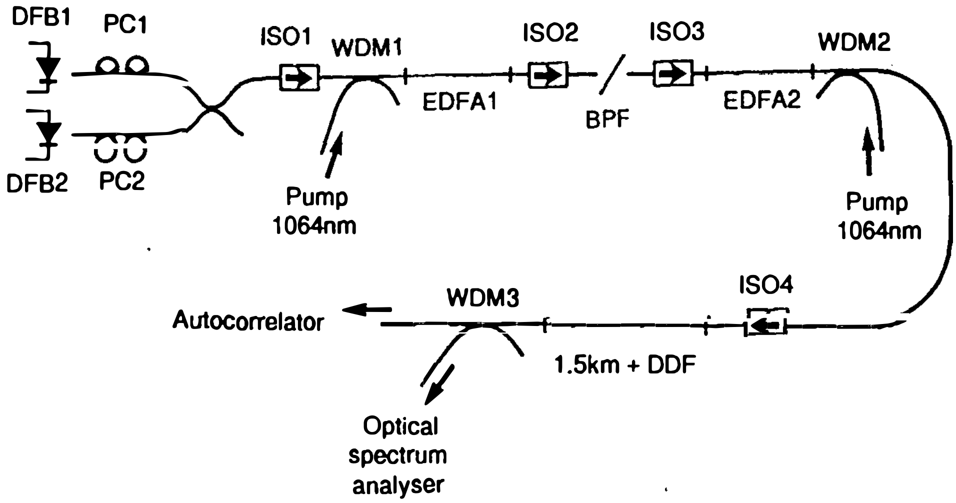

Fig. 1 Experimental configuration of dark soliton source.

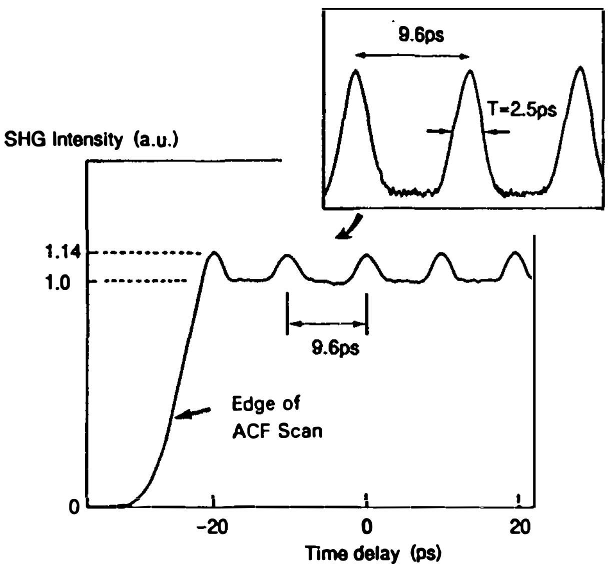

Fig. 2 Autocorrelation trace of 103 GHz, 1.6 ps dark soliton train at source output.

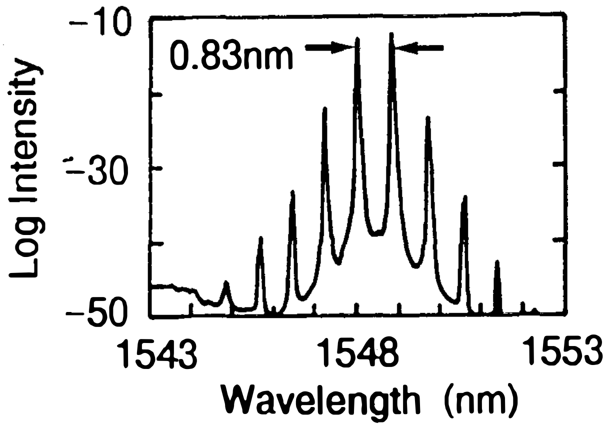

Fig. 3 Optical spectrum of 103 GHz, 1.6 ps dark soliton train.

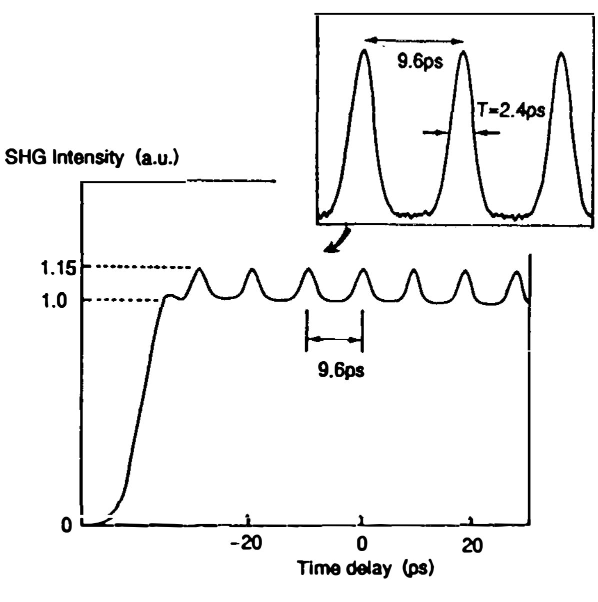

Fig. 4 Autocorrelation of dark soliton train shown in Figs. 2&3 after propagation through 2.2 km of +GVD DSF.