Generation of dark pulse trains from continuous-wave light using cross-phase modulation in optical fibers

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A technique for the generation of dark pulse trains from continuous-wave (cw) light is presented. It consists of co-propagating a cw signal with intense pump pulses in an optical fiber where both the signal and the pump experience normal group-velocity dispersion. The pump imposes a positive frequency chirp on the signal through cross-phase modulation while normal dispersion tends to chip out the signal energy in the chirped region, thus leading to the generation of a dark pulse train with a repetition rate identical to that of the pump. A train of 30.3 ps dark pulses has been observed when using 31.7 ps pump pulses from an actively mode-locked fiber ring laser. The experimental results agree well with numerical simulations. © *1999 American Institute of Physics.*
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Dark solitons or dark pulses in optical fibers have attracted considerable attention in recent years[1,2] as they have advantages in terms of loss, noise, and mutual interactions between adjacent pulses when compared with their bright counterparts. Since the first experimental observation of dark pulses in fibers,[3] significant work has been carried out on the generation and propagation of such pulses.[4–6] However, the generation of dark pulses by these schemes involves very complicated experimental requirements. In other approaches, dark pulses have also been generated from continuous-wave (cw) light by means of (i) electro-optic modulators;[7–9] (ii) propagating of a dual-frequency beat signal of two distributed feedback laser diodes in either a dispersion decreasing fiber[10] or a comb-like dispersion profile fiber;[11] (iii) passive spectral filtering of standard mode-locked bright pulse trains;[12] and (iv) induced modulational polarization instability in birefringent fibers.[13] These techniques strongly differ in their approaches and have their own difficulties. For example, method (i) is limited by its typical electronic bandwidth; method (ii) requires spatial facilities for the fabrication of special fibers; and methods (iii) and (iv) involve quite specific or elaborate experimental devices and, to our knowledge, have not observed in method (iv) dark pulse trains in the time domain. In this letter we experimentally and numerically demonstrate another technique for the generation of dark pulse trains from cw light. It is based on the copropagation of a cw signal with intense pump pulses in the normal group-velocity dispersion (GVD) regime of an optical fiber. The interplay between cross-phase modulation (XPM) and normal GVD induces the cw signal to evolve into a train of dark pulses at a repetition rate identical to that of the pump.

The experimental setup is illustrated in Fig. 1. A wavelength-tunable single-mode laser with a side mode suppression ratio of >40 dB was used as the cw signal (λ_S). A polarization controller was used to adjust the polarization state of the cw to maximize the interaction between the pump and the signal. The pump pulses (λ_p) were generated from an actively mode-locked fiber ring laser. These pulses were then amplified by an erbium-doped fiber amplifier (EDFA) with a high saturation power. The signal and the pump were combined using a 50:50 coupler and then launched into a 0.98 km dispersion shifted fiber (DSF). A Fabry-Pérot optical filter with a 3 dB bandwidth of ~0.7 nm was connected to the DSF and tuned to extract the signal light from the output of the DSF. Then, another EDFA was connected after this filter to amplify the signal light. Finally, another Fabry-Pérot filter with the same bandwidth was connected to the EDFA to remove the amplified spontaneous emission noise. The pump and signal pulse waves were measured by a fast sampling oscilloscope through a fast photodetector, and their spectra were analyzed by an optical spectrum analyzer.

The wavelength of the pump pulses was 1557.1 nm with a full width at half maximum (FWHM) of 0.15 nm. The repetition rate and pulse width (FWHM) of the pump pulses were, respectively, 776.4 MHz and 31.7 ps, and its peak power launched to the DSF was ~1.3 W. The wavelength and power of the cw signal was 1565 nm and 2 mW, respectively. In order to let the wavelengths of both waves be within the normal dispersion regime, a DSF with zero dispersion at wavelength of about 1570 nm was chosen as the

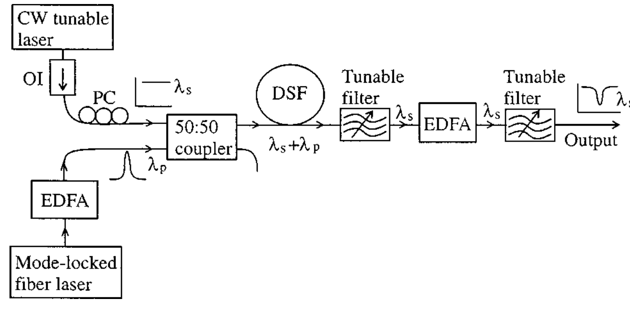

FIG. 1. Experimental setup used for generating trains of dark pulses. EDFA: erbium-doped fiber amplifier, OI: optical isolator, PC: polarization controller, DSF: dispersion shifted fiber, λ_S: signal wavelength, λ_p: pump wavelength.

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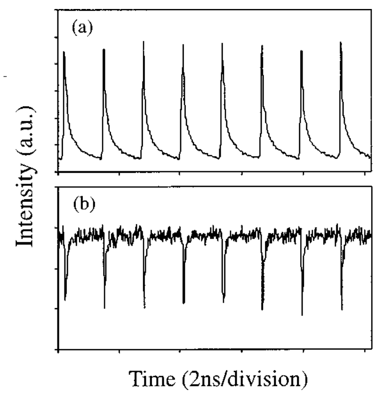

FIG. 2. (a) Wave form of the incident pump pulses with wavelength $\lambda_p = 1557.1$ nm. (b) Wave form of the output dark pulses with wavelength $\lambda_S = 1565$ nm.

nonlinear medium. The dispersion parameters at pump and signal wavelengths were, respectively, 2.3 and 0.9 ps^2/km. Figures 2(a) and 2(b) show, respectively, a typical wave form of the pump pulses (at the input end of the DSF) and the output signal. It is clearly seen that a dark pulse train with the same repetition rate as the pump was achieved at the signal wavelength. The spectral bandwidth (FWHM) and the pulse width (FWHM) of the dark pulses were, respectively, $\sim$0.2 nm and 30.3 ps. The contrast of the dark pulses was about 25%. The average output power of the signal was 1.45 mW.

In order to explain the experimental results, numerical simulations were carried out using the above experimental parameters. Mathematically the process is described by a system of two coupled equations for the complex amplitudes of the pump and signal[14]

$$\frac{\partial u_p}{\partial \xi} + \frac{i}{2}\frac{\partial^2 u_p}{\partial \tau^2} = i(|u_p|^2 + 2|u_s|^2)u_p, \tag{1}$$

$$\frac{\partial u_s}{\partial \xi} - \delta\frac{\partial u_s}{\partial \tau} + \frac{i}{2}\frac{\beta_{2s}}{\beta_{2p}}\frac{\partial^2 u_s}{\partial \tau^2} = \frac{i\lambda_p}{\lambda_s}(|u_s|^2 + 2|u_p|^2)u_s, \tag{2}$$

where

$$u_p = \left(\frac{\gamma_p T_0^2}{\beta_{2p}}\right)^{1/2}\sqrt{P_0}, \quad u_s = \left(\frac{\gamma_p T_0^2}{\beta_{2p}}\right)^{1/2}\sqrt{P_{\rm cw}},$$
$$\tau = \frac{t - z/\nu_{\rm gp}}{T_0}, \quad \xi = \frac{z\beta_{2p}}{T_0^2}, \tag{3}$$

and

$$\delta = T_0(\nu_{\rm gp}^{-1} - \nu_{\rm gs}^{-1})/\beta_{2p}. \tag{4}$$

In Eqs. (1)–(4) u_j with $j = p$ (pump) or $j = s$ (signal) is the complex amplitude of the wave envelope, $\nu_{\rm gj}$ is its group velocity, β_{2j} is the GVD coefficient, γ_p is the nonlinearity parameter at the wavelength of λ_p, P_0 and $P_{\rm cw}$ are, respectively, the peak power of the incident pump pulse and the power of the cw signal, T_0 is the half-width (at $1/e$-intensity point) of the incident pump pulse, and δ is a normalized walk-off parameter that accounts for the group-velocity mismatch between the two waves. The second term on the right-hand side of Eqs. (1) and (2) describes the XPM effect that is

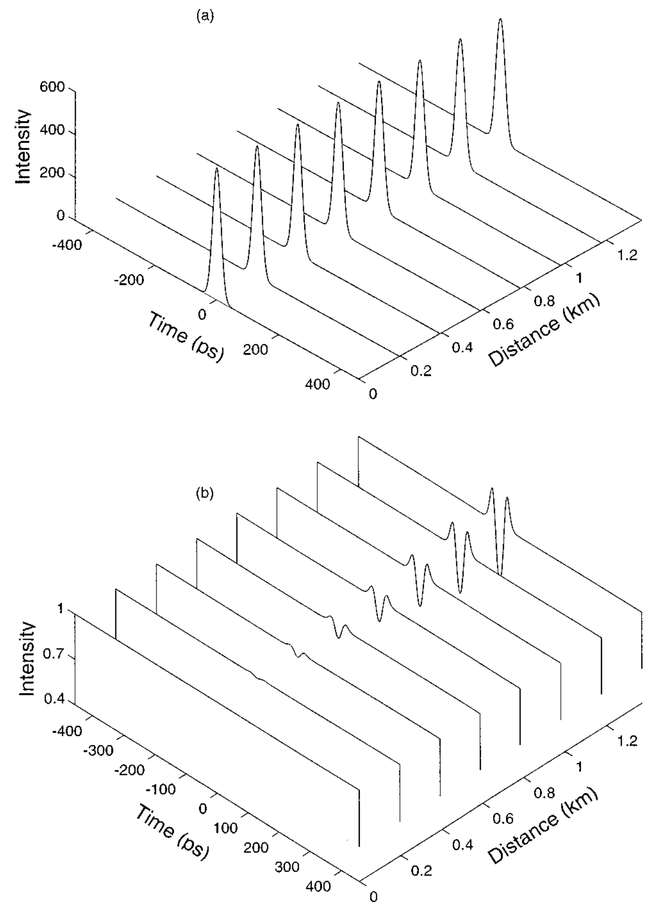

FIG. 3. Evolution of (a) a pump pulse and (b) a cw signal when they propagate together in the normal dispersion regime of an optical fiber. The simulation parameters used here are identical to those of experiment.

responsible for the nonlinear coupling between the pump and the signal. We have neglected the effect of fiber loss as the fiber length used in our experiment was only 0.98 km.

Equations (1) and (2) are solved numerically by using the split-step Fourier method and assuming periodic boundary conditions. The input pulse is assumed to be Gaussian in shape as $u_p(0,\tau) = A_p \exp(-\tau^2/2)$, and the input cw signal is expressed as $u_S(0,\tau) = A_S$. Using the experimental parameters above and assuming that the fiber has a nonlinearity parameter of $\gamma_p = 3\ \mathrm{km}^{-1}\,\mathrm{W}^{-1}$, we obtain from Eq. (3) $A_p \approx 24.8$ and $A_S \approx 1$. Since the wavelength difference between the pump and the signal was small and the fiber used in experiment was much shorter than the dispersion length L_D ($L_D = T_0^2/\beta_{2p} \approx 157$ km), the walk-off between the two waves can be neglected.

Figures 3(a) and 3(b) show, respectively, the evolution of the pump and the signal over a fiber length of 1.37 km, where the scales of the time and distance are transformed into physical units. It can be clearly seen from Fig. 3(b) that a dark pulse begins to emerge at $z \approx 0.5$ km and one similar to that of Fig. 2(b) appears at $z \approx 0.98$ km. This dark pulse has nearly the same width as the initial pump pulse and a contrast of about 23%. Further propagation results in a decrease of the pulse width and an increase of the contrast, but the pedestal around the dark pulse is also increased. Experimentally, when the peak power of the pump pulse was increased, a narrower dark pulse with enhanced contrast and tolerable pedestal could be obtained, and the fiber length for obtaining the dark pulse could be reduced. This has also been confirmed by our simulations. On comparing Fig. 2(b) with Fig. 3(b), we can see that there are close agreements on both pulse width and contrast between the experimental and the numerical results at the distance of $z=0.9$ km. The pulse shapes do not match well because the pump emitted from the fiber laser is not really Gaussian in shape.

The generation of dark pulses can be explained as follows. During its propagation, the cw signal is phase modulated by the pump pulse. Since this modulation depends on the time derivative of the pump pulse intensity, the signal region overlapping the leading edge of the pump is downshifted in frequency while the region overlapping the trailing edge is upshifted, which imposes a positive chirp on the signal. Since the signal wavelength is in the normal GVD regime, the higher frequency components travel slower than the lower frequency components, thus giving rise to an amplitude modulation of the signal and eventually the formation of dark pulses.

In conclusion, we have experimentally and numerically demonstrated a simple technique to generate very stable and uniform dark pulse trains from cw light. It makes use of XPM from pump pulses at a different wavelength in the normal GVD regime of the optical fiber. It is also found that narrower dark pulse with higher contrast will be obtained by using more intense pump pulses with shorter propagation distance. The observed results agree well with theoretical calculations.

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