Restoration Of Dual-Frequency Signals With Nonlinear Propagation In Fibers With Positive Group-Velocity Dispersion

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It is shown experimentally and theoretically that a sinusoidally modulated pulse evolves with time into a train of dark soliton-like pulses and then returns to its initial sinusoidal shape on propagation through a nonlinear single-mode fiber with positive group velocity dispersion. The experimental results are in agreement with predictions from the nonlinear Schrödinger equation.

Optical signals propagating at power levels for which the nonlinear Schrödinger equation (NSE) is operative exhibit interesting behavior both from a fundamental point of view as well as for practical applications.[1–9] The NSE is of special interest because of the existence of soliton solutions, both dark and bright. NSE solitons have been experimentally demonstrated both in the temporal[10,11] and spatial[12–15] domains. Propagation of laser radiation through single-mode optical fibers appears to be the best physical example of a system described by the NSE.[3] Modulational instability in fibers due to a dual-frequency input signal (with unequal relative intensities of the spectral components) has been experimentally investigated in the negative group velocity dispersion spectral region. It led to the formation of trains of bright soliton-like pulses in the first stage of the signal propagation.[4] The generation of a stable train of fundamental solitons from a dual-frequency input signal in nonuniform fibers with slowly decreasing value of the dispersion has also been demonstrated experimentally.[9]

One of the interesting theoretical predictions of the NSE is the restoration with propagation of some periodic signals and higher-order soliton pulses.[1,5–8] The restoration of higher-order soliton pulses over a soliton period has been experimentally observed,[16] but to the best of our knowledge this effect has not yet been studied experimentally for the case of periodic input signals. Here we investigate the restoration phenomena of a dual-frequency signal

$$E(z=0,t)=E_0 \cos \frac{\Delta \omega t}{2} \exp\left[-i\, \frac{\omega_1+\omega_2}{2}\, t\right] \qquad (1)$$

in the region of positive group velocity dispersion, where $\Delta\omega=\omega_1-\omega_2$ is the frequency difference between the input frequencies. We show both theoretically and experimentally that this periodic input signal evolves into a train of dark soliton-like pulses, and then with further propagation returns to a sinusoidally modulated pulse.

The nonlinear Schrödinger equation is given by[1]

$$i\, \frac{\partial}{\partial \xi} A \pm \frac{1}{2}\, \frac{\partial^2}{\partial \eta^2} A + A|A|^2=0, \qquad (2)$$

which has nonlinear eigenmodes known as bright (+ sign) and dark (− sign) solitons. In this case the dimensionless parameters are as follows: $E(z,t)=\tilde{A}(t,z)\exp(ikz-i\omega_0 t)$ is the electric field; ω_0 is the center frequency $(\omega_1+\omega_2)/2$; z is the axial fiber coordinate; t is time; $k=n_0\omega_0/c$ is the propagation constant; $A(\xi,\eta)=\tilde{A}(z,t)/\tilde{A}_0$; $\tilde{A}_0^2=2ck_2/(t_0^2\omega_0 n_2)$; $n=n_0+n_2|E|^2$ is the refractive index; $\xi=z/z_{\rm disp}$; $z_{\rm disp}=t_0^2/|k_2|$ is the dispersion length; $\eta=(t-k_1 z)/t_0$; t_0 is a normalization parameter; $k_i=\partial^i k/\partial\omega^i$; and the sign in Eq. (2) is opposite to the sign of the fiber group velocity (or second-order) dispersion k_2. Note that the signal given by Eq. (2) is written in dimensionless units and the normalization parameter t_0 in Eq. (2) is chosen to be a duration [full width half-maximum (FWHM) intensity] of the input signal beat cycle. In dimensionless units the input signal is

$$A(0,\eta)=A_0 \cos\left(\pi\, \frac{\eta}{2}\right). \qquad (3)$$

Theory[6,7] predicts periodic (or quasiperiodic) with normalized distance ξ behavior for such a signal, shown in Fig. 1 by the dashed line in (a), (c), and (e).

This periodic behavior was investigated with a mode-locked NaCl color center laser operating in the wavelength range $\lambda=1.53–1.54\ \mu$m and a 0.9 km long, low-loss (0.25 dB/km), single-mode, dispersion-shifted fiber (zero dispersion point $\lambda_0=1.555\ \mu$m). Because the fiber was dispersion shifted, the group velocity dispersion, which would be negative in a normal fiber, exhibits positive group velocity dispersion ($k_2>0$) for the wavelengths used. By appropriately adjusting the cavity, the laser generated dual-frequency pulses of 10–20 ps duration. The intensities of the spectral components were equal. The separation between the two spectral components $\Delta\omega/(2\pi c)=1/(2t_0 c)$ could be varied from 5–22 cm^{-1}, which corresponded to a temporal sinusoidal pulse modulation of 150–600 GHz. The intensity autocorrelation function of the pulses showed a sinusoidal modulation with a contrast of 3:1 [Figs. 1(a) and 1(b); Fig. 2(a)]. The fact that we used dual-frequency pulses instead of a continuous-wave dual-frequency signal, means that A_0 in Eq. (3) is not a constant but a pulse duration is much larger than 1 in our normalized units. In this spectral region and with our experimental input parameters, Raman self-scattering effects[17] are of no importance for propagation of our signal, and Eq. (2) is still valid. [In the negative group-velocity-dispersion spectral region, however, the Raman self-scattering effect can dramatically change the evolution of the dual-frequency signal from that predicted by Eq. (2)[18].]

The laser radiation was coupled into the fiber with 10× objective, and the input power was varied by combination of

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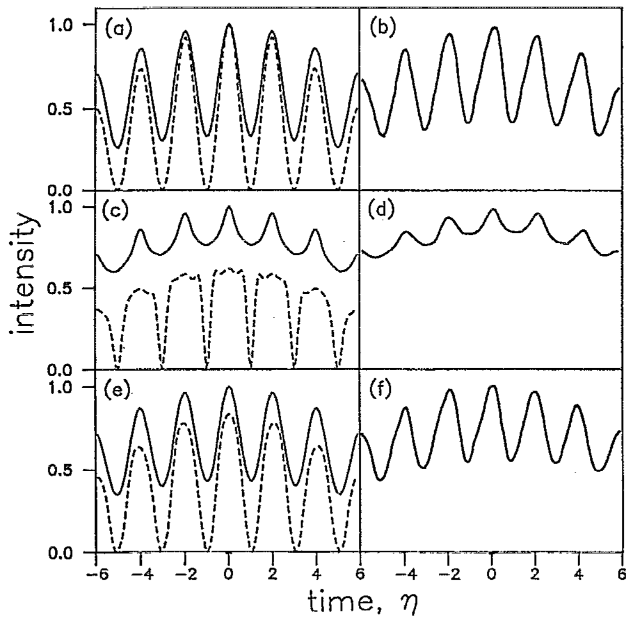

FIG. 1. Evolution of a dual frequency signal in a fiber. Left column—numerical simulations, right column—experiment. Dashed lines—intensity envelopes $|A(\xi,\eta)|^2/|A_0|^2$, solid lines—intensity autocorrelation functions. The dimensionless parameters are $A_0=4$, first row (a) and (b) $\xi=0$; second row (c) and (d) $\xi=0.14$; third row (e) and (f) $\xi=0.4$. Experimental parameters: fiber length 0.9 km; (c) and (d) $\Delta\omega/(2\pi c)=5.5\ \mathrm{cm}^{-1}$, input intensity$=2\times10^6\ \mathrm{W/cm}^2$; (e) and (f) $\Delta\omega/(2\pi c)=11\ \mathrm{cm}^{-1}$, input intensity$=6\times10^6\ \mathrm{W/cm}^2$.

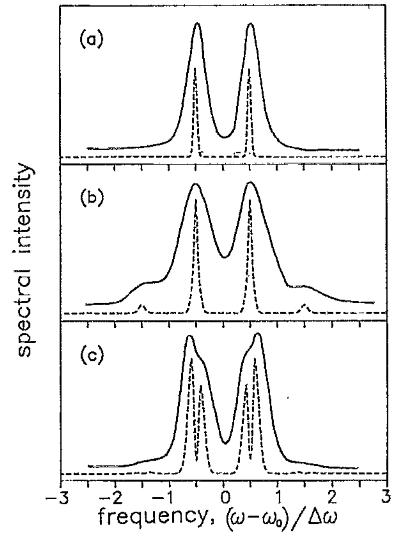

FIG. 2. Evolution of the frequency spectrum in a fiber. Solid lines—experiment, dashed lines—numerical simulations. (a), (b), and (c) are the spectra of the signal shown, corresponding to the first, second, and third row of Fig. 1.

the rotation of a half-wave plate followed by a polarizer. By changing the frequency separation between the two laser spectral components $\Delta\omega$ (i.e., by changing the modulation frequency of the input signal) we could change the dimensionless length of the 0.9-km-long fiber. (The dimensionless fiber length could also be changed by tuning the laser wavelength via the frequency dependence of the fiber dispersion.) This means that by changing the modulation period of the signal and correspondingly adjusting the input intensity (so that the dimensionless input intensity remained constant), we could effectively investigate the spatial evolution of the dual-frequency signal without changing the actual physical fiber length. The temporal characteristics of the output signal were determined by measuring the background-free intensity autocorrelation functions. Output spectra were measured with a scanning Fabry–Perot interferometer.

At low input intensities the effects of the nonlinearity are negligible for the fiber length used and the signal propagates (almost) without change of its spectral and temporal envelopes. In our normalized units, a low intensity input corresponds to a dimensionless peak intensity for which the input sinusoidal modulation period is much smaller than that required for a fundamental soliton, that is, $A_0 \ll 1$. Nonlinear effects become important at higher input intensities, i.e., when A_0 is of the order of, or larger than 1. Experimental results for the case of $A_0=4$ are shown in Figs. 1 and 2. For comparison, results of numerical simulations are also shown in these figures. New spectral sidebands separated by $\Delta\omega$ are generated due to parametric processes at the early stages of the propagation through the fiber [Fig. 2(b)].[12,19] Their relative phases are such that the signal is reshaped into a train of dark pulses in the time domain [Figs. 1(c) and 1(d)]. There are π phase jumps across the minima of the dark pulses, a feature characteristic of dark solitons. Nevertheless, the pulses are not stable with respect to further propagation in the fiber as shown in Figs. 1(e) and 1(f). To understand qualitatively the reason for the instability of these soliton-like pulses, one can find from numerical simulations that (i) the pulse background is chirped, and (ii) the background intensity $|A_b|^2$ is less than that needed for dark solitons with the same pulse width τ (FWHM). That is, the area of the dark pulses, defined as $s\equiv0.322|A_b|^2\tau^2$, is less than 1. Note that for clean dark solitons the background should be unchirped and the dark pulse area should be $s=1$. With further propagation the spectral sidebands disappear [Fig. 2(c)] and the signal almost returns to its initial sinusoidal shape [Figs. 1(e) and 1(f)]. The two spectral components of the restored signal are broadened by self-phase modulation at the fiber output [Fig. 2(c)], because we used a pulsed input signal instead of a cw one. Note that our numerical simulations show that for a cw input signal the recurrence phenomenon occurs at $\xi\approx1$, and at the fiber length corresponding to $\xi=0.4$ an approximate recurrence takes place.

In conclusion, we have investigated experimentally the propagation of a dual-frequency signal through a single-mode fiber in the positive group velocity dispersion spectral region. The results confirm theoretical predictions that the dual-frequency signal propagating in a physical system described by the "self-defocusing" nonlinear Schrödinger equation first evolves into a train of dark soliton-like pulses, and then evolves back into almost its initial sinusoidal shape. The two spectral components of the restored signal are broadened in comparison with the input spectral components. This broadening is due to self-phase modulation in the fiber, because we used a pulsed dual-frequency signal instead of a cw one.

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