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Self-induced-transparency solitons in an erbium-doped fiber waveguide

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Self-induced transparency (SIT) has been observed in an erbium-doped resonant fiber waveguide. The waveguide had an erbium ion concentration of 8900 ppm, and was cooled to 4.2 K. The pulse source was a 1.53-μm mode-locked Er-doped glass laser with a pulse width of 500 ps. Stable 2π, 4π, and multiple soliton pulses that broke up were clearly observed.

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The notable discovery of self-induced transparency (SIT) by MaCall and Hahn has made it possible to understand many of the interesting physical properties related to coherent pulse propagation in highly absorptive two-level media [1]. The steady-state solution is a secant-hyperbolic- (sech) shaped soliton with an area of 2π. The media used for the SIT experiments were ruby [1], molecular gas [2], and atomic gas such as Rb[3]. The breakup of a SIT pulse and peak intensity amplification were first clearly demonstrated in Rb gas [3]. SIT offers a possibility of pulse shaping and standardization that is different from nonlinear Schrödinger (NLS) soliton formation [4]. Since some of the energy generated in the pulse-reshaping process remains in the medium and eventually decays via material relaxation processes, pulse shaping by the SIT soliton may yield cleaner pulses than those produced by NLS soliton formation in an essentially loss-free fiber.

An optical fiber amplifier, the erbium-doped fiber amplifier (EDFA), has recently been developed, which shows great potential for opening new fields in optical communications [5,6]. The typical advantages of this amplifier are a polarization-insensitive high gain of more than 40 dB in the 1.5 μm region, low noise, wide bandwidth, and high output power. We have recently reported femtosecond optical soliton amplification and trapping in an EDFA [7,8], and the coexistence of SIT and NLS solitons [9].

The development of the EDFA offers the possibility for use of the fibers for experiments on coherent pulse propagation such as SIT. The guiding of the radiation by the fiber structure eliminates diffraction effects and makes possible the interaction of the radiation with the fiber medium which has resonance effects over long distances. To date, experiments on SIT solitons have suffered from diffraction effects that were further complicated by nonlinear interactions. Thus, from a purely scientific point of view, it would be beneficial to perform an SIT experiment in an environment in which diffraction effects can be completely ignored.

In the present paper, we report the observation of SIT soliton propagation in an erbium-doped resonant fiber waveguide.

Using typical values for the nonlinear refractive index n_2 and the dipole moment $|p_{12}|$ in silica-based erbium-doped optical fibers, we investigate the possibility of generating SIT solitons in those fibers. The absorption cross section σ at the line center is given by

$$\sigma=\frac{\omega|p_{21}|^2}{\pi\varepsilon_0\hbar nc\Delta\nu_H}, \tag{1}$$

where $\Delta\nu_H$ is the half width at half maximum of the absorption, $\omega=2\pi\nu$ is the resonance frequency, and h is the Planck constant. Assuming a typical linewidth $\Delta\lambda_H$ of 3 nm ($\Delta\nu_H=\Delta\lambda_H c/\lambda^2$) and $\sigma=5\times10^{-25}$ m^2 [10], one obtains $|p_{21}|=1.4\times10^{-32}$ Cm$=4.7\times10^{-3}$ De, where $\lambda=1.55$ μm and $\varepsilon_0=8.85\times10^{-12}$ F/m. In silica fibers, n_2 is equal to 1.2×10^{-22} m^2/V^2.

The peak intensity of a 2π pulse, $I_{\text{peak (SIT)}}$, is given by

$$I_{\text{peak (SIT)}}=\tfrac{1}{2}cn\varepsilon_0(1.76)^2\left(\frac{\hbar}{|p_{21}|\tau_F}\right)^2 \text{W/m}^2, \tag{2}$$

where τ_F ($=1.76\tau_s$) is the full width at half maximum of a sech SIT pulse. At room temperature, the homogeneous lifetime T_2 is shorter than a picosecond, so that subpicosecond pulses must be used for the SIT experiment, for example, by adopting a value of $\tau_F=0.1$ ps, $I_{\text{peak (SIT)}}=3.4\times10^{19}$ W/m^2. Thus, for a typical core diameter of 10 μm in a single-mode fiber, the peak power in the fiber, P_{SIT}, is as large as $P_{\text{SIT}}=2.7$ GW. For reference, we calculate the $N=1$ NLS soliton power, $P_{N=1\,(\text{NLS})}$, by the following,

$$P_{N=1\,(\text{NLS})}=0.776\frac{\lambda^3}{\pi^2cn_2}\frac{|D|}{\tau_F^2}S, \tag{3}$$

where $|D|$ is group-velocity dispersion (GVD) given by $2\pi c|k''|/\lambda^2$. For $\tau_F=0.1$ ps, $S=\pi\,(5\times10^{-6})^2$ m^2, $\lambda=1.55$ μm, and $|D|=20$ ps/km nm, $P_{N=1\,(\text{NLS})}=4.8\times10^3$ W. This result implies that the SIT soliton requires a power approximately 6 orders of magnitude larger than that for the NLS soliton. Thus, it seems to be difficult to observe subpicosecond to femtosecond SITs because of the extremely high coupled power. Before the SIT phenomenon is observed, other nonlinear effects such as self-phase modulation, stimulated Raman scattering, or excited-state absorption may occur.

In order to observe SIT solitons in fibers, τ_F should be long enough to decrease the coupled peak power, but it should also be shorter than T_2. Hence, the erbium-doped fiber should be cooled to 4.2 K to prolong T_2. For example, at 4.2 K, T_2 of Nd^{3+} ions in an optical fiber is of the order of ~10 ns [11]. For $\tau_F = 500$ ps, P_{SIT} for erbium fibers is calculated to be as low as 107 W.

$P_{N=1\,(NLS)}$ for $\tau_F = 500$ ps and $|D| = 20$ ps/km nm is 1.9×10^{-4} W. A peak power of 107 W for the SIT measurement corresponds to the excitation of a very-high-order NLS soliton. Since the peak power of the N soliton is given by $P_N = N^2 P_{N=1\,(NLS)}$, N is as large as 751. In order to remove the NLS soliton effect and to observe pure SIT, the GVD should be as small as possible, resulting in a large extension of the soliton period compared to the absorption length. Hence, a fiber with zero dispersion at the resonance wavelength is used.

The optical source is a Q-switched and mode-locked Er-doped glass laser with a Q-switch repetition rate of 10 Hz. The repetition rate of the mode-locked pulse was 160 MHz and the pulse width was 400–500 ps. Since high-repetition-rate pulses cause unwanted accumulated phenomena or additional nonlinear effects, an optical pulse slicer (Pockels cell) was used to select a single pulse. The maximum energy of the one pulse was 10 μJ (25-kW peak) and the oscillation wavelength was 1.534 μm, which coincides with the absorption peak of erbium ions from $^4I_{15/2}$ to $^4I_{13/2}$.

A special cryogenic system for cooling erbium fibers to 4.2 K was developed in which the temperature could be controlled between room temperature (RT) and 4.2 K. In order to cool only the erbium fiber, dispersion-shifted fibers were fusion spliced at both ends of the erbium fiber. The pulse delay caused by SIT was measured by inserting a reference arm of a dispersion-shifted fiber (RT) through a pair of 3-dB couplers. The erbium fiber used in the experiment had an erbium ion concentration of 8900 ppm. The cutoff wavelength, zero dispersion, and relative refractive-index difference were 1.26 μm, 1.53 μm, and 1.3%, respectively. The output pulse through the erbium fiber was detected with an In-Ga-As p-i-n photodiode with a rise time of 30 ps and was monitored with a high-speed CRT which had a rise time of less than 80 ps.

The linear absorption spectrum of a 21-cm-long erbium fiber is shown in Fig. 1(a), in which the dashed curve and the solid curve are absorption spectra at RT and 4.2 K, respectively. The absorption at 1.530 μm was 25 dB. Since we used 1.5-, 3-, and 6-m-long fibers, the total linear absorption at 4.2 K reached as high as 179, 358, and 716 dB, respectively. A continuous wave from a tunable single-frequency laser diode was used as the input signal. Figure 1(b) shows absorption change versus average input power to the fiber at RT and 4.2 K. At RT, the absorption at 1.534 μm remains unchanged from -50 to -20 dBm inputs, but it changes drastically when cooled to 4.2 K, at which temperature absorption bleaching occurs. When the coupled intensity I is much lower than I_{sat} $(=h\nu/\sigma\tau)$, the absorption coefficient is completely unbleached and linear at 4.2 K. However, when I is higher than I_{sat}, the absorption is given as $\alpha \cong \hbar\omega_0(N_1-N_2)/2T_1 I$. Here ω_0 is the resonance frequency, T_1 is the population relaxation time, and N_1-N_2 is the population difference. Thus, the absorption decreases in inverse proportion to I between -50 and -30 dBm, as shown in Fig. 1(b). Therefore, it should be noted here that when the input pulse width is broader than T_2 (incoherent case), the peak power of a

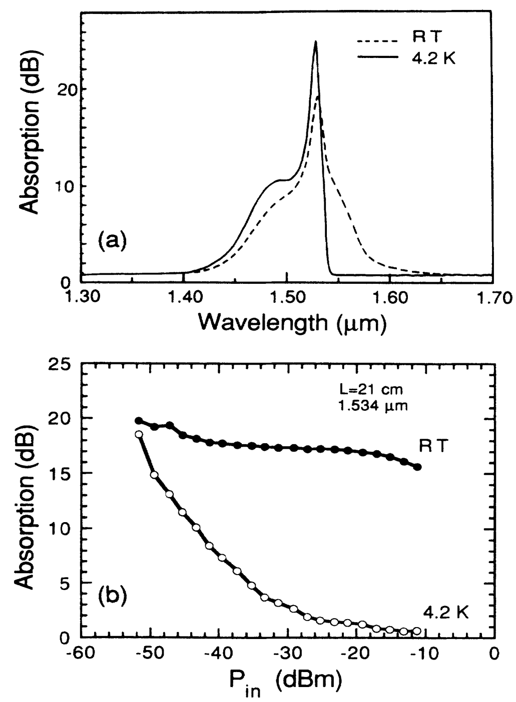

FIG. 1. Absorption characteristics of an erbium-doped optical fiber waveguide. (a) Linear absorption spectra of the erbium-doped fiber at room temperature (RT) and 4.2 K; (b) changes in absorption vs average input power at RT and 4.2 K.

coupled pulse causes absorption bleaching, which means that a transparency itself is not sufficient proof of SIT. Here we measure SIT soliton narrowing, changes in separation between two 2π solitons, and pulse breakup due to the excitation of multiple 2π solitons.

Figure 2 shows experimental results for SIT in a 1.5-m-long erbium fiber. The linear absorption was as large as 179 dB, corresponding to $\alpha L = 41.2$. Photo 2(a) is an input pulse with a width of 500 ps. At a peak intensity of 50–70 W [photo 2(b)], it was possible to transmit the pulse although it had a lower intensity. Below 40 W, no transmitted pulse was observed. For a peak power of 100–130 W, a considerable pulse narrowing was observed from 500 to 120 ps as shown in photo 2(c), which is the resolution limit of the measurement system. This situation corresponds to an excitation of $2\pi < \theta < 3\pi$ pulses, in which an input pulse with an area of just under 3π evolves into a 2π pulse with decreased duration and increased intensity. It is important to note here that the coupled power of 100–130 W agrees well with our estimation of 107 W for the generation of a SIT soliton. By increasing the coupled peak intensity to 170–250 W, a double peak pulse was clearly observed as shown in photo 2(d), which corresponds to a 4π pulse (two separated 2π pulses) due to the excitation of a $3\pi < \theta < 5\pi$ input pulse. By further increasing the input peak power to above 300 W, pulse breakups with more than four 2π pulses were observed as shown in photos 2(e) and 2(f). This is attributed to the fact that multiple solitons were excited by the high power. These breakups and the pulse narrowing with an increase in intensity are proofs of the SIT. It is important to note

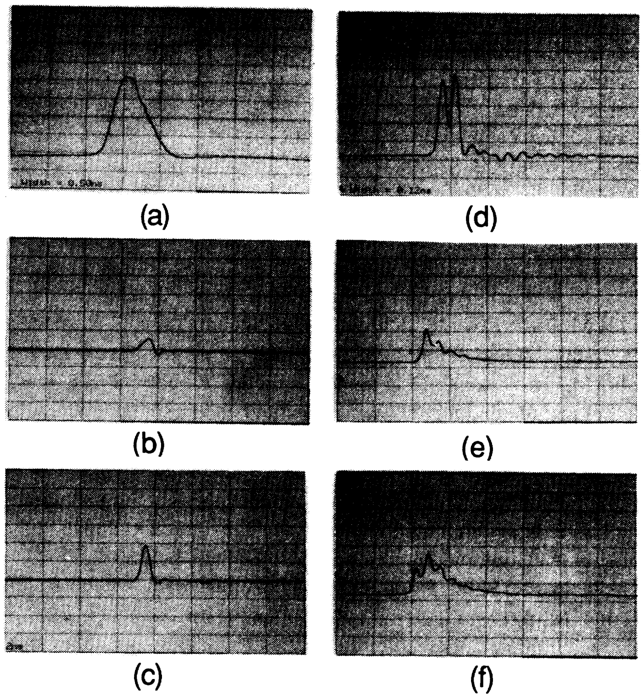

FIG. 2. Experimental results for SIT in a 1.5-m-long erbium fiber. The longitudinal axis in each photo is in arbitrary units and the transverse axis is 500 ps/div. 2π and multiple 2π solitons are clearly observed.

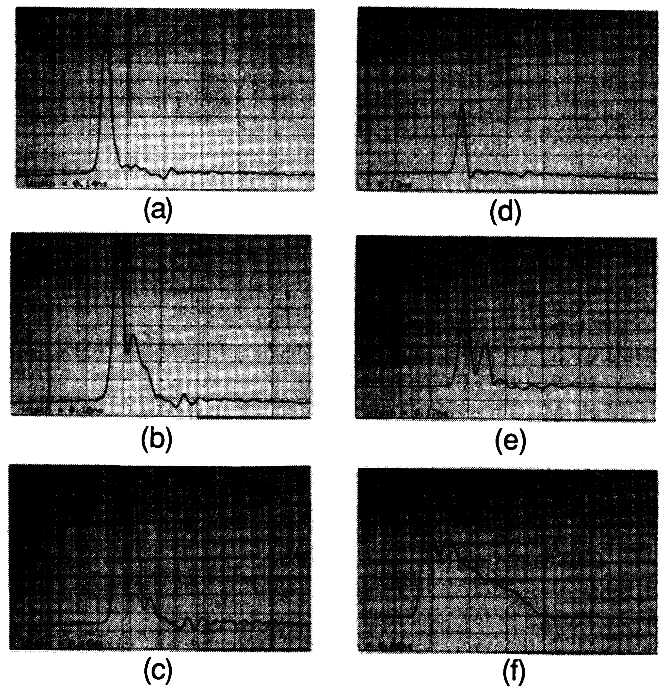

FIG. 3. Experimental results for SIT in 3- and 6-m-long erbium-doped fibers. (a)–(c) 3-m fiber; (d)–(f) 6-m fiber. The transverse axis is 500 ps/div. The separation between the two 2π pulses in photo (e) is larger than that in photo (c). This change is much clearer when photo (e) is compared with photo (d) in Fig. 2.

that this pulse splitting and narrowing completely disappeared when the temperature increased to 10 K, which means that the present results strongly depend on T_2 and T_2 is no longer broader than 500 ps at 10 K.

Experimental results for SIT in 3- and 6-m-long erbium fibers are shown in Fig. 3. Photos 3(a)–3(c) correspond to a 3-m-long fiber. By increasing the coupled peak power, soliton narrowing from 500 to 140 ps [photo 3(a)], a soliton with small humps on the right-hand side of the 2π SIT soliton [photo 3(b)], and double pulses resulting from the excitation of multiple solitons [photo 3(c)] were clearly observed. The coupled peak powers for photos 3(a) and 3(c) were almost the same as those for the 1.5-m-long fiber. Photos 3(d)–3(f) correspond to a 6-m-long erbium fiber. In photo 3(d), soliton narrowing was also observed. An interesting feature appears in photo 3(e) in which the separation between the two 2π pulses is larger than that in photo 3(c). This can be seen more clearly when the separation in photo 3(e) is compared with that in Fig. 2(d). This agrees well with the theory of 4π SIT pulse propagation. By further increasing the coupled power to above 300 W, an unfamiliar distorted wave form was observed as shown in photo 3(f), which may be due to a nonlinear effect which generates a continuum to longer wavelengths or excited state absorption.

Delay measurements are shown in Fig. 4, where photos 4(a) and 4(b) correspond to the 1.5-m-long fiber, and 4(c) and 4(d) to the 3-m-long fiber. In both cases, the initial pulse is a reference. With a low coupled peak power of around 70 W, which corresponds to a 1.6π pulse the transmission was low as shown in photo 4(a), and delay between the two pulses was 2.72×10^3 ps. When the peak power was increased to the 2π-pulse area, where soliton narrowing occurs, the delay changed to 2.64×10^3 ps. That is, the decrease in the delay between the lower intensity pulse and the 2π pulse was approximately 80 ps. When the fiber was extended to 3 m, the decrease in the delay between photos 4(c) and 4(d) became as large as approximately 170 ps, which was almost twice the delay

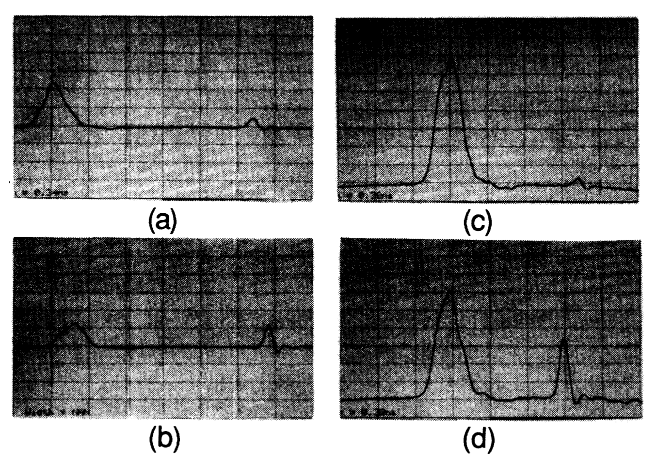

FIG. 4. Optical delay measurements between a low-power pulse (1.6π) and a high-power 2π pulse. (a) Low power (1.5 m); (b) high power (1.5 m); (c) low power (3 m); (d) high power (3 m). The transverse axis is 500 ps/div. The decrease in the pulse delay for a 3-m fiber is approximately 170 ps, and 80 ps for a 1.5-m fiber.

decrease of that in a 1.5-m-long fiber. In the present case, the low-intensity pulses had a larger area than π, which means that the pulse delay decreases with an increase in the area. These results agree well with SIT theory [12] and previous experiments [13,14].

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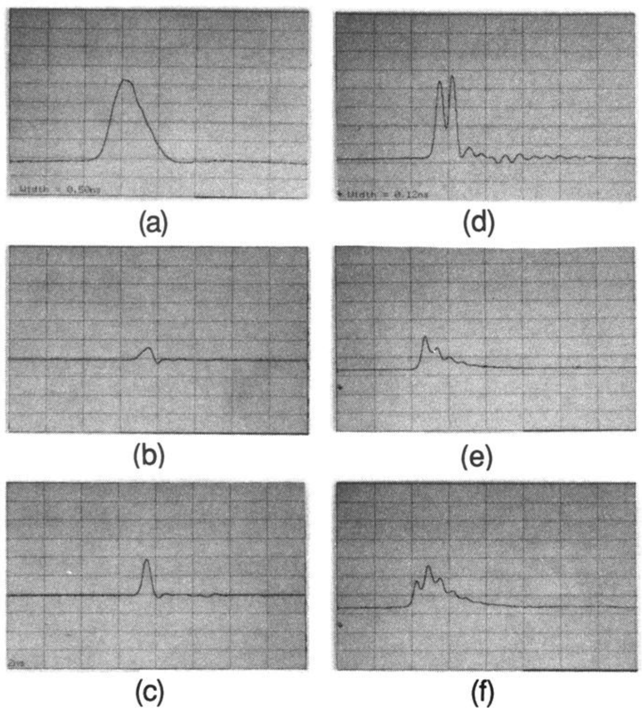
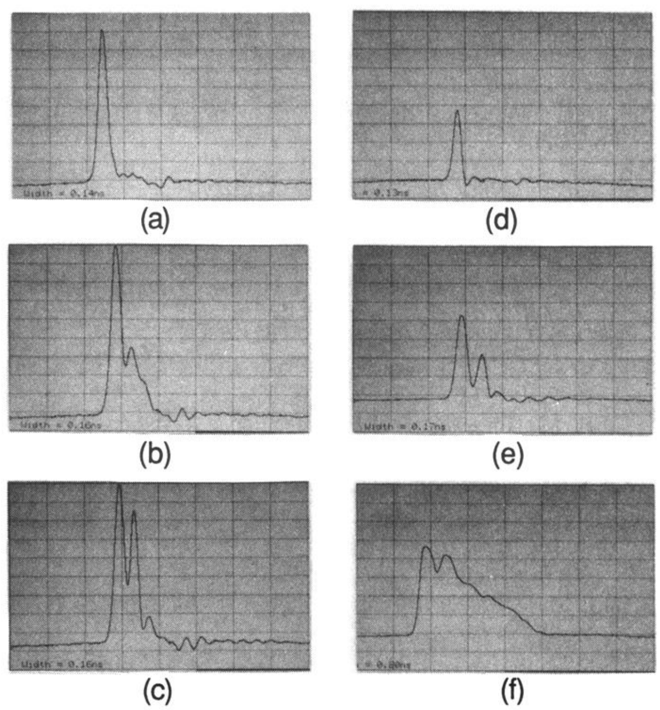


FIG. 2. Experimental results for SIT in a 1.5-m-long erbium fiber. The longitudinal axis in each photo is in arbitrary units and the transverse axis is 500 ps/div. 2π and multiple 2π solitons are clearly observed.



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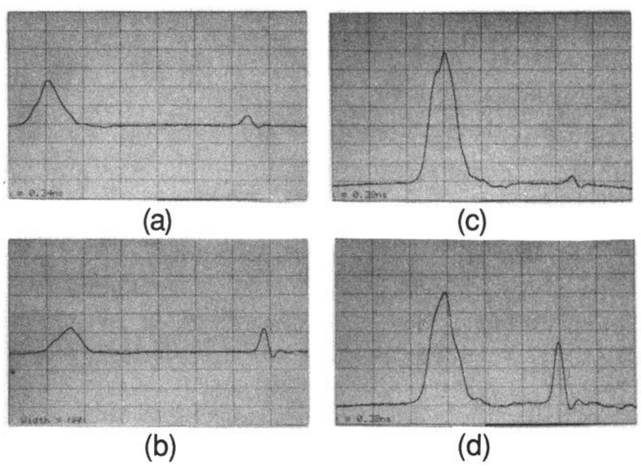

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