Observation of the Trapping of an Optical Soliton by Adiabatic Gain Narrowing and Its Escape

Masataka Nakazawa, Kenji Kurokawa, Hirokazu Kubota, and Eiichi Yamada

NTT Transmission Systems Laboratories, Lightwave Communication Laboratory, Tokai, Ibaraki-Ken 319-11, Japan

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Trapping of femtosecond optical solitons has been observed for the first time in an erbium-doped fiber amplifier operating at 1.55 μm. The pulse width of the trapped soliton is adiabatically narrowed by the moderate optical gain. By further increasing the gain, the trap is broken and the carrier wavelength of the soliton starts to move toward longer wavelengths by the soliton self-frequency shift.

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Erbium-doped fiber amplifiers (EDFA) are of great interest since they show a great potential for opening new fields in optical communications.[1-3] Among such excellent characteristics as a polarization-insensitive high gain of more than 30 dB in the 1.5-μm region, low noise, wide bandwidth, and large output power, the wide-band property, greater than 30 nm, is very useful not only for high-speed communication, but also for amplifying ultrashort pulses including optical solitons. Picosecond- and subpicosecond-soliton amplification using EDFAs has been reported in which the peak power of the amplified pulse reached as high as 96 W.[4,5] Recently, Zhu, Kean, and Sibbett reported the application of an erbium-doped fiber to the coupled-cavity mode locking of a KCl:Ti femtosecond laser,[6] and Ainslie *et al.*[7] and Khrushchev *et al.*[8] reported the amplification of femtosecond soliton pulses.

However, no one has succeeded in observing the theoretically predicted soliton trapping.[9,10] In the present paper, we report for the first time trapping of the femtosecond soliton by bandwidth-limited optical gain and its escape in an erbium-doped optical-fiber amplifier.

Femtosecond infrared pulses in the 1.5-μm region for the soliton-trapping experiment are generated by using difference-frequency mixing in a potassium-titanyl(II)-phosphate (KTP) crystal.[11] The pulse repetition rate is 3.8 MHz and the output pulse has a width of 250 fs with peak powers of 2-4 kW. These femtosecond pulses are coupled into an EDFA through a 1.48-μm–1.55-μm WDM (wavelength-division-multiplexing) fiber coupler. The EDFA is pumped by 1.48-μm InGaAsP laser diodes.[12] The length of the erbium fiber is 3 m and the doping concentration of erbium ions is 1900 ppm. The zero group-velocity dispersion (GVD) wavelength and the spot size are 1.46 μm and 3.5 μm.

Changes in the pulse width of the output soliton and nonsoliton pulses as a function of the pump power are given in Fig. 1, where the solid circles, open squares, and open circles correspond to the peak powers (the average powers) of 30 (27), 55 (50), and 219 W (200 μW), respectively. The input pulse width was 240 fs, the erbium fiber length was 3 m, and the center wavelength of the input pulse was 1.557 μm. A pulse width of 240 fs and a GVD of -6.8 ps/km nm at 1.557 μm give an $N=1$ soliton peak power of 140 W and a soliton period Z_{sp} of 3.3 m. When the input peak power was as low as 30 W (solid circles), no pulse shortening or pulse-spectrum changes occur, although the EDFA gain for an average input power of 27 μW was 9 dB for a pump power of 25 mW. This is because the propagation distance as a $N=1$ soliton was too short in the erbium fiber. When the input peak power was 55 W (open squares), a small amount of soliton narrowing from 240 to 206 fs was observed, since the peak power of the propagating pulse was already in the $(N=1)$-soliton power regime.

Drastic changes in the output pulse width were observed for an input peak power of 219 W (open circles), corresponding to an $N=1.2$–1.3 soliton. The soliton width decreases linearly with an increase in the pump power (the optical gain). When the average input power for the soliton input was 200 μW (-7 dBm), the gain was approximately 5 dB (a gain coefficient of 1.67 dB/m) for a pump power of 19–20 mW because of gain saturation. When the pump power was 20–24 mW, the

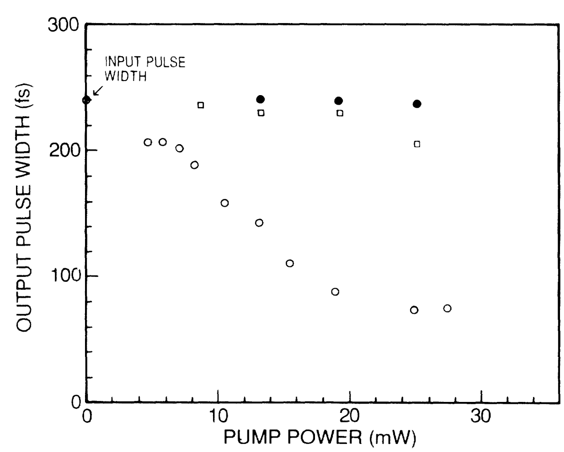

FIG. 1. Changes in output soliton width as a function of the EDFA pump power. The input pulse width was 240 fs. For pump powers smaller than 5 mW, the EDFA acts as a loss medium, so that the output power is too small to measure the pulse width with an autocorrelator. ●, □, and ○ correspond to the peak powers (the average powers) of 30 (27), 55 (50), and 219 W (200 μW), respectively.

pulse narrowing stopped and the pulse width was 74 fs. With a slow-scan autocorrelator, the value of 74 fs measured in the fast-scan mode was estimated to be 60 fs. It is clearly seen in Fig. 1 that adiabatic soliton narrowing occurs with an increase in the gain as long as the gain is moderate.

Figure 2 shows how the spectrum of the output soliton pulse changes for the open circles shown in Fig. 1. The dashed profile in Fig. 2(a) is the spectrum of the 240-fs input soliton pulse, where the $\Delta\nu\Delta\tau$ product was 0.37. The pulse width became 203 fs for an EDFA pump power of 7–7.5 mW where the gain was zero, indicating the pump threshold. In this case, the spectrum changed as shown by the solid line in Fig. 2(a), where $\Delta\nu\Delta\tau$ was 0.34. This pulse shortening is due to an excitation of the $N=1.2$–1.3 soliton. By increasing the pump power to 13 mW, the output soliton width shortened to 142 fs as shown in Fig. 1 and the spectrum broadened to 21.3 nm as shown in Fig. 2(b). Here, $\Delta\nu\Delta\tau$ was 0.37, which means that the output pulse was almost transform limited. For a pump power of 25 mW, corresponding to a gain coefficient of 2.3 dB/m, the output spectrum changed as shown in Fig. 2(c), which is logarithmically transformed in Fig. 2(d). The spectral broadening observed in Fig. 2(b) disappeared. The spectrum component at 1.557 μm is rather less and two new peaks have appeared; one is at 1.535 μm, which is another gain peak of the EDFA, and the other is at 1.576 μm, which is due to the soliton self-frequency shift (SSFS).[13] The SSFS causes the shift of a soliton carrier wavelength toward longer wavelengths. For Fig. 2(c), the corresponding pulse width was 60 fs in a slow-scan mode. When the pump power was further increased, pedestal components appeared on the wing of the amplified soliton pulse and a further shift of the spectrum due to the SSFS was observed. However, no further pulse shortening was observed.

An interesting feature exists in the transition process between Figs. 2(b) and 2(c). The physics behind Fig. 2(b) can be explained by soliton trapping with adiabatic pulse narrowing. When the gain is less than a few dB, the system is adiabatic, where the SSFS can be compensated for by the gain bandwidth of the EDFA.[9,10] In Fig. 2(c), the EDFA gain no longer acts adiabatically, so that the input soliton amplitude is simply increased and the high-order solitons are excited, resulting in a further shortening of the pulse width. In this case, no soliton trapping occurs and the SSFS dominates even if the EDFA gain is bandwidth limited. In our experiment, this critical gain was approximately 5 dB.

Using the perturbation theory for the $N=1$ soliton,[14] the soliton intensity (or inverse of the width) 2η and the

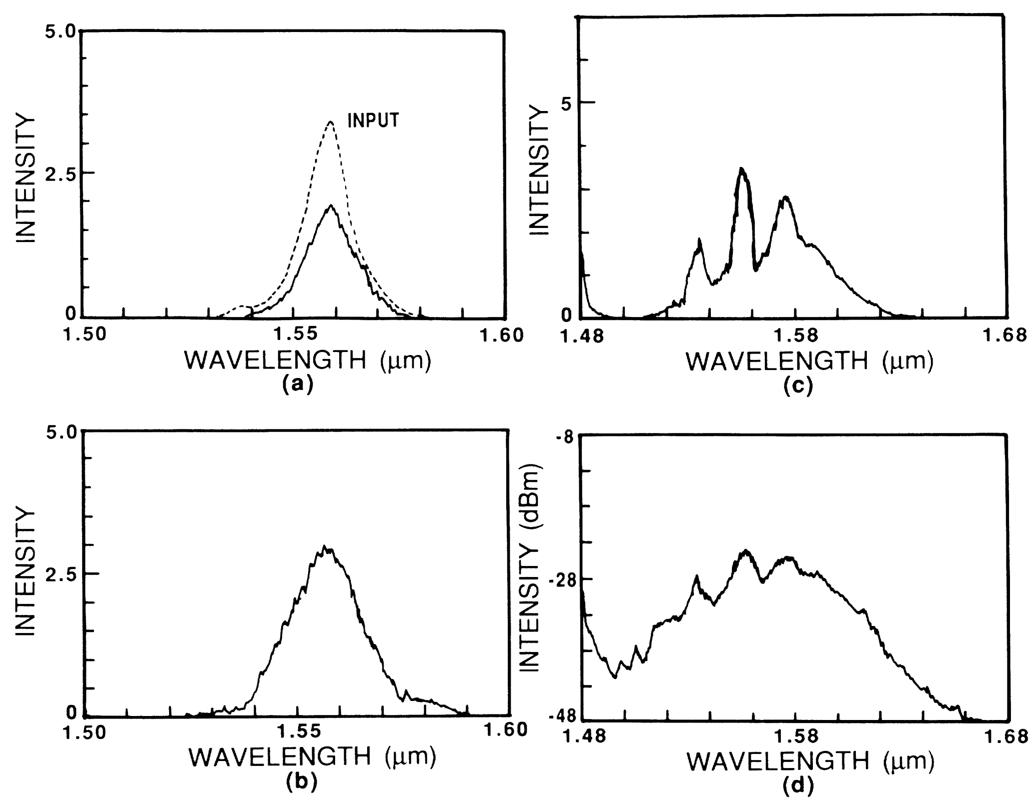

FIG. 2. Adiabatic soliton narrowing of the trapped soliton and the soliton self-frequency shift. (a)–(c) correspond to pump powers of 7, 13, and 25 mW to the EDFA, respectively. (c) is logarithmically transformed in (d).

frequency shift ξ for a perturbed soliton with gain and SSFS can be described as[9]

$$\frac{d(2\eta)}{dq}=2\eta\left\{2G-\frac{4G}{3(\omega_g\tau_0)^2}(2\eta)^2-\frac{4G}{(\omega_g\tau_0)^2}(2\xi)^2\right\}, \tag{1a}$$

$$\frac{d\xi}{dq}=-\left\{\frac{4G}{3(\omega_g\tau_0)^2}(2\eta)^2(2\xi)+\frac{8}{15}\left(\frac{\tau_n}{\tau_0}\right)(2\eta)^4\right\}. \tag{1b}$$

Here, G is the normalized field gain coefficient given by $G=gZ_0$, Z_0 is the normalized distance, g is the gain per unit length, ω_g is the gain bandwidth, τ_0 is the normalized input pulse width given by $\tau_{in}/1.76$, q is the normalized propagation distance given by z/Z_0, and τ_n is the finite response time of the nonlinear refractive index n_2 or the Raman process.[9,13] The first, second, and third terms on the right-hand side of Eq. (1a) represent adiabatic soliton narrowing, gain decrease due to the gain dispersion, and gain decrease due to the soliton frequency shift, respectively. The first and second terms in Eq. (1b) are the frequency-pulling effect toward the center of the gain bandwidth and the SSFS. It has been shown that the soliton pulse has a steady-state carrier wavelength which satisfies $d\xi/dz=0$.[9] In addition, from Eq. (1a), there exists a steady-state soliton amplitude caused by balancing the adiabatic gain narrowing and the gain dispersion with the SSFS. The pulse-width change $(1/2\eta)$ and the frequency change ξ as a function of the distance are given in Fig. 3(a) by solving Eqs. (1), where $\tau_{in}=250$ fs, $D=-5$ ps/km nm, $Z_0=3.16$ m, $\omega_g\tau_0=3$, $\tau_n/\tau_0=4\times10^2$, $g=0.19$ m^{-1}, and $G=gZ_0=0.6$. As can be clearly seen a steady-state $1/2\eta$ and ξ exist when the soliton propagates down the erbium fiber. At 3.0 m, soliton narrowing to about $\tau_{in}/2.5$ and a frequency shift of $\xi=-0.17$ occur, which means $\delta\omega=0.11\omega_g$. When G is larger, ξ is smaller. In fact, a slight frequency pulling toward a gain peak at 1.552 μm was observed when the gain increased in the experiment [cf. Figs. 2(a) and 2(b)]. These results indicate that soliton trapping occurs in the gain bandwidth and the pulse width is shortened by adiabatic gain narrowing.

For a -7-dBm input, the gain was about 5 dB. From Eq. (1a) the soliton pulse is shortened to approximately $1/(1+2\Delta)$ when a perturbation $\Delta=Gq=gl$ exists (l is the actual propagation length). Here Δ for the gain medium is given by $2\Delta=G_P/(10\log_{10}e)$. G_P is the power gain in dB. 2Δ for $G_P=5$ dB is 1.15 and hence the pulse width is shortened to 0.46 ($=1/2.15$) that of the input pulse [(240 fs)$\times$0.46$=$110 fs], which is a little larger than the 80–90 fs that we observed. This is because an $N=1.2$–1.3 soliton rather than an $N=1$ soliton is excited in the experiment. It should be noted that complete adiabatic soliton narrowing occurs when $2\Delta\ll1$.

It not clear from the perturbation theory how a large

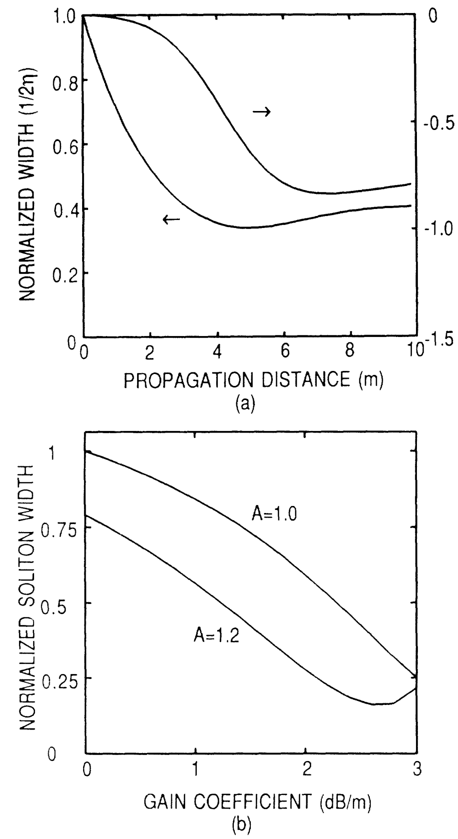

FIG. 3. Transient behavior of the trapped soliton with adiabatic narrowing. (a) Changes in soliton width and frequency as a function of distance (perturbation theory). (b) Changes in output soliton width at 3 m as a function of the gain coefficient (direct calculation of the nonlinear Schrödinger equation).

gain nonadiabatically modifies the input solitons. To analyze this, a perturbed nonlinear Schrödinger equation given by

$$(-i)\frac{\partial u}{\partial q}=\frac{1}{2}\frac{\partial^2u}{\partial\tau^2}+|u|^2u-iG\left(u+\frac{1}{(\omega_g\tau_0)^2}\frac{\partial^2u}{\partial\tau^2}\right)-\frac{\tau_n}{\tau_0}u\frac{\partial|u|^2}{\partial\tau} \tag{2}$$

was run on a computer. The output soliton width as a function of the optical gain G_P is given in Fig. 3(b). Here $A=1.0$ and 1.2, the fiber length is 3.0 m, and other parameters are the same as those in Fig. 3(a). The corresponding spectrum changes for the $A=1.2$ soliton are shown in Figs. 4(a)–4(d), where 4(a)–4(d) refer to $g=1.0$, 1.5, 2.0, and 2.5 dB/m, respectively. The dashed profile is the input spectrum of the soliton and is $\frac{1}{3}$ of the gain bandwidth. In Fig. 3(b), the adiabatic narrowing of the trapped soliton is clearly seen, in which the pulse width is not so rapidly narrowed since a small nonadiabatic gain contribution coexists. It should be noted that a propagation distance of 3 m is comparable

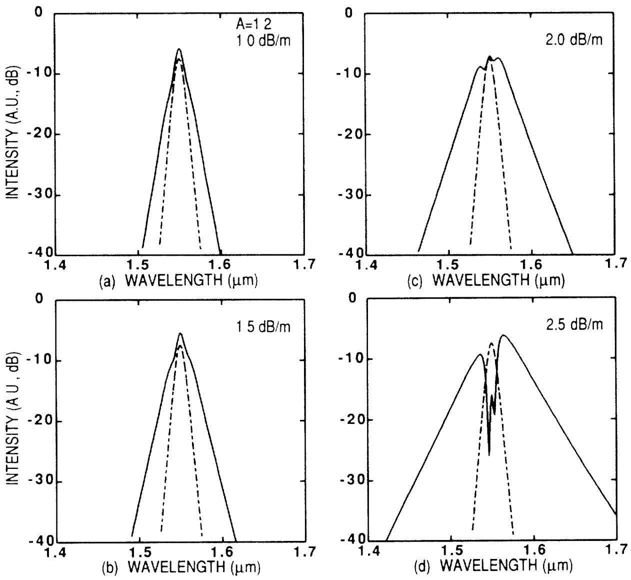

FIG. 4. Changes in the spectrum of the calculated output solitons. (a)-(d) refer to gain coefficients of 1.0, 1.5, 2.0, and 2.5 dB/m, respectively.

to the soliton period. The gain of 2 dB/m for 3 m shown in Fig. 4(c) produces $2\Delta = 1.38$, which means that the condition is already beyond the limits of the perturbation theory. Here the nonadiabatic gain contribution becomes larger, resulting in the excitation of a high-order soliton and fission of the soliton due to the SSFS. That is why small humps appear on the wings of the spectrum in Fig. 4(c). When the gain further increases, the pulse width is no longer shortened, since the SSFS dominates despite the existence of the gain bandwidth. At this point, the soliton trap is broken because the gain is too large to trap the $N=1$ soliton. As seen in Figs. 4(c) and 4(d), corresponding to total gains of 6 and 7.5 dB, respectively, a considerable SSFS occurs. This situation corresponds to our experimental result (open circle at a pump power of 25 mW) in Fig. 1. For the $A = 1.2$ soliton input, the pulse shortening is offset, as is well known from the initial-value problem of the nonlinear Schrödinger equation.[14] For a gain of 5 dB (1.67 dB/m, 3 m) at $A = 1.2$, the pulse narrowing is approximately 1/2.6 of the input soliton, which agrees well with our experimental result shown in Fig. 1.

In summary, it has been experimentally and theoretically shown that the soliton trapping which accompanies the adiabatic narrowing occurs when the gain is moderate. By increasing the gain, the soliton self-frequency shift (SSFS) dominates, and the existence of the gain bandwidth does not effectively trap the soliton since the gain is nonadiabatic.

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