PHYSICAL REVIEW A VOLUME 45, NUMBER 5 1 MARCH 1992

Coherent π-pulse propagation with pulse breakup in an erbium-doped fiber waveguide amplifier

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(Received 8 August 1991)

Coherent π-pulse propagation with pulse breakup has been observed in an erbium-doped fiber waveguide amplifier. The waveguide was pumped by a 1.48-μm In-Ga-As-P laser diode. 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 400 ps. A pulse advance of approximately 130 ps was observed between a low-intensity transmitted pulse with a low pump power and an amplified π pulse in a 1.5-m-long fiber.

PACS number(s): 42.50.Md, 42.50.Rh, 42.65.−k

Coherent pulse propagation in a resonant fiber waveguide is very interesting since it offers new possibilities for optical signal processing such as pulse reshaping and switching. The guiding of the radiation by the fiber structure eliminates diffraction effects and makes it possible for the radiation to interact with the resonant medium over long distances. McCall and Hahn discovered self-induced transparency (SIT) in 1967, at which time they showed the importance of the area theorem [1]. For example, initial pulse areas between π and 3π evolve into steady-state 2π pulses, where the pulse area is defined by the integral of the field envelope over time. 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]. We have observed SIT solitons in an erbium-doped fiber waveguide by cooling the waveguide to 4.2 K [4].

The erbium-doped fiber amplifier (EDFA), which has recently been developed, 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 nonlinear Schrödinger (NLS) solitons [9].

The coherent amplification of pulses in a population-inverted medium [10–13] is another interesting area of study since it offers the possibility of controlling the pulse width and amplitude by changing the degree of population inversion. However, no one has yet succeeded in observing coherent pulse propagation in a population-inverted resonant two-level medium, since it is not easy to incorporate a pumping source in SIT experiments and achieve uniform pumping when gas or bulk materials are used. However, the development of the EDFA offers the possibility of using fibers in experiments on coherent pulse amplification as well as SIT solitons.

In the present paper we report coherent π-pulse propagation with pulse breakups in an erbium-doped fiber waveguide amplifier.

It is well known that when intrinsic loss is present, a single steady-state pulse exists in a coherent amplifier [10–13], which is somewhat similar to SIT. The existence of the steady-state pulse is readily understood since it can be generated by a balance between the gain and the intrinsic loss. On the other hand, if the fiber has no intrinsic loss, the coherently amplified pulse exhibits ringing (pulse breakup), although the area of the field envelope always remains π and stable. If the homogeneous time constant, T_2', is infinite, this ringing continues over infinite time. It should be noted here that if the pulse area is between 0 and 2π, the energy of the coherently amplified pulse with ringing increases through the amplification process although the area remains π. When finite T_2' is taken into account, the ringing stops within T_2'.

For 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 [14], one obtains $|p_{21}| = 1.4\times10^{-32}$ C m $= 4.7\times10^{-3}$ D in a typical erbium-doped fiber [4]. The peak intensity of a 2π pulse, $I_{\text{peak(SIT)}}$, is given by $I_{\text{peak(SIT)}} = \frac{1}{2} c n \varepsilon_0 (1.76)^2 (\hbar/|p_{21}|\tau_F)^2$ W/m^2, where τ_F ($=1.76\tau_s$) is the full width at half maximum of a hyperbolic secant SIT pulse, h is the Planck constant, and $|p_{21}|$ is the dipole moment. Thus, for $\tau_s = 0.1$ ps, $I_{\text{peak(SIT)}}$ is equal to 3.4×10^{19} W/m^2. This means the peak power is as large as 2.7 GW for an erbium-doped fiber with a 10-μm core diameter. Even for a π-pulse excitation, the peak power reaches as high as 0.68 GW. Therefore, it appears to be difficult to observe subpicosecond to femtosecond π pulses because of the extremely high coupled power. Before the SIT phenomenon is observed, other nonlinear effects such as self-phase-modulation, stimulated scattering, or excited-state absorption may occur.

In order to observe coherent π-pulse propagation is a fiber amplifier, τ_F should be long enough to reduce 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 [15]. For $\tau_F = 500$ ps, P_{SIT} and P_π for erbium fibers are calculated to be as low as 107 and 27 W. In order to remove the NLS soliton effect [16] and to observe pure π-pulse propagation, the group velocity dispersion should be as small as possible, resulting in a large extension of the soliton period compared to the absorption length. Hence, a fiber with

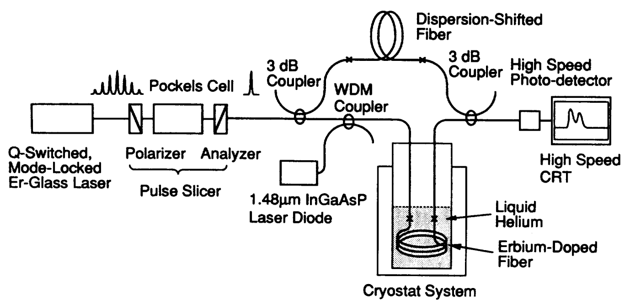

FIG. 1. Experimental setup for the observation of coherently amplified π pulses in an erbium-doped fiber waveguide amplifier.

zero dispersion at the resonance wavelength was used.

The experimental setup is shown in Fig. 1. 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 approximately 400 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 one pulse was 10 μJ (25-kW peak) and the oscillation wavelength was 1.534 μm, which coincides with the emission peak of erbium ions from $^4I_{13/2}$ to $^4I_{15/2}$.

A cryogenic system for cooling erbium fibers to 4.2 K was used. In order to cool only the erbium fiber, dispersion-shifted fibers were fusion spliced at both ends of the erbium fiber. The pulse advance caused by the coherent pulse amplification was measured by inserting a reference arm of a dispersion-shifted fiber (room temperature) through a pair of 3-dB couplers as shown in Fig. 1. 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 erbium-doped fiber was pumped by an In-Ga-As-P laser diode which had a peak emission wavelength at 1.48 μm [17] and a wavelength division multiplexing (WDM) coupler was used to launch the continuous-wave pump beam into the fiber. The output pulse through the erbium fiber was detected with an $In_{1-x}Ga_xAs$ p-i-n photo diode 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 change in gain at 4.2 K versus launched pump power into the erbium fiber (P_p) is shown in Fig. 2(a). The erbium-doped fiber length was 3 m. ■, □, ●, and ○ correspond to average input signal powers of −36.4, −32.5, −21.3, and −11.4 dBm, respectively. It was found that a lower input signal requires a larger pump power to achieve transparency (zero net gain). This is because a low signal power causes large absorption, while a strong signal causes the saturation of absorption. Here a large signal requires only a small gain to achieve transparency. This gain does not directly correspond to the gain for the pulse propagation. Since the gain recovery time of the erbium-doped fiber is about 1 ms, the gain can be completely recovered because the repetition rate of the input coherent pulse is 10 Hz. Thus, the pulse gain was +2 to +3 dB for a signal peak power of 25 W and a pump power of 7 mW.

Photo (b-1) in Fig. 2 is a typical input pulse wave form. When an input pulse with a peak power of 25 W, which corresponds to a 0.97π pulse, was coupled into a 1.5-m erbium fiber that was cooled to 4.2 K, no transmitted pulse

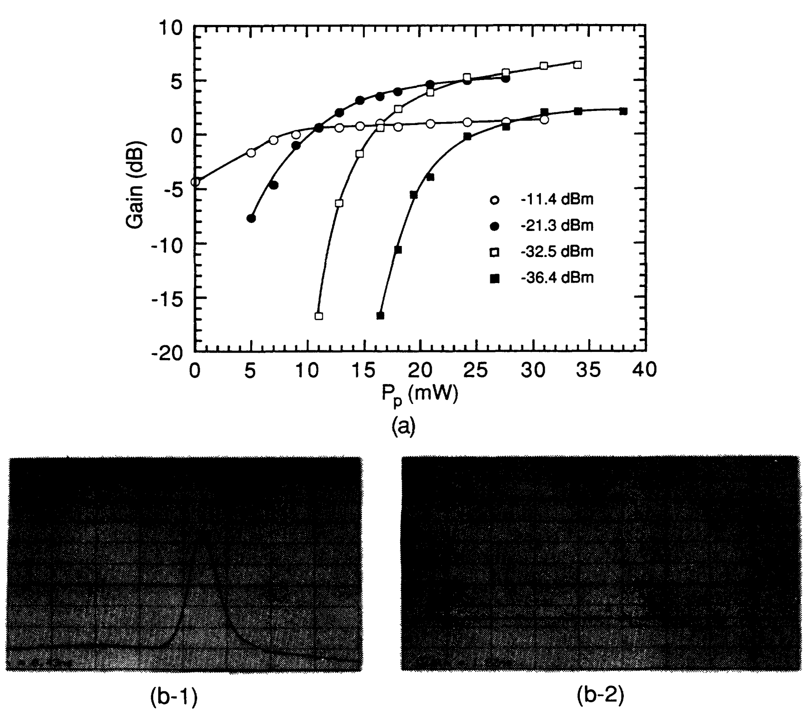

FIG. 2. The gain characteristics of the erbium-doped fiber amplifier. (a) Change in gain vs launched pump power for the erbium amplifier, in which the input signal is a continuous wave. (b-1) A typical input signal wave form. (b-2) Fiber output when the pump power was not applied. The transverse axis is 500 ps/div.

was observed when the fiber was not pumped. The results are shown in photo (b-2). This condition corresponds to π-pulse propagation in a SIT experiment. Since the absorption is larger than 100 dB, the π pulse is eventually absorbed.

Experimental results for coherent π-pulse propagation in an erbium-doped fiber amplifier are shown in Fig. 3, in which the fiber length was 1.5 m. Photos (a-1)–(a-3) refer to an input power of 25 W corresponding to a 0.97π pulse. Photos (b-1)–(b-3) refer to an input power of 40 W which corresponds to a 1.22π pulse. In the SIT process, a pulse which has an area between π and 3π eventually becomes a 2π pulse and no ringing can be found on the wings of the 2π soliton pulses. A $2n\pi$ pulse breaks into 2π pulses, but still no ringing appears on any 2π soliton. In a coherent amplification process, however, a coherently amplified π pulse has ringing behind the first pulse. This ringing is generated by a coherent interaction among the electric field, dipole, and population difference between two levels. The envelope of the electric field becomes negative and the ringing lasts infinitely if T_2' is infinite. Even if an amplified pulse has long ringing, its area remains π and its energy increases.

When the pump power is increased from zero to 7 mW, transmission occurs as shown in photo (a-1). The undershoot in the wave form is due to a sharp decrease in the optical pulse amplitude. The input pulse width was 400 ps, which was shortened to approximately 110 ps. In this condition, the gain is slightly larger (+2 to +3 dB) than the threshold. From computer simulations, when the population inversion is 0.5 rather than full inversion, "1," narrowing occurs but no ringing appears up to a certain propagation distance. However, the pulse narrowing is approximately 25%, which cannot fully explain the present result. The additional narrowing can be explained as follows. In Fig. 2(a), the low-intensity signal was more strongly absorbed than the high-intensity signal even when the erbium fiber was pumped. This saturable absorber effect (incoherent effect) implies that the wing of the pulse was absorbed and the top of the pulse was transmitted, resulting in an even narrower pulse. Therefore, when T_2' is not much longer than 400 ps and the input pulse area exceeds π, such a narrowing may occur.

When the pump power was increased to 11 mW, a breakup of the coherently amplified pulse was clearly observed as shown in photo (a-2). It can be easily confirmed from computer runs that, in π-pulse propagation, the self-consistent interaction between the field and the resonant medium gives rise to such a ringing. When the pump power was increased to 30 mW, the output pulses with breakups disappeared and rather broad pulses (~400 ps) appeared which were almost the same as the input pulse wave form. The coherent amplification process is destroyed because gain saturation occurs due to incoherently amplified components since T_2' may not be much longer than 400 ps or excited-state absorption occurs due to the amplified high-intensity pulse. Photo (a-3) shows the output pulse for a pump power of 55 mW, in which no coherent pulsation is observed.

Photo (b-1) shows a coherently amplified pulse for a

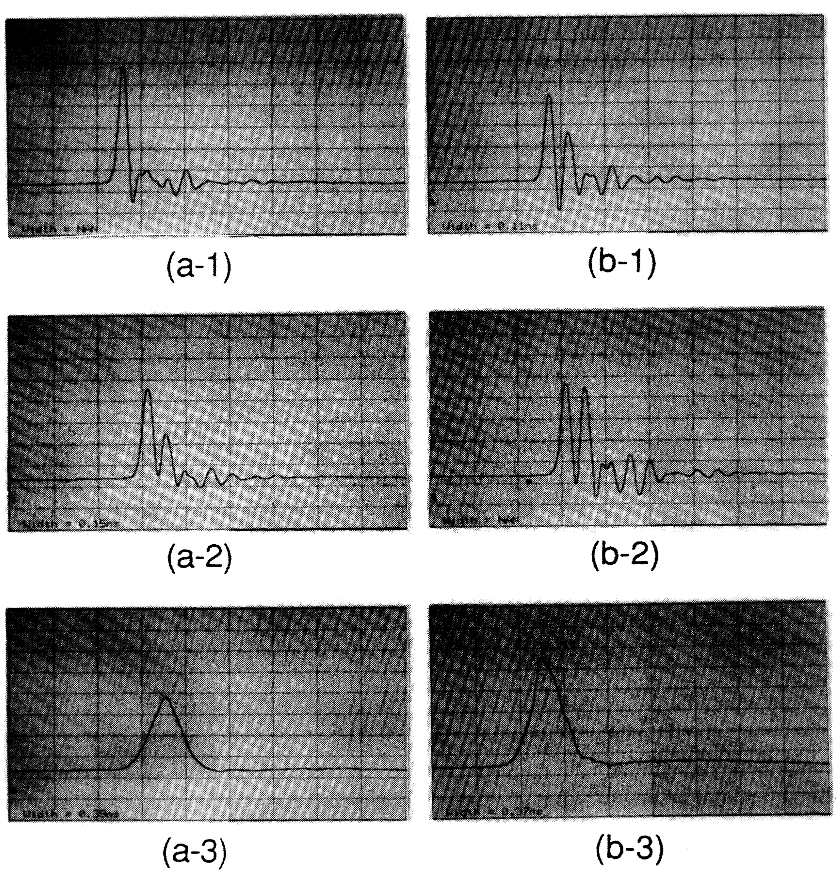

FIG. 3. Experimental results for coherently amplified π-pulse propagation. (a-1)–(a-3) A 0.97π-pulse input. (b-1)–(b-3) A 1.22π pulse. Pump powers for (a-1) and (b-1), (a-2) and (b-2), (a-3), and (b-3) were 7, 11, 55, and 25 mW, respectively. The transverse axis is 500 ps/div.

pump power of 7 mW, in which pulse breakup is already seen. The input pulse had a 40-W peak power corresponding to 1.22π. Further cleaner ringing is observed in photo (b-2) where the pump power was increased to 11 mW. This is firm proof of π-pulse propagation in an active medium, which does not occur in incoherent pulse amplification processes. When the pump power is further increased to 25 mW, the coherent ringing disappeared as in photo (b-3). When the input peak power reached as high as 2π–3π, SIT solitons were observed when the fiber was not pumped. However, when a pump power of 7–10 mW was applied in such a condition, the coherent pulsation disappeared and the SIT pulses changed into broad single pulses similar to those seen in photos (a-3) and (b-3).

Another distinctive feature in the coherent amplification process is that the input pulse advances because of the presence of the gain medium. The front edge of the pulse is always pulled further forward since the front always experiences a different population-inverted medium. Figure 4 shows a measurement of pulse advance due to coherent amplification. The fiber length was 1.5 m and the coupled power was 25 W corresponding to a π pulse. The first pulse in each photo is a reference pulse which passes through the reference arm as shown in Fig. 1. In photo (a) the pump power was as low as 3–4 mW, and the initial pulse delay between the reference and the signal pulse (the second pulse) was 1.92×10^3 ps. The signal pulse was weak because of the low pump power. By increasing the pump power to 7 mW, the delay changed to 1.79×10^3 ps. This means that the coherently amplified π pulse advanced approximately 130 ps. When the pump power was further increased to 11 mW shown in photo (c), we observed the pulse breakup shown in Fig. 3. The advance was 1.76×10^3 ps, which means that the advance between photos (b) and (c) is about 30 ps.

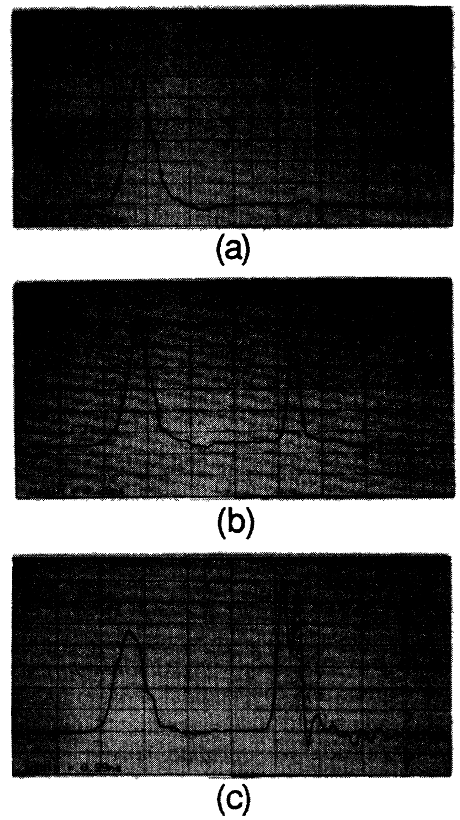

FIG. 4. The experimental results for pulse-advance measurement in an erbium-doped coherent amplifier. The input pulse was a π pulse (25-W peak power) and the erbium fiber length was 1.5 m. Pump powers for photos (a), (b), and (c) were 3–4, 7, and 11 mW, respectively. The pulse advance between (a) and (c) was about 130 ps. The transverse axis is 500 ps/div.

We have undertaken similar experiments using a different erbium fiber which had a doping concentration of 600 ppm and a length of 6 m. In this case neither coherent pulse amplification with pulse breakup nor pulse advance was observed. This was because the gain in the 6-m erbium-doped fiber was still negative for a pump power of over 40 mW in the π-pulse regime.

The authors would like to express their thanks to H. Wakui and M. Kawase for their encouragement.

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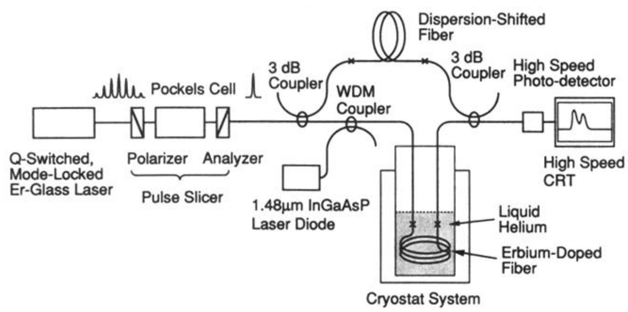
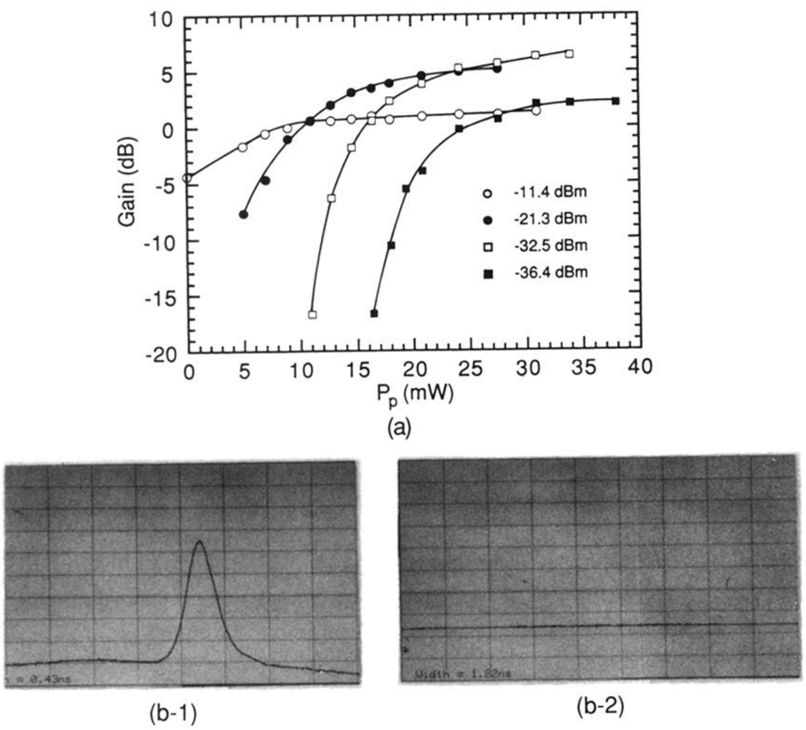


FIG. 1. Experimental setup for the observation of coherently amplified π pulses in an erbium-doped fiber waveguide amplifier.



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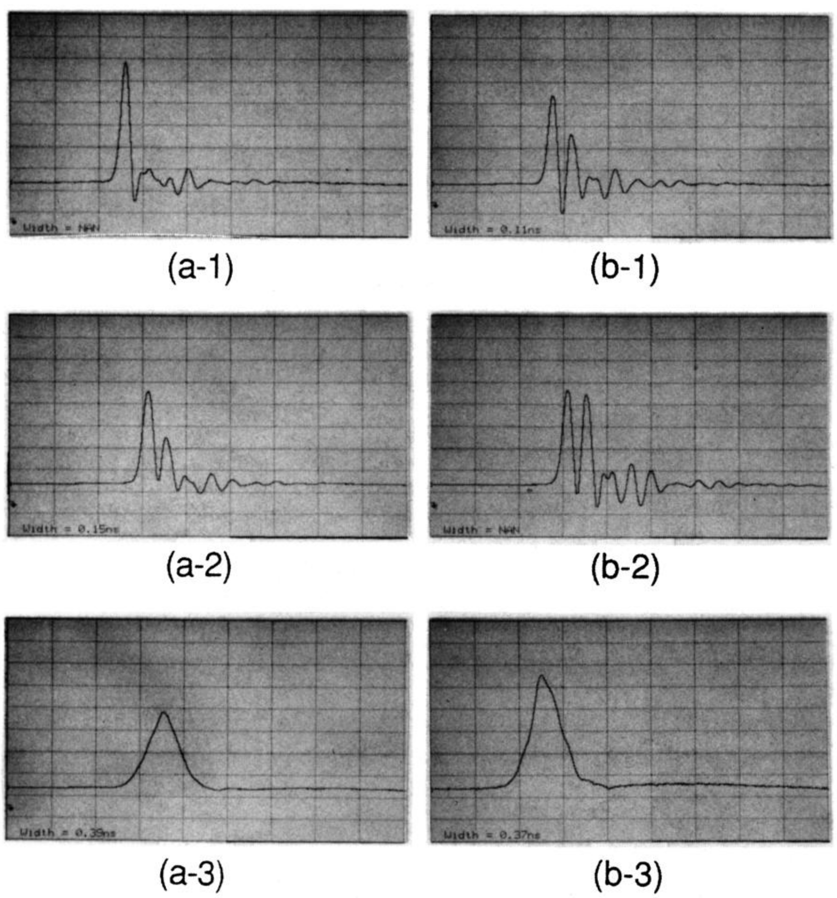

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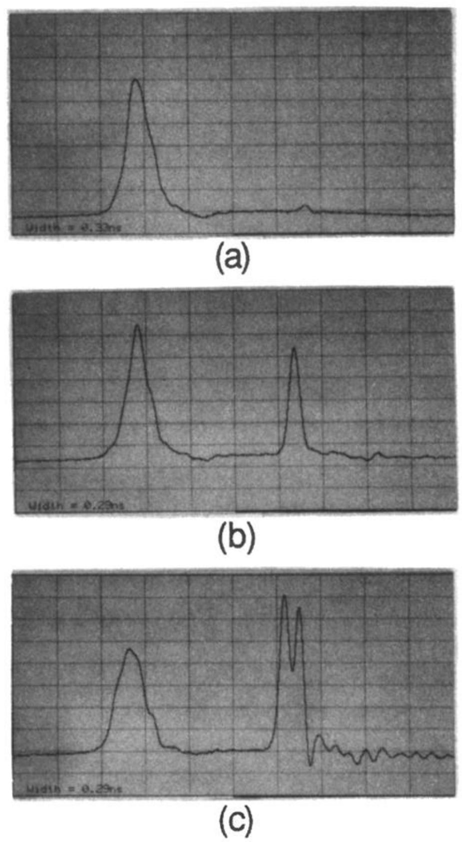

FIG. 4. The experimental results for pulse-advance measurement in an erbium-doped coherent amplifier. The input pulse was a π pulse (25-W peak power) and the erbium fiber length was 1.5 m. Pump powers for photos (a), (b), and (c) were 3–4, 7, and 11 mW, respectively. The pulse advance between (a) and (c) was about 130 ps. The transverse axis is 500 ps/div.