Picosecond soliton transmission using concatenated gain-distributed nonlinear amplifying fiber loop mirrors

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Stable picosecond soliton transmission is demonstrated numerically by use of concatenated gain-distributed nonlinear amplifying fiber loop mirrors (NALMs). We show that, as compared with previous soliton transmission schemes that use conventional NALMs or nonlinear optical loop mirror (NOLM) and amplifier combinations, the present scheme permits significant increase of loop-mirror (amplifier) spacing. The broad switching window of the present device and the high quality pulses switched from it provide a reasonable stability range for soliton transmission. Soliton-soliton interactions can be reduced efficiently by using lowly dispersive fibers.

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One of the major problems of soliton transmission is energy attenuation resulting from fiber loss. Most system experiments employ lumped amplification for loss compensation. The principal concept that has emerged in the context of lumped amplification is the path-average or guiding-center solitons[1,2]. Its use allows propagation of solitons through lossy fibers provided that the amplifier spacing L_a is short compared with the dispersion length L_d. However, since L_a is proportional to the square of the soliton width, the condition $L_\mathrm{a} < L_\mathrm{d}$ results in unreasonably short amplifier spacing if the soliton width reduces to a few picoseconds. Several techniques have been proposed to design soliton communication systems that can operate beyond the path-average-soliton regime[3−7]. Among them the use of nonlinear optical loop mirrors (NOLMs)[4] or nonlinear amplifying fiber loop mirrors (NALMs)[5] is shown to result in the largest L_a to L_d ratio. However, the amplifier spacing (i.e., the loop-mirror spacing in Refs. [4] and [5]) is still short. For 1.5-ps soliton transmission, the loop-mirror spacing is only 10 km.

Recently[8], we have studied self-switching of ultrashort optical pulses in a NALM which has a gain uniformly distributed around whole loop length, and compared to the switching characteristics of the NOLM and the conventional NALM. It is shown that, as compared with the conventional NALM or the NOLM, the gain-distributed NALM can produce higher-quality pulses and permits more efficient pulse compression. It is also shown that the gain-distributed NALM has additional advantages over the conventional NALM such as sharpened switching edges, flattened switching peak, and robustness to gain variations. In this letter, it is numerically demonstrated that the loop-mirror spacing of the soliton transmission schemes described in Refs. [4] and [5] can be significantly increased if gain-distributed NALMs are used instead of the conventional NALMs[5] or the NOLM and amplifier combinations[4].

For simulations of pulse evolution in a loop mirror or a uniform fiber, we use the split-step Fourier method to solve the nonlinear Schrödinger equation which takes the form

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = \frac{i}{2}\mu u, \tag{1}$$

where $u(\xi, \tau)$ is the normalized pulse envelope and

$$\xi = \frac{z}{L_\mathrm{d}} = \frac{z\,|\beta_2|}{T_0^2}, \quad \tau = \frac{t - z/v_\mathrm{g}}{T_0}, \quad \mu = (g_0 - \alpha)\,L_\mathrm{d}. \tag{2}$$

The parameter T_0 is the half-width (at $1/e$-intensity point) of the input pulse, v_g is the group velocity, β_2 is the dispersion coefficient, g_0 is the unsaturated gain, α is the attenuation constant, and $L_\mathrm{d} = T_0^2/|\beta_2|$ is the dispersion length. We neglect the effect of Raman self-scattering because it has negligible influence on the switching characteristics of the device for input pulse wider than 2 ps.

Figure 1 shows the transmission scheme which is similar to that described in Refs. [4] and [5] except that gain-distributed NALMs[9,10] are used instead of the conventional NALMs or the NOLM and amplifier combinations. Each gain-distributed NALM incorporates the same gain of 10 dB and is placed in the transmission link at exactly equal distance. The coupler power-splitting ratio of the NALM is chosen to be 56:44 in order that the switching window is broad and flat and the transmitted pulse is of high quality. In order to provide an uniform gain along the entire loop length, the loop can be constructed from erbium-doped fiber and pumped simultaneously in both clockwise and counterclockwise directions using two

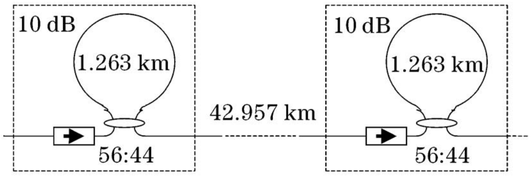

Fig. 1. Schematic diagram of the soliton transmission line.

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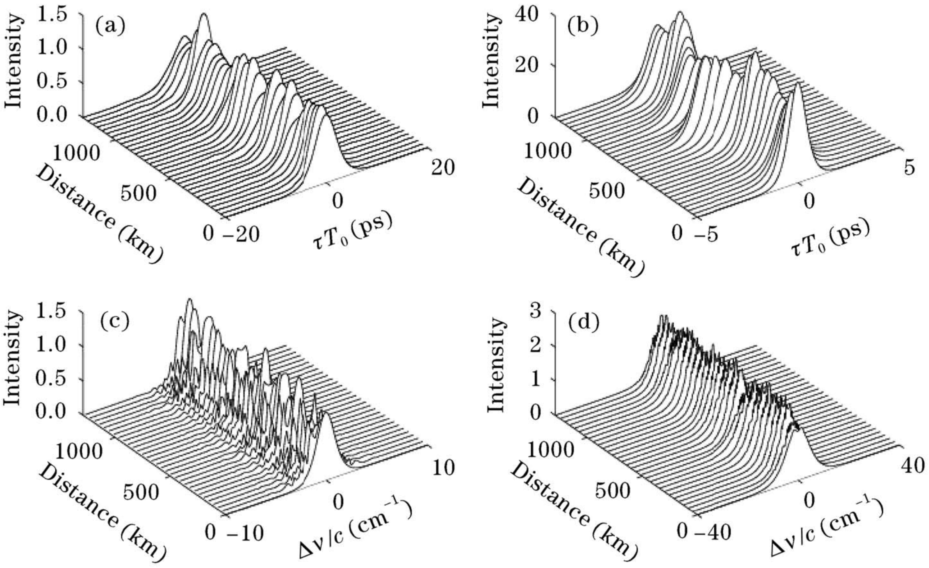

Fig. 2. Pulse shape and spectral evolution through a transmission fiber link with concatenated gain-distributed NALMs. Where (a) and (c) are measured at the inputs of the NALMs, and (b) and (d) are measured at the outputs of the NALMs.

semiconductor lasers located at the two ends of the loop. The transmission fiber loss is 0.2 dB/km. The input pulse is assumed to be $u(0,\tau) = A\mathrm{sech}(\tau)$, where A is related to the physical parameters by $A^2 = \gamma P_0 T_0^2/|\beta_2|$, γ is the nonlinearity coefficient and P_0 is the peak power of the input pulse. The NALM and the transmission fiber have the same parameters of $\beta_2 = -20$ ps^2/km and $\gamma = 5$ W^{-1}km^{-1}. Pulse propagation within both the NALM and the transmission fiber is modeled by numerical integration of Eq. (1).

Figure 2 shows soliton transmission over 1288.71 km with loop-mirror spacing of 42.957 km, where the input pulse to the first NALM is 1.05sech(τ) with $P_0 = 548.3$ mW and $T_{\mathrm{FWHM}} = 5$ ps ($T_0 \approx 2.836$ ps) which is close to a fundamental soliton. The loop length is fixed at πL_{d} ($\sim$ 1.263 km) and the first NALM is set to operate at a switching point slightly past its switching peak. Figures 2(a) and (b) show the pulse shapes measured, respectively, at the input and output of each NALM, and Figs. 2(c) and (d) show the spectra of the pulses corresponding to Figs. 2(a) and (b), respectively. The intensities of the pulse shapes and spectra are normalized, respectively, to the peak intensities of the input pulse shape and spectrum. We see that the input pulse is amplified and compressed with a compression ratio around 4 when it is switched by the NALM every time. The switched pulse is very close to a fundamental soliton but with a higher energy than that of the input pulse[8,9]. Transmission loss attenuates the pulse energy and broadens its width, and the pulse is nearly recovered after it passes through the next NALM. We see that although the pulse intensity varies at the input of each NALM, it does not affect the periodic transmission because the NALM provides a negative feedback mechanism as analyzed in Refs. [4] and [5]. Figure 2(c) shows that, at the input of each NALM, sidebands are formed in the pulse spectra owing to power variations in the transmission fiber. The sidebands are suppressed and the soliton nature of the pulse is recovered when it passes through the NALM every time as shown in Fig. 2(d). Note that the 10-dB gain incorporated in each NALM is larger than that needed to balance the transmission loss, the residual gain is consumed by the reflection of the NALM. We have assumed that any pulse component reflected back up the input is absorbed by optical isolators.

One may feel that the comparison of the present loop-mirror spacing of 42.957 km to that achieved in Refs. [4] and [5] (where it was about 6—15 km) is unfair, because the initial pulse width of 5 ps assumed here is larger than that assumed in Refs. [4] and [5] (where it was 1.5 ps). However, the loop-mirror spacing is determined by the gain rather than the initial pulse width. Our simulations (not shown here) indicate that, for a same gain of 10 dB, the loop-mirror spacing is nearly the same as that of Fig. 2 when the initial pulse width is 2 ps provided that the soliton order A of the input pulse is the same as that assumed for Fig. 2 and that the loop length is decreased to 0.202 km ($\sim \pi L_{\mathrm{d}}$) so that the switching window is the same as before. The reason for the small loop-mirror spacing achieved in Refs. [4] and [5] is that the amplifier gain incorporated there cannot be too large, otherwise, pulse cannot be periodically recovered[5] because the adiabatic nature of the loop-mirrors used there decreases as gain increases[11].

In practice, once the NALM structure and its spacing are fixed, stable soliton transmission should be maintained even with small variations of the initial pulse parameters such as amplitude and width. Fortunately, the NALM provides such a stabilization scheme because it provides a negative feedback mechanism for soliton transmission. Figure 3 shows the evolution of the pulse width under conditions identical to those of Fig. 2 except that the peak power of the input pulse to the first NALM is varied for 548.3, 517.4, and 467.9 mW, which correspond to input soliton orders of 1.05, 1.02, and 0.97, respectively. We see that stable transmission can be achieved

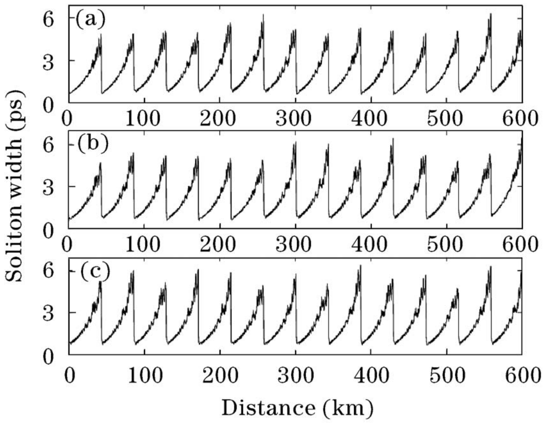

Fig. 3. Pulse width evolution under conditions identical to those of Fig. 2 except that the peak power of the input pulse is varied for (a) 548.3 mW, (b) 517.4 mW, and (c) 467.9 mW.

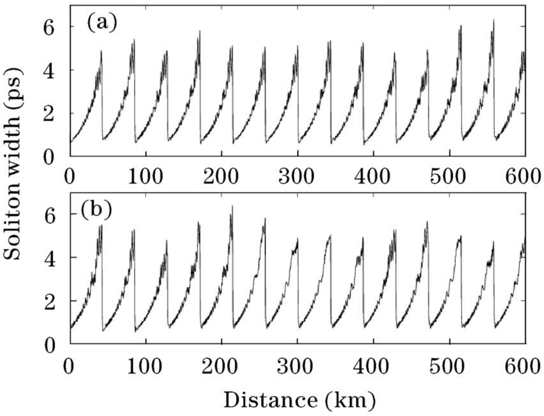

Fig. 4. Pulse width evolution under conditions identical to those of Fig. 2 except that the input pulse width (FWHM) is varied for (a) 4.65 ps and (b) 5.4 ps.

over a relatively large range of the peak power of the input pulse. Figure 4 shows pulse width evolution under conditions identical to those of Fig. 2 except that the input pulse width (FWHM) to the first NALM is varied for 4.65 and 5.4 ps (the peak power of the input pulse is fixed at 548.3 mW). Again, we see evolution patterns similar to those of Fig. 3.

The large stability range of the system benefits from the fact that the gain-distributed NALM has a broad switching window over which the quality of the transmitted pulse is very high. As shown in Ref. [8], the switching window of the gain-distributed NALM is twice as broad as that of the conventional NALM for a same gain of 10 dB. According to previous analyse[5], the broader the switching window is, the larger the stability range will be. Thus, for a similar loop mirror-spacing (or a similar gain), soliton transmission with gain-distributed NALMs should be more robust to small variations of the initial conditions than that with conventional NALMs.

Soliton-soliton interaction is shown by Fig. 5, where Fig. 5(a) is obtained under conditions identical to those of Fig. 2 except that two in-phase solitons with initial separation of 30 ps are considered, where each curve represents the pulse shape at the input of each NALM. Similar to that described in Ref. [4], we observed both repulsion and attraction of the pulses by adjusting the initial pulse separation. The interaction caused by the dispersive background waves is detrimental to soliton communication. It can be partially suppressed by using lowly dispersive fibers to increase the dispersion length as shown in Fig. 5(b), where β_2 of both the loop mirror and the transmission fiber is reduced to -10 ps^2/km, and, correspondingly, the loop length is increased to 2.526 km and the peak power of the input soliton is decreased to 274.1 mW in order that the NALM has the same switching window as before and operates at the same switching point. We have attempted to decrease β_2 to -5 ps^2/km to further suppress soliton interaction, but the soliton cannot be periodically recovered. The reason is that the pulse switched by the NALM contains non-soliton components, so the ratio of the loop-mirror spacing L_a to the dispersion length L_d should be large enough in order that the pulse can evolve into a fundamental soliton.

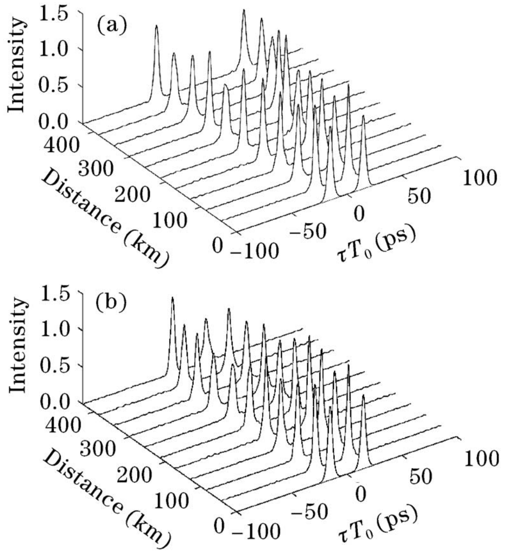

Fig. 5. Interaction of two in-phase pulses initially separated by 30 ps. (a) $\beta_2 = -20$ ps^2/km and (b) $\beta_2 = -10$ ps^2/km.

We have shown that the amplifier spacing of a picosecond soliton transmission system can be significantly increased by use of gain-distributed NALMs instead of conventional NALMs or NOLM and amplifier combinations. The scheme is quite robust to variation of the initial conditions such as initial pulse power and width, which benefits form the fact that the present device has a broad switching window over which the quality of the transmitted pulses is very high. We also show that soliton-soliton interactions can be reduced by using lowly dispersive fibers.

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