4× repetition-rate multiplication and Raman compression of pulses in the same optical fiber

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Received January 25, 2002

A 21.7-km nonzero dispersion-shifted fiber was used to obtain 4× multiplication of the repetition rate of a 20-GHz train of 4.2-ps optical pulses through the temporal Talbot effect. Raman compression in the same fiber shortened and developed the pulses into 2.0-ps solitons and resulted in a lower duty cycle. It is shown that the linear Talbot effect and nonlinear Raman compression occurred in different sections of the fiber, the lengths of which could be varied through adjustments in the input pulse power. © 2002 Optical Society of America

The temporal Talbot or self-imaging effect has been studied for many years but was only recently considered as a technique for repetition-rate multiplication for use in high-bit-rate optical fiber telecommunication systems. In the temporal Talbot effect the spectral components of a pulse train that is incident upon a linearly dispersive element acquire phase delays that can cause either a regeneration of the original pulse train (integral Talbot effect) or the generation of a pulse train at a multiple of the original repetition rate (fractional Talbot effect). Both fiber Bragg gratings and optical fibers have been proposed and used as the dispersive element to obtain repetition-rate multiplication. Azana and Muriel theoretically predicted that repetition-rate multiplication by a factor of 25 could be obtained from a 10-GHz train of 0.5-ps pulses by use of a linearly chirped fiber grating. Longhi et al. experimentally generated a 40-GHz, 10-ps pulse train through 16× repetition-rate multiplication, using a linearly chirped fiber grating as the dispersive element. Using optical fiber as the dispersive medium, Shake et al. showed 5× and 40× multiplication of 10-GHz repetition-rate pulse trains. Arahira et al. demonstrated 2×, 3×, and 4× multiplication of a 49-GHz train of ~1.6-ps pulses, using different lengths of the same fiber as the dispersive element.

In optical fibers, to obtain repetition-rate multiplication by a factor \( m \), one must satisfy the following equation:

\[
\frac{DL\Delta\lambda}{T} = \frac{s}{m},
\]

where \( D \) is the fiber dispersion parameter, \( L \) is the fiber length, \( \Delta\lambda \) is the spacing between spectral components of the pulse train, \( T \) is the pulse train period, and \( s \) is a positive integer. Note that the numerator on the left-hand side of the equation is the temporal delay experienced by a spectral component relative to its adjacent component. In the case of the integral Talbot effect \( m = 1 \) and, therefore, \( s/m \) is always an integer. However, in the case of the fractional Talbot effect, \( s/m \) is a fraction in its most reduced form. The highest repetition rate obtainable is limited by the duration of the individual pulses, as pulses start to overlap when the pulse duration becomes comparable to the pulse train period.

If pulses exist in the nonlinear regime and experience anomalous dispersion along the fiber, solitonic action occurs and prevents the linear Talbot effect from occurring. In a well-established technique, known as Raman compression, gradual Raman amplification along the fiber can be used to compress the solitons temporally and consequently decrease the duty cycle of the pulse train. In this Letter we show that, by combination of the linear fractional Talbot effect with nonlinear Raman compression in different sections of the same fiber, an 80-GHz train of 2.0-ps solitons can be generated from a 20-GHz train of 4.2-ps pulses. It is shown that varying the input pulse power alters the relative linear and nonlinear lengths in the fiber.

The experimental configuration is shown in Fig. 1. A 1550-nm, 20-GHz pulse train was generated with an external-cavity tunable laser (TL) and an electroabsorption modulator (EAM). A polarization controller (PC) was used before the EAM to optimize the modulation process. The EAM-induced frequency chirp on the pulse train was reduced through the use of 60.4 m of dispersion-compensating fiber (DCF).

Fig. 1. Experimental configuration for 4× repetition-rate multiplication and Raman compression of pulses in the same fiber. Abbreviations defined in text.
A series of erbium-doped fiber amplifiers (EDFA1 and EDFA2) and tunable bandpass filters (TBPF1 and TBPF2) were used to adjust the power of the pulses and to remove amplified spontaneous emission generated in the amplifiers. The average post-TBPF2 power of the pulse train was variable from 1.7 to 78 mW through control of the EDFA2 gain. Optical circulators (OC1 and OC2) were used to launch and extract the pulse train from a 21.7-km nonzero dispersion-shifted fiber (NZ-DSF), which had a dispersion of 3.8 ps nm$^{-1}$ km$^{-1}$ at 1550 nm and was employed as the dispersive element for the fractional Talbot effect. From Eq. (1), these experimental parameters yield an $s/m$ value of 0.26, which corresponds to $m = 3.8$ when $s = 1$. By use of OC2, light from a cw 1455-nm fiber Raman laser with a post-OC2 power of 1.28 W was launched into the NZ-DSF counterdirectionally to the pulse train to yield nonlinear Raman compression of the pulses. Simultaneous spectral and temporal measurements of the pulse train were made using an optical spectrum analyzer and a second-harmonic generation (SHG) autocorrelator, respectively.

The Talbot effect in optical fibers and the Raman amplification process were modeled in computer simulations, and the results were compared with those from the experiment. In the Talbot effect simulation, we assumed a sech$^2$ pulse profile and linearly delayed each spectral component of an input pulse train in accordance with experimental parameters to derive the resulting pulse train. The Raman amplification simulation modeled the power evolution along the fiber of a cw signal with a power equal to the average power of the pulse train in the presence of a counterpropagating Raman pump. This cw approximation suffices in this pump-signal counterpropagating configuration as the pump traverses at least $2 \times 10^6$ signal pulses along the fiber and effectively amplifies an averaged signal. Fiber loss and pump-to-signal Raman gain were considered, while other terms and nonlinear effects were not included.

Autocorrelations of the pulse train are depicted in Fig. 2 under various conditions for an average post-TBPF2 power of 1.7 mW. Figure 2(a) shows the case of the pre-OC1 20-GHz train of 4.2-ps pulses. The cross-correlated peak is of lower amplitude than the autocorrelated pulse. Note that this feature is a limitation of the measurement system and can be attributed to deviations from the linear behavior of the autocorrelator at large time delays such as 50 ps. Assuming sech$^2$ profiles, the corresponding peak power of the pulse is 17.8 mW. This value is significantly lower than the 493-mW peak power necessary for the formation of 4.2-ps fundamental solitons in the NZ-DSF, assuming a typical dispersion-shifted fiber nonlinear refractive index, $n_2$, of $2.3 \times 10^{-20}$ m$^2$ W$^{-1}$. As a result, propagation along the fiber, without Raman pumping, occurs in the linear regime, and the fractional Talbot effect can take place. Figure 2(b) shows the output pulses under these circumstances and, as can be seen, multiplication of the repetition rate by 4. In Fig. 2(b), the autocorrelation trace has a background that is 46% of the peak. This background is believed to be primarily due to overlap of the autocorrelated pulses. Note that there should not be significant pulse overlap in the actual generated 80-GHz pulse train as the train period is 12.5 ps, and as a consequence of the fractional Talbot effect the output pulse duration is expected to be 4.2 ps. In support of this expectation, the fractional Talbot effect computer simulation with experimental parameters predicted backgrounds that were 9% and 37% of the corresponding peaks for the actual pulse train and its autocorrelation, respectively. The discrepancy between the 46% and 37% autocorrelation backgrounds obtained experimentally and theoretically, respectively, is believed to be a result of the sech$^2$ pulse profile approximation that was made in the Talbot effect simulation. The computer simulation also shows that a slight improvement in the background is obtained if parameters are used that correspond exactly to a multiplication factor of $m = 4$. Further background improvements are expected with shorter pulse durations because of a lower duty cycle.

When the Raman pump is launched into the NZ-DSF, the pulse train experiences Raman amplification in addition to dispersing linearly along the fiber. When the 493-mW threshold peak power necessary to generate 4.2-ps fundamental solitons is reached, repetition-rate multiplication stops and Raman compression of the solitons commences. Figure 2(c) shows the autocorrelation of the 2.0-ps, 80-GHz pulse train that resulted from a 1.28-W post-OC2 Raman pump power. These pulses had an average power of ~300 mW and a 0.340 bandwidth–duration product, in close agreement with that of solitons. As can be seen from Fig. 2(c), the autocorrelation of the soliton train has a lower background, i.e., 10% of the peak level. The lower background is due to the decreased duty cycle that was obtained and, consequently, to less overlap of the autocorrelated pulses. The Raman amplification simulation predicts that the $4 \times$ repetition-rate multiplied 4.2-ps pulse train will reach the threshold power to become fundamental solitons at a distance of 20.5 km into the NZ-DSF, indicating that Raman compression occurs only in the last 1.2 km.

Fig. 2. Normalized autocorrelation of the pulse train (a) after TBPF2, (b) at the output without Raman pumping, and (c) with a Raman pump power of 1.28 W.
of the fiber. According to Eq. (1), a 20.5-km length for repetition-rate multiplication corresponds to a multiplication factor $m = 4.0$ for $s = 1$, which indicates that a higher-quality pulse train is expected with the use of the Raman pump. From the simulations, Raman compression by a factor of $\sim 2$ shown in Fig. 2 occurs over the remaining 1.2 km of the NZ-DSF. Note that the soliton period for a 4.2-ps soliton in this fiber is 1.8 km. Such compression over a fraction of the soliton period is excessive for the adiabatic regime, and consequently shedding of energy is expected.

In both Figs. 2(b) and 2(c), the cross-correlated pulses arising from repetition-rate multiplication are of lower amplitude than the autocorrelated pulses. In Fig. 2(b) the autocorrelation resembles a regular pulse train superposed with a noise burst at zero delay. This result indicates phase irregularities in the pulse train. This feature is believed to be a result of nonlinear chirp generated in the EAM that could not be compensated for in the DCF. In Fig. 2(c) the pulses are solitons, and hence no phase irregularities are expected. The decreased cross-correlated amplitudes in this case are likely due to timing jitter that is characteristic of nonadiabatic Raman compression.

Figure 3 shows that autocorrelations of the output pulse trains for various input pulse train powers and for a post-OC2 Raman pump power of 1.28 W. As can be seen, increasing the input pulse power gradually inhibits the pulse train repetition-rate multiplication process. With high input powers, the pulse train reaches the nonlinear threshold earlier in the fiber and the combination of the resulting shorter linear length and the 4.2-ps initial pulse duration does not support the fractional Talbot effect. Such is the case for an input average power of 78 mW, shown by the solid curve in Fig. 3. Also, note that with an increased signal power the cross-correlated peak at a delay of 50 ps is reduced in amplitude. This effect is believed to be a result of timing jitter caused by the high input peak power, i.e., $\sim 1.7 \times$ higher than that required for a fundamental 4.2-ps soliton. The excess energy is shed as a dispersive wave that subsequently interacts with the soliton and results in train period fluctuations. In addition, at such high input powers the compressed solitons have durations of $\sim 0.6$ ps and corresponding peak powers that cause soliton self-frequency shift and timing jitter. The pulse train was observed spectrally and was confirmed to exhibit a spectral displacement that is characteristic of soliton self-frequency shift.

Here we have shown $4 \times$ repetition-rate multiplication of a 4.2-ps, 20-GHz pulse train with an average input power of 1.7 mW in a 21.7-km NZ-DSF. The use of a counterpropagating cw 1.28-W Raman pump in the same fiber resulted in the generation of a 2.0-ps soliton train with a lower duty cycle and an $\sim 300$-mW average power through Raman compression. Computer simulations indicate that the linear Talbot effect occurred in the first $\sim 20.5$ km of the fiber and that Raman compression took place in the remaining length. It has also been shown that by variation of the input pulse train power the relative linear and nonlinear lengths can be adjusted. Slightly uneven soliton amplitudes were observed under repetition-rate multiplication that are due to nonideal experimental conditions. Further experimental optimization should lead to a higher-quality pulse train. The results show that the combination of the fractional temporal Talbot effect and Raman compression could allow the development of a compact pulse source that exhibits tunability in repetition rate, wavelength, and pulse duration.

D. A. Chestnut was supported by a United Kingdom Engineering and Physical Science Research Council studentship. C. J. S. de Matos was supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior Brazil and an Overseas Research Student UK award. The authors thank P. C. Reeves-Hall for developing the Raman amplification computer simulation. D. A. Chestnut’s e-mail address is david.chestnut@ic.ac.uk.

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