Tunable repetition-rate multiplication of a 10 GHz pulse train using linear and nonlinear fiber propagation

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The temporal Talbot effect and soliton propagation in an optical fiber were exploited to yield a series of pulse train sources with tunable repetition rate simply through variation of the pulse train power in sections of the fiber. In a dual-repetition-rate configuration, 10 and 20 GHz or 10 and 30 GHz repetition rates could be achieved depending on the fiber length used, with pulse durations lower than 21 ps. In a triple-repetition-rate configuration, 10, 20, and 30 GHz repetition rates were obtained, with pulse durations lower than 15 ps. © 2003 American Institute of Physics.

High repetition rate pulse sources are essential for upgrading current optical telecommunication systems and have received significant attention in the past few years. Sources of up to ~40 GHz repetition rate can be directly obtained electronically with the use of Mach–Zehnder electro-optic modulators and electroabsorption modulators. Optical techniques, such as modulational instability, rational mode-locking, split semiconductor laser cavities, and laser beating, offer more repetition rate flexibility and can be used to achieve higher frequencies.

All-optical repetition rate multiplication through the temporal Talbot effect has been recently proposed as means to obtain high-frequency pulse sources. In this simple and flexible technique, a pulse train at a certain repetition rate is chromatically dispersed in an optical fiber or in a chirped fiber Bragg grating to the point that neighboring pulses overlap and interfere with one another. By carefully adjusting the fiber or grating dispersion, the interference can be such that a multiple of the original repetition rate is obtained. The use of an optical fiber as the dispersive element is particularly interesting, as the Talbot effect achieved by linearly propagating the pulse train in a section of the fiber can be employed in combination with nonlinear soliton propagation of the train in a different section to result in useful and flexible devices. Recently, 4× repetition rate multiplication and Raman-assisted temporal soliton compression in the same fiber have been demonstrated.

In this letter we present a pulse source with selectable repetition rate based on the propagation of a 10 GHz pulse train in an optical fiber. By varying the launched power into the fiber it was possible to either obtain repetition rate multiplication due to the temporal Talbot effect or to maintain the original repetition rate through soliton transmission. Using this concept, a repetition rate selectable between 10 and 30 GHz was achieved by varying the power launched into the fiber. The configuration was used and, when the pulse train power was below the soliton threshold, gave repetition rate multiplication factors of 3 and 2, respectively. When the pulse train power was above the soliton threshold, a 10 GHz output train was obtained as expected. The output pulse train was simultaneously analyzed in an optical spectrum analyzer and in an autocorrelator. A 20 ps impulse response detector and a 50 GHz digital sampling oscilloscope were also used to directly probe the pulse train temporally but in this case the actual pulse shape was hindered by the detector resolution.

The experimental setups used for the repetition-rate-selectable pulse sources are shown in Fig. 1. Figure 1(a) shows the first setup used, which allows selectivity between two repetition rates. Pulses at 1549.4 nm with durations of ~6.8 ps were generated in a 10 GHz pulse source and amplified in an erbium-doped fiber amplifier (EDFA) before being launched into a length of standard telecommunication fiber (STF). The pulse source consisted of a cw, single-longitudinal-mode semiconductor laser, an electroabsorption modulator, and a linearly chirped fiber Bragg grating used to compensate for the chirp produced by the modulator. The gain of the EDFA was variable and was adjusted to give in-STF average powers that were either above or below the fiber soliton threshold for the input pulses used (estimated to be ~100 mW). STF lengths of 25.4 and 38.3 km were separately used and, when the pulse train power was below the soliton threshold, gave repetition rate multiplication factors of 3 and 2, respectively. When the pulse train power met the soliton threshold, a 10 GHz output train was obtained as expected. The output pulse train was simultaneously analyzed in an optical spectrum analyzer and in an autocorrelator. A 20 ps impulse response detector and a 50 GHz digital sampling oscilloscope were also used to directly probe the pulse train temporally but in this case the actual pulse shape was hindered by the detector resolution.

![FIG. 1. Experimental configurations for the repetition-rate-selectable pulse source; (a) setup for obtaining 10 and 20 GHz or 10 and 30 GHz repetition rates; (b) setup for obtaining 10, 20, and 30 GHz repetition rates.](https://example.com/figure1.png)
Figure 1(b) shows the setup used for obtaining 10, 20, and 30 GHz selectable repetition rate from a single device. In this case, 38.3 km of STF were split into two sections of 12.9 and 25.4 km so that either linear or nonlinear propagation could be independently obtained in each section. The same 10 GHz pulse source was utilized and the power in each fiber section was controlled by adjusting the attenuation (Atten) before each section. When the pulse train power was below the soliton threshold in both fiber sections, the temporal Talbot effect led to an output repetition rate of 20 GHz. When the train power met the soliton threshold only in the 12.9 km STF, temporal Talbot effect in the 25.4 km STF generated a 30 GHz output repetition rate. Finally, when soliton propagation occurred in both fibers, a 10 GHz output pulse train was obtained.

It was found that when the pulse train propagated in the soliton regime in the 12.9 km STF, pulse energy shedding occurred both due to nonadiabatic soliton attenuation in the STF (the STF attenuation was measured to be 0.19 dB/km) and due to the fact that the pulses generated by the 10 GHz pulse source had a small chirp. This energy shedding led to pulse train spectral degradation that prevented quality repetition rate tripling to be obtained in the subsequent, 25.4 km STF section. To improve the input pulse train quality, a nonlinear optical loop mirror (NOLM) was added between the EDFA and the 12.9 km STF, which comprised a 32:68 coupler, a ~2 km STF, and a polarization controller (PC). The NOLM operated in the nonlinear switching regime, outputting solitons. The EDFA output power and the NOLM polarization were adjusted while the configuration was set to 30 GHz operation so that the quality of the 30 GHz output pulse train was optimized. These parameters were then left constant for the 10 and the 20 GHz repetition rate cases. To overcome the soliton attenuation, Raman amplification was provided in the 12.9 km fiber section by a counterpropagating Raman pump consisting of a fiber Raman laser (FRL) at 1455 nm. Optical circulators OC2 and OC1 were, respectively, used to insert and extract the Raman pump to and from this fiber section. The FRL output power was also chosen in order to optimize the 30 GHz repetition rate case and was increased only in the 10 GHz case, in which the power reaching the 25.4 km STF had to meet the fiber soliton threshold. The output pulse train was analyzed as in the case of the previous setup. Alternatively, both sources of soliton energy shedding could be addressed by placing the NOLM between fiber sections so as to spectrally clean the 25.4 km STF input pulses. This scheme would require an additional EDFA and was not tested in the present work.

Figure 2 depicts the autocorrelation traces of the output pulse train when the configuration illustrated in Fig. 1(a) was used. Figure 2(a) shows the case when the 38.3 km STF was employed and the in-STF average pulse power was set to ~130 (top) and ~18 mW (bottom). When the train power met the soliton threshold, a 10 GHz output pulse train with pulse durations of ~21 ps was obtained. The pulse broadening observed can be accounted for by the fiber attenuation that reduces the soliton peak power and consequently leads to an increase in soliton duration. When the input pulse train power was below the fiber soliton threshold, the temporal Talbot effect led to a 20 GHz output pulse train with 8.5 ps pulses. The slight pulse duration increase in this case is due to a small deviation from the optimal fiber length required for repetition rate doubling. Figure 2(b) shows similar traces for when the 25.4 km STF was employed. The top trace shows the autocorrelation of the output pulse train for an average input power of ~140 mW. As in the previous case, soliton propagation prevented the temporal Talbot effect to take place and a 10 GHz pulse train with pulse durations of ~15 ps was obtained. The bottom trace shows the autocorrelation of the output pulse train for an average input power of ~11 mW. In this case the temporal Talbot effect tripled the repetition rate and a 30 GHz train of 7.2 ps pulses was achieved. For both fiber lengths used the temporal traces obtained with the sampling oscilloscope and the detector indicated that the pulse trains had a low amplitude fluctuation of ~8% or less.

Figure 3 shows autocorrelations of the output pulse train at the three different repetition rates obtained with the experimental configuration depicted in Fig. 1(b). For all cases shown, the pulse train at the NOLM output had an average power of 120 mW and a pulse duration of 9.7 ps. The 10 GHz output train of 14.5 ps pulses obtained when no attenuation was used can be seen in Fig. 3(a). The FRL power utilized was 590 mW, providing an internal gain (ratio between Raman gain and fiber loss) of 3.6 dB and inducing soliton temporal compression by a factor 2.1. Figure 3(b) illustrates the case in which 18 dB attenuation was induced...
prior to the 12.9 km STF and the FRL power was set to 390 mW. Linear propagation along both fiber sections resulted in a 20 GHz train of 10 ps pulses. The case in which 18 dB attenuation was induced before the 25.4 km STF can be seen in Fig. 3~c~. The 390 mW FRL provided an internal gain of 1.8 dB and soliton compression by a factor 1.9. Repetition rate multiplication in the 25.4 km fiber section resulted in a 30 GHz train of 6.1 ps pulses. The pedestal levels observed in Figs. 2 and 3 are believed to result from two main sources. In conditions involving repetition rate multiplication, the presence of spurious spectral components and deviations from the optimum fiber length and dispersion are expected to have increased the pedestal. In conditions involving nonlinear propagation, the soliton energy shedding processes mentioned earlier are believed to have led to some pedestal, even with the use of the NOLM. Further optimizing the fiber parameters, the input pulse quality, and the Raman gain distribution along the fiber could improve the pulse-to-pedestal ratio.

When the pulse train generated by the configuration in Fig. 1(b) was measured using the sampling oscilloscope and the 20 ps detector ~17% and ~16% amplitude fluctuations were observed in the 20 and 30 GHz cases, respectively. A simulation of the temporal Talbot effect indicated that these fluctuations were a consequence of the imperfect pulse train spectral profile obtained at the NOLM output, in the 20 GHz case, and at the 12.9 km STF output, in the 30 GHz case. The simulation also showed that a significant reduction on such fluctuations could be obtained if the input pulse train quality is improved.

Due to the different nature of light propagation in the linear and nonlinear regime, one could expect to observe different polarization states when solitons or repetition-rate-multiplied pulses reached the autocorrelator. In this work, this feature was not observed.

In conclusion, fiber pulse train sources have been demonstrated that offer selectable repetition rate. Depending on the configuration used, 10 and 20 GHz, 10 and 30 GHz, or 10, 20, and 30 GHz repetition rates could be obtained simply by varying the pulse train power. Pulses with durations equal to or lower than 21 ps were achieved. The dual-repetition-rate configurations exhibited low pulse train amplitude fluctuations. ~17% amplitude fluctuations were observed in the triple-repetition-rate configuration but could be reduced if higher-quality input pulse trains are used. The technique described here can be readily applied to obtain other repetition rates simply by choice of the fiber length used.

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