Tunable pulse repetition-rate multiplication using phase-only line-by-line pulse shaping

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We demonstrate a method for all-optical, tunable pulse repetition-rate multiplication of a mode-locked laser based on spectral line-by-line control. In particular, two-to-five-times repetition-rate multiplication of a 9 GHz source is achieved with very high fidelity. © 2007 Optical Society of America

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Optical pulse trains with high repetition rates are very attractive for future ultrahigh-speed optical communication systems and ultrafast signal processing. Recently, several research groups have been exploring techniques for generating periodic pulse trains at repetition rates beyond those achievable by mode locking or direct modulation. One alternative is repetition-rate multiplication of a lower rate source by applying amplitude[1–3] or phase[4–6] spectral filtering. In this way, a technique based on the temporal Talbot effect[7] is a simple and energetically efficient method, as it simply requires the propagation of the pulse train in a first-order dispersive medium. This option, which is equivalent to a phase-only filtering process, has been traditionally demonstrated by using conventional optical fibers[4,5] or linearly chirped fiber Bragg gratings.[6] In practice, however, this approach is highly sensitive to the applied spectral phase. When the dispersion deviates from that given by the so-called Talbot condition,[7] degradations of the multiplied pulse trains such as peak-to-peak pulse intensity variations[4,7] are observed. Group delay ripple accompanying fiber Bragg grating implementations leads to similar distortions.[8]

In this Letter, we demonstrate a new approach for high-quality repetition-rate multiplication based on programmable line-by-line pulse shaping.[9] In particular, we use a recently developed high-resolution pulse shaper to impose different, user-defined periodic spectral phases onto the individual spectral lines of a 9 GHz repetition-rate mode-locked laser. Although a pulse shaper was previously used to place periodic phase-only functions onto the spectrum of ultrashort pulses,[10] in those experiments the resolution was insufficient to address individual spectral lines. Consequently, an isolated burst of pulses, rather than true repetition-rate multiplication, was obtained. Here, by programming a line-by-line shaper according to the Talbot condition, we achieve high-quality repetition-rate multiplication, leading to repetition frequencies as high as 45 GHz and time-domain peak-to-peak pulse intensity variations as small as 1%.

The experimental setup is shown in Fig. 1. A home-built actively mode-locked Er-fiber laser producing ~3 ps pulses at a 9 GHz repetition rate is the pulse source. The discrete spectral lines of the mode-locked laser are manipulated by a fiber-coupled Fourier-transform pulse shaper in a reflective geometry. The loss in the optical system is compensated by an erbium-doped fiber amplifier. The resulting optical signal is characterized by using an optical spectrum analyzer with 0.01 nm resolution and a 50 GHz photodiode followed by a sampling oscilloscope and an rf spectrum analyzer, each with a 50 GHz bandwidth. Our line-by-line pulse shaper is described in detail in Ref. 9. Briefly, the shaper comprises an ~18 mm diameter input beam, a 1200 grooves/mm diffraction grating, a 1000 mm focal length lens, a liquid-crystal modulator (LCM) array with a 12.8 mm aperture and 2×128 independent pixels, a retroreflecting mirror, and a circulator. The LCM allows us to independently control both the amplitude and phase of individual spectral lines. The fiber-to-fiber insertion loss is 11.6 dB (including circulator loss), although this level of loss is not fundamental. Other pulse shapers, admittedly not with the current high resolution, have been reported with as little as 4 dB loss (including circulator). The spectral dispersion of the pulse shaper is designed such that the spacing between adjacent spectral lines corresponds to precisely two LCM pixels. The pulse shaper is adjusted for zero chromatic dispersion[11]; hence, negligible broadening is observed when 3 ps pulses pass through the pulse shaper without spectral filtering.

To achieve repetition-rate multiplication, we refer to the temporal Talbot effect.[7] This phenomenon occurs when periodic trains of optical pulses propagate through a first-order dispersive medium. An appropriate amount of dispersion leads either to reproduction of the original pulse train (integer temporal Tal-

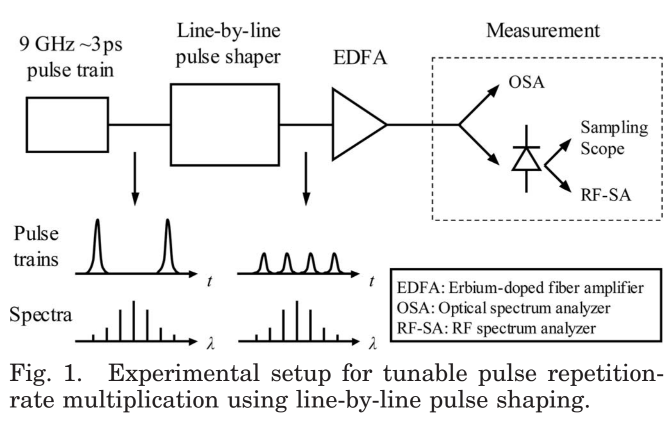

Fig. 1. Experimental setup for tunable pulse repetition-rate multiplication using line-by-line pulse shaping.

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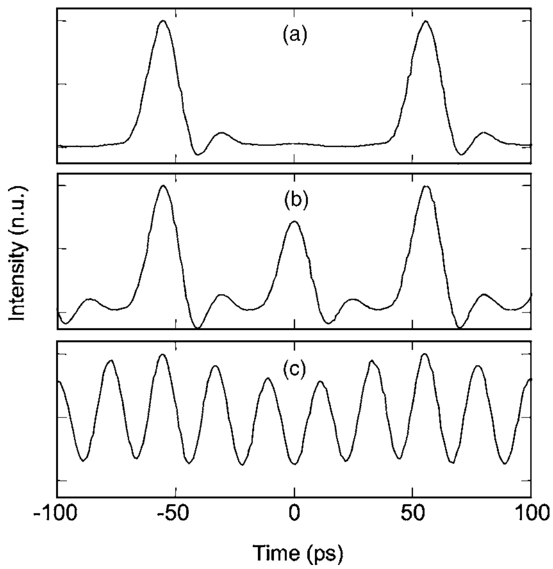

Fig. 2. Tunable pulse repetition-rate multiplication. (a) Measured oscilloscope trace when the 9 GHz input pulse train passes through the setup in Fig. 1 with the pulse shaper inactive. Output pulse train at (b) 2×9 GHz and (c) 5×9 GHz. Nonidealities in the line-by-line pulse shaper lead to multiplied trains with significant peak-to-peak pulse intensity variations.

bot effect) or repetition-rate multiplication by an integer factor (fractional temporal Talbot effect). For our purposes it is important to note that it is unnecessary to introduce continuous first-order dispersion. In fact, only the spectral phases at frequencies equal to the discrete spectral lines, $\omega_n=\omega_0+n\omega_{\mathrm{rep}}$, are relevant, where ω_0 is the carrier frequency, ω_{rep} is the input repetition rate, and n is an integer. The Talbot condition[7] provides the phase shifts that must be applied to the different spectral lines to obtain repetition-rate multiplication:

$$\phi(\omega_n)=\frac{s}{r}\pi n^2, \tag{1}$$

where s and r are mutually prime integer numbers. The multiplication factor is given by the integer r. Maximum repetition-rate multiplication is limited by the input pulse duration, which must be short enough to prevent pulse overlapping in the multiplied train. In practice, the actual phase shifts are applied by the pulse shaper modulo 2π, which yields a periodic phase filter.[12,13]

In the experiments, approximately 40 spectral lines are individually controlled in the wavelength range (1541–1544 nm). Figure 2(a) shows the measured oscilloscope trace when the input pulse train passes through the setup with the pulse shaper inactive. Figures 2(b) and 2(c) show multiplied trains at 18 and 45 GHz, with $s=1$, $r=2$, and $s=2$, $r=5$, respectively. The traces are the average of 60 measurements. The background level in the 45 GHz train is caused by the limited bandwidth of the measurement system. Three- and four-times repetition-rate multiplication is also easily obtained by reprogramming the LCM according to Eq. (1) with $s=2$, $r=3$, and $s=1$, $r=4$, respectively. As observed in Figs. 2(b) and 2(c), initially the multiplied trains show significant peak-to-peak pulse intensity variations. Approximately 20%–30% maximum variations are typical. We attribute this undesired effect to small errors in the calibration of the LCM and to weak cross talk between adjacent spectral lines due to the finite spectral resolution.

To generate uniform pulse intensities, we use an iterative correction algorithm that adaptively modifies the phases applied by the LCM. The algorithm starts with the phase sequence $\{\phi_0,\phi_1,\phi_2,\ldots,\phi_N\}$, obtained from Eq. (1). Next, the first phase ϕ_0 is modified, $\phi_0'=\phi_0\pm\varepsilon$, with ε a preset phase error, and the resultant output trains are measured. The algorithm selects the new phase ϕ_0' that generates the output train with smallest peak-to-peak pulse intensity variation. If there is no improvement, the initial phase is preserved. Next, a similar procedure is applied sequentially for the second and other phases in the sequence, finally obtaining a new series of phase values $\{\phi_0',\phi_1',\phi_2',\ldots,\phi_N'\}$. For some of the multiplication factors, namely, three-to-five-times repetition-rate multiplication, we also used a similar procedure to adjust the spectral amplitudes. We iteratively repeated this procedure, while decreasing the value of ε from one iteration to the next. Typically five or six iterations were required to minimize peak-to-peak pulse intensity variations in the output pulse train. The rms (maximum) spectral phase and intensity changes imposed by the algorithm were 0.076 rad (0.135 rad) and 7.5% (15%), respectively. These small changes were found to have quite a significant effect on the quality of the output pulse trains (see below), thus underscoring the need for high accuracy in Talbot effect experiments and the benefit of fine-tuning capability in the apparatus.

In Fig. 3 (top row), we show experimental oscilloscope traces both for the unfiltered pulse train and for the multiplied trains at 18, 27, 36, and 45 GHz, respectively, obtained after applying the iterative correction algorithm. The multiplied trains now have very low peak-to-peak pulse intensity variations. In particular, we obtain $\sim$1%, 1.5%, 1.5%, and 2% maximum peak-to-peak variations for the 18, 27, 36, and 45 GHz output trains, respectively. In general, we are able to routinely generate multiplied trains with less than 3% peak-to-peak pulse intensity variations. For comparison, we must mention that tunable pulse repetition-rate multiplication experiments in which the temporal Talbot effect was implemented by using dispersive fibers[14] and linearly chirped fiber Bragg gratings[15] yielded multiplied trains with significantly larger intensity variations in the range (8%–17%) and (7%–17%), respectively. Note that repetition-rate multiplication is observed by temporal intensity-based measurements, but adjacent pulses have different phase shifts in the multiplied trains. However, this method can be combined with other schemes to obtain real repetition-rate multiplication.[16] Further, it is also possible to multiply the repetition rate by performing spectral selection[1,2] with our line-by-line shaper as an amplitude filter.

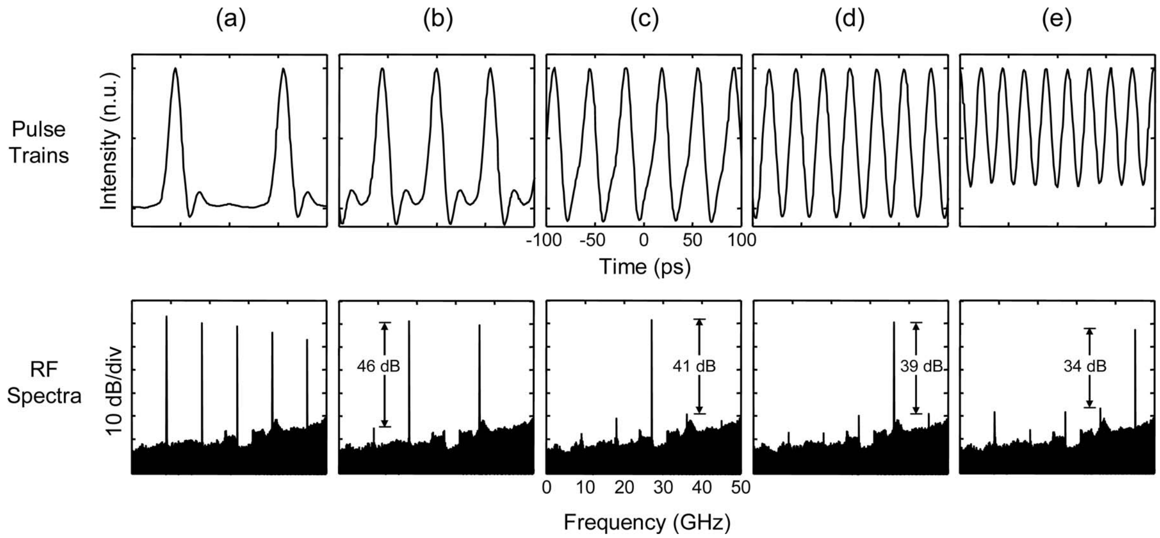

Fig. 3. Sampling oscilloscope traces and rf spectra of: (a) unfiltered pulse train and (b)–(e) multiplied pulse trains obtained with the setup in Fig. 1. The pulse repetition rates are: (a) 1×9 GHz, (b) 2×9 GHz, (c) 3×9 GHz, (d) 4×9 GHz, and (e) 5×9 GHz. The application of an iterative correction algorithm allows us to generate multiplied trains with very uniform pulses by compensating for the line-by-line pulse-shaper nonidealities.

To further illustrate the high degree of uniformity we have achieved, rf spectrum analyzer measurements of the multiplied pulse trains are also plotted in Fig. 3 (bottom row). For the original pulse train (without spectral filtering), rf tones at 9 GHz and its harmonics are observed, as expected. When the pulse shaper is programmed for two-times multiplication, Fig. 3(b), the now undesired tones at 9 and 27 GHz are suppressed almost into the noise floor, 46 dB below the 18 GHz tone. This large suppression factor is consistent with the degree of intensity variation from the scope traces. Figures 3(c)–3(e) depict the rf spectra of the multiplied trains at 27, 36, and 45 GHz, respectively. Relative to the desired tone at the multiplied repetition rate, the undesired tones are suppressed by 41, 39, and 34 dB, respectively. Much of the slight reduction in suppression ratio with increasing repetition rate can be explained due to the roll-off of our measurement system at higher frequencies. In any case, the strong suppression of unwanted tones in our phase-filtering experiments significantly exceeds the already strong suppression observed in previous four-times multiplication experiments based on amplitude filtering via a double-pass Fabry–Perot.[3]

In conclusion, we have experimentally demonstrated two-to-five-times reconfigurable repetition-rate multiplication of a 9 GHz mode-locked laser by periodic spectral phase filtering implemented via line-by-line pulse shaping. Higher repetition-rate multiplication factors can be readily achieved if trains with shorter pulses are used as the input. This experiment also illustrates the ability of our high-resolution pulse shaper to perform simultaneous, accurate, and independent programmable control of individual spectral lines over the whole optical bandwidth of the mode-locked laser. As a result, we have achieved unprecedented uniformity in pulse trains multiplied according to the temporal Talbot effect.

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