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Periodic Time-Domain Modulation for the Electrically Tunable Control of Optical Pulse Train Envelope and Repetition Rate Multiplication

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Abstract—An electrically tunable system for the control of optical pulse sequences is proposed and demonstrated. It is based on the use of an electrooptic modulator for periodic phase modulation followed by a dispersive device to obtain the temporal Talbot effect. The proposed configuration allows for repetition rate multiplication with different multiplication factors and with the simultaneous control of the pulse train envelope by simply changing the electrical signal driving the modulator. Simulated and experimental results for an input optical pulse train of 10 GHz are shown for different multiplication factors and envelope shapes.

Index Terms—Optical fiber dispersion, optical pulse shaping, optical signal processing, temporal Talbot effect.

I. INTRODUCTION

OPTICAL ultrashort pulses and pulsed sequences have been found to be useful in many different fields [1]–[3], but specific and well-controlled shapes for the pulses or sequences are needed for some of the applications. Optical pulse shaping techniques have, consequently, received an increasing attention in the last few years [4]–[6]. Of specific interest are techniques for pulse repetition rate multiplication (RRM), which are used to generate ultrafast optical pulse trains from a low repetition rate input pulse train [7]–[14]. In applications such as ultrahigh-speed optical communications and the optical generation of millimeter-wave waveforms, uniform multiplication of the input repetition rate is not enough, since the amplitude of each of the resulting pulses needs to be controlled individually [15]–[20].

One of the most applied schemes for optical pulse control and pulse RRM is based on the manipulation of the input spectrum by properly altering the amplitude and phase of its frequency components [4]. In particular, RRM can be achieved with a linear filtering of the periodic comb that a mode-locked laser produces [17]. Amplitude filters [7]–[9] are configured to periodically eliminate some of the spectral lines or modes, since the repetition rate of the pulse train is inversely proportional to the frequency spacing. Phase filtering approaches [10]–[14], which are more efficient in terms of energy, are usually explained in terms of the fractional temporal Talbot effect [21]. In this second case, a dispersive medium, such as an optical fiber or a linearly chirped fiber Bragg grating (LC-FBG), is employed to impose the required phase to the spectrum of the train of pulses. However, this phase filtering technique results in output pulse trains with only uniform envelopes (constant amplitude of the pulses). Another popular implementation, that is also usable for amplitude filtering, uses bulk diffraction gratings to resolve the individual lines of the spectrum of incoming pulses in the space where spatial light modulators, based on liquid crystals, acoustooptic modulators, or deformable mirrors, perform the complex Fourier-domain filtering [4], [13], [18]. A similar setup can be configured to work as a direct space-to-time optical shaper [16]. These last two approaches require the use of bulk optics with the typical shortcomings such as significant insertion losses, limited integration capabilities with fiber or waveguide optics systems, and the need of accurate alignment and stability. Periodic filters based on planar lightwave circuits to permit the use of integrated optics have also been proposed [14], [19], [20], [22], but degradations in output pulse trains are found due to imperfections in the fabrication of the devices. Moreover, modifying the multiplication ratio or the train envelope is difficult in the integrated devices and slow in the case of the schemes based on liquid crystal modulators.

Temporal pulse shaping techniques [23]–[25] have been previously proposed to overcome these limitations and because they allow the fast reconfiguration of the pulse shape by changing only an electrical signal. These schemes use a pair of dispersive elements to temporally stretch and compress the input optical pulse and an electrooptical modulator to perform the shaping in the Fourier domain. Hence, in those conventional temporal pulse shaping systems, the input pulse must be first stretched before being modulated, mapping the spectrum to the time domain. The shaping of the pulse spectrum is then directly performed by the modulation with a previously calculated set of coefficients within the pulse period. In this paper a new technique is presented where only one coefficient is applied within one pulse period, being thus the modulation speed the same than
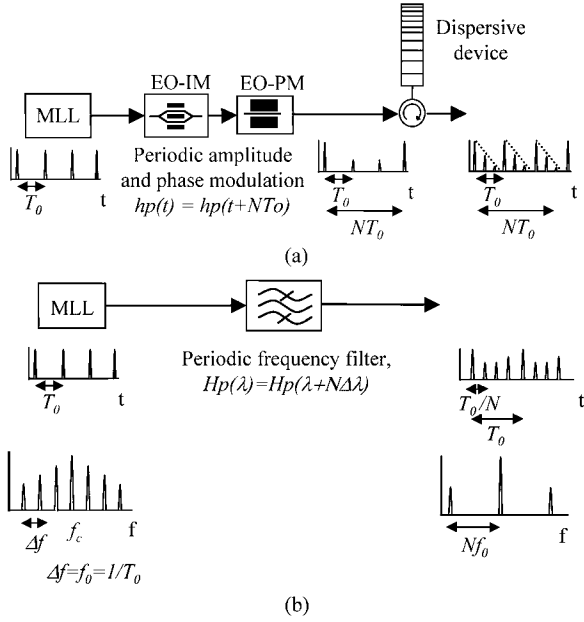
Fig. 1. (a) Proposed technique with shaping in the time domain followed by a dispersive device. (b) Conventional technique with shaping in the frequency domain. MLL: mode-locked laser, EO-IM: electrooptic intensity modulator, EO-PM: electrooptic phase modulator.

the input train repetition rate. Afterward, the shaped train of pulses is obtained by conveniently dispersing the modulated signal, requiring thus only one dispersive element. Besides, as the speed at which the modulation is performed is slower than in other previously proposed techniques, the system is more robust against desynchronization between the electric signal applied and the input train of pulses. It is worth emphasizing that whereas in [23]–[25] the shaping is made pulse by pulse, allowing the individual modification of each pulse, in our setup it is the envelope of a high-speed train what is shaped. Examples of the application of both techniques in an optical code division multiple access system can be seen in [26] and [27].

II. FUNDAMENTALS OF THE PROPOSED TECHNIQUE

The proposed technique is shown schematically in Fig. 1(a). The input signal is a periodic train of short optical pulses with a repetition rate $f_0 = 1/T_0$, where T_0 is the delay between two consecutive pulses, as in the conventional pulse train shaping technique represented in Fig. 1(b). The spectrum of this train of pulses is a series of discrete spectral lines with locked phases and frequency spacing equal to the pulse repetition rate, f_0.

In the conventional approaches [see Fig. 1(b)], the spectrum of the input signal is periodically filtered in amplitude, in phase, or in both. Multiplication of the repetition rate by an integer factor N can be obtained by letting pass to the output only one of every N spectrum lines when using amplitude filters or, if the filtering is in phase, by applying the phase shifts associated with each spectral component determined by the fractional Talbot effect [13]. In both cases, all the output pulses have the same amplitude and shape (the same shape as in the input train). However, to modify also the envelope of the train of pulses,

more complex nonintuitive filters have to be applied [15]–[20]. This prevents the use of simple phase devices such as fiber optics or LC-FBGs, requiring the use of optical filters able to process individual spectral lines and being thus limited by the available filtering resolution.

The proposed technique is based on the manipulation of a periodic train of pulses on the time domain and a controlled interference between them caused by a dispersive device. As shown in Fig. 1(a), the input train of pulses is processed in phase, amplitude, or both by using electrooptical modulation in the time domain, which acts as dual of the periodic filter in Fig. 1(b). To that purpose, a periodic time modulation is introduced by applying an electrical signal to the modulator electrodes with a period of NT_0. In order to model the system, the complex envelope of the input train of pulses can be represented as

$$x_1(t) = \sum_{k=-\infty}^{\infty} a(t - kT_0) \qquad (1)$$

where $a(t)$ is an arbitrary complex function that models the shape of the individual pulses. The train of pulses in (1) is modulated with a signal $m(t)$ which is chosen to be periodic with period NT_0. However, if the pulse width Δt of the pulses $a(t)$ is much smaller than the time variations of the modulating signal, the modulation applied can be assumed to be constant during the whole duration of the individual pulses. Therefore, the modulated signal is given by

$$\begin{aligned} x_2(t) &= m(t) \cdot x_1(t) \\ &= \sum_{l=0}^{N-1} m(lT_0) \sum_{k=-\infty}^{\infty} a(t - lT_0 - kNT_0). \end{aligned} \qquad (2)$$

As can be observed in (2), the time-modulated pulse sequence can be expressed as the superposition of N trains of pulses, where each of them has a period of NT_0 and is multiplied by a complex coefficient $m_l = m(lT_0)$. There is also an additional time shift of T_0 between two consecutive trains. As demonstrated in [21], a temporal fractional Talbot effect with $s = 1$ and $m = N^2$ occurs when a train of pulses of period NT_0 passes through a dispersive device with dispersion given by

$$\ddot{\Phi} = \frac{s(NT_0)^2}{m2\pi} \bigg|_{s=1, m=N^2} = \frac{T_0^2}{2\pi}. \qquad (3)$$

That is, when the modulated sequence is dispersed, each of the N subtrains of pulses results in another pulse train with a period of $NT_0/N^2 = T_0/N$ that superposes coherently with the rest of incident trains to give the output sequence $x_3(t)$. Consequently, the pulses in the resulting sequence are obtained by combining the different weighted trains, taking into account the coefficients imposed by the electrooptic modulator m_l, the phase factors given by the fractional Talbot effect A_k, and the time shift between the trains

$$x_3(t) = \sum_{l=0}^{N-1} m_l \sum_{k=-\infty}^{\infty} A_k a\left(t - lT_0 - k\frac{T_0}{N} - \frac{T_0}{2}\right)$$

$$= \sum_{k'=-\infty}^{\infty} \sum_{l=0}^{N-1} m_l A_{k',l} a\left(t - k'\frac{T_0}{N} - \frac{T_0}{2}\right) \qquad (4)$$

where as stated in [10] and assuming that N is even

$$A_{k',l} = \frac{1}{N^2} \sum_{q=0}^{N^2-1} \exp\left(j\frac{\pi}{N^2}\left\{q^2 + 2\left(k' - lN\right)q\right\}\right). \qquad (5)$$

As a result, the average optical power of the signal at the output of the system is given by

$$P_3(t) \propto \sum_{k'=-\infty}^{\infty} \left|\sum_{l=0}^{N-1} m_l A_{k',l}\right|^2 \left|a\left(t - k'\frac{T_0}{N}\right)\right|^2$$

$$= \sum_{k'=-\infty}^{\infty} |n_{k'}|^2 \left|a\left(t - k'\frac{T_0}{N}\right)\right|^2. \qquad (6)$$

This corresponds to a train of pulses with a repetition factor T_0/N as expected, where the peak power of the pulses $|n_{k'}|^2$ is determined by a set of coefficients that depend on the modulating signal. If N is odd a similar expression can be found, the only differences being an additional time shift of $T_0/2N$ and some minor changes in $A_{k',l}$ as shown in [10]. Therefore, by choosing a suitable modulating signal, the amplitude of the output train of pulses can be controlled, and the relation between the modulating coefficients m_l and the output envelope coefficients is

$$n_{k'} = \begin{cases} \dfrac{1}{N^2} \displaystyle\sum_{l=0}^{N-1} m_l \sum_{q=0}^{N^2-1} \exp\left(j\frac{\pi}{N^2}\left\{q^2 + 2\left(k' - lN\right)q\right\}\right) \\ \qquad\qquad\qquad\qquad\qquad N \text{ even} \\ \dfrac{1}{N^2} \displaystyle\sum_{l=0}^{N-1} m_l \sum_{q=0}^{N^2-1} \exp\left(j\frac{\pi}{N^2}\left\{q^2 + \left(2k' - 2lN + 1\right)q\right\}\right) \\ \qquad\qquad\qquad\qquad\qquad N \text{ odd.} \end{cases} \qquad (7)$$

One of the main advantages of this approach is that, as stated by (3), the dispersion that has to be introduced is independent of the RRM factor N allowing the tuning of this factor without changing the dispersive element. In fact, the advantage of this new approach is, besides its compatibility with fiber optic systems, the easy change of the resulting signal that only needs the modification of the electrical signal applied to the modulator.

As in a conventional setup, if an arbitrary envelope of the output train of pulses is to be obtained, both amplitude and phase manipulation of the input pulses are required. However, if only the temporal intensity profile is to be controlled leaving the phase unconstrained, as in [18] or in [25], it has been found that with only phase modulation many interesting envelopes can still be synthesized [4], [18], including the RRM at the output of the system. Phase-only shaping is preferred in these cases because of its greater energetic efficiency and also because it only requires the use of one electrooptic phase modulator to perform the shaping. This is our choice, since we apply a temporal phase modification of the input pulses. Moreover, for simplicity only two different levels for the introduced phase were used, resulting in an additional constraint to the envelopes that can be obtained.

If a multilevel phase function is applied by employing an RF arbitrary waveform generator as simulated in [23], this limitation will be avoided. When phase-only shaping is used, the spectral (conventional approach)/temporal (our approach) amplitude at the output of the filter/modulator is fixed and an optimization algorithm is needed to calculate the phase modulation required to generate a specific output waveform [13], [18]. In our case, the main goal is that the amplitudes of the coefficients resulting from the interference due to the fractional Talbot effect, which are given by $|n_{k'}|$, match the desired amplitudes of the N pulses that appear at the output in one period of the original signal $y_{k'}$. Therefore, the function that has to be minimized is defined by

$$F(c_0, ..., c_{N-1}) = \sum_{k'=0}^{N-1} ||n_{k'}| - y_{k'}| \qquad (8)$$

where c_k are the coefficients that determine the phase values applied by the phase modulator ($m_l = e^{j\pi c_l}$) and the amplitude of the pulses at the output of the system $|n_{k'}|$ can be obtained using (7).

In order to generate more complex waveforms, the use of multilevel modulation would be required. This implies the need of new algorithms to solve the complexity of the involved computation when the conventional approach is used [23]. However, in our approach no additional complexity is required in the optimization process, as we are not shaping a single pulse but the envelope of a train of N pulses. Therefore, only the peaks of N pulses are to be controlled, resulting in the simple cost function in (8) and with only N values (the c_k coefficients) to be estimated.

III. RESULTS AND DISCUSSION

In order to prove the proposed shaping technique, the setup shown in Fig. 2 was implemented in our laboratory. A Calmar mode-locked laser (PSL-10) centered at 1539.2 nm with a repetition frequency of 10 GHz and a pulse width of 5 ps was used as the optical pulsed source. The train of pulses was then phase modulated with a 12.5-GHz bandwidth electrooptical modulator by using an electrical signal given by a pattern generator at a rate of 10 Gb/s. The control of the phase-shift values was achieved by modifying the peak-to-peak voltage of the electrical signal driving the modulator. Finally, the phase-modulated optical pulses were dispersed using a linearly chirped-fiber Bragg grating with a dispersion slope of approximately -1590 ps^2 accordingly to (3) and a bandwidth of 0.7 nm. The resulting signal was analyzed using a photodiode and sampling scope with a 65-GHz bandwidth and a measurement average of 16 samples at the oscilloscope.

In Fig. 3, the output of the system is analyzed when no coefficients are applied at the electrooptic modulator. As can be seen, the filtering produced by the fiber Bragg grating affects the performance of the system, resulting in an increased pulse width at the output of the system that can cause overlapping between adjacent pulses when the repetition rate is increased. Also, the reduction in the number of spectral components that pass to the output of the system will limit the maximum repetition rate achievable, causing variations in the peak power of the
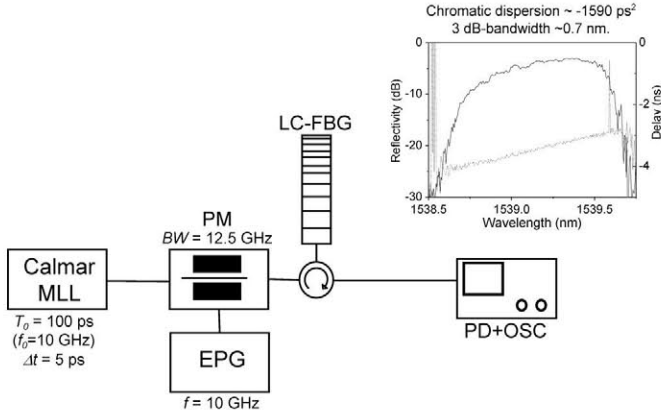
Fig. 2. Experimental setup (MLL: mode-locked laser, PM: phase modulator, LC-FBG: linearly chirped-FBG, PD: photodetector, OSC: oscilloscope, EPG: electric pattern generator).
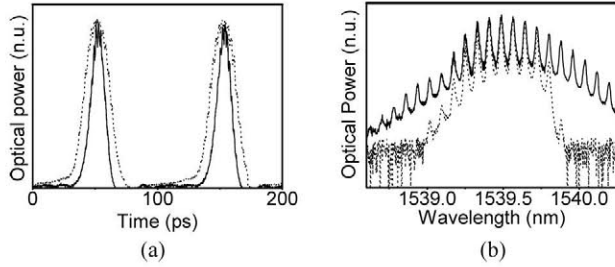

Fig. 3. (a) Pulses and (b) spectrum at the input (solid) and output (dotted) of the system when no modulating signal is applied.
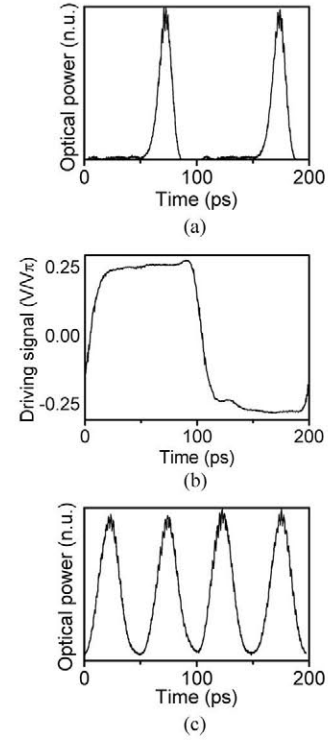

Fig. 4. (a) Input optical pulses, (b) electric signal applied to the modulator and (c) output optical pulses, when phase coefficients [0.5 0] are applied to obtain the [1 1] pattern.

pulses. Simulation results indicate that using a different dispersive medium without the filtering limitation, such as a dispersion compensating fiber (DCF), results in a more accurate control of the output signal, allowing higher repetition rates and a more precise amplitude manipulation, as will be further commented later.

In order to illustrate how the electrical signal applied to the phase modulator is synchronized with the input train of pulses, we have chosen the specific example in which a multiplication factor of 2 is achieved for the pulse train repetition rate. Fig. 4 shows (a) the input pulse train to the modulator, along with (b) the signal in the electrical pattern generator and (c) the resulting pulse train at the system output. As shown in the figures, the input pulse lasts only a small part of the bit interval, while the electric signal applied to the phase modulator scans the whole bit. This allows the system to be robust against signal desynchronization. Fig. 4(b) shows a single period of the electrical signal that is in this case twice the input train period, as corresponds to the case of multiplying by 2, i.e., $N = 2$. This means that the maximum speed at which the modulator is operated with our setup is given by the input repetition rate, which avoids the need of high-bandwidth electrooptic modulators.

Fig. 5 shows the optical power of the output train for four different examples that are obtained when different groups of coefficients, obtained with the procedure explained in the previous section [see (8) and (7)] and indicated in Table I, are applied. Dotted lines indicate measurements while solid lines correspond
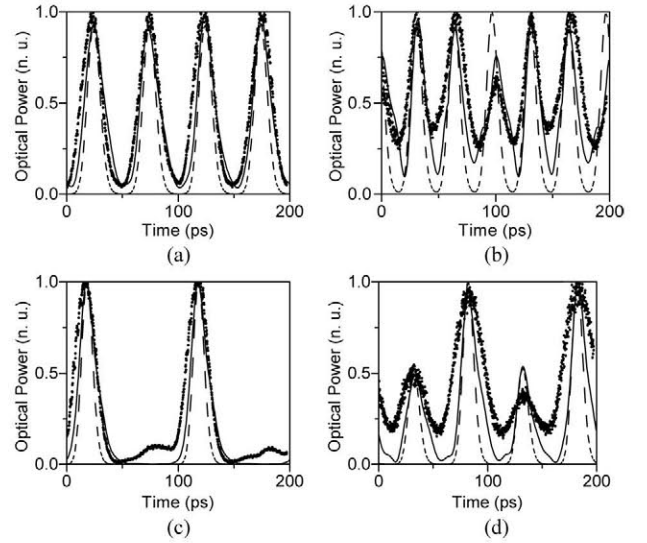

Fig. 5. Experimental (dotted), simulated with LC-FBG (solid) and simulated with DCF (dashed) results at the output of the system when different phase coefficients are applied to obtain the patterns (a) [1 1], (b) [1 1 1], (c) [1 0], and (d) [0.5 1].

to simulated waveforms taking into account the measured amplitude and group delay response of the LC-FBG used in the experiments (see Fig. 2 inset). Simulations in which a DCF (15.4 km with −80 ps/nm·km and 0.19 ps/nm^2·km) is used as the dispersive device are also shown in dashed lines. All the simulations are performed taking into account the bandwidth limitation of the photodetector in the oscilloscope. However,

TABLE I
PHASE COEFFICIENTS FOR DIFFERENT PERIODIC PATTERNS

Periodic pattern, y_k^2	Phase coefficients (V_{pp}/V_π), c_k
[1 1]	0.5, 0
[1 0]	0, 0
[0.5 1]	0, 0.4
[1 1 1]	0.6, 0, 0
[0.5 1 0.5]	0.54, 0.54, 0
[1 1 1 1]	1, 0, 0, 0
[0 0.5 1 0.5]	0.5, 0, 0, 0.5

the source used was an ideal periodic train of Gaussian pulses, without the jitter or amplitude fluctuations that are present in the experiment (see Fig. 3, solid line).

As expected, by only changing the electrical signal driving the modulator, the multiplication factor can be changed from 2 to 3, resulting in 20 and 30 GHz repetition rates, respectively, [see Fig. 5(a) and (b)]. However, as has been previously explained, overlapping between the pulses occurs in the measurements, being especially notorious when a higher repetition rate is used [see Fig. 5(b)] where not all the pulse amplitudes are equal. These effects can be avoided by using another dispersive media without filtering, as it can be seen in the DCF simulation results also shown in Fig. 5.

Besides, as an example of envelope control, Fig. 5(a), (c), and (d) shows how the relative amplitude of one of the two pulses in the $N = 2$ case can also be tuned to the desired value (0, 0.5, and 1 in the experiments). Fig. 5(d) presents a higher noise and broadened pulses compared to those shown in Fig. 5(a) and (c). We attribute this effect to a change in the conditions of the input pulse train due to our laser source instabilities. When several pulses interact due to the temporal Talbot effect to conform new pulses, it has been demonstrated [28], [29] that the jitter and fluctuations in the input pulses result in higher amplitude fluctuations, pulse broadening, and a pulse pedestal if RRM is being considered, as found in our measurement. The effect is not seen in the simulations since an ideal source was considered.

In order to show a wider variety of the output pulse trains that one may obtain with our method, simulations for different electrical signals are plotted in Fig. 6. Now, to avoid the bandwidth reduction by the dispersive device, the same DCF as in Fig. 5 was used in the computation. Moreover, to show higher output repetition rates, narrower input pulses (1 ps pulse width) were considered and the bandwidth limitation of the sampling scope was also withdrew. Only the case of bilevel phase modulation was considered for the simulations, limiting thus the possible outputs of the system.

Fig. 6 shows the output of the system for different envelope patterns with multiplication factors 3 and 4. Fig. 6(a) shows the output for the RRM case with $N = 4$. As can be observed, the use of a smaller pulse width has induced a deformation on the shape of the pulses due to the effect of the transmission along the DCF. As another example of envelope control, also a triangular envelope shape is shown in Fig. 6(b) and (c) with repetition factors 3
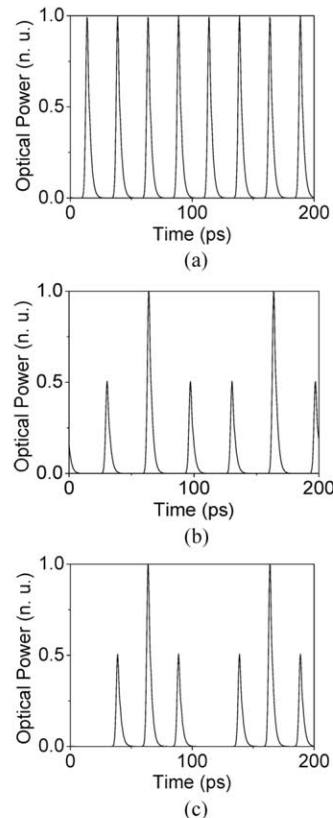

Fig. 6. Simulated results at the output of the system when the coefficients are applied to obtain the patterns (a) [1 1 1 1], (b) [0.5 1 0.5], and (c) [0 0.5 1 0.5] and no bandwidth limitations are imposed by the dispersive device or the photodetector.

and 4. However, in order to obtain more complex envelopes or higher repetition ratios, the use of multilevel coefficients both in phase and in amplitude is required, resulting in an increased complexity for the system, but simplifying the required optimization process. Also, the deformation of the output pulses indicates that, when moving to the femtosecond regime, a very strict control of the applied dispersion is required. The greater influence of the high-order dispersion terms to be expected in this case could be faced with the use of an LC-FBG with negligible high-order dispersion over its whole reflection bandwidth or high-order dispersion compensation techniques.

IV. CONCLUSION

A simple scheme has been presented for the simultaneous control of the repetition rate and the envelope of an optical train of pulses. The technique is based on the application of a different coefficient to each pulse via electrooptical modulation and their recombination using the fractional Temporal Talbot effect with the dispersion introduced by a linearly chirped fiber Bragg grating. As the shaping is made for a train of pulses instead of the individual pulses, the required dispersion is independent of the repetition factor desired and the shape of the individual pulses, depending only on the initial repetition ratio of the input train. An optimization algorithm for obtaining the modulating signal when only phase modulation is applied is also presented.

Simulated and experimental results show the validity of the proposed scheme, allowing the electronic tunability of the amplitude and repetition rate of the output train of pulses. Results also indicate a high dependence on the dispersion applied when smaller pulse widths are considered, making necessary a very strict control of both the slope and higher order terms if the technique is applied in the femtosecond regime.

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