Reconfigurable generation of high-repetition-rate optical pulse sequences based on time-domain phase-only filtering

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Received April 25, 2005; accepted July 25, 2005

We propose and demonstrate a fiber-based phase-only filtering technique for programmable optical pulse shaping, in which the filtering operation is implemented in the time domain by means of an electro-optical (EO) phase modulator. The technique has been applied for generating customized ultrahigh-repetition-rate optical pulse sequences (>40 GHz) from single input pulses by driving the EO phase modulator with a periodic electronic waveform (RF tone). The generated output pulses are replicas of the input pulse and both the repetition rate and the envelope profile of the generated sequences can be controlled and tuned electronically using this approach. © 2005 Optical Society of America

OCIS codes: 320.5540, 200.4740, 060.7140, 060.5060, 260.2030.

Techniques for the generation and control of optical pulse sequences at repetition rates beyond those achievable by conventional methods (e.g., mode locking) are becoming increasingly important for numerous applications, including ultrahigh-speed optical communications, photonic signal processing, and molecular coherent control.[1–4] An attractive method is to use periodic spectral filtering to spread an individual input pulse into a burst of high-repetition-rate pulses. Weiner *et al.* demonstrated generation of terahertz repetition rate pulse bursts by means of phase-only filtering of individual femtosecond pulses.[1] In this pioneer approach, the original temporal pulse is first transformed into a spatial signal and then optically processed. Drawbacks associated with this approach, including the need for high-quality bulk optical elements and limited integration with waveguide devices, have motivated recent research on alternative solutions. In particular, integrated solutions where the required periodic filtering stages are implemented by either arrayed waveguide gratings[2] or fiber Bragg gratings[3,4] have recently been demonstrated. The main limitation of these solutions is that they do not allow one to tune the temporal features of the generated pulse burst (e.g., repetition rate or envelope temporal shape).

In this Letter we propose and experimentally demonstrate a novel fiber-based technique for the reconfigurable generation of high-repetition-rate optical pulse bursts from a single input pulse. The proposed technique offers the inherent advantages of an integrated (fiber) solution, including full compatibility with waveguide–fiber devices, and it provides the additional functionality of electronic programmability. Basically, our method involves a phase-only periodic filtering process, where the filtering operation is implemented in the time domain by means of an electro-optical (EO) phase modulator driven by a periodic electronic waveform. Both the repetition rate and the envelope shape of the generated temporal sequence can be easily controlled and tuned using this approach. Here we demonstrate the proposed concept by generating optical pulse bursts at 1.55 μm with different temporal envelope profiles and different repetition rates ($\approx$56.5 and $\approx$113 GHz in the experiments shown here).

Figure 1 shows a schematic of the proposed technique. This system is similar to that used by Saperstein *et al.* for microwave spectrum analysis.[5] The idea of time-domain spectral shaping using dispersion followed by amplitude temporal modulation has also been demonstrated.[6] However, the key aspect of our proposal is that we use EO phase modulation instead of amplitude modulation, thus implementing a phase-only filtering process. It is well known that, compared with amplitude filtering, phase-only filtering is advantageous in that it allows one to achieve a much larger variety of possible output waveforms while providing a higher energetic efficiency.[1] Specifically, ultrafast optical pulse bursts can be generated from a single input pulse using a periodic phase-only filter, i.e., the filter's phase response must vary periodically with frequency.[1,3]

In reference to Fig. 1, let us assume that the input optical pulse $u(z=0,t)$ first propagates through a length L_1 of an optical fiber (dispersion coefficient $\ddot{\beta}_1$). The pulse after dispersion $u(L_1^-,t)$ keeps the same amplitude spectrum as that at the input, $|U(0,\omega)|$; if the fiber dispersion is sufficiently high, then the dispersed temporal waveform is proportional to the pulse amplitude spectrum,[6] i.e., $|u(L_1^-,t)| \propto |U(0,\omega)|_{\omega=t/\ddot{\beta}_1 L_1}$. In this case, there is a direct correspondence between the temporal and the frequency domains such that the pulse frequency components can be manipulated independently by temporally modulating the stretched waveform. In our application, the dispersed pulse is temporally

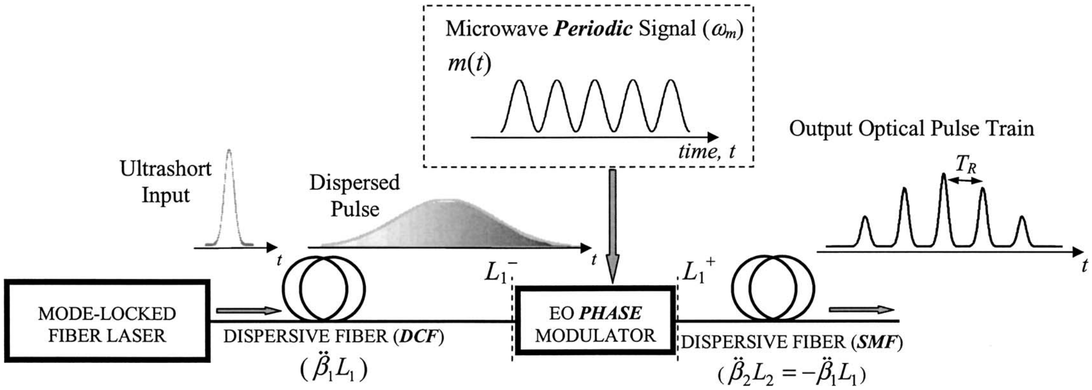

Fig. 1. Schematic of the proposed fiber-based programmable optical pulse burst generator.

modulated with an EO phase modulator driven by a periodic electronic waveform $m(t)$ (normalized in amplitude) of repetition frequency ω_m (period $T_m = 2\pi/\omega_m$). A minimum modulation frequency ω_m is set to ensure that the corresponding period is shorter than the time window created by the dispersion-broadened optical pulse. Time windows longer than a few tens of nanoseconds can be achieved using highly dispersive fiber Bragg gratings.[6] The optical signal at the output of the EO modulator is $u(L_1^+,t) = u(L_1^-,t)\exp[-jAm(t)]$, where A is the amplitude of the EO phase modulation (modulation index). The modulation function $\exp[-jAm(t)]$ can be developed in a Fourier series, i.e., $\exp[-jAm(t)] \propto \sum_{k=-\infty}^{+\infty} a_k \exp(jk\omega_m t)$, with Fourier coefficients

$$a_k = \omega_m \int_{T_m} \exp[-jAm(t)]\exp(-jk\omega_m t)\mathrm{d}t. \qquad (1)$$

Because of the direct correspondence between the time and frequency domains in the modulated pulse mentioned above, the temporal modulation function $\exp[-jAm(t)]$ is in turn modulating the input pulse spectrum. As a result, this periodic phase modulation function directly determines the spectral filtering operation that is finally implemented with our system. A nondispersive filtering operation is realized by adding a second dispersive fiber at the output of the system so that to exactly compensate for the dispersion induced by the input fiber, i.e., $\ddot{\beta}_2 L_2 = -\ddot{\beta}_1 L_1$. In this case, it can be easily demonstrated that the spectral transfer function of the system is given by $H(\omega) = \{\exp[-jAm(t)]\}_{t=\ddot{\beta}_1 L_1 \omega} \propto \sum_{k=-\infty}^{+\infty} a_k \exp(jk\ddot{\beta}_1 L_1 \omega_m \omega)$. The temporal impulse response of this filter system is simply the inverse Fourier transform of $H(\omega)$:

$$h(t) \propto \sum_{k=-\infty}^{+\infty} a_k \delta(t - kT_R), \qquad (2)$$

where $T_R = \ddot{\beta}_1 L_1 \omega_m$. The output temporal waveform is given by the convolution of the input pulse $u(0,t)$ with the impulse response function in Eq. (2). Thus, the output signal is a periodic optical pulse sequence, where (i) the output pulses are replicas of the input optical pulse; (ii) repetition period T_R can be tuned in a continuous fashion by simply changing modulation frequency ω_m (a higher repetition rate requires a lower modulation frequency); and (iii) the sequence temporal envelope is determined by complex Fourier coefficients a_k, which can be tailored by customizing modulation electronic waveform $m(t)$ and (or) modulation index A.

Our experimental setup was an extension of the configuration shown in Fig. 1. The optical pulse source was an erbium-doped fiber ring laser generating chirped optical pulses with a full width at half-maximum (FWHM) time duration of ≈ 1.5 ps and a FWHM bandwidth of ≈ 4.3 nm (around 1550 nm); the laser operated at a repetition rate of 10 MHz. The fiber laser pulses were stretched by the first dispersive stage (dispersion-compensating fiber providing a normal dispersion of $\ddot{\beta}_1 L_1 = +176\ \mathrm{ps}^2$) to a FWHM time width of ≈ 0.6 ns. After suitable polarization control, the stretched pulses were temporally modulated in phase using an EO modulator driven by amplified sinusoidal microwave voltage from a RF synthesizer, i.e., $m(t) = \cos(\omega_m t)$. The optical signal at the output of the EO phase modulator was amplified and propagated through a second dispersive stage providing anomalous dispersion (conventional telecommunication fiber, SMF-28). The length of this second dispersive stage was fixed to minimize the time width of the output pulses (as measured with an autocorrelator) when no phase modulation was applied in the system, i.e., to ensure that the input and output dispersions were nearly compensated for. Figure 2 shows the results from a first experiment, in which the modulation frequency and the modulation index were fixed to $\omega_m/2\pi = 16$ GHz and $A = 1.24$ rad, respectively. Figure 2(a) shows the periodic comb spectrum (intensity) associated with the temporal modulation function $\exp[-jAm(t)]$ (measured with an optical spectrum analyzer with a resolution of ≈ 0.01 nm). This spectrum can be obtained at the output of the system by simply operating the input laser in the CW regime (without mode locking). The values of modulation index A in our experiments were estimated by fitting the measured spectra with the calculated Fourier coefficients. The temporal impulse response of our system should be a replica of the periodic comb spectrum in Fig. 2(a) evaluated at $\omega = t/\ddot{\beta}_1 L_1$. This was experimentally confirmed by measuring the autocorrelation of the output pulse sequence [Fig. 2(b), solid curve], which resembles very closely the numerically computed autocorrelation of the comb spectrum in Fig. 2(a) after the proper variable change [Fig. 2(b), dashed curve]. As theoretically predicted, the repetition period of the generated pulse sequence is fixed by the modulation frequency and, in particular, $T_R = \omega_m \ddot{\beta}_1 L_1 \approx 17.7$ ps (repetition rate $\approx$56.5 GHz). The temporal envelope is fixed by the Fourier coefficients corresponding to the specific phase modulation function. In our experiments, different temporal envelopes were achieved by simply varying modulation index A. In particular, in Fig. 3 the modulation index was fixed to $A = 1.62$ rad, while the rest of the parameters were kept as in our previous experiment. The expected change in the profile of the sequence envelope (as determined by the new Fourier coefficients) was achieved. Repetition rate tuning can also be easily achieved by changing modulation frequency ω_m in the system. Figure 4 presents the results corresponding to two different cases in which the respective modulation indices were fixed to be the same as in our previous examples, i.e., $A = 1.24$ rad in Fig 4(a) and $A = 1.62$ rad in Fig. 4(b), respectively, but the modulation frequency was reduced to half that in our previous examples, $\omega_m / 2\pi = 8$ GHz. As a result, optical pulse sequences with nearly identical temporal profiles (envelopes) as in the corresponding previous examples but with twice the repetition rate ($\approx$113 GHz) were generated.

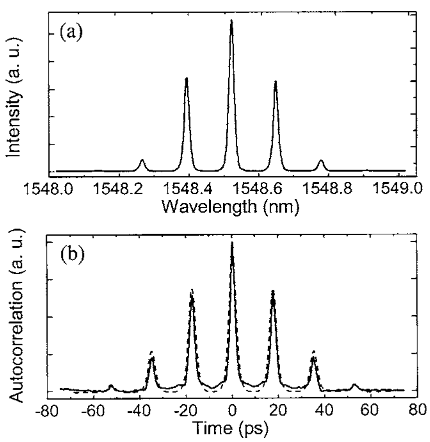

Fig. 2. (a) Measured spectrum of the periodic phase modulation function induced by EO modulation of CW light with a sinusoidal waveform of frequency 16 GHz and a modulation index of 1.24 rad (a.u. is arbitrary units). (b) Measured autocorrelation of the generated optical pulse sequence (solid curve) and numerically calculated autocorrelation of the measured comb spectrum in (a) (dashed curve).

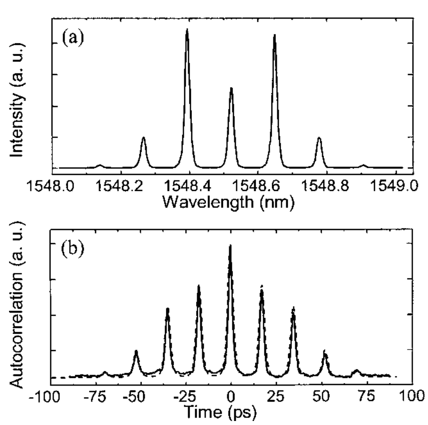

Fig. 3. Same as for Fig. 2 but with a modulation index of 1.62 rad.

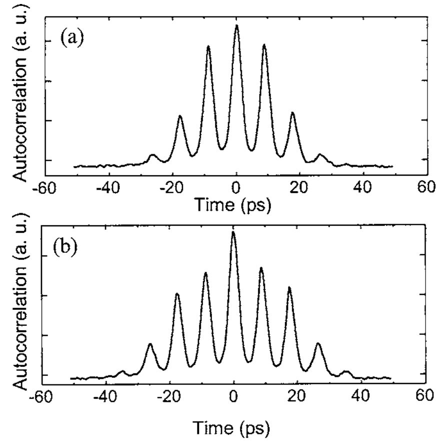

Fig. 4. Measured autocorrelation of the generated optical pulse sequence with a sinusoidal modulation waveform of frequency 8 GHz and a modulation index of (a) 1.24 rad, (b) 1.62 rad.

The proposed pulse-shaping mechanism can be interpreted as the time-domain equivalent of a conventional 4-f optical pulse shaper.[1] A degree of flexibility similar to that available in spatial phase-only pulse shapers for customizing the generated temporal envelope (e.g., to generate a flat-top envelope or coded temporal bursts[1]) could be achieved by driving the EO phase modulator either with a RF bit pattern generator (to implement binary phase control) or with an arbitrary waveform generator (to implement gray-level phase control).

In conclusion, we have proposed and demonstrated a fiber-based, phase-only filtering technique for programmable optical pulse shaping. The technique has been applied for generating customized ultrahigh-repetition-rate optical pulse sequences (>40 GHz) from single input pulses, in which the repetition rate and envelope profile of the generated sequences can be controlled and tuned electronically via EO phase modulation. In general, the proposed method should prove to be very useful for ultrafast optical pulse processing and shaping applications.

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