2047

Multiplication and reshaping of high-repetition-rate optical pulse trains using highly-dispersive fiber Bragg gratings

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Abstract

A novel technique for simultaneous pulse reshaping and repetition-rate multiplication of mode-locked laser pulse trains using linearly-chirped apodized fiber Bragg gratings is proposed. Simple analytical expressions for apodization and phase profiles of the grating are derived. The practical feasibility of this technique is discussed in detail for the case of high-repetition-rate square pulse generation and multiplication.

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The development of all-optical techniques for the manipulation and shaping of optical pulse trains at high repetition rates is of major importance for the advent of future ultrahigh-capacity optical communication systems. Although optical pulse processing has been traditionally achieved using time-space conversion in bulk or arrayed-waveguide gratings (see, e.g., [1–3]), recent advances in fiber Bragg grating (FBG) technology have demonstrated that precise pulse manipulation can be achieved using a FBG as a Fourier filter, featuring the advantages of an all-fiber low-loss integrable device. In particular, FBGs have been demonstrated to be effective tools for manipulation and processing of picosecond mode-locked pulse trains at relatively high repetition rates, including the generation of dark soliton pulses [4], optical square waves [5], and pulse train multiplication using either superstructured sinc-sampled gratings [6] or linearly-chirped gratings exploiting the temporal Talbot effect [7,8]. For many applications, it would be desirable to achieve simultaneous pulse reshaping and multiplication of a pulse stream emitted by a mode-locked laser source, still maintaining a grating design practically realizable using FBG writing technology nowadays available. For instance, the possibility of generating picosecond optical square pulses from a mode-locked laser at a repetition rate higher than that typically available from the laser itself ($\sim$ 10 GHz) would be of great interest for optical switching applications in ultra-dense time-division multiplexing optical systems.

In this Letter we show that linearly-chirped FBGs with relatively simple apodization profiles can be used for the *simultaneous* pulse reshaping and repetition-rate multiplication of a mode-locked pulse train, and we provide general insights into the design of such fiber gratings. In particular, we describe in detail the generation and multiplication of optical square pulses up to tens of gigahertz repetition rates.

Let us consider a periodic optical pulse train emitted by a mode-locked laser source with repetition rate $1/T$ and carrier frequency ω_0, described by the slowly-varying periodic complex field envelope $f(t)$, and a FBG with a spectral field reflectivity $r(\omega - \omega_0)$ which is used as a Fourier filter. If $S^{in}(\omega)$ is the spectrum of the incoming mode-locked signal $f(t)$, the spectrum of the reflected field is merely given by $S^{out}(\omega) = S^{in}(\omega)r(\omega)$, so that the timedomain reflected field envelope $F(t)$ may be reconstructed by spectral inversion. As we are interested in simultaneous pulse reshaping and pulse multiplication, it is worth representing the spectral reflectivity of the grating by the following factorization:

$$r(\omega) = Q(\omega)\exp(i\beta\omega^2/2) \tag{1}$$

where β is a dispersion parameter. As we will show below, the first factor $Q(\omega)$ is responsible for pulse reshaping, whereas the second one $\exp(i\beta\omega^2/2)$ leads to the multiplication of the pulse repetition-rate by a suitable choice of the dispersion parameter β. In order to achieve a multiplication factor M, we choose the dispersion parameter β according to the fractional Talbot condition [7–9]:

$$\beta = \pm T^2/(2\pi M) \tag{2}$$

In this case, after spectral inversion, it may be shown that the field envelope $F(t)$ reflected from the fiber grating is given by:

$$F(t) = \frac{1}{\sqrt{M}} \sum_{k=0}^{M-1} g\left(t - k\frac{T}{M} - \sigma\frac{T}{2M}\right)\exp(i\psi_k) \tag{3}$$

where $\sigma = 0$ if M is even, $\sigma = 1$ if M is odd, $\psi_k = \pm[(M-\sigma)\pi/(4M) - k(k+\sigma)\pi/M]$, and $g(t)$ is the convolution between $f(t)$ and the impulsive response of the grating with $\beta = 0$, i.e. $g(t)$ accounts for the reshaping effect provided by the spectral factor $Q(\omega)$. From Eq.(3) it follows that the periodicity of the reflected field $F(t)$ is the same as that of the initial mode-locked signal. In addition, if $g(t)$ is tailored so that the target pulse duration is shorter than T/M, the delayed replica of $g(t)$ with different phases, appearing in Eq.(3), are not overlapped, and their superposition leads to an effective multiplication of the pulse-train repetition rate. The spectral shape of $Q(\omega)$ is left at this stage arbitrary and has to be chosen in order to achieve the desired pulse reshaping; in particular, if $Q(\omega)$ is spectrally flat (both in phase and amplitude) over the bandwidth of the mode-locked pulse train, one has $g(t) \sim f(t)$ and pulse multiplication without pulse reshaping occurs. Let us now consider, as a significant example, the problem of square pulse generation and multiplication of a periodic stream of transform-limited pulses with duration τ_p emitted by a mode-locked laser at a wavelength of 1.5 μm. To generate a square pulse of duration τ_s, with $\tau_p < \tau_s < T$, the spectral function $Q(\omega)$ has to be chosen to produce a sinc-like pulse spectrum, i.e. $S^{out}(\omega) \sim \sin(\omega\tau_s/2)/(\omega\tau_s/2)$. Since this spectrum is unbounded, a truncated sinc function is in practice used, with a sufficiently smooth truncation envelope to avoid the appearance of ringing in the final square wave [1,5]. In addition, the rise time and duty cycle of the square wave are subjected solely to the usual limits imposed by the finite bandwidth of incoming mode-locked laser field. Figure 1 shows an example of target spectral reflectivity of a nonunifrom grating used for square pulse generation; parameter values for the mode-locked pulse train are taken from Ref. [9] and correspond to T=100 ps, τ_p=700 fs and ω_0=1.2137 x 10^{15} rad/s. A multiplication factor $M = 8$ has been chosen, leading to generation of square wave pulse trains at 80 GHz repetition rate.

The synthesis of the FBG can be performed starting from coupled-mode equation analysis by using either approximate methods, such as the first-order Born approximation valid for weak reflectivity profiles, or more exact methods based, e.g., on inverse scattering techniques [10]. The latter approach permits a precise reconstruction of the index profile, needed for a reliable FBG design, but it turns out to be inevitably numerical; conversely, the former method provides analytical approximations useful to get general insights into practical feasibility of the gratings. We assume a FBG of length L with a refractive index profile $n(z) = n_0[1 + 2h(z)\cos(2k_B z + \phi(z))]$, where n_0 is the average effective index, $k_B = n_0\omega_0/c_0$ is the Bragg reference wavenumber, c_0 is the speed of light in vacuum, and ($\phi(z)$,$h(z)$) are the phase and depth of index modulation, respectively, with $h(z) = 0$ for $|z| < L/2$. In case of a weak reflectivity ($|r(\omega|) \ll 1$), from a first-order analysis of coupled-mode equations it can be easily proven that:

$$h(z)\exp[i\phi(z)] \simeq \frac{i}{\pi\omega_0}\int_{-\infty}^{\infty} d\omega Q(\omega)\exp\left(\frac{2in_0\omega z}{c_0} + i\frac{\beta}{2}\omega^2\right) \tag{4}$$

We note that, in most cases of practical interest (e.g., for the experimental conditions of Refs. [8,9]), pulse multiplication requires highly dispersive gratings, with a dispersion parameter

β such that $\beta\Delta\omega^2 >> 1$, $\Delta\omega$ being the bandwidth of the spectral function $Q(\omega)$. The integral in Eq.(4) can be thus calculated in the asymptotic limit $\beta \to \infty$ using the method of stationary phase, yielding the simple and general relation:

$$h(z)\exp[i\phi(z)] \simeq \frac{i}{\omega_0}\sqrt{\frac{2i}{\pi\beta}}Q\left(-\frac{2n_0 z}{c_0\beta}\right)\exp\left(-\frac{2in_0^2 z^2}{c_0^2\beta}\right) \tag{5}$$

Equation (5) shows that the required FBG has an almost quadratic phase profile, that provides pulse multiplication, and a modulation depth $h(z)$ that reproduces the shape of target spectral function $Q(\omega)$ and not its Fourier transform, as it occurs in non-dispersive gratings [5]. From a physical viewpoint, this circumstance can be understood by observing that, for a highly dispersive grating, different spectral components of the incoming field are reflected at different positions along the FBG with a reflection coefficient proportional to the local refractive index modulation depth. Notice also that from Eqs.(2,5) the grating length can be estimated as $L \sim c_0\Delta\omega T^2/(4\pi n_0 M)$. For typical repetition-rates (e.g. 10 GHz) and pulse duration (e.g. 3 ps) of mode-locked lasers used in optical communications, a grating length up to a few tens of centimeters is required, which is readily obtainable using recently developed continuous writing techniques [5,6,11]. In order to show the feasibility of the technique and to provide practical examples of FBG design, let us focus again our attention to the problem of square pulse generation and multiplication. The refractive index variations $(h(z), \phi(z))$ needed to obtain the reflectivity profile of Fig.1 are numerically computed using an inverse scattering method based on a differential layer-peeling algorithm [10]; the result is shown in Fig.2 and compared to the approximate profile as predicted by Eq.(5). In addition, by direct integration of coupled-mode equations, we checked that the calculated FBG index profile exactly reproduces the target spectral reflectivity. The corresponding multiplied square pulse train and pulse shape are shown in Fig.3. In order to assess the robustness of the proposed technique against imperfections of the FBG or possible spectral drifts that may occur in an experiment, pulse distortions induced by different detuning conditions have been simulated, and the main results are shown in Fig.4. The dotted curve in the figure reproduces the distorted square pulse as obtained by detuning the central frequency of the

FBG reflectivity spectrum by 130 GHz away from that of the mode-locked pulse spectrum; the dashed curve in the figure shows the reflected pulse train intensity when the dispersion parameter β differs by 0.2% from its ideal value (see Eq.(2)).

In conclusion, we have proposed and designed a class of highly-dispersive apodized fiber Bragg gratings for the simultaneous pulse shaping and repetition-rate multiplication of mode-locked pulse trains. As example simultaneous square pulse generation and multiplication have been studied, showing the practical feasibility using current FBGs technology. This work may be important for all-optical switching in TDM (e.g. demultiplexing) and WDM (e.g. frequency conversion) networks where high repetition rate pulses of suitable shape are highly desirable.

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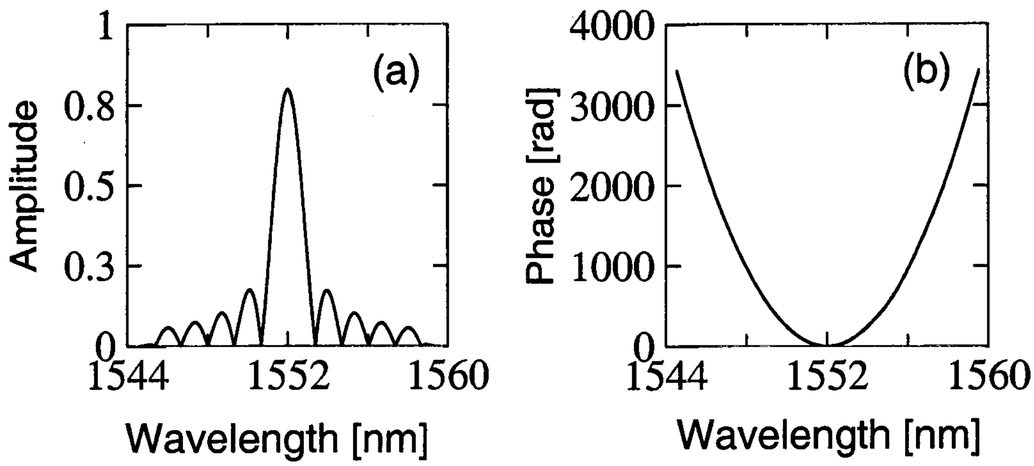
Figure Captions.

Fig.1. Spectral reflectivity r, both in amplitude (a) and phase (b), of a FBG for square pulse generation. Target and numerically computed spectral reflectivity curves are practically overlapped.

Fig.2. Refractive index depth (a) and phase (b) profiles of the designed FBG as calculated by the inverse scattering method (solid curves) and by first-order analysis (Eq.(5), dashed curves) for n_0=1.452. Note that the two curves are almost overlapped, except for the central lobe in (a).

Fig.3. (a) Multiplied square pulse train reflected by the FBG, designed according to Figs.1-2, and (b) enlarged view of pulse shape. The dotted curves in the figures correspond to the incident mode-locked pulse train.

Fig.4. Shape of a distorted square pulse as obtained by 130-GHz spectral detuning of FBG (dashed-dotted curve) and change of dispersion parameter β by 0.2% (dotted curve). The solid curve shows the undistorted square pulse shape. Distortions of other pulses in the train are almost identical.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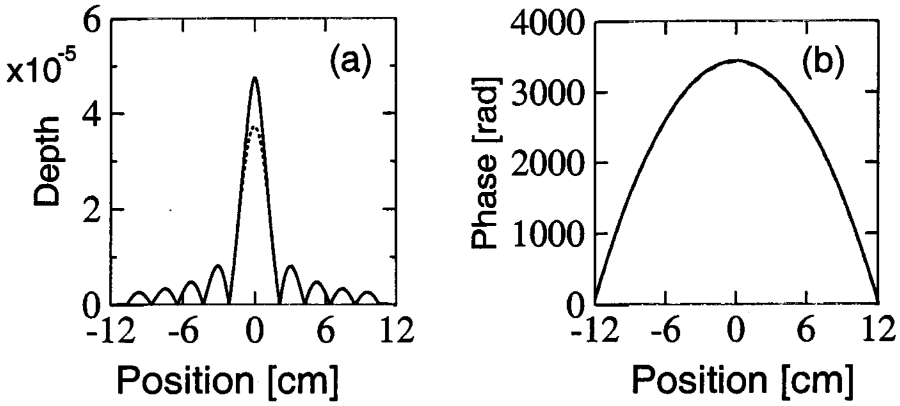

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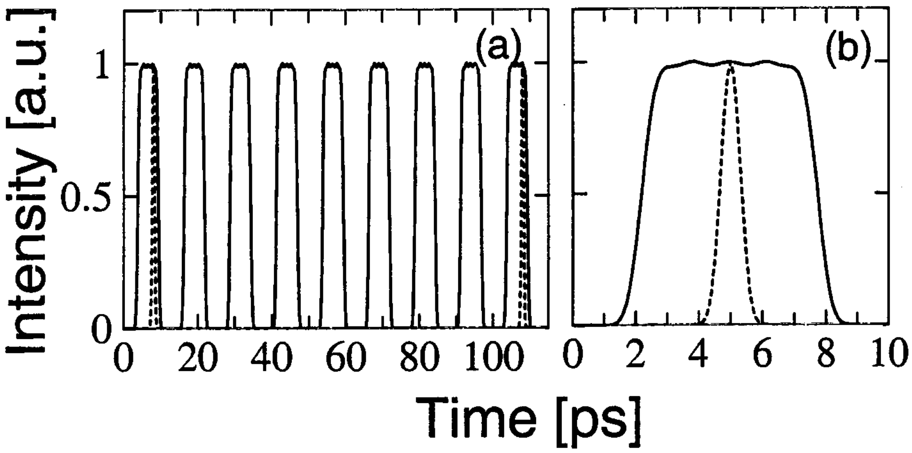
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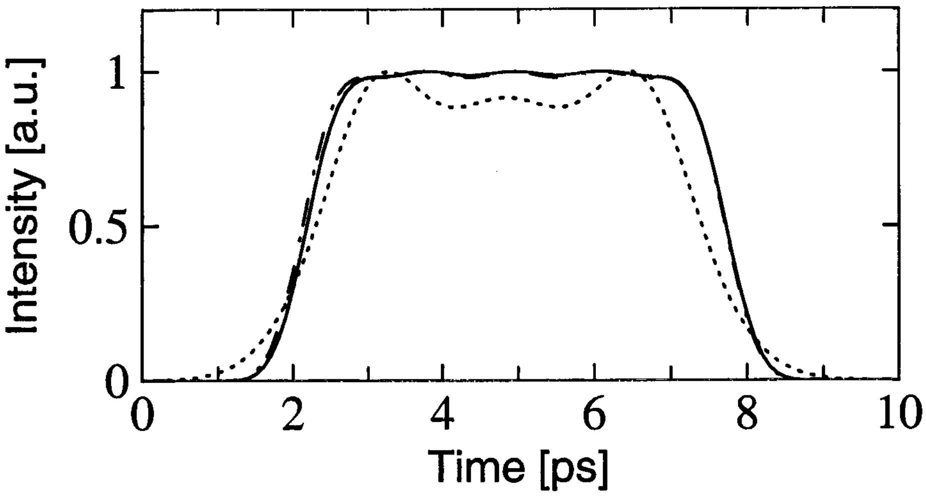

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