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40-GHz pulse train generation at 1.5 μm by using a chirped fiber grating as frequency multiplier

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Abstract

Pulse train multiplication based on the temporal Talbot effect in a linearly-chirped fiber Bragg grating has been experimentally demonstrated. A 40-GHz repetition-rate, nearly transform-limited 10-ps duration optical pulse train at 1.533 μm has been obtained from a 2.5-GHz mode-locked Er-Yb:glass laser using a 100-cm long linearly-chirped apodized fiber grating.

OCIS Terms:

050.2770 Gratings

070.6760 Talbot effect

230.1480 Bragg reflectors

320.5540 Pulse shaping

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Generation of high-repetition-rate optical pulse trains in the wavelength region of 1.5 μm is a topic of major importance for the realization of future ultrahigh-speed soliton-based optical communication systems. Active mode-locking methods have been proven to be attractive for the generation of short optical pulses synchronized with an external clock. However, the repetition rate of pulse trains directly obtainable from a mode-locked laser is limited by the modulation frequency at which the intracavity modulator can operate, that ranges usually from few up to few tens of GHz [1]. Different techniques have been recently proposed and demonstrated to increase pulse repetition rates, including soliton compression of the beat signal between two optical carriers [2], rational harmonic mode-locking [3], higher-order FM mode-locking [4], and pulse train multiplication by propagation in long fiber dispersion lines [5]. The latter method appears extremely promising because it allows, by suitable adjustment of the group-delay dispersion of the dispersive medium, to multiply the repetition rate of the original pulse train without introducing pulse distortions, the maximum multiplication factor achievable being limited solely by the duty cycle of the original mode-locked pulse train [5]. It has been very recently recognized [6] that the basic physical mechanism underlying pulse train multiplication in this case can be ascribed to a temporal counterpart of the fractional Talbot effect known since a long time in diffractive optics [7]. Since this is a purely linear effect, the use of a chirped Bragg grating instead of a long fiber dispersion line, as suggested in Ref. [6], seems very attracting and of practical implementation owing to the recent advancements in the fiber grating technology [8]. Indeed, another promising technique of pulse train multiplication, based on fiber Bragg grating technology that uses a sampled Bragg grating in the frequency domain as a selective filter, has been recently demonstrated in Ref. [9].

In this Letter we report on the first experimental demonstration of pulse train multiplication at 1.5 μm by use of a chirped Bragg grating as a dispersive element exploiting the fractional Talbot effect in the time domain. Gaussian pulse trains with 10-ps pulse width and 2.5-GHz repetition-rate, generated from a FM mode-locked Er-Yb:glass laser, have been optically converted into 40-GHz pulse trains by using a 100-cm long apodized chirped Bragg grating.

The experimental layout for pulse train multiplication is shown in Fig.1. This comprises an Er-Yb:glass laser source, FM mode-locked at 2.5 GHz, and a chirped fiber Bragg grating for pulse train multiplication, connected to a three-port optical circulator to retrieve the reflected signal. The laser source is similar to that reported in Refs. [10] and it consists of a 18-cm-long, one-folded cavity with a 1-mm-thick Er-Yb:glass disk end-pumped at 980 nm, containing a high-Q $LiNbO_3$ phase modulator with a resonance frequency at 2.493 GHz and an uncoated 120-μm thick etalon with anisotropic losses (Polarcor) that forces the laser field to be linearly-polarized along the optical Z axis of the electro-optic crystal. In addition, tilting of the etalon permits the central wavelength of laser emission to be adjusted close to the central wavelength of the grating. The laser is FM mode-locked in the third-order harmonic at 2.49 GHz, producing stable output Gaussian pulses of ~10 ps duration with a time-bandwidth product, as measured from spectral and autocorrelation measurements, of ~0.63. The output laser beam is launched, by a microscope objective, into a single-mode fiber, and an average fiber-coupled optical power of ~ 5mW is available for the experiment. The pulse repetition rate, as imposed by the modulation frequency, can be tuned by few MHz within the bandwidth of the mode-locker.

The fiber Bragg grating was designed and fabricated to achieve a multiplication factor $M = 16$ of the mode-locked pulse train, thus providing a 40-GHz repetition-rate for the converted optical signal. According to the theory of Talbot effect [6,7], the optical field reflected by a Bragg grating with a spectral reflection coefficient $r(\omega) = |r(\omega)| \exp[-i\Phi(\omega)]$, in the ideal case of flat amplitude reflectivity and quadratic phase response ($\partial^2\Phi/\partial\omega^2 = const$), is a fractional Talbot image of the original pulse train provided that:

$$\frac{\partial^2\Phi}{\partial\omega^2} = \frac{T^2}{2\pi}\frac{N}{M} \tag{1}$$

where T is the period of the incident periodic optical field envelope $f(t)$ and M,N are arbitrary irreducible integer numbers (pulse self-imaging condition). In this case, the reflected optical field envelope $F(t)$ is given by:

$$F(t) = \frac{1}{\sqrt{M}}\sum_{m=0}^{M-1} f\left(t - \frac{mT}{M} - \delta\frac{T}{2M}\right)\exp[i\phi_m(M,N)] \tag{2}$$

where $\delta = 0$ if MN is odd, $\delta = 1$ if MN is even, and $\phi_m(M, N)$ are purely phase terms whose explicit expression is rather cumbersome [7] but not of particular relevance for the present work. Equation (2) clearly shows that, if the original optical field $f(t)$ is a pulse train with a pulse extension $\tau < T/M$, the reflected signal intensity is an undistorted replica of the original pulse train but with a repetition rate enhanced by a factor of M. In practice, numerical simulations show that an almost ideal pulse train multiplication can be achieved using apodized linearly-chirped Bragg gratings with a nearly flat dispersion within the bandwidth of the incident optical pulses. From a physical viewpoint, the dispersion introduced upon reflection from a chirped grating (as well as that arising from propagation in an optical fiber) broadens each single pulse of the train, so that temporal overlapping of contiguous pulses occurs. The resulting interference pattern, when the Talbot condition (1) exactly holds, leads to the self-imaged multiplied pulse train.

The fiber grating designed for our experiment is 100-cm long and was written using the continuous writing technique [11]. An UV beam from a frequency-doubled Ar-ion laser is focused on a phase mask and strobed using an acousto-optic modulator with period corresponding to the desired grating pitch, while the fiber moves continuously in front of the phase mask. The apodization profile and the chirping were achieved by dithering and gradually increasing the phase of the strobed beam, respectively. The accurate control of the fiber movement and of the acousto-optic modulator allowed us to obtain a chirped grating with small phase ripples, lower than 10 ps, and with the exact value of the dispersion. The measured reflectivity and group-delay $(\partial\Phi/\partial\omega)$ characteristics of the grating are shown in Fig.2. The center wavelength of the grating is $\lambda_0 = 1533.7$ nm, with a spectral bandwidth (at -1 dB) $\Delta\lambda = 6.5$ nm and a mean dispersion of ~ -1280 ps/m, which was chosen to satisfy the Talbot condition (1) for $M = 16$, $N = 1$ and $f = 1/T \sim 2.494$ GHz. Notice that the bandwidth of the grating is about 13 times wider than the spectral bandwidth (FWHM) of the mode-locked optical pulses, and that the group delay is nearly flat for a few nanometers within the central zone of high reflectivity of the fiber grating. The optical signal reflected by the grating was amplified using an erbium-doped fiber amplifier to increase the average optical power to ~ 15 mW, and a fast PIN photodiode (New Focus Model 1434) connected to a sampling oscilloscope head (Tektronix Model SD24), with ~ 22 ps rise time, was used in the first stage of the experiment to monitor the multiplied pulse train in the time domain and to find, by fine adjustments of both central laser wavelength and mode-locker frequency, the Talbot condition of pulse self-imaging. A more accurate characterization of the mode-locked pulse trains incident and reflected from the fiber grating was performed both in the spectral domain using a scanning Fabry-Perot interferometer (Burleigh Model RC1101R) with 165 GHz free-spectral range and a resolution of ~ 1.3 GHz, and in the time domain by noncollinear autocorrelation measurements. Figure 3 shows a typical spectrum of the mode-locked pulse train impinging on the grating (Fig.3(a)) and the corresponding spectrum of the reflected signal (Fig.3(b)). It can be noticed that the reflected spectrum remains smooth and is not appreciably influenced by the residual ripples that are present in the reflectivity curve of the fiber grating (see Fig.2). A typical background-free autocorrelation trace of the multiplied pulse train, measured over the entire 400 ps time window corresponding to one period of the original mode-locked pulse train, is shown in Fig.4. The sixteen peaks in the figure correspond to average auto- and cross-correlations of the multiplied pulses in the converted optical signal. For comparison, in the figure is also shown the autocorrelation trace of the 10-ps Gaussian pulses of the mode-locked laser, which well overlaps to a single peak in the autocorrelation function of the converted pulse train. Notice that the low but nonvanishing background level in the autocorrelation measurement is ascribable to a slight overlapping of adjacent pulses in the autocorrelation of the multiplied pulse train, which are separated by 25 ps. The simulated autocorrelation function of the multiplied pulse train, obtained by numerical computation of the reflected optical signal using the measured spectral response of the grating and assuming a 10-ps chirped Gaussian pulse train as the incident signal, shows indeed a good agreement with the experimental data. By a suitable adjustment of the mode-locking frequency, we were also able to obtain, in the multiplied train, pulses narrower by ~ 10 % with respect to those arising from the mode-locked laser. This fact is explained by observing that the FM mode-locked pulses are linearly chirped [10] so that, for a proper sign of pulse chirp, a slight deviation of the self-imaging condition (1) can directly lead to a partial compensation of the initial pulse chirp.

In conclusion, we have experimentally demonstrated for the first time pulse train multiplication based on the temporal Talbot effect by using a linearly-chirped Bragg grating. A 40-GHz optically-converted 10-ps pulse train has been obtained by 16× multiplication of a 2.5 GHz pulse train from a FM mode-locked Er-Yb laser. Higher multiplication factors may be achieved starting using shorter pulse durations, making this technique promising for the development of compact and reliable ultra-high speed devices aimed at >100 GHz pulse train generation.

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Figure Captions.

Fig.1. Schematic of the experimental layout for pulse train multiplication. MO: microscope objective, EOM: electro-optic phase modulator, OC: optical circulator, EDFA: erbium-doped fiber amplifier.

Fig.2. Reflectivity and group-delay profiles of the fiber grating used for pulse train multiplication.

Fig.3. Measured optical spectra of the 2.5 GHz FM mode-locked laser (a). and of the multiplied pulse train reflected from the fiber grating (b).

Fig.4. Noncollinear autocorrelation traces of the multiplied pulse train (continuous curve) and of the 2.5-GHz mode-locked pulses before multiplication (dashed curve).

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Fig. 1

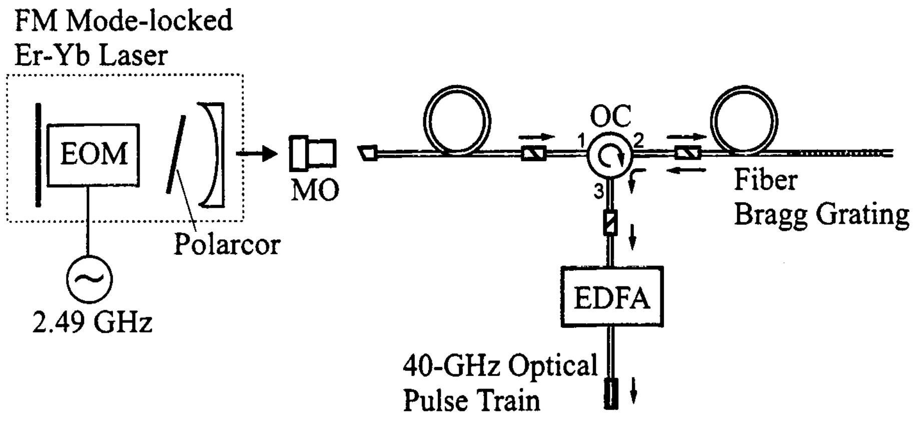

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Fig. 2

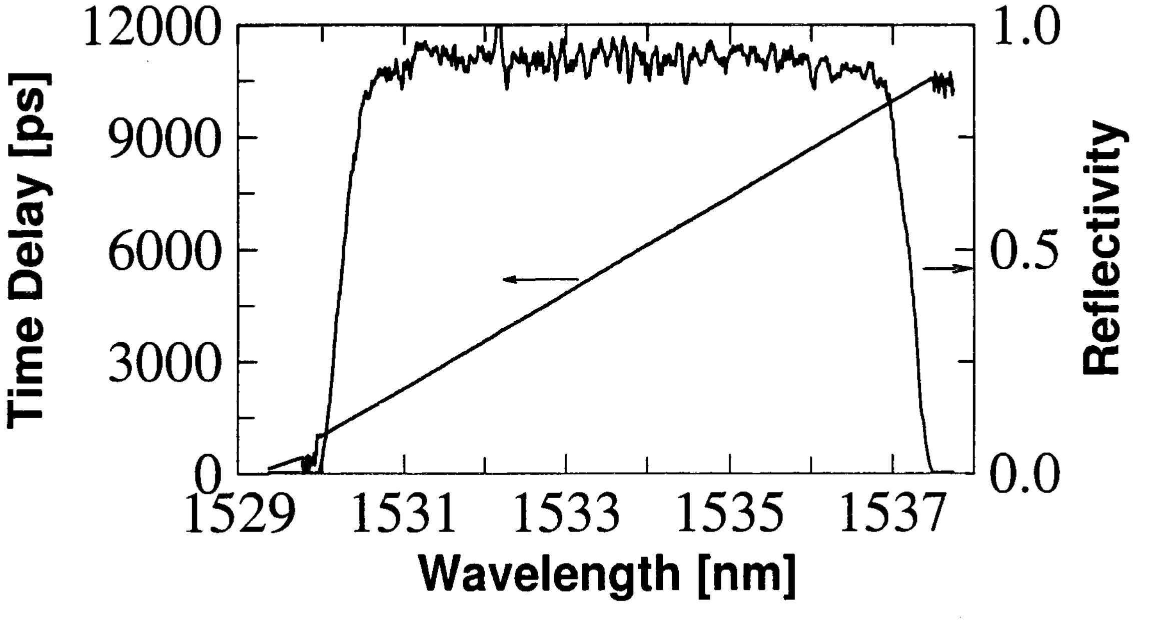

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Fig. 3

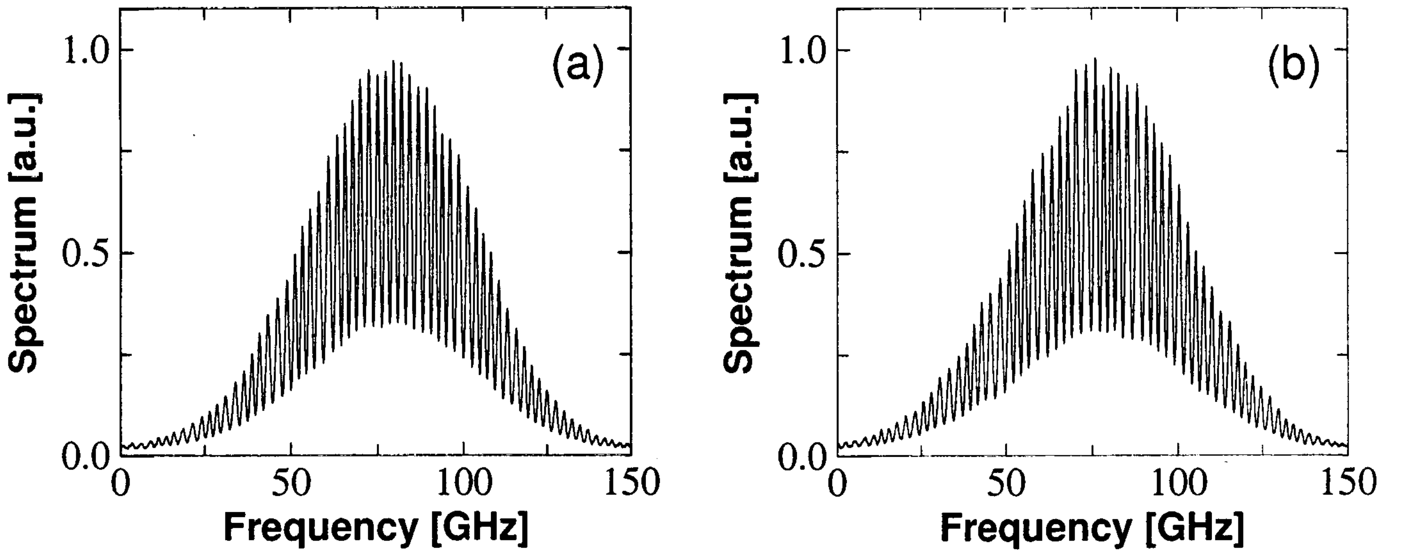

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Fig. 4