All-optical frequency multiplication of pulse trains up to 40 GHz using wide-band chirped fibre gratings

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Abstract – Pulse train multiplication based on the temporal Talbot effect in a linearly-chirped fibre grating is demonstrated. A 40-GHz converted optical pulse train is generated from a 2.5-GHz FM mode-locked Er-Yb:glass laser at 1.5 μm using a 100-cm long linearly-chirped apodized fibre grating.

1 INTRODUCTION

Chirped fibre gratings have been demonstrated in recent years to be an effective tool for pulse manipulation and dispersion compensation in high-bit-rate optical transmission systems. Another new application, yet extremely important, where fibre gratings can be usefully exploited, is the multiplication of optical pulse train repetition rate. All-optical techniques for the generation and manipulation of optical signals at repetition rates of the order of 40 GHz or higher in the 1.5 μm wavelength region are, in fact, of major importance for the development of future ultrahigh-speed optical systems. Optical multiplication of pulse trains repetition rates, aimed to overcome bandwidth limitations imposed by electronically-driven devices, has been indeed demonstrated using, e.g., soliton compression of the beat signal between two optical carriers [1], rational harmonic mode-locking [2,3] or higher-order FM mode-locking [4].

The feasibility of fibre grating technology for pulse train multiplication has been very recently demonstrated in Ref. [5], where a sampled Bragg grating in the frequency domain has been designed and fabricated to operate as a selective filter capable, by spectral mode suppression, of increasing the repetition-rate of a mode-locked pulse train.

A different technique for pulse train multiplication, which uses a fibre grating as a dispersive instead of a filtering element, has been proposed in Ref.[6]. The

basic physical mechanism underlying pulse train multiplication in this case is the temporal counterpart of the Talbot effect well-known in diffractive optics, by means of which temporal dispersion causes pulse broadening and pulse overlapping with an interference pattern that reproduces the initial pulse train with a multiplied repetition rate. Pulse train multiplication based on Talbot self-imaging was demonstrated earlier in Ref. [7] by using, a long fibre line as dispersive medium,

In this paper we demonstrate that optical fibre gratings can be used to achieve pulse train multiplication, exploiting the temporal Talbot effect, of a relatively low-frequency pulse stream from a mode-locked laser source.

Although the technique is very general and any suitable pulsed source (including waveguide/fibre-based) could be used, in our experiments the initial pulse train is generated by a 2.5 GHz repetition-rate FM mode-locked Er-Yb:glass laser, and a multiplication factor of 16 is demonstrated using a 100-cm long linearly-chirped apodized fibre grating.

2 CHIRPED FIBRE GRATING FABRICATION TECHNIQUE

The characteristics of the chirped fibre grating used in the experiment are shown in Fig. 1 in which the amplitude and phase curve are represented. The grating has been written using the continuous writing technique. A UV beam generated by a commercial 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. The apodization profile can be achieved by dithering the phase of the strobed beam while the chirping can be obtained by gradually increasing the phase of the strobed beam. Furthermore, to achieve very long length gratings the fibre moves continuously in front of the phase mask..

The accurate control of the fibre movement and of the acousto-optic modulator allowed to obtain a chirped grating with small phase ripples, lower than 10 ps, and with the exact value of the dispersion.

3 PULSE TRAIN MULTIPLICATION BY THE TEMPORAL TALBOT EFFECT

The experimental layout for pulse train multiplication is shown in Fig.2. This includes an Er-Yb:glass laser source, FM mode-locked at 2.5 GHz, and a chirped fibre grating for pulse train multiplication. connected to a three-port optical circulator to retrieve the reflected signal.
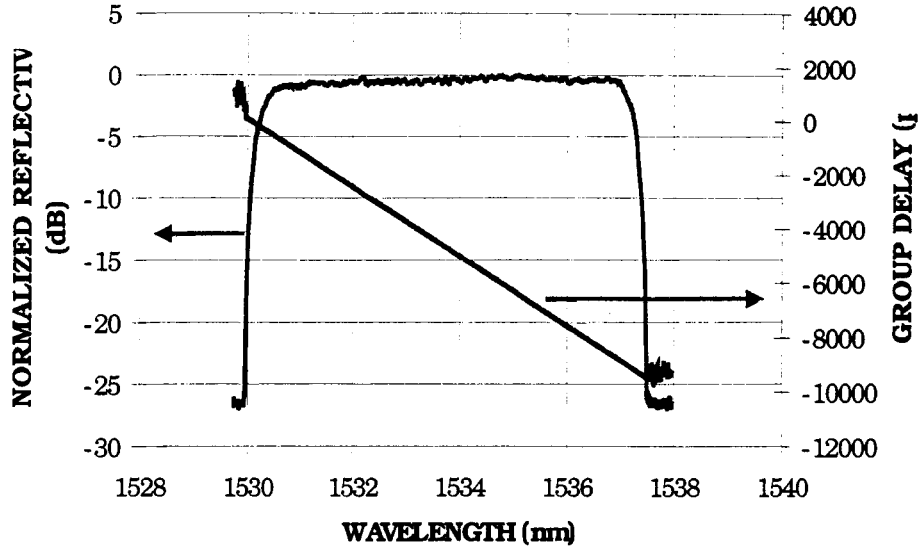
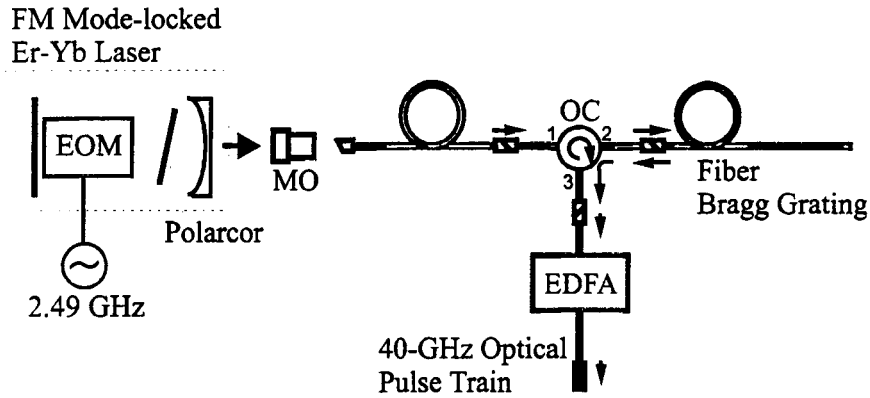Figure 1. Chirped fibre grating normalised reflectivity and group delay

Figure 2. Experimental layout for pulse train multiplication. MO: microscope objective; EOM: electro-optic phase modulator; OC:optical circulator; EDFA: erbium-doped fibre amplifier.

The laser source 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 120μm-thick etalon with anisotropic losses (Polarcor), which forces the polarisation state of the laser field allowing, at the same time, a fine tuning of the laser wavelength close to the central wavelength of the grating.

Frequency mode-locking is achieved in a third-order harmonic configuration at 2.49 GHz, and Gaussian pulses of $\cong 10$ ps duration are generated with a time-bandwidth product of 0.63. The output laser beam is launched, by a microscope objective, into a single-mode fibre, and an average fibre-coupled optical power of $\cong 5$ mW is available for the experiment. The linearly-chirped fibre grating is designed and fabricated to achieve a pulse multiplication factor $M=16$, with a nearly flat dispersion of $\cong -1280$ ps/nm within a spectral bandwidth (at -1 dB) $\Delta \lambda \cong 6.5$ nm around the central wavelength $\lambda_0 = 1533.7$ nm. The value of dispersion was chosen to satisfy the fractional Talbot condition [6]

$$\ddot{\Theta} = 1/(2\pi M f^2) \tag{1}$$

where f is the repetition rate of the mode-locked laser and $\ddot{\Theta}$ is the grating dispersion expressed in ps^2/rad. The converted optical pulse train, available at port 3 of the optical circulator, is monitored by a PIN photodiode and a sampling oscilloscope (13 ps rise time) and characterised by background-free SHG autocorrelation measurements.
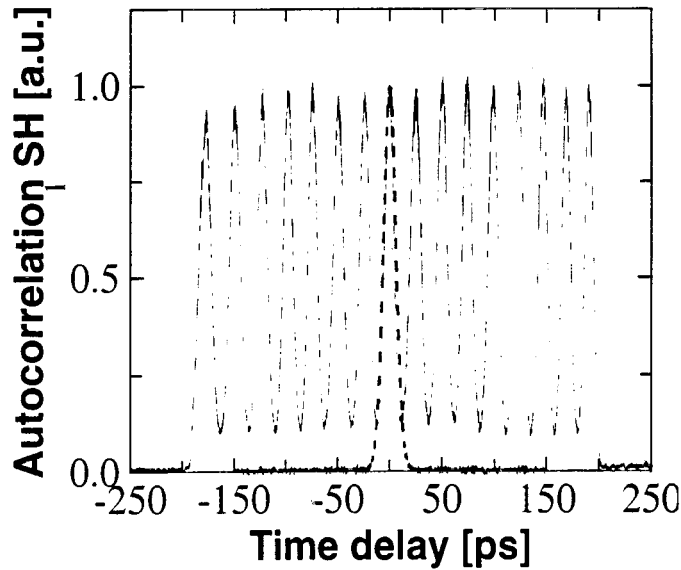

Figure 3. Noncollinear SHG autocorrelation of the multiplied pulse train at 40 GHz reflected by the chirped fibre grating. The dashed curve is the autocorrelation trace of the Gaussian mode-locked pulses incident to the fibre grating.

The Fig. 3 shows a typical measured autocorrelation trace of the reflected optical field over the entire 400 ps periodicity of the original mode-locked pulse train. The resultant 40 GHz pulse train shows an excellent agreement with that

predicted by numerical simulations based on the measured characteristics of the fibre grating. For comparison, in the figure it is also shown the autocorrelation trace of the 10-ps Gaussian pulses of the mode-locked laser. The pulse train deforms or disappears whenever the fractional Talbot condition is lost, requiring a fine tuning of the laser wavelength and/or of the modulation frequency. In this experiment the repetition rate of the converted optical pulses is limited by the duty cycle of the initial pulse train, but higher repetition rates may be achieved by using shorter pulse durations, promising for the development of compact and reliable devices for pulse train generation higher than 100 GHz.

4 CONCLUSIONS

In conclusion, pulse train multiplication based on the temporal Talbot images has been experimentally demonstrated by using a linearly chirped fibre grating. A 40-GHz optically-converted 10-ps pulse train has been obtained multiplying, by a factor 16, a 2.5 GHz pulse train from a FM mode-locked Er-Yb laser.
These results highlight the recent advances in fibre grating technology and could be of great interest for ultra-high-speed communication systems.

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