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Repetition-rate multiplication of optical pulses using uniform fiber Bragg gratings

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Abstract

A simple method for repetition-rate multiplication of optical pulses using uniform Bragg gratings is demonstrated. The grating formation system for this application requires positioning accuracy of only 1 μm. A simple method of control for each of the gratings in the writing process is proposed. Compensation of fiber dispersion using rate multiplication of pulses is also demonstrated.

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1. Introduction

The generation of optical pulses with repetition rates higher than tens of gigahertz is of great interest to applications such as large-capacity optical communication systems. However, the repetition rate of pulses generated from mode-locked lasers is limited to the operational frequencies of the optical modulators, therefore, development of an all-optical method of pulse repetition-rate multiplication is important. Recently, the temporal fractional Talbot effect in optical fibers was successfully used to accomplish this goal [1,2]. Rate multiplication using a chirped fiber Bragg grating based on the same effect has also been proposed [3] and realized [4]. The methods based on the fractional Talbot effect appear promising due to their simplicity and the possibility of achieving high repetition rates. However, it must be mentioned that when using these methods for rate multiplication by M, each of the M pulses has, in the general case, its own phase. According to the fractional temporal Talbot effect, the pulse field at the output of a dispersive delay line can be represented as a sum of phase shifted replicas of the original pulse train [5]. For instance, in the case of multiplication by $M = 4$, the dispersive delay line produces four replicas of the pulses with a time delay of $T/4$ (T is the pulse period) between the adjacent replicas and phase shifts

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of – π/4, 0, 3π/4, and 0, respectively, relative to the original pulse train. Yet, in many applications (one will be demonstrated here), it is important that the phases of the pulses be identical. Such multiplication can be performed using methods of frequency selection using a free-space [6] or fiber [7] Fabry–Perot interferometer or sampled fiber Bragg gratings [8]. However, in these methods the individual passbands for selection of necessary modes must be very narrow, which requires careful adjustment between the spectral structures of the filter and of the optical pulses and correspondingly requires high stability of the system. Aside from this, writing a sampled fiber Bragg grating requires high accuracy of positioning of ~1 nm [9].

In this paper, a simple method for repetition-rate multiplication of optical pulses using a number of uniform fiber Bragg gratings is demonstrated, where the positioning accuracy in the grating formation was only 1 μm. The lack of narrow passbands in the proposed method provides stability for the multiplied pulses. We propose a simple method of control for each of the gratings in the writing process. We also demonstrate the use of repetition-rate multiplication for compensation of fiber dispersion.

2. Principle of multiplication

Multiplication of the pulse repetition rate by M is equivalent to adding to the original pulse train $M-1$ replicas that are temporally shifted by NT/M, where T is the pulse period and N is an integer ($N = 1, 2, \ldots, M-1$). This multiplication is performed by a linear system with a frequency response of

$$F(\omega) = \exp[-i\omega(1 - 1/M)T/2] \times [\sin(\omega T/2)/\sin(\omega T/2M)]. \quad (1)$$

For a system comprised of fiber Bragg gratings, the spectral dependence of the total reflectivity should be of the form of (1). It is known that for low reflectivities the spatial envelope of the Bragg gratings should be the Fourier transform of the reflection spectrum. The Fourier transform of (1) gives a sum of δ functions. In other words, in order to obtain reflection of the form (1) we need to write M point Bragg gratings with low reflection, where the distance between the gratings provides the time delay T/M between the pulses. M replicas of the original pulse train with the relevant time delays are obtained as a result of the reflection from M fiber Bragg gratings. It must be mentioned that this is similar to rate multiplication using an arrayed-waveguide grating [10] where the replicas are obtained as a result of the splitting of the original pulse train and propagation in channels with different optical paths. It is clear that in reality, the lengths of the gratings must be small to provide an almost constant spectral reflectivity of each grating in the region of the input pulse spectrum.

3. Writing a Bragg grating multiplier

The Bragg gratings were obtained in boron-doped photosensitive fiber using cw (continuous wave) UV radiation ($\lambda = 244$ μm) and a phase mask. In order to set to zero undesired frequencies in the spectrum of the original pulses the reflectivity of all the gratings must be equal. In addition, as was mentioned before, the phases of reflections from all the gratings must be equal. These values were measured during the writing process in the following manner. Using a broadband light source (spontaneous emission from an erbium-doped fiber amplifier) and an optical spectrum analyzer the total spectrum of the gratings was measured. This spectrum can be considered as the spectral interference of the reflections from M fiber gratings. Therefore, we processed it similarly to fringe pattern analysis for spatial interference [11]. During the writing of the gratings, a fast Fourier transform was performed in real time of the reflection spectrum measured by the optical spectrum analyzer. The Fourier transform of the reflection spectrum was comprised of several bands of different orders n: the central band ($n = 0$) and the side bands ($n = \pm 1, \pm 2, \ldots$). The central band represents the Fourier transform of the sum of the reflection spectra of all the gratings. The band of the order $n = 1$ is the Fourier transform of the spectral interference between the reflections from adjacent gratings that are at a distance d from one another. The band with $n = 2$ corresponds to the spectral interference between reflections from gratings that are at distances $2d$ from one another and so on. Each of the bands was filtered out separately then an inverse Fourier transform was performed. The component of zeroth order enabled control of the reflection spectrum of each grating. From the inverses of the components of orders 1, 2, and 3 that were measured during the writing of the gratings, the phase differences were calculated between the reflections from the gratings 1 and 2, 1 and 3, and 1 and 4, respectively. These phase differences depend on the distances between the gratings. The resolution of our positioning system of 1 μm was enough to create the necessary time delay between the gratings but was not enough to adjust the distances between the gratings with the necessary accuracy. Therefore, adjusting the optical paths between the gratings was accomplished after writing each of the gratings by UV irradiation of the spacing between the gratings without the phase mask.

4. Experimental results and discussion

The original optical pulses in the experiment were generated by a mode-locked semiconductor laser with an external cavity, where one of the mirrors was a fiber Bragg grating. To compensate for the chirp of the laser pulses and to minimize the pulse width we used compensating fiber with a total dispersion of 148 ps/nm. In this manner, the pulses were compressed from 22 to 15 ps. In Fig. 1 we show the compressed pulses (solid curve) measured using a photodiode and a sampling oscilloscope (both with bandwidth 50 GHz). The pulse repetition rate was 6.25 GHz. The repetition-rate multiplication of these pulses by $M = 4$ was accomplished using a multiplier consisting of four fiber Bragg gratings whose reflection spectrum can be seen in Fig. 2. The spectrum was measured using a tunable semiconductor laser with a narrow line width. The length of each of the gratings was 0.3 mm, the distance between the grating centers was 4 mm. The maximum reflectivity of each grating for wavelength 1543.3 nm was 2%. The condition of low reflectivity of the Bragg gratings is not necessary. However, when designing a multiplier with higher reflectivity gratings multiple reflections should be taken into account. It is clear that in this case the reflectivity of the gratings would not be equal. In Fig. 3, the pulse spectrum before (dotted curve) and after (solid curve) reflection by the multiplier are shown for comparison. The spectra were measured by an optical spectrum analyzer with a resolution of 0.01 nm. From the spectral standpoint, rate multiplication by 4 is equivalent to reflecting every fourth mode of the laser and setting all other modes to zero. This filtering was achieved with good results in the experiment and is shown in Fig. 3. The suppression of the undesired laser modes by the fabricated Bragg grating filter was 22 dB. The pulses with

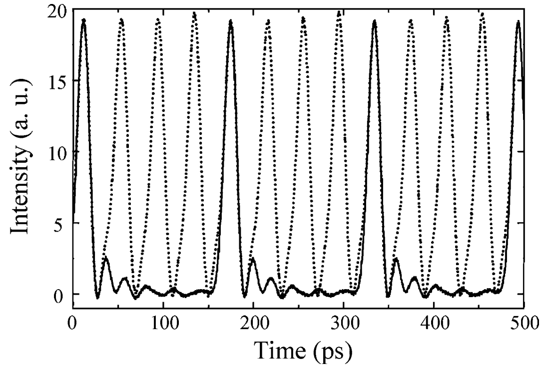

Fig. 1. Compressed pulses of the mode-locked semiconductor laser before (solid curve) and after (dotted curve) reflection from the multiplier consisting of four Bragg gratings.

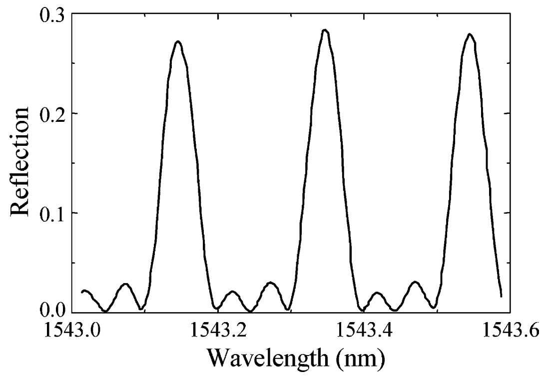

Fig. 2. Reflection spectrum of the multiplier consisting of four Bragg gratings.

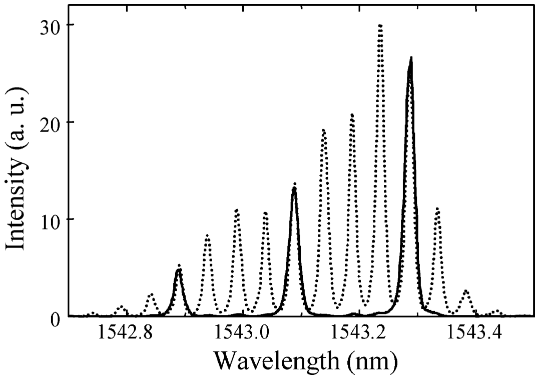

Fig. 3. The spectrum of the mode-locked semiconductor laser pulses before (dotted curve) and after (solid curve) reflection from the multiplier.

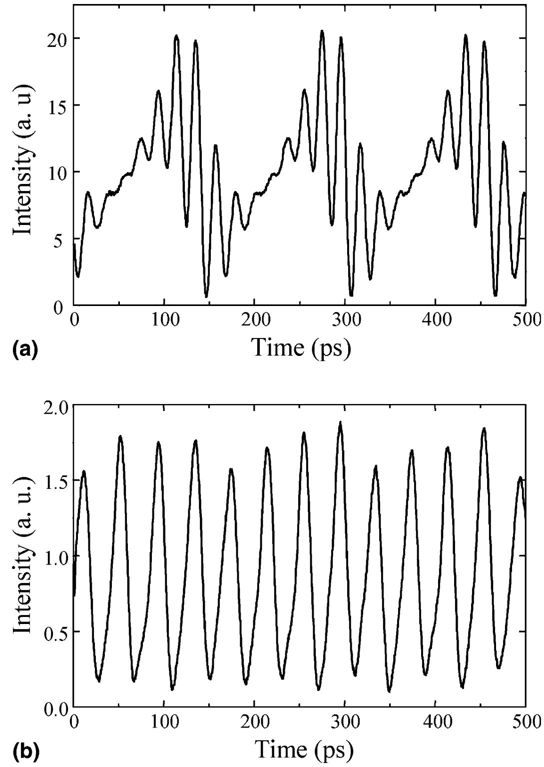

Fig. 4. Laser pulses that propagated through the fiber with dispersion 402.5 ps/nm (a) before and (b) after the rate multiplication of $M = 4$.

multiplied rate are shown in Fig. 1 (dotted curve). It can be seen that the multiplied pulses have almost equal amplitudes and reproduce the shape of the original pulses. The spectral response of the proposed multiplier, as well as in [6–8], consists of individual passbands. Detuning of the pulse spectral lines from the passband centers leads to degradation of the output signal power. Our method allows obtaining the wider individual passbands for the same parameters. Therefore, the proposed multiplier is more insensitive to detuning of the pulse spectrum and provides more stable multiplied pulses.

In the next experiments we propagated chirp compensated pulses at the original repetition rate along a fiber with dispersion 402.5 ps/nm, equivalent to 24 km of standard fiber, and then multiplied the pulses with the same multiplier. For this dispersion, each single pulse is broadened from 15 to 95 ps. At a rate of 6.25 GHz between the broadened pulses there is overlapping. These broadened pulses are shown in Fig. 4(a). Here the interference between the pulses that occurs due to the superposition can be seen.

The fiber dispersion was chosen from the condition that for the new rate of 6.25×4 GHz this dispersion corresponds to the Talbot length $z_T = 2c/\lambda^2|D|f^2$, where c is the speed of light, λ is the central wavelength of the spectrum, D is the group velocity dispersion of the fiber, and f is the modulation rate of the pulses. According to the definition of the temporal Talbot effect [12] at multiples of the Talbot length the pulse shape is reproduced. After multiplication of the pulse rate by 4 there is superposition of the broadened pulse train and its three replicas that are shifted each in relation to the previous by 40 ps. The three replicas may be conceived as originating from a virtual source in the form of the three replicas of the compressed pulses at the fiber input that are shifted, respectively. Then, as a result of the Talbot effect the superposition between the multiplied broadened pulses at the fiber output should give the same pattern as we obtained for the rate multiplication by 4 of the original compressed pulses shown in Fig. 1 (dotted curve). It is clear that this is possible only under the condition that the shapes and phases of all the replicated pulses are identical. In Fig. 4(b), the results for repetition-rate multiplication by 4 of the broadened pulses at the fiber output are presented. The difference between the multiplied pulses in Figs. 1 and 4(b) can be explained by the inaccurate fulfilling of the condition given above.

5. Conclusion

In conclusion, we have demonstrated a simple method for repetition-rate multiplication of optical pulses using fiber Bragg gratings. This method allows writing of grating with a positioning resolution of only 1 μm and multiplies the pulse rate with good temporal stability. A simple controlling method was proposed for each of the gratings during the writing process. This method enables obtaining not only Bragg gratings with identical reflectivities but also those with given complex reflectivities, which is very important for many applications. In addition, we demonstrated fiber dispersion compensation using the repetition-rate multiplication of broadened pulses.

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