Delay Lines With Tailored High-Dispersion Orders for Periodic Optical Pulses

Naum K. Berger, Boris Levit, and Baruch Fischer

***Abstract*—We derive an expression for the temporal fractional Talbot effect in delay lines with arbitrary orders of dispersion. We then demonstrate, experimentally and by numerical simulations, that a simple device consisting of a number of uniform fiber Bragg gratings or of waveguides can serve for such a tailored dispersive delay line for periodic optical pulses. The device produces temporally delayed and phase-shifted replicas of the original pulses, similarly to what happens in dispersive delay lines in the fractional Talbot effect. Such devices can be useful for compensation for the nonquadratic spectral phase of diode lasers, of dispersive elements in systems used for temporal imaging, real-time spectral analysis, and periodic pulse generation.**

***Index Terms*—Bragg grating control, dispersive delay line, fiber Bragg grating, high-order dispersion, periodic optical pulses, temporal Talbot effect.**

I. Introduction

ALL-FIBER devices used for chromatic dispersion compensation, such as chirped fiber Bragg gratings [1], are usually suitable both for periodic and aperiodic optical pulses. However, for applications in periodic pulses only, such devices can substantially be simplified. An interesting realization of a delay line for periodic pulses with all-pass optical filters was previously discussed in [2]. A more recent study [3] demonstrated the implementation of dispersive delay lines for periodic pulses with purely quadratic spectral phase response based on M uniform fiber Bragg gratings, or M waveguides with a $1 \times M$ splitter and $M \times 1$ combiner. For instance, four uniform fiber Bragg gratings, each of 0.2-mm length, with a spacing of 4 mm provided the same first-order dispersion for periodic pulses with a repetition rate of 6.25 GHz as approximately 50 km of standard telecommunication fiber [3]. The action of the gratings or the waveguides is based on the temporal fractional Talbot effect [4], [3]: the propagation of a periodic optical pulse train in a first-order dispersive medium of certain lengths (namely, fractional Talbot lengths) is equivalent to the summation of temporally delayed and phase-shifted replicas of an input pulse train. The function of the Bragg gratings or waveguides is to produce such replicas with the needed temporal delays and phase shifts.

It was pointed out in [5] that the integer temporal Talbot effect operates not only for first-order dispersion but also for arbitrary dispersion orders. In this letter, we show that also the fractional temporal Talbot effect is extendable to dispersive delay lines with arbitrary orders. We derive the appropriate equations and demonstrate their use for devices, which are equivalent to dispersive delay lines with arbitrary orders for periodic optical pulses. Finally, we present numerical simulations and experimental results that show good agreement and confirm the proposed idea.

Manuscript received March 1, 2006; revised April 28, 2006.

The authors are with the Department of Electrical Engineering, Technion-Israel Institute of Technology, 32000 Haifa, Israel (e-mail: chrberg@techunix.technion.ac.il).

Digital Object Identifier 10.1109/LPT.2006.877550

II. Description of Principle

For a dispersive delay line with a specific dispersion order $s-1$, the spectral phase response is

$$\varphi_{\text{sr}} = -(1/s!)\beta_s L r^s \omega_m^s$$

where β_s is the dispersion coefficient, L is the length of the delay line, r is the pulse harmonic order, $\omega_m = 2\pi f_m$, and f_m is the pulse repetition rate. For line lengths that are multiples of the Talbot length

$$z_T = 2\pi s!/(|\beta_s|\omega_m^s)$$

the spectral phase of each harmonic is a multiple of 2π, and the output pulses have the same temporal profile as the input pulse train. This is the integer temporal Talbot effect. For the fractional Talbot effect, the delay line length is a fractional of the Talbot length

$$z_{fT} = (m/p)z_T$$

where m and p are integers with no common factor. The field amplitude of the pulses at the line output can be obtained in the same form as in [3] for the conventional temporal fractional Talbot effect in first-order dispersive delay lines ($s = 2$)

$$E(t, \text{mz}_T/p) = \sum_{n=0}^{p-1} C(n,m,p)E(t - nT/p, 0) \quad (1)$$

but with Talbot coefficients $C(n,m,p)$ depending now on the order s

$$C(n,m,p) = (1/p)\sum_{q=0}^{p-1} \exp\{(2i\pi q/p) \times [n - mq^{s-1}\text{sgn}(\beta_s)]\} \quad (2)$$

where $E(t,0)$ is the input field amplitude of the pulses, T is the pulse period, and sgn denotes signum function. The derivation of (1) and (2) is similar to that obtained in [6] for the spatial fractional Talbot effect. It can be seen from (1) that for line lengths $L = \mathrm{m}z_T/p$ the output pulse field is a sum of the input pulse train replicas, each weighted by the factor $|C(n,m,p)|$, temporally delayed by nT/p and phase shifted by $\varphi_n = \arg[C(n,m,p)]$ (n is the number of the pulse replica). Devices that would be designed to produce the same number of the pulse train replicas with the same temporal delays and phase shifts as given previously will be completely equivalent to dispersive delay lines with $s-1$ dispersion order and of length $L = \mathrm{m}z_T/p$ for periodic pulses with a given repetition rate.

It should be mentioned that for the conventional fractional Talbot effect ($s = 2$), the nonzero coefficients $C(n,m,p)$ have the same absolute values for fixed p. This implies that all of the pulse train replicas have the same intensities and this property is used for pulse repetition rate multiplication [4]. According to (2), for arbitrary s these coefficients may be equal only in particular cases, for specific values of p and s.

III. Numerical Simulations

For the simulations (and the experiment), we chose the following parameters: $s = 3, m = 1, p = 4, f_m = 6.25$ GHz. Note that for the conventional fractional Talbot effect ($s = 2$)), the number M of the nonzero replicas is equal to p for odd p or to $p/2$ for even p [6]. For instance, for $p = 4$, one needs two replicas. In contrast, for $s = 3$ and $p = 4$ the number of the replicas, according to (2), is four. This implies that we design a device consisting of four fiber Bragg gratings (or waveguides) which is equivalent to a dispersive delay line with dispersion $|\beta_3|L = 3/(8\pi^2 f_m^3)$. We assumed that the reflection of each grating is low, such that the multiple reflections between the gratings can be neglected. The spectrum of each grating was assumed to be much wider than the bandwidth of the reflected pulses and can be considered as constant. The distance between the adjacent gratings ought to provide $T/4$ delay between the reflected replicas. It follows from (2) that the amplitudes of all replicas (and accordingly the grating reflectivities) are equal and their phases are: $\varphi_1 = \varphi_3 = \varphi_4 = 0, \varphi_2 = \pi$ (for $\beta_3 < 0$). It is clear that such characteristics ought to be provided by appropriate reflectivities and reflection phases of the fiber Bragg gratings.

The calculated amplitude and phase response of the four fiber Bragg gratings are shown in Fig. 1(a) and (b) (dashed curves), respectively. For comparison, the same calculated characteristic of an equivalent second-order dispersive delay line are also presented in these figures (by solid curves). It can be seen that the curves intersect at frequencies corresponding to the pulse harmonics $r\omega_m (r = 0, \pm 1, \pm 2 \ldots)$. These points are shown by the circles.

To compare with the experiment, we also calculated propagation of periodic optical pulses through an equivalent second-order dispersive delay line. As input pulses, we took sinusoidally phase-modulated cw laser light with modulation frequency of 6.25 GHz and modulation index of 1.6 rad. The calculated output pulses are shown in Fig. 2 (dashed curve). The calculation of the reflection from the four fiber Bragg gratings gave, of course, exactly the same result.

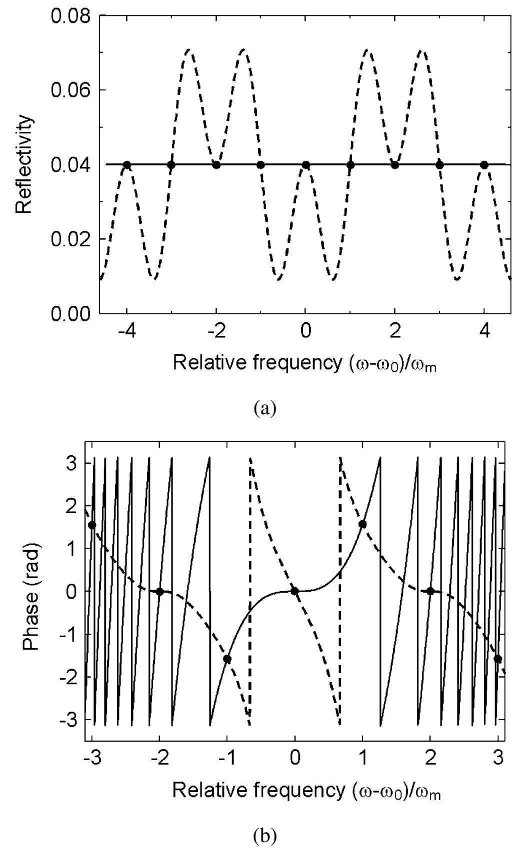

Fig. 1. Calculated (a) amplitude and (b) phase response of four fiber Bragg gratings (dashed curve) with proper temporal delays and phase shifts and of equivalent second-order dispersive delay line (solid curve).

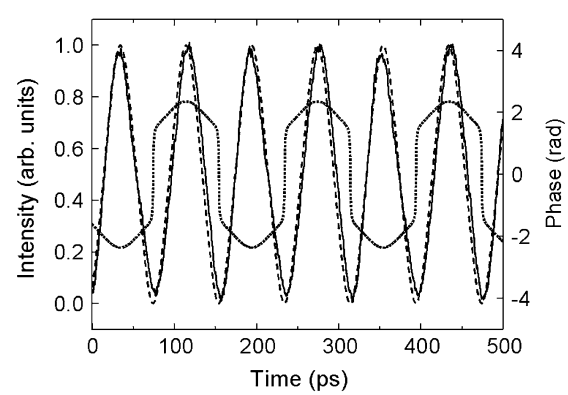

Fig. 2. Measured pulses (solid curve) produced by reflection from four fiber Bragg grating system and calculated intensity (dashed curve) and phase (dotted curve) of pulses obtained by using equivalent second-order dispersive delay line.

IV. Experimental Results

The fiber Bragg gratings were fabricated by UV laser radiation (with a wavelength $\lambda = 244$ nm) through a phase mask. The gratings, each with a length of 0.25 mm, were spaced by an interval of 4.2 mm. The reflectivity magnitude (1%) and the reflection phase of each grating were controlled by a method similar to that described in [7]. The reflection spectrum of the gratings and its fast Fourier transform (FFT) were measured during the fabrication process. The FFT for four written gratings is presented in Fig. 3. The reflection spectrum of the gratings can be

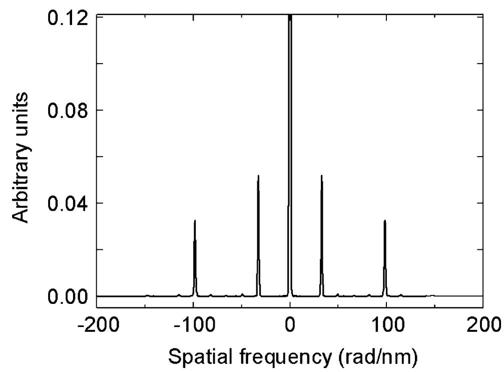

Fig. 3. FFT of measured reflection spectrum of four written fiber Bragg gratings.

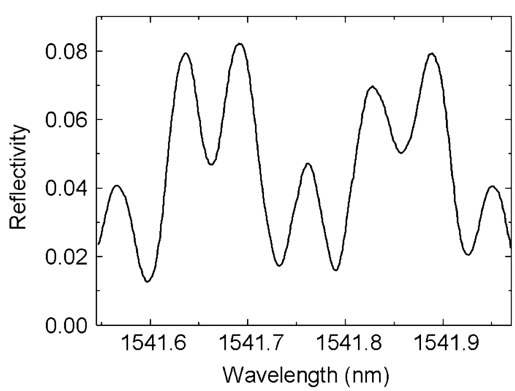

Fig. 4. Measured spectral reflectivity of four fiber Bragg gratings.

considered as spectral interference between the reflections from the gratings. Therefore, the inverse FFT of the central band in Fig. 3 is equal to the sum of the reflection spectra of all written gratings. The last sideband corresponds to the interference between the reflections from the first and fourth gratings, and the argument of its inverse FFT gives the phase shift between them. By monitoring the FFT during the writing process, we were able to measure and correct the reflectivity and the reflection phase of each grating. The second sideband that corresponds to the sum of the interference between the first and third, second and fourth gratings is missing in the figure. Its location would be between the first and the last sideband in Fig. 3, but it is almost equal to zero because of the relationship between the grating reflection phases. It indicates good quality of the fabricated gratings, as also evident from the comparison between the measured spectral response, presented in Fig. 4, and the calculation shown in Fig. 1(a). The resolution of the grating phase measurement is limited by the minimal sampling interval of the optical spectrum analyzer. This resolution varied from 0.05 to 0.15 rad for the gratings closest to and farthest from the fiber end, respectively. Our estimations show that for obtaining a needed grating spectrum, the phase measurement error ought to be less than 0.1 rad.

In the experiment, sinusoidally phase-modulated light of a cw laser diode ($\lambda = 1541.77$ nm) with modulation frequency of 6.25 GHz and modulation index of 1.6 rad was reflected from the four written fiber Bragg gratings. (The experimental setup is the same as that used in our previous work [8].) The obtained pulses are shown in Fig. 2 (solid curve). We can see in this figure that the measured pulse shape is very close to the intensity shape of the calculated pulses (dashed curve), obtained for transmission trough an equivalent second-order dispersive delay line. Fig. 2 also shows the calculated phase of these pulses (dotted curve). It is interesting to note that the pulse intensity has a doubled repetition rate.

V. Conclusion

We have demonstrated experimentally and by numerical simulations that for periodic optical pulses, dispersive delay lines of arbitrary orders can be implemented using simple devices consisting of a number of uniform fiber Bragg gratings or of waveguides, providing proper phase shifts and temporal delays. It is interesting to note that it is easier to obtain, in this way, high dispersion values rather than low dispersions that would require a larger number of gratings (or channels, in a waveguide method). Indeed, the array-waveguide methods that were developed for photonics planar technologies in glasses and semiconductors can allow the fabrication of a few hundreds of channels. It would also be advantageous that the number of active channels, their phase shift, and attenuation can be tuned electrically, providing programmable control of the order and the value of dispersion.

The proposed devices can be useful for many applications, such as for compensation of nonquadratic spectral chirp of mode-locked laser diodes, for compensation and tailoring nonquadratic spectral phases of dispersive elements in systems for temporal imaging, real-time spectral analysis, and generation of periodic optical pulses.

References

[1] F. Ouellette, J.-F. Cliche, and S. Gagnon, “All-fiber devices for chromatic dispersion compensation based on chirped distributed resonant coupling,” *J. Lightw. Technol.*, vol. 12, no. 10, pp. 1728–1738, Oct. 1994.

[2] G. Lenz, B. J. Eggleton, C. K. Madsen, and R. E. Slusher, “Optical delay lines based on optical filters,” *IEEE J. Quantum Electron.*, vol. 37, no. 4, pp. 525–532, Apr. 2001.

[3] N. K. Berger, B. Levit, A. Bekker, and B. Fischer, “Compression of periodic optical pulses using temporal fractional Talbot effect,” *IEEE Photon. Technol. Lett.*, vol. 16, no. 8, pp. 1855–1857, Aug. 2004.

[4] J. Azaña and M. A. Muriel, “Temporal self-imaging effects: Theory and application for multiplying pulse repetition rates,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 7, no. 4, pp. 728–744, Jul./Aug. 2001.

[5] J. Azaña, “Pulse repetition rate multiplication using phase-only filtering,” *Electron. Lett.*, vol. 40, no. 7, pp. 449–451, 2004.

[6] V. Arrizón and J. Ojeda-Castañeda, “Multilevel phase gratings for array illuminators,” *Appl. Opt.*, vol. 33, pp. 5925–5931, Sep. 1994.

[7] N. K. Berger, B. Levit, S. Atkins, and B. Fischer, “Repetition-rate multiplication of optical pulses using uniform fiber Bragg gratings,” *Opt. Commun.*, vol. 221, pp. 331–335, 2003.

[8] N. K. Berger, B. Levit, and B. Fischer., “Reshaping periodic light pulses using cascaded uniform fiber Bragg gratings.,” *J. Lightw. Technol.*, vol. 24, no. 7, Jul. 2006.