# Phase measurement of periodic optical pulses using temporal fractional Talbot effect

N.K. Berger, B. Levit and B. Fischer

Proposed and demonstrated is a novel method for time-domain interferometry of optical pulse trains that does not need light pulse splitting. The interference is between time-shifted pulse-train replicas produced in a dispersive delay line via the temporal fractional Talbot effect. A built-in advantage of the method is its low sensitivity to environmental disturbance. In the experiment the method was used to demonstrate phase characterisation of periodic optical pulses.

*Introduction:* The development of methods for complete characterisation of optical pulses has great importance for optical communications applications and other areas in optics. Linear interferometric measurements in the spectral [1], spectral-temporal [2], spatial-spectral [3] and time [4] domains provide simple and direct (i.e. non-iterative) processing of the results and high sensitivity. In the conventional time-domain interferometry, a pulse train is split, as in spatial interferometry, and the interference in the time domain is obtained between two replicas of the original pulse train. However for periodic pulses, it is possible to obtain interference between pulses in the same pulse train. In [5] the interference between adjacent pulses which were broadened by reflection from a chirped Bragg grating was used for characterising the pulses. An advantage of such ‘self’ pulse-train interferometry is the stability of the interference pattern and the insensitivity to environmental influence as the optical path difference, usually needed for the split branches in regular interferometry, is eliminated.

In this Letter we suggest an alternative method to obtain the temporal interference pattern that avoids splitting of the original pulse train. Here the interference occurs between time-shifted pulse-train replicas produced by the temporal fractional Talbot effect [6, 7] in a dispersive delay line. Processing of the temporal interference pattern gives the phase profile of the original pulse. Therefore, we obtain a very robust method for the pulse phase characterisation.

*Measurement principle:* The temporal integer Talbot effect [8] is the temporal analogy of the spatial integer Talbot effect. At the propagation of periodic pulses in media with first-order dispersion, the temporal shape of periodic pulses is reproduced at multiples of the so-called Talbot length: $z_T = T^2/\pi|\beta_2|$, where T is the pulse-train period and $\beta_2$ is the group velocity dispersion. For the fractional Talbot effect, the propagation length in the dispersion line is $z_{fT} = (m/p)z_T$, where m and p are integers with no common factor. For such length the field amplitude of the output pulses is transformed to [9, 7]:

$$E(t, z_{fT}) = \sum_{n=0}^{p-1} C(n, m, p)E(t - nT/p, 0) \tag{1}$$

where $E(t, 0)$ is the time-dependent field amplitude of the pulses at the line input and the coefficients $C(n, m, p)$ are given by

$$C(n, m, p) = (1/p)\sum_{q=0}^{p-1} \exp[(2i\pi q/p)(n - \beta_2 mq/|\beta_2|)] \tag{2}$$

It can be seen from (1) that the output pulse field represents in the general case, a sum of $p$ replicas of the original pulse train, each weighted by a complex coefficient $C(m, n, p)$ and shifted by a multiple of $T/p$. When these replicas do not overlap the fractional Talbot effect can be used for pulse rate multiplication [10, 6]. For a phase measurement, the number $p$ is chosen from the condition that the pulses should overlap. Under this condition, the pulse intensity at the output can be considered as resulting from the interference of $p$ time-shifted replicas of the input pulse train. The pulse phase can be found from the measurement of the input and the output pulse intensities.

From this point of view our method is similar to shearing interferometry, in which the interference occurs between two replicas of an original pulse train time shifted by a small amount. The difference is in that the replicas number in our method can be larger than two and the time shift between them is not small. We emphasise that the elimination of the optical path difference for the interfering light forms makes our method insensitive to environmental influences. We also note that interference in the time domain due to propagation of light is of course a basic and simple phenomenon. The idea behind the present method is to apply intra pulse-train interference for pulse-train characterisation via the fractional Talbot effect.

*Experiment and results:* In the experiment, the pulses, shown in Fig. 1, were obtained by a sinusoidal phase modulation of a tunable continuous-wave laser diode followed by propagation of the light in an optical fibre with a total dispersion of −223 ps/nm. The pulses were measured by a photodetector and an oscilloscope having a bandwidth of 50 GHz. The pulse repetition rate and width were 6.12 GHz and 33 ps, respectively. The modulation index was measured to be 1.6 rad from the harmonic intensity relation in the pulse spectrum (see Fig. 2). We chose in the experiment $m = 1$, and $p = 8$. We can find from (2) that for odd $n$ $C(n, 1, 8) = 0$ and only four nonzero replicas contribute to the interference; $C(0, 1, 8) = 0.5\exp(-i\pi/4)$, $C(2, 1, 8) = C(6, 1, 8) = 0.5$, $C(4, 1, 8) = 0.5\exp(3i\pi/4)$. We used an optical fibre with a total dispersion of −840 ps/nm line giving an effective length of $z_T/8$.

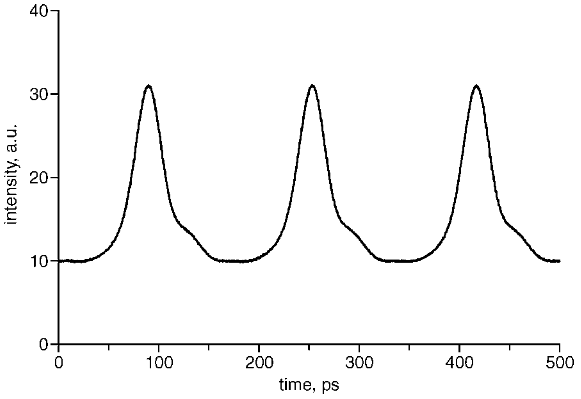

**Fig. 1** *Input optical pulses*

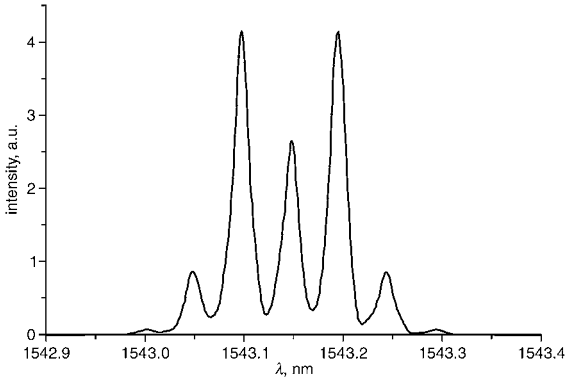

**Fig. 2** *Spectrum of input pulses (resolution 0.01 nm)*

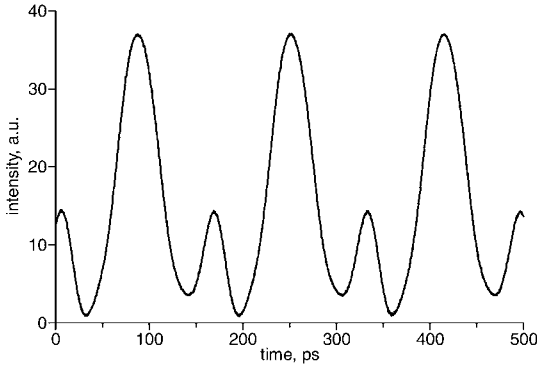

**Fig. 3** *Interference pattern dispersive line output*

Because the shift between the pulse replicas is not small, we could not process the measurement results as in shearing interferometry. Therefore, the pulse phase $\varphi(t)$ was sought in the form of a polynomial.

The polynomial coefficients were found by fitting the experimental data to the calculated values given by (1). The pulse intensity measured at the dispersive line output is shown in Fig. 3. Fig. 4 shows the pulse phase, measured by this method (solid curve). For comparison, we also give in Fig. 4 (dotted curve), the pulse phase calculated for a modulation index of 1.6 rad and a dispersion of the pulse shaping fibre of $-223$ ps/nm that show a very good agreement.

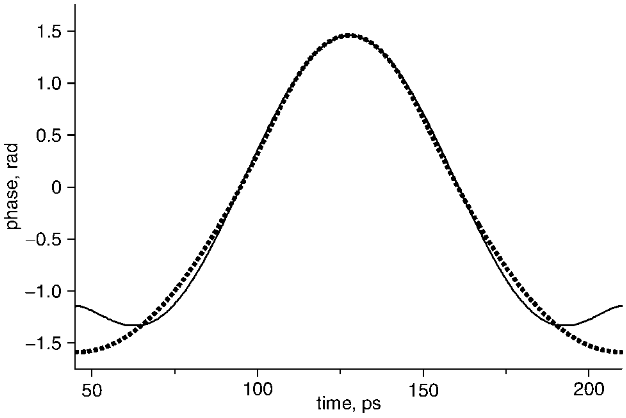

**Fig. 4** *Phase of input pulse*
——— measured
--------- calculated

*Conclusion:* We present a phase measurement method of pulses using the temporal fractional Talbot effect. The dispersive media, that can be an optical fibre or a chirped fibre Bragg grating, acts to perform intra pulse-train interferometry without splitting the original pulse train. Such an interferometer is very robust and simple for implementation.

© IEE 2005
*27 June 2005*
*Electronics Letters* online no: 20052323
doi: 10.1049/el:20052323

N.K. Berger, B. Levit and B. Fischer (*Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel*)

E-mail: fischer@ee.technion.ac.il

## References

1 Iaconis, C., and Walmsley, I.A.: ‘Spectral phase interferometry for direct electric-field reconstruction of ultrashort optical pulses’, *Opt. Lett.*, 1998, **23**, (10), pp. 792–794
2 Chu, K.C., Heritage, J.P., Grant, R.S., Liu, K.X., Dienes, A., White, W.E., and Sullivan, A.: ‘Direct measurement of the spectral phase of femtosecond pulses’, *Opt. Lett.*, 1995, **20**, (8), pp. 904–906
3 Meshulach, D., Yelin, D., and Silberberg, Y.: ‘Real-time spatial-spectral interference measurements of ultrashort optical pulses’, *J. Opt. Soc. Am. B*, 1997, **14**, (8), pp. 2095–2098
4 Rothenberg, J.E., and Grischkowsky, D.: ‘Measurement of optical phase with subpicosecond resolution by time-domain interferometry’, *Opt. Lett.*, 1987, **12**, (2), pp. 99–101
5 Berger, N.K., Levit, B., and Fischer, B.: ‘Complete characterization of optical pulses using a chirped fiber Bragg grating’, *Opt. Commun.*, 2005, **251**, (4–6), pp. 315–321. (In press, available online at www.sciencedirect.com)
6 Azaña, J., and Muriel, M.A.: ‘Temporal self-imaging effects: theory and application for multiplying pulse repetition rates’, *IEEE J. Sel. Top. Quantum Electron.*, 2001, **7**, (4), pp. 728–744
7 Berger, N.K., Levit, B., Bekker, A., and Fischer, B.: ‘Compression of periodic optical pulses using temporal fractional Talbot effect’, *IEEE Photonics Technol. Lett.*, 2004, **16**, (4), pp. 1855–1857
8 Jannson, T., and Jannson, J.: ‘Temporal self-imaging effect in single-mode fibers’, *J. Opt. Soc. Am.*, 1981, **71**, (11), pp. 1373–1376
9 Arrizón, V., López-Olazagasti, E., and Serrano-Heredia, A.: ‘Talbot array illuminators with optimum compression ratio’, *Opt. Lett.*, 1996, **21**, (4), pp. 233–235
10 Arahira, S., Kutsuzawa, S., Matsui, Y., Kunimatsu, D., and Ogawa, Y.: ‘Repetition-frequency multiplication of mode-locked pulses using fiber dispersion’, *J. Lightwave Technol.*, 1998, **16**, (3), pp. 405–410