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Complete characterization of optical pulses using a chirped fiber Bragg grating

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Abstract

A simple method for complete characterization of periodic optical pulses based on time domain interferometry is demonstrated. The method does not require the use of an interferometer. A chirped fiber Bragg grating is used for stretching the pulses to be characterized. The interference between the stretched overlapped pulses is recorded by a photodiode and a sampling oscilloscope. The phase response of the chirped fiber Bragg grating is measured by an all-fiber Michelson interferometer. A fast-Fourier-transform method is used for processing of interference patterns in both the time and spectral domain.

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Keywords: Optical pulse characterization; Chirped fiber Bragg grating; Time-domain interferometry; Intensity and phase retrieval

The development of methods for complete characterization of ultrashort optical pulses has great importance for optical communication implementations. One of the widely used methods is frequency-resolved optical gating (FROG) (see, for instance, reviews [1,2]). Compared to the above method, linear interferometric measurements that are done in the spectral [3–5], time [6,7] and spatial-spectral [8,9] domains or using spectral filtering [10] or real-time spectral interferometry [11] offer simpler and direct (i.e., noniterative) processing of the results and much higher sensitivity. However, even the linear methods, very often include nonlinear ingredients, such as cross-correlation recording [6], nonlinear frequency shear [4] or FROG for characterization of the reference pulse [3].

For pulses shorter than ~15 ps, recording the temporal pattern of the interference becomes

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problematic due to limited resolution of the oscilloscope and the photodetector. In this case, methods such as expanding the time scale with a time microscope [12] or a dispersive delay line [7], conversion the time scale to spectral or spatial scales [13,9] can be applied.

In the conventional time-domain interferometry, an original pulse train is split, as in spatial interferometry, and the interference is obtained between two replicas of the original pulse train. However, for periodic pulses there is a unique possibility of obtaining interference between pulses of the same pulse train without splitting.

In this paper, we present a simple method of complete optical pulse characterization based on time domain interferometry. In this method, the interference between adjacent pulses that are broadened as a consequence of reflection from a chirped Bragg grating is used for characterizing the pulses. Our method can be called "interferometry without an interferometer". Therefore, typical drawbacks, mostly connected with stability of the mechanical system and disturbance due to environmental conditions are eliminated. The oscilloscope interference pattern is always stable. The method is very simple to implement. The chirped Bragg grating and the circulator can be replaced by a span of standard optical fiber.

We had a brief conference presentation of this method [14], but here we expand the work and include in it characterization of short pulses, for which the temporal resolution of an oscilloscope is insufficient for a direct pulse measurement. Our analysis in this paper shows that the method can be applied to such short pulses, only that periodic pulse bursts ought to be formed from the pulse train, while taking into account the interference between multiple neighboring pulses.

The optical pulses to be characterized are reflected by the chirped fiber Bragg grating. For an ideal chirped grating the time delay of the reflected light can be expressed as [15]

$$\tau(\omega) = \beta_2 L(\omega - \omega_0), \quad (1)$$

where

$$\beta_2 = 2\pi c/(\omega_0^2 v_g \Delta\lambda_{chirp}), \quad (2)$$

is the group velocity dispersion of the grating, $L = 2L_g$, L_g is the grating length, ω is the angular frequency of the pulse spectrum, ω_0 is the frequency corresponding to the central Bragg wavelength of the grating, v_g is the average group velocity in the fiber, and $\Delta\lambda_{chirp}$ is the chirped bandwidth. It can be seen from (1) that the different spectral components of the reflected pulse undergo different delays and therefore the pulses are spread after the reflection (see Fig. 1). The grating dispersion was chosen, such that the spreading of the pulses causes a slight overlap between them that provides the interference pattern shown in Fig. 2 (solid line). If the overlap is small,

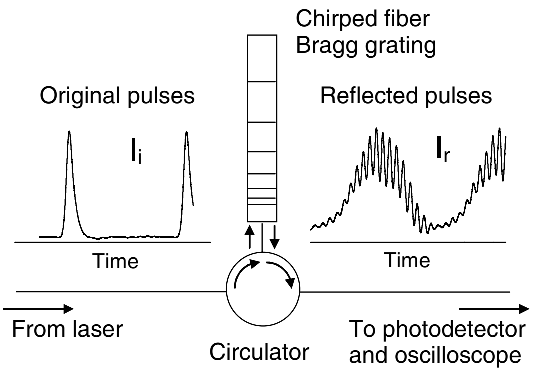

Fig. 1. Schematic representation of the measurement setup.

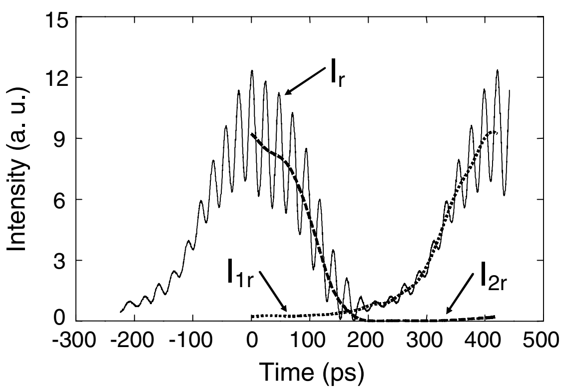

Fig. 2. Oscilloscope trace (solid line) of the pulses measured after the reflection from the chirped fiber Bragg grating. Reconstructed left side (dotted line) and right side (dashed line) of the reflected pulse (with the no interference between adjacent pulses).

it can be assumed that the interference occurs only between adjacent pulses. Then, the method is similar to shearing interferometry, where the phase difference is measured between two replicas of the same pulse, with a relative time shift Δt, giving a phase difference: $\Delta\varphi_r(t) = \varphi_r(t) - \varphi_r(t - \Delta t)$, where the index r refers to the pulse that is reflected by the grating. In our method, this shift is equal to the pulse period T. Thus, the phase difference can be rewritten as

$$\Delta\varphi_r(t) = \varphi_r(t) - \varphi_r(t - T). \quad (3)$$

The phase difference $\Delta\varphi_r(t)$ and then the phase $\varphi_r(t)$ as well as the intensity $I_r(t)$ of the reflected single pulse can be reconstructed from the interference pattern (see below). The intensity $I_i(t)$ and the phase $\varphi_i(t)$ of the original pulse (before the reflection) can be reconstructed by calculating the pulse as being reflected again from the chirped grating with an opposite dispersion.

The interference within the period (from 0 to 420 ps in Fig. 2) can be considered as a result of the superposition of the left and right side of the pulse with intensities $I_{1r}(t)$ and $I_{2r}(t)$, respectively. In this case, the intensity of the interference is equal to

$$I_r(t) = I_{1r}(t) + I_{2r}(t) + 2[I_{1r}(t)I_{2r}(t)]^{1/2}\cos[\Delta\varphi_r(t)]. \quad (4)$$

We can roughly estimate the expected frequency of the oscillations in the interference pattern. The spectral phase $\phi(\omega)$ acquired by the pulse in the reflection from the grating and the time delay $\tau(\omega)$ are related as

$$\tau(\omega) = \partial\phi/\partial\omega. \quad (5)$$

In the first-order dispersion approximation (1), we obtain from (5)

$$\phi(\omega) = \beta_2 L(\omega - \omega_0)^2/2. \quad (6)$$

It is formally analogous to the phase acquired by the spatial frequency components of a paraxial spatial beam propagating along a distance z: $\phi(k_\perp) = zk_\perp^2/(2k)$, where k is the wavenumber and $k_\perp$ is the transverse component of the wave vector. By using this space-time duality [16], we can present the field of the reflected pulse for sufficiently large dispersion of the grating as the time-domain analog of the spatial Fraunhofer diffraction

$$E_r(t) \propto \exp(it^2/2\beta_2 L)F(t/\beta_2 L), \quad (7)$$

where $F(\omega)$ is the complex spectrum of the pulse to be measured. It can be seen from (7) that in this approximation the spectral components of the reflected pulse are mapped to the temporal domain. This effect was exploited for real-time spectrum analysis of optical pulses using the dispersion of standard optical fiber [17]. Neglecting the chirp of the original pulse, we obtain from (7) the phase of the reflected pulse

$$\varphi_r(t) = t^2/2\beta_2 L$$

and from (3) the phase difference is

$$\Delta\varphi_r(t) = Tt/(\beta_2 L) - T^2/(2\beta_2 L). \quad (8)$$

It follows from (8) and (4) that the expected frequency of the oscillations in the interference pattern can be estimated as

$$f_{int} = T/(2\pi\beta_2 L). \quad (9)$$

Note that the frequency dependence of the spectral phase can deviate from the quadratic form given by (6). Therefore, we measured this dependence as seen below. We also obtained f_{int} experimentally.

In the experiments, the optical pulses were produced by a mode-locked laser diode. The modulation frequency was 2.38 GHz and the pulse width was 28 ps. We also measured those pulses directly by an oscilloscope, and compared the result obtained by our method. We used a dispersion compensating fiber grating, produced by E-TEK ElectroPhotinic Solutions, with 1 dB bandwidth of 0.528 nm and first-order dispersion of $D \cdot L = -1108$ ps/nm ($D = 2\pi c\beta_2/\lambda_0^2$, c is the velocity of light, $\lambda_0 = 1541.3$ nm is the central Bragg wavelength of the grating, $\beta_2 \cdot L = 1397$ ps^2). We have assumed above that the pulses are strictly periodic. However, this condition was slightly violated in the experiment because of the laser instability. Therefore, the interference patterns recorded by an oscilloscope were averaged.

The processing of the interference pattern, presented in Fig. 2, was accomplished as follows. Similarly to reference [18], the Fourier transform of the interference intensity is calculated. The result is shown in Fig. 3. Since the overlap between the reflected pulses is small, the frequency of the rapid oscillation of the interference is large enough to allow separation in the Fourier transform between the central band that corresponds to the slow variation of $I_{1r}(t) + I_{2r}(t)$ in (4) and the sidebands, related to the oscillations $\cos[\Delta\varphi_r(t)]$ of the interference pattern. The absolute value of the inverse Fourier transform of the central band only gives the value $I_{1r}(t) + I_{2r}(t)$ in relative units. The same calculation for the sideband gives the value of $2[I_{1r}(t)I_{2r}(t)]^{1/2}$. From these two equations, we can calculate the values of $I_{1r}(t)$ and $I_{2r}(t)$, thus reconstructing the shape of the intensity of the single pulse (with no interference), reflected from the chirped grating. The results of the reconstruction are shown in Fig. 2.

The argument of the inverse Fourier transform of the sideband in Fig. 3 gives the phase difference $\Delta\varphi_r(t)$. It is significant that in our method there is no ambiguity in the choice of the sign of $\Delta\varphi_r(t)$ (or in the choice of the right or left sideband, which is the same). This sign is completely defined by the sign of the Bragg grating chirp. Therefore, the proposed method is unambiguous. The phase $\varphi_r(t)$ cannot be found using the shearing interferometry method because in this case the time shift Δt is not small. We assume that the phase can be described in a polynomial form and the coefficients are calculating by optimal fitting to the values of $\Delta\varphi_r(t)$.

To reconstruct the intensity $I_i(t)$ and phase $\varphi_i(t)$ of the original pulse, the pulse reflection with $I_r(t)$ and $\varphi_r(t)$ was calculated from the same chirped grating, but with opposite dispersion, similarly to [7].

The spectral characteristics of the chirped Bragg grating were measured using a broadband light source (amplified spontaneous emission of an erbium doped fiber amplifier) and an optical spectrum analyzer with a resolution of 0.01 nm. An all-fiber Michelson interferometer was used to measure the spectral phase of the reflection. One of the reflecting mirrors of the interferometer was the chirped fiber Bragg grating. The light reflected from the grating and from the reference mirror interfered. Since the grating reflection phase depends on the wavelength, the intensity of the interference sinusoidally varies as the function of the wavelength. For the nearly quadratic frequency dependence of the spectral phase (6), the period of the sinusoidal intensity should vary approximately linearly with the wavelength. The interference pattern, recorded in the spectral domain with an optical spectrum analyzer is shown in Fig. 4. The decay of the interference pattern is attributed to insufficient resolution of the spectrum analyzer. Processing of the interference pattern using Fourier transform, in the same way as was described above for the temporal interference pattern, enabled calculation of the spectral reflection phase. Note that the slow variation of the interfer-

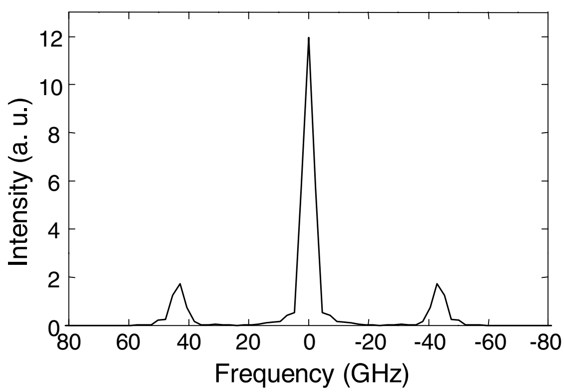

Fig. 3. Calculated Fourier transform of the interference pattern, presented in Fig. 2.

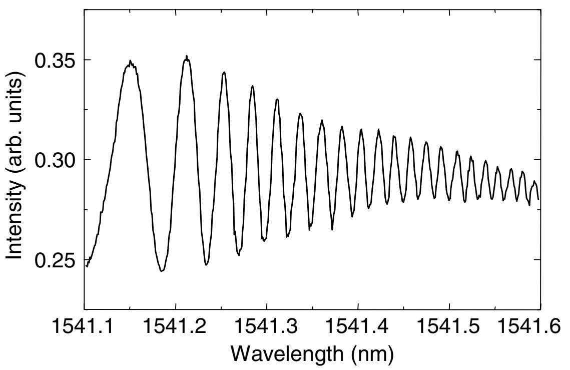

Fig. 4. Spectral interference between the light reflected from the chirped Bragg grating and from the reference mirror in the Michelson interferometer, measured by an optical spectrum analyzer.

ence pattern envelope does not affect the extracted spectral phase [18]. Fig. 5 shows the measured grating reflectivity (solid line) and the spectral reflection phase (dotted line) reconstructed from the interference pattern shown in Fig. 4.

The reconstructed intensity $I_i(t)$ and phase $\varphi_i(t)$ of the original pulse are given in Fig. 6. For comparison, the intensity of the original pulse, measured using an oscilloscope is also shown. The figure shows very good agreement between the two measurements.

To verify that the phase measurement by the proposed method is correct we have calculated the spectrum of the reconstructed original pulse and compared it with that measured by an optical spectrum analyzer. Comparison of the results is presented in Fig. 7. Notice that the calculated spectrum of the single pulse should be the envelope of the measured spectrum of the periodic pulses. The figure shows good agreement.

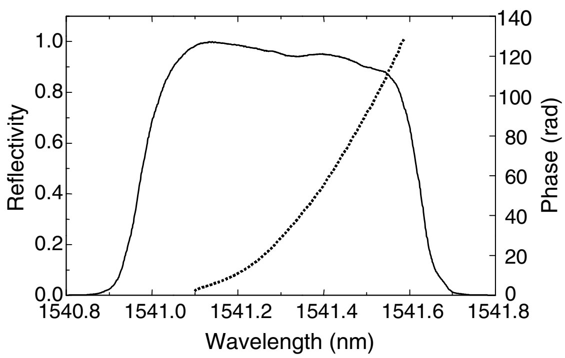

Fig. 5. Measured reflectivity (solid line) and reflection phase (dotted line) of the chirped Bragg grating.

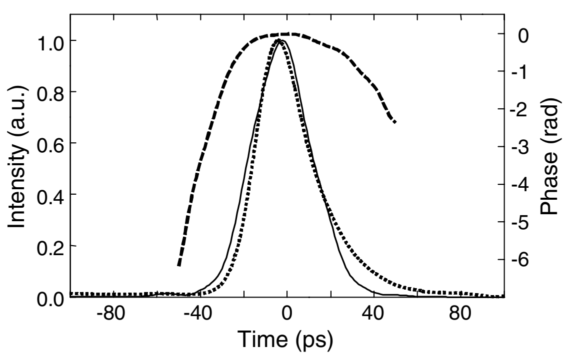

Fig. 6. Pulse intensity profile measured by the proposed method (solid line) and an oscilloscope (dotted line). Pulse phase profile measured by the proposed method (dashed line).

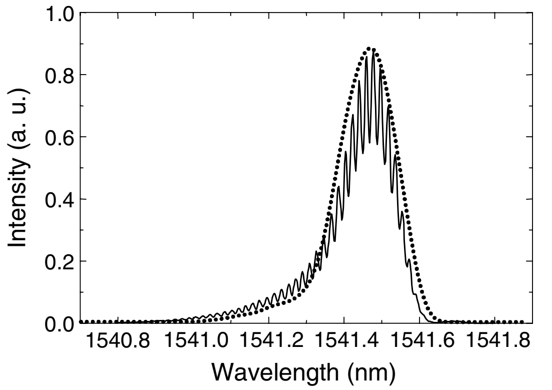

Fig. 7. Spectrum of the original pulses: solid curve – measured by an optical spectrum analyzer, dotted curve – calculated for the reconstructed pulse.

According to (9), the group velocity dispersion of the grating has to be sufficiently high so that the frequency f_{int} of the sideband in the Fourier transform be within the bandwidth Δf of an oscilloscope and a photodiode

$$f_{\text{int}} < \Delta f. \tag{10}$$

On the other hand, it was assumed that the interference occurs only between adjacent pulses. This implies that the pulse stretching by a fiber Bragg grating is limited by

$$\tau_{\text{out}} < T/1.5, \tag{11}$$

where τ_{out} is the width of the single stretched pulse. For Gaussian pulses, inequalities (10) and (11) give the following estimations:

$$\tau_{\text{in}} > 4.2(\beta_2 L/T), \tag{12}$$

$$\beta_2 L/T > 1/(2\pi\Delta f), \tag{13}$$

where τ_{in} is the width of the original pulse. It was assumed in the derivation of (12) and (13) that $\tau_{\text{out}} \gg \tau_{\text{in}}$. It follows from (12) and (13) that for a bandwidth Δf = 50 GHz (of the oscilloscope plus detector), the pulses measured by the described method cannot be shorter than 13 ps.

For pulses shorter than this limit, the method is slightly modified. It should be taken into account that now the interference occurs not only between adjacent pulses, and in the Fourier transform, higher sideband orders appear. In this case, periodic pulse bursts ought to be selected from the pulse train, for instance, by using amplitude modulation with square waveform. It is clear, that a sideband of order m in the Fourier transform corresponds to interference between all pulses in the burst with a time distance $m \cdot T$. The case $m = 0$ corresponds to the sum of the intensities of all stretched pulses in the burst. Then, the signals, corresponding to the sidebands of order $m = 0, -1$ (for $\beta_2 L < 0$) can be expressed in the form:

$$I_0(t) = \sum_{n=-N}^{N} I_r(t - nT) = \int_{-\infty}^{\infty} \left[\sum_{n=-N}^{N} \exp(-\mathrm{i}n\omega T) \right] F(\omega) \exp(\mathrm{i}\omega t)\, \mathrm{d}\omega, \tag{14}$$

$$I_{-1}(t) = \sum_{n=-N}^{N-1} E_r(t - nT) E_r^*(t - nT - T) = \int_{-\infty}^{\infty} \left[\sum_{n=-N}^{N-1} \exp(-\mathrm{i}n\omega T) \right] G(\omega) \exp(\mathrm{i}\omega t)\, \mathrm{d}\omega, \tag{15}$$

where $E_r(t)$ and $I_r(t)$ are the field and the intensity of the central pulse in the reflected pulse burst (with no interference), $2N + 1$ is the number of the pulses selected in the burst, $E_r^*(t)$ is the complex conjugate field, $F(\omega)$ and $G(\omega)$ are the Fourier transforms of the functions $I_r(t)$ and $E_r(t) \cdot E_r^*(t - T)$, respectively. The Fourier transform of $I_0(t)$ and $I_{-1}(t)$ in (14) and (15) gives the Fourier coefficients c_{mk} of the sidebands with $m = 0, -1$:

$$c_{0k} = \left[\sum_{n=-N}^{N} \exp(-\mathrm{i}2\pi knT/T_m) \right] F(2\pi k/T_m), \tag{16}$$

$$c_{-1k} = \left[\sum_{n=-N}^{N-1} \exp(-\mathrm{i}2\pi knT/T_m) \right] G(2\pi k/T_m), \tag{17}$$

where T_m is the period of the amplitude modulation. From (16) and (17), $F(\omega)$ and $G(\omega)$ can be found for the discrete values $\omega_k = 2\pi k/T_m$, when the coefficients c_{0k} and c_{-1k} are obtained from the Fourier transform of the experimental interference pattern. Then, $I_r(t)$ and the phase difference $\Delta\varphi_r(t)$ between two adjacent reflected pulses are reconstructed by the inverse Fourier transform.

We emphasize again that the chirped grating dispersion chosen has to be sufficiently high so that at least the frequencies of the sideband of the order $m = 1$ are less than the bandwidth of an oscilloscope and a detector. The sidebands with $m > 1$ will be rejected in this case by an oscilloscope and a detector, but anyhow there is no need to process these sidebands. It implies that our method can also be used in cases of insufficient temporal resolution of an oscilloscope and a detector. It is clear that for shorter pulses, the bandwidth of the gratings has to be appropriately increased. It leads, according to (2), to decreasing of the group velocity dispersion and requires, for keeping the same interference frequency (Eq. (9)), fabrication of longer gratings with stringent performance in their temperature stability.

In conclusion, a method for complete characterization of periodic optical pulses based on time domain interferometry with a chirped fiber Bragg grating is demonstrated. The method is very simple for implementation. An additional advantage of the method is stability of the interference pattern and insensitivity to environmental influences. Therefore, we have a very robust technique for the pulse characterization. Expanding of the time scale allows measurement of pulses with duration of shorter than the time response of the photodetector and the oscilloscope. A drawback of the use of Bragg gratings is the need to match the central Bragg wavelength and the bandwidth of the grating to the spectrum of the pulses. Nevertheless, there are ways to make the right tuning. One can use, for example, standard optical fibers with a wide bandwidth, as a pulse stretcher. Our technique can also be applied for a single pulse or for pulses with very small duty-cycle. In this case, two replicas of the original pulse has to be produced, for instance, by reflection from two sides of a glass plate [11] and then stretching as was described above.

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