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All-fibre optical gating system for measuring a complex-shaped periodic broadband signal with picosecond resolution in a nanosecond time window

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Abstract. **We have developed an optical gating system for continuously monitoring a complex-shaped periodic optical signal with picosecond resolution in a nanosecond time window using an all-fibre optical gate in the form of a nonlinear loop mirror and a passively mode-locked femtosecond laser. The distinctive features of the system are the possibility of characterizing signals with a very large spectral bandwidth, the possibility of using a gating pulse source with a wavelength falling in the band of the signal under study and its all-fibre design with the use of standard fibres and telecom components.**

Keywords: *measurements of ultrashort pulses, optical gating, nonlinear gate, nonlinear Sagnac fibre interferometer.*

1. Introduction

In spite of the great advances in measurements of ultrashort optical pulses, the problem of measuring very complex shaped pulses and long pulse trains containing structures greatly differing in timescale has attracted much attention. The applicability of standard all-optical methods capable of reconstructing the temporal pulse shape with femtosecond resolution (such as FROG, SPIDER and their modifications [1]) is limited by difficulties in achieving a wide time scan range (which is usually ensured by mechanically tunable optical delay lines) and the complexity of the inverse problem of reconstructing the pulse shape, which shows up clearly in the case of complex-shaped pulses and trains of several closely spaced pulses. Modern high-speed photodetectors and oscilloscopes allow optical signals to be detected with a resolution down to tens of picoseconds, but they are very expensive and have inherent limitations related to distortions in signal shape measurements (e.g. 'ringing' or an extended pulse 'tail') due to limitations on the bandwidth of photodiodes and electronic circuits and difficulties in matching microwave channels [2]. Thus, the above methods are difficult to employ for signal characterisation in the 'intermediate' time range (1–100 ps) and practically inapplicable to very long (nanosecond and longer) pulses or long pulse trains if picosecond resolution is needed.

A large class of methods that allow one to study very complex shaped pulses with high time resolution in a wide time window are based on the optical gating (see reviews in Refs [2–4]) of a signal of interest using an ultrashort gating pulse generated by an independent separate source (usually by a mode-locked laser). This approach is applicable to studies of periodic signals and trains, which is a standard situation in many experiments. It is important to note that the repetition rate of gating pulses is not necessarily equal to that of the signal of interest. In contrast, a slight frequency difference allows the gating signal to be scanned relative to the signal under study in an all-optical configuration without tunable delay lines or moving parts, which underlies so-called asynchronous gating systems [5] (Fig. 1). Let the pulse repetition rate of a signal under study be f_1 (with a period $T_1 = 1/f_1$) and the repetition rate of gating pulses be f_2 (with a period $T_2 = 1/f_2$). During a measurement time of $1/|f_1 - f_2|$, the gating

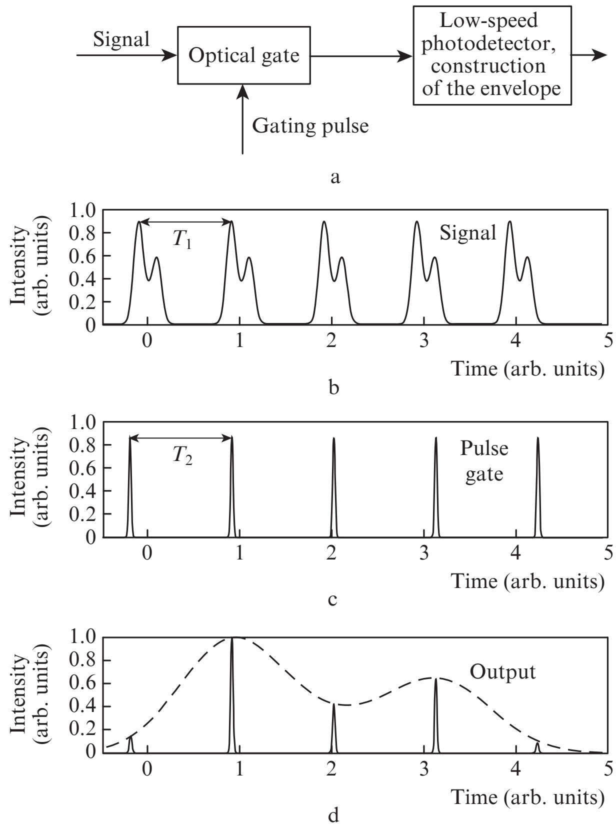

Figure 1. (a) General schematic of the method of asynchronous optical gating of a periodic complex-shaped signal, (b) input signal with a repetition period T_1, (c) gating pulses with a repetition period T_2, (d) output signal of the optical gate (solid lines) and its envelope (dashed line).

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method allows one to acquire a number of counts sufficient for completely reconstructing the signal shape through the period T_1. The effective time resolution is then $|T_1 - T_2|$.

In addition to a gating pulse source, a key element of all optical gating systems is an optical gate: a circuit whose output signal is proportional to the input signal at the instant when a gating pulse arrives (see a review by Fok and Prucnal [6]). This may be e.g. both a second-order nonlinear medium, in which a sum or difference frequency signal is generated [7], and a third-order nonlinear medium, where gating is based on various versions of cross-phase modulation processes [8], four-wave mixing [2, 9] and parametric amplification [10]. A large number of studies have been concerned with optical gates based on highly nonlinear fibres [2] and waveguides [11, 12]. In all studies known to us, the performance of configurations based on third-order nonlinear fibres and waveguides is only ensured if there is a sufficiently large difference in centre wavelength between the signal under study and gating signal and their spectra do not overlap, which allows one to use an output spectral filter for separating these signals. This places serious limitations on the bandwidth of both the signal under study and the gating signal, because their centre wavelengths are usually chosen to differ relatively little in order to ensure quasi-synchronous propagation of the signals in the fibre or waveguide. Given the tendency toward spectral range extension in data transmission systems and for the purpose of monitoring broadband pulses in laser systems, e.g. a pulsed supercontinuum or highly chirped pulses, the problem of broadband optical gating is becoming more and more important.

In this paper, we report a modified method of optical gating in an all-fibre system based on a nonlinear Sagnac interferometer and polarisation separation of gating and signal pulses, which allows one to use a gating source with a wavelength within the band of the signal under study. The method was successfully tested in an experiment aimed at observing a complex train of broadband pulses from a specially designed fibre laser mode-locked at high cavity harmonics [13]. We present approximate analytical estimates of the time resolution of this method, which agree well with experimental data.

2. Description of the method

Figure 2 shows a schematic of the all-fibre configuration used to implement the method proposed by us. The gating pulse source used is a mode-locked fibre laser whose pulse repetition rate, f_2, should approach the repetition rate of pulses under investigation, f_1. A nonlinear Sagnac fibre interferometer (nonlinear Sagnac loop mirror) is suggested to be used as an optical gate in our method. The signal arrives at the input (*1*) of the fibre coupler of the interferometer, which is fully balanced in the absence of gating pulses and, hence, does not transmit the signal to the output (*2*). A gating pulse is introduced into the loop mirror using an additional fibre coupler (*3*) and it passes the loop mirror in only one direction (clockwise in Fig. 2). Owing to cross-phase modulation, the gating pulse causes the signal propagating clockwise to acquire an additional, unbalanced phase shift. As a result, part of the signal reaches the output (*2*).

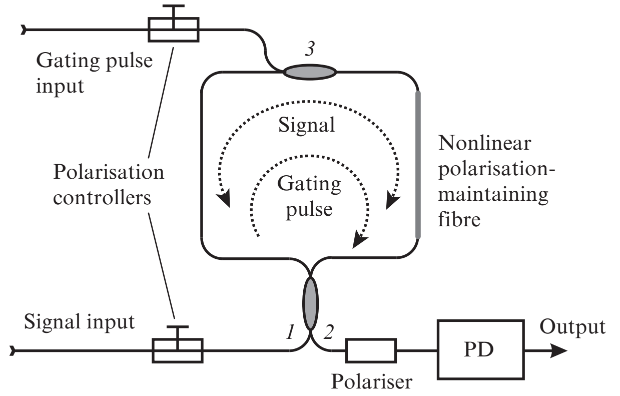

Figure 2. Schematic of the optical gate (see text).

The key feature of the scheme is the polarisation separation of gating and signal pulses. To this end, a gating pulse is introduced into a nonlinear loop mirror with polarisation orthogonal to that of the signal, and a polariser transmitting only the signal is placed at the output of the scheme. Note that a standard fibre polarisation splitter can be used as combiner (*3*), which allows one to employ all the power of the signal and gating pulses essentially without losses. Moreover, a standard 50/50 polarising fibre coupler (transmitting light with only one polarisation) can be used to build a Sagnac interferometer, which makes an output polariser unnecessary. The light at the output of the scheme is detected by a photodetector (PD) (e.g. by a photodiode) having a time resolution that allows individual gating laser pulses to be distinguished (typical repetition rates in the range 10–100 MHz). In further processing and visualisation of the signal shape, use is made of a digital oscilloscope connected to a computer. In the simplest case, the signal shape can be visually observed on the oscilloscope as the envelope of the pulses detected by the photodiode.

It is worth noting that some schemes based on a nonlinear Sagnac interferometer were considered previously as a nonlinear gate in optical gating systems [14, 15]. In an initial implementation [14], the signal and gating pulses were combined using a WDM and were jointly fed to the input port of a nonlinear interferometer. Later, Hall et al. [15] proposed introducing gating pulses through another fibre coupler placed directly in the nonlinear interferometer. Nevertheless, a bandpass filter was placed at the output of the scheme in order to separate gating and signal pulses, which produced drawbacks inherent in schemes based on the spectral separation of signals.

A nonlinear Sagnac interferometer with an additional port for introducing orthogonally polarised light was studied previously from the viewpoint of making an optical switch for very long (nanosecond) pulses [16] and short soliton pulses [17], but we have found no data on the use of this configuration for optical gating.

3. Experimental implementation of the method

To experimentally verify the proposed method, the following scheme was made: The signal under study arrived from a specially designed fibre laser mode-locked at high cavity harmonics [13], which was adjusted in those experiments to generate bunches of ultrashort pulses. The bunch repetition rate was 25.04 MHz, and we were able to gradually vary the pulse spacing within each bunch. In this paper, we do not address issues pertaining to the mechanism and specific features of the generation of bunches of pulses in our laser and focus only on the optical gating scheme.

For the generation of gating pulses, we built a standard femtosecond all-fibre ring laser operating at the fundamental frequency of the cavity. Sequentially reducing the length of the fibre laser cavity (in small portions), we adjusted its pulse repetition frequency close to the bunch repetition frequency (25.04 MHz). The frequency difference was about 600 Hz and could be tuned by varying the temperature of the gating laser. No special measures were taken to stabilise the frequency or synchronise the lasers: the two lasers operated independently in a passive mode-locking regime. Gating laser pulses, of initial duration near 400 fs, were amplified in a fibre amplifier with compensation for dispersion in active and passive fibres to an average power of 30 mW (which corresponds to an energy near 1 nJ). The signal was also amplified in a fibre amplifier with partial compensation for dispersion to an average power of 200 mW. At a characteristic number of pulses circulating in the laser cavity between 200 and 400, this corresponds to a pulse energy of just 20–40 pJ. Since both lasers and both amplifiers were made using non-polarisation-maintaining fibres, polarisation controllers and polarising Faraday isolators were placed in front of the optical gate input.

A typical spectrum of a signal under study is presented in Fig. 3 together with the spectrum of a gating pulse. The spectrum of the signal had a very jagged shape due to the presence of bunches of closely spaced pulses. Its centre was located near 1560 nm and it had a rather broad envelope: the 30-dB width of the spectrum was above 80 nm and it extended from 1520 to 1600 nm. The spectrum of the gating pulse experienced fairly large broadening in the amplifier due to nonlinearity and fully overlapped with the spectrum of the signal. At the output of the nonlinear gate, the signal was detected by a photodiode with a 1-GHz bandwidth and was fed to a digital oscilloscope (bandwidth, 300 MHz; sampling rate, 2 GS s^{-1}; memory depth, 28 Mpts).

Figure 4a shows the signal obtained by continuously recording and processing (noise filtering, construction of the envelope and time axis renormalisation) four periods of laser pulses (one period is 39.9 ns). During these measurements, the laser generated bunches of closely spaced pulses: two bunches of pulses circulated in the cavity (one consisted of 51 pulses, and the other, of 73 pulses), and the pulse spacing was 92 ps. Owing to the gating principle, the actual measurement time for a 40-ns time interval is about 12 ms. The equivalent time resolution (time spacing) is 1.3 ps and the total number of counts during one period is about 30 000. Figure 4b shows an enlarged portion of the signal, where one can see one bunch of pulses and where individual pulses are clearly seen. Finally, Fig. 4c shows a portion of the signal with a still higher time resolution, where two adjacent pulses are seen. Thus, such measurements allow one to examine the entire time interval corresponding to the signal repetition period (40 ns) with high repetition (several picoseconds) using one oscilloscope trace. In particular, this allowed us to accurately determine the number of pulses per bunch, ascertain that the pulses were equidistant within a given bunch and investigate its structure and the properties of individual pulses. For example, the amplitude of the first and last pulses in a bunch was found to differ from that of the pulses in the middle of the bunch.

The ultimate time resolution of the described scheme can be estimated using the following measurements: Figure 5 shows the signal directly from the photodiode at the output of the system before processing, the signal after processing, which

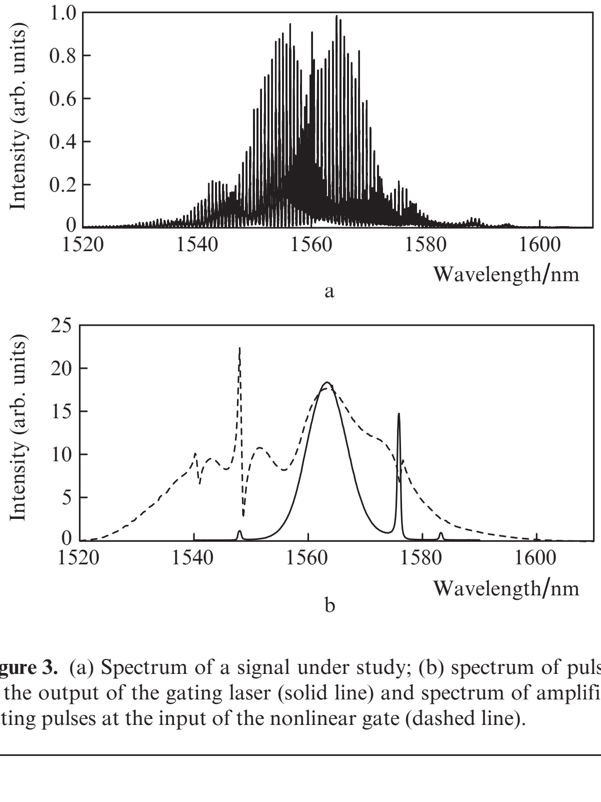

Figure 3. (a) Spectrum of a signal under study; (b) spectrum of pulses at the output of the gating laser (solid line) and spectrum of amplified gating pulses at the input of the nonlinear gate (dashed line).

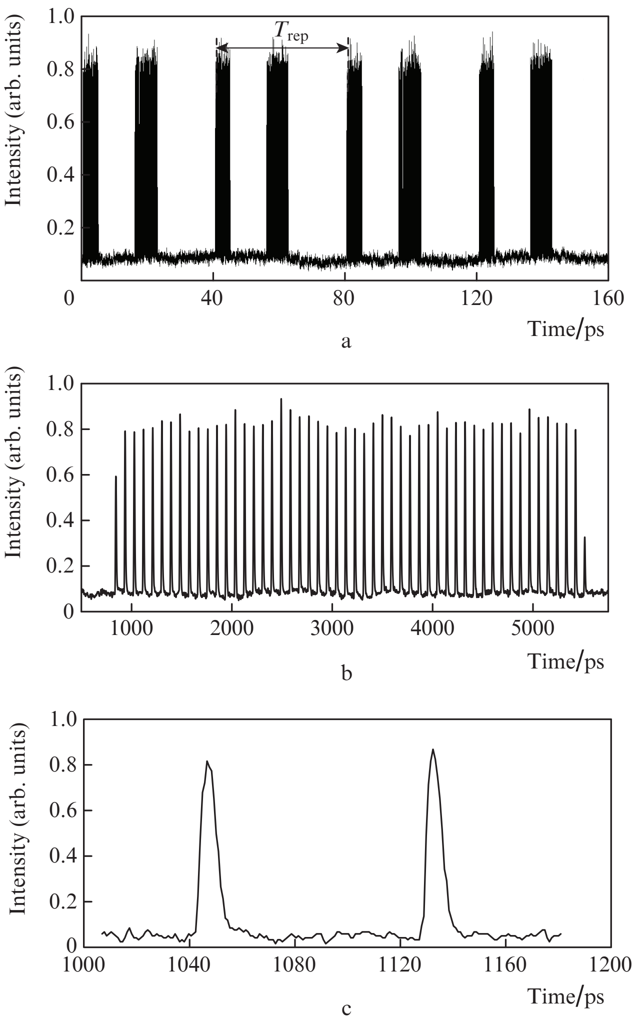

Figure 4. (a) Signal shape measured using optical gating during four laser repetition periods; (b) enlarged portion showing one bunch of pulses; (c) enlarged portion showing two adjacent pulses.

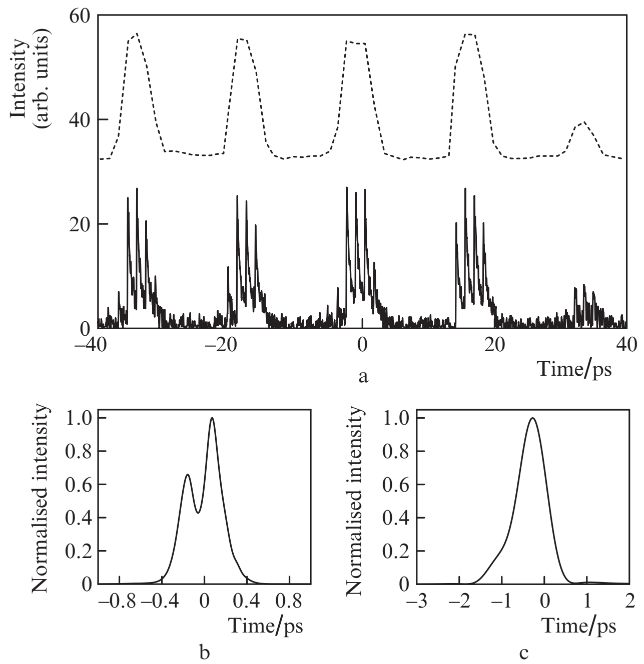

Figure 5. (a) Signal shapes at the output of the photodetector of the optical gating system before processing (solid line) and the envelope of the signal (dashed line); FROG-retrieved shapes of (b) a gating pulse and (c) one signal pulse.

was constructed like its envelope, and the shapes of the gating and signal pulses measured independently using FROG. It is seen that the duration of both pulses is noticeably smaller than the envelope width measured using an optical gating scheme. This strongly suggests that it is the optical gating scheme which makes the main contribution to pulse broadening, so its ultimate time resolution can be estimated as the measured pulse width, which is about 5 ps.

4. Estimated ultimate time resolution

To estimate the ultimate time resolution, consider in greater detail the processes that take place in the optical gate scheme built by us. Note first of all that, if a symmetric (50/50) coupler is used in a Sagnac interferometer, all linear and even nonlinear effects for a linearly polarised signal leads to identical phase shifts in all the fibres of the interferometer for light propagating in both directions (in the absence of gating pulses). By virtue of the properties of the Sagnac interferometer, the signal is fully reflected from the interferometer and does not arrive at the output of the scheme. Given this, we consider in detail only a segment of a birefringent fibre where, interacting with a gating pulse, the signal may acquire an uncompensated phase shift while propagating clockwise. The signal and gating pulses are taken to have orthogonal eigenpolarisations of the fibre, oriented along the x and y axes.

The electric field can be represented in the form $E_{\rm signal} = \boldsymbol{e}_x U\exp(\mathrm{i}\beta_x z)$ and $E_{\rm gating} = \boldsymbol{e}_y V\exp(\mathrm{i}\beta_y z)$, where e_x and e_y are the unit vectors along the x and y axes; β_x and β_y are the propagation constants for x- and y-polarised modes; and U and V are the slow envelopes of the signal and gating pulses, respectively. The basic equations describing nonlinear propagation of light along the z axis of a birefringent fibre have the form [18]

$$\frac{\partial U}{\partial z} + \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 U}{\partial t^2} = \mathrm{i}\gamma U\left(|U|^2 + \frac{2}{3}|V|^2\right) + \mathrm{i}\frac{\gamma}{3}U^*V^2\exp(-2\mathrm{i}\Delta\beta z), \quad (1)$$

$$\frac{\partial V}{\partial z} + \frac{1}{\Delta v}\frac{\partial V}{\partial t} + \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 V}{\partial t^2} = \mathrm{i}\gamma V\left(\frac{2}{3}|U|^2 + |V|^2\right) + \mathrm{i}\frac{\gamma}{3}V^*U^2\exp(2\mathrm{i}\Delta\beta z). \quad (2)$$

Here β_2 is the second-order dispersion coefficient; γ is the nonlinearity coefficient; $1/\Delta v = 1/v_y - 1/v_x$; v_x and v_y are the group velocities of x- and y-polarised modes; and $\Delta\beta = \beta_y - \beta_x$. These equations are valid in a moving frame, to which we transform by changing the time variable t to $t - z/v_x$ and in which the signal pulse (U) is at rest.

Even though the signal and gating pulses have orthogonal polarisations, nonlinear interaction is in general sensitive to the phase difference between them, which shows up as coherent coupling between the equations (the last terms on their right-hand side). However, because of the considerable difference between the phase velocities of signals with orthogonal polarisations ($\Delta\beta$), the phase difference between them oscillates rapidly and the average effect of the coherent terms on the right-hand side of the equations tends to zero, which allows us to neglect them. Further, due to the low intensity of the signal, its self-action [the term $U|U|^2$ in (1)] and its effect on the gating pulse [the term $V|U|^2$ in (2)] can be neglected, which makes Eqn (2) independent of (1), i.e. allows the evolution of the gating pulse to be considered independently of the signal using the standard nonlinear Schrödinger equation.

For further simplification, we make the following assumptions: First, we assume the effect of dispersion on the signal pulse to be relatively small, which is quite valid for a characteristic pulse duration of the order of 1 ps or longer and a standard fibre length of 1 m. Second, we assume the intensity profile of the gating pulse to vary little over the fibre length, which is possible either in the case of a weak effect of dispersion (long gating pulse) or if the pulse is a fundamental soliton. The shape of the intensity profile of the gating pulse, $I = |V|^2$, along the fibre can then be represented in the form $I(z,t) = I_0(t - z/\Delta v)$, and the equation for the signal takes the simple form

$$\frac{\partial U}{\partial z} = \mathrm{i}\gamma U I_0(t - z/\Delta v). \quad (3)$$

Its solution $U(z,t) = U(z = 0, t)\exp(\mathrm{i}\varphi(t))$, where $\varphi(t)$ is the cross-phase modulation-induced nonlinear phase shift of the signal. In a fibre segment of length L, the phase shift is

$$\varphi(t) = \frac{2\gamma}{3}\int_0^L [I_0(t - z/\Delta v)]^2 \mathrm{d}z = \frac{2\gamma v}{3}\int_0^{T_{\rm g}} [I_0(t - t')]^2 \mathrm{d}t'. \quad (4)$$

It can be seen that the phase shift is essentially proportional to the convolution of the square of the intensity of the gating pulse with that of a rectangular pulse of duration $T_{\rm g} = L/\Delta v$. This duration (group delay) is determined by the difference in group velocity between the signal and gating pulses over the fibre length.

With the above approximations, pulses propagating in a loop mirror in opposite directions acquire a phase difference given by (4) by the instant of return to the coupler. The profile of the pulse intensity J at the output of the nonlinear loop mirror can be found as

$$J(t) = J_0(t)[1 - \cos(\varphi(t))], \tag{5}$$

where J_0 is the input intensity profile. We assume the maximum nonlinear phase shift to be relatively small. Then, we have

$$J(t) \propto J_0(t)\varphi^2(t). \tag{6}$$

The photodetector response to one signal pulse at its output is proportional to the pulse energy. During the operation of the scheme, gating pulses arrive with a gradually varying time delay T relative to signal pulses. As a result, the shape of the oscilloscope trace obtained at the output of the system after processing can be represented as

$$S(T) \propto \int_{-\infty}^{+\infty} J(t)A(t-T)\,\mathrm{d}t, \tag{7}$$

where

$$A(t) = \left[\int_0^{T_g} [I_0(t-t')]^2 \mathrm{d}t'\right]^2. \tag{8}$$

Thus, the measured oscilloscope trace has the form of the convolution of the intensity profile of the signal under study and the instrumental function of the gating system, $A(t)$.

Figure 6a shows the shape of the instrumental function of our experimental scheme, calculated under the above assumptions using the measured gating pulse shape. The group delay between signals with orthogonal polarisations in our fibre segment is T_g = 3.56 ps, as determined by observing spectral interference, and makes the main contribution to the broadening of the instrumental function. The calculated shape of the oscilloscope trace of one signal pulse at the output of the system is shown in Fig. 6b.

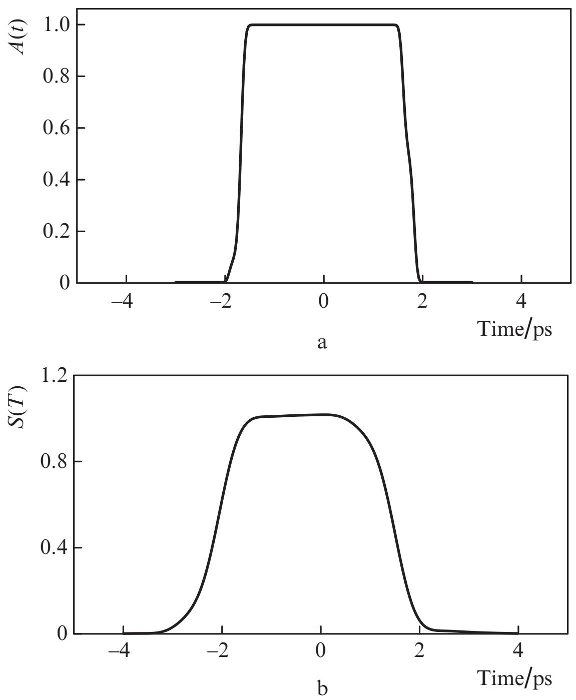

Figure 6. Calculated shapes of (a) the instrumental function of our optical gating system and (b) the oscilloscope trace of one signal pulse.

The width of the calculated oscilloscope trace is about 4 ps, in agreement with the experimentally measured width: 5 ps. The additional broadening of the measured pulse is attributable to the effect of the dispersion-induced broadening of both the gating and signal pulses and other factors left out of account.

5. Discussion

The present experimental data and analytical estimates show that our optical gating scheme with polarisation separation of gating and signal pulses can be successfully used to study a signal whose spectrum overlaps with that of the gating source. The feature of crucial importance in our scheme is the use of a birefringent fibre as a nonlinear medium where nonlinear interaction between pulses takes place, which makes it possible to avoid phase sensitivity of nonlinear interaction between orthogonally polarised pulses. It is worth noting that, inherently insensitive to a relative phase, nonlinear interaction can be organised in an isotropic medium using circularly polarised pulses (with left and right circular polarisations). However, in our experiments we failed to achieve reliable operation of the scheme, in which we used a segment of isotropic fibre and polarisation controllers to obtain circularly polarised signals. This is attributable to the complexity of obtaining and controlling circular polarisation upon adjusting the fibre controllers and to the residual birefringence, which rapidly distorts circular polarisation and leads to a noticeable phase sensitivity of the scheme.

The necessity of using a birefringent fibre degrades the time resolution of the system. One way to obviate this limitation is to use a nonlinear element consisting of several segments of a birefringent fibre, fusion-spliced to each other so that their axes make an angle of 90° (nevertheless, the length of each fibre segment should then considerably exceed the beat length), as proposed by Leng et al. [17] and Moores et al. [19]. The group delay between pulses in one fibre segment is compensated for in the next segment. As a result, the insensitivity to the phase of signals is retained and the total fibre length can be sufficiently large. We anticipate that this solution will allow our scheme to reach a time resolution at a level of 1 ps, which is limited by dispersion-induced signal broadening.

6. Conclusions

We have developed an optical gating system ('all-optical gating oscilloscope') for continuously monitoring a complex-shaped periodic optical signal with picosecond resolution using an all-fibre optical gate in the form of a nonlinear loop mirror and a passively mode-locked femtosecond laser. The advantages of the system are the possibility of characterising signals with a very large spectral bandwidth, the possibility of using a gating pulse source with a wavelength falling in the band of the signal under study and its all-fibre design with the use of standard polarisation-maintaining fibres and standard telecom components. We anticipate that it can find wide application in studies of complex-shaped pulse trains containing different timescales and for monitoring the shape of broadband and relatively long pulses, e.g. in chirped pulse amplification systems.

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