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Phase-sensitive optical coherence reflectometer with differential phase-shift keying of probe pulses

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Abstract. **We report a new method for reconstructing the signal shape of the external dynamic perturbations along the entire length of the fibre of an optical coherence reflectometer. The method proposed is based on differential phase-shift keying of a probe pulse and demodulation of scattered light by the phase diversity technique. Possibilities of the method are demonstrated experimentally.**

Keywords: *phase-sensitive reflectometer, optical coherence reflectometer, scattered radiation, differential phase modulation, phase diversity.*

1. Introduction

Optical coherence-domain reflectometry is a widespread method used to detect dynamic perturbations in an optical fibre [1–4]. Despite a considerable interest in this method, caused by the possibility of determining dynamic perturbations along the entire length of an optical fibre, most currently available optical coherence reflectometers allow one to detect the presence and location of perturbations on a particular segment of the fibre and to quantify its value, the type of the perturbation remaining unknown [2–4]. At the same time, demodulation of scattered light of the reflectometer and reconstruction of the signal shape of external perturbations is a key factor necessary for identification of the signal and determination of its source.

For interferometric sensors, the issue of light demodulation is fairly well studied [5–8]. One of the demodulation methods is based on the phase diversity technique (first proposed by Koo et al. [6]) utilising an optical hybrid. This technique is essentially an analogue of the method of quadrature processing of angle-modulated signals, studied in [9]. First, the phase diversity technique was considered by Posey et al. [10] to quantify the strain of a fibre in an optical coherence reflectometer. An extension of this work was paper [11], which demonstrated the reconstruction of the frequency of the dynamic, external perturbation signal. Farhadiroushan et al. [12] showed the possibility of utilising a 3×3 coupler as an optical hybrid for measuring dynamic perturbations in optical coherence reflectometers. The possibility of using the phase diversity technique for signal demodulation in a fibre scattered-light interferometer, which is an integral part of an optical coherence reflectometer, was studied by Alekseev et al. [13, 14] in order to detect the acoustic phase perturbation in an optical fibre and to reconstruct its shape.

In this work, we consider the application of the phase diversity technique in an optical coherence reflectometer, which allows the shape of the external phase perturbation signal to be reconstructed along the entire length of the fibre without the use of an optical hybrid [15]. The phase diversity of received scattered-light signals is achieved by differential phase shift keying (DPSK) of a probe pulse of the reflectometer. Unlike the method utilising the optical hybrid [10–12], the technique described involves the use of only one optical receiver and makes it possible to maximise the received scattered-light signals under the existing constraints on the peak power of the probe pulse, which are caused by nonlinear effects in fibre.

2. Theoretical part

The proposed scheme of an optical coherence reflectometer with DPSK of a probe pulse is shown in Fig. 1.

A detailed description of the experimental setup is given in Section 3. A key element that allows the light scattered by the fibre to be demodulated by the phase diversity technique and the shape of the external perturbation signal to be determined is a phase modulator with DPSK of probe pulses. In the case of phase modulation of consecutive probe pulses, they are conventionally divided into three groups, the pulses being differently phase-modulated in the groups. The first group consisted of probe pulses with ordinal numbers 1, 4, 7, etc.; the second – of pulses with numbers 2, 5, 8, etc.; and the third – of pulses with numbers 3, 6, 9, etc. The first and second groups of probe pulses were phase-modulated in such a way that the optical field in the first half of the pulse was not subjected to phase modulation, whereas the optical field in the second half of the pulse experienced a phase shift by $\delta = +2\pi/3$ for the first group of pulses and by $\delta = -2\pi/3$ for the second group. The third group of probe pulses was not phase-modulated (Fig. 2). Such a phase modulation of the optical field of the probe pulse allowed one to reconstruct completely the function of an optical six-port hybrid [13, 14] and apply the phase diversity technique.

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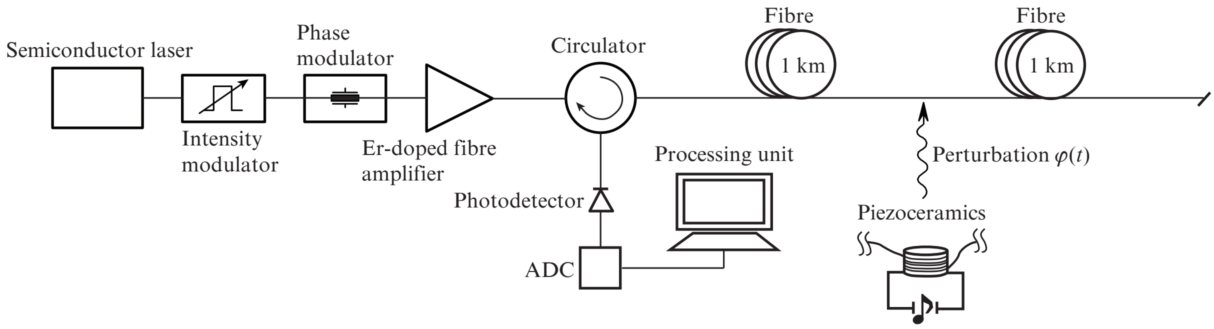

Figure 1. Scheme of an optical coherence reflectometer with DPSK of probe pulses.

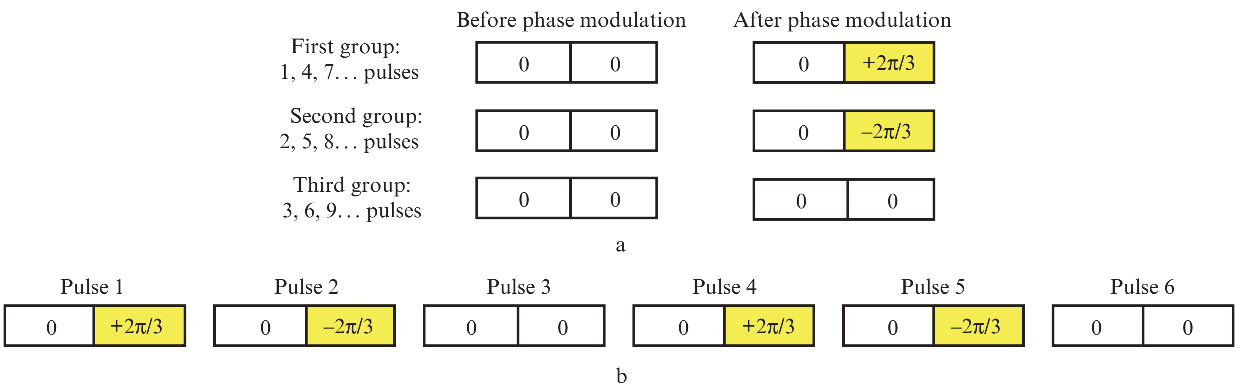

Figure 2. DPSK of the field of optical probe pulses: (a) relative phases of the optical fields of pulses and (b) sequence of optical pulses.

Suppose that at some point O of a fibre segment, the fibre experiences an external phase perturbation $\varphi(t)$, which represents the fibre stretching according to some law. Consider a probe pulse (the optical field of which is modulated in phase by the above method) propagating along the fibre. After some time, this pulse will move to the region of the fibre experiencing an external perturbation. For simplicity, we assume that the spatial extent of this region is much smaller than the spatial extent of the probe pulse, i.e., we shall consider the external perturbation to be point-like. It is worth noting that, because the light pulse propagates, the length of the effective region of the optical fibre, which scatters light and in which the light fields experience interference, is twice less than the spatial extent of the probe pulse. Thus, the fields scattered by a fibre segment, which is located within the half of the spatial extent of the probe pulse, are simultaneously incident on a receiver. Without loss of generality, we assume that the signal scattered by the fibre is measured and digitised only at those instants of time when point O of application of the external perturbation is located at some distance x from the middle of the effective scattering region, which constitutes a half of the spatial extent of the probe pulse (Fig. 3).

Let us divide the effective scattering region into three sections: A, B and C (Fig. 3). Segment A is located before the perturbation point O, and the optical field scattered by this segment has not been phase-modulated by the phase modulator; moreover, the light scattered by this segment has not been subjected to phase modulation due to external perturbations. Segment B is located before the perturbation point O, and the optical field scattered by this segment has been already phase-modulated by the phase modulator so that an additional phase difference between the fields scattered by segments A

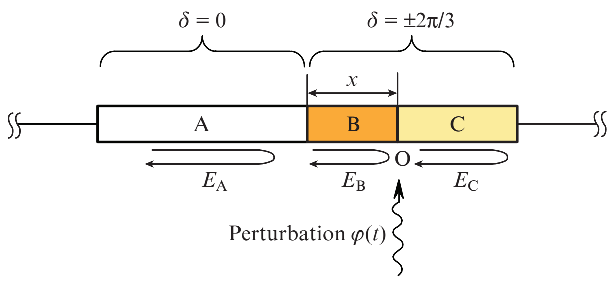

Figure 3. Schematic representation of the effective scattering region.

and B of the fibre amounts to δ, which may be equal to $+2\pi/3$, $-2\pi/3$ or 0 depending on the group of pulses in question: first, second or third. Light scattered by segment B of the fibre has not been subjected to phase modulation due to external perturbations. Segment C is located after the perturbation point O, and the optical field scattered by this segment has also been phase-modulated by the phase modulator so that the additional phase difference of the fields scattered by segments A and C of the fibre amounts to δ as well. Light scattered by segment C has been subjected to phase modulation due to external perturbations in the fibre.

Assuming, for simplicity, the degree of coherence of scattered light to be high and neglecting additional effects of modulation broadening of the spectral band of scattered light, we write the expressions for the complex amplitudes of the fields scattered by segments A, B and C in the form

$$U_A = \boldsymbol{p}_A E_A \exp(i\varphi_A),$$

$$\boldsymbol{U}_{\mathrm{B}} = \boldsymbol{p}_{\mathrm{B}} E_{\mathrm{B}} \exp(\mathrm{i}\varphi_{\mathrm{B}} + \mathrm{i}\delta), \tag{1}$$

$$\boldsymbol{U}_{\mathrm{C}}(t) = \boldsymbol{p}_{\mathrm{C}} E_{\mathrm{C}} \exp[\mathrm{i}\varphi_{\mathrm{C}} + \mathrm{i}k\varphi(t) + \mathrm{i}\delta],$$

where E_{A}, E_{B}, E_{C} are the amplitudes of scattered fields; φ_{A}, φ_{B}, φ_{C} are the phases of scattered fields; $\boldsymbol{p}_{\mathrm{A}}$, $\boldsymbol{p}_{\mathrm{B}}$, $\boldsymbol{p}_{\mathrm{C}}$ are the polarisation vectors; and $k\varphi(t)$ is the signal that is proportional to the external perturbation with the coefficient k. In a simple case, when all the scattered fields have the same polarisation, the resulting complex amplitude of the scattered field will have the form

$$U_{\Sigma} = E_{\mathrm{A}} \exp(\mathrm{i}\varphi_{\mathrm{A}}) + E_{\mathrm{B}} \exp(\mathrm{i}\varphi_{\mathrm{B}} + \mathrm{i}\delta)$$

$$+ E_{\mathrm{C}} \exp[\mathrm{i}\varphi_{\mathrm{C}} + \mathrm{i}k\varphi(t) + \mathrm{i}\delta], \tag{2}$$

where, depending on the group of pulses, $\delta = +2\pi/3, -2\pi/3, 0$.

The scattered light intensity is equal to the product of expression (2) and its complex conjugate value. We will write in the explicit form the expressions for the intensities of light scattered by the pulses of the first, second and third groups:

$$I_{\mathrm{I}} = E_{\mathrm{A}}^2 + E_{\mathrm{B}}^2 + E_{\mathrm{C}}^2 + 2E_{\mathrm{B}}E_{\mathrm{A}}\cos(\varphi_{\mathrm{B}} - \varphi_{\mathrm{A}} + 2\pi/3)$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t) + 2\pi/3]$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{B}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{B}} + k\varphi(t)], \tag{3}$$

$$I_{\mathrm{II}} = E_{\mathrm{A}}^2 + E_{\mathrm{B}}^2 + E_{\mathrm{C}}^2 + 2E_{\mathrm{B}}E_{\mathrm{A}}\cos(\varphi_{\mathrm{B}} - \varphi_{\mathrm{A}} - 2\pi/3)$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t) - 2\pi/3]$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{B}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{B}} + k\varphi(t)], \tag{4}$$

$$I_{\mathrm{III}} = E_{\mathrm{A}}^2 + E_{\mathrm{B}}^2 + E_{\mathrm{C}}^2 + 2E_{\mathrm{B}}E_{\mathrm{A}}\cos(\varphi_{\mathrm{B}} - \varphi_{\mathrm{A}})$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t)]$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{B}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{B}} + k\varphi(t)]. \tag{5}$$

One can see from expressions (3) and (4) that one of the terms in (3), containing a variable component $k\varphi(t)$, is shifted in phase relative to the same term in (4) by $2\pi/3$, which is the main feature of the phase diversity technique. Expressions (3)–(5) also have terms, which contain the variable component $k\varphi(t)$, but do not have an additional phase shift; these terms do not give additional information about the external perturbation signal $k\varphi(t)$, unlike the terms that are shifted relative to each other in phase. It is reasonable to exclude from further analysis the terms, which do not give additional information about the external perturbation; to this end, we consider the sum of expressions (3)–(5):

$$I_{\Sigma} = I_{\mathrm{I}} + I_{\mathrm{II}} + I_{\mathrm{III}} = 3(E_{\mathrm{A}}^2 + E_{\mathrm{B}}^2 + E_{\mathrm{C}}^2)$$

$$+ 6E_{\mathrm{C}}E_{\mathrm{B}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{B}} + k\varphi(t)], \tag{6}$$

where we have used the well-known trigonometric identity

$$\cos(\alpha + 2\pi/3) + \cos(\alpha - 2\pi/3) + \cos\alpha \equiv 0. \tag{7}$$

Subtracting from expressions (3), (4) and (5) expression (6) divided by 3, we obtain

$$I_{\mathrm{I}} - I_{\Sigma}/3 = 2E_{\mathrm{B}}E_{\mathrm{A}}\cos(\varphi_{\mathrm{B}} - \varphi_{\mathrm{A}} + 2\pi/3)$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t) + 2\pi/3], \tag{8}$$

$$I_{\mathrm{II}} - I_{\Sigma}/3 = 2E_{\mathrm{B}}E_{\mathrm{A}}\cos(\varphi_{\mathrm{B}} - \varphi_{\mathrm{A}} - 2\pi/3)$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t) - 2\pi/3], \tag{9}$$

$$I_{\mathrm{III}} - I_{\Sigma}/3 = 2E_{\mathrm{B}}E_{\mathrm{A}}\cos(\varphi_{\mathrm{B}} - \varphi_{\mathrm{A}})$$

$$+ 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t)]. \tag{10}$$

We have excluded from expressions (8)–(10) the terms that do not have an additional phase delay. In these expressions, useful information about the external perturbation is given only by the second term, the first terms, which contain only amplitudes and phases of scattered fields, gradually changing over time under the action of the environment and giving no information about the external perturbation. By assuming that the minimum frequency in the spectrum of the external perturbation signal $\varphi(t)$ exceeds the frequency of temporal fluctuations of amplitudes and phases of the scattered fields, as evidenced by the experimental data, the terms without the variable component can be excluded from expressions (8)–(10) if use is made of a filter of higher frequencies. The terms independent of the external perturbation can be also excluded by appropriately selecting the spatial location of the probe pulse, so that the distance x be equal to zero (see Fig. 3); in this case the factor $E_{\mathrm{B}} = 0$. Moreover, these terms can be eliminated by adjusting the start of DPSK of the second part of probe pulses of each of the three groups.

Excluding from consideration the terms without the variable signal component $k\varphi(t)$, we will write expressions (8)–(10) in the form

$$\tilde{I}_{\mathrm{I}} = 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t) + 2\pi/3], \tag{11}$$

$$\tilde{I}_{\mathrm{II}} = 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t) - 2\pi/3], \tag{12}$$

$$\tilde{I}_{\mathrm{III}} = 2E_{\mathrm{C}}E_{\mathrm{A}}\cos[\varphi_{\mathrm{C}} - \varphi_{\mathrm{A}} + k\varphi(t)]. \tag{13}$$

As can be seen from (11)–(13), for each of the three groups of pulses the external phase perturbation $k\varphi(t)$ causes a nonlinear response of the reflectometer; nevertheless, it can be retrieved using the technique proposed in [6] and developed in [8]. For a fibre scattered-light interferometer, this method is described in [13, 14]. The main idea is to form, from any two signals spaced in phase by $2\pi/3$ [for example, signals (11) and (12)], a signal of the form:

$$S = I^{+}\frac{\mathrm{d}I^{-}}{\mathrm{d}t} - I^{-}\frac{\mathrm{d}I^{+}}{\mathrm{d}t}, \tag{14}$$

where $I^{+} = \tilde{I}_{\mathrm{II}} + \tilde{I}_{\mathrm{I}}$, and $I^{-} = \tilde{I}_{\mathrm{I}} - \tilde{I}_{\mathrm{II}}$. The variable S in this case is proportional to the time derivative of the modulating signal $\mathrm{d}(k\varphi(t))/\mathrm{d}t$, and the integral of it, with the accuracy to a scale factor, is equal to the modulating signal $k\varphi(t)$, i.e., the shape of the perturbation signal is reconstructed. For expression (14) to be applied, the scattered-light signals obtained from the pulses of the first and second groups must be synchronised in time. This can be achieved by processing appropriately the reflectometer signal. This method for selecting the analysed scattered-light signals limits the maximum frequency of the external perturbation signal $\varphi(t)$, which can be detected: this frequency should not, according to the Nyquist criterion, exceed the half of the sampling frequency, which in this case is 1/3 of the repetition rate of probe pulses in the reflectometer.

Forming a combination of equations (11) and (12) in accordance with (14), we obtain

$$I^+ = 4E_A E_C \cos[\varphi_C - \varphi_A + k\varphi(t)]\cos(2\pi/3),$$

$$I^- = 4E_A E_C \sin[\varphi_C - \varphi_A + k\varphi(t)]\sin(2\pi/3),$$

$$\frac{dI^+}{dt} = -4E_A E_C \sin[\varphi_C - \varphi_A + k\varphi(t)]\cos(2\pi/3)\frac{d(k\varphi(t))}{dt},$$

$$\frac{dI^-}{dt} = 4E_A E_C \cos[\varphi_C - \varphi_A + k\varphi(t)]\sin(2\pi/3)\frac{d(k\varphi(t))}{dt}.$$

As a result, for S we have the expression

$$S = 8(E_A E_C)^2 \sin\left(\frac{4\pi}{3}\right)\frac{d(k\varphi(t))}{dt}. \tag{15}$$

Thus, by integrating (15) over time we can obtain the recovered signal

$$\Phi(t) = \int_0^t S dt$$

of the phase perturbation, proportional to $k\varphi(t)$ with the accuracy to a factor, weakly dependent on time.

As seen from expression (15), if the amplitudes of the fields scattered by segment A or C are close to zero, the recovered signal is close to zero; in this case, the recovered signal experiences so-called fading. Note that according to expression (15), for the recovered signal to be more uniform, it can be normalised to a weakly time-dependent factor $(E_A E_C)^2$, which can be obtained from expressions (11)–(13).

3. Experiment

The scheme of the experimental setup corresponded to that shown in Fig. 1. A Rio Orion semiconductor laser (Redfern Integrated Optics Inc.) with a high degree of light coherence (with the spectral bandwidth of 2 kHz) generated cw radiation at a wavelength of 1550.92 nm and a power of 10 dBm. The intensity modulator produced 100-ns rectangular pulses with a rise time of less than 5 ns. Pulsed radiation was coupled into a JDSU phase modulator, which implemented DPSK of probe pulses by the method described in the theoretical part. The duration of the front of phase switching was 2 ns. Amplitude- and phase-modulated optical radiation was amplified by an erbium-doped fibre amplifier to a power having a peak value of 25 dBm; then, using a circulator radiation was coupled into a 2-km-long optical fibre under test. Optical radiation scattered by the fibre was coupled out of the fibre using the same circulator and fed to a 50-MHz photodetector. The signal from the photodetector was either fed to a digital oscilloscope or to an ADC coupled to the personal computer processing the signal.

The external phase perturbation was modelled by feeding a low-frequency signal of harmonic or triangular shape from a Tektronix AFG3021B generator to a piezoceramic cylinder with a fibre of length of about 30 cm wound around it, which was located at a distance of 1 km from the beginning of the fibre. The received signal was processed by separating (in accordance with the previously described procedure) successive scattered-light signals into three groups; then, the signals generated by these groups were synchronised in time and used to extract the external perturbation signal by the methods discussed above.

The three groups of successive probe pulses with a positive relative phase shift of the field in the half of the pulse ($\delta = +2\pi/3$), with a negative relative phase shift of the field in the half of the pulse ($\delta = -2\pi/3$) and without a phase shift of the field in the pulse resulted in the appearance of three different successive reflectograms. Figure 4 shows the reflectograms recorded using an Agilent MSO7104A oscilloscope with 4-GHz sampling rate.

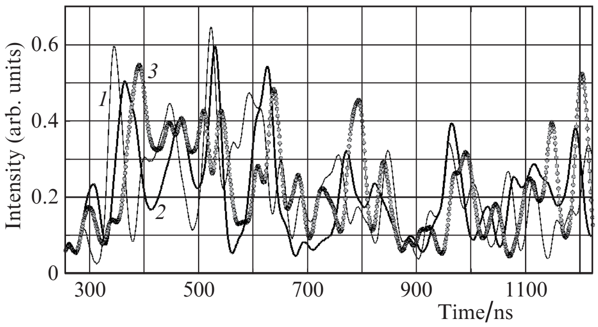

Figure 4. Reflectograms for groups of pulses with δ = (*1*) $+2\pi/3$, (*2*) $-2\pi/3$ and (*3*) 0. Region near t = 880 ns corresponds to the fading region.

The reflectograms for the three groups of probe pulses differ due to different phase ratios of the interfering fields of scattered light. One can see from Fig. 4 that near t = 880 ns, all the three reflectograms have a small intensity; this region can be classified as a low-sensitivity region of the reflectometer, or fading, occurring due to the smallness of the $(E_A E_C)^2$ value in expression (15).

The experimental dependences of the signals scattered by the region subjected to the external phase perturbation are shown in Figs 5a and 5b for the first and second groups of the pulses. The external perturbation was modelled using a fibre wound around the piezoceramic cylinder, to which harmonic voltage with a frequency of 100 Hz and phase modulation index equal to 3 was applied. The recovered signal of the external perturbation is shown in Fig. 5c; in this case, it completely repeats the initial signal.

The experimental dependences of the signals scattered by the region subjected to the external phase perturbation are shown in Figs 6a and 6b for the first and second groups of pulses when a triangular signal with a frequency of 100 Hz and phase modulation index equal to 3 is applied to the piezoceramic cylinder. The recovered signal of the external perturbation is shown in Fig. 6c. As in the first case, it completely repeats the initial signal.

Thus, DPSK of the probe pulse of an optical coherence reflectometer and the use of the phase diversity technique allow one to reconstruct the shape of the external phase per-

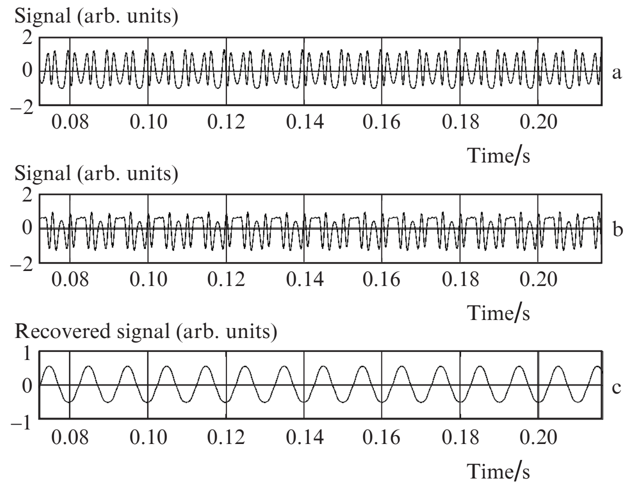

Figure 5. Experimental time dependences of the scattering signals for (a) first and (b) second pulse groups, when external harmonic voltage with a frequency of 100 Hz and modulation index 3 is applied to the piezoceramic modulator, as well as (c) signal reconstructed by the phase diversity technique.

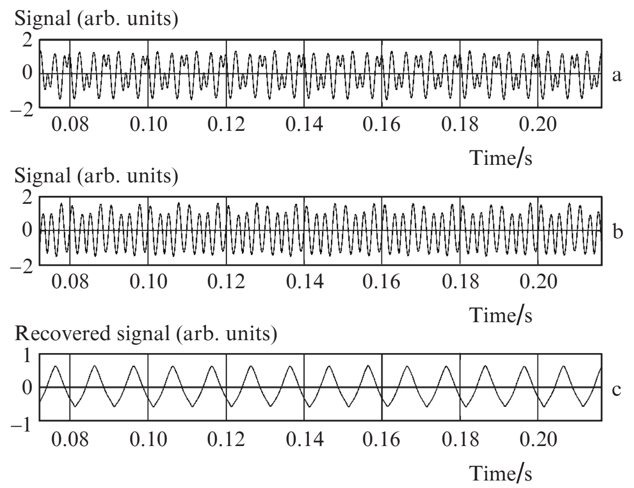

Figure 6. Same as in Fig. 5, but when external voltage of triangular shape with a frequency of 100 Hz and modulation index 3 is applied to the piezoceramic modulator.

turbation signal in optical fibre with the accuracy to a scale factor.

4. Conclusions

We have considered an optical coherence phase-sensitive reflectometer capable of reconstructing the shape of the external phase perturbation signal. The main feature of the scheme proposed is the use of DPSK of probe pulses, which allows for demodulation of scattered-light signals by the phase diversity technique. The advantage of this scheme consists in the fact that it makes it possible not to use an optical hybrid and three photodetectors recording phase-spaced scattered-light signals. Thus, this scheme provides a higher signal/noise ratio at the photodetector output at an equal peak power of pulsed radiation coupled into the optical fibre.

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