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Coherent reflectometer with a two-fibre scattered-light interferometer

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Abstract. **We have designed and implemented a new fibre-optic phase-sensitive coherent reflectometer configuration, which allows one to avoid signal fading owing to the use of a two-fibre scattered-light interferometer.**

Keywords: *coherent optical reflectometer, two-fibre interferometer, scattered light, signal fading.*

1. Introduction

Coherent optical reflectometers were first proposed as a basis for distributed sensors of various physical variables in the early 1990s [1, 2], but the performance of such systems has only recently been brought to a level attractive for, e.g., intrusion sensing systems owing to advances in the technology of fibreoptic amplifiers [3, 4]. There is particular interest in optical time-domain reflectometers (OTDRs), which allow one to easily obtain a spatial resolution of several metres at a sensing element length limited by optical losses in the fibre and reaching tens of kilometres. One important feature of coherent OTDRs is that each point of a reflectogram corresponds to a pulse-duration-limited portion of the fibre and that the cross talk between neighbouring information channels can be left out of consideration. Numerical simulation indicates, however, that a weak point action on a sensing element may lead to both weakly distorted and considerably nonlinearly distorted output signals. This depends on the position of the working point of a virtual interferometer in its transformation function (modulation characteristic). The transformation function is harmonic in itself, but the transformation coefficient in a linear portion has a random value, down to zero. Therefore, a sensing element may have insensitive parts (signal fading), which is undesirable for intrusion sensing systems. A natural way to prevent this effect is to change the laser source frequency, but this would add complexity to both apparatus and action identification algorithms.

In this paper, we propose combining a coherent reflectometer with a two-fibre scattered-light interferometer. An action on one of the optical fibres should cause a phase shift in all the subsequent measurement channels along the fibre length. Even if the response at the point of action will be zero, the action will be identified in most of the subsequent channels. The point of action can be found with an uncertainty of one resolution cell, which is immaterial for most applications.

2. Model for scattered signal formation

To analyse coherent light pulse scattering signals, we use a mathematical model in which an optical fibre is represented by a set of scattering centres evenly distributed along the z axis, with coordinates z_n. Polarisation effects are left out of consideration. To obtain random phases of scattered light, we introduce small (comparable to the light wavelength) random variations in the position of the centres. The field backscattered by one fibre can be described by the complex amplitude

$$E_j = \sum_{n=j}^{j+k} A_n e^{-2i\beta z_n}, \qquad (1)$$

where A_n is the amplitude of the wave scattered by the nth centre; β is the longitudinal propagation constant; j is the number of a point in the reflectogram; and k is the spatial extent of the probe pulse (the number of simultaneously scattering centres).

The backscattered intensity is given by

$$I_j = E_j E_j^*. \qquad (2)$$

If there is no external influence on the phase of the light, the complex amplitude of the field scattered by the other fibre is

$$E_j' = \sum_{n=j}^{j+k} A_n e^{-2i\beta z'_n}, \qquad (3)$$

where z'_n are the coordinates of the scattering centres in this fibre. The waves from the two fibres combine to give an interference pattern described by

$$I_j = (E_j + E_j')(E_j + E_j')^*. \qquad (4)$$

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This relation clearly describes a rugged reflectogram typical of coherent pulsed reflectometers [3, 4].

To model a point phase action on the second fibre, all the coordinates of the scattering centres in (3) and (4) are shifted by Δz along the z axis starting at a point of action with $n > n_0$:

$$E_j' = \sum_{n=j}^{j+k} A_n \mathrm{e}^{-2\mathrm{i}\beta(z_n' + \Delta z)}. \quad (5)$$

Figure 1 shows the response of a scattered-light interferometer, I_m, in a distance channel with a point $j > n_0$ to a combination of two actions, one linear, slowly varying (imitating a temperature drift of the interferometer), and the other harmonic, with an amplitude a factor of 4 smaller than the light wavelength in the fibre, λ:

$$\Delta z_m = km + \frac{\lambda}{4}\cos\Omega m. \quad (6)$$

Here, m is the number of realisation (reflectogram), which has the meaning of time at a constant repetition rate of probe pulses, and k and Ω describe the rate of the phase change from one reflectogram to another.

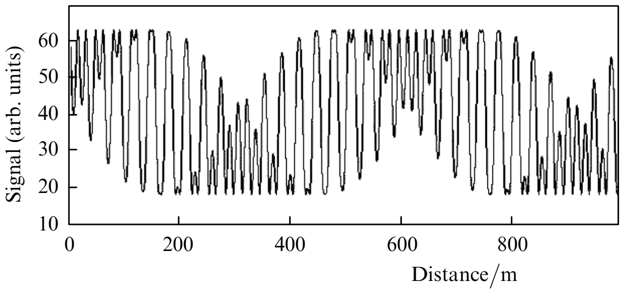

Figure 1. Interferometer response to an action represented by function (6).

Similar signals are generated in all the distance channels behind the point of action. This rules out a situation where an 'insensitive' channel is acted upon and the action remains undetected.

3. Experimental

A schematic of the experimental setup is shown in Fig. 2. The coherent reflectometer [4] comprises a pulsed semiconductor laser (*1*), fibre amplifier (*2*), fibre circulator (*3*) and InGaAs PIN photodiode (*4*). The laser wavelength is 1550 nm, and the pulse duration is 100 ns FWHM, with a repetition rate of 1 kHz and a pulse power of 1 W. The reflectometer output is divided into two components by a 50/50 coupler (*5*), which are then launched into SMF-28 single-mode fibre coils 4.5 (*6*) and 19 km (*8*) in length. The backscattered light interferes in the coupler (*5*) and passes through the circulator (*3*) to the photodetector (*4*) of the reflectometer. One arm of the resultant interferometer contains a piezoceramic phase modulator (*7*) connected to an acoustic generator. The photodetector signal was digitised using an A-to-D card with a sampling rate of 20 MHz. To analyse signals, we designed an appropriate graphical shell which allowed us to detect and record both

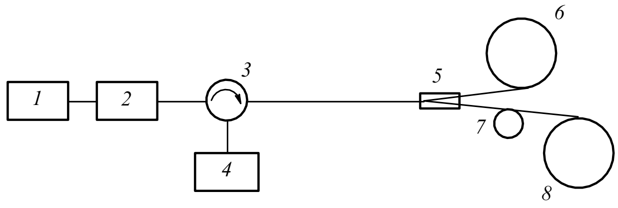

Figure 2. Schematic of the experimental setup.

signals and their time dependences at particular points along the reflectogram (in different distance channels) in the oscilloscope mode.

A typical signal at the photodiode input is displayed in Fig. 3 (one reflectogram). The signals obtained at distances within 4.5 km, where the waves scattered in the two arms interfered, were qualitatively similar to those at longer distances (except for the natural drop in the signal amplitude). 50-Hz phase modulation had no effect on the signal detected at distances longer than 4.5 km, as in an earlier study [4].

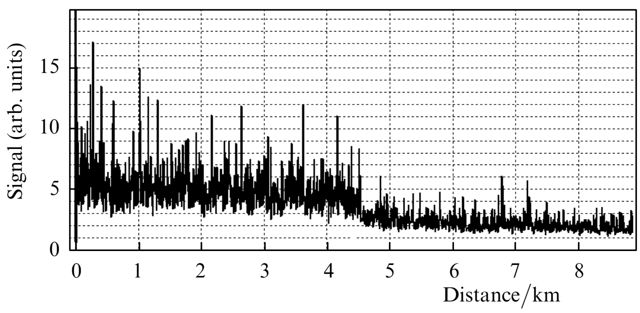

Figure 3. Backscattering signal.

In contrast, between the phase modulator and the point at a distance of 4.5 km we observed changes in signal in all the distance channels, attributable to the 50-Hz modulation. The time dependence of the output signal for one distance channel from one realisation to another demonstrates that the signal varies in amplitude and shape and is superimposed over the slowly varying signal arising from the temperature drift of the two-arm interferometer due to the spatial separation between the coils in the laboratory. Figure 4 shows the time dependence of the signal for the point 420 m from the circulator at a phase modulation depth of $\pm 90^{\circ}$. Because of the drift, the working point gradually shifts from the linear portion of the characteristic, where the harmonic signal has a frequency of 50 Hz, to a nonlinear portion, where the second harmonic emerges. Clearly, there is no fundamental distinction between the measured signal and the simulated signal in Fig. 1. These results lead us to conclude that action parameters (frequency, phase, amplitude and site) can be determined with sufficient accuracy using appropriate algorithms, which are beyond the framework of this paper. Moreover, if the number of actions is not very small, joint analysis of the information from the subsequent distance channels may provide more accurate information about the action in comparison with the single-fibre coherent reflectometer reported by Gorshkov et al. [4]. In addition, at a large number of distance channels, at least one of them will have weakly distorted, complex-shaped signals, including those

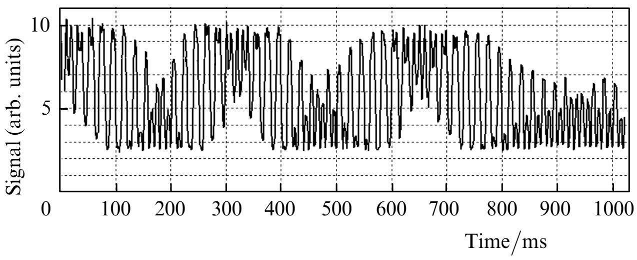

Figure 4. Time dependence of the signal in the 420-m distance channel with 50-Hz phase modulation.

arising from a shock wave. Various criteria can be proposed for selecting an undistorted signal, e.g. through identification of higher harmonics.

One drawback to the coherent two-arm interferometer under discussion (as a basis for intrusion sensing systems) is the above-mentioned temperature drift, which restricts the monitored length. This is illustrated in Fig. 5 by the signal measured in the 4200-m distance channel with no phase modulation, which is thus only due to the temperature drift. A useful signal, if present, would be extremely difficult to separate from this background.

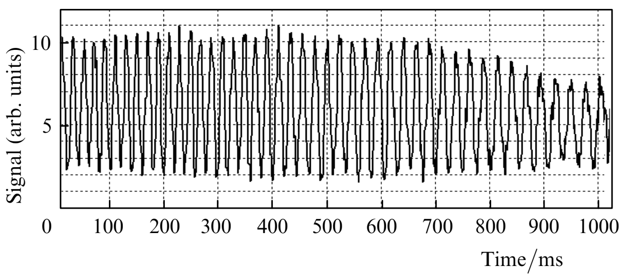

Figure 5. Time dependence of the signal in the 4200-m distance channel with no phase modulation.

Here, we cannot specify the maximum length of fibreoptic sensing elements for practical applications because it depends to a significant degree on the configuration and location of the optical cable. In particular, we expect that combining two fibres in a single cable and laying it at a depth of 0.5 – 1 m would enable multikilometre lengths to be dealt with. It should further be noted that, when the monitored length is limited to several kilometres, one can raise the probe pulse repetition rate to tens of kilohertz and detect the action at higher frequencies in comparison with this study. The temperature drift will then have a weaker limiting effect on the acceptable sensing element length.

Thus, the proposed two-fibre phase-sensitive coherent reflectometer design allows one to avoid signal fading and build a distributed interference sensor system ideally suited for perimeter security systems.

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