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Distributed external-action sensor based on a phase-sensitive fibre reflectometer

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Abstract. **A model of a sensor of an external action on a fibreoptic cable used in extended-perimeter security systems with localisation of the action site is developed. The detection principle is based on phase-sensitive reflectometry with the use of a narrowband pulsed radiation source. The model has a high sensitivity inherent in interference sensors. The maximum detection range and spatial resolution are 35 km and 5 m, respectively.**

Keywords: *fibreoptic cable, security systems, phase-sensitive reflectometry.*

1. Introduction

Pulsed fibre reflectometers, or OTDR devices, are one of the most widespread types of instruments for measuring parameters of optical fibres. Their operation principle is rather simple. A light pulse is coupled through a coupler into an optical fibre. During the pulse propagation in the fibre, a part of radiation experience Rayleigh scattering in the backward direction. By measuring through the coupler the time dependence of the backscattered radiation power, one can easily determine the law of power variation along the fibre length. This makes it possible to measure the distribution of losses over the fibre length and, in particular, to localise possible defects. By separating individual spectral components from the scattering spectrum, for example, spontaneous Raman scattering, it is possible to use a reflectometer as a distributed temperature sensor [1].

Radiation sources used in reflectometry are, as a rule, semiconductor lasers emitting at many longitudinal modes. The laser linewidth can be a few nanometres, or a few hundreds of gigagahertz. For this reason, the coherence length of laser radiation is ~ 1 mm, which virtually excludes interference effects during the propagation of radiation in a fibre. An increase in the coherence length causes the appearance of the characteristic noise of a reflectogram deteriorating the metrological parameters of the device. At the same time, modern semiconductor lasers can operate in the single-frequency regime, when the laser linewidth is $10^5 - 10^6$ Hz, which corresponds to the coherence length achieving tens and hundreds of metres. In this case, the chaotic interference of radiation scattered by different parts of the fibre can appear, which opens up new possibilities for applications of reflectometers. Thus, it was proposed [2, 3] to use such reflectometers as sensors of external mechanical perturbations. Their obvious advantages are a relatively high sensitivity caused by the interference mechanism of the response and the possibility of spatial localisation of action due to the reflectometric measurement principle, which suggests that they can find wide applications in security alarm systems. However, the authors of [2, 3] have failed to obtain the adequate contrast of the interference signal and good spatial resolution.

The aim of this paper was to fabricate a pulsed coherent radiation source with spectral, temporal, and energy parameters satisfying the requirements imposed on a radiation source used in a distributed fibreoptic sensor of mechanical perturbations and to demonstrate the possibilities of this sensor by the example of the model developed.

2. Pulsed narrowband radiation source

One of the key elements of a phase-sensitive reflectometer is a pulsed radiation source with a high degree of coherence. In papers mentioned above, a single-frequency erbium-doped fibre laser with an external modulator was used. Such a laser emits the line of width ~ 10 kHz; however, the integral electrooptical modulator used in [2, 3] to obtain pulsed radiation had a low contrast (20 dB). This gave rise to a strong background illumination, which was accumulated in the intervals between pulses, resulting in a low visibility of the interference pattern in the reflectometer.

We used a narrowband radiation source based on a semiconductor laser with selection of longitudinal modes, which was achieved by using a photoinduced fibre Bragg grating (FBG) [4]. Figure 1 presents a simplified scheme of the radiation source. Its cw emission spectrum was studied with a fibre scanning interferometer with the 40-MHz free spectral range. The laser linewidth in the cw regime was estimated as 1.6 MHz. To obtain pulsed lasing, a scheme based on passing a current pulse through the laser in the presence of a small constant bias was developed and fabricated. The scheme included a thermostat for temperature tuning the mode of the Fabry–Perot resonator of a

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semiconductor crystal to the maximum of the FBG reflection spectrum. In addition, the constant bias and pulsed current amplitude could be varied. Special attention was given to the current pulse shape. To prevent the distortion of the lasing spectrum, pump regimes were selected to provide the smooth bell-shaped pulse of duration $\sim$ 50 ns. The pulse repetition period could be changed by varying the frequency of a control signal applied to the semiconductor laser and was usually 1 ms.

The output pulsed power of the semiconductor laser was $\sim$ 1 mW, which is not sufficient for reflectometry. Because of this, a two-cascade erbium-doped fibre amplifier was used to amplify optical signals in the region between 1.53 and 1.6 μm. The hybrid radiation source and amplifier were decoupled with the help of a two-step optical isolator. The total gain of the two cascades was about 30 dB. Amplified spontaneous emission was suppressed by placing between amplifying cascades a fibre circulator with a FBG whose resonance coincided with the reflection wavelength of the stabilising grating of the hybrid source. Figure 2 presents the spectrum of the amplified pulsed signal measured with a resolution of 0.01 nm. The width of the emission spectrum at the -3-dB level does not exceed the resolution of a spectrum analyser used in experiments, and the output pulse power is $\sim$ 1 W.

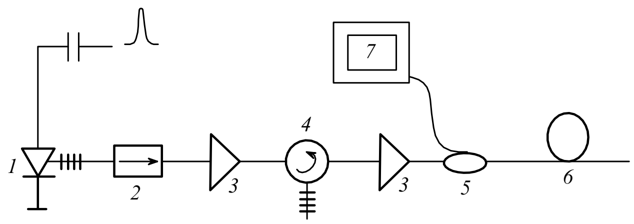

Figure 1. Simplified scheme of the sensor model: (*1*) semiconductor laser with an external FBG; (*2*) optical isolator; (*3*) erbium-doped fibre amplifier; (*4*) FBG circulator; (*5*) coupler; (*6*) fibreoptic line; (*7*) unit for detection and processing of scattered radiation.

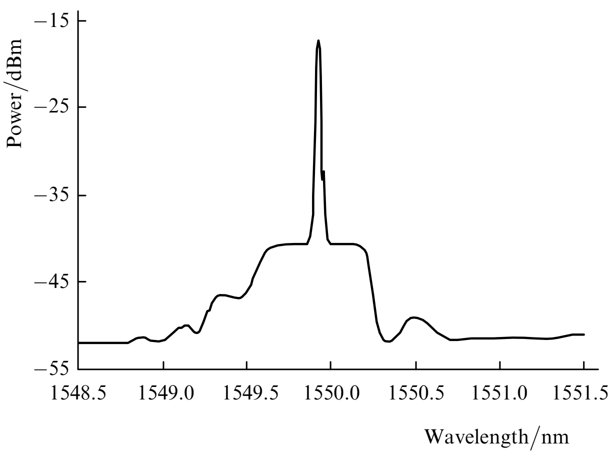

Figure 2. Amplified emission spectrum of the pulsed hybrid radiation source.

3. Measurement of coherent scattering

To test a fibreoptic line, we used a standard single-mode SMF-28 fibre of length 50 km. The scattered signal was detected with a 12-digit analog-to-digit converter with a digitisation rate of 20 MHz. Figure 3 shows the reflectogram obtained from the first three kilometres of the fibre length. The presence of almost 100 % noise-like modulation suggests that the laser linewidth is determined by the pulse duration, i.e. the laser emits at a single frequency. The signal decays slowly along the fibre length, which is consistent with the rating decay of 0.19 dB km^{-1}. Note that the observed pattern is not stable in time. The 'dark' and 'light' bands interchange for the time of the order of a few seconds, which is caused by a slow change in the fibre temperature and drift of the radiation source frequency. At the same time, local acoustic, mechanical, thermal and other perturbations cause a considerably faster modulation of the radiation intensity scattered in the given fibre piece. This makes it possible to determine the coordinates of the perturbed region by knowing the delay between the probe pulse and the instant of appearance of the rapid modulation.

To determine the coordinate of an external perturbation (mechanical or thermal), the entire fibre line was divided into independent channels (up to 7000 channels), and in each of them the signal amplitude was measured with the specified digitisation in the millisecond range and the obtained information was digitally processed. The criterion for the presence of the external action was a considerable change in the signal amplitude in a spatial channel during the time 1 – 50 ms.

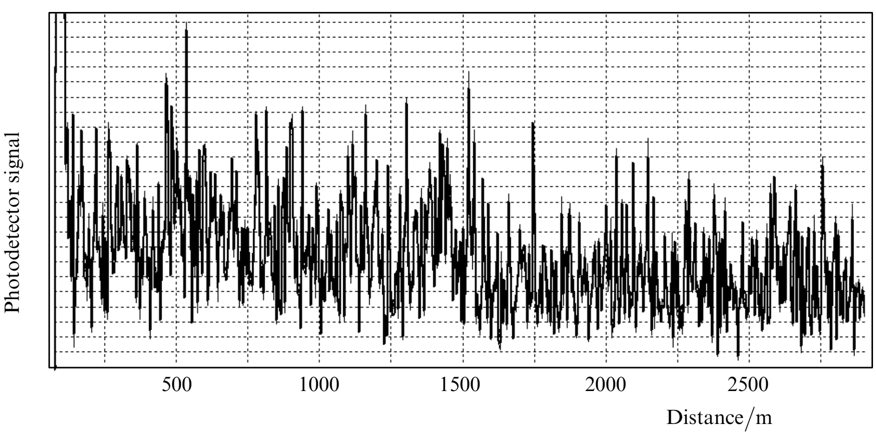

Figure 3. Reflectogram of the signal of scattering by the first three kilometres of the fibre of length 50 km.

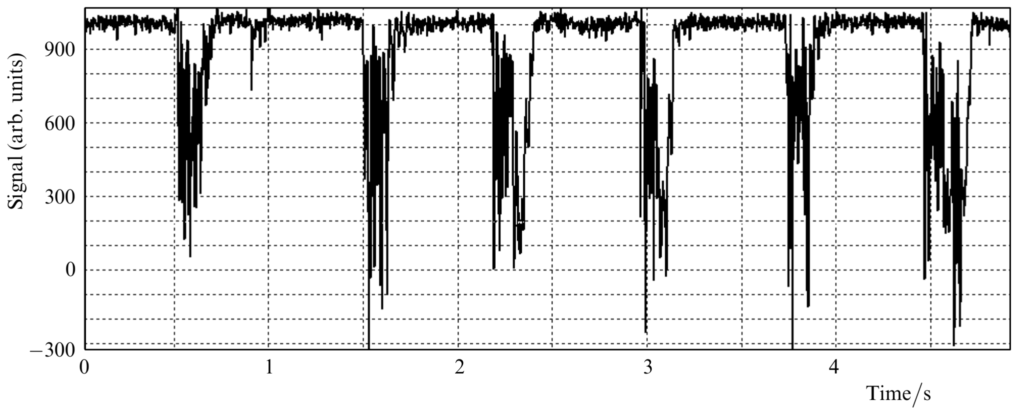

Figure 4. Signal (time scan) of mechanical perturbations caused by excavation and earth moving performed at a distance of 2 m from the optical cable.

The spatial resolution of the sensor is determined by the light pulse duration and is ~ 5 m. The detection range is limited by the optical signal decay. Note that an increase in the pump power does not result in an increase in the detection range due to the appearance of nonlinear effects. Thus, parametric effects cause the transfer of the signal radiation to other spectral components, which is equivalent to the appearance of nonlinear optical losses at the given wavelength. The maximum detection range of the action on a fibre was estimated as 35 km.

4. Study of the sensor model

The operation of the sensor model developed in the paper was studied by using an OKL-0.22 optical cable as a sensitive element. The cable of diameter 14 mm had a metal sheath. The cable of length 3 km was dug into the earth at a depth of 0.5 m. Figure 4 shows the signal from the measured part of the cable located at a distance of 2800 m. At a distance of 2 m from the buried cable, the earth was dug out manually with a shovel. Signals obtained from the adjacent parts of the cable (at 2795 and 2805 m) did not reveal any features of mechanical action on the earth. This suggests that the spatial resolution of the sensor is 5 m. The observed noise level allows us to estimate the interference sensitivity of the sensor as 0.1 rad. We developed simplest algorithms for the automatic determination of the site of action exceeding the specified sensitivity level. The system can detect the steps of a human on the earth surface over the cable.

An interesting result was obtained with a cable located on the support of an electric supply line. We found that not only the attempt of a human to climb in the support but also the vibrations of the support can be easily detected. This suggests that the reflectometer can be used not only in security systems but also for detecting vibrations of buildings and various constructions.

5. Conclusions

We have fabricated a single-frequency pulsed radiation source emitting 50-ns, 1-W pulses. By using this source in the reflectometer, we observed the high-contrast interference signal in backscattered radiation. The reflectometer has been used in the model system for detecting the external action on a long fibreoptic cable for security systems. The model has the following parameters:

(i) The spatial resolution is 5 m;
(ii) the detection range without an amplifier is 35 km;
(iii) the number of independent spatial measurement channels is up to 7000;
(iv) the time resolution in each channel is 1 ms;
(v) the interference sensitivity is ~ 0.1 rad.

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References

1. Gorshkov B.G., Gorbatov I.E., Danileiko Yu.K., Sidorin A.V. *Kvantovaya Elektron.*, **17**, 345 (1990) [*Sov. J. Quantum Electron.*, **20**, 283 (1990)].
2. Choi K.N., Juarez J.C., Taylor H.F. *Proc. SPIE Int. Soc. Opt. Eng.*, **5090**, 134 (2003).
3. Juarez J.C., Taylor H.F. *Proc. Optical Fiber Commun. Conf. OFC'2005* (New York: OSA, 2005) p. OThX 5.
4. Archambbault J.-L., Grubb S.G. *J. Lightwave Technol.*, **15** (8), 1378 (1997).