Anisotropic optical fiber in distributed acoustic sensing

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ABSTRACT

This work presents one of the ways to use anisotropic optical fiber as a sensing element in distributed acoustic sensing. Unique features of the created setup are based on the ability the probe the sensing element with a pulse of ligth from both of its sides in opposite directions and polarization axes continuously, without the reconnection or movement of the interrogator. A hypothesis under investigation was the opportunity to enhance the resolution of the multiple close events on the fiber with the proposed sensing element construction. Initial tests have been carried out under static events, e.g. inducted losses. Though the method is theoretically not limited by this type of anisotropic optical fiber, the present research includes the data obtained only with the "Panda" fiber. We believe the setup can be a more comfortable analog to the two-way trace analysis in a bunch of distributed acoustic sensors' applications. Higher losses of anisotropic fiber, comparing to the SMF-28, for example and higher price of the whole setup turn out to be its main disadvantages. Despite the fact that current report is based on the setup interaction with optical time-domain reflectometer, the crucial aim of the research is its application in coherent distributed optical sensing system, like the one for agriculture and biological purposes proposed before.

Keywords: Rayleigh backscattering, acoustic vibrations, DAS, anisotropic optical fiber

1. INTRODUCTION

The functioning of a distributed acoustic sensor is often based on the technology of coherent time-domain reflectometry.[1] However, it can also work when using a laser with a small coherence length, that is, using common-known time-domain reflectometry (OTDR), which will further reduce the cost and complexity of the finished device. None of the proposed technologies is perfect, and, among others, they are limited to varying degrees by such phenomenons as, for example, a spatial resolution of at least half the pulse length[2] or event dead zones. The first problem is that, because the momentum is not infinitesimal, it is impossible to resolve two separate events within its length, nor to locate an event with an accuracy greater than half its length. The second problem is that, especially in the presence of a reflective inhomogeneity, it is impossible to distinguish between two separate events, not only because of the pulse length, but also because after a bright event, the photodetector, as a rule, does not immediately completely restore its sensitivity, and also due to the fact that the pulse is not perfectly rectangular. This results in the less reflective or absorbing event being lost in the tail trailing the brighter event. In OTDR technology, the problem of event dead zones can be solved with the help of two-way trace analysis. After all, it can be seen, the dead zone is located mainly behind the event, therefore, if a pulse is injected into the fiber from the opposite side, then the dead zone on such a reflectogram will be opposite. But in order to realize the advantages of two-way analysis of traces, it is necessary to have access to both ends of the fiber under study, which is far from always possible or convenient, especially, for example, if the fiber communication line or fiber optic sensing element has already been mounted or installed inappropriately.

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2. SETUP CONSTRUCTION

To solve the problem of dead zones and access to the two ends of the fiber, mainly in the design of the proposed distributed acoustic sensor,[3] it is proposed to refine its design in terms of the sensing element. So, instead of a standard single-mode fiber, it is supposed to use an anisotropic optical fiber of the "Panda" type, which provides a sufficiently independent propagation of 2 polarization modes,[4] a fiber polarizer and a polarization beam splitter (PBS) (Figure 1).

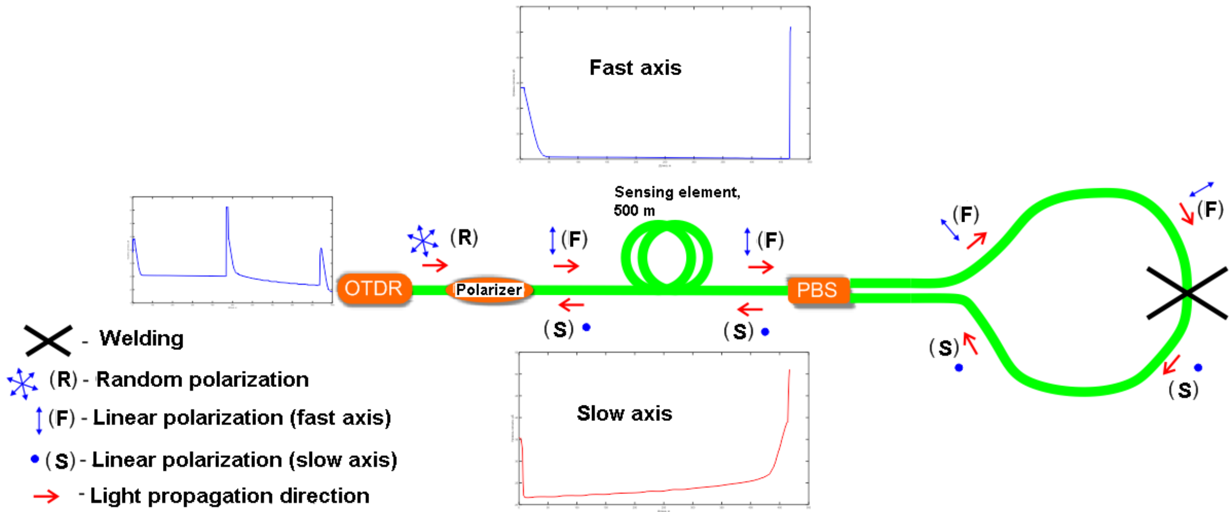

Figure 1. Suggested improvements to the distributed acoustic sensor

The presented optical scheme is arranged and operates as follows: a laser pulse emitted by a reflectometer or a unit consisting of a pulsed laser (a continuous laser and a modulator), an amplifier, a circulator (splitter) and a photodetector, and having a random polarization, passing through the polarizer acquires linear polarization. The output of the polarizer and one of the ends of the sensing element are welded in such a way that the light coming out of it almost completely enters only one of the polarization axes of the fiber in the sensing element (fast). The other end of the sensing element is welded to the PBS inlet. By the time the light pulse reaches the PBS, the interrogator will have acquired a reflectogram for the fast polarization axis. Because the pulse is linearly polarized and propagates along the fast axis of the anisotropic fiber, the PBS will send it to whichever of its two outputs matches that polarization. The second PBS outlet is welded to the first in such a way that the light from the first one completely enters the second one. Thus, the pulse again returns to the divider, but already through the output corresponding to the slow axis, therefore, it is also transferred to the anisotropic sensitive element in the slow axis (polarization is orthogonal to the original one). At the same time, it continues to dissipate part of its power in the direction opposite to the direction of propagation, and this signal continues to travel all the way through the optical scheme in the opposite direction, but since it travels from the PBS to the data acquisition device in the fast polarization axis (and the signal is received only from it due to the polarizer at the input), then the pulse propagating in the slow axis does not have a significant effect on it. When the pulse in the slow axis reaches the polarizer at the input of the circuit, its residual power will be absorbed and / or scattered by it, since by this moment it will have a polarization orthogonal to that which passes the polarizer. The data acquisition device will record the reflectogram of the second polarization axis of the anisotropic sensitive element, obtained, in fact, from its other end. Thus, it is possible to analyze two-way reflectograms without physical access to both ends of the sensitive element (Figure 2).

3. HYPOTHESIS INVESTIGATION

In addition to trying to solve the problem of the event dead zones, it was decided to test the hypothesis that the configuration of the sensing element used can better distinguish between closely spaced events.[5] To do this,

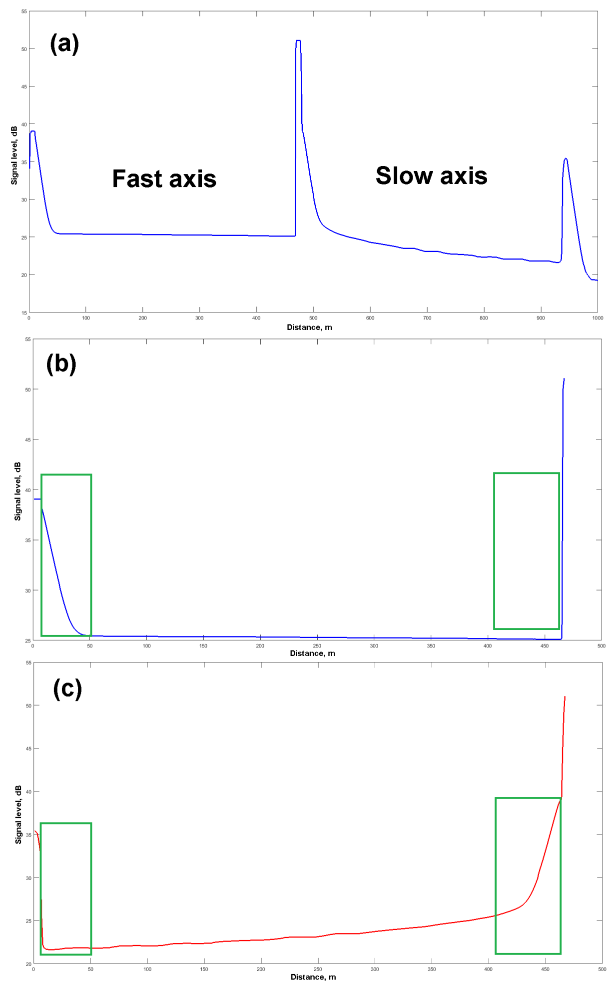

Figure 2. (a) the data as received before processing; (b), (c), fast and slow axes, respectively, oriented correctly relative to the beginning of an anisotropic optical fiber. Green indicates the areas in which the decrease in dead zones is most clearly visible.

far from the ends of the sensitive element, two sections of significant losses were created using loops of small radius, which were then shifted towards each other. For each distance between losses, reflectograms of both polarization axes were recorded using a Yokogawa AQ7280 OTDR reflectometer with a pulse duration of 100 ns, averaging over 10 s, and a wavelength of 1550 nm. The dynamic range of the reflectometer reaches 50 dB, which is quite important when using the technological ends of a special anisotropic fiber as a sensitive element, since the losses in them are higher than, for example, in the standard SMF-28 single-mode fiber used earlier. When processing the obtained data, the reflectograms were mutually oriented relative to the origin of coordinates as in Figures 2 (b), (c), and only the area of interest was selected for further processing. For each reflectogram, the first derivative was found. In view of the fact that in some cases they contained significant noise components, they were further approximated by the spline method. The values of the approximated derivative of the second function were additionally inverted so that the induced losses corresponded to a decrease in the derivative in the same way as for the first trace (on the second trace, the losses formally decrease with increasing distance from the origin). Then, for the found approximations of the derivatives, the cross-correlation coefficient according to Pearson with a sliding window was calculated. In each window, the minimum and maximum of each function were calculated, and the correlation coefficient in each window was multiplied by the following expression, also calculated for each window.

$$(Y(i)_{1max} - Y(i)_{1min})(Y(i)_{2max} - Y(i)_{2min}) \,, \tag{1}$$

where $Y(i)_{1min}$ is minimum of the approximate derivative of the first trace in the i-th window, $Y(i)_{1max}$ is its maximum there, $Y(i)_{2min}$ is minimum of the approximate derivative of the second trace in the i-th window, $Y(i)_{1max}$ is its maximum.

This is necessary in order to avoid large correlation values in those cases when both derivatives change in a similar way within the window, but within insignificant limits. Since in this study it was the significant positive correlation of two derived reflectograms that was of interest, and their negative relationship did not carry significant information, the negative correlation coefficients were equated to zero. Then, the set of cross-correlation coefficients found for a specific window value was normalized, and the operations were repeated for a different window value in the range from 2 to 50 counts. Based on the data obtained, a pseudo-three-dimensional dependence of the correlation coefficient on the distance and window size was built (the so-called "heat map"). On the heat map, the window value that best reflected the location and magnitude of induced losses was found, and for it the dependence of the normalized correlation coefficient on the distance was plotted, as well as the normalized reflectograms of both axes, their derivatives and approximations of the derivatives. The results obtained are shown in Figure 3.

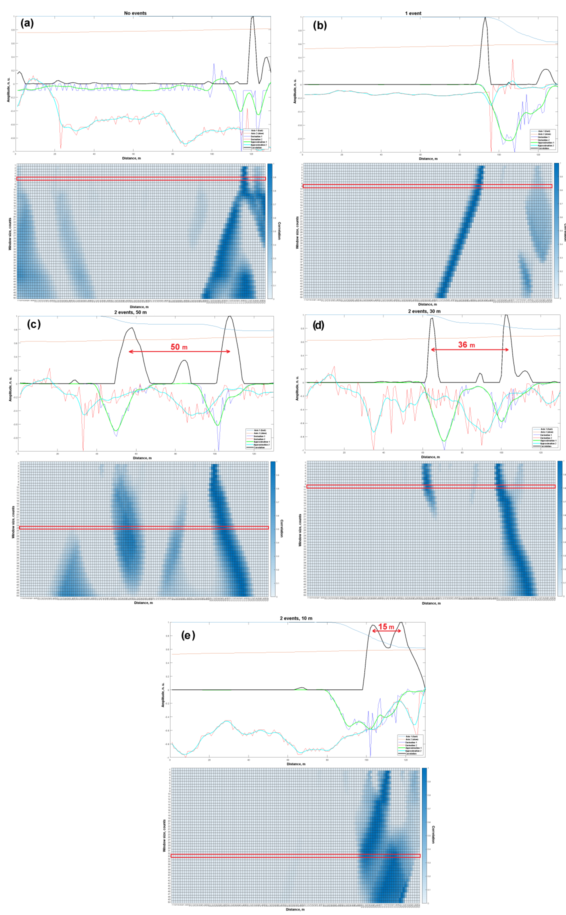

Figure 3. Heat maps and reflectograms with derivatives, approximations and correlation coefficients. (a) – without impacts; (b) - 1 impact; (c) - 2 impacts with a gap of 50 m, (d) - with a gap of 30 m, (e) - with a gap of 10 m. The area corresponding to the value of the window for which the sections were plotted is highlighted in red on the heat map.

4. RESULTS AND DISCUSSION

It can be noted that not all distances between events calculated in this way correspond to the real ones, however, this error is contributed not only by the limitations of the data acquisition technology and the processing methods used, but also by the fact that the actual distances were calculated approximately, using the known number of turns per spool and spool diameter. However, when the distance between events becomes equal to the pulse duration, it becomes almost impossible to resolve them. The location of the events, as already noted, is determined with an accuracy of half the pulse length, in this case, with a pulse duration of 100 ns (length 20 m), this is 10 m. By analyzing the derivative of the reflectogram of any single axis, it is impossible to say unambiguously where the events are located, since the first one has three pronounced local minima, and the second near this area has two, but hardly noticeable inflections, while the proposed processing technique allows us to distinguish two well resolvable cross-correlation peak and, in a sense, overcomes one of the limitations of OTDR technology. Thus, in the first approximation, one can judge the confirmation of the previously put forward hypothesis and the expediency of further, more accurate and extensive research in this area.

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