
GENERAL EXPERIMENTAL
TECHNIQUE

Investigation of Signal Reception—Transmission Parameters in a Distributed Acoustic Sensor¹

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Abstract—This paper analyses the spectral, spatial and temporal probing pulse characteristics of the fiber-optic distributed acoustic sensor prototype. The signal spectral distribution and mean value, the interference pattern contrast dependencies on the light source pulse duration and the optical amplifier pump current are obtained. Directions for further research in this area are proposed. The collected data made it possible to draw conclusions about such devices cost reduction possibilities and the proposed design operation suitability.

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1. INTRODUCTION

Vibration (acoustic) background monitoring today is vital in many areas of human activity – mineral deposits exploration [1, 2], oil and gas production, processing [3] and transportation [4–6], engineering structures operation [7, 8], transport [9], perimeters' security [10]. New potential applications are emerging, agriculture [11, 12], for instance. Often this type of monitoring implements a fiber optic distributed acoustic sensor (DAS). The integration of technology into new industries is frequently confined, among other things, to the high cost of such devices. Reduction of such devices' cost can be achieved both by some components omitting, which is acceptable for a particular application [13, 14], and by selecting equipment with the most suitable parameters for certain purposes. The latter will avoid the inclusion of equipment with high cost and redundant characteristics for the measurement in the device.

In its turn, DAS commonly uses the technology of optical time domain reflectometry (OTDR). The spatial resolution in it depends on the pulse duration. The same relation binds the signal-to-noise ratio (SNR) and the length of the sensor. The pulse duration decrease in such designs cannot be indefinitely compensated by an increase in its peak power as when a

certain threshold is exceeded, inelastic scattering (for example, Brillouin), and other nonlinear effects emerge in the fiber-optic sensing element in addition to the elastic, Rayleigh, scattering used by the technology. Therefore, one of the most important trade-offs in DAS and OTDR is the ratio between the pulse duration (sensing element length, data contrast) and spatial resolution [15].

Often, the power of the radiation source in DAS and OTDR is not enough to achieve the required operating parameters, and the pulse is passed through an optical amplifier before injection into the fiber optic sensing element. As the latter, an optical amplifier based on erbium ion doped fiber (EDFA) is usually used. EDFA also makes up a significant contribution to the device's final cost, so the study of its influence on signal characteristics in the spectral and spatial domains is an integral part of the path to optimizing and reducing the cost of DAS. However, in most of the studies dedicated to these phenomena [16–21], investigate the associated parameters fractionally, also it is rather difficult to reconstruct the whole picture from experiments performed on different setups.

In this paper, the dependences of the spatial and spectral characteristics of DAS on the operating parameters of the radiation source and the optical amplifier associated with it are thoroughly studied. Obtaining of essential characteristic dependencies

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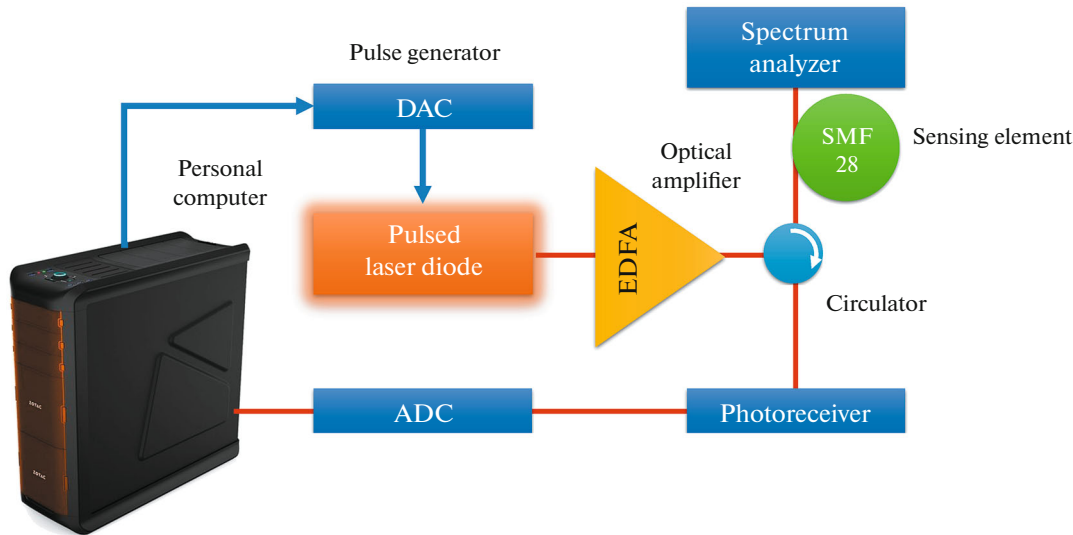


Fig. 1. Schematic representation of the setup used for the study.

performed for the single “classical” implementation of a sensor with direct detection, comparison with theoretical estimates and deviations explanation can be extremely useful in the further creation of simple and affordable devices of this kind, as well as in adapting them to the requirements of new interested industries. This study, apart from the planned future work, of course, does not claim to be the declared completeness, but is only the start of a cycle of empirical research aimed at conducting experiments on a single, “classical” direct detection DAS setup and obtaining the dependencies that are important for DAS developers, previously described theoretically, subject to various assumptions.

2. EXPERIMENTAL SETUP

To study the dependence of the characteristics of the Rayleigh backscattering signal, which carries information about external impacts on the sensing element, on the characteristics of the probing signal and the operating parameters of the radiation source and amplifier, the setup shown in Fig. 1 was used. It is a phase-sensitive optical reflectometry (Ph-OTDR)-based DAS. A more detailed description is presented in [14]. The radiation source “DenseLight DL-B12-CLSwwwB-Sxxxx-yy-zz” generated pulses with a bandwidth of 5 kHz, a wavelength of 1550 nm and a power of 10 mW, which were then amplified by the “Amonics AEDFA-23” and injected through a circulator into a sensing element consisting of 1 km “SMF-28” optical fiber. At the end of the line, the pulses entered the Yokogawa spectrum analyzer. The Rayleigh backscattering signal from the sensing element was recorded by a PC as a function of time through a “lanlusb” ADC and an InGaAs-based Femto HCA-S-200M photodetector tuned to 1550 nm.

3. EXPERIMENT AND OBTAINED RESULTS

It was decided to focus the research of the dependences indicated earlier on the study of the mean backscattered signal level dependence nature (traces, Fig. 2) on the EDFA amplification current and pulse duration, as well as the full width at half maximum (FWHM) of the probing signal spectrum on the same parameters. In the first series of experiments, the pump current of the second stage of the erbium amplifier was varied from 180 mA to 440 mA with a step of 20 mA at a pulse duration of 15 ns. The pump current of the first stage remained unchanged (70 mA) and was chosen based on the minimum value at which an interference pattern of sufficient quality was observed. For each current value, the trace and the probing pulse spectrum at the end of the line were recorded. Then the same was repeated for a pulse duration of 150 ns.

In the second series of experiments, the pump current of the second stage was 440 mA; for pulse durations of 10 ns, 100 ns, and 1000 ns, the trace and spectrum were also recorded.

A significant increase in the signal level towards the end of the line with a short pulse duration and a high amplification current can be explained by an increased proportion of spontaneous EDFA emission in the signal: such a pulse duration is insufficient for significant amplification. Ph-OTDR trace can be considered an interference pattern. In this case, the interference occurs between the components of the backscattered signal within the pulse duration. Spontaneous emission radiation in an optical amplifier does not have sufficient coherence to form an interference pattern. At short pulse durations, not all of the pump energy has time to be realized in the form of stimulated emission, and therefore the level of continuous spontaneous emission begins to rise rather quickly. Under

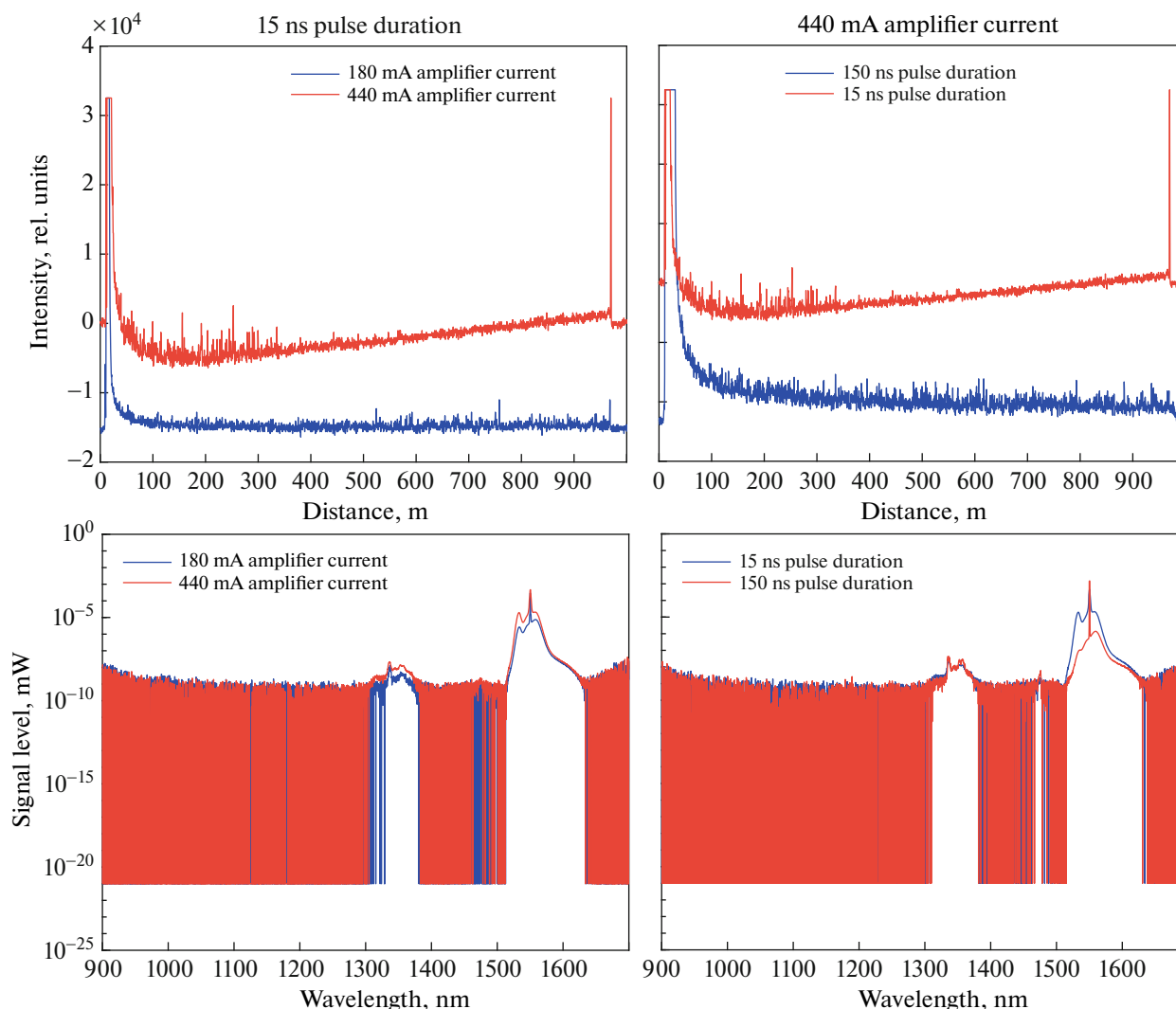


Fig. 2. Spectra and traces for various amplification currents and pulse durations.

these conditions, at a certain amplification current, spontaneous emission begins to prevail over backscattering from the useful signal pulse before the photodetector has time to obtain information about the scattering at the end of the sensing element. Thus, the trace slope for certain values of the pulse duration and amplification current can be explained. At long pulse durations, this process is shifted in time so that the backscattering signal from the end of the sensing element reaches the photodetector before spontaneous emission rises to its level. This, however, only means that the phenomenon can be observed with a longer length of the sensing element. The shape of the spectra obtained from the end of the sensing element at various values of current and pulse duration confirms this assumption (Fig. 2, bottom row).

For each trace, the mean signal level was calculated and its dependences on the amplification current (Fig. 3)

and pulse duration were plotted. For each spectrum, FWHM was calculated and its dependences on the amplification current and pulse duration were plotted (Fig. 4).

While the dependences for FWHM are not of particular interest, since they are consistent with the expectations (the wider the spectrum, the shorter the pulse duration, due to the predominance of broadband spontaneous emission in EDFA and the pulse chirp introduced by a current-driven pulsed laser), the dependences of the mean signal level deviate somewhat from the initial theoretical assumptions. With a pulse duration of 150 ns, which should be sufficient for a good amplification of the useful signal (Fig. 2), its mean level is lower for all values of the amplification current than for a pulse with a duration of 15 ns. Moreover, the dependence of the mean signal level on the pulse duration reveals some of its growth at long durations (around 1000 ns).

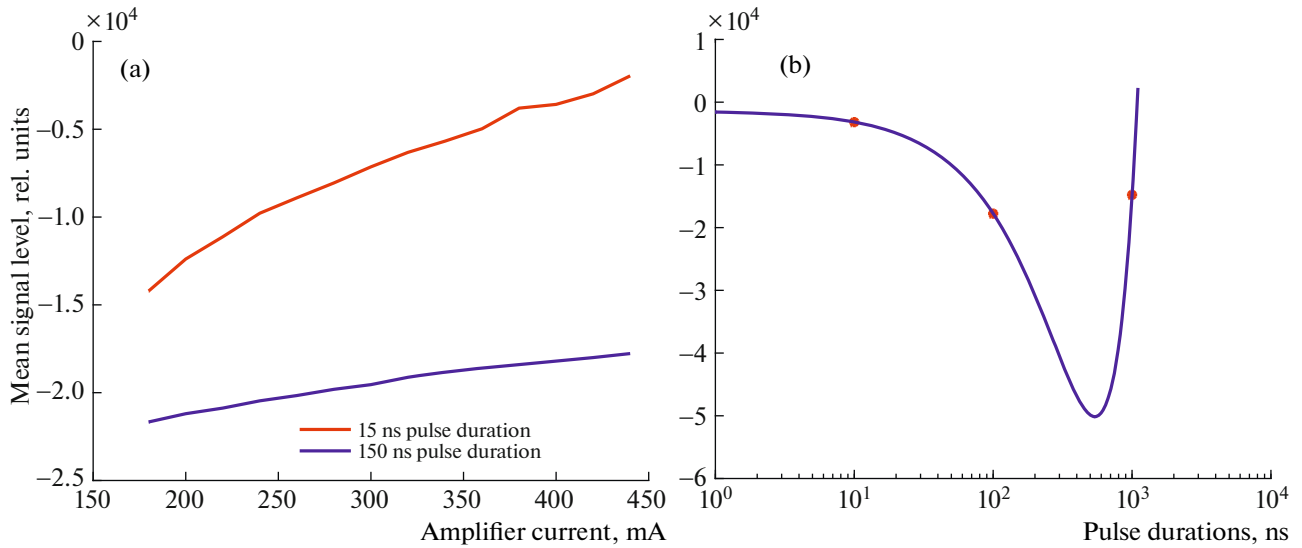


Fig. 3. The dependence of the mean signal level on the amplification current (a) and the pulse duration (b), points obtained during the experiment are marked in red.

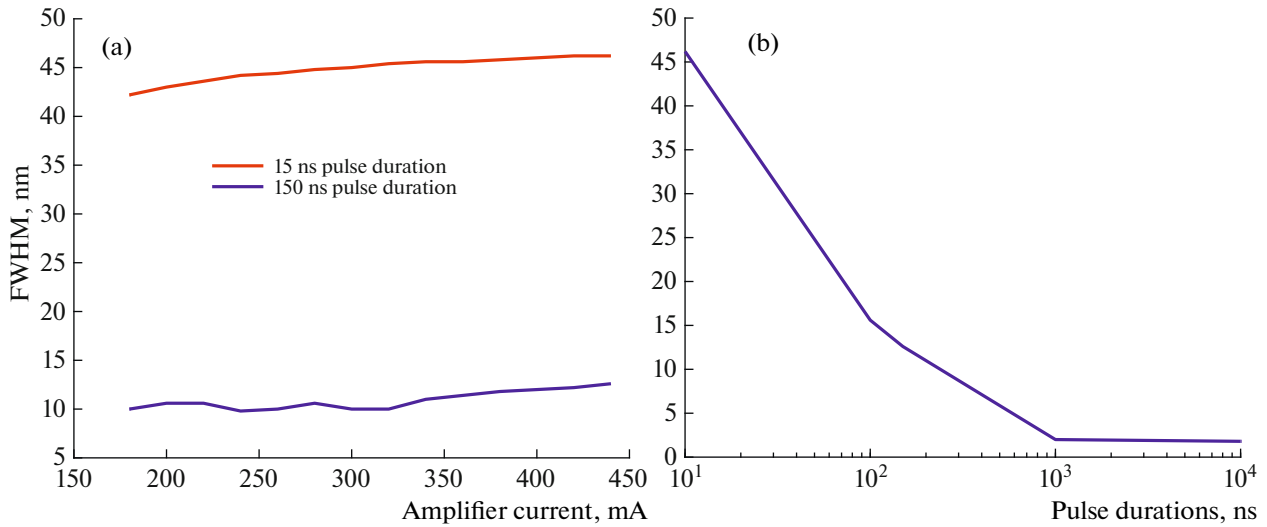


Fig. 4. Dependence of FWHM on amplification current (a) and pulse duration (b).

It was suggested that with a pulse duration of about 100 ns, due to sufficient amplification, the contrast of the interference pattern (trace) increases – the signal level becomes higher at the maxima, but lower at the minima. Probably, the generally rather complex form of the resulting interference pattern can affect the decrease in the signal level because of this. At long pulse durations, multipath interference affects the deterioration of contrast.

To confirm this hypothesis, it was decided to calculate for each trace the visibility of the interference pattern (Fig. 5), and for each spectrum, the ratio of the

spectral power density of the useful signal (narrow peak in the vicinity of 1550 nm) and spontaneous emission (Fig. 6), for which the dependences on amplification current and pulse duration are plotted.

The visibility of the interference pattern (trace contrast) was calculated by the formula

$$V = \frac{\max - \min}{\max + \min},$$

where max is the signal level mean value in the trace peaks, min is the signal level mean value in the trace

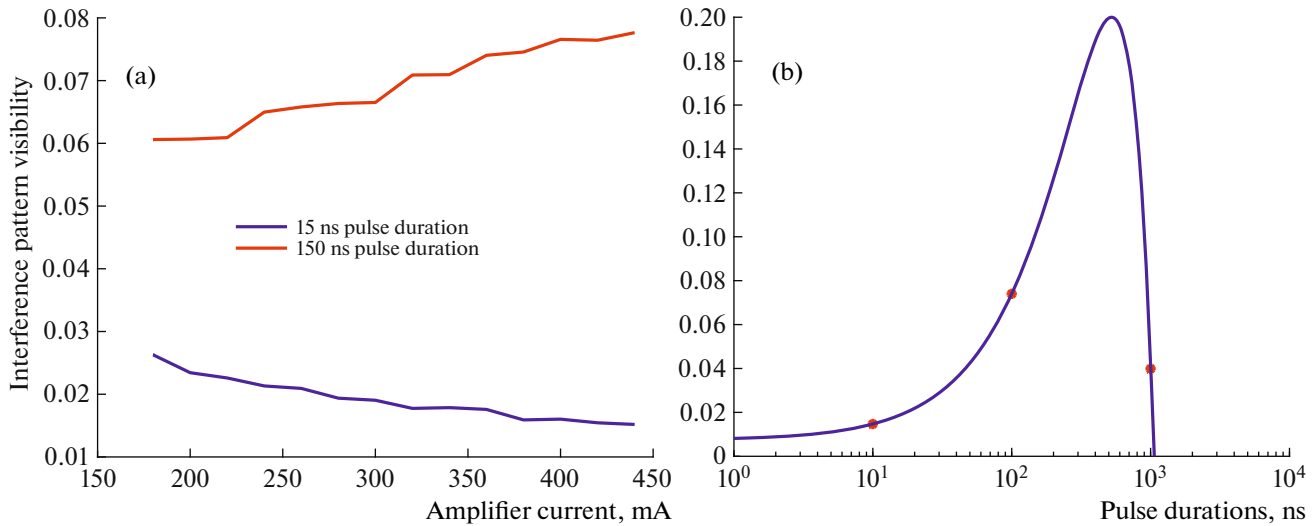


Fig. 5. Dependence of the interference pattern visibility on the amplification current (a) and pulse duration (b).

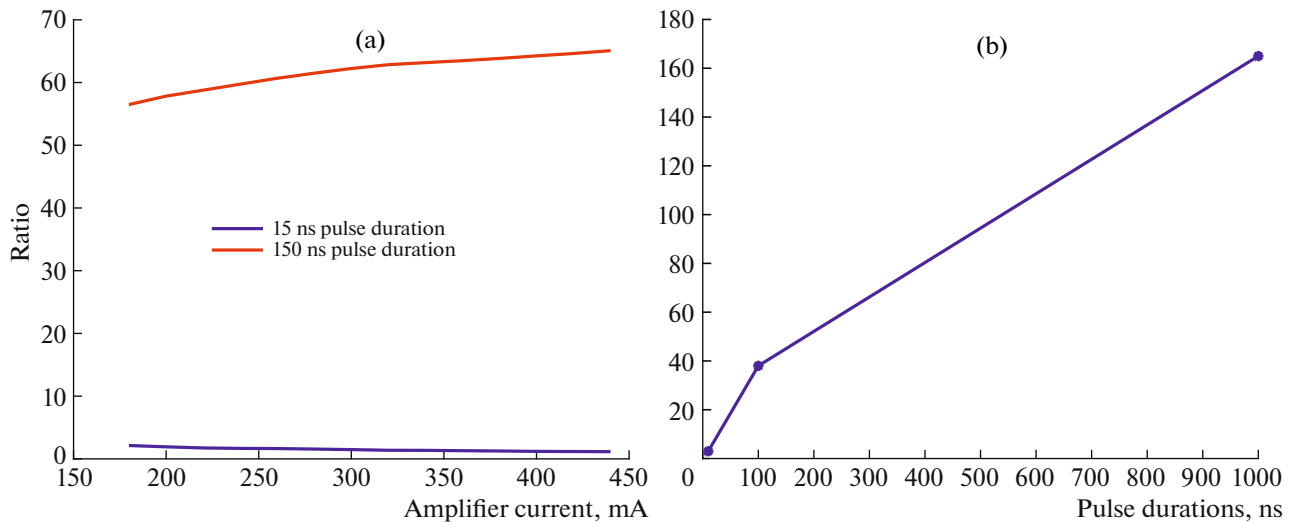


Fig. 6. Dependence of the useful signal spectral density and spontaneous emission ratio on the amplification current (a) and the pulse duration (b).

troughs. The trace span from 200 to 960 m was used for the calculation.

The dependences obtained confirm the assumption that at short pulse durations and with an increase in the amplification current, the already low visibility deteriorates due to the enhancement of spontaneous emission. At optimal pulse durations for this length of the sensing element, visibility is better, and it increases with increasing amplification current. At too long pulse lengths, the visibility is again somewhat degraded, but in this case, probably due to multipath interference.

For any pulse duration, there are no significant changes in the ratio between the spectral density of the useful signal and spontaneous emission with a change in the amplification current. At a short pulse duration, a slight decrease in the ratio of the useful signal to spontaneous emission is observed, which is consistent with the assumptions and the corresponding dependence for visibility. With a pulse duration of 150 ns and an increase in current, the share of the useful signal in total also increases, which also correlates with the theoretical prediction and the visibility function. An expected significant increase in the fraction of the useful signal relative to spontaneous emission is observed

with increasing pulse duration. In the studied range of pulse durations, only an increase in the share of the useful signal in total is observed, which is also in good agreement with estimations.

4. CONCLUSIONS

In conclusion, it should be noted that in this work, the dependences of the spatial and spectral characteristics of the DAS output signal on the parameters of the probing pulse and, in turn, the parameters of the generating and amplifying equipment were studied. The influence of the laser pulse duration and the EDFA amplification current on the mean output signal level and its contrast, width and shape of the probing signal spectrum is revealed and explained. No extraneous components corresponding to nonlinear effects were detected in the spectrum at any value of the parameters from the studied, or the equipment used did not allow them to be resolved (the resolution of the spectrum analyzer was 0.2 nm). The not quite linear nature of the dependences of the mean signal level for 1550 nm on the amplification current and pulse duration, taking into account the available spectral information, remains explainable and does not imply energy transfer from the main wavelength to those that correspond to nonlinear effects. Further work in this area can be aimed at obtaining spectral information with a higher resolution and obtaining a larger number of intermediate points for calculating the dependences associated with the pulse duration. In addition, the accuracy of the data obtained can be increased by the sensing element soundproofing, using a continuous-wave laser with an optical modulator, and filtering the radiation at the output of the optical amplifier (for example, using a fiber Bragg grating – FBG). Nevertheless, it is worth noting that previous works [12, 14] demonstrate the possibility of using DAS in new industries and without using the elements mentioned above, which makes it possible to reduce the cost and susceptibility to environmental conditions while maintaining performance within acceptable limits. In this work, the spectral characteristics of the transmitted radiation were studied – the spectrum analyzer was installed at the end of the sensing element. However, it is also important to study the spectral characteristics of the backscattered radiation arriving at the input facet of the sensing element and forming the trace.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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