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DISTRIBUTED FIBER-OPTIC SENSOR FOR DETECTION AND LOCALIZATION OF ACOUSTIC VIBRATIONS

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Abstract

A sensing system utilizing a standard optical fiber as a distributed sensor for the detection and localization of mechanical vibrations is presented. Vibrations can be caused by various external factors, like moving people, cars, trains, and other objects producing mechanical vibrations that are sensed by a fiber. In our laboratory we have designed a sensing system based on the Φ-OTDR (phase sensitive Optical Time Domain Reflectometry) using an extremely narrow laser and EDFAs.

Keywords: optical fiber sensor, acoustic vibrations, detection, localization, Φ-OTDR.

1. Introduction

Optical fibers have been used in a wide range of applications during several last decades. The most visible and known utilization is in the area of telecommunications as the optical fiber technologies can offer bit rates in the range of terabits per second [1]. Fibers have been deployed not only in the area of optical networks but they are also more and more common in the fiber sensor technologies.

Sensor applications are an attractive area of the optical fiber usage. The fiber construction, the principle of operation (the total reflection) and the signal form (radiation) make the transmission of data very safe and resistant to many sources of disturbances. At the same time transmitted signals are sensitive to ambient conditions, like the temperature, strain, vibrations or strong ambient electromagnetic field, which make them suitable for sensing purposes. Fiber sensors can be divided into two groups - extrinsic (hybrid) fiber optic sensors and intrinsic fiber optic sensors [2].

1.1 Distributed fiber-optic sensors

Distributed fiber sensors are a very important part of the fiber optic sensor area as a fiber behaves like hundreds or thousands of sensors spread along it [2]. To enable this, the fiber response to the test signal has to provide an information not only about the value of the measured quantity but also about the created response location. The most common solutions of these systems are based on the reflectometry principle [3].

Using the distributed fiber sensors it is possible to measure such quantities, like the fiber loss pattern, temperature, pressure or vibrations along the distance from several meters up to tens of kilometers, depending on a particular solution. The spatial resolution that can be obtained spans from micrometers for short sensor lengths (equal to single meters) to tens kilometers for long range sensors [4].

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The localization of a physical quantity occurrence is based on the transmission of short-time and high-power pulses that travel along the fiber while a portion of the radiation (light) is scattered due to elastic or inelastic effects that are influenced by the physical quantity (temperature, pressure, radiation, strain, etc.), which can be measured by processing the scattered signal [5]. A portion of this scattered signal is re-captured by the fiber and is being spread farther. Capturing and processing the back-scattered signal is the most common technique. The best known elastic effect is the Rayleigh scattering; the Brillouin and the Raman scatterings belong to the inelastic ones [3].

An optical time domain reflectometer (OTDR) was demonstrated over three decades ago [6], [7]. Now it is widely used for localizing fiber breaks and other types of anomalies occurring in the optical fiber. The system detects the presence and location of perturbations, which were affected by the intensity of the radiation (light) returned from the fiber, but do not respond to phase changes of the radiation (light) [8].

The distributed sensor system presented in this paper utilizes a Φ-OTDR designed to enhance coherent effects rather than avoid them [3]. The core of this system is a floating interferometer – a phase sensitive device measuring the interference of the radiation (light) back-scattered from different parts of the optical fiber, which arrives at the same time to the photo-detector [8]. That is the reason why the Φ-OTDR can detect much smaller perturbations than a conventional OTDR.

Many distributed sensors based on the phase-sensitivity have been proposed. Nowadays it is the most advanced principle which can be used for monitoring of more than one vibration source along the optical route [10]. For example, in [3] a system based on the phase-sensitivity for 19 km long perimeters was described. The system used a real 8.5 km fiber cable and a 10.5 km fiber on coils. The real fiber cable was buried in the ground at the 20-46 cm depth. In [4] a distributed vibration sensor based on the coherent detection of Φ-OTDR was proposed. This sensor achieved the spatial resolution of 5 m and the maximum frequency response of 1 kHz for a 2 km long optical route. In [8] a system for 128 km with the spatial resolution of 15 m, using the Raman amplifying, was proposed.

2. System description and experimental measurement

We have designed the Φ-OTDR according to the scheme shown in Fig. 1. The key element of this scheme is a highly coherent and frequency stable DFB (Distributed Feedback) laser source Koheras Adjustik with an ultra-narrow spectral line width of about 100 Hz.

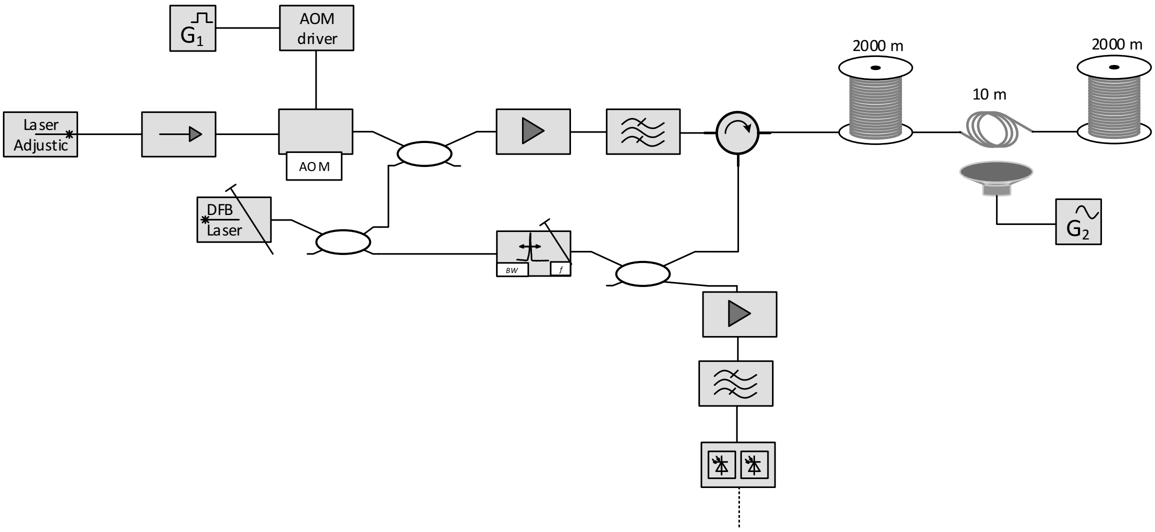

Fig. 1. A scheme of the tested topology.

The second most important element is an acoustic-optic modulator (AOM) with a high extension ratio > 50 dB. This modulator must be driven by a special driver, which needs a precise source of the DC voltage and a generator of the RF (Radio Frequency) signal. We have used two EDFA (Erbium Doped Fiber Amplifier) modules. The first one is used as a booster in a direct branch for amplifying the pulsed signal and the second one is used as a pre-amplifier for amplifying the back-scattered signal. We have also used three couplers. The first coupler, which is situated behind the second auxiliary DFB laser, is used for separating the optical signal from this laser. The couplers in front of the amplifiers are used for merging the useful signal with the signal from the second auxiliary laser. The variable attenuator is used for optional power level setting of the second laser.

The CW (Continual Wave) signal from the Koheras Adjustik laser (with the central wavelength of 1540 nm) goes through an optical isolator into the acoustic-optic modulator, where pulses are created using a special driver and a signal generator. It is very important to use an optical isolator behind the laser to prevent the laser from damage by back-scattered optical signals. The pulse width was set to 500 ns with the frequency of 17 kHz. This frequency is given by the equation (1) and is adequate to the fiber length of 4 km. The pulsed optical signal is then amplified by an EDFA and goes through an optical band-pass filter and a circulator into the FUT (Fiber Under Test). We have used a common telecommunication optical fiber G.652.D.

$$f \le \frac{1}{\tau}[Hz], \tag{1}$$

where [3]:

$$\tau = \frac{2 \cdot s}{v}[s]. \tag{2}$$

The total fiber length is s and v is the velocity of light in an optical fiber, which is given by the equation (3):

$$v = \frac{c}{n} = 2 \cdot 10^8 [m/s], \tag{3}$$

where c is the velocity of light in the vacuum and n is the refractive index.

The spatial resolution for the pulse width of T_p = 500 ns is given by the equation (4):

$$\Delta z = \frac{v \cdot T_p}{2} = \frac{2 \cdot 10^8 \cdot 5 \cdot 10^{-7}}{2} = 50\ m. \tag{4}$$

One sample is adequate to the fiber length:

$$l = \frac{v}{F_s} = \frac{2 \cdot 10^8}{30 \cdot 10^6} = 6{,}67\ m, \tag{5}$$

where l is the adequate fiber length and F_s is the sampling frequency in Hz.

Since it is not possible to directly amplify a pulsed optical signal with a pulse repetition of 17 kHz we have proposed and designed a system with a second DFB-CW laser to suppress this problem. The principle is that the CW laser (a standard laser with the central wavelength of 1550 nm) with a different wavelength is merged with the pulsed signal by a coupler. The EDFA is then optically suspended on the signal from the CW laser and power fluctuations are minimal. The power of the second laser must be a little bit higher than the power of the pulsed signal.

Acoustic vibrations were created by a speaker and a generator in the middle of the 4 km optical fiber cable. The back-scattered signal is distributed by the Rayleigh scattering from each point of the fiber. This signal passes through an optical circulator to a coupler where it is merged with the optical signal from the second CW laser. The signal is then amplified, filtered by a band-pass filter and converted to the electrical signal by a balanced photodetector. Both filters are used for filtering-out the optical signal from the second auxiliary laser.

3. Measurement results

It is very difficult to set power levels of both lasers and gains of amplifiers. If the gain of the first amplifier is too high, there is a risk of the Brillouin scattering generation. That is the reason why the power levels in each part of the fiber have to be balanced and optical filters should be used for adverse signal filtering.

After the opto-electrical conversion the signal is displayed on an oscilloscope and recorded by a two-channel digital acquisition card (DAQ) with the sampling rate of 30 MS/s. We tested our proposed scheme for different pulse widths, frequencies and fiber lengths. The best results were achieved for the pulse width of 500 ns and the total fiber length of 4 km. With this set up it is possible to see the vibrations with a naked eye on the oscilloscope. After DAQ recording and post processing we achieved the location of vibrations with the spatial resolution of 50 m. The most important part of this system is signal processing.

3.1 Average fiber response

At first the individual fiber responses $h_m[n]$ to the measured pulse were recorded. The responses do not have a monotonically decreasing character, but due to reflections and scatterings on the fiber non-homogeneities the maxima or minima appear at different distances from the near end of the fiber. If we calculate the average of all responses, we can get a typical fiber response to the measured pulse.

$$\bar{h}[n] = \frac{1}{M}\sum_{m=0}^{M-1} h_m[n]. \tag{6}$$

The average response for the total number of M = 40,000 responses is shown in Fig. 2.

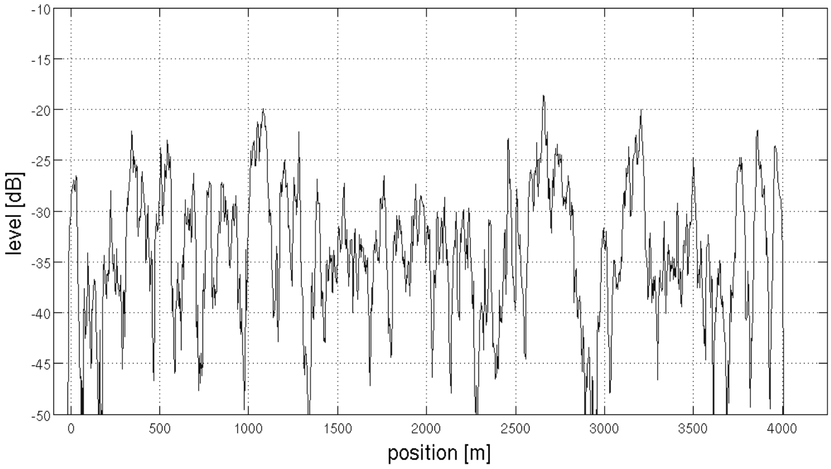

Fig. 2. The average long-time fiber responses to the measured pulses.

3.2 Detection and localization of vibrations

If the individual responses are synchronized with the measured pulse we can get a waveform which is shown in Fig. 3. The positions of maxima approximately correspond to the positions of the peaks in the fiber response average (see Fig. 2). Approximately at the half of the fiber length, i.e. at a distance of 2,000 m from the near end of the fiber there is an evident maximum but with a periodically varying value. This fast changing maximum corresponds to the vibration on the fiber.

We can remove maxima with the constant value and position. For removing the offset the 1^{st} order high-pass filter is used. The transfer function *H(z)* is given by the equation (7):

$$H(z) = \frac{1+a}{2}\frac{z-1}{z-a} = \frac{0.995z - 0.995}{z - 0.99}, \tag{7}$$

where a is the coefficient of the transfer function and z is the operator of the transfer function.

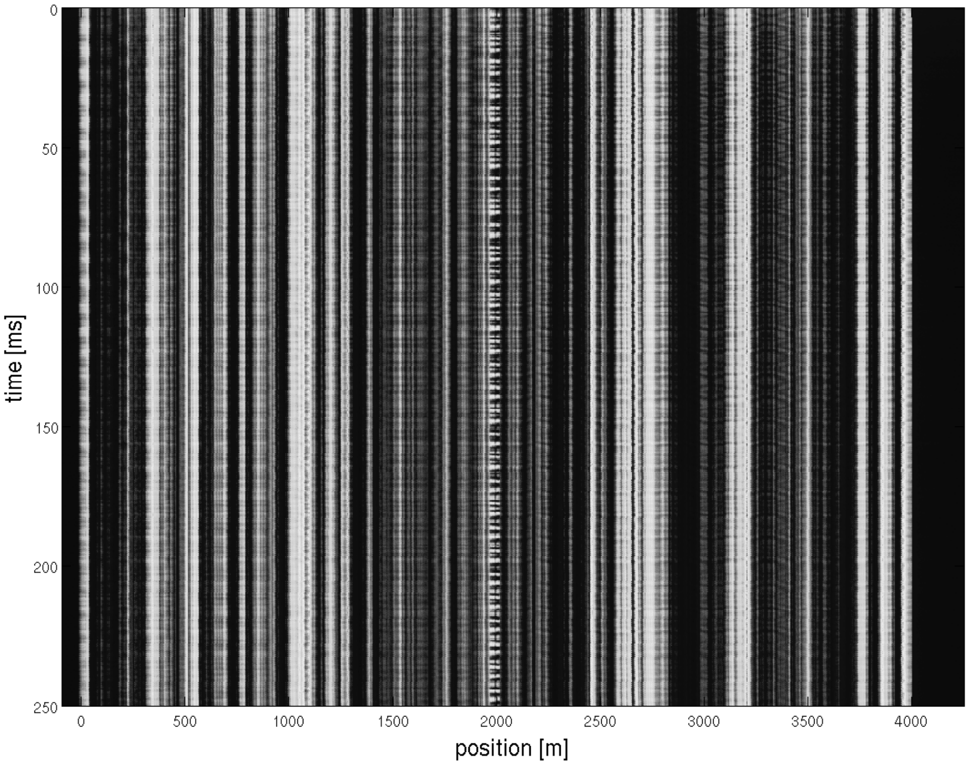

Fig. 3. The waveform of individual responses.

The filtration is carried out along the vertical axis, so there is actually a subsampling of the fiber response. The input sample is always got from the same position of the next fiber response. In the original sampling frequency of 30 MHz and the length of one response equal to 1,305 samples, the sampling rate drops to 22.989 kHz. The cutoff frequency of a high-pass filter with the transfer function (6) is then about 30 Hz. The filtered responses $\hat{h}_m[n]$ are shown in Fig. 4.

After offset filtering the vibrations at the distance of 2,000 m are clearly visible. Nevertheless, the waveforms are still interfered by the wideband noise. To remove this component a low-pass filter was used. The cutoff frequency was set to 200 Hz. The filter was realized as a floating average of 50 responses:

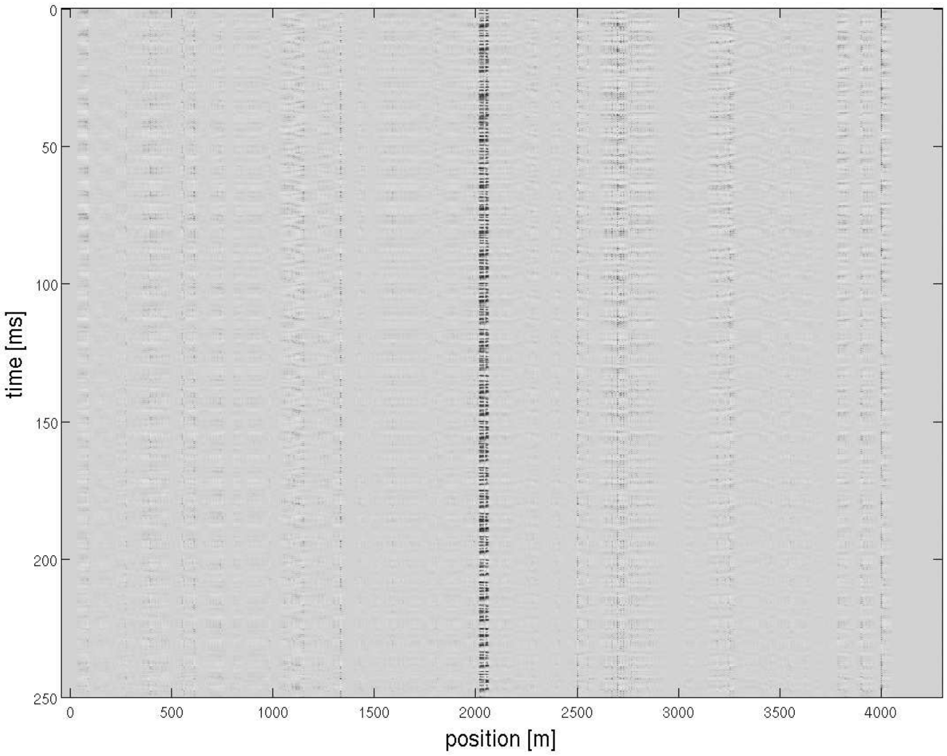

Fig. 4. The waveform of individual responses without the offset.

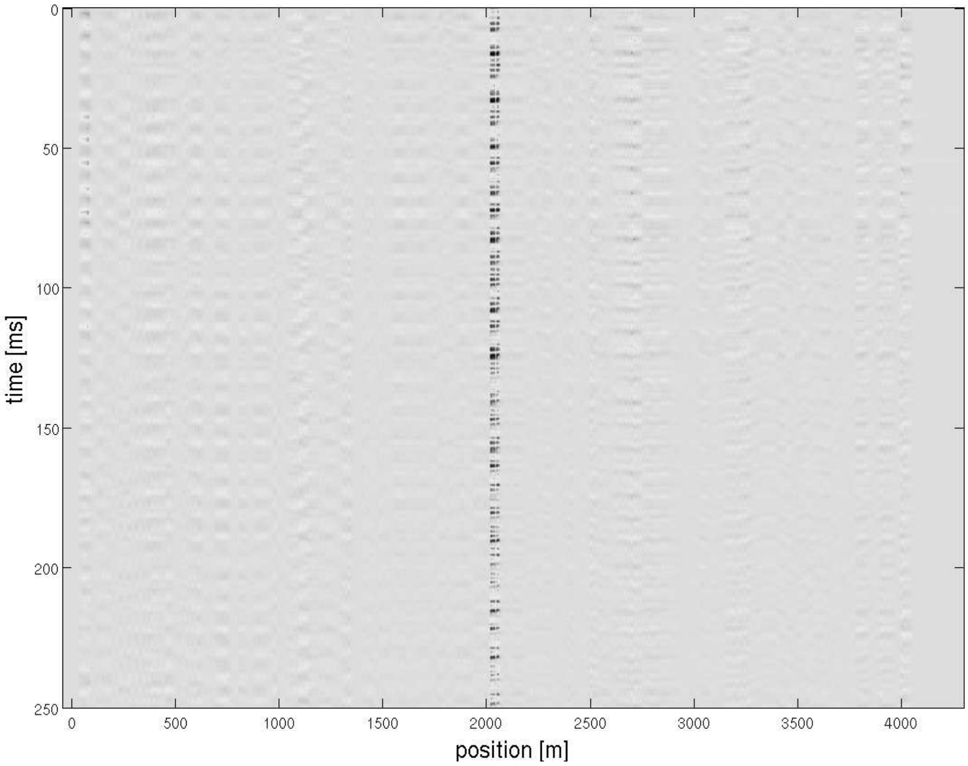

Fig. 5. The waveform of individual responses without the offset and after low-pass filtering.

$$g_m[n] = \frac{1}{50}\sum_{k=0}^{49} \hat{h}_{m-k}[n]. \tag{8}$$

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The floating average was applied along the vertical axis like in the case of a high-pass filter. The final responses are shown in Fig. 5.

The final step before the automatic detection was thresholding:

$$\hat{g}_m[n] = \max(g_m[n], \theta) - \theta. \tag{9}$$

The threshold value θ was suitably selected, so that for the measurement on the fiber without vibrations all values $g_m[n]$ were thresholded. The results after thresholding are shown in Fig. 6. The only non-zero samples are at the distance of 2,000 m from the near end of the fiber, where the vibrations really occurred. It is possible to convert the detection and localization into searching the non-zero values.

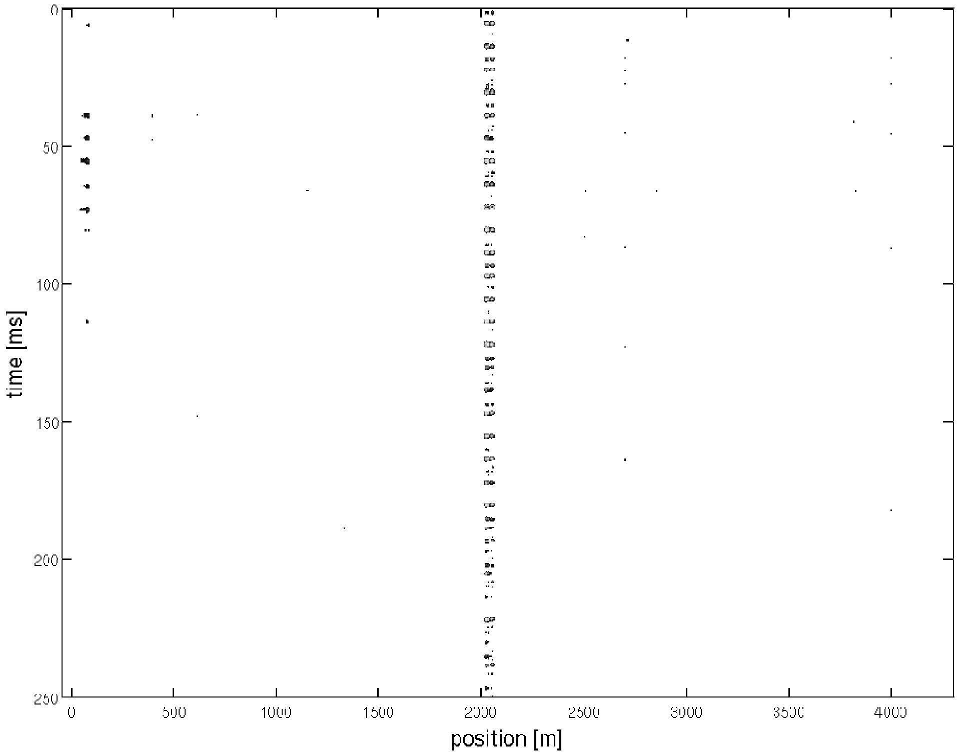

Fig. 6. The waveform of individual responses after filtering and thresholding.

4. Conclusion

Nowadays optical fibers are increasingly used in the area of sensors. Using the distributed fiber sensors it is possible to measure such quantities, like the fiber loss pattern, temperature, pressure or vibrations along the distance from several meters up to tens of kilometers, depending on a particular solution.

In this paper we have proposed a distributed fiber sensor system based on the Φ-OTDR. This system was tested on the fiber length of up to 4 km with the spatial resolution of 50 m. The vibrations were created by a speaker for different frequencies from 100 Hz up to 1 kHz with a successful sensitivity. A practical usage for the buried optical cable is the aim of the further research. The system should be used for the detection, localization and classification of acoustic vibrations caused, for example, by moving people, cars, trains and other objects producing mechanical vibrations that are sensed by a fiber. The system could be used also for monitoring pipeline damages, seismically active areas, etc.

The recorded data were post-processed in the Matlab environment. It is necessary to filter all undesirable components of the signal and noise to get a clearly visible location of occurred vibrations. For this, high-pass and low-pass filters, as well as thresholding, were applied.

Many systems were proposed for monitoring acoustic vibrations, based on Rayleigh's scattering. A general problem of these systems is the amplification of a pulsed signal with respect to the OSNR (Optical Signal to Noise Ratio). Our proposed system uses EDFAs with the second auxiliary laser and optical filters to solve this problem.

The system described in this paper has a significant potential and will be gradually improved in the future.

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