Mathematical analysis of marine pipeline leakage monitoring system based on coherent OTDR with improved sensor length and sampling frequency

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Abstract. A system based on coherent optical time domain reflectometry (OTDR) for subsea pipeline monitoring is described. The fiber sensor length is increased using erbium-doped fiber amplifier (EDFA) cascades. The sampling frequency is increased by dividing the fiber sensor into separate sensitive areas, with parallel scanning. The calculation of the erbium amplifier cascade spontaneous noise influence on the signal-to-noise ratio (SNR) is carried out.

1. Introduction
Hydrocarbons, in particular gas and oil, are some of the most in demand goods at present. The main transport systems for hydrocarbon delivery are pipelines. Their length can vary from a few hundred meters to several thousand kilometers. They can be installed both on land and at the bottom of the sea. More than one hundred leaks are found in pipelines in Russia every year. According to experts, that number is going to increase significantly in the future. According to information from Greenpeace, Russia annually loses 10 to 20 million tonnes of oil and 6 to 50 billion m$^3$ of gas due to leaks. Such a leakage volume represents from 3% to 7% of the total transported oil or gas. All of these hydrocarbons eventually pollute the environment. According to calculations, up to 24 billion m$^3$ of gas can be saved by reducing the number of leaks to international standards.

The occurrence of leaks also leads to environmental pollution by hydrocarbons, which have a strong negative impact on the biosphere. The importance of leak detection is obvious. The economically efficient use of pipelines requires early detection by means of a monitoring system.

This paper is organized as follows. In Section 2, we briefly describe the most common methods of leak detection and introduce a fiber optic system for pipeline monitoring. In Section 3, we show disadvantages of this system. In Section 4, we propose a method to eliminate them and theoretically calculate SNR of the considered system. Section 5 concludes the main results of the paper.

2. Methods
The monitoring system must satisfy a number of requirements: high sensitivity, high accuracy for determining the location of the leak, safe and reliable long-term use, possibility for long-distance pipeline control, high degree of automation, absence of interruption in the pumping process, efficiency, and a capability to work in any climate and weather conditions.
Existing methods can be classified into two large groups: dynamic and static. The first group does not require stopping product transportation, and the second group does. Existing dynamic control methods have the capability to detect leakages of more than 50 L/h. Smaller leaks can only be detected by static methods. Each method has its own set of parameters: sensitivity, scanning speed, positioning accuracy, etc. The most widespread techniques are as follows: wave alert, mass balance, and acoustic emission systems [1]. The first and second methods cannot detect small leaks. The last method can, but, at present, it requires a special staff with acoustic detectors that can scan only a few kilometers of pipeline per day. These disadvantages impair the automation of the process, prolong the inspection time, and reduce the rate of detection.

According to Riemsdijk et al., [2] the sound pressure level of a leak is about 120 dB. This level is comparable to that from the passage of heavy trucks; hence, it is possible to detect leaks not only by means of point sensors, but also by using distributed fiber-optic sensors. In this paper, we propose a system that allows continuous monitoring of acoustic signals along the entire length of the pipeline, in a fully automated mode. It is based on the principle of coherent optical time domain reflectometry (OTDR). In this method, the optical signal that propagates along the fiber is partially attenuated and scattered by inhomogeneities. Part of the radiation scattered within the fiber is sent backwards. By recording and analyzing the backscattered signal, we can recover losses distributed along the length of the fiber.

![Figure 1. Rayleigh scattering in an optical fiber.](image)

If the coherence length of the laser is greater than the pulse width, we can see the effect of coherent scattering of light, and the photoreceiver measures summed amplitudes of the backscattered waves. The total amplitude of that signal can be represented as a sum of vectors with random amplitude and phase. For coherent scattering of light, the total amplitude of the scattered wave varies randomly along the fiber from its maximum value to zero, due to interference. Consequently, relative power fluctuations of the scattered radiation are approximately equal to one, and a signal (reflectogram) detected by a photoreceiver undergoes significant deviations. If something impacts the fiber at a given place, the interference pattern changes at this location because of phase modulation of the backscattered wave from that region. It causes changes in the reflectogram. Systems, based on this method, attract a significant research attention [3-11].

3. Existing parameters

Application of such systems for industrial leak detection is only now in the development stage. One of the tasks necessary to improve the system quality is matching the acoustic bands of the leak emission (10-40 kHz) and the sampling frequency of the coherent OTDR:

\[
f_{\text{samp}} = \frac{c}{2L_{\text{sens}}n} = 2 \text{ kHz}
\]  

where \(c\) - speed of light in vacuum, \(L_{\text{sens}}\) - fiber sensor length, and \(n\) - refractive index of the fiber. For typical values \(L_{\text{sens}} = 50\) km and \(n = 1.5\). This means that we have to increase the sampling frequency...
limit by at least a factor of 10. As can be seen from equation (1), these target values can be achieved only by reducing the length of the sensor. This would be a problem because the pipelines may have lengths of several hundred kilometers, so the length of the fiber sensor is a critical issue.

4. Proposed solution and theoretical calculation

As shown in figure 2, a system has been proposed to combine the advantages.

![Figure 2. Scheme of proposed COTDR.](image)

In this scheme, the pulse from the source node propagates to each branch, where a fraction of the radiation is sent to the sensor section and another part is amplified and transmitted to the next coupling. Thus, amplification of the pulse, propagating through the couplings, by the EDFA simultaneously reduces the sensor section length and increases the sampling frequency. The optimum length of the fiber section should be equal to the submarine cable installation length, which, at present, is 5 km. This will provide both ease of system assembly and the desired range for acoustic frequencies, because in this scheme $f_{samp} = 20 \text{ kHz}$.

The disadvantage of a system with a large number of branches and, consequently, erbium amplifiers, is spontaneous emission, which reduces the SNR. Calculations of couplers’ influence on the SNR of the system are described in two stages:
1. definition of $SNR_t$ for one sensor section;
2. definition of the deterioration of the SNR due to the amplified spontaneous emission (ASE) from cascades of $N$ erbium amplifiers.

In the first stage, we calculate the SNR of a system without EDFA, constructed as shown in figure 3.

![Figure 3. Scheme without EDFA. The components are: 1 - narrow bandwidth laser, 2 – acousto-optic modulator, 3 - optical circulators, 4 - fiber sensor, 5 - optical pre-amplifier, 6 - optical filter, 7 - photoreceiver, 8 - analog-digital converter, 9 - field-programmable gate array (FPGA), and 10 – personal computer.](image)
The maximum input power for this scheme is limited by nonlinear effects (primarily by self-phase modulation) [12], so we choose the source power, $P_{in} = 200$ mW = 23 dBm. The SNR of a system without amplifier cascades is analyzed as follows:

$$\text{SNR}_1 = 10 \log \left( \frac{P_{out}}{\sqrt{\sigma_T^2 + \sigma_n^2 + \sigma_A^2 + \sigma_{s-ASE}^2 + \sigma_{ASE-ASE}^2}} \right) \approx 17.5 \text{ dB}$$

where $P_{out}$ - the power obtained on the photoreceiver, $\sigma_T$ - the variance of receiver thermal noise, $\sigma_n$ - the variance of receiver shot noise, $\sigma_A$ - the variance of electrical amplifier noise, $\sigma_{s-ASE}$ - the variance of signal-ASE beat noise in an optical pre-amplifier, and $\sigma_{ASE-ASE}$ - the variance of ASE-ASE beat noise in optical pre-amplifier.

In the second stage, the SNR is calculated for a system with EDFA cascades, as shown in figure 4.

Effects from all the cascades are combined to one equivalent cascade (3, 4).

**Figure 4.** Equivalent cascade scheme. 1 - narrow bandwidth laser, 2 – acousto-optic modulator, 3 - EDFA booster, 4 - optical filter, 5 - optical circulators, 6 - fiber sensor, 7 - optical pre-amplifier, 9 - photoreceiver.

We have to define the influence ASE of these EDFA on the SNR. A single-cascade is shown in figure 5. The attenuation coefficient for a 5-km-long sensor section equals $K_{att} = \alpha L = 0.17 \text{ dB/km} \times 5 \text{ km} = 0.85 \text{ dB}$. Furthermore, we use the coupler ($K_{div} = 99\%$ to sensor), so the reduction of ASE on the next cascade is achieved.

**Figure 5.** $i^{th}$ cascade scheme.

Based on the condition that the input power on every stage must be equal ($P_{in \ i} = P_{in \ i+1}$), we can estimate the EDFA gain $G = K_{div} K_{att} \approx 120$. Finally, we find the equation for the output pulse power of the $N^{th}$ cascade, considering the ASE of previous EDFA by induction:

$$P_{out \ N} = K_{att} \left( \frac{G}{K_{div} K_{att}} \right)^N P_{in} + \frac{P_{ASE}}{K_{div}} \sum_{m=0}^{N-1} \left( \frac{G}{K_{div} K_{att}} \right)^m = K_{att} P_{in} + \frac{N}{K_{div}} P_{ASE}$$ (3)
From the obtained expression, one can see that the power of the background noise will increase with the number of cascades and does not depend on the propagating pulse power. After computation, the power of ASE was estimated as:

\[
P_{\text{ASE}} = (NFG - 1)h\nu\Delta\nu = 1.915 \times 10^{-6} \text{ W}
\]

where \(NF = 4\) - pre-amplifier noise figure, \(G = 100\) - pre-amplifier gain, \(h\) - Planck's constant, \(\nu = 193.4\) THz - radiation frequency, and \(\Delta\nu = 12.5\) GHz - optical pre-amplifier bandwidth, we obtained the noise power as a function of the number of amplifiers:

\[
P_{\text{noise}} = \frac{N}{K_{\text{div}}} P_{\text{ASE}}G = N \times 2.3 \times 10^{-6} [\text{W}]
\]

In equation (2), the pulse power fluctuations produce the major contribution to the signal-ASE beat noise:

\[
\sigma_{s-\text{ASE}}^2 = 2S^2G^2(P_{\text{sig}} + P'_{n})NFh\nu\Delta f
\]

where \(\Delta f = 5\) MHz - receiver bandwidth, and

\[
\sigma_{s-\text{ASE}}^2 = 2S^2G^2(P_{\text{sig}} + P'_{n})NFh\nu\Delta f
\]

- Rayleigh scattering from the ASE of all EDFA in cascades, calculated as shown in [13], where \(L\) - losses in the line. The term \(10\log(1/f_{\text{samp}})\) takes into account the fact that the ASE is generated continuously, not only during the pulse width \(\tau\). Because the signal power, \(P_{\text{out}} \approx 10^{-5}\) W, one can see that even for a total sensor length of 200 km (corresponding to \(N = 40\) cascades), ASE does not significantly affect the SNR:

\[
\text{SNR} = 10\log\left(\frac{P_{\text{out}}}{(\sigma_T^2 + \sigma_n^2 + \sigma_N^2 + (\sigma_{s-\text{ASE}}(1 + 0.0018N))^2 + \sigma_{\text{ASE-ASE}}^2)^{1/2}}\right) \approx 17 \text{ dB}
\]

Figure 6 shows a detailed schematic of the final technical solution proposed in this paper and we provide a description of the device’s operation. Radiation from the source, 1, acquires pulse modulation in the acousto-optic modulator (AOM), 2. In the optical amplifiers, 3, it gains the level required for entry into the fiber sensor and transmission to the next section. The optical filter, 4, reduces the spontaneous emission. The signal then enters the optical coupler, 5, from which one part of the pulse is transmitted to the next sections, and another part enters the current branch. Before the sensor itself, a small part of the radiation is routed by the coupler, 6, to an auxiliary receiver, 7.1, for pulse start synchronization. The main part of the power entering the circulator, 8, is directed to the sensor, 9, and then the backscattered radiation is directed by the circulator to the pre-amplifier, 10, with an optical filter, 4, to increase signal power, and is detected by the receiver, 7.2. Next, the field-programmable gate array (FPGA), 12, controls the analog-digital converter (ADC), 11, that translates the signal into a digital form that passes through the communication devices, 13, to the host processor, located at the station on the coast.

We now focus on some of the practical features of this scheme. Devices 3, 4, 5, 6, 7.1, 7.2, 8, 9, 11, 12, and 13 are placed in small waterproof couplings. These couplings are standard telecommunication devices. Couplings are united in pairs with one common EDFA to decrease its influence on the pulse form. Electrical power is supplied by a special marine cable, which lies along an underwater pipeline.
5. Discussion and conclusions

A system based on a cascade coherent OTDR was developed that was capable of registering acoustic emission signals from leaks in pipelines. The range of detected sound frequencies was increased to 10 kHz using a cascade scheme to implement coherent OTDR. It was shown that the spontaneous emission noise of the amplifiers for a 200-km sensor array does not have a significant effect on the SNR of the system.

Acknowledgments

This work is supported by Russian Ministry of Industry and Trade, State Contract № 13411.1007499.09.033.

References

[1] Stafford M and Williams N 1996 Pipeline leak detection study (London: HSE Books)
[2] Riemdijk A J and Bosselaar H 1970 Erdol – Erdgas – Zeitschrift 86 12-8
[3] Taylor H F and Lee C E 1993 US 5194847 A
[4] Qin Z, Zhu T, Chen L and Bao X 2011 IEEE Photonics Technol. Lett. 23 1091-3
[5] Bao X and Chen L 2012 IEEE Sensors J. 12 8601-8639
[6] Peng F 2014 Optical Fiber Communication Conference pp. M3J-4
[7] Peng F, Wu H, Jia X H, Rao Y J, Wang Z N and Peng Z P 2014 Opt. Express 22, 13804-10
[8] Juarez J C and Taylor H F 2007 Appl. Opt. 46 1968-71
[9] Zhu T, He Q, Xiao X and Bao X 2013 Opt. Express 21 2953-63
[10] Parker T, Shatalin S and Farhadi roushan M 2014 First Break 32 61-9
[11] Alekseev A E, Tezadov Y A and Potapov V T 2013 Tech. Phys. Lett. 39 42-45
[12] Izumita H, Koyamada Y, Furukawa S I and Sankawa I 1994 J. Lightwave Technol. 12 1230-8
[13] Listvin A V and Listvin V N 2005 Reflectometry of optical fibers (Moscow: LESARart)