Distributed Raman sensor system with point spots for downhole telemetry

I I Nureev¹, R R Gubaidullin¹, V V Kadushkin¹, I Y Kurbiev² and A D Proskuriakov²

¹Kazan National Research Technical University named after A.N. Tupolev-KAI, Kazan, Russia
²SPC “Sensorika”, Ltd., Skolkovo, Russia

E-mail diablogrr@gmail.com

Abstract. The article explores the use of two-element fiber Bragg structures as point spots for a distributed downhole telemetry, namely, to calibrate Raman systems and to refine their readings for distributed temperature, and additionally get values of pressure at the end of probe fiber. For this purpose, a structural scheme of a distributed-pointed sensor system was proposed that combines a distributed temperature sensor based on incoherent optical frequency reflectometry using Raman scattering with a point thermomanometer based on two-element fiber Bragg structures for observing wells at a wellhead and at the end. Thus, according to the results of the research, the following principles are proposed: the principles of building combined fiber optic systems for the downhole thermometry to solve the problems of compensating for an influence of temperature in point manometry and to clarify the readings of Raman distributed sensors at their key points.

1. Introduction
Distributed fiber optic sensor systems (DFOSS) for the downhole telemetry often have promising qualities. Similar systems use linear scattering, such as Raman scattering as a detection mechanism, in which physical parameters, such as temperature and strain, can be continuously measured over several kilometers, thus leading to thousands of practically equivalent detection points with meter spatial resolution [1]. However, as shown in [2], the required temperature resolution, as the main target parameter of the downhole telemetry (DHT), is often not achieved.

In many areas of industrial application, it is necessary to implement simultaneous measurement of distributed and point field values, thereby ensuring accurate and complete monitoring of the integrity of structures, for example, in monitoring industrial oil and gas enterprises, distributed profile analysis throughout the well. All this, together with information about the temperature at some key points, can help to effectively detect irregularities in operating conditions and at the same time increase the resolution of both temperature measurements using sensors based on fiber Bragg gratings (FBG) at a key point and distributed temperature by improving quality of its calibration.

It should also be noted that the bulk of the costs of measurements in the well using fiber optic sensors (FOS) are optical signal demodulation devices and a special fiber for harsh conditions. In order to optimize the structure of the system and reduce the cost of the system, several combined structures with fiber Bragg gratings and sensors based on the Fabry-Perot resonator with externally
varying distance (EFPI) [2-4] were proposed, but all of them are for point measurements of temperature and pressure. While the combined DTS/FBG scheme (there DTS – a distributed temperature sensor) was proposed for measuring distributed temperature and discrete dynamic pressure [5-9]. Broadband low-reflectivity FBGs, a narrow-band light source and a common receiver were used in this scheme.

2. General scheme of combined sensor system
The pressure and distributed temperature can be measured in an alternative way by controlling a injected current of a laser diode (LD). The structural scheme of the measuring elements of a Raman/DTS/TEFBS system [10-19] (without a recording part, where TEFBS is a two-element fiber Bragg structure) is shown in figure 1.

![Figure 1. The structural scheme of the distributed and point temperature and pressure sensors in the Raman/DTS/TEFBS system.](image)

The system has the TEFBS1 point temperature sensor, which is used as a reference temperature sensor, the TEFBS2 point temperature sensor, a combined pressure and temperature sensor, and a distributed temperature sensor, which uses the entire portion of the optical fiber (figure 1). Since the pressure sensor is sensitive both to pressure and to ambient temperature at the same time, the sensor scheme implies an approach with temperature compensation to achieve high-precision pressure measurements, for which the TEFBS4 pressure sensor is manufactured combined with the TEFBS3 temperature sensor [12]. Here the temperature sensor in this pair is used as a compensation one in a combined pressure and temperature sensor. A sensitive element of all point sensors are TEFBSs with difference frequencies Ωi (i = 1..4), to which a requirement is made for their mutual uniqueness.

3. Incoherent optical frequency reflectometry
The incoherent optical frequency reflectometry uses a laser source of an undamped wave, which is a sinusoidal amplitude modulated by several stepwise variable frequencies. A physical property, such as a position function, can be determined by performing a Fourier transform with the measured frequency response of the backscattered light signal. Thanks to the narrow-band signal detection method and the frequency-modulated continuous wave technology, the incoherent optical frequency reflectometry method has a number of technological advantages, such as an increased signal-to-noise ratio (SNR), lower tuning speed, and longer laser life.

In the Raman DTS system, temperature information is contained in the ratio of anti-Stokes intensity (IaS) to Stokes intensity (IS), which can be expressed as [1]:

\[ R(T(z)) = \frac{I_{aS}(T(z))}{I_S(T(z))} = \kappa \frac{n_{aS} \lambda_{aS}}{n_S \lambda_S} \exp \left( - \frac{h \Delta \nu}{k_B T(z)} \right) \]

where \( \lambda_S \) and \( \lambda_{aS} \) are the wavelengths of Stokes and anti-Stokes scattered light; \( n_S \) and \( n_{aS} \) are the refractive indices for \( \lambda_S \) and \( \lambda_{aS} \), respectively; \( h \) is the Planck constant; \( \Delta \nu \) is the Raman frequency displacement in the fiber; \( k_B \) is the Boltzmann constant; \( T(z) \) is the absolute temperature at \( z \); \( \kappa \) is the calibration constant.

It is known that a semiconductor LD emits stimulated emission if the injected current is above a threshold, and broadband spontaneous emission if the injected current is below the laser generation threshold. A continuous laser source with frequency modulation can be used for the DTS based on the
incoherent optical frequency reflectometry. Broadband light that can be used to demodulate data from the temperature and pressure point sensors based on the TEFBS. Due to the adjustment of the injected current, a single laser diode can be used as a light source for demodulating the DTS and TEFBS sensors. Thus, the pressure and temperature at individual points, and the distributed temperature can be measured in a manner independent of each other.

As a rule, the $\lambda_S$ and $\lambda_aS$ are located in tens of nanometers from the center of the laser light wave ($\lambda_0$) for the DTS system. At the same time, when measuring pressure, reflected light from the TEFBS propagates a wavelength range measured in tens of nanometers with a central wavelength of $\lambda_0$. One can show that there can be no overlap in the spectral ranges of reflected light from TEFBS sensors (for measuring pressure and temperature) with the spectral range of Raman back-scattered light for measuring distributed temperature. Therefore, using the technique of spectral channel multiplexing, the combined Raman/DTS/TEFBS sensor scheme provides a new approach for measuring distributed temperature and pressure and temperature at key points.

4. Structural scheme of the combined Raman/DTS/TEFBS sensor system

The structural scheme of the combined Raman/DTS/TEFBS sensor system is schematically presented in figure 2a.

![](image)

**Figure 2.** a) The experimental installation of the combined Raman/DTS/TEFBS sensor system; b) the optical scheme of the combined pressure and temperature sensor.

As a common light source, a single-mode LD is used with a central emitted wavelength of 1490 nm and the threshold current of 31.7 mA, and the injected current is provided by a reference circuit. To
adjust the operation of the control unit and signal processing, a corresponding unit has been created. The distributed temperature and pressure at key points can be measured both by temporary compaction technology and spectral channel compaction technology [20-28].

When measuring the distributed temperature by the incoherent optical frequency reflectometry, the LD is modulated by a stepwise increase in frequency, and the injected current is above the laser generation threshold. A splitter with a coupling factor of 1:99 separates 1% of the incident light, which is then detected by the photodiode, to measure the initial phase. The laser is launched into a single-mode sensor fiber, and the Raman light scattered backward is filtered by two bandpass optical filters. A filter with a central wavelength of 1390 nm filters the anti-Stokes component, and a filter with a central wavelength of 1590 nm filters the Stokes component, both filters have a 10 nm bandwidth. In addition, the isolation of a filter port at 1490 nm is 70 dB. The filtered Raman light is detected by an avalanche photodiode module. The distributed temperature is demodulated by the signal processing unit.

When measuring pressure (and temperature at control points), the LD emits spontaneous broadband radiation with the injected current of 28 mA. The incident light is directed into the fiber and passes through two frequency filters and enters the optical fiber. The radiation should pass through Sensor 1, 2, and 3 (figure 2a), form a polyharmonic reflected radiation, and through the circulator and an inclined filter, get to the corresponding photodetector.

In works [16-18], two approaches were proposed for the formation of the sensitive elements for the sensors based on the TEFBSs, one of which involves the use of the TEFBSs consisting of two identical spaced apart wavelengths over narrow-band FBGs, and the second - the use of the TEFBSs consisting of FBGs with two symmetrical phase π shifts.

It was also noted there that the use of the TEFBS with two phase shifts is possible when working on signal reflection, which implies the optoelectronic scheme shown in figure 2, while the TEFBS of the through type is advisable to apply for precision measurements. Based on this information, it would be logical to take advantage of both types of the TEFBSs, using the reflective TEFBSs at temperature measuring points (sensor 1 and 2, figure 2a) and a trough type of the TEFBS for a combined pressure and temperature sensor (sensor 3, figure 2a). Therefore, the optical interrogation scheme should be organized in such a way as to simultaneously provide the possibility of interrogating both the distributed temperature along the entire fiber section and the temperature at the control points (sensor 1 and 2, figure 2a) and pressure with temperature (sensor 3, figure 2a).

The combined pressure and temperature sensor is located at the end of the fiber, which makes it possible to organize a measuring interrogation scheme in such a way as to ensure that the radiation passes through the sensor 3 - through both DVBS (DVBS-Temperature and DVBS-Pressure) separately - return it in the opposite direction of the optical fiber, thereby ensuring unified processing of the reflected signal at the photodetector. The optical scheme of the combined pressure and temperature sensor is shown in figure 4b. In the combined pressure and temperature sensor, Insulators 1 and 2 are installed at 1490 nm, and optical splitters are used (figure 2b) to ensure parallel passage of the light flux through the TEFBS-Pressure and TEFBS-Temperature and return of the reflected signal to the fiber in the opposite direction.

5. Simulation of the combined Raman/DTS/TEFBS sensor system

The equivalent computer model of the optoelectronic interrogation system of the TEFBS sensors, made in the OptiSystem software package, where, in contrast to the functional scheme (figure 2), only the part of the functional scheme that is responsible for interrogating the TEFBS sensors, which is a justifiable solution, since the TEFBS and DTS polling is conducted independently.

The broadband light signal, modulated by four TEFBS sensors, is reflected back and sent by the optical circulator through the filter with an inclined characteristic to the photodetector. The resulting signal after the photodetector is a multiplexed beat signal of all frequency components of all sensors between each other. After that, the resulting signal is subjected to frequency filtering at the differential frequencies of the TEFBS and processed by a computer according to the algorithm described in [45,
A specialized FBG with a pre-synthesized spectral shape of the profile can be used as the filter with the inclined amplitude-frequency characteristic.

To increase the accuracy of measurements of four TEFBS sensors, which are sensitive elements of three sensors, it is proposed to group by wavelengths by combining two temperature sensors per wavelength (1490.50 nm) and TEFBS pressure sensors (TEFBS-Temperature and TEFBS-Pressure) to another wavelength (1490.00 nm), thereby ensuring higher measurement accuracy and a low-touch approach to determining the shift of the central wavelength for each group of sensors.

The distributed temperature and temperature with pressure at the control points are measured independently and spaced in time. The first part of the period is used to measure the distributed temperature, and the rest of the period is used to measure pressure and temperature. There is no influence of the TEFBS array of sensors on the measurement of distributed temperature, since measurements are made at different frequencies, so that the array of TEFBS sensors is transparent to the radiation used for measuring the distributed temperature, and does not affect the measurement results. The readings of the TEFBS sensors for each measurement period are averaged to improve the SNR [28-32]. A figure 3 shows situational graphs of the reflection spectra from the TEFBS array in the optical range (figure 3a) and after the photodetector (figure 3b). The dashed line in figure 6a denotes the amplitude-frequency characteristic of the linear inclined filter. In figure 3b, the dashed line shows the difference frequencies of the TEFBS sensors.

Perform a simulation of the central wavelengths displacement of the TEFBS-Temperature (in the range from 1490.00 to 1490.10 nm) and TEFBS-Pressure (in the range from 1490.00 to 1490.15 nm) with a uniform discrete step that provides 20 independent positions of the TEFBS. The dependence of the electric signal power on the central frequencies displacement of the TEFBS-Temperature and TEFBS-Pressure, which passed through the frequency filters corresponding to the difference frequencies of the TEFBS, is shown in figure 4.

The values of the signal power after filtering at the difference frequencies of the TEFBSs at each of their positions are the input data for determining the displacements of the central wavelengths of the TEFBSs. And the determination of the central frequencies (central wavelengths) of the WBS is carried out according to the method described in [2], since the relative position of the TEFBS-Temperature and TEFBS-Pressure with respect to the TEFBS used to determine the temperature excludes the occurrence of multiple or equal frequencies to the difference frequencies. Certain center frequencies
(center wavelengths) of the TEFBSs sensors serve as the basis for measuring the conversion of the center frequency displacement to the temperature and pressure values.

![Graph](image)

**Figure 4.** Results of pressure measurement with the temperature compensation.

Consider how to increase the resolution of the temperature sensor. By analogy with the fact that the TEFBS sensor can be three orders of magnitude narrower than the original FBG from which it is formed. Accordingly, when forming a double TEFBS, it is possible to obtain the required bandwidth of the difference frequency bands of 1 kHz. Thus, a realistic achievable resolution of 0.01°C can be obtained with the difference frequency spacing of the order of 20 MHz, which significantly reduces the requirements for the element base of photodetectors and reduces the device cost.

6. Conclusion

Based on the presented studies, the principles of constructing of combined fiber-optic systems for the downhole thermometry to solve the problems of compensating for the influence of temperature in point manometry and to clarify the readings of the Raman distributed sensors at their key points are proposed; the technique of combined microwave-photonic measurement conversion and determination of its main methodological errors was developed.

To monitor wells at the wellhead and at the end, the structural scheme of the combined sensor system based on the incoherent optical frequency reflectometry of the temperature sensor based on Raman scattering of the DTS with the thermomanometer based on the TEFBS is proposed. Using the LD as the common radiation source, the combined single-fiber DTS/TEFBS sensor system was created, where activated and spontaneous LD radiation are used for solid-state radiation and probing TEFBS, respectively. The obtained experimental data show that the distributed temperature and temperature at key points can be measured in an alternative way with low noise and higher resolution, reaching 0.008°C, especially when using the TEFBS as the temperature sensor.

The temperature measured by the combined TEFBS sensor was used to compensate for the pressure measurement. The distributed temperature was measured using the method of the incoherent optical frequency reflectometry with the injected current modulated above the laser generation threshold.

The possibilities for measuring point pressure and distributed temperature are opened independently as a result of the work done. And the results of numerical experiments show that both
the distributed temperature and pressure can be measured with only minor hindrances. Additionally we use this system in collaboration for power transmission line monitoring [33].

References
[1] Toccafondo I, Taki M, Signorini A, Zaidi F, Nannipieri T, Faralli S and Di Pasquale F 2012 Hybrid Raman/fiber Bragg grating sensor for distributed temperature and discrete dynamic strain measurements Opt. Lett. Papers 37 4434-6
[2] Chen K, Zhou X, Yang Y and Yu Q 2016 A hybrid Raman/EFPI/FBG sensing system for distributed temperature and key-point pressure measurements Proc. SPIE 9620 96200R
[3] Zaidi F, Nannipieri T, Soto M A, Signorini A, Bolognini G and Di Pasquale F 2012 Integrated hybrid Raman/fiber Bragg grating interrogation scheme for distributed temperature and point dynamic strain measurements Appl. Opt. 51 7268-75
[4] Bao X and Chen L 2012 Recent progress in distributed fiber optic sensors Sensors Papers 12 8601-39
[5] Gogolla T and Krebber K 1997 Fiber sensors for distributed temperature and strain measurements using Brillouin scattering and frequency-domain methods Proc. SPIE 3105 168-80
[6] Zaidi F and Krebber K. 2014 Advanced hybrid BOFDA/FG sensor system for simultaneously point-wise and distributed temperature/strain measurements Proc. SPIE 9157 915768
[7] Motil A, Bergman A and Tur M 2016 State of the art of Brillouin fiber-optic distributed sensing Opt. Laser Technol. 78 81-103
[8] Bao X and Chen L 2011 Recent Progress in Brillouin Scattering Based Fiber Sensors Sensors 11 4152-87
[9] Morozov O G, Nureev I I, Sakhabutdinov A Zh, Feofilaktov S V, Danilaev D P, Denisenko P E and Dautova R V 2014 Software defined down-hole telemetric systems: training course Proc. SPIE 9533 953311
[10] Morozov O G, Natanson O G, Aibatov D L, Ilyin G I and Kalatcheva E A 2006 Two-frequency analysis of fiber-optic structures Proc. SPIE 6277 62770E
[11] Natanson O G, Morozov O G, Akhtiamov R A and Gusev V F 2005 Development problems of frequency reflectometry for monitoring systems of optical fiber structures Proc. SPIE 5854 215-23
[12] Sahabutdinov A Z, Kuznetsov A A, Nureev I I, Morozov O G, Faskhutdinov L M, Petrov A V and Kuchev S M 2015 Calibration of combined pressure and temperature sensors Int. Journal of Applied Engineering Research 10 44948-57
[13] Morozov O G, Talipov A A, Morozov G A and Kupriyanov V G 2013 Characterization of stimulated Mandelstam-Brillouin scattering spectrum using a double-frequency probing radiation Proc. SPIE 8787 878709
[14] Morozov O G, Talipov A A and Morozov G A 2014 Principles of multiple frequencies characterization of stimulated Mandelstam-Brillouin gain spectrum Proc. SPIE 9156 91560K
[15] Morozov O G, Morozov G A, Nureev I I, Kasimova D I, Zastella M Y, Gavrilo P V, Makarov I A and Purtov V A 2016 Optical vector network analyzer based on amplitude-phase modulation Proc. SPIE 9807 980717
[16] Morozov O G and Sakhabutdinov A J 2019 Addressed fiber Bragg structures in quasi-distributed microwave-photonic sensor systems Computer Optics 43 535-43
[17] Agliullin T A, Gubaidullin R R, Ivanov V, Morozov O G and Sakhabutdinov A Zh 2019 Addressed FBG-structures for tire strain measurement Proc. SPIE 11146 111461E
[18] Gubaidullin R R, Agliullin T A, Ivanov V, Morozov O G and Sakhabutdinov A Zh 2019 Tire dynamic monitoring system based on microwave photonic sensors Proc. SPIE 11146 111461J
[19] Morozov O G, Denisenko P E, Denisenko E P, Zastela M Y, Kuznetsov A A and Kazarov V Y 2017 Fiber-optic Bragg sensors with special spectrum shapes for climatic test systems Proc. SPIE 10342 1034217

[20] Morozov O G, Il'in G I, Morozov G A, Nureev I I and Misbakhov R S 2016 External amplitude-phase modulation of laser radiation for generation of microwave frequency carriers and optical poly-harmonic signals: an overview Proc. SPIE 9807 980711

[21] Il'in G I, Morozov O G and Il'in A G 2014 Theory of symmetrical two-frequency signals and key aspects of its application Proc. of SPIE 9156 91560M

[22] Morozov O G, Natanson O G, Aybatov D L, Prosvirin V P and Talipov A A 2008 Methodology of symmetric double frequency reflectometry for selective fiber optic structures Proc. SPIE 7026 70260J

[23] Morozov O G, Natanson O G, Aybatov D L, Talipov A A, Prosvirin V P and Smirnov A S 2008 Metrological aspects of symmetric double frequency and multi frequency reflectometry for fiber Bragg structures Proc. SPIE 7026 70260J

[24] Morozov O G and Sadeev T S 2011 All-optical microwave photonic filter based on two-frequency optical source Proc. SPIE 7992 79920C

[25] Sadeev T S and Morozov O G 2012 Investigation and analysis of electro-optical devices in implementation of microwave photonic filters Proc. SPIE 8410 841007

[26] Aybatov D L, Morozov O G and Sadeev T S 2011 Dual port MZM based optical comb generator for all-optical microwave photonic devices Proc. SPIE 7992 7992002

[27] Morozov O G 2012 RZ, CS-RZ, and soliton generation for access networks applications: problems and variants of decisions Proc. SPIE 8410 84100P

[28] Aybatov D L and Morozov O G 2010 Spectrum conversion investigation in lithium niobate Mach-Zehnder modulator Proc. SPIE 7523 75230D

[29] Sakhabutdinov A J, Morozov O G, Ivanov A A and Misbakhov Rin Sh 2018 Multiple frequencies analysis in FBG based instantaneous frequency measurements IEEE Proc. 2018 Int. Conf. on System of Signals Generating and Processing in the Field of on Board Communications (14-15 March 2018, Moscow, Russia) pp 1-5

[30] Sakhabutdinov A J, Morozov O G, Ivanov A A, Morozov G A, Misbakhov Rin Sh and Feofilaktov S V 2018 Multiple frequencies analysis in tasks of FBG based instantaneous frequency measurements Proc. SPIE 10774 107740Y

[31] Ivanov A A, Morozov O G, Andreev V A, Morozov G A, Kuznetsov A A and Faskhutdinov L M 2017 Microwave photonic system for instantaneous frequency measurement based on principles of “frequency-amplitude” conversion in fiber Bragg grating and additional frequency separation Proc. SPIE 10342 103421A

[32] Ivanov A A, Morozov O G, Andreev V A, Kuznetsov A A and Faskhutdinov L M 2017 Radiophotonic method for instantaneous frequency measurement based on principles of “frequency-amplitude” conversion in Fiber Bragg grating and additional frequency separation IEEE 2017 XI International Conference on Antenna Theory and Techniques (24-27 May 2017, Kiev, Ukraine) pp 425-8

[33] Misbakhov R S 2019 Combined Raman DTS and Address FBG Sensor System for Distributed and Point Temperature and Strain Compensation Measurements IEEE Proc. 2019 Int. Ural Conf. on Electrical Power Engineering (1-3 Oct. 2019, Chelyabinsk, Russia) pp 64-8