Combined Brillouin sensor system for simultaneous local and distributed temperature and strain measurements for downhole telemetry

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Abstract. The work proposes and experimentally demonstrates the feasibility of creating a combined sensor system for simultaneous local and distributed temperature and strain measurements using the Brillouin optical frequency distributed analysis. The system uses a quasi-distributed approach based on two-element fiber Bragg structures (TEFBS), which makes it possible to carry out simultaneously distributed and local measurements of temperature. The proposed highly integrated circuit uses a conventional narrow-band optical source corresponding to the spectral range of temperature measurements, and a common receiving module on the same sensor fiber. For distributed detection, a single-mode optical fiber is used, and for the local detection, two TEFBS pass-through and reflective types are used.

1. Distributed Brillouin optical frequency analysis system
The Brillouin optical frequency distributed analysis system is based on measurement of the complex transmission function of the modulating frequency band associated with the amplitudes of both a counter-propagating continuous wave (i.e. pumping, sinusoidal modulated by the intensity), and a tuned light probe along the fiber. The latter interacts with acoustic phonons launched into the sensing fiber by stimulated Brillouin scattering [1-2]. The working frequency of a narrow-band light probe is reduced in comparison with the working frequency of the pump laser by an amount equal to the characteristic Brillouin frequency of the fiber. The maximum energy transfer from the pump to the probe occurs at each point of the fiber when the frequency spacing between the optical waves becomes equal to the local acoustic frequency in the fiber, which is called the Brillouin frequency shift that is a parameter dependent on temperature and strain. By measuring the transfer function of the modulating frequency band of the sensing fiber and calculating the inverse fast Fourier transform, the Brillouin gain spectrum can be recreated and the Brillouin frequency shift can be roughly calculated, which will provide information on the variation in temperature and strain along the entire sensing fiber [3-5].

On the other hand, FBG-based point detection is a well-known method [6], which uses a linear shift in the Bragg wavelength using local changes in temperature and strain:
\[ \Delta \lambda_B = (\alpha + \xi) \Delta T + (1 - p_e) \Delta \varepsilon \]  

where \( \Delta T \) and \( \Delta \varepsilon \) are temperature and strain variations; \( \alpha \) and \( \xi \) are the coefficient of thermal expansion and thermo-optical coefficient, respectively; \( p_e \) is the constant of optical sensitivity of the fiber material.

Let’s take for our system TEFBS as point sensors. Theory of TEFBS based on two-frequency probing methods of classical FBG [7-16] and methods of instantaneous frequencies measurements as a result of two components beating [17-20].

A working probing scheme for two TEFBSs [21-23] interrogation for simultaneous local measurements is shown in figure 1.

![Figure 1. Probing scheme of two TEFBSs.](image)

The red and green lines in figure 1 represent the spectral characteristics of TEFBS\(_{1,2} \), in the case of radiation passing through them (TEFBS reflecting); LR is the laser radiation, Stokes is the Stokes component, Probe is the radiation of the probe signal. In the general case, if there is an effect on the optical fiber, the Stokes component and the probe radiation will not coincide; if there is no effect, they will coincide.

The method uses a narrow-band laser with continuous pump radiation, a laser with the radiation bandwidth to control the central wavelength position of local temperature sensors, two TEFBS\(_{1,2} \) with a Bragg frequency \( \omega_B \) and difference frequencies \( \Omega_1 \) and \( \Omega_2 \), \( \Omega_1 \neq \Omega_2 \). The optoelectronic circuit of the proposed combined sensor is shown in figure 2. The full width at half height of the TEFBS\(_{1,2} \) is about 250 GHz, the distance between the central frequency \( \omega_B \) and the laser frequency is selected in such a way to exclude the possibility of the intersection of the TEFBS spectrum and the pump laser frequency with its probe component.

An optical coupler C\(_1 \) into two branches divides the light from a source of continuous narrow-band laser radiation (Laser, figure 2, \( \sim 17 \) dBm of output power at \( \sim 1550 \) nm). One of the branches is used to create a continuous signal, which is used as Brillouin pumping, while the other branch is responsible for creating a continuous temperature probe. Broadband laser radiation corresponding to the temperature measurement range of the TEFBS\(_{1,2} \) sensors from the LD laser source (figure 2) enters the fiber from the side of the pump arm after the circulator Circ. 1.

It is designed to determine the central wavelength position of the local temperature sensors TEFBS\(_1 \) and TEFBS\(_2 \). The radiation bandwidth of the LD corresponds to the temperature measurement range of the temperature sensors TEFBS\(_1 \) and TEFBS\(_2 \). The polarization control device – the polarization controller (PC\(_1 \)) and the Mach-Zehnder modulator (MZM\(_1 \)), controlled by a vector network analyzer (Vector Analyzer), are used to sinusoidal modulate the intensity of continuous radiation. An optical frequency filter (OF\(_1 \)) is used to remove noise, and a polarization coder (Pol. Cod.) is used to depolarize the pump signal and to avoid fluctuations caused by polarization in Brillouin amplification. In the other branch, the laser radiation is modulated by the second MZM\(_2 \) using a microwave signal.
generator to create a two-way band probing signal. After that, OF$_2$ is used to select low-frequency probes (Stokes component), thereby removing noise, secondary suppressed carrier, and to select a high-frequency probe sideband (anti-Stokes component). The pump laser is directed into a $\sim 2.1$-km standard single-mode fiber (SMF-28) through an optical circulator (Circ.1), which is also used to extract both the probe signal and the reflected components at the pump frequency.

![Figure 2. Optoelectronic scheme of combined sensor system of distributed Brillouin optical frequency analysis.](image)

Both components of the radiation enter a common receiving unit, which consists of an optical circulator (Circ. 2) and two FBGs. The first one is a narrow-band FBG with a bandwidth of 2 GHz, used as a filter - 2 GHz OF, figure 2, while the second FBG has a reflection band corresponding to the transparency windows of TEFBS$_{1,2}$, directing the probe and reflected pump light to different ports of the photodetector, and to the Vector Analyzer. A pair of weakly reflecting TEFBSs (TEFBS$_1$, TEFBS$_2$) with a full width at half maximum of $\sim 2.5$ nm are used in the scheme - one at the probe entrance (TEFBS$_1$), and the second one - at the tip of the probe (TEFBS$_2$). The TEFBSs are connected by $\sim 2.2$-km sections of the sensing fiber to assess the temperature at the points of their location. The central wavelengths of the TEFBSs are chosen so that they are transparent both for the probing signal and for the pump wavelength, together with their Stokes and anti-Stokes components. Laser light can be amplified with an erbium-doped fiber amplifier to create a pump, as well as to provide a reference signal.

The response of TEFBS$_{1,2}$ taken at the PD$_1$ photodetector (figure 2) after its reflection from frequency filters that cut out the initial reflection of the signal (Rayleigh) and from TEFBS (figure 3, a) will take the form of five-frequency radiation, the spectral shape of which is shown in figure 3, b.

In this case, the beat signal [24-29] that will appear on the PD$_1$ photodetector (figure 2) will be similar to the beating signal that occurs in a two-sensor TEFBS system, with the addition of the cross-beat frequencies of the laser frequency $\omega_L$ from each of the frequency components of the TEFBS$_{1,2}$ - (2). The first six terms in (2) coincide with the type of signal for a dual TEFBS sensor [3]; the last four terms describe the contribution of cross beats from the presence of the laser frequency in the signal.

2. Temperature determination
The condition that the spectra of the laser and TEFBS$_{1,2}$ do not intersect means that the relative position of the TEFBS and the laser in the amplitude-frequency plane ensures that the last term does not contribute (underlined in (2)) to the oscillations at the difference frequencies $\Omega_1$ and $\Omega_2$ for any relative position of TEFBS$_{1,2}$ and the laser (figure 3, b) in the amplitude-frequency plane [30].
Figure 3. (a) – intensity of the reflected pulse from TEFBS\textsubscript{1}, and (b) – from TEFBS\textsubscript{2} at different temperatures.

\[
P(t) = \left[ A_i^2 + B_i^2 + A_j^2 + B_j^2 + L^2 \right] + \left[ A_i B_i \cos(\Omega_1 t) + A_j B_j \cos(\Omega_2 t) \right] + \]
\[
+ \left[ A_i A_j \cos\left( \omega_1 - \Omega_1 \right) - \left( \omega_2 - \Omega_2 \right) \right] + A_i B_j \cos\left( \omega_1 - \Omega_1 \right) - \left( \omega_2 + \Omega_2 \right) \right] + \]
\[
+ B_i A_j \cos\left( \omega_2 - \Omega_2 \right) - \left( \omega_1 + \Omega_1 \right) + B_i B_j \cos\left( \omega_2 + \Omega_2 \right) - \left( \omega_1 - \Omega_1 \right) \right] \]
\[
+ A_L \cos\left( \omega_1 - \Omega_1 - \omega_L \right) + B_L \cos\left( \omega_2 + \Omega_2 - \omega_L \right) + \]
\[
+ A_L \cos\left( \omega_2 - \Omega_2 - \omega_L \right) + B_L \cos\left( \omega_1 + \Omega_1 - \omega_L \right) \right]
\]

This requirement can be easily fulfilled by requiring that the minimum distance between the right frequency component of TEFBS\textsubscript{1,2} and the laser frequency does not exceed the maximum difference frequency of TEFBS, namely:

\[
\left[ u \left( \omega_i \pm \Omega_1 \right) + v \right] - \omega_k > \Omega_k, \quad \forall i, k = 1, 2 \cdot
\]

When fulfilling (3), the position determination of the TEFBS\textsubscript{1,2} can be carried out according to the algorithm proposed in [3] by frequency filtering (2) at difference frequencies \(\Omega_1\) and \(\Omega_2\) and not taking into account the probability of the contribution of the probable contribution of the terms emphasized in (2) to the filtering result, which significantly simplifies the task.

The frequency filtering (2) at the difference frequencies \(\Omega_1\) and \(\Omega_2\) gives two equations (4) for determining two unknown values \(\omega_1\) and \(\omega_2\), with the previously known relation between the amplitudes \(A_i\) and \(B_i\) and the frequencies \(\omega_k\) through linear inclined filter parameters \(u, v\).

An example of computer simulation of extreme values of the TEFBS\textsubscript{1,2} parameters and the laser position, which satisfy the abovementioned requirements, is presented below. The optical spectra of TEFBS\textsubscript{1,2} are shown in figure 4 (a) and (b), respectively, while the difference frequency of TEFBS\textsubscript{1} is \(\Omega_1 = 6.15\) GHz, for TEFBS\textsubscript{2} is \(\Omega_2 = 8.96\) GHz. The situational spectrum of the closest possible mutual arrangement of the TEFBS\textsubscript{1,2} and the laser is shown in figure 4 (c) and the spectrum at the photodetector – in figure 4 (d).
Figure 4, the letter “A” indicates the laser radiation, the letter “B” indicates the left frequency component of the TEFBS$_1$, and the letter “C” is the right frequency component of the TEFBS$_2$.

![Graphs showing optical spectra and situational spectrum.](image)

Figure 4. (a), (b) – optical spectra of TEFBS$_{1,2}$, respectively; (c) – the situational spectrum of the closest possible mutual arrangement of the TEFBS$_{1,2}$ and the laser; (d) – the spectrum at the photodetector.

It can be concluded that the minimum distance between the laser radiation and the position of TEFBS$_1$ (“A – B”) is 2.19 GHz, which exceeds the maximum distance between the frequency components of TEFBS$_1$ and TEFBS$_2$ (“B – C”), which is equal to 20 GHz. Thus the requirement (3) is provided.

The requirement (3) does not impose an additional restriction on the range of the center frequency shift of the TEFBS$_{1,2}$, if the task is to measure only the temperature (4).

Therefore, it is enough to separate the central frequencies of the TEFBS$_{1,2}$ sensors and the laser to a distance that is higher than the maximum difference frequency in the system or greater than the frequency limit of the sensitivity of the photodetector. It is worth noting that frequencies above 40 GHz are beyond the capabilities of the available photodetectors and ADCs [31], therefore, the beating signal with a frequency exceeding the maximum allowable frequency will not occur on the photodetector. Therefore, by spreading the laser and the TEFBS by more than 40 GHz, it is possible to guarantee the possibility of temperature measurements in an arbitrary range.

3. Monitoring of laser position

The expression (3) can be supplemented with the requirement (5) so that the maximum difference frequency that occurs in the system does not exceed the maximum capacity of the receiving equipment.
measures of temperature. The proposed highly integrated circuit uses a conventional narrow-band optical source broadened in spectrum to a temperature measurement range and has a common receiving module on the same sensor fiber. For distributed measurements, a single-mode
optical fiber is used, and for the local measurements, two DEFBS are used. The achieved resolution for calibrating the distributed system is 0.01 °C and is determined by DEFBS.

The possibilities for measuring point pressure and distributed temperature are opened independently because of the work done. 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 [32].

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