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Distributed temperature sensing in optical fibers based on Raman scattering: theory and applications

Abstract

Distributed temperature sensing (DTS) based on Raman scattering in optical fibers gains more importance in several applications, due to its accuracy, immunity to electromagnetic interference and corrosion, durability, low cost and availability. DTS systems are configured differently depending on the environment of application, and uses Optical Time Domain Reflectometry (OTDR) or Optical Frequency Domain Reflectometry (OFDR) for data analyzes. This study features a theoretical background and an introduction to DTS systems' configurations and applications.

Keywords: Distributed Temperature Sensing (DTS), Optical Time Domain Reflectometry (OTDR), spontaneous Raman scattering, distributed fiber sensor.

1. Introduction

Distributed temperature sensing (DTS) based on Raman scattering in optical fibers is commonly used in spectroscopy applications [1], remote sensing [1], fire and leak detection in oil and gas industries [2-5], energy cables thermal distribution [3, 5], nuclear industry [2, 6], pipeline monitoring [7], structure monitoring [5] and hydrology [7-9]: atmospheric processes [10], temperature in lakes [11], soil water content [12], groundwater-surface water interactions [13]. The advantage of using silica fibers in such applications results from their immunity to electromagnetic interference, durability, low cost and availability, large bandwidth and their efficiency in light transport [1, 14].

DTS is a method, in which only one detector receives data from various measurement points along the cable. The fiber itself is a sensor, while the detector is placed at the beginning of the fiber cable [14]. Optical fibers are largely used in fiber attenuation, temperature and strain measurements [15]. DTS systems are built in different configurations, depending on the application and the environment, in which the optical fiber is placed.

Raman back-scattered light is analyzed using Optical Time Domain Reflectometry (OTDR) [2, 3, 14] or Optical Frequency Domain Reflectometry (OFDR) [15], focusing on the back-scattered light's components: Rayleigh, Stokes and anti-Stokes [14, 15] in order to obtain calibrated measurements of the temperature, strain and distance. Raman analyzes based on OTDR is used for distributed temperature measurements through studying the back scattered light to determine the optical loss and the temperature along the fiber. OFDR analyzes are used to determine the modulation transfer function of a length of the fiber [15].

This study presents a theoretical background, configuration and components of DTS systems based on Raman scattering, essential calculations and calibrations for different configurations.

2. Theory

The relation between frequencies of incident and scattered photons determine the effect of light scattering in the fiber. This classification distinguishes two groups: elastic scattering and inelastic scattering. In elastic scattering, the frequencies of incident and scattered photons are equal, which means that Rayleigh scattering, which occurs due to the transfer of a part of the optical power from one mode to another linearly, is an example of elastic scattering. Rayleigh scattering is caused by the density and structure of fiber's material. In inelastic scattering, the frequencies of incident and scattered photons are not equal, which examples are Raman and Brillouin scatterings. Raman and Brillouin scatterings occur due to molecular and volumetric vibrations. In Raman scattering, the frequency of scattered photons shifts to a specific value, which is equal to the characteristic vibration frequency of the molecules. This shift might be to higher frequencies (Raman anti-Stokes) or lower frequencies (Raman Stokes) [14].

DTS systems for measuring temperature, strain and distance are based on spontaneous Raman scattering [15, 16]. One must notice the difference between spontaneous and stimulated Raman scattering. Generally, the spontaneous Raman scattering is a linear phenomenon, while the stimulated Raman scattering is a third order nonlinear process [17]. The way the Raman resonance is created and the mechanism of detection define the classification of Raman scattering. The Raman resonance is created in a spontaneous manner if one input field is addressing the molecule, while stimulated Raman resonance is created when two input fields are addressing the molecule. Raman signal is spontaneous if detected in an initially vacant mode field, and the Raman signal is stimulated If detected at a field mode occupied by one of the input fields [18]. The advantage of the spontaneous Raman scattering technique is the ability to provide instant and spatially resolved temperature measurements using a single laser beam without the need for tuning [19].

Optical fibers have applications in noncontact vibration measurements and indicating the relative position of the reflective surface (end of the fiber, strain). Optical fibers are immune to electromagnetic fields' influence and corrosion and can transmit modulated optical signals over long distances. DTS exploits optical fibers as sensors, providing sensing points over very wide area [20]. Raman scattering distributed temperature sensing is strongly sensitive to temperature, which is its big advantage over Rayleigh or Brillouin, which are sensitive to strain. One can achieve combined measurements of discriminated temperature and strain values using two fibers and both Raman and Rayleigh (or Brillouin) scattering [21].

DTS systems are defined in the means of performance and limitations [14]:

1. Fiber length (spatial range): is the maximum length of the fiber, over which measurements can be made within a specific accuracy:

$$L_{max} = \frac{cT}{2n}, \tag{1}$$

where: c – is the speed of light in the vacuum, T – is the laser pulse period, n – is the reflective index of the fiber.

2. Spatial resolution and sampling interval: is the distance between 10% and 90% of the temperature variation in the temperature versus distance graphic. This parameter determines the DTS system response to local temperature variations and its ability to measure and locate the features of interest:

$$\Delta z_{min} = \frac{c\tau}{2n}, \tag{2}$$

where: τ – is the pulse duration.

3. Temperature resolution: is the minimum noticeable difference between two temperatures that can be expanded by the measuring system. It indicates the system's ability to respond to minimum temperature variations.

4. Measurement time: is the time required to obtain the temperature profile with a specific resolution of the fiber sensor.
5. Thermal response time: In general, thermal response time is typically less than 0.5 s in the fiber.

The capability of the distributed temperature sensing systems based on optical fibers has improved over the years. Systems' spatial resolution, temperature resolution and time resolution have been improved through apparatus optimization, system configuration and demodulation algorithms [22].

In 1976, Barnoski and Jensen [23] proposed the optical time domain reflectometry (OTDR) as the first method for optical fiber distributed sensing. They used OTDR using Rayleigh scattering to determine optical loss along the fiber and estimate its length. Barnoski and Jensen reached a conclusion that this method determines attenuation characteristics of the fiber independently from fiber's length and coupling constant for the results depend only on the shape of the detected signal and not its absolute magnitude. Thanks to this method, fiber's length can be easily determined, and distributed scattering along the fiber can be used to study the fiber's state and efficiency.

In spontaneous Raman scattering, the fiber absorbs light and reemits it as photons with a different energy distribution, which is determined by the Raman spectrum of the fiber's material [20]. In Raman stokes, the final energy state energy E2 is higher than the initial energy state E1, and the frequency of the emitted photon is lower than the frequency of incident. This difference in energy means that the molecule is exited. In Raman anti-stokes, the initial energy state is E2, and by interacting with incident photon the molecules is exited to virtual energy state E4, and drops to the lower, final energy state E1, which means that the frequency of the emitted anti-stokes photon is higher than the frequency of incident. The intensity of stokes signals is higher than the anti-stokes intensity. The anti-stokes transition probability is higher when molecules temperature is increased [15].

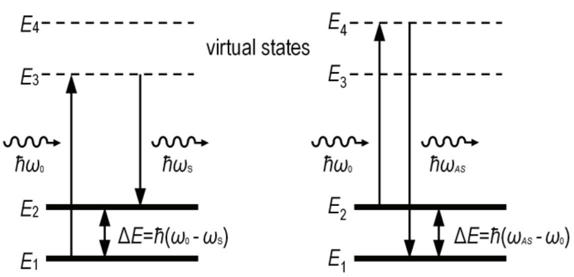

Fig. 1. Raman Stokes scattering (left) and anti-stokes scattering (right) [15]

Placzek [24], Loudon [25] and Long [26] studied Raman intensity. The backscattered intensity profile is a function of local attenuation, which can be caused by physical perturbations, i.e. bends, tensions, compressions, radiation and chemical contamination, as well as pure temperature effects. These attenuations may lead to an error in temperature measurements due to differential attenuation problems [27]. For an accurate temperature measurement, the effect of local attenuations should be eliminated at the time of deployment and afterward continuously. This is mainly due to the inherent attenuation difference in stokes and anti-stokes components, as their wavelengths are different, ranging from 100 to 200 nm depending on the light source [28]. Stokes and anti-Stokes intensities can be obtained using the equations [29]:

$$I_S(T) = k_S\left(\frac{1}{\exp(A)-1} + 1\right), \tag{3}$$

$$I_{AS}(T) = k_{AS}\left(\frac{1}{\exp(A)-1}\right), \tag{4}$$

$$A = \frac{h\Delta v}{kT}, \tag{5}$$

where: k_S, k_{AS} – are the coefficient of temperature sensitivity of the Raman intensity ($k_S \sim 0.8\%$K, $k_{AS} \sim 0.1\%$K), h – is Planck constant, k – is Boltzmann constant, Δv – is the Raman frequency shift in Hz.

Raman anti-stokes lines are very sensitive to temperature changes around the cable [3]. The intensity of the Raman anti-stokes component is three orders of magnitude less than the whole scattered signal, but its sensitivity in room temperature is high [30]. In temperature calculations, Raman anti-Stokes component is normalized to the Raman Stokes or Rayleigh backscattered component to compensate for spurious losses along the sensing fiber [30].

3. Configurations of DTS systems

The fundamental components of a Raman DTS system for temperature measurements are the light source, which can be a laser or a laser diode, the fiber, which is the multipoint sensor, and the receiver, which is commonly an avalanche photodiode [29]. One must notice the peak power and pulse width of the laser, since the laser's peak power should be greater than the threshold value, therefore the spontaneous Raman scattering occurs, and the importance of pulse width in determining the spatial resolution. The threshold power can be obtained by [14]:

$$P_0^{th} = \frac{16A_{eff}}{L_{eff}g_r}, \tag{6}$$

$$A_{eff} = \pi\, r^2\left(0.65 + 1.619v_0^{-3/2} + 2.879v_0^{-6}\right)^2, \tag{7}$$

$$L_{eff} = \frac{1}{\alpha_p[1-exp(-\alpha_p L)]}, \tag{8}$$

where: A_{eff} – is the effective cross-sectional area, L_{eff} – is the effective length of the fiber, g_r – is the Raman gain constant (10^{-13} mV), r – is the fiber's core radius, v_0 – is the source's frequency, α_p – is the absorption constant of the pumping light, L – is the fiber's length.

Overall DTS system configuration based on OTDR is shown in Fig. 2. A pulse of the laser is launched in the fiber at a known wavelength. The anti-Stokes band, which is weak but temperature sensitive, is chosen from the backscattered light spectrum, and is separated from the generated pulses using a directional coupler. The anti-Stokes signal is later filtered and detected by the photodiode. Next the analog-to-digital converter amplifies and digitalizes the signal, leading it to the computer to be analyzed [14].

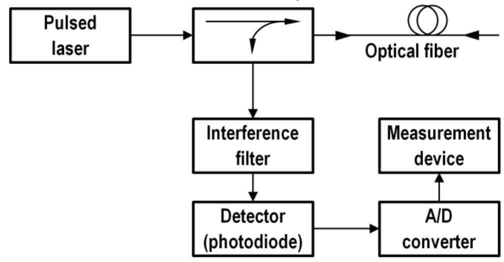

Fig. 2. DTS system based on OTDR analyzes [14]

DTS system configuration based on OFDR is shown in Fig. 3. The laser pulses are modulated by an electrooptic modulator (EOM), which is driven by a signal generator, producing modulated light not simultaneously with different frequencies but one after another. This input signal is detected on PIN photodiode.

The back scattered Stokes and anti-Stokes components are divided and separately leaded to the detectors. Next, the network analyzer down-converts the signals to a low frequency range, and the analog-to-digital converter digitizes them in order to calculate their phase and amplitude by a digital signal processor [15].

The signal input unit in DTS systems can be a laser or a laser diode. Commonly used are ND:YAG [15] or EDFA [32] lasers, with pulse width of 10 ns [3], 40 ns [23], 200 ns [30] or other values depending on the application.

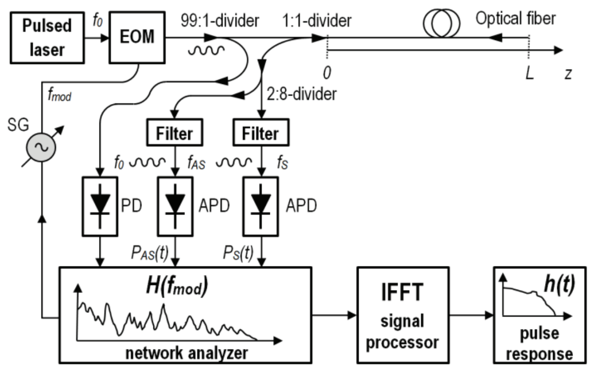

Fig. 3. DTS system based on OFDR analyzes [14, 15]

Liquid-core fibers [34] were used in DTS systems to estimate both temperature and distance using OTDR. However, their longevity is not known, resulting solid-core fibers to be preferred [30]. The type of fiber determines its field of use. Single-mode fibers and multi-mode graded index fibers are used in applications demanding long spatial range and high spatial resolution [14], while multi-mode step index fibers are suitable for low modulation frequencies, short probe lengths and low spatial resolutions [15]. Fibers are set in a one-ended configuration [16, 32, 33] or in a loop configuration [15, 23], also depending on the type of application and the environment of studies. The one-ended configuration in Raman DTS relies on the measurement of Raman stokes and anti-stokes components at one end of the fiber. Therefore, the temperature readings are sensitive to the slope of the radiation-induced attenuation spectrum (for silica the Raman shift is 440 cm^{-1}). This configuration suffers a relatively large error that precludes its use without calibration.

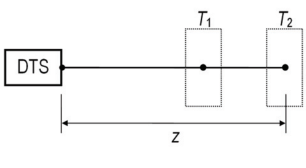

Fig. 4. DTS system in single-ended configuration

The single-ended configuration also suffers from the impact of fiber wavelength-dependent losses (WDL). This can be eliminated using a loop scheme with double-end fiber interrogation. In this configuration, Raman stokes and anti-stokes are obtained in backward and forward directions and then averaged [7, 32].

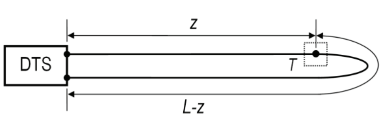

Fig. 5. DTS system in double-ended configuration

A duplexed single-ended setup is also proposed, which allows two temperature observations at every point along the cable, one going away from the instrument, and one coming back towards the instrument [7].

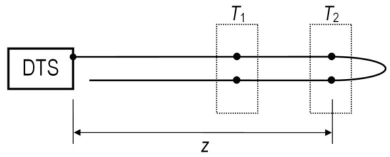

Fig. 6. DTS system in duplexed single-ended configuration

The loop configuration relies on setting the fiber parallel sections in a loop that result effectively equivalent points along adjacent fiber sections. This configuration is effective in separating temperature modulations from fiber attenuation [4]. Duplexed single-ended and loop double-ended configurations are much preferred due to their ability to correct non-uniform attenuation (step losses) along the cable, compared to single-ended that needs calibration for the DTS [7].

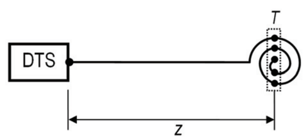

Fig. 7. DTS system in loop configuration

4. Conclusions

DTS systems' spatial resolution, temperature resolution and time resolution have been improved through apparatus optimization, system configuration and demodulation algorithms [22].

Optical system optimization and pulse fiber laser improvement improve temperature resolution, time resolution and spatial resolution of the spontaneous Raman scattering system [3, 32]. Nowadays, DTS systems' spatial resolution is less than 1 m, and their temperature accuracy is below ±0.1°C [7].

5. References

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Received: 04.10.2016 *Paper reviewed* *Accepted: 05.01.2017*

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