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Measurement of Temperature Through Raman Scattering

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Abstract

This paper treats the theory of distributed optical fiber sensing measurement used in the monitoring of the structures civil, like tunnels, bridges, buildings, dams, pipeline… While resorting to distributed temperature sensors Raman scattering, we present a theoretical and simulation measurement of temperature. We highlight the effect of distance in temperature measurement in particular the work in this article provides the equation which shows well the relationship between the temperature and distance in optical fiber. The results indicate that the anti stokes signal is strongly dependent on the temperature; therefore the temperature varies slightly by changing the point of measurement.

Keywords: Raman scattering, distributed sensor, stimulated Raman scattering, optical fiber (OF), temperature, measurement, ROTDR

1. Introduction

Nowadays, structural health monitoring (SHM) is a famous and fundamental tool, used to control the civil infrastructures lifetime[10]. SHM system consists of many distributed sensors, this system is used to collect structural information, and these sensors must be placed at 'good' positions to detect damage. Compared to electric sensors, the Optical fiber sensors (OFS) are the most interesting and promising sensing technologies due to the advantages over traditional electronic sensing, therefore account to the reduced weight and volume, the high precision, the immunity to electromagnetic interference, the insensitive to external perturbations, the electrical isolation and low transmission losses[11]. Considering these advantages we will interested specially in distributed OFS.

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These OFS are able to measure the change of a specific parameter (measurand) along the whole fiber transducer which is always consisting of a fused silica (SiO). Hence, the interaction between silica and an electromagnetic wave generate variations in the molecular structure of the fiber[10]. Classically, the incident light wave generates acoustic waves owing to the electrostriction effect. In silica optical fibers, the most important effects are the nonlinear phenomenon: Stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), and the Kerr effect are the three famous nonlinear effects[2].So far, Raman scattering phenomena have widely been used in SHM, chemistry, materials engineering, and physics for research on the nature of interactions, and properties of semiconductors. During the last decade the interest in the stimulated Raman scattering and other nonlinear optical phenomena has significantly increased with the development of optical telecommunication[12] .The Raman distributed temperature sensor (RDTS) based on spontaneous SRS is one of the high-tech equipments for real-time measuring the spatial distribution of temperature, which has been mostly used and investigated in recent years [4]. In this paper, we highlight how we can use SRS to take a temperature's measurement along optical fiber. In the beginning, we start by explained the DTS's standard, Raman scattering, temperature dependence and then we investigate the basic equation used to measure temperature through Raman scattering.

2. Physics & Theoretical Model

2.1 Raman Distributed Temperature Sensor

Distributed fiber optic sensors is used to monitor the variation of aerospace and civil structural conditions, the sensing length varies from meters to over 100 km. Generally, a distributed sensor can replace many point sensors[13]. Recently, the distributed fiber optical temperature measurement system has been widely used for measurement of real-time space temperature distribution. OF is a transmission medium as well as a sensor. We remedy optical time-domain reflectometry technology to locate the measurement points, the system measures the temperature information by the temperature effects of Raman backscattering[14].

2.1 Raman Scattering

Raman optical time domain reflectometry (ROTDR) is based on back scattering of the spontaneous Raman stokes and anti stokes waves.

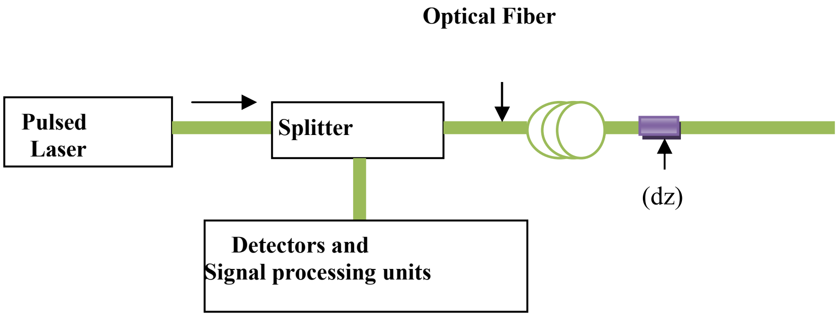


Fig.1. ROTDR system for temperature distribution measurement

ROTDR systems for distributed temperature measurements have a short laser pulse injected into the optical fiber. The splitter named also coupler: in our case is a device connecting a signal entered to two. It makes it possible the separation of signals within the optical fiber. The backscattered Raman photons contains information about the temperature distribution along the optical fiber. The minimum spatial resolution depends on the pulse width of the injected laser.

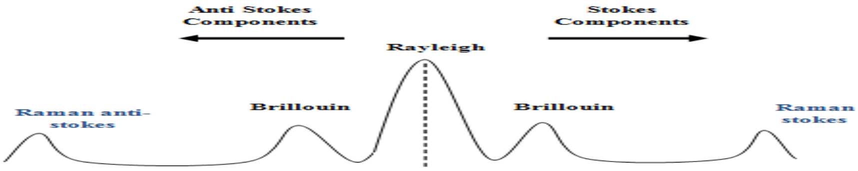


Fig.2. Scattered spectrum of light in the sensing fiber

The basic principle of Optical Sensor is based on optical Time-domain reflectometry (OTDR) involving time of temperature's measurement in conjunction with Raman scattering, in which sensing fiber is coupled to short interrogating laser pulses and the backscattered optical anti-Stokes and Stokes components are monitored for signal changes. These anti-Stokes and Stokes components are caused by nonlinear process precisely inelastic nature of spontaneous Raman scattering in which change in incident light takes place due to vibration properties of molecular in this substance[3]. The scheme (fig2) describes the scattered spectrum of light in the sensing fiber. It's easy so to notice the components and direction of waves (Raman stokes and anti stokes).

2.2 Stimulated Raman Scattering (SRS)

In an optical fiber, SRS is an inelastic process where a photon of the pump optical signal (incident) stimulates molecular vibration of the silica material and loses part of its energy [HUI].Therefore, SRS is caused by the interaction between the optical signal photons and the energy states of the silica molecules.

The scheme below (fig3) illustrated the state energy in SRS process:

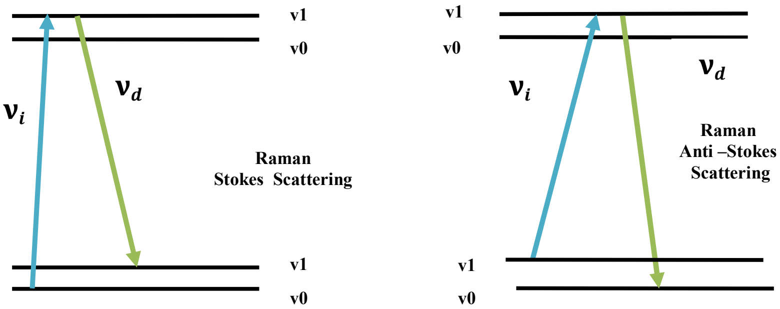


Fig.3. Scheme of Raman scattering

The final energy state of Raman Stokes scattering is higher than that of the initial state. The Raman Stokes wave gained a quantum of vibration energy; here we speak about photon's creation (stokes components). This energy yielded by the incidental light (pulsed laser) is usually diffused with a lower frequency. However, the final energy state of Anti-Stokes Raman scattering is lower than that of the initial energy (show fig.3).

The energy gained by the laser light which is diffused with a higher frequency causes a loss of photon[8].

3. Raman Scattering: dependence and measurements

3.1 Raman dependences

The inelastic nature of spontaneous Raman scattering causes anti-Stokes and Stokes components. Any change in pump light takes place in these components, then the incident light has a widely impact in SRS. The scattered light power of Raman stokes and anti-stokes is inherently weak (of the order of pW) and need amplification by several orders (~10^7) of magnitude[3].

The stokes and anti-stokes occupation probabilities of SRS are obtained by[1]:

$$P_s = \frac{1}{1-\exp\left(-\frac{\Delta E}{K*T(z)}\right)} \quad (1)$$

$$P_{as} = \frac{\exp\left(-\frac{\Delta E}{K*T(z)}\right)}{1-\exp\left(-\frac{\Delta E}{K*T(z)}\right)} \quad (2)$$

Where $\Delta E = h\,(w_s - w_p)$ is the Raman energy shift, w_s is scattered wavelength, w_p pump's wavelength, h Planck's constant and k is the Boltzmann constant. To check the dependence of these equations (stokes and anti-stokes occupation) to temperature change. To validate equations (1) and (2), we chose to represent the Raman stokes and anti-stokes scattered powers at varying temperature. Fig.4 shows that lifetime of anti-stokes waves in optical fiber senor is lower than stokes waves.

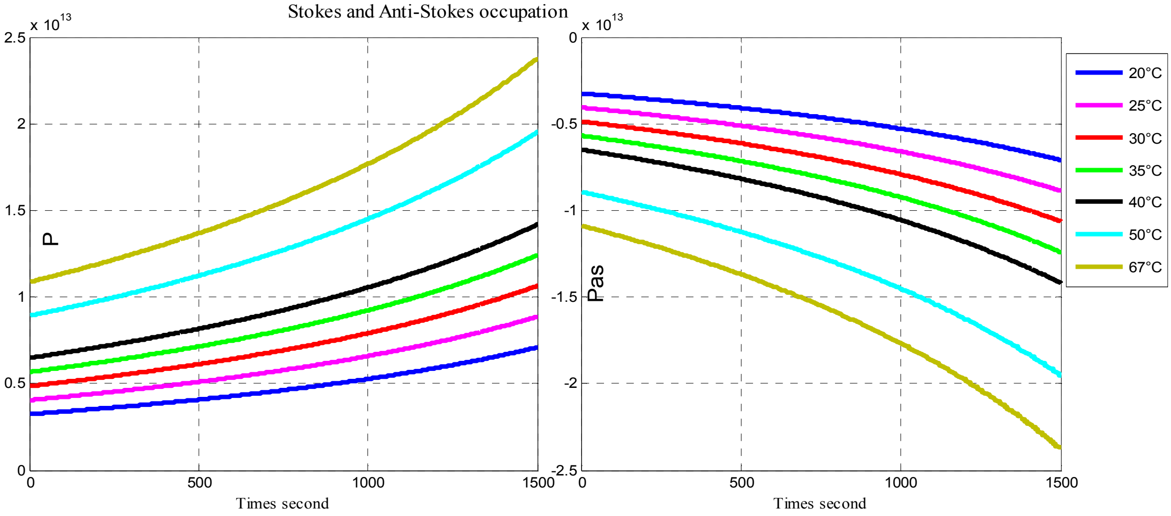


Fig.4. Stokes and Anti-stokes Occupation at different Temperatures

3.2 Raman Measurements

$$I_{as}(T) = K_{as} * \frac{1}{(\exp(A\,) - 1)} \qquad (3)$$

$$I_s(T) = K_s * \left(\frac{1}{(\exp(A) - 1)} \;+ 1\right) \qquad (4)$$

Where A= (h*ΔV)/ (K*T) and ΔV the Raman frequency shift expressed in Hz[5]… The intensity of Raman anti-Stokes wave is strongly dependent to temperature, while the intensity of the Stokes wave is not affected by a temperature change. In fact, the intensity of the Raman lines is proportional to the initial level of the pump intensity. Indeed, the energy level of the anti-Stokes wave is populated by the statistical law of Boltzmann according to dependence in $\exp\left(-\frac{h*\Delta V}{(K*T)}\right)$[9].

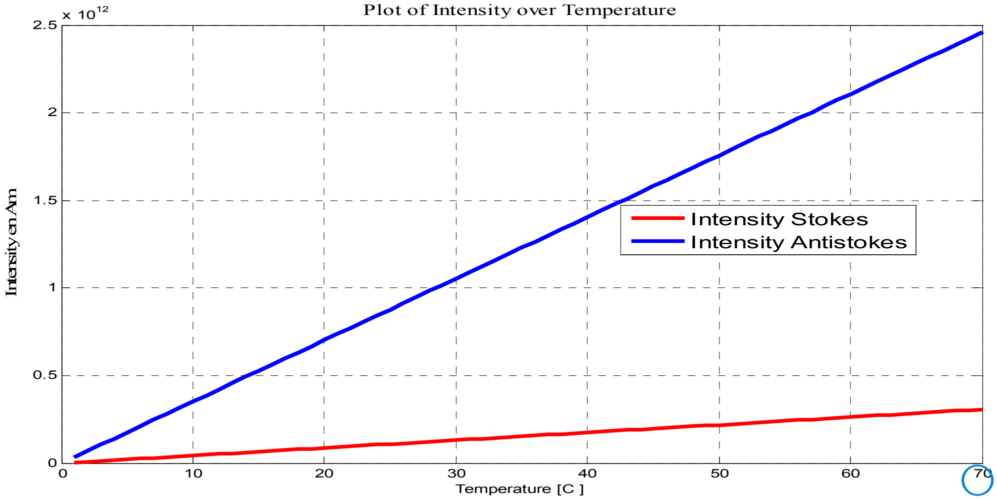


Fig.5. Intensity stokes/Anti-stokes over Temperature

The temperature of the optical fiber sensor zone for which Raman anti-Stokes (IAS) and Stokes (IST) intensities have been measured can be found from ratio (RATIO) of these two intensities. It’s expressed by the following equation[5].

$$R(T) = \frac{I_{as}\ (T)}{I_s\ (T)}$$

$$R(T) = \frac{K_{as}}{K_s} * \exp\left(-\frac{h * \Delta V}{(K * T)}\right) \qquad (5)$$

K_{as} and K_s are the coefficient of the temperature sensitivity of the Raman intensity. K_{as} is ~0.8%K and $K_s$is ~0.1% K .

$$\frac{I_s\ (T)}{I_{as}\ (T)} = \left(\frac{V_0 + V_V}{V_0 - V_V}\right)^4 * \exp\left(-\frac{h * \Delta V}{(K * T)}\right) \qquad (6)$$

The ratio of anti-Stokes to Stokes signal should be 0.1428 in the ideal case[4].The bottom plot in Fig. 6 shows the plot of this theoretical ratio as a function of absolute temperature for the Raman signals generated for a source laser wavelength of 632 nm and a silica fiber with wave number shift of 440 cm1.

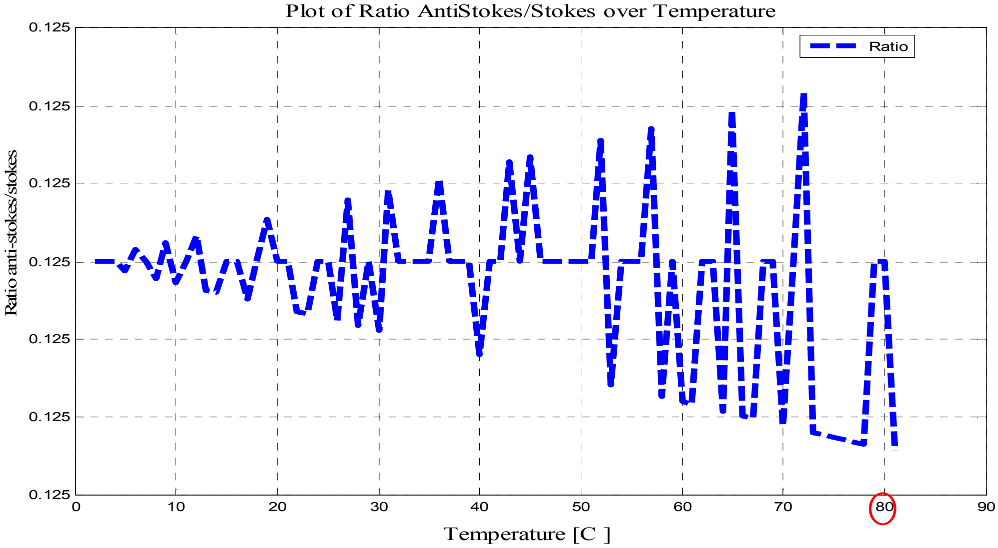


Fig.6. Ratio Anti-Stokes/ Stokes over Temperature

In our case, the measurement of RATIO (Anti-stokes/ stokes) is free from external influences such as changes of the light source or of the optical fiber attenuation and without dynamic losses e.g. due to bends while leaving only the temperature changes. So the difference between experimental and theoretical values of RATIO exists certainly[3]. Fig.6 shows that at higher temperature (>50°C) values of RATIO are more sensible.

Table.1 Values of parameters used in Simulations

Symbol	Parameter	Value	Unit
K	Boltzmann’s constant	$1.28 \text{ X } 10^{-23}$	J/K
H	Planck’s constant	$6.626 \text{ X } 10^{-34}$	J-s
Λ	Laser wavelength	$1.553 \text{ X}10^{-6}$	m
K_s	The coefficient of the temperature sensitivity stokes	0.1	--
K_{as}	the coefficient of the temperature sensitivity anti-stokes	0.8	--
α	Fiber attenuation	0.217	Db/Km

Both anti-stokes and stokes scattering are temperature dependent with different proprieties. Classically, temperature variation is negligible in the measurement time so it is assumed that T is function of z only[1]. Heat exchange is a slow process in SRS, so to find the temperature variation along optical fiber, we generally use the ratio R(z,t) of stokes and anti-stokes intensity. Hence using the following equation (eq.5) we deduce temperature values along optical fiber:

$$R\ (z,T)=\left(\frac{\lambda_s}{\lambda_{As}}\right)^4 * \exp\left(- \frac{h\Delta\nu}{k*T(z)} \int_0^z (\alpha_{As}\ (\xi)-\alpha_s(\xi))\ d\xi\right) \quad (7)$$

Where λ_s and λ_{As} representing the Stokes and anti-Stokes wavelengths respectively; α_{As} and α_s are the respective fiber attenuation coefficients; $\Delta\nu$ is the frequency variation between AS and pump signal[7].

In our simulation, in order to find temperature through Raman distributed sensor we use the following equation:

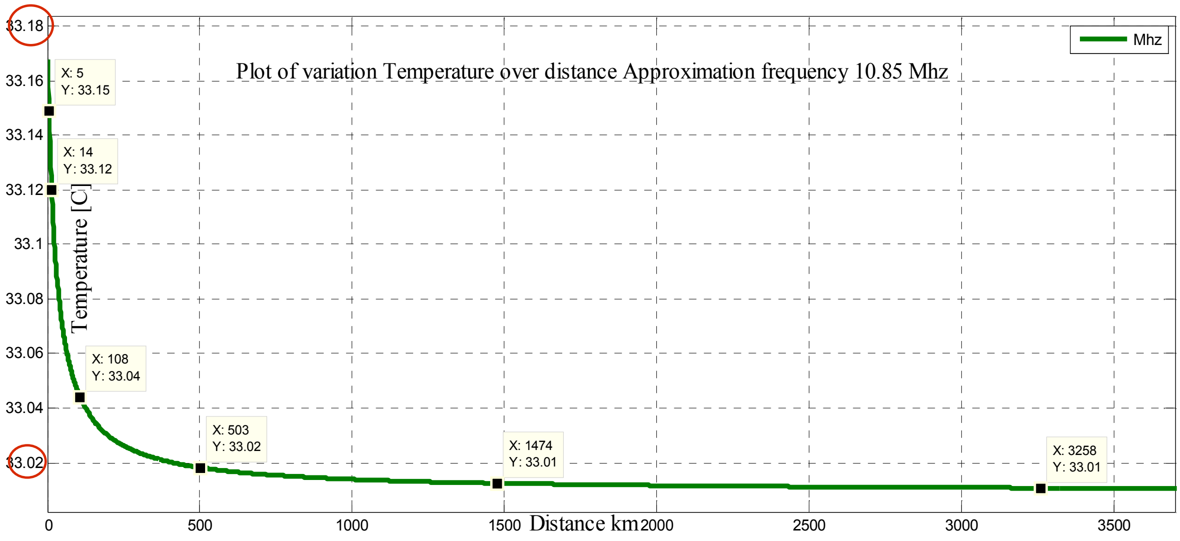
$$T\ (z)= (-h\ \Delta V/K)* \frac{1}{\ln\left(R*\left(\frac{V_0 + v_V(z)}{V_0 - v_V(z)}\right)^4\right)}$$

$$v_V(z) = \frac{z}{t*f}$$

$$T\ (z)= (-h\ \Delta V/K)* \frac{1}{\ln\left(R*\left(\frac{V_0 + \frac{z}{t*f})}{V_0 - \frac{z}{t*f})}\right)^4\right)} \quad (8)$$

The sensing range of the Raman OTDR sensors is typically limited between 900m-37 km. This sensing length limitation is due in large part to fiber loss and fiber intermodal dispersion (if multi-mode fiber is used as the sensing fiber). Thus, another factor affecting the Raman OTDR range is the repetition rate of the pump laser; however this can be modified with modulation, either internal or external to the pump laser. The use of multimode fibers to measure temperature is common. Indeed, these last are less susceptible to bending and allow for better signal to noise ratios, the temperature measurements are more reliable[9].

To deduce the effect of distance variation in temperature's measurement, we use the Raman scattering combined with OTDR system. We selected different point of measurement dz in the optical fiber, the ratio stokes/ anti-stokes is fixed to 0.148, we varied also the frequency of pump signal, as a results we show that values of temperature varied slightly. The distributed sensor applied to Raman measurements is very sensible to the fluctuations of intensity. When the frequency of laser signal is in the vicinity of 10.85 Thz, temperature's values are the most accurate and faithful.



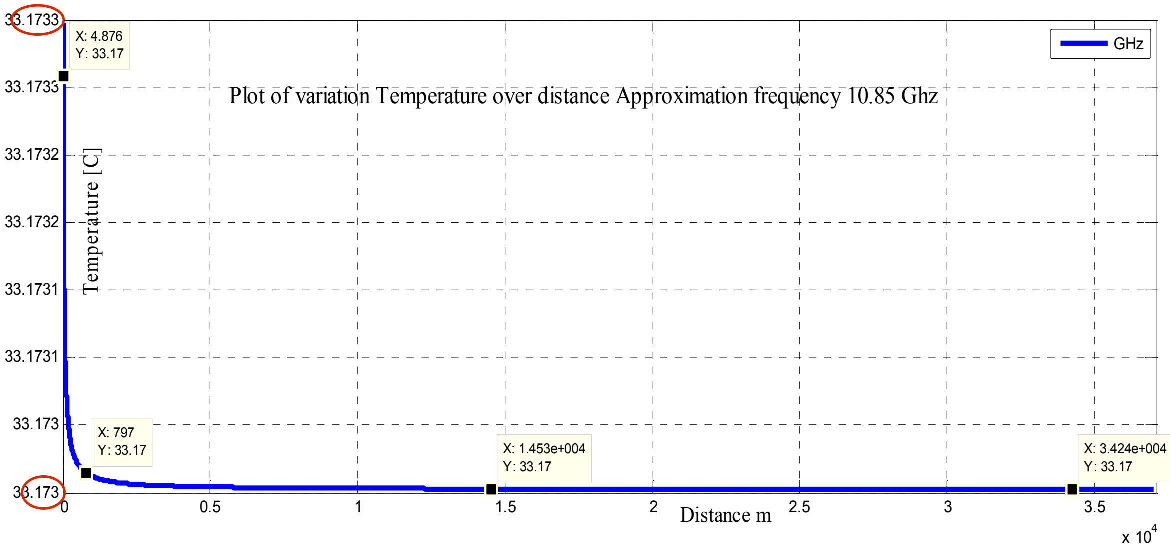


Fig.7. Variation Temperature over distance at different frequency

3.3 SRS Spectrum

The Raman gain spectrum is defined by the coupling of optical mode in the optical fiber. Raman-gain g_R is related to vibrational modes in material.

The coefficient of Raman gain in the stokes wave can be written as:

$$\frac{dI_s}{dz} = g_R\, I_p\, I_s - \alpha_s\, I_s \; (9)$$

Where α_s is the attenuation fiber. For pump wave the coupled equation is:

$$\frac{dI_p}{dz} = -\frac{w_p}{w_s} g_R I_p\, I_s - \alpha_p\, I_p \;\; (10)$$

Where w_p the pump frequency, w_s the stokes frequency. The gain band is relatively wide and it is about 5THz, therefore Raman gain takes place in every fiber, which permits to avoid the expensive material modifications[12]

The Raman shift is :

$$w_R = w_p - w_s$$

4. Applications of Raman distributed sensor

Distributed sensors offer an advantage over point sensors for global temperature measurements. For large scale structures, the number of this distributed sensors needed to generate complete temperature information is very great[13]. Until now, RDTS is mainly used to detect temperature information, so it has been employed in a wide range of application domains[5]:

These applications offer real measurements and include structure monitoring, leakage detection, applications in Mines, oil and gas, fire detection security, and power lines monitoring…

4.1 SHM

The use of RDTS is a promising measurement technology for Structural Health Monitoring (SHM) such the possibility of continuous monitoring of temperature along optical fiber.

SHM offers a real time temperature profiles in cable trays, tunnels and special hazardous zones, and offer automatically triggered alarms[15]. Thus, real measurements can be used to reveal the global behavior of a structure rather than extrapolation from a few point measurements[13]. Continuous health monitoring sensors laid along the concrete structures could indicate incipient damages, difficult to pick up by human inspection, leading to catastrophic failures[15].

4.2 Leakage Detection

In civil engineering, health monitoring of buildings, dams and dikes is very important to detect and identify early any leakage in order to prevent catastrophic failures like flooding, etc.

4.3 Fire detection

Automatic fire detection is an interesting topic to prevent asset damage and human casualty. Fire detection is a system based on optical smoke detector, ionization detector, infrared or ultraviolet flame detection, etc. One of the most promising technologies is linear optical fire detection, based on the DTS principle, e.g, Raman scattering. Using frequency domain reflectrometry in optical fiber sensor, the study reported tracking of rapid changes in the temperature profile to detect fire and localize the seat of the fire within a building with 1 m resolution[15]

4.4 Applications in Mines

For sheltered and safe electrical operation, in mines, shuttle car trailing cables should be operated below the safety limit which is about 90°C. Operation in temperature condition more than that can cause premature insulation failure. Therefore, in mines the distributed temperature reported use of fiber optic technology to monitor atmospheric related parameters like methane (CH) and carbon monoxide(CO)[15].

5. Conclusion

Raman distributed sensor technology is actually mature and very useful for short range and fast temperature sensing applications, for example, fire detection in a tunnel. In this article we explain clearly the Raman scattering processes, therefore the results of Matlab simulation indicate that the anti stokes signal is strongly dependent on the temperature, thus the temperature varies slightly by changing the point of measurement. A typical performance of Raman sensing will give a temperature reading that is accurate to 34°C with a 0.148 ratio (stokes/anti-stokes) and a 1-m spatial resolution at a distance of 37 km maximum, obtained after a 5-minute averaging. We have demonstrated that Raman scattering give us exact measurement of temperature, in the future work we will try to measure other parameters (pressure, strain …) .

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