RAMAN SCATTERING AND OTDR BASED DISTRIBUTED SENSOR FOR TEMPERATURE MONITORING APPLICATIONS

Sait Eser KARLIK

Uludağ University
Faculty of Engineering and Architecture
Department of Electronics Engineering
Görükle/Bursa
TURKEY
E-mail: ekarlik@uludag.edu.tr

Güneş YILMAZ

Türk Pirelli Cables and Systems A.S.
R&D Department
Mudanya/BURSA
TURKEY

E-mail:gunes.yilmaz@tr.pirelli.com

Abstract- **In this study, optical fibre applications in the area of distributed temperature sensing (DTS) are presented. Sensing system configuration and required system parameters for determining the temperature profile of an HV cable are given. Optical time domain reflectometry (OTDR) and Raman scattering phenomena of light are used in the practical application whose results are very promising for the ultra-long range DTS systems.**

I. INTRODUCTION

The coherent distributed sensing nature of optical fibres can be used to create unique forms of intrinsic sensors for which, in general, there may be no counterpart based on conventional sensor technologies. In an intrinsic optical fibre sensor, the modulation of the optical carrier induced by the measurand field occurs while the light remains guided within the fibre. This is in contrast to extrinsic sensors, where the fibres serve as "light pipes" to carry the optical information to and from the sensing element. Most of the intrinsic fibre sensors are inherently distributed, as the measurand acts over the whole length of fibre. That is, there are thousands of independent measuring points along the fibre which give information about the measurand in distributed sensing.

Examples of possible application areas for intrinsic distributed sensors include stress monitoring of large structures such as buildings, bridges, dams, storage tanks, oil platforms, aircraft, spacecraft and so on; temperature profiling in electrical power transformers, generators, reactor systems, process control systems and fire detection systems; leakage detection in pipelines, fault diagnostics and detection of magnetic/electrical field anomalies in power distribution systems and intrusion alarm systems; embedded sensors in composite materials for use in the real-time evaluation of stress, vibration and temperature in structures and shells [1] .

In this paper, distributed temperature sensing (DTS) method is examined. There are various sensing principles in DTS, such as Rayleigh, Raman and Brillouin scatterings, mode coupling and optical Kerr effect. Among these, we are dealing with Raman scattering in combination with optical time domain reflectometry (OTDR). We describe the OTDR concept in Section II and present the principles of Raman scattering as well as its temperature dependency in Section III. Section IV is dedicated to sensing system configuration, critical design parameters and measurement results.

II. OPTICAL TIME DOMAIN REFLECTOMETRY

Although researches about reflectometry methods have been made in time domain, frequency domain and coherence domain for distributed sensors, the most popular technique is the optical time domain reflectometry (OTDR). The basic method of optical time domain reflectometry, devised by Barnoski *et al* [2] was the first type of distributed optical fibre sensor.

When light is guided by an optical fibre, loss occurs due to Rayleigh scattering which arises as a result of random microscopic variations in the refraction index of the fibre core. A fraction of the light that is scattered in a direction 180° to the propagation axis of the light (back-scattered light) is recaptured by the fibre aperture and returned towards the source. By pulsing the input optical signal to a length of fibre and monitoring the variation in the returned back-scattered intensity, spatial variations in the fibre scattering coefficient or cross section, or attenuation can be determined. This forms the basis of OTDR.

The OTDR method is depicted in Fig. 1. in its most usual current implementation. A pulsed laser, typically a high-power GaAlAs diode laser or solid-state Q-switched Nd:YAG laser, is coupled into a section of fibre via a directional coupler, which serves also to couple the back-scattered light fraction, captured and returned via the fibre to be tested, to the avalanche photo-diode detector (APD). The processing electronics monitor the level of back-scattered light with time relative to the input pulse.

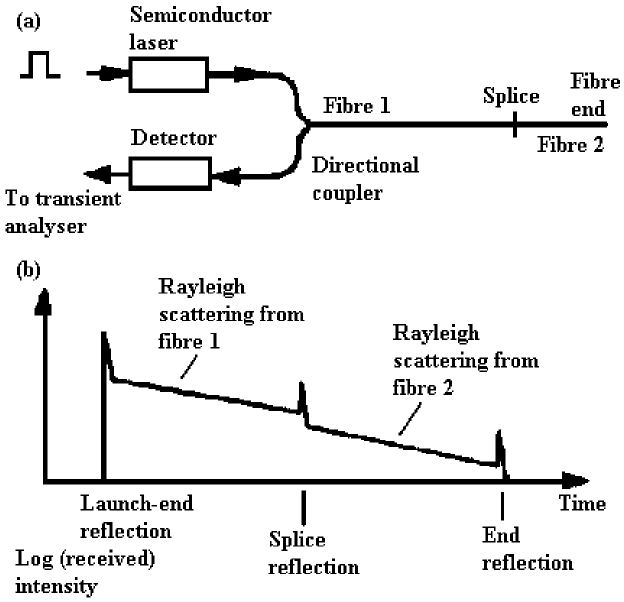

Fig. 1. Basic Concept of OTDR:
(a) Optical Arrangement (b) Typical OTDR Trace

The Rayleigh component of the scattered light represents, for good quality fibres, well over 98% of the returning signal, except during the intervals when more intense pulses return from discrete discontinuities, such as connectors and splices. For uniform fibres, the back-scatter intensity decays exponentially with time and the back-scattered power detected at a time delay t for an input pulse coupled into the fibre with a peak power P_0 and duration τ can be written as

$$P_s(t) = (1-\kappa)\kappa P_0 D r(z) \exp\left\{-\int_0^z 2\alpha_i(z)dz\right\} \quad (1)$$

where $z = ct/2n$ is the location of the forward-travelling pulse at the time of the generation of the detected back-scatter signal, $\alpha_i(z)$ is the attenuation coefficient in nepers, n is the refractive index of the fibre core, c is the velocity of light, κ is the input fibre coupler power splitting ratio, $r(z)$ is the effective back-scatter reflection coefficient per unit length that takes into account the Rayleigh back-scattering coefficient and fibre numerical aperture, and $D(=c\tau/n)$ is the length of the optical pulse in the fibre at any instant in time [1].

The spatial resolution of an OTDR instrument is the smallest distance between two scatterers that can be resolved and is determined by the input pulse width according to

$$\Delta z_{\min} = c\tau/2n \quad (2)$$

For a pulse width of 10 ns a spatial resolution of ~ 1m can be obtained. In general, the signals produced by OTDR analysis are weak and considerable averaging of the detected signals is required to achieve a good SNR.

III. RAMAN SCATTERING OF LIGHT AND ITS TEMPERATURE DEPENDENCY

The effects of light scattering are classified by the relation between the frequencies of the incident and those of the scattered photons. When these frequencies are equal, one speaks of unshifted scattering, i.e. Rayleigh or elastic scattering. But if these frequencies differ, the term shifted or inelastic scattering is used. An example is the Raman scattering. Here, the frequency shifts equal the characteristic vibrational frequencies of the molecules. Photons scattered to lower frequencies are termed Stokes lines and those scattered to higher frequencies are the anti-Stokes lines. In the Raman spectrum of fused silica fibre, which is shown in Fig. 2., the frequency shift Δf is 13.2 THz or $\Delta f/c$ = 440 cm^{-1}, where c denotes the speed of light in vacuum.

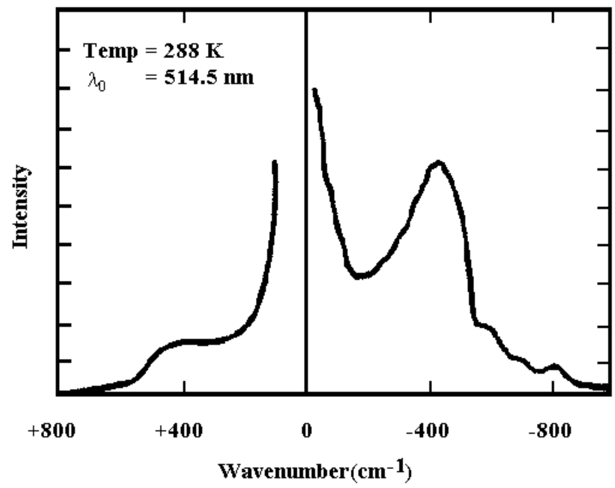

Fig. 2. Raman Spectrum in Fused Silica Fibre

If one assumes the interaction of a molecular system with a harmonic electric field initiated by a laser of angular frequency ω_0 , one can interpret the Raman scattering as an inelastic scattering of a photon of energy $\hbar\omega_0$ with a molecule of initial energy state E_1 and final state E_2. Here, $\omega_0 = 2\pi f_0$ is the angular frequency of the incident light, f_0 is its frequency and $\hbar = h/(2\pi)$; h is the Planck's constant. Now, we suppose the scattering system as one vibrating molecule with the fixed energy states E_1 and E_2 as shown in Fig. 3. By elastic or inelastic collision of an incident photon of energy $\hbar\omega_0$ with the molecule, the system initially in the state E_1 is excited to the virtual state $E_3 = \hbar\omega_0 + E_1$. Since this state is prohibited, the system immediately decays to some other third state. Because of the virtual nature of the state E_3 , no real absorption takes place, but only light scattering. The virtual energy levels are not fixed, i.e., they float with the wavelength of the incident photons [3].

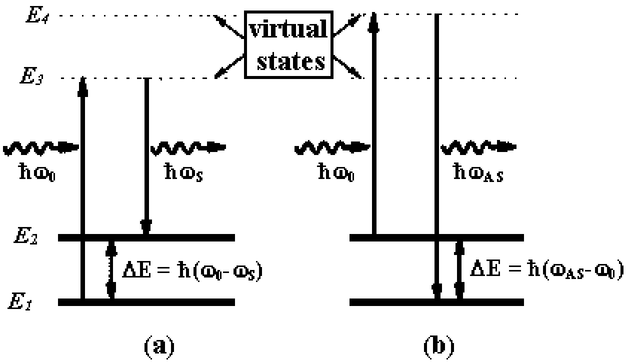

Fig. 3. Schematic Diagram of Raman Scattering: (a) Stokes Scattering (b) Anti-Stokes Scattering

The transition $E_1 \rightarrow E_2 \rightarrow E_3$ in Fig. 3(a) represents the Raman Stokes scattering. Here, the final state E_2 is of higher energy than the initial state E_1 and the angular frequency ω_S of the emitted Stokes photon is lower than that of the incident photon. The energy difference $\Delta E = \hbar(\omega_0 - \omega_S)$ converts into vibration of the molecule, i.e., a phonon is excited. ΔE is about 50 meV for vitreous SiO_2. Fig. 3(b) shows the Raman anti-Stokes scattering, which is represented by the transition $E_2 \rightarrow E_4 \rightarrow E_1$. Here, the initial state is E_2 . It is excited by molecule vibration. By interacting with an incident photon, the molecule is excited to the virtual state $E_4 = \hbar\omega_0 + E_2$ and may drop spontaneously to the lowest energy level E_1. The emitted anti-Stokes photon is of higher angular frequency ω_{AS} , because the energy of the final state E_1 is lower than that of the initial state.

Stokes and anti-Stokes emissions of Raman scattering can be used to detect temperature profiles in conventional vitreous communication fibres using modified OTDR techniques. The ratio R_r of anti-Stokes to Stokes intensity in the back-scattered light is given by

$$R_r = \left(\frac{\lambda_S}{\lambda_A}\right)^4 \exp\left(-\frac{hc\nu}{kT}\right) \qquad (3)$$

where λ_S and λ_A are Stokes and anti-Stokes wavelengths, h is Planck's constant, c is the velocity of light, ν is the optical frequency of the exciting radiation, k is the Boltzmann constant and T is the absolute temperature. At a pump wavelength of 514 nm, this ratio has a magnitude of ~ 0.15 at room temperature and a temperature dependency of approximately 0.8%/°C in the range 0 to 100 °C [4].

Therefore, a measurement of the ratio of Stokes and anti-Stokes back-scattered light in a fibre should provide an absolute indication of the temperature of the medium, irrespective of the light intensity, the launch conditions, the fibre geometry and even the composition of the fibre. In practice, however, a small correction has to be made for the difference in fibre attenuation between the Stokes and anti-Stokes wavelengths.

The Raman technique appears to have only one significant practical drawback. As it can be easily understood from Fig. 3 the anti-Stokes emissions are rare in comparison to Stokes emissions and so the intensity of the Stokes wave is higher than that of the anti-Stokes wave, as shown in Fig. 2. The anti-Stokes Raman-scattered signal is between 20 and 30 dB weaker than the Rayleigh signal. This is obvious in Fig. 4., where the Raman back-scatter signal for a pump wavelength of 514 nm is depicted.

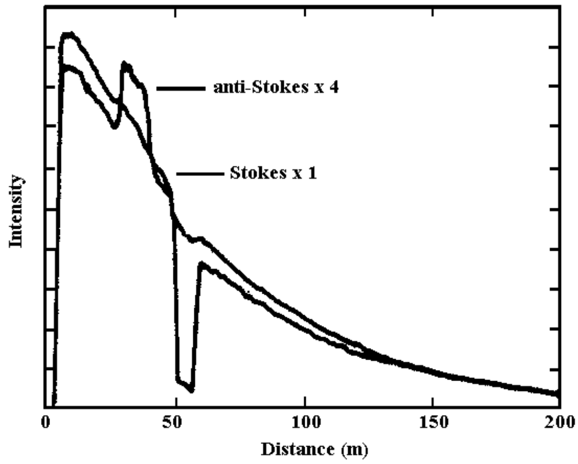

Fig. 4. Raman Back-Scatter Signal

In order to avoid an excessive signal averaging time, measurements can be taken using relatively high launched powers from pulsed lasers.

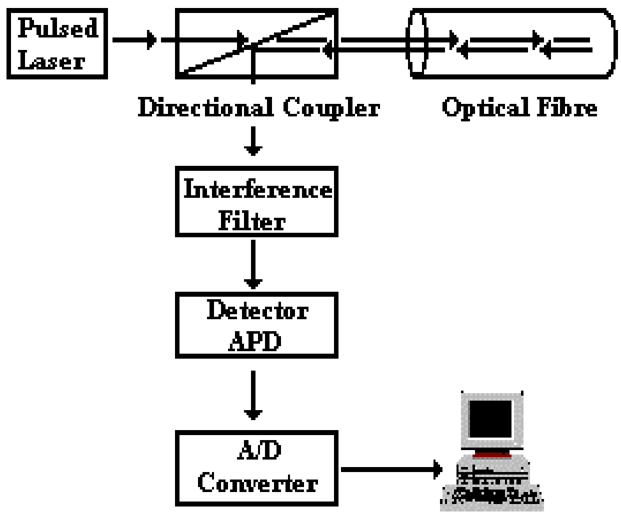

Fig. 5. Sensing System Configuration

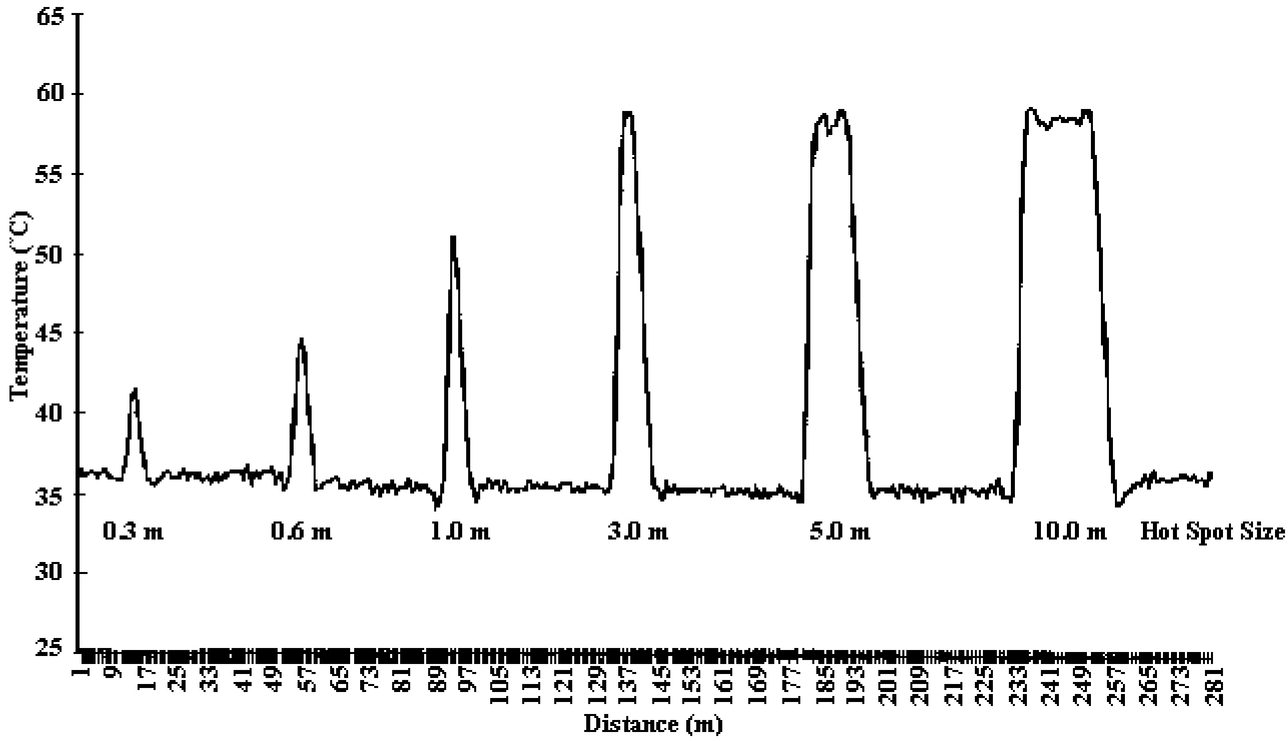

Fig. 6. Effect of Spatial Resolution to Detection of Hot-Spot Amplitude

III. SENSING SYSTEM CONFIGURATION AND REQUIRED PARAMETERS

Sensing system configuration is shown in Fig. 5. The light is pumped into the fibre from a pulsed laser. Directional coupler is used to separate the back-scattered light from laser pulses. The scattered Raman signal is filtered by interference filter and detected by a photodiode. Detected signal is then amplified and digitized by a high-speed analogue-to-digital converter. Digital averaging techniques improve the signal/noise ratio in a highly efficient manner prior to the data being sent to the display unit.

The prime characterising parameters for this system can be defined as follows:

- *Fibre Length (Spatial Range):* The maximum length of the fibre over which measurements can be made within the specified accuracy is defined as the spatial range. It is determined by the total two-way loss in the fibre and must include connectors as well as the fibre.
- *Spatial Resolution:* This is the minimum length of the fibre over which sensible change in the spatial variation of the temperature can be detected.
- *Temperature Resolution:* Temperature resolution relates to the consistency of measured values and is expressed at one standard deviation of the measurement.
- *Thermal Response Time:* The thermal response time of a sensor loop depends strongly on the cladding and cabling structure and on the quality of the thermal contact between the sensor loop and the object whose temperature is to be measured. In general, the heat capacity of fibre with its secondary coating is very low and the response time is <0.5 s.

Temperature resolution is an indication of the repeatability of successive measurements of a single point at the maximum specified DTS range, while spatial resolution reflects the ability of the DTS to accurately locate and measure specific features of interest.

Spatial resolution is critical for correctly assessing potential ‘hot spots’. A hot spot which occupies a fibre length that is less than the spatial resolution of the DTS instrument will not indicate it’s true amplitude. This is shown in Fig. 6. In fact, temperatures of all hot spots in this figure are approximately 60 °C, but since the spatial resolution is 1.3 m hot spots whose sizes are 0.3 m, 0.6 m and 1 m are detected as much colder than their original temperature.

Selection of pump wavelength depends on various factors according to the application area of DTS Raman sensor. Whatever wavelength is selected, the most important design criteria of the source are the pulse width and the peak power of the laser. A narrow laser pulse width is required to achieve a high spatial resolution – a pulse width of 10 ns limits the spatial resolution to 1 m –

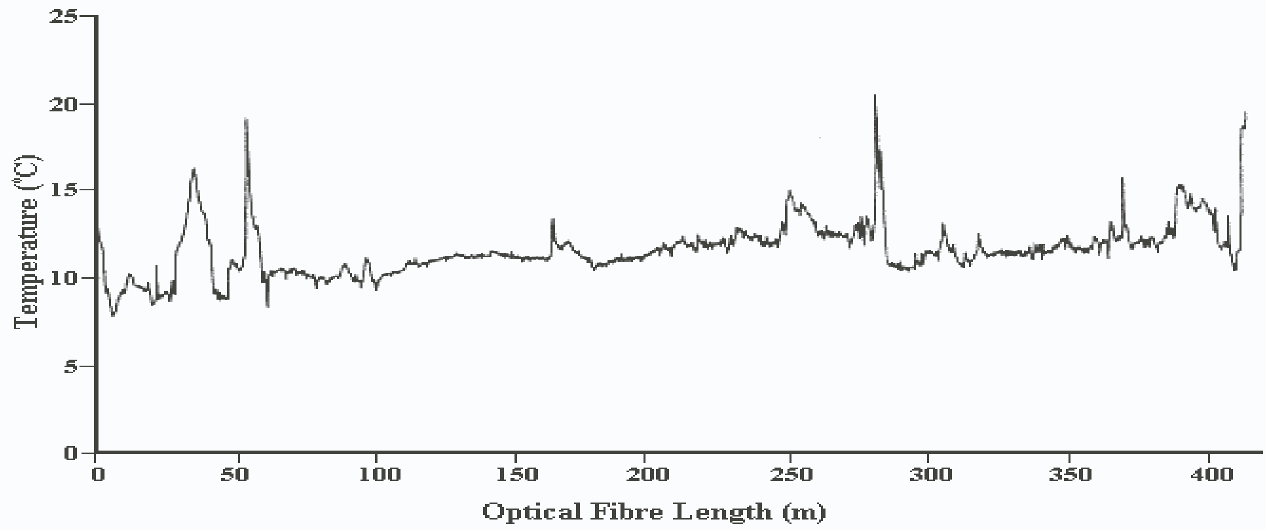

Fig. 7. Temperature Profile of an XLPE Cable

but this potentially limits the maximum range of DTS. Increasing the peak power of the laser to extend the range is one possibility but this may have safety implications. The alternative is to use single-mode optical fibres which have lower attenuation levels enabling lower laser powers to be effective over longer distances.

Theoretical computations show that temperature and spatial resolutions of 1 °C and 1 m are possible for ranges up to 10 km using multi-mode fibres and 2 °C and better than 5 m up to 20 km using single-mode fibres. For even longer ranges, a spatial resolution of 8-10 m over 30 km is possible [4].

The pumping threshold power required for the stimulated Raman scattering to occur can be written as

$$P_0^{th} = \frac{16A_{eff}}{L_{eff} \cdot g_R} \tag{4}$$

where g_R is the Raman gain constant (10^{-13} m/W), A_{eff} and L_{eff} are the effective area and length of the fibre, respectively and can be computed by

$$A_{eff} = \pi r^2 \left(0.65 + 1.619\nu^{-3/2} + 2.879\nu^{-6}\right)^2 \tag{5}$$

$$L_{eff} = \frac{1}{\alpha_p}\left[1 - \exp\left(-\alpha_p L\right)\right] \tag{6}$$

where r is the fibre diameter, ν is the frequency, α_p is the absorption constant of the pumping light and L is the fibre length. For example, Raman threshold power will be 1.26 W for a fibre sensor that has an effective area of 60 μm^2 and an effective length of 7.87 km if a pulse width of more than 30 ns is selected.

Our sensing system has a temperature resolution of 1 ^{0}C and spatial resolution of 1 m. Neodymium doped laser with a wavelength of 1064 nm is used as the source. This source produces pulses which have 10 ns widths. Since our system is designed to measure the temperature of HV cables, the fibre is surrounded by a steel tube which is installed under the lead sheath of the HV cable. Experiments have been made on a 154 kV cross-linked polyethylene (XLPE) test cable which has a length of 400 m. The temperature profile which has been deriven out by Raman DTS system is shown in Fig. 7.

CONCLUSION

Distributed temperature sensing applications with the help of optical time domain reflectometry (OTDR) and Raman back-scattering of light in the fibre have been presented in this paper. Theoretical computations and experiments on 400 m XLPE cable have shown that our sensing system can be developed to ultra-long range DTS systems which will cover distances up to 20 kilometers.

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