Invited Paper

Fiber Optic Distributed Sensing Applications in Defense, Security and Energy.

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ABSTRACT

Distributed Fiber Optic Sensing is a powerful technology with wide spread use in applications from down-hole oil & gas wells to environmental monitoring of streams. This paper will highlight some of the various technologies and applications. Recent advances in multi wavelength Raman systems will also be discussed.

Keywords: Distributed Fiber Optic Sensing, Distributed Monitoring Systems, Rayleigh, Brillouin, Raman, Distributed Temperature Sensing, DTS, Hydrogen induced attenuation, steam drive

1. INTRODUCTION

Distributed Monitoring Systems (DMS) are widely used in Defense, Security and Sensing applications and the adoption rate of fiber optic sensing systems is growing across many industries. Attributes like high sensitivity, large bandwidth and wide dynamic range coupled with small form factor, light weight, high temperature performance, immunity to shock/vibration, challenge and displace conventional electrical sensors in many applications. This paper gives a high level technology overview of the most common distributed monitoring systems. A number of applications based on commercially available systems using Rayleigh, Brillouin and Raman scattering are reviewed.

2. BRIEF TECHNOLOGY INTRODUCTION

The majority of Distributed Monitoring Systems are based on Optical Time Domain Reflectometry (OTDR) principle. A very short light pulse is launched into an optical fiber and interacts with the fused silica in the optical fiber. This interaction will cause light to scatter back along the full length of the optical fiber. The backscattered light will consist of 3 different components, Rayleigh, Brillouin and Raman backscattered light, figure 1.

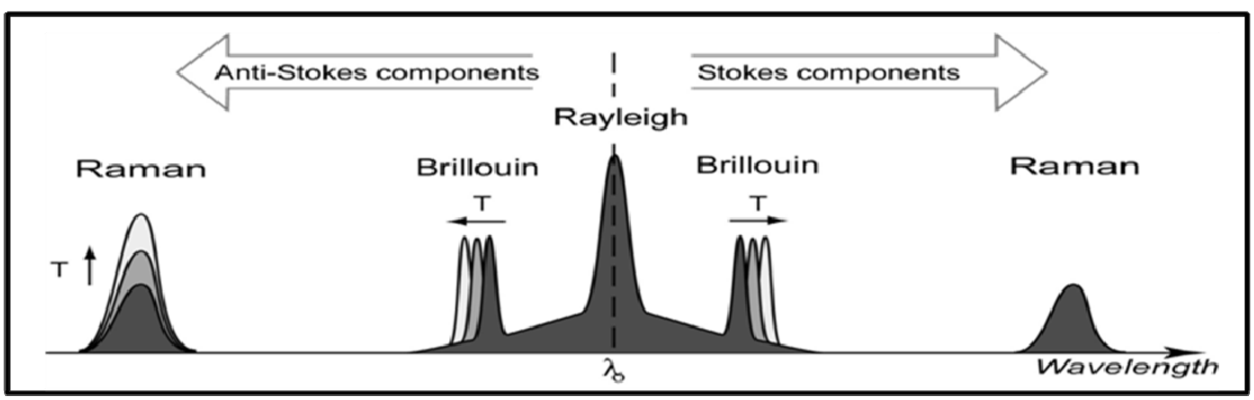

Fig. 1. Backscattered Rayleigh, Brillouin and Raman light in optical fibers.

The Rayleigh component is scattered back at the same wavelength as the launched pulse whereas both the Brillouin and Raman components are shifted in wavelength.

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- Rayleigh scattering is proportional to the optical loss in the fiber.
- Brillouin wavelength shift is temperature and strain sensitive.
- Raman component intensity is a function of temperature.

Well designed systems use these effects to measure various parameters in a wide range of applications.

3. DISTRIBUTED RAYLEIGH SCATTERING AND APPLICATIONS

Rayleigh scattering is a fundamental loss mechanism arising from random density fluctuations frozen into the fused silica fiber during manufacture [1]. Resulting fluctuations in the refractive index scatter light in all directions. The light scattered back in the fiber is often used in telecommunication OTDRs to assess the loss and health of optical fibers. Rayleigh scattering is also used in Distributed Acoustic Sensing (DAS) systems originally developed for intrusion detection and sonar systems.

The US Naval Research Laboratory (NRL) began the development of fiber optic sensors for Navy surveillance applications in the late 1970's [2]. High-performance dynamic fiber optic sensors are typically based on interferometric techniques that can detect extremely small changes in the phase of the light that has traveled through different paths. High performance fiber optic acoustic point sensors using Michelson and Mach-Zehnder interferometers have traditionally been used in towed arrays and hull mounted arrays on submarines. These interferometer configurations use reference coils, sensing coils, optical components and require a fair amount of manual labor to manufacture. This drives system cost and complexity.

True distributed OTDR based interferometric sensors based on Rayleigh scattering and a receiving interferometer can be used to reduce system cost and complexity [3]. The sensing fiber can be coated with a suitable material, wrapped around a compliant cable or mandrels in an automated manufacturing operation, thus reducing manufacturing complexity and eliminating components. Figure 2 below show a basic block diagram for a Rayleigh based distributed acoustic sensing system.

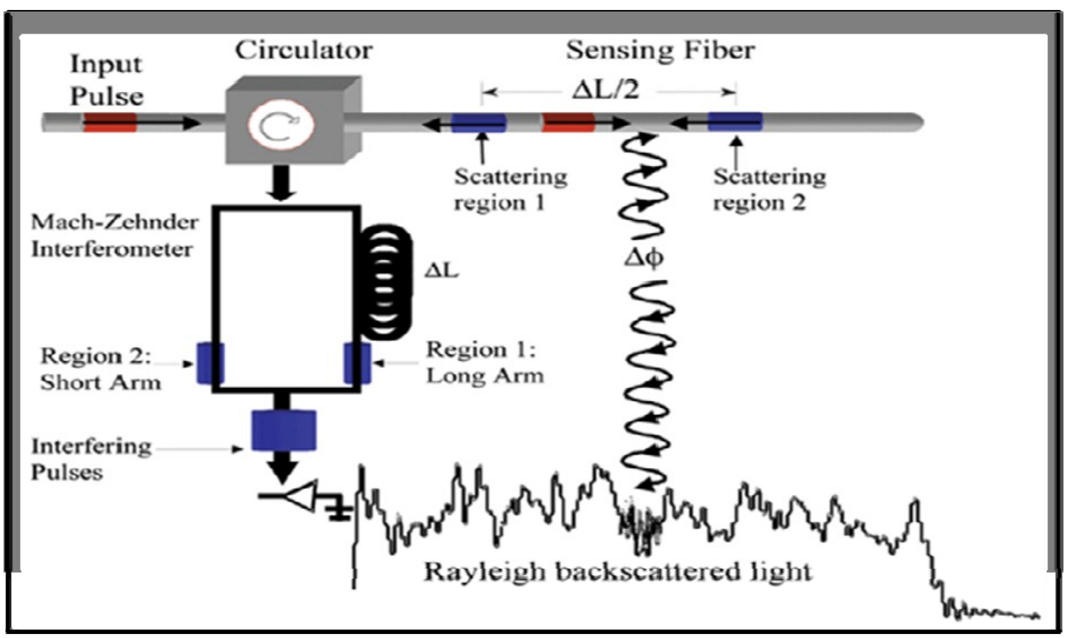

Fig. 2. Example of a Rayleigh backscatter interrogation system block diagram [3].

These systems enable cost efficient monitoring in homeland security applications where borders and ports must be monitored and protected [4].

3.1 Applications

Distributed acoustic systems are emerging on the market and show promise in perimeter security and pipeline monitoring applications. Perimeter security systems in sensitive military applications as well as refineries have been reported [5-6], and there is a general trend to increase monitoring of critical assets after 9/11 and the Iraq war.

There are many reasons to monitor pipelines using distributed acoustic sensing, and the main driver varies with the region where the pipeline is located. For example, 50% of all gas pipeline incidents in Europe are caused by third party interference [7], where diggers or tractors accidentally damage the pipeline. In many cases, un-authorized construction around pipelines can be detected, classified and acted upon before the pipeline is un-intentionally damaged [8-9].

There are parts of the world like Nigeria, where intentional damage is the main concern and there are 400-500 acts of vandalism every year. People are tapping into pipelines to steal gas at great risk to life and infrastructure. Several examples of major explosions with hundreds of casualties in Lagos, Nigeria, can be found in the media. Distributed acoustic systems could detect, classify and alarm when people approach and tamper with the pipelines. Early detection and alarming would allow for corrective action and potentially save hundreds of lives.

4. DISTRIBUTED BRILLOUIN SCATTERING AND APPLICATIONS

Brillouin scattering results from the scattering of light by sound waves. Thermally excited acoustic waves (acoustic phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light is diffracted backward on this moving grating, giving rise to frequency shifted Stokes and anti-Stokes components [10]. Brillouin scattering is used for strain and temperature sensing in applications from structural health monitoring to pipeline leak detection. Commercially available Brillouin systems have been on the market since the early 1990's, and the two most common configurations include systems based on spontaneous scattering and systems based stimulated scattering.

4.1 Brillouin Systems Based on Spontaneous Scattering

Brillouin systems measure the amplitude of the backscattered light over wavelength and the peak wavelength of the Stokes and/or anti-Stokes component is identified. The peak wavelength of the Stokes and anti-Stokes components vary with the temperature and strain of the optical fiber. The sensing fiber is deployed on the measurement object or in close proximity of the measurement object. The fiber deployment will dictate what is measured.

To measure temperature, the sensing fiber must be deployed strain free and the Brillouin shift of the fiber must be well known and calibrated. In many applications, it is difficult to ensure a completely strain free fiber deployment over the full environmental range given the difference in Thermal Coefficient of Expansion (TCE) between the optical fiber and e.g. a Stainless Steel Tube protecting the fiber during deployment and operation.

To measure strain accurately, the fiber must be attached to the measurement object without any creep between the fiber and the measurement surface. The strain sensing fiber experiences both temperature and strain. The temperature of the strain sensing fiber or measurement object must be measured and subtracted from the total Brillouin shift. Brillouin systems often utilize a cable with a polymer or stainless steel tube containing a second non-strained fiber to enable temperature measurements. This tube however, may be subjected to mechanical strain and movement, and this may induce fiber strain and impact the temperature measurement accuracy.

For accurate single ended strain measurements, it is often required to measure the temperature in the same fiber using a single mode Raman based DTS or to deploy a second multi mode fiber for multi mode Raman temperature measurements. The temperature can also be measured over a limited range using the Landau-Placzek Ratio (LPR) [11] or permutations thereof. One of the Brillouin systems on the market claim independent temperature and strain measurement capability.

4.2 Brillouin Systems Based on Stimulated Scattering

The Brillouin scattering process can be stimulated when the interference of the laser light and the Stokes wave reinforces the acoustic wave through electrostriction. This is done by transmitting a seed signal from one end of a fiber and a pump laser signal from the other end [10]. In practice, this often results in looped systems with two fibers deployed along the asset where temperature and strain needs to be measured.

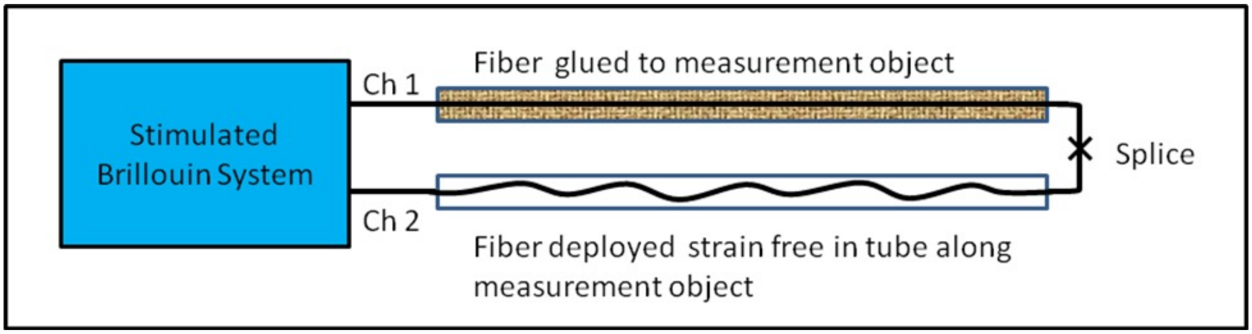

Fig. 3. Stimulated Brillouin System measuring strain and temperature

It is practical to leave one of the fibers strain de-coupled and use it to measure temperature while the other fiber is exposed to both temperature and strain. The main advantages of stimulated Brillouin systems over spontaneous Brillouin systems is the extended dynamic range enabling longer range measurements with higher optical signal to noise ratios. This translates into better measurement resolution and faster measurement speeds.

Challenges to Brillouin technology include sensitivity to Hydrogen in optical fibers as the refractive index varies with Hydrogen concentration. The change of effective refractive index induces a change in measured Brillouin peak wavelength introducing a measurement error. Brillouin systems are challenged to measure temperature accurately in applications like down-hole distributed temperature sensing in hydrocarbon wells as hydrogen, strain and temperature induce wavelength change. Challenges for spontaneous Brillouin systems include limited dynamic range and the inability or difficulty to accurately measure temperature and strain simultaneously over long distances.

Benefits of Brillouin system include the temperature and strain sensing capability, which is a double edged sword as the cross sensitivity poses some practical challenges. The long range measurement capability is very attractive for long span pipeline monitoring, both for temperature and strain measurements. Stimulated Brillouin systems are well suited for long range applications where deviations from the baseline can be measured and used as good indicator of events.

4.3 Applications

Monitoring of concrete curing in civil engineering projects [10] is one of several applications where Brillouin systems have successfully been applied. Optical fibers can be embedded in concrete and measure the temperature over time during the curing process. Temperature monitoring is important as the density and micro-cracks are directly related to the maximum temperature experienced during the chemical setting process. The measured information can be used to maintain the temperature within a suitable range using water to cool the concrete structure during the curing process.

A pipeline leak detection system using Brillouin technology in a 55 km brine pipeline in Germany has been deployed [12]. Two Brillouin systems are used to monitor 4 segments of the 55km pipeline as leaks could contaminate the ground water. Leaks as small as 50ml/minute has successfully been detected showing the value of fiber optic leak detection.

A fiber optic monitoring system is deployed in the Ooguruk subsea pipeline in Alaska [13]. The distributed Brillouin system monitor temperature and strain to detect leaks and pipeline movement due to ice keel gouging, strudel scour, river channel migration, migrating sand due to waves and currents. Several of these effects are unique to the arctic sea ice conditions and river discharge processes that occur as ice and snow melts. Monitoring to avoid spills and discharge in High Consequence Areas (HCAs) is critical to protect the environment and arctic wild life.

5. DISTRIBUTED RAMAN SCATTERING AND APPLICATIONS

Raman scattering converts a small fraction of the power from the launched light pulse into frequency shifted Stokes and anti-Stokes components due to vibrational modes of the fused silica. The temperature can be calculated as a function of the ratio between the anti-Stokes and Stokes intensity. Raman based Distributed Temperature Sensing (DTS) is the most common Distributed Monitoring System, with widespread adoption across oil & gas, power, fire detection and other industrial applications.

The system performance ranges from basic single ended short range systems to high end multi wavelength long range systems. System performance is normally a trade-off between temperature resolution, measurement time and fiber length.

Deployed DTS systems can be divided in three categories: Single ended single wavelength systems, double ended single wavelength systems and single ended multi wavelength systems.

5.1 Single Ended Single Wavelength DTS Systems

The classical way to measure distributed temperature using Raman scattering is to send a single pulse at wavelength λ_0 down the optical fiber and measure backscattered Raman Stokes (λ_s) and anti-Stokes (λ_{as}) components as a function of time. Time of flight will allow a calculation of the location, and the temperature can be calculated as a function of the ratio between the intensity of the anti-Stokes and Stokes components at any given location. Figure 3 below show a single ended system.

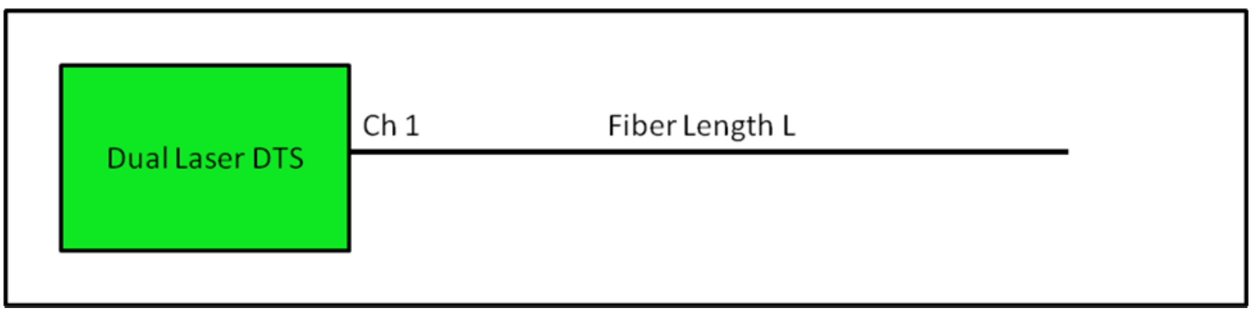

Fig. 3. Single ended DTS system.

Fiber attenuation due to absorption and Rayleigh scattering introduce wavelength dependent attenuation [1]. The peak wavelengths of the Stokes and anti-Stokes components are separated by 13THz from the transmitted pulse. A system operating at λ_0 = 1550nm produces Stokes wavelength λ_s at 1650nm and anti-stokes wavelength λ_{as} at 1450nm. This difference in wavelength dependent optical attenuation ($\Delta\alpha$) between the Stokes and anti-Stokes wavelengths must be compensated for. This is often added to the fundamental Raman equation (1) where the impact of differential attenuation $\Delta\alpha$ is corrected for over distance z.

$$R(T) = \frac{I_{AS}}{I_S} = \left(\frac{\lambda_s}{\lambda_{as}}\right)^4 \cdot \exp\left(-\frac{hc\upsilon'}{kT}\right) \cdot \exp(-\Delta\alpha z) \qquad (1)$$

The underlying fundamental assumption for accurate temperature measurements with a single wavelength DTS is a constant differential attenuation $\Delta\alpha$.

This assumption is not valid in many applications. Examples of situations where the differential loss $\Delta\alpha$ varies are cabling induced bends, radiation induced attenuation or Hydrogen induced attenuation to name a few. Hydrogen caused small attenuation increases in early sub-marine communication cables, and this resulted in the development of carbon coatings. Carbon coatings mitigate Hydrogen permeation in optical fibers up to 150°C. Steam drive heavy oil wells operate at elevated temperatures up to 300°C and Hydrogen induced attenuation is a challenge for single wavelength single ended systems.

Hydrogen induced optical attenuation is caused when Hydrogen react with defect sites in optical fibers [14]. The Hydrogen induced attenuation varies with fiber chemical composition, Hydrogen concentration, temperature and exposure time. The induced optical attenuation is therefore likely to be non-uniform along the length of the optical fiber.

Advantages of a classical single ended system are the simple deployment and long reach in applications where the differential attenuation between Stokes and anti-Stokes components remain constant.

Disadvantage of a classical single wavelength DTS system is that it will experience significant measurement errors due to wavelength dependent dynamic attenuation when e.g. the fiber is exposed to Hydrogen. The total increase in optical attenuation in many fibers may be in the order of 10’s of dB/km, and may exceed the dynamic range of the system.

5.2 Double Ended Single Wavelength DTS Systems

The impact of varying differential attenuation $\Delta\alpha$ can be mitigated using double ended fiber deployments. Figure 4 below show a double ended system.

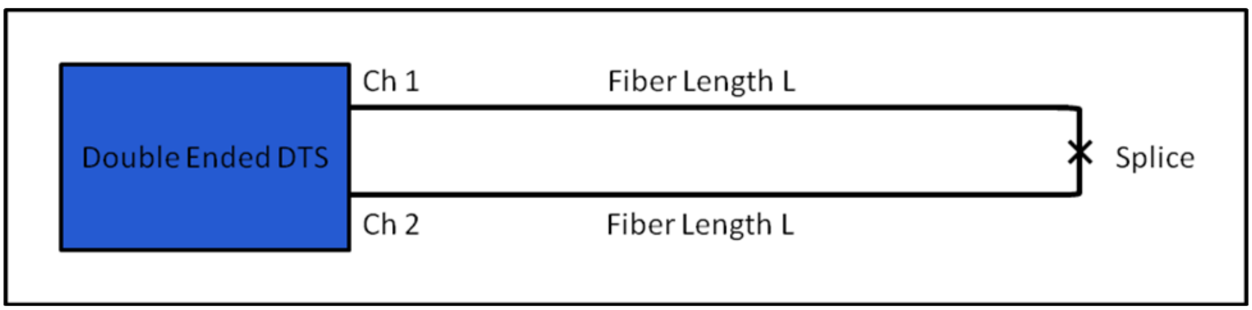

Fig. 4. Double ended DTS System

A fiber is deployed in a loop configuration and a full temperature trace is taken from channel 1 to channel 2 for a total fiber length of 2L. A second full temperature trace is taken from channel 2 giving two temperature points at every point along the sensing fiber. Using this information, the differential attenuation factor $\Delta\alpha$ can be calculated at every location along the optical fiber [15]. This distributed differential attenuation factor $\Delta\alpha(z)$ can then be used to calculate a corrected temperature trace.

There are several issues to be aware of and to consider when considering using a double ended system [15].

1. Using twice the fiber length requires twice the optical budget on the DTS instrument. This is often at the limit of double ended system performance thus reducing any margin in the optical budget.
2. Interrogating sensing fibers from two directions require twice the optical connections and drives system complexity.
3. Twice the fiber is exposed to the environment so Hydrogen induced attenuation will create twice the attenuation increase in a loop when compared to a single ended system.
4. The noise increases exponentially with distance and this shows up in the distributed differential attenuation factor distance $\Delta\alpha(z)$.

Numbers 1 and 2 increase the total system cost while adding deployment complexity. Number 3 reduces the service life of the system. Number 4 impacts the quality of the data, which in turn makes the interpretation of temperature data more difficult. In many installations, it is impractical or even impossible to deploy double ended systems.

The advantage of a double ended system is the ability to correct for dynamic differential attenuation changes. The disadvantages are cost, complexity, system performance and data quality.

5.3 Single Ended Multi Wavelength DTS Systems

A new single ended multi-laser technology [16] has been introduced. It solves all the issues with a double ended system, while providing all the benefits of a single ended system. The system uses multiple lasers and will by design be tolerant to wavelength dependent attenuation. Careful selection of the laser wavelengths will provide signal paths with equal amount of round-trip attenuation for the launched light and backscattered Stokes and anti-Stokes components thus eliminating the effect of distributed differential attenuation $\Delta\alpha(z)$. The performance of a multi wavelength system will be illustrated in figures 5-6 and explained. Figure 5 below shows OTDR data for 4 different optical fibers at room temperature.

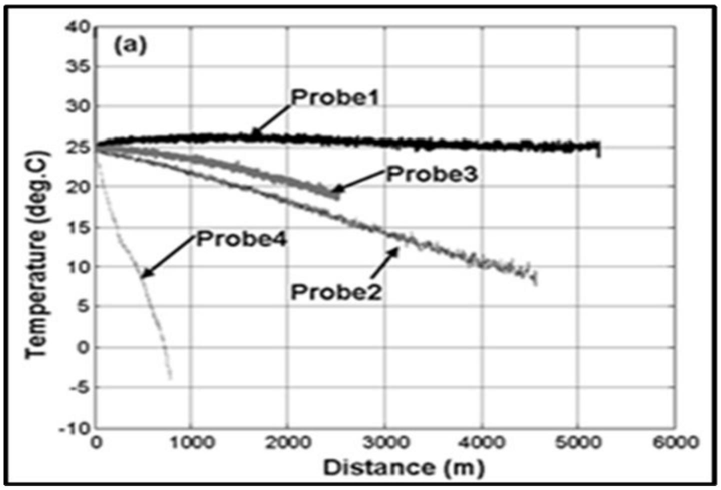

Fig 5. Single ended single wavelength DTS temperature traces.

Fiber probes 1-3 are pristine fibers on shipping spools while the 4th fiber probe is recovered from a steam drive well in Canada. The 4th fiber was retrieved for failure analysis after the operator came to the conclusion that a single wavelength single ended system could not measure any useful temperature data due to Hydrogen induced attenuation. The results in fibers 1-3 show expected linear optical attenuation values while the 4th fiber shows high non-linear attenuation.

Figure 6(a) show DTS data measured with a classical single wavelength DTS, and figure 6(b) show the same DTS data with a multi-wavelength DTS.

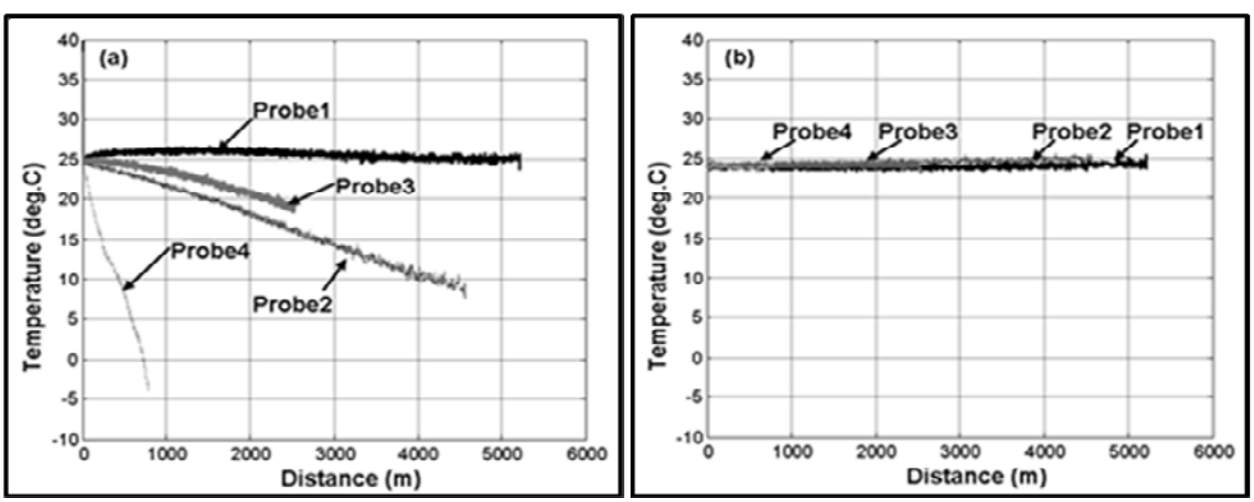

Fig 6. Single ended single wavelength DTS data(a) and multi wavelength DTS data(b).

When the fibers are interrogated using a classical single ended DTS, fibers 1-3 show a largely linear behavior (fig. 6.a). The slope in the measurement for fibers 1-3 can be calibrated out by varying the differential attenuation $\Delta\alpha$ assuming the temperature is known at some point along the fiber. Each of the fibers must be individually calibrated for accurate measurements, but non-linear contributions cannot be calibrated out as can be seen on fiber probe 1 (fig.6a). The 4th fiber shows a large non-linear temperature error due to the Hydrogen induced attenuation. In steam drive wells, the distributed differential attenuation would vary with time, temperature and Hydrogen exposure making any calibration attempts inaccurate.

The same fibers were interrogated using a multi wavelength PerfectVision™ (fig. 6.b). The measured temperature data for all fiber probes, regardless of the difference in distributed differential attenuation, agrees well with the room temperature. The system is by design immune to changes in differential attenuation. Dynamic time varying changes in differential attenuation $\Delta\alpha(z)$ in the fiber probe are automatically cancelled out. This clearly shows the capability of the multi wavelength technology to overcome dynamic non-linear distributed differential attenuation variations [16].

Challenges for single wavelength Raman based systems include sensitivity to distributed dynamic differential attenuation changes due to Hydrogen when fibers with dopants in the core are used. The sensitivity to dynamic differential attenuation effects can to some extent be mitigated using double ended systems and pure silica core type fibers. Double ended systems are challenged in performance, complexity, deployment and operational cost.

Advantages of the latest generation multi-wavelength Raman technology [16] eliminate the sensitivity to dynamic differential attenuation effects while providing the simplicity of single ended systems. When combined with the latest generation Hydrogen tolerant fibers, this translates into greatly extended service life at reduced total cost of ownership.

5.4 Applications

Raman based DTS systems is the most widely deployed distributed monitoring technology with a proven track record in oil & gas exploration & production [17] , power cable monitoring [18], linear heat detection systems [19] and many other applications. DTS systems provide increased efficiency and better utilization of many capital assets like hydrocarbon reservoirs, the power grid, green technology like geothermal wells and concentrated solar power.

Raman based DTS systems can be applied to pipeline monitoring for flow assurance and leak detection in applications up to 40km [20]. Fiber optic sensing systems are intrinsically safe and well suited for hazardous area and zone rated applications.

Raman based systems are used in the latest technology advances where super conduction cables are being developed for increased efficiency and better resilience of the power grid. When combined with renewable energy sources like wind, solar and geothermal, this provides better utilization of the power grid with increased reliability and lower operational cost.

Defense applications for DTS systems include temperature monitoring of towed sensing arrays as the speed of sound changes by 4 meter/second for every degree Celsius of temperature change in sea water. Accurate temperature measurements allow for a more accurate detection and ranging of naval threats. Optical slip-rings are often used during the deployment/operation of the acoustic sensing arrays and the differential attenuation across the slip-ring changes as the slip-ring rotate. Field trials with multi-wavelength DTS systems show good performance across optical slip-rings during deployment and operation of sensing systems.

Security applications for DTS systems include fire detection and monitoring of how the fire and hot smoke spreads. It is desirable to detect the rate of temperature rise as this may indicate a potential hazard that can be mitigated before loss of life and property damage occur. Once a fire has developed, it is desirable to know how the fire is progressing, where the smoke is and how the smoke moves. This knowledge allows the emergency response team to control fans to divert smoke away from people and guide people away from potential danger locations. Distributed fiber optic systems show clear advantages over electrical digital fire detection systems. Electrical digital fire detection systems rely on insulation between two conductors to melt at elevated temperatures, and thereby short circuit two conductors. Electrical digital fire detection systems cannot monitor the rate of temperature rise or the movement of smoke and fire due to the system design.

Environmental applications include distributed temperature measurements in streams, lakes, mines, glaciers, air and snow [21]. For example, to understand the proper habitat for trout and salmon, it is critical to explore the processes that control a stream's peak daily temperature. The endangered Chinook salmon, and many other fish, become stressed and die when rising temperatures simultaneously decrease oxygen content of the water, increase the fishes' base metabolism, and increase the reproduction of parasites, leading to catastrophic die-offs when threshold temperatures are crossed. Better understanding of our environment will allow us to act responsibly and avoid man made disturbances with potential catastrophic effects in our ecosystem.

6. CONCLUSIONS

Distributed Monitoring Systems provide valuable contributions to applications in Defense, Security and Sensing across a large number of applications. The distributed nature of these systems offers unparalleled advantages over electrical systems and new applications develop as the market for distributed fiber optic sensing systems continue to grow.

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