Distributed Temperature Sensing

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Introduction

The purpose of this paper is to acquaint the engineer with the technology, terms and physical principles of Distributed Temperature Sensing (DTS), a technology that allows the measurement of temperature along a passive fiber optic element.

Keywords: distributed temperature sensing, DTS, fiber optic, thermocouple, Rayleigh, Brillouin, backscatter, Stokes, Anti-Stokes, double-ended system

A Rising Technology

Imagine having the ability to view a 3D model of an environment's temperature profile and watch it change over time. Now imagine being able to maintain accuracy over kilometers of distance through rock and under water. Care to map groundwater flow patterns beneath the surface or detect leakage in dikes and dams? How about monitoring the temperature along high voltage cables or detecting fires in tunnels and monitoring their growth? Want to extrapolate fluid flow information down a bore hole? With Distributed Temperature Sensing technology, all of this is possible.

Distributed Temperature Sensing is a rising technology. As the technical limitations and cost of DTS systems decrease the applications and prevalence will increase over former technologies providing greater accuracy and resolution of data across longer distances. This technology can be used in hash environments where former technology would have been prone to failure or unreasonable to deploy.

What is it?

The measurements do not rely on electronic or mechanical sensors at discrete locations along the line, but rather by observing the physical interactions between probing light energy and the fiber optic medium. Because the measurements do not rely on a multitude of discrete sensors, they can be taken at virtually all locations along the length of a cable and are inherently more reliable than former technology. The optical fiber can be thought of as a long thermocouple, along the entire length of which the distributed temperature profile can be determined.

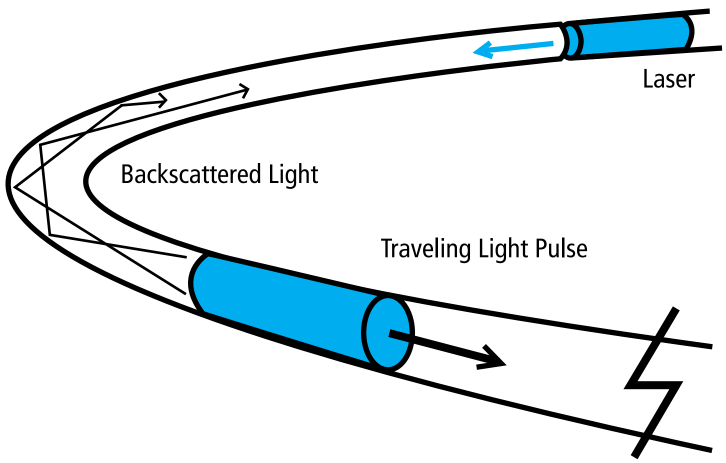
How it Works

A short laser pulse is launched down a fiber optic cable. The length of the pulse is typically 10 nanoseconds or less for increased spatial resolution. This light pulse propagates down the fiber through a region of the core and cladding glass known as the mode field. The velocity of light is dependent on the medium through which it travels. For glass with an index of refraction of $\mathbf{n} \approx 1.5$, the velocity of light is $v \approx 2 \cdot 10^8$ m/s.

$$v = \frac{c}{n} = \frac{3{\cdot}10^8 m/s}{1.5} = \frac{2{\cdot}10^8 m}{s}$$

In the equation above, **c** is the velocity of light in a vacuum, **c** ≈ 300,000 km/s or $3{\cdot}10^8$ m/s, **n** is the refractive index of the glass and **v** is the velocity of light in glass.

Traveling Light Pulse Through Fiber Optic Cable



$$t = \frac{2z}{v}$$

FIGURE A

The time it takes for a pulse to travel down a length of the fiber and return to the sensor is referred to as the time of flight. The time of flight (t) of the pulse is proportional to the distance and speed it travels.

In the equation above, **t** is the time of flight and **z** is the distance along the fiber from the light source. By knowing the velocity of light in the fiber and timing the flight of the signal, the distance can be calculated where that signal event occurred. This yields the spatial component of the reading, allowing the distance of each reading to be plotted against its magnitude for a temperature profile, which can, in turn, be projected over time.

The pulse width required to achieve a one meter length resolution along the fiber (Δz = 1m) is:

$$\Delta t = \frac{2\Delta z}{v} = \frac{2{\cdot}1m}{2{\cdot}10^8 m/s} = 10^8 s = 10ns$$

As the light pulse travels, a portion of the photons interact with the glass medium through which it travels. The portion of light that is absorbed and re-emitted is dependent on the number of molecules in the different vibrational energy states, $\mathbf{N}_i$, described by Boltzmann distribution. As temperature (**t**) goes up, the ratio also goes up, since there are proportionally more high energy states.

$$\frac{N_i}{N} = \frac{g_i}{g} e^{-\frac{E_i}{k_B T}}$$

Here, **N** is the number of molecules, **g** is the dependency factor, or number of available degenerate energy states, **E** is the energy, $\mathbf{k_B}$ is the Boltzmann constant and **T** is temperature.

When a photon is absorbed by a molecule, an electron is excited to a higher energy state. When the electron falls back to a lower energy state, a photon is emitted with a proportional difference in energy. The emitted photon could have either more, less or the same amount of energy as the incident photon dependent on the change in energy states from excitation to de-excitation of the depleted electron.

Photon/Molecule Interactions

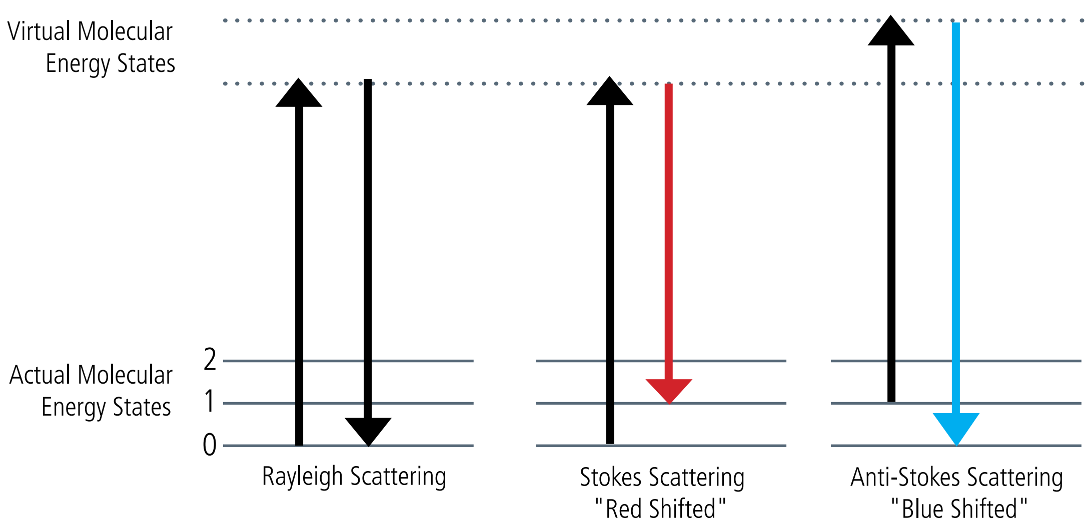


FIGURE B

Photons can be re-emitted at several different energy states. The majority of emitted photons have the same energy as the incident photons. This is called Rayleigh Scattering. Rayleigh Scattering represents an elastic response of the photon/electron interaction. The molecules' electrons are raised to a virtual energy state, then fall back to their original energy state, releasing light at the same wavelength of stimulation.

The second order energy state is called Brillouin Scattering and represents inelastic interactions between the photons and electrons due to the vibrational state of the lattice structure of the glass. This is dependent on physical properties of the fiber, such as pressure, temperature, lattice strain and elastic properties.

The third order energy state is called Raman Scattering, it also represents inelastic interactions, which arise from molecular vibration of the $SiO2$ and to a lesser degree, $GeO2$. The Raman backscatter is weaker in amplitude than the others mentioned. This is the most common signal response used in DTS systems.

Both Brillouin and Raman Scattering produce photons at longer and shorter wavelengths than the incident light. Photons which are emitted with less energy are referred to as red shifted, Stokes Scattering. Photons which are emitted with more energy are referred to as blue shifted, Anti-Stokes Scattering. This shift is a function of the incident light and the material they interact with.

Observed Response Signal, Intensity on the Ordinate vs. Frequency on the Abscissa

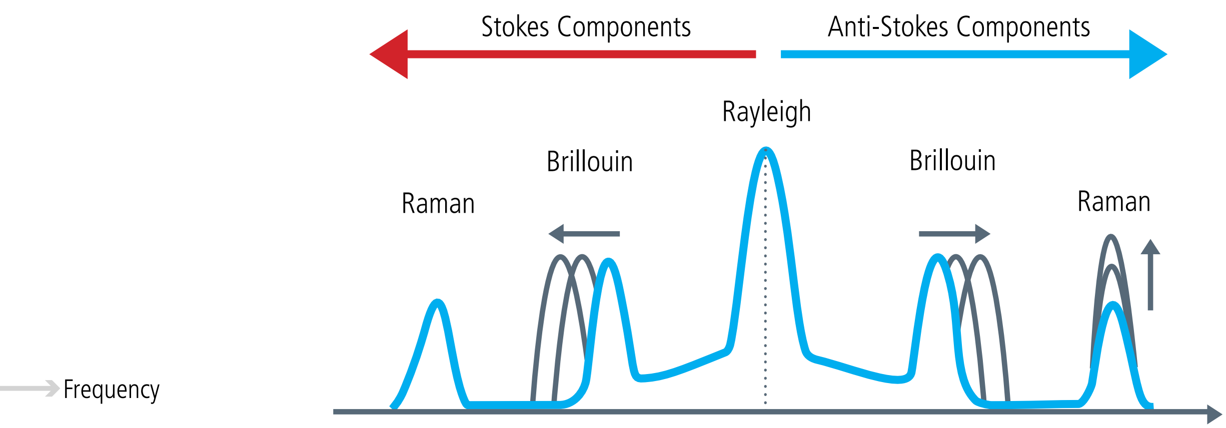


FIGURE C

For Raman sensing, the Anti-Stokes signal is strongly temperature dependent, whereas the Stokes signal is weakly temperature dependent. As temperature increases, more Anti-Stokes photons are produced than Stokes photons for any given interaction. If a reference temperature is known and the system is calibrated for the optical fiber being used, then a ratio of the Anti-Stokes to Stokes intensities can yield the temperature at any given location. The simplified Anti-Stokes/Stokes equations solved for temperature at a given location, T(z), are shown below.

$$T(z) = T_{ref} \cdot \left[1 + \frac{\Delta\alpha z}{\ln\left(\frac{C_{Stokes}}{C_{Anti-Stokes}}\right)} + \frac{\ln\left(\frac{I_{Stokes}(z)}{I_{Anti-Stokes}(z)}\right)}{\ln\left(\frac{C_{Stokes}(z)}{C_{Anti-Stokes}(z)}\right)} \right]$$

In the equation above, **T(z)** is the temperature along the fiber at distance **z** in degrees K, $\mathbf{T_{ref}}$ is the reference temperature in degrees K, $\boldsymbol{\Delta\alpha}$ is the differential attenuation between Stokes and Anti-Stokes backscatter wavelengths, **m-1**, $\mathbf{C_{Stokes}}$, $\mathbf{C_{Anti\text{-}Stokes}}$ are constants relating to sensitivity of I_{Stokes} /$I_{Anti\text{-}Stokes}$ to temperature, $\mathbf{I_{Stokes}}$ is the intensity of Stokes band as a function of location and $\mathbf{I_{Anti\text{-}Stokes}}$ is the intensity of Anti-Stokes band as a function of location.

Attenuation of the Scattered Light

Photons are re-emitted in random directions. Those that are released at an angle greater than the critical angle of the glass, escape and cannot be detected by monitoring either end of the fiber. This is known as attenuation. Some of the photons are emitted and continue down the fiber path. Some return in the direction from which they came. This is known as backscatter. Since the amount of light re-emitted in one direction is minuscule, a "double-ended system" is typically preferred.

A double-ended system observes the light emitted in the direction of transmission and the backscattered light traveling in the opposite direction. The ability to look at both signals significantly improves the accuracy of results. Because the light that returns to the sensor is scarce, Raman systems typically use multimode fiber to maximize the amount of return light.

Light Pulse Diffusion Point in a Fiber

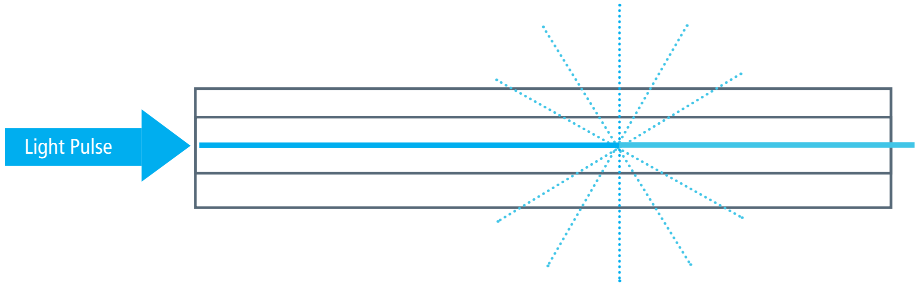


FIGURE D

The portion of light that returns to the detector can be estimated by Beer's Law: $I(z) = I_0 \exp(-\alpha_\lambda z)$

In Beer's Law **I(z)** is the detected intensity of light from a given location, $\mathbf{I_0}$ is the transmitted intensity of light and $\boldsymbol{\alpha_\lambda}$ represents the wavelength dependent attenuation coefficient in m^{-1}.

Because the light that the detector sees in the Raman band is weak and the signal-to-noise ratio is high, it is preferred to look at many of the pulses stacked on top of each other and statistically normalized. Typically, a log may run for five minutes or more, continuously pulsing the fiber and recording the results to yield a suitable temperature accuracy such as 1°C. If a higher degree of accuracy is desired, more pulses could be analyzed and a longer data logging period would be required, such as one hour for a temperature resolution of 0.1°C. This trade-off of sensing time versus accuracy approaches a threshold of diminishing returns. By taking more time to get a more accurate result, you increase the period over which the temperature can fluctuate. This fluctuation will eventually be greater than the accuracy gained by waiting for additional data points.

System Components

A DTS System is comprised of electrical and optical devices working together to collect and process optical signal responses and derive the thermal component of the environment in which they are deployed. With the exception of the recording instrumentation at one or both ends of the fiber, there are no electronics, no sensors, no electrical wires nor electrical connections along the line. This makes the cable less complex with fewer components that can fail. Fiber cables are much safer in environments where high voltage or amperage is required or where an electrical spark could ignite a fire. All-optical cables can operate at much higher temperatures and pressures than cables with integrated electronics. The bit error rate is usually less than 10^{-13} in optical cables, mostly due to a much lower susceptibility to electromagnetic interference than electrical cables. This results in a high data accuracy of the transmitted signal. Typically, a DTS system is comprised of a laser, decoupler, optical cable and signal processor.

DTS System Diagram with an Illustrated Response Signal Plot from the Signal Processor

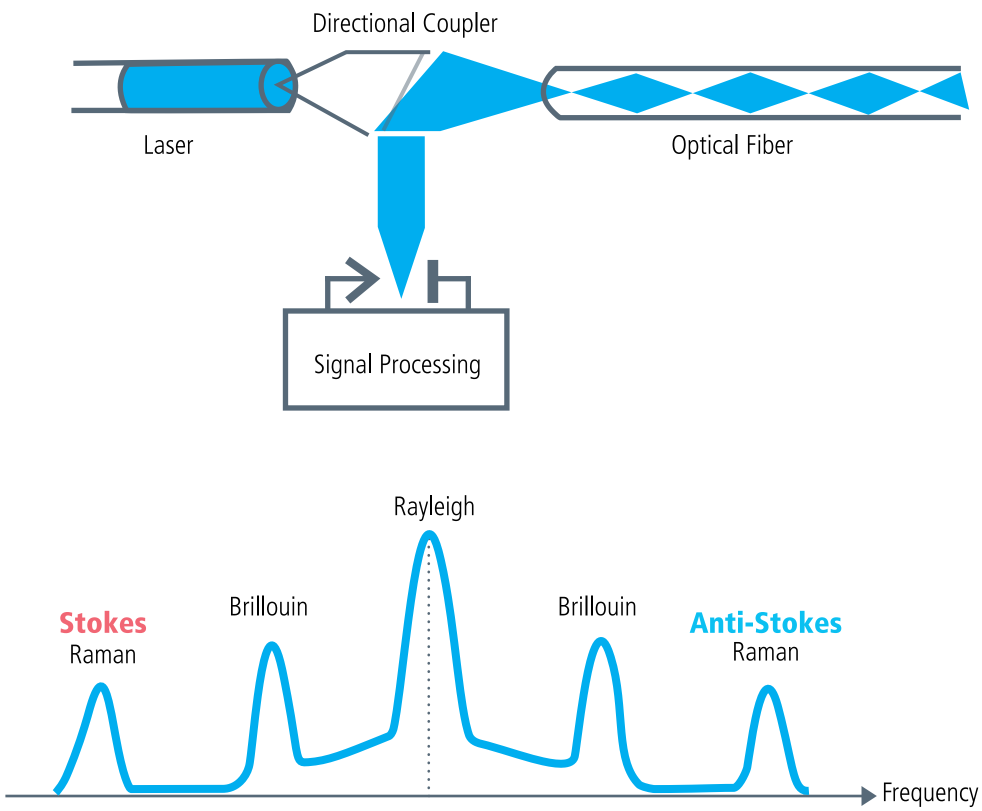


FIGURE E

When DTS was first used, several limitations slowed enthusiasm for the technology. Many of these limitations have already been overcome. Fiber temperature ratings have drastically increased, up to 700°C. Optical fibers susceptibility to Hydrogen darkening has been delayed if not prevented through the use of hydrogen scavenging protective compounds, hermetic carbon coatings and improved glass chemistry. Fiber comes in much longer lengths and at much lower costs.

Summary

Distributed Temperature Sensing is a rising technology. System costs are likely to continue to reduce and system performance is likely to increase over the coming years. As it does, and as former limitations are overcome, the technology becomes practical for many applications. This technology is inherently less prone to failure and can be employed in environments considered far too harsh or dangerous for former technologies.

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