White Paper

Distributed Strain and Temperature Sensing Using Brillouin Scattering

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Abstract

The purpose of this paper is to acquaint the engineer with the technology, terms and physical principles of Distributed Strain and Temperature Sensing (DSTS) using Brillouin Scattering. This is a technology that allows the measurement of strain and temperature along a passive fiber optic element or waveguide path over long distances utilizing the phenomenon of Brillouin Scattering.

Keywords: distributed strain and temperature sensing, DSTS, DTSS, fiber optic, Brillouin, backscatter, Stokes, Anti-Stokes and strain sensing

Introduction

Distributed Strain and Temperature Sensing (DSTS), also known as Distributed Temperature and Strain Sensing (DTSS), is a rising technology. As the technical limitations and cost of DSTS 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 employed in harsh environments where former technology would have been prone to failure or unreasonable to deploy. It also excels in long-haul, continuous spans where a multitude of point sensors or FBGs would be too costly or challenging to power.

Single-mode optical fibers have commonly been used as inexpensive communication channels. Traditionally, the fibers are protected from external influences by means of cabling to protect the fibers. However, by enhancing the environmental influences on a waveguide, the fibers can be used to detect, monitor and even measure external perturbations (measurands) in an integral or distributed format.[9]

What is it?

Distributed Sensing (DS) refers to the use of an optical fiber as a linear sensor. Measurements of back-scattered light from laser pulses transmitted down the fiber are recorded for analysis. The back-scatter signal can be processed to yield information on the strain and temperature along the length of the fiber. 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 physical fiber optic medium. A single telecommunications-grade single-mode fiber can replace thousands of point sensors or multiple fibers of other systems reducing installation, calibration and maintenance costs. Because the measurements do not rely on a multitude of discrete sensors, they can be taken at virtually all locations along the length of cable and are inherently more reliable than former technology. This grade of optical fiber has a service life in excess of 40 years. It is inexpensive, lightweight, pliable and immune to electromagnetic interference (EMI). When properly cabled, fiber is a cost-effective, durable and inert sensor. A single fiber can measure the distributed temperature, strain and vibration along the length of the cable. This measurement can be used to monitor and detect events along the object on which it is installed. With the use of remote optically-powered amplification, a detection range of 24-100 km is achievable in any direction from the monitor/power station. Thus, some manufacturers' systems can stretch 200 km (100 km in opposite directions) from a single location.

The Physics

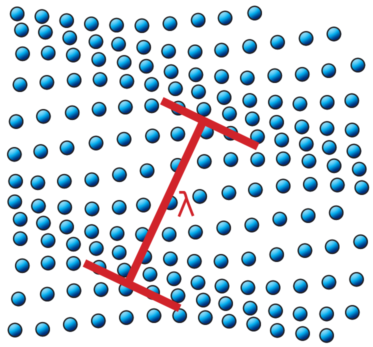


FIGURE A

Brillouin sensors make use of the effect of light scattering in an optical fiber caused by the presence of acoustic waves and thermal vibration. The interaction between an electromagnetic wave and matter can generate variations in the molecular structure of the material, particularly in crystalline structures such as optical fiber. Incident light waves generate acoustic waves through the *electrostriction effect* (the tendency of materials to become compressed in the presence of an electric field). When a medium is compressed, its index of refraction changes. Periodic elastic modulation of molecular density caused by local compression and expansion patterns of collective atoms or molecules is known as a *phonon*.

Provoked phonons induce a time-dependent, modulated refractive index of material that results in a light-backscattering similar to a Bragg grating. This scattered light is shifted in frequency due to the *Doppler shift* (change in frequency due to the motion of the source) associated with the grating phonon moving at the acoustic velocity.[9, 11]

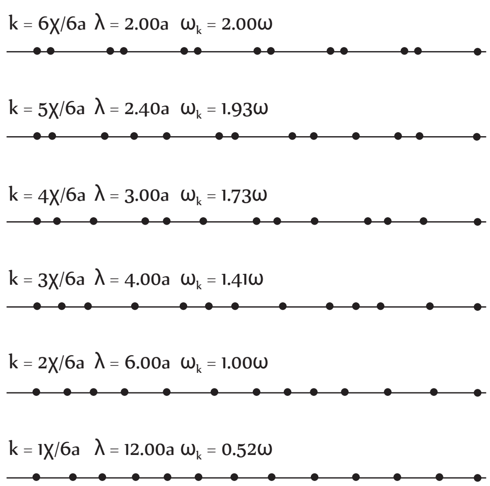


FIGURE B

Brillouin scattering is an interaction between an electromagnetic wave and a density wave (photon-phonon scattering). From a quantum physics perspective, when the intensity of light can locally modify the density of the solid, a constructive/destructive electromagnetic *Fabry-Pérot interferometer* pattern can appear.

In this process, the material absorbs part of the energy from the electromagnetic wave. This energy is used for generating a periodic structure, while the remaining energy is re-emitted as a wave of lower frequency provided that conditions of resonance between the light wave and the phonon are met. The photon may lose energy to create a quasiparticle (Stokes process) or gain energy by destroying one (anti-Stokes process). This shift in photon frequency, known as the *Brillouin shift*, is equal to the energy of the interacting phonon and thus *Brillouin scattering* (named after Léon Brillouin who first described this theory in 1910) can be used to measure phonon energies.[9, 11]

Time of Flight

A short laser pulse is launched down a fiber optic cable. The length of the pulse is typically 10-100 nanoseconds (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 $n \approx 1.5$, the velocity of light is $v \approx 2 \cdot 10^8$ m/s.

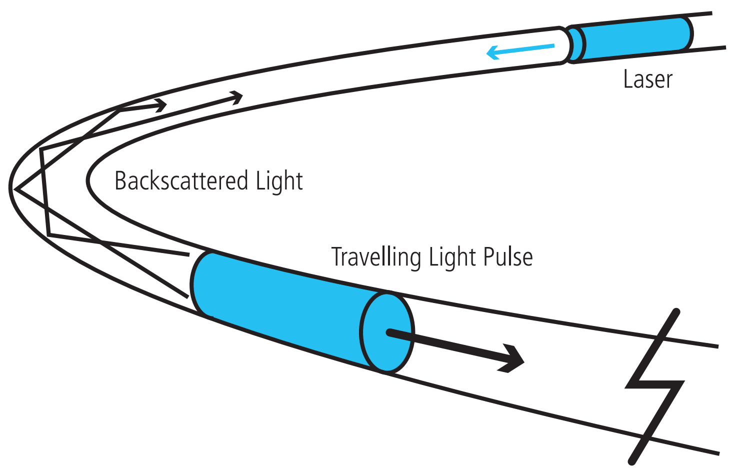
EQUATION 1

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

c is the velocity of light in a vacuum, c≈300,000 km/s or $3 \bullet 10^8$ m/s
n is the refractive index of the glass
v is the velocity of light in glass

FIGURE C

Travelling Light Pulse Through Fiber Optic Cable



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.

EQUATION 2

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

t is the time of flight
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 ($\Delta z = 1$ m) is

EQUATION 3

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

Devices that measure the time of flight and therefore distance are called Optical Time Domain Reflectometers (OTDRs).

Backscatter and Frequency Shift

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, N_i, described by Boltzmann's distribution. As temperature, T, goes up, the ratio goes up since there are proportionally more high energy states.

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

N is the number of molecules
g is the dependency factor or number of available degenerate energy states
E is the energy
kB is the Boltzmann constant
T is temperature

EQUATION 4

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.[7]

Photon/Molecule Interactions

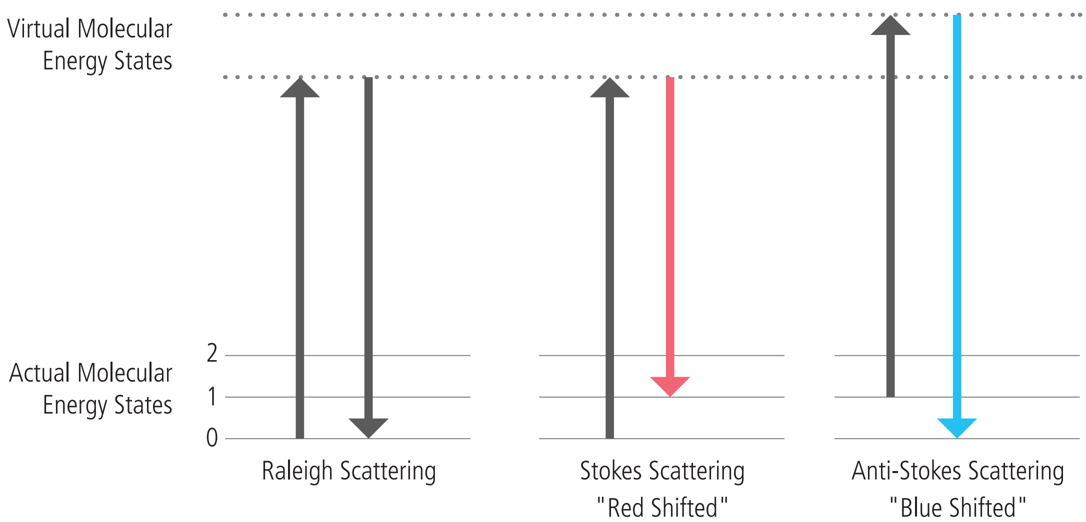


FIGURE D

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* which 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* which also represents inelastic interactions and arises from molecular vibration of the SiO_2 and to a lesser degree GeO_2. The Raman backscatter is weaker in amplitude than the others mentioned. This is the most common signal response used in Distributed Temperature Systems (DTS).

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 with which it interacts.

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

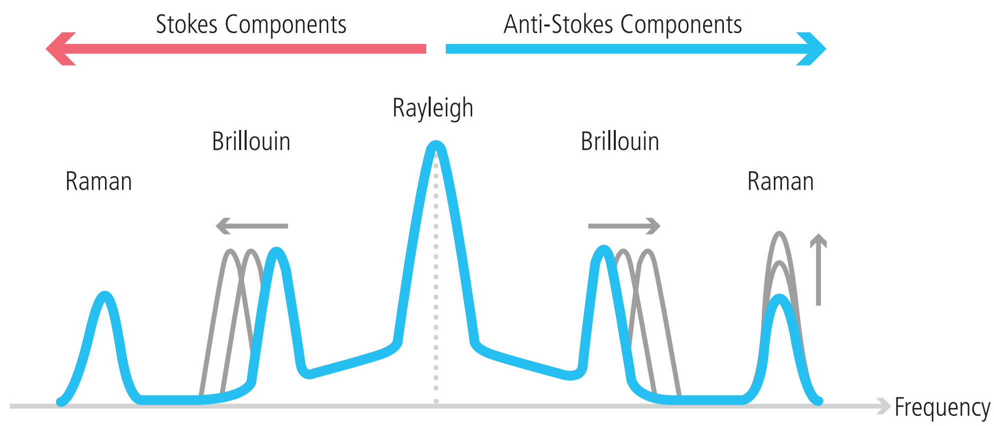


FIGURE E

Types of Brillouin Sensors

There are two general types of Brillouin fiber optic sensors based on different technology. A Brillouin Optical Time Domain Reflectometer (BOTDR) resolves the strain or temperature based on Brillouin scattering of a single pulse. Brillouin Optical Time Domain Analysis (BOTDA) is based on a more complex phenomenon known as Stimulated Brillouin Scatter (SBS).[7]

How Does a BOTDR Work?

A BOTDR works just like an OTDR and inspects the Brillouin band reflections.

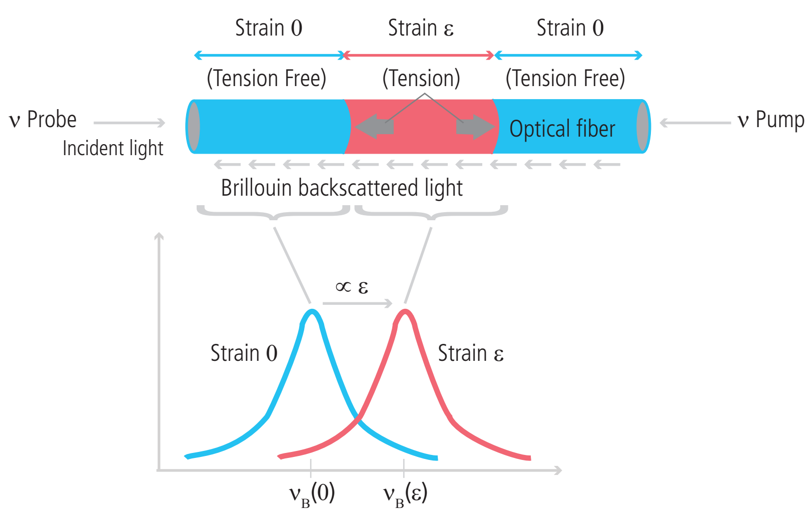
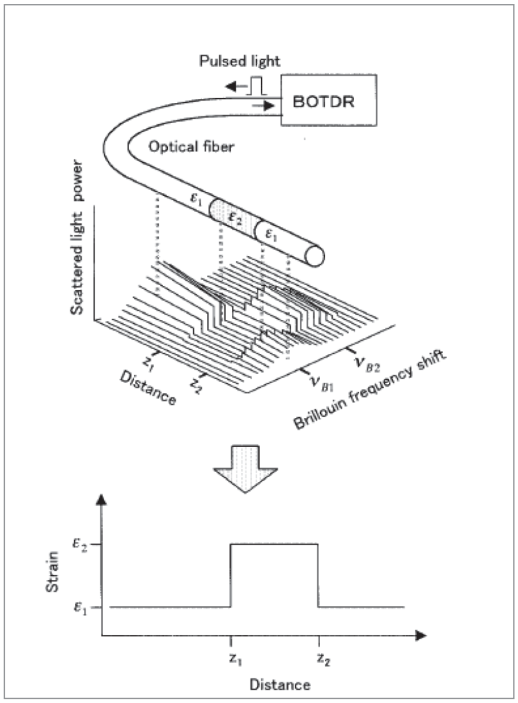


FIGURE F

The Brillouin frequency shift is proportional to the change in temperature and strain as shown in Figure F. This relation can be expressed as:

$$\nu_B(\varepsilon) = \nu_B(0) + C_T(T-T_0) + C_\varepsilon(\varepsilon-\varepsilon_0)$$

Decoupling results from strain and results from temperature is necessary for useful data. In some optical fibers such as dispersion-shifted fiber, there are actually two peaks in the Brillouin spectrum and it is possible to extract both temperature and strain information simultaneously from a single fiber.[14] An advantage of a BOTDR is that only one end of the fiber needs to be accessible.



BOTDR measurement process[12]

FIGURE G

Simulated Billion Scattering

Stimulated Brillouin Scattering (SBS), also known as Coherent probe-pump-based Brillouin scattering, can be optically stimulated leading to the greatest intensity of the scattering mechanism and consequently an improved signal-to-noise ratio. The Brillouin frequency-based technique, as opposed to intensity-based techniques such as Raman, is inherently more accurate and more stable over time since intensity-based techniques suffer from a sensitivity to drifts. Some sensor units utilize Stimulated Brillouin Scattering and are especially suited for applications requiring speed, distance or higher optical budget.

System Capabilities

System capabilities vary from different manufacturers over different distances and different system configurations, but the following values are typical for the industry at the time of writing.

- Spatial Accuracy: resolution of 0.1-50 m
- Measurement Precision: resolution of 0.1°C for temperature and 2 microstrain for strain
- Speed: one second for dynamic measurements, 20 minutes for high resolution measurements
- Distance per unit: 24-200 km
- Power: optical budget 20-30 dB

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 while some return in the direction from which they came. This is known as *backscatter*.

Light Pulse Diffusion Point in a Fiber

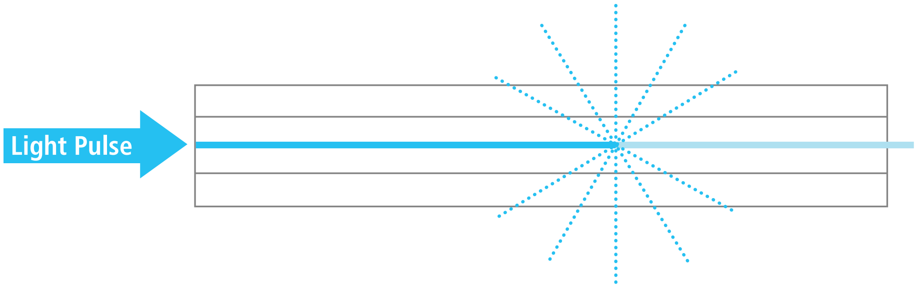


FIGURE H

The portion of the light that returns to the detector can be estimated by Beer's Law.

$$I(z) = I_0 \exp(-\alpha_\lambda z)$$

EQUATION 5

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}.

In the case of Stokes scattering (including Brillouin and Raman), only a small fraction of light (approximately 1-in-1000 photons for example, though the equation is not linear) is scattered at frequencies different from, and usually lower than, the frequency of the incident photons. Since the intensity of a backscattered Brillouin band is a few orders of magnitude less than that of the incident light, the Brillouin backscatter signal is very weak. With a weak scatter signal, the signal-to-noise ratio becomes an important parameter of the system.[7]

Because the light that the detector sees in the Brillouin 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 1-20 minutes or more, continuously pulsing the fiber and recording the results to yield a suitable accuracy. If a higher degree of accuracy is desired, more pulses could be analyzed and a longer data logging period would be required. This trade-off of sensing time versus accuracy approaches a threshold of diminishing returns. By taking more time to get a more accurate result, the period over which the temperature can fluctuate is increased. This fluctuation will eventually be greater than the accuracy gained by waiting for additional data points.

Trade-offs When Selecting a System

Applications

- Structural health smart monitoring (concrete and composite structures)
- Bridge monitoring
- Dam, dike, embankment and levee monitoring
- Buildings
- Pipeline monitoring
- Power line monitoring
- Process control
- Boarder/security monitoring
- Fire detection
- Crack detection
- Corrosion/erosion monitoring of pressurized pipe
- Oil and gas subsea infrastructure
- Casing monitoring
- Gas line leaks via the Joule-Thompson effect

System Components

The distance component and therefore, location, can be measured by an OTDR. In BOTDA, this yields the temperature or strain at any particular location along the fiber. A Coherent Rayleigh OTDR provides distributed information on dynamic events, such as those caused by third-party intervention.

A DSTS System is comprised of electrical and optical devices working together to collect and process optical signal responses and derive the strain and 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^{-11}% in optical cables in large part due to a much lower susceptibility to electromagnetic interference than electrical cables. This results in a high data accuracy of the transmitted signal. Typically, an OTDR DSTS 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

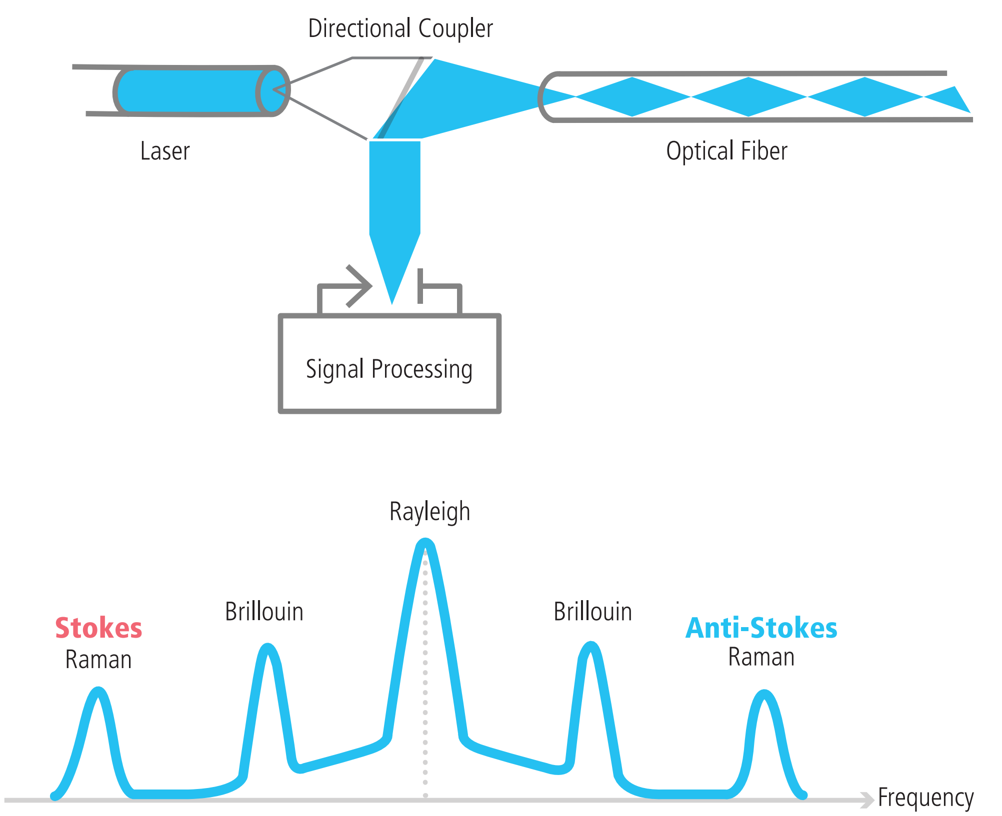


FIGURE I

Early in the infancy of DSTS, several limitations were used that slowed the enthusiasm for the technology. Today, many of these limitations have already been overcome. Fiber temperature ratings have drastically increased. The susceptibility of optical fibers to Hydrogen darkening has been delayed, if not prevented. This has occured through the use of hydrogen-scavenging protective compounds, hermetic carbon coatings and improved glass chemistry. Fibers are now available in much longer lengths and at much lower costs.

Summary

Distributed Strain and Temperature Sensing is a rising technology. System costs are likely to continue to decrease 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 and over distances unmatched by other competing technologies.

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