Figure 11.26 Photograph of a fiber Bragg grating temperature sensor (photo courtesy of Micron Optics Inc.).

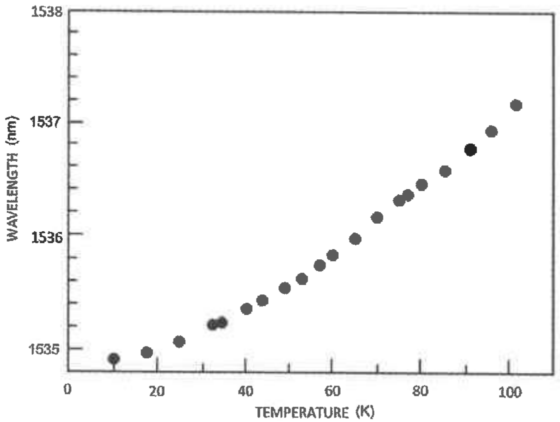


Figure 11.27 Wavelength shift of a grating at cryogenic temperatures.[35]

in a stable manner is at cryogenic levels to about 400 °C. Figure 11.27 shows a plot for temperature response in the 0–100 K range. Bragg grating temperature sensors have the potential to be used in temperature measurements associated with superconducting devices, which require electromagnetic interference (EMI) isolation at liquid helium temperatures.[35]

11.9 Distributed Temperature Sensing (DTS)

In the early 1980s, Raman scattering was first proposed for temperature sensing applications,[36] as it was demonstrated that the magnitude of the anti-Stokes Raman scattering component is highly temperature sensitive, whereas the Stokes component is not. The Raman scattering DTS method is based on the measurement of the ratio of the anti-Stokes to Stokes backscatter intensity components as a function of time (distance); this provides a distributed temperature profile along the fiber, as depicted in Fig. 11.28. To date, the technique has been used extensively in various applications and industries, and several commercial DTS instruments are available.

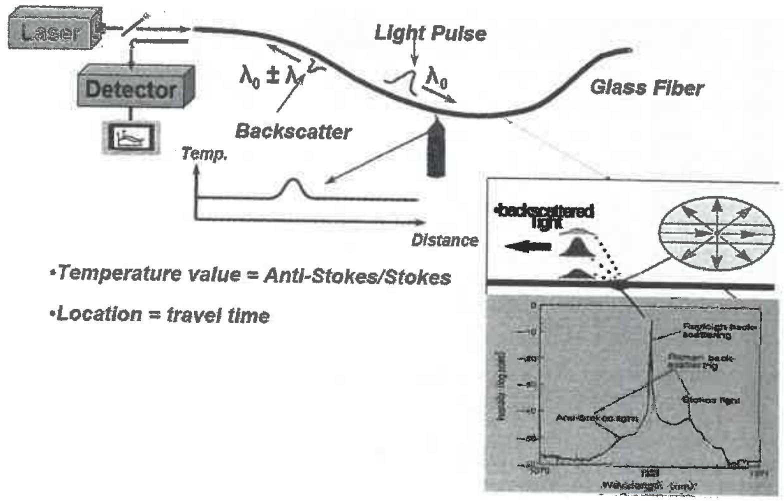


Figure 11.28 Operating principle of Raman scattering distributed temperature sens (DTS).

The intensity of the Raman scattering I_R is expressed as[37]

$$I_R = \frac{I_o N_o \sigma_R}{(\lambda_i \pm \lambda)^4}, \qquad (11.$$

where I_o is the intensity of the incident light, λ_i is the incident bea wavelength, N_o is the population of the starting ground level (equal to N_g, t ground level population for the Stokes line, and $N_o = N_g\, e^{\nu/kT}$ for the an Stokes component), and σ_R is the Raman cross section for silica glass. T Stokes and anti-Stokes intensity expressions become

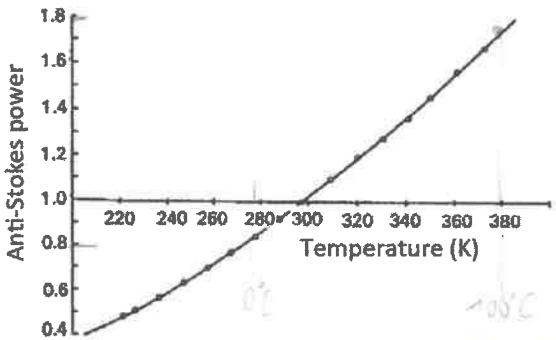
$$I_S = \frac{I_o N_g \sigma_R}{(\lambda_i + \lambda)^4}, \qquad (11.$$

and

$$I_{AS} = \frac{I_o N_g e^{\nu/kT} \sigma_R}{(\lambda_i - \lambda)^4}, \qquad (11.$$

respectively.

The anti-Stokes component is highly sensitive to temperature due to i intrinsic dependence on the absorption of energy from phonons, which is Boltzmann-driven process with its energy population driven by temperatur Figure 11.29 is a graph of the relative intensity of the anti-Stokes compone power versus temperature.



jure 11.29 Temperature dependence of the Raman anti-Stokes component.[36]

he ratio R of the anti-Stokes to Stokes components is given by

$$R(T) = \frac{I_{AS}}{I_S} = \left(\frac{\lambda_s}{\lambda_a}\right) e^{-(hc\Delta v/kT)}. \tag{11.8}$$

:atio is practically independent of the material (cancelling most of the ıon fiber effects for both scattering components—within a certain al range) and depends only on temperature. Thus, a Raman DTS ırement provides an absolute indication of the temperature distribution medium, irrespective of the received light intensity, launch conditions, er geometry of material composition. Furthermore, by taking the ratio Raman backscatter components, the temperature measurement itself is :ferencing.

ɔ determine the absolute temperature value from this ratiometric ırement of the backscattering signals, Raman DTS systems utilize a nce fiber coil inside their electronics or, alternatively, a calibration run is :med by placing a test fiber coil in a controlled temperature bath. This s kept at a constant known temperature, say θ, which produces a catter ratio $R(\theta)$. Then, any unknown measured temperature T can be ated from a re-arrangement of Eq. 11.8 as follows:

$$T = \left\{\frac{1}{\theta} - \frac{k}{hcv}\ln\left[\frac{R(T)}{R(\theta)}\right]\right\}^{-1}, \tag{11.9}$$

: $R(T)$ is the uncalibrated Raman backscattering ratio and $R(\theta)$ is the from the fiber reference coil at the known temperature θ.

urrent commercial Raman DTS systems are well established, functional, effective devices displaying a very low cross-sensitivity to other ıeters, such as pressure or strain. Their main disadvantage is the weak catter signal that requires long averaging times and the use of pulsed to achieve adequate returned signal intensity.

The basic setup of a Raman DTS comprises a pulsed laser source that injects a high intensity light pulse into a fiber (typically multimode, but single-mode fiber are used for long-range systems) that acts as the sensing element. Raman backscattered light travels back to the fiber's input where it is coupled out via a splitter into a pair of photodetectors fitted with thin optical filters to select the specific peaks of the Stokes and anti-Stokes spectral components. The photodetectors convert the optical intensity into electrical signals, and the ratio of anti-Stokes/Stokes intensity is obtained. It should be noted that, because of the small intensity of the backscattering signals, signal averaging and integration must be done over a certain time interval in order to obtain a reasonable signal strength and adequate signal-to-noise ratio in the system. The anti-Stokes/Stokes intensity ratio is converted into temperature units by the use of a calibration factor that takes into consideration the fiber characteristics and the particular set-up configuration. Distance information is calculated using the OTDR principle by the specific travel time of each pulse received from the pulse train coupled into the fiber. The data is processed and displayed in graphical form to show a plot of temperature magnitude versus distance. Figure 11.30 illustrates an example of a Raman DTS measurement setup. A portion of the fiber under test is kept in an ice-water bath, while another fiber loop is placed inside hot water. The bottom trace shows the overall temperature profile for the entire fiber length, with the regions of cold and hot temperatures corresponding to the ice and hot water baths, respectively.

Most commercial Raman DTS systems operate using the OTDR configuration, although there is at least one system that operates using the OFDR technique. Each manufacturer uses a different type of laser source (either a laser diode or fiber laser) in their system, operating in one of several wavelength ranges: 900 nm, 1060 nm, 1310 nm, or 1550 nm. In general, most systems are designed for use with multimode optical fibers in order to take advantage of their large numerical aperture (the large acceptance cone of the fiber increases the amount of

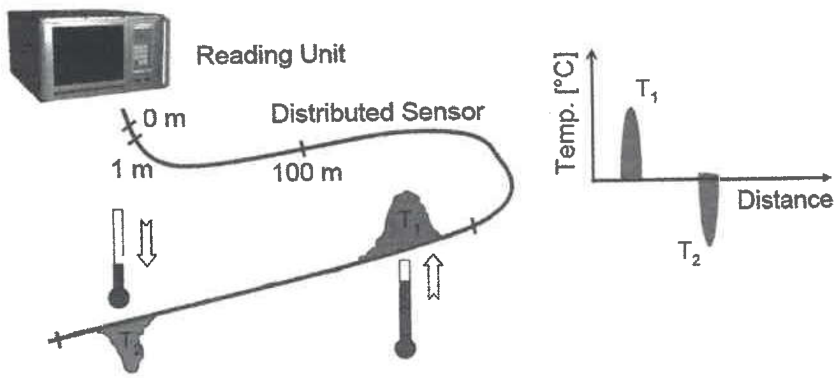


Figure 11.30 Illustration of the Raman DTS measurement (courtesy of Omnisens).

cattered light that is guided, i.e., useable for sensing purposes) and to ımodate the low intensity of the spontaneous Raman backscatter light. ›ver, the high attenuation of multimode fibers limits the spatial range of ın DTS to a few kilometers. Hence, some Raman DTS systems are available perate with single-mode fibers and have range capabilities in excess of 10 km.
most powerful and unique feature of Raman DTS systems is their ›ility to perform continuous, distributed measurements of temperature long distances (tens of kilometers) providing both absolute-temperature distance-localization information. Raman DTS readings provide a ›rature-versus-distance profile of the thermal distribution along a specific pecimen or process onto which the sensing fiber optic cable has been ıed. In essence, Raman DTS operates in reflection, such that the onics remotely interrogates the backscatter light along one or more ıte fibers. The continuous temperature profile is composed from hundreds ›usands of measurement points provided by the train of optical pulses hed into the system. Such a multitude of scanning light pulses provides the ique with the capability to measure temperature at meter intervals along nsing fiber. This approach is simpler and more effective than installing a quantity of conventional temperature sensors such as thermocouples or ›; the cost, installation effort, and wiring requirements would make this ›ach extremely cumbersome, impractical, and cost prohibitive.
urthermore, by comparing temperature profiles over time, it is possible ermine the dynamics of any specific process or event of interest, such as l flow dynamics in a reservoir or the thermal insulation changes caused ıx buildup in an oil pipeline.
mong the many advantages that Raman DTS offers are the following:

Distributed temperature measurement over multi-kilometer distances,
Distance localization of temperature events with 1-m spatial resolution,
Temperature measurement in the −190 °C to +500 °C range,
Remote interrogation,
Immunity to electromagnetic interference,
Intrinsically safe operation in hazardous or explosive environment locations,
Simple use and installation,
Ability to interrogate multiple fibers and set-up measurement zones,
Capability to measure and compare temperature profiles taken at different times, and
Possibility to perform real-time temperature measurements and setup alarms.

) Applications

ɾange of applications of temperature sensors is quite broad, from ›oring relatively low-temperature biological processes to monitoring ›emperature engine parts and furnaces. Several concepts have had great

commercial success and broad use, such as the GaAs reflective sensor, the fluorescent sensor, FBG thermometers, and Raman-scattering distributed sensing systems.

Bimetallic sensors are available in a range from 50 °C to 300 °C. Their potential for use lies in applications such as engine control, air compressors, and industrial processing equipment. Such sensors can be made rugged to withstand shock and vibration. Generally, they are large relative to the fiber and intrinsic sensors, and as a result, have limited dynamic response.

The fluorescence sensor has no metallic components and can be put into an extremely small package. It is especially useful in applications requiring electrical immunity or isolation. The high accuracy (0.1 °C) and small size have made the sensor concept ideal for biological and physiological applications. Hyperthermia, one such area, is a potential cancer therapy requiring local tissue heating using an RF field. The fluorescent sensor has been successfully used in such applications.

Any relatively low-temperature (less than 250 °C) processes using RF heating (such as wood processing and revulcanization of rubber) are potential candidates for this sensor type. The technique is also useful in diagnostic instrumentation associated with high-voltage equipment. The detection of localized heating can often predict the onset of equipment malfunction.

Thermometers based on GaAs etalon devices have been used extensively in biomedical and electric transformer hot spot detecting applications. Similarly, FBG-based temperature sensors are very common and used in a broad variety of applications, primarily for civil infrastructure monitoring.

The blackbody sensor concept has a range of 500–2000 °C. Due to its small size and extremely fast response time, it has applications in many high-temperature processes such as characterizing the heat flow in a gas turbine engine.

The intrinsic concept (such as the approach using absorption) provides a sensing mechanism that can detect hot spots. If such an intrinsically sensing fiber were used in electric motor or transformer windings, it could provide an overheat alarm. It also has potential in distributive temperature sensors, which will be discussed in Chapter 18.

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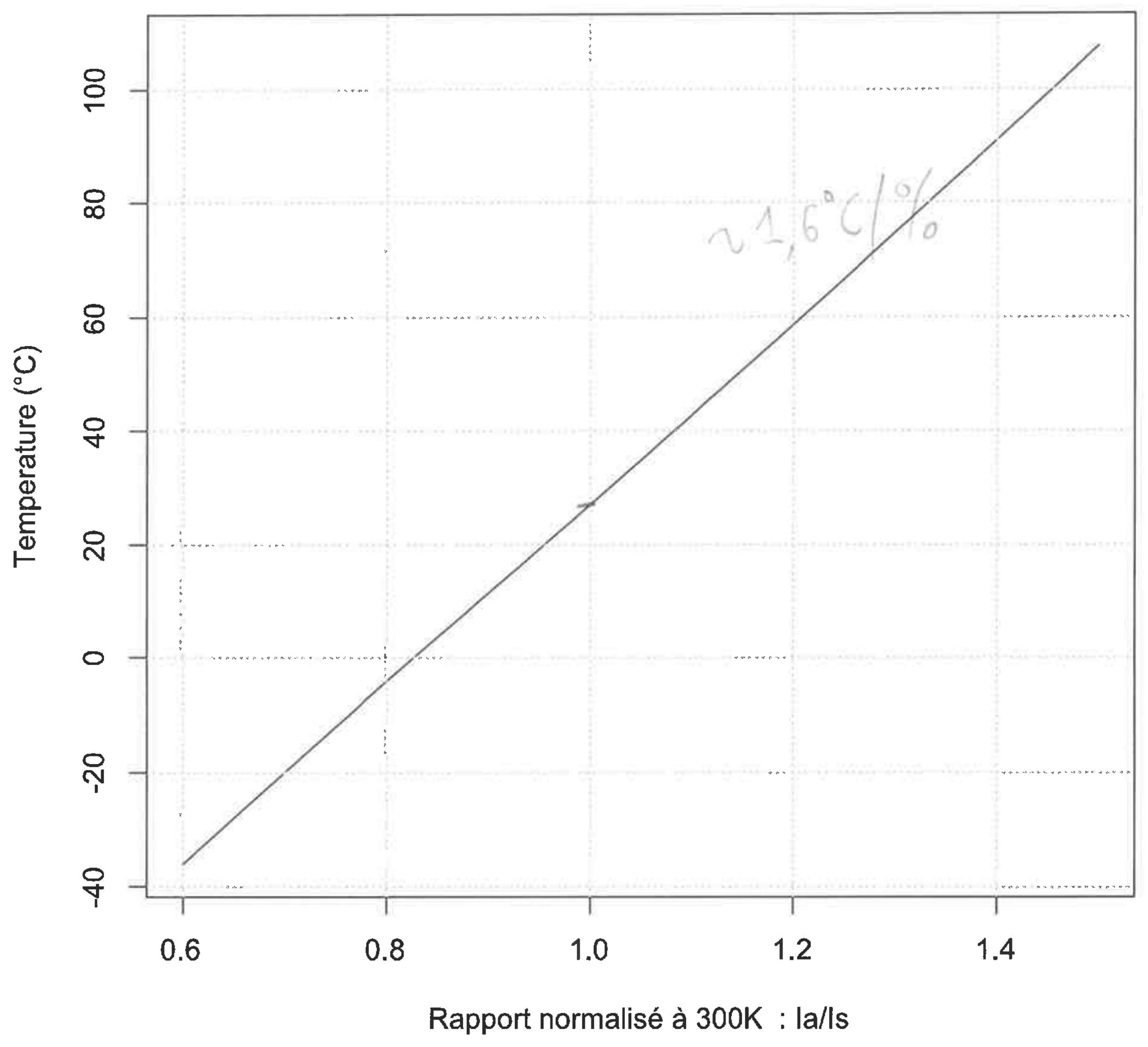
~1,6°C/%
Temperature (°C)
100
80
60
40
20
0
-20
-40
0.6
0.8
1.0
1.2
1.4
Rapport normalisé à 300K : Ia/Is