

# Development of distributed strain and temperature sensing cables

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## ABSTRACT

Distributed fiber optic sensing presents unique features that have no match in conventional sensing techniques. The ability to measure temperatures and strain at thousands of points along a single fiber is particularly interesting for the monitoring of large structures such as pipelines, flow lines, oil wells, dams and dikes. Sensing systems based on Brillouin and Raman scattering have been used for example to detect pipeline leakages, verify pipeline operational parameters, prevent failure of pipelines installed in landslide areas, optimize oil production from wells and detect hot-spots in high-power cables.

The measurement instruments have been vastly improved in terms of spatial, temperature and strain resolution, distance range, measurement time, data processing and system cost. Analyzers for Brillouin and Raman scattering are now commercially available and offer reliable operation in field conditions.

New application opportunities have however demonstrated that the design and production of sensing cables is a critical element for the success of any distributed sensing instrumentation project. Although standard telecommunication cables can be effectively used for sensing ordinary temperatures, monitoring high and low temperatures or distributed strain present unique challenges that require specific cable designs.

This contribution presents three cable designs for high-temperature sensing, strain sensing and combined strain and temperature monitoring.

**Keywords:** distributed sensing, Raman scattering, Brillouin scattering, strain monitoring, temperature monitoring, cable design

## 1. INTRODUCTION

Traditional fiber optic cable design aims to the best possible protection of the fiber itself from any external influence. In particular it is necessary to shield the optical fiber from external humidity, side pressures, crushing and longitudinal strain applied to the cable. These design have proven very effective in guaranteeing the longevity of optical fibers used for communication and can be used as sensing elements for monitoring temperatures in the  $-20^{\circ}\text{C}$  to  $+60^{\circ}\text{C}$  range, in conjunction with Brillouin [1] or Raman monitoring systems.

Sensing distributed temperature below  $20^{\circ}\text{C}$  or above  $60^{\circ}\text{C}$  requires a specific cable design, especially for Brillouin scattering systems, where it is important to guarantee that the optical fiber does not experience any strain that could be misinterpreted as a temperature change due to the cross-sensitivity between strain and temperature.

On the other hand, the strain sensitivity of Brillouin scattering prompts to the use of such systems for distributed strain sensing, in particular to monitor local deformations of large structures such as pipelines, landslides or dams. In these cases, the cable must faithfully transfer the structural strain to the optical fiber, a goal contradicting all experience from telecommunication cable design where the exact opposite is required.

Finally when sensing distributed strain it is necessary to simultaneously measure temperature to separate the two components. This is usually obtained by installing a strain and a temperature sensing cables in parallel. It would be therefore desirable to combine the two functions into a single packaging.

These very practical requirements have lead to the development of cables specifically designed for sensing applications that will be presented next, together with a few application examples.

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## 2. GENERAL REQUIREMENTS

All cable designs share common goals independently from the used sensing technique (Brillouin or Raman scattering) and application domain:

- The optical fibers must be compatible with the selected sensing system: singlemode fibers for Brillouin scattering and (usually) multimode fibers for Raman scattering systems.
- The fibers must be protected from external mechanical actions during installation and while in use. In particular the cable design must allow easy manipulation without the risk of fiber damage.
- The cable design must allow sufficient shielding of the optical fibers from chemical aggression by water and other harmful substances.
- All optical losses must be kept as low as possible in order not to introduce degradations to the native instrument's distance range.
- Installation of connectors and repair of damaged sensors should be compatible with field operations.

The next paragraph will describe cable designs for high and low temperatures, distributed strain and combined strain and temperature sensing

## 3. EXTREME TEMPERATURE SENSING CABLE

The extreme temperature sensing cables are designed for distributed temperature monitoring over long distances. They consist of up to four single mode or multimode optical fibers contained in a stainless steel loose tube, protected with stainless steel armoring wires and optionally a polymer sheath. These components can be differently combined in order to adapt the cable to the required performance and application. The use of appropriate optical fibre coating (polyimide or carbon/polyimide) allows the operation over large temperature ranges, the stainless steel protection provides high mechanical and additional chemical resistance while the polymer sheath guarantees corrosion protection. The carbon coating offers improved resistance to hydrogen darkening. The over-length of the optical fibers is selected in such a way that the fiber is never pulled or compressed, despite the difference in thermal expansion coefficients between glass and steel. The total cable diameter is only 3.8 mm.

These cables can be used in a wide range of applications that require distributed temperature sensing, such as temperature monitoring of concrete in massive structures, waste disposal sites, onshore, off-shore and downhole sites in gas and oil industry, hot spots, cold spots and leakage detection of flow lines and reservoirs, fire detection in tunnels and mapping of cryogenic temperatures, just to name a few.



Figure 1: Extreme temperature sensing cable design and termination.

## 4. STRAIN SENSING TAPE: SMARTAPE

When strain sensing is required, the optical fiber must be bonded to the host material over the whole length. The transfer of strain is to be complete, with no losses due to sliding. Therefore an excellent bonding between strain optical fiber and the host structure is to be guaranteed. To allow such a good bonding it has been recommended to integrate the optical fiber within a tape in the similar manner as the reinforcing fibers are integrated in composite materials [2]. To produce

such a tape, we selected a glass fiber reinforced thermoplastic with PPS matrix. This material has excellent mechanical and chemical resistance properties. Since its production involves heating to high temperatures (in order to melt the matrix of the composite material) it is necessary for the fiber to withstand this temperature without damage. In addition, the bonding between the optical fiber coating and the matrix has to be guaranteed. Polyimide-coated optical fibers fit these requirements and were therefore selected for this design.

The typical cross-section width of the thermoplastic composite tape that is used for manufacturing composite structures is in the range of ten to twenty millimeters, and therefore not critical for optical fiber integration. The thickness of the tape can be as low as 0.2 mm, and this dimension is more critical since the external diameter of polyimide-coated optical fiber is of 0.145 mm approximately. Hence, only less than 0.03 mm of tape material remains on top or bottom of the optical fiber, with the risk that the optical fiber will emerge from the tape. The scheme of the sensing tape cross-section, with typical dimensions, is presented in Figure 2.

The use of such sensing tape (called SMARTape) is twofold: it can be used externally, attached to the structure, or embedded between the composite laminates, having also a structural role.

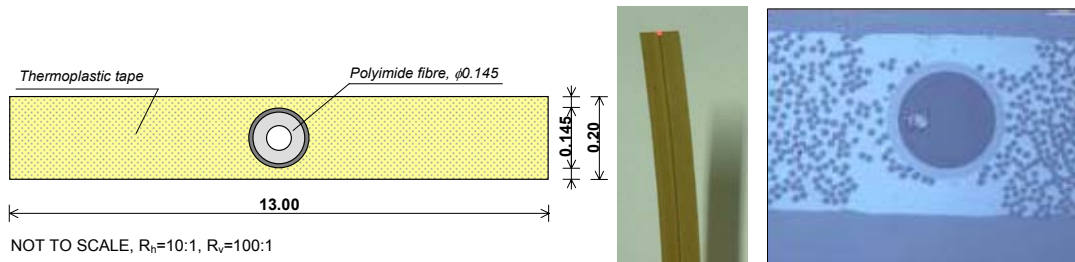


Figure 2: Cross-section picture and micrograph of the sensing tape: SMARTape

This type of sensors has been used for example to monitor the strain evolution in a pipeline installed in a landslide area in Italy (see figure 3) and for the monitoring of the deformations of a concrete dam in Latvia.



Figure 3: Example of SMARTape integration on a pipeline for strain monitoring

## 5. COMBINED STRAIN AND TEMPERATURE SENSING: SMARTPROFILE

The SMARTprofile sensor design combines strain and temperature sensors in a single package.

This sensor consists of two bonded and two free single mode optical fibers embedded in a polyethylene thermoplastic profile [3]. The bonded fibers are used for strain monitoring, while the free fibers are used for temperature measurements and to compensate temperature effects on the bonded fibers. For redundancy, two fibers are included for both strain and temperature monitoring. The profile itself provides good mechanical, chemical and temperature resistance. The size of the profile makes the sensor easy to transport and install by fusing, gluing or clamping. The SMARTprofile (see figure 4)

sensor is designed for use in environments often found in civil geotechnical and oil & gas applications. However, this sensor cannot be used in extreme temperature environments nor environments with high chemical pollution. It is not recommended for installation under permanent UV radiation (e.g. sunshine).

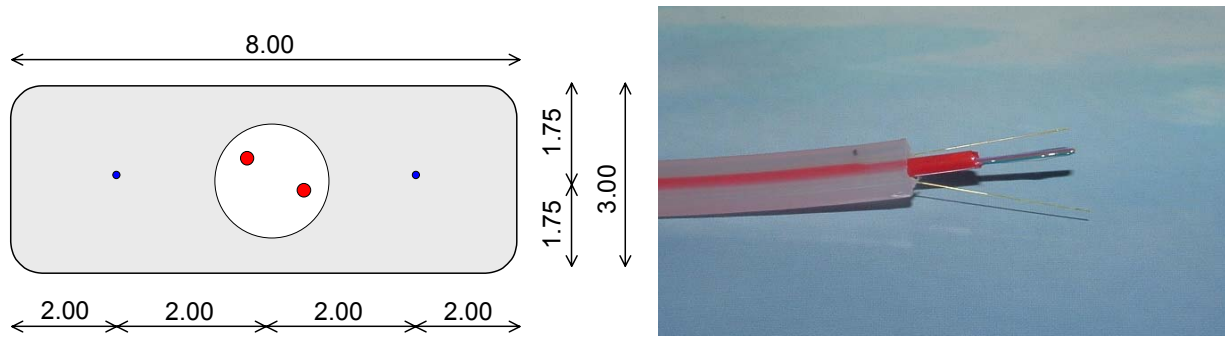


Figure 4: SMARTprofile cross-section and sample. The red tube contains the free fibers.

## 5. CONCLUSIONS

The following table compares the performances of the presented cable designs and specifies their application domains and limitations.

	<b>Extreme temperature sensor</b>	<b>SMARTape</b>	<b>SMARTprofile</b>
Measurement parameters	Temperature	Strain	Strain and temperature
Number of fibers	1 to 4	1	2 for strain and 2 for temperature
Typical losses @1550nm	0.3 dB / km	5 dB / km	2.0 dB/km for strain 0.3 dB/km for temperature
Temperature range	-180 to +300 °C	-180 to +140 °C	-40 to + 60 °C
Chemical aggression resistance	Good to Excellent (with polymer sheath)	Excellent	Good
Application examples	Fire detection, cryogenic tanks, high-temperature pipeline monitoring, remote heating system monitoring, steam generator monitoring	Pipeline strain, composite pipes monitoring, surface installation on concrete, steel and timber, embedding in composites	Strain, temperature, leakage and 3 <sup>rd</sup> party intrusion detection for pipelines

Table 1: Comparison of the sensor performances and characteristics.

The presented sensor designs were developed explicitly for use with distributed sensing systems, in particular with Brillouin scattering systems (BOTDR, BOTDA and BOFDA). Their characteristics are optimized for sensing fidelity and longevity in structural health monitoring applications. This required new approaches departing from the conventional telecommunications cable design, but using similar processes to achieve mass-production and low cost per meter. The first application examples show how these new designs can be effectively used in field conditions.

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