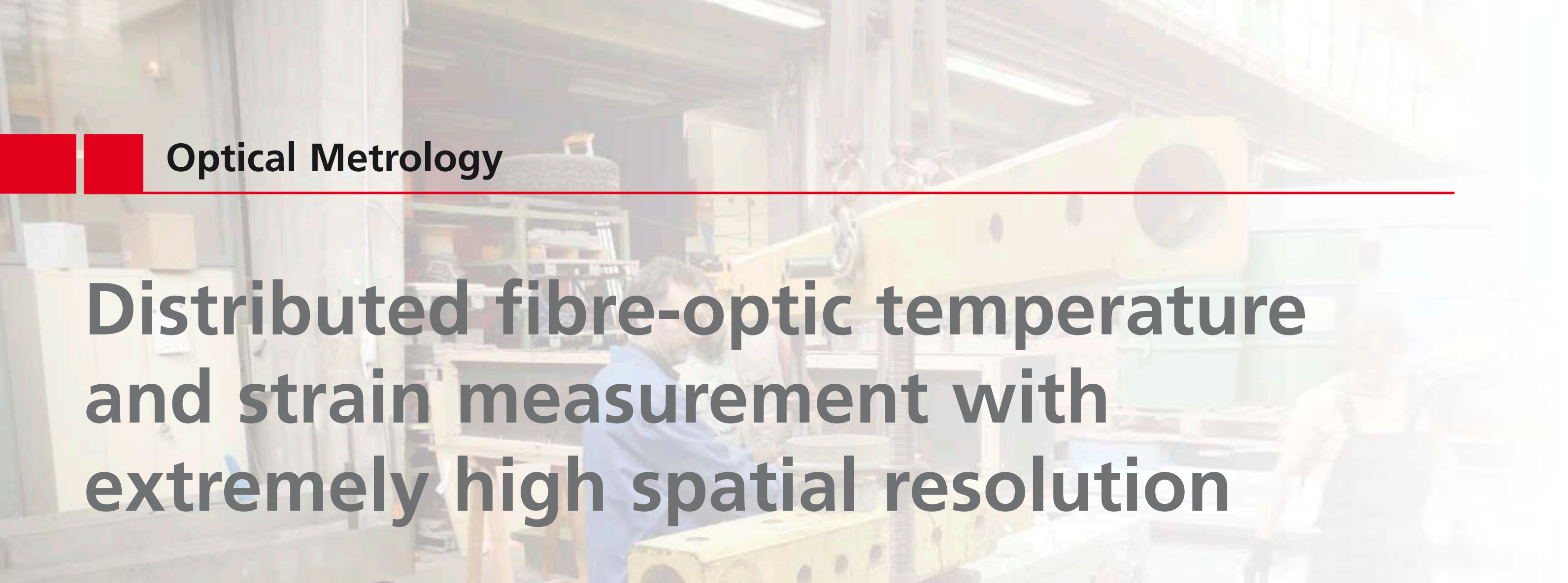

Distributed fibre-optic temperature and strain measurement with extremely high spatial resolution

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Scanning the Rayleigh scattering along a length of optical fibre enables a distributed sensor system where every point along the fibre acts as a sensor. This novel method allows quasi-continuous measurement of temperature and strain profiles over distances of up to 70 m. The spatial resolution is on the order of millimetres, which is equivalent to thousands of individual conventional sensors.

1 Fibre-optic sensor technology

For many years, fibre sensors have measured temperature or mechanical quantities, particularly in environments where electrical sensors reach their performance limits; this may occur in environments with large electromagnetic fields or difficult chemical conditions. Likewise, in applications involving great distances, requiring low weight, or inside compact diameters, the physical characteristics of glass fibre are advantageous.

Basically, fibre-based measurement systems inlcude an active monitoring unit, which is connected to the passive sensor fibre. The monitoring unit transmits light into the fibre from either a tunable frequency laser or a broadband source. Characteristics of the light traveling within the fibre are modified as a function of the temperature and the strain. These changes are detected in the back-scattered light, which is later collected by the monitoring unit, analysed, and then converted into strain and temperature data.

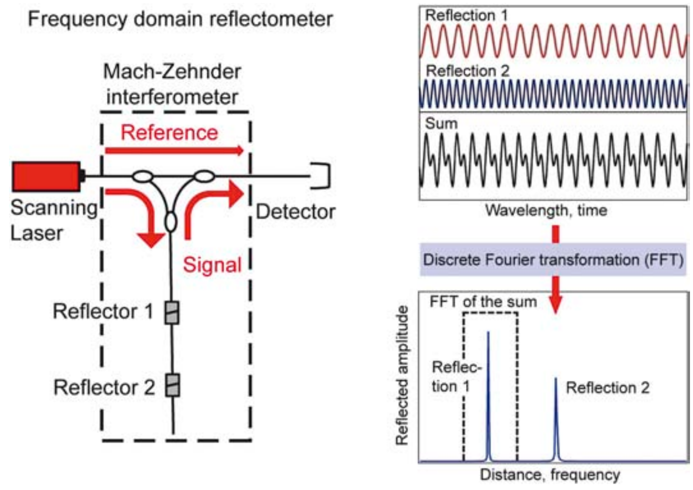

Figure 1: Optical frequency domain reflectometry (OFDR) uses a variable frequency laser beam that is coupled into a fibre-based Mach-Zehnder interferometer. The frequency components in the detector signal define the respective location of the reflection

1.1 Single-point fibre sensor systems

On the fibre sensor side, a distinction is made between single-point and distributed sensing. Single-point sensors can be realized by writing Bragg gratings into the fibre, which then generate a reflection centred on a wavelength that depends on the strain and temperature of the fibre. In an alternative version, called an optical endpoint sensor, the temperature dependent absorption properties of a semiconductor crystal attached to the tip of the fibre are read out.

As these sensors only work at discrete measurement locations, both the number of sensors as well as their precise position are critical features in the design of the overall system, especially with regard to the total cost. With these types of sensors, one fundamental challenge is the capture of events when their location is not previously known, such as the development of temperature hotspots or crack formation within a concrete structure. In such cases, individual sensors positioned incorrectly can lead to completely useless measurements and interpretations. A similar problem occurs if temperature and strain profiles have a steep gradient, or if spatially extended structures (2- or 3-dimensional) need to be precisely monitored.

1.2 Distributed sensing

Sensing solutions that enable a quasi-continuous distributed measurement along the length of sensing fibres help to overcome these issues. These systems use light backscattered from the fibre material itself, which delivers the required temperature and strain related information.

Two measurement methods have been established for long-distance applications, making use of Raman and Brillouin scattering within the fibres, respectively. These systems allow distributed temperature and strain measurements over distances in the range of tens of kilometres. However, the distance resolution of Raman and Brillouin based distributed sensing systems is limited to approx. 1 m. The limiting factor is the extremely low intensity of the scattered light used here, which makes it very difficult to increase the resolution.

Viewed in absolute terms, the Rayleigh scattering in the backscattered light is also small, but significantly larger than the Raman and Brillouin scattering. Recently the US company Luna Technologies succeeded in developing a system that uses the Rayleigh scattering to making distributed measurements with a spatial resolution in the millimetre range.

Originally published in German in Photonik 6/2011

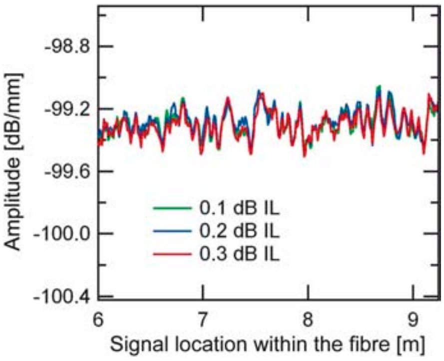

Figure 2: Profile of the Rayleigh intensity along a glass fibre segment. With constant external conditions the profile of the signal remains the same in consecutive scans. This characteristic fingerprint is used as a reference for measurements, which are captured under altered conditions

2 Optical frequency domain reflectometry (OFDR)

One essential part of a sensor system making distributed measurements is a reflectometer to provide spatial resolution. In many cases, Raman and Brillouin systems work with an optical time domain reflectometer (OTDR), in which the monitoring unit transmits a short light pulse and uses the time of flight of the back- scattered light to determine the location of the reflection.

For the Rayleigh sensor technology, a significantly higher resolution is required than can be achieved with an OTDR. This is attained using a coherent optical frequency domain reflectometer, c-OFDR (**figure 1**).

In c-OFDR systems, the beam of a variable frequency CW laser is coupled into a fibre-optic Mach-Zehnder interferometer. One fibre represents the reference arm with a fixed path length, while the second arm is formed by the sensing fibre. The light scattered back from the sensing fibre interferes with the light from the reference arm at the output coupler. Varying the frequency of the laser wavelength creates a periodic signal at the detector, the frequency of which depends on the location of the respective fibre segment scattering the light back. The further the segment is away from the detector, the greater the frequency of the interference signal. As the detector receives the backscatter signals from all the segments simultaneously, the total signal must be split into its frequency components using a Fourier transform technique. The frequencies then correspond to the signal locations in the fibre. The amplitude of each frequency component indicates the strength of the respective reflection.

The attainable spatial resolutions depend on the wavelength range over which the laser can be tuned. Commercial systems from Luna Technologies work at 1550 nm and can be tuned over a maximum range of 90 nm. This corresponds to a spatial resolution of 10 µm. With fibre lengths of up to a maximum of 70 m, such a system provides the Rayleigh backscatter signals from 7 million fibre segments per laser scan.

3 Analysis of the Rayleigh signal

When a commercially available glass fibre is scanned using OFDR, a fluctuating intensity profile of the Rayleigh scattering along the glass fibre will be detected. This profile is absolutely stable when the measurement is repeated under unaltered external conditions, such that it represents a characteristic “fingerprint” for a specific fibre segment (**figure 2**). The reason for this lies in the nature of the Rayleigh scattering. It is caused by the elastic scattering process at local defects, refractive index variations or distortions of the waveguide geometry, which although it varies from segment to segment, is still stable.

If you now change the temperature or strain conditions of the fibre, the fingerprint is spatially stretched or compressed (**figure 3**). This phenomenon is the basis for the Rayleigh sensor technology as the changes to the local Rayleigh pattern can be converted into local temperature or strain values.

To achieve this, the measurement signal returned from the fibre is divided into small (≥ 1 mm) windows of analysis. The signals from each of those sections are transformed into the frequency range (**figure 4**). The result is a fluctuating reflection pattern depending on the frequency. Changes to the temperature or strain condition of the fibres lead to a frequency shift Δf, which is proportional to the changes in the external conditions affecting the fibre. This process basically resembles measurements based on fibre Bragg gratings, where similarly, the shift in reflected frequency peaks is detected, when the external conditions change.

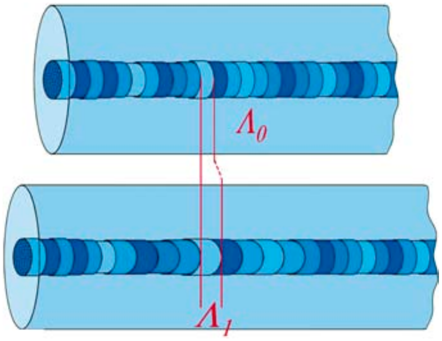

Figure 3: Rayleigh scattering caused by local refractive index fluctuations along the glass fibre. With changes to the temperature or strain, this characteristic profile is stretched or compressed, and can be used to measure these quantities

Finally, to provide a distributed measurement, the analysis window must be slid over each section of the fibre length by a software algorithm, such that a complete profile along the path is created.

4 Advantages of Rayleigh sensor technology

The combination of OFDR and Rayleigh scattering allows true distributed measurements of both temperature and strain with the following unique properties:

High spatial resolution: The variable analysis window for each fibre segment determines the spatial resolution. With currently commercially available systems, spatial resolution can be set to a minimum of 1 mm and the total fibre length can be up to 70 m. However, this does not repre-

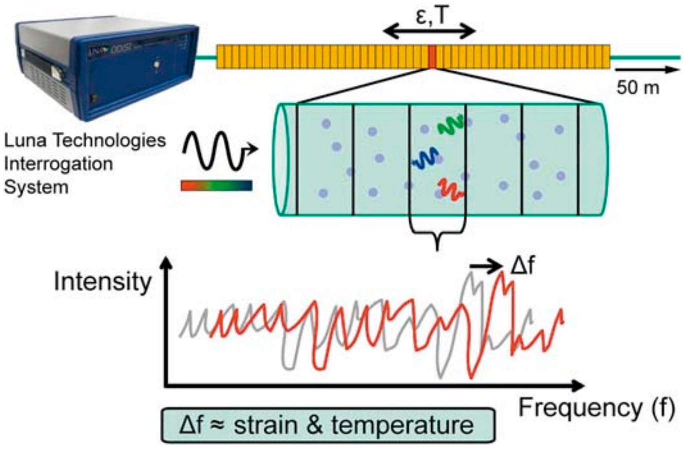

Figure 4: To analyse the Rayleigh scattering, the measurement signal is divided into small analysis windows for each fibre segment. Any local changes are detected in the form of frequency shifts and then converted into temperature and strain measurements

Originally published in German in Photonik 6/2011

Figure 5: Load bearing test on a reinforced concrete girder that has an integrated fibre-optic cable which measures the strain using Rayleigh scattering (image source: [1])

sent a physical boundary but is a limited by the data processing.

Flexible, virtual sensor positions: In principle, a single laser scan provides all the relevant information. However, the analysis window can be positioned anywhere along the fibre with a variable width, both continuously as well as at fixed measurement locations. Thus, the complicated question of physical sensor positioning no longer arises as this is now determined in the software either before or after the measurement.

Standard glass fibre as a sensor: Because even glass fibres with ultra-low scattering are still producing enough Rayleigh signal, it is possible to use both many commercial standard fibres, as well as special fibre types after appropriate calibration. However, the coating of the fibre must be adapted for the particular application. For temperature measurements of up to 350°C, the fibre needs a polyimide coating, and up to 700°C, a gold coating is required. For strain measurements, the coating needs to optimally transfer the strain changes on the object to the fibre. The maximum strain that can practically be reached with a standard glass fibre is approx. 30 000 µm/m.

High measurement sensitivity: Temperature changes can be captured with 0.1°C resolution, changes in strain with 1 µm/m resolution.

Parallel interrogation of all sensors: With the measurement method described, all segments of the fibre are read simultaneously. The maximum rate is up to 5 Hz. This allows easy observation of the overall dynamics of an object measured with the system.

Figure 6: Reinforced concrete girder with fibre-optic cable (blue) before filling with concrete. The cable runs as a loop in the upper and lower segment to capture tensile and compression stresses (image source: [1])

5 Applications

The range of possible applications for distributed Rayleigh sensor technology is extensive. This method is particularly useful when a large number of temperature or strain sensors need to be interrogated with a high density.

There are applications in practically all areas of research and technology. Two examples are described in the following which illustrate the special features and also the robustness of the method.

5.1 Testing and monitoring concrete structures

A research project was carried out by Electricité de France EDF to investigate the load bearing capacity of different structural elements in which a fibre-optic cable was integrated into a reinforced concrete beam alongside a conventional strain gauge (**figure 5** and **figure 6**). The subsequent load test was taken to the non-elastic region that lead to localized cracks appearing in the structure.

Figure 7 shows the strain changes recorded over the full length of the beam. The upper graph shows the segment under compressive stress, the lower graph under tensile stress. The distinct peaks allow localized, considerably higher strain values to be identified which correlate precisely with the formation of cracks observed in this segment.

Although the conventional sensor captures one of these cracks, it is purely by accident. The other cracks that appeared in adjacent locations are not identified at all. This is where the superiority of the distributed measurement technology can be readily seen because it registers all events and significantly simplifies the interpretation.

5.2 Distributed measurement of high temperatures

Rayleigh sensor technology is ideally suited for recording complete temperature profiles, particularly in high temperature

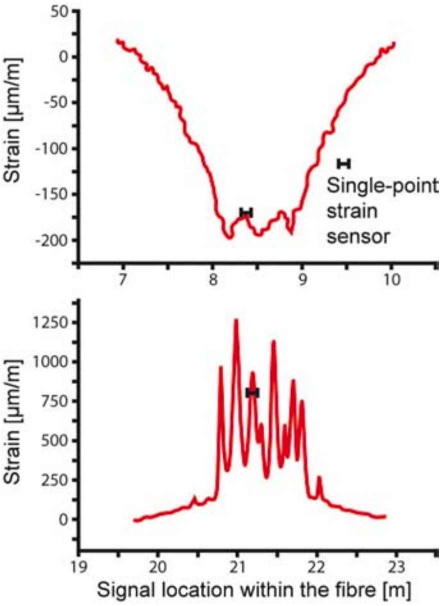

Figure 7: Distributed measurement of strain in a reinforced concrete girder stressed with 100 kN as per [1]. Top: Segment under compression stress with negative strain changes. Bottom: Segment under tensile stress. Here the elastic range has been exceeded and local cracks appear, each of them clearly to be identified by the local strain peaks. For comparison purposes, a conventional sensor had been installed that only supplies a strain value at a single measurement point

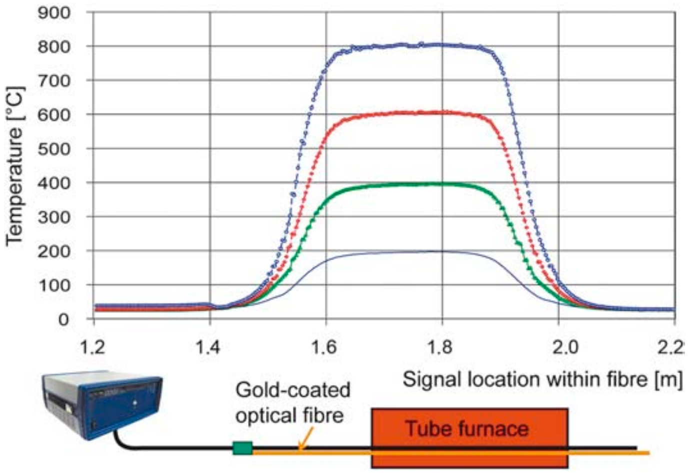

***Figure 8:** Measurement of temperature distributions in an oven. The gold coated glass fibres work continuously at temperatures up to 700°C, briefly even at higher temperatures*

ranges, which can be found in the exhaust system on cars, in microwave ovens, or in large furnaces in the steel industry.

Figure 8 shows several temperature profiles which have been captured with the aid of a gold coated fibre in a tube furnace. Such commercially available fibres can be permanently operated at up to 700°C, and for short periods, at even higher temperatures.

6 Outlook

Rayleigh sensing is done via a glass-fibre based process well suited toward distributed measurements of temperature and strain, and features a particularly high level of spatial resolution in the millimetre range. Due to the internal design, comprising reliable components from the optical telecommunications industry, this technique has so far proven to be a very robust and flexible solution for many everyday applications.

To extend the measurement options, development is currently focusing on the subjects "Range" and "Processing speed". In the near future, a version of the device is being planned that extends the measurement range from 70 m to 2 km, with a spatial resolution in the centimetre range. This makes it possible to monitor extended objects. Furthermore, it allows measurement configurations in which the measurement location is further remote from the monitoring unit.

For dynamic investigations the market requires acquisition rates in the range of up to 1 kHz. Here the combination of OFDR technology and continuously written fibre Bragg gratings is a promising approach.

Literature:

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[2] M. Froggatt, B. Soller, D. Gifford, M. Wolfe, *Correlation and keying of Rayleigh scatter for loss and temperature sensing in parallel optical networks*, OFC Technical Digest, paper PDP 17 (2004)

[3] Graphics apart from figure 5–7 with kind permission from Luna Technologies, Blacksburg, Virginia, USA

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