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Applications of fibre optic temperature measurement

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Abstract. Temperature measurement is crucial for many industrial processes and monitoring tasks. Most of these measurement tasks can be carried out using conventional electric temperature sensors, but with limitations. Particularly under harsh conditions, fibre optic temperature sensors show their advantages over conventional instrumentation. Three common principles of fibre optic temperature measurement are exemplarily examined: fibre Bragg gratings, Raman scattering and interferometric point sensors. Their working principles along with recent findings and applications of the sensing concepts are presented. So far their application is still limited to niche markets but with decreasing system prices fibre optic temperature sensing has great potential for further growth.

Key words: fibre optic sensor, temperature, fibre Bragg grating, Fabry Perot, Raman scattering.

1. INTRODUCTION

Many material properties show strong temperature dependence. In order to utilize or compensate temperature effects, its measurement is required. Examples of such temperature dependencies are dew point, density, electrical conductivity, refractive index, rigidity and diffusion. Temperature measurement also plays an important role in health monitoring of electric circuits or civil structures.

Most measurement tasks in industrial applications and research can be carried out using conventional electric temperature sensors such as thermocouples, junction temperature sensors, resistance temperature detectors or thermistors. But conventional temperature sensors have their limitations especially if

– large distances have to be covered as is the case of many distributed measurements,
– large numbers of sensors have to be integrated in order to monitor many system states or even temperature fields or gradients,
– electromagnetic interference decreases the signal to noise ratio significantly,
– explosive environments prohibit the application of electric devices,
– light-weight structures and monitoring equipment with low mass impact are desired.

Particularly under these conditions fibre optic temperature sensors are able to show their full potential. But depending on the actual application, different types of fibre optic temperature sensors can be used. The most common fibre optic temperature sensors are:

– fibre Bragg gratings, where the temperature dependence of distributed optical reflection is used,
– extrinsic interferometric optical structures, which show a temperature dependent behaviour,
– Raman scattering distributed temperature sensors, that use the temperature dependence of inelastic scattering on optical phonons,
– Brillouin scattering distributed temperature sensors, using scattering on acoustic phonons,
– semiconductor band gap technology, based on the temperature dependence of the band gap of semiconductor crystals.

Fibre-optic sensing has already found wide access to monitoring applications of civic structures (especially Raman scattering based sensors). A good overview of this field is given in [1]. Application of fibre optic temperature sensors in process control or machine monitoring has increased to date but still shows great potential for growth.

This article exemplarily looks at fibre Bragg gratings and thin-film interferometric point temperature sensors as well as at distributed temperature measurement based on Raman scattering. For each sensor type the basic working principle is explained and performance is discussed. Besides that, examples of recent applications are presented.

2. TEMPERATURE SENSING WITH FIBRE BRAGG GRATINGS

The influence of temperature on the response on fibre Bragg gratings (FBGs) has already been discussed in the first publication describing their fabrication [2]. The upcoming of a new fabrication technique allowed the production of gratings at arbitrary wavelength, at any position along the fibre. As proposed by Meltz et al. [3], multiple gratings, multiplexed by an offset in their centre reflection wavelength $\lambda_{\mathrm{B},i}$ could be used to measure quasi-distributed temperature at various locations, all connected by a single optical fibre.

2.1. Working principle

Fibre Bragg gratings are formed by a periodic perturbation of the core refractive index of an optical fibre. Coupling between modes of the fibre may thus be achieved. A popular FBG couples a forward-propagating mode into its contra-directional propagating version. With an adequate design this reflective coupling may be limited to a narrow spectral range, typically to a few hundred picometers.

The model, underlying the sensing properties of FBGs for mechanical and thermal parameters considers three effects:

– the change in geometry due to strains, caused either by mechanical stresses σ or temperature changes ΔT,
– the change in refractive index due to strain (photoelastic effect),
– the change in refractive index due to temperature changes (thermooptical effect).

The sensing parameters are usually calculated from the reflection spectrum centre wavelength shift. It is given by the resonance or Bragg condition

$$\lambda_{\mathrm{B}} = 2 n_{\mathrm{eff}} \Lambda, \tag{1}$$

where n_{eff} is the effective refractive index of the mode in consideration and Λ is the spacial refractive index perturbation period.

Numerous concepts of interrogation schemes for FBGs have been published to date. Most of them use the power reflection spectrum of the sensor, often combined with a peak finding algorithm to follow the Bragg reflection peak. The resolution achieved is well below a picometer [4]. For the sensor sensitivity towards temperature, this allows resolutions in the range of 100 mK.

2.2. Sensitivity

The change in the reflected wavelength can be computed from the total derivative relative to the respective parameter. Taking into account the isotropic and homogeneous properties of silica fibres, the derivative for temperature changes reads

$$\frac{\Delta\lambda_{\mathrm{B},T}}{\lambda_{\mathrm{B}}} = \frac{1}{\lambda_{\mathrm{B}}}\frac{\mathrm{d}\lambda_{\mathrm{B}}}{\mathrm{d}T} = \left(\frac{1}{n_{\mathrm{eff}}}\frac{\partial n_{\mathrm{eff}}}{\partial T} - \frac{\partial n_{\mathrm{eff}}^2}{2}(p_{11} + 2p_{12})\alpha_T + \alpha_T\right). \tag{2}$$

Here $\Delta\lambda_{\mathrm{B},T}/\lambda_{\mathrm{B}}$ is the relative change in centre wavelength per Kelvin temperature change, $\partial n_{\mathrm{eff}}/\partial T$ is the thermooptical coefficient, p_{11} and p_{12} are Pockel's coefficients, representing the photoelastic effect and α_T is the thermal expansion coefficient of the fibre material.

The thermal expansion coefficient of bare silica fibres is approximately 0.5×10^{-6} 1/K [5], Pockel's constants p_{11} and p_{12} are in optical fibres 0.113 and 0.252, respectively [6]; n_{eff} depends on the wavelength and refractive index profile but can typically be estimated to be 1.46. The thermooptical coefficient is

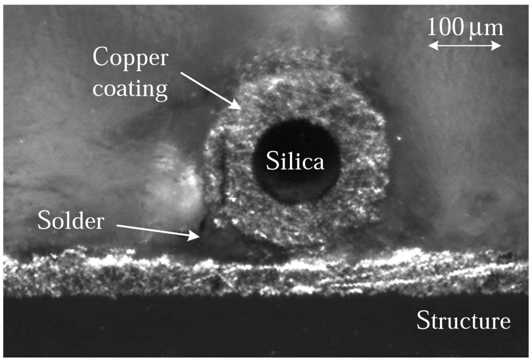

Fig. 1. Copper coated fibre for enhancing temperature sensitivity. The copper has been applied by electrode positioning on a conductively lacquered fibre.

experimentally determined by the refractive index dependence on the temperature variation, which gives the total derivative $\mathrm{d}n/\mathrm{d}T$. If all other material parameters are known, the partial derivative $\partial n_{\text{eff}}/\partial T$ is equal to 9.7×10^{-6}. This results in a general sensitivity of approximately 6.8×10^{-6} 1/K or around 10.5 pm/K at a wavelength of 1550 nm.

The mentioned coefficients depend on temperature [7–9], leading to non-linearities in sensor response. For modest temperature changes around room temperature they can often be neglected. But especially for cryogenic temperature sensing, the non-linearity leads to a strongly reduced sensitivity. In order to increase sensitivity, especially for low temperature applications, the fibre may be bonded to materials with high thermal expansion coefficients in the interesting temperature region. With aluminium substrate, sensitivity of 20 pm/K at 1500 nm wavelength and 100 K have been achieved [9]. Substrate application techniques include surface bonding and embedding [10–12]. In Fig. 1 a sample of a 125 µm silica fibre, coated with copper by electrodeposition and soldered to a copper substrate, is depicted.

2.3. Thermal stability

Beside sensitivity, durability plays a key role in long-term monitoring. After FBGs are fabricated, they show a decay in reflectivity under elevated temperatures. This decay decreases with time and settles to a quasi-stable value for long time. To obtain stable sensors, thermal annealing is usually performed prior to installation. The annealing allows a reflectivity stability over a lifetime of 25 years of less than 0.3% at 80 °C, depending on the type of the fibre [13]. For applications exceeding 500 °C, the normal or "type I" gratings can no longer be applied due to the strong decay in reflectivity and the durability of the fibre coating, which typically is of polymer-based materials. Nonetheless, temperatures up to 800 °C can be applied with so-called “type II” gratings. Their fabrication exploits a different effect for generating the Bragg pattern; the sensor response, important for sensor demodulation, is still comparable [14]. Combining these FBGs with a high-temperature coating, such as metals, makes them suitable for long-term high-temperature measurements.

2.4. Applications

The high technological effort for fabricating fibre Bragg gratings as well as for interrogating them, so far limits their use to niche applications, where high electromagnetic fields, small space, chemical harsh environments or weight considerations rule out conventional temperature sensors. For example, FBGs are employed is aeronautics, where carbon fibre reinforced plastic (CFRP) structures are monitored with embedded Bragg sensors. Figure 2 shows 150 sensors, distributed on a CFRP structure before sealing and curing.

Quasi-distributed dynamic strain measurement on the outer seat of a roller bearing is an example, where the small dimension of the fibre (typically 250 μm in diameter) is a crucial benefit. The test setup consisted of the bearing built into a gear test stand and equipped with an array of fibre Bragg grating sensors (Fig. 3). Since both strain and temperature influence the sensor output and the bearing temperature is likely to vary, a temperature reference measurement had to be carried out. Therefore the mechanical coupling to the bearing’s strain field was eliminated by fixing it solely with a heat-conducting glue with low Young’s modulus. Depending on the shaft speed and oil cooling performance, the temperature varied significantly

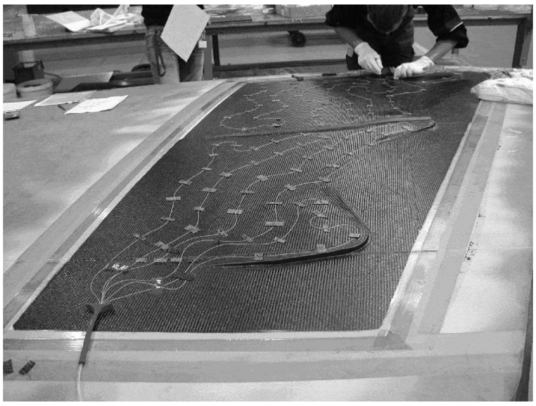

Fig. 2. The figure shows 150 fibre Bragg grating temperature sensors, embedded into a CFRP structure to monitor temperature gradients and mechanical stress during the curing process and over lifetime (courtesy of Kayser-Threde GmbH).

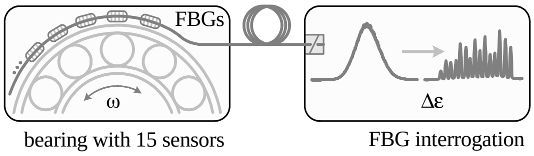

Fig. 3. Application of 15 fibre Bragg grating sensors to a roller bearing's outer seat; one sensor is solely thermally coupled to distinguish between temperature and strain signals.

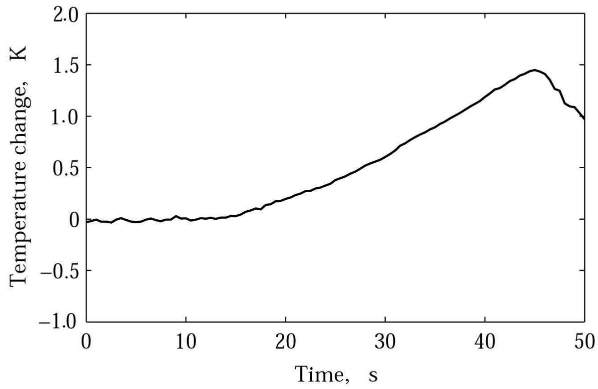

Fig. 4. Results from the temperature measurement on the roller bearing. The temperature varies over the test cycle, which has to be considered for correct strain monitoring.

as can be seen from Fig. 4. Ignoring the temperature would therefore falsify the strain measurement.

Another actual study at the Technical University of Munich deals with the design of a measurement system that is capable of interrogating more than 100 FBG temperature sensors with a central spectrometric demodulation unit. The advantages of fibre sensors in this application are seen in their light weight, their ease of integration and their high multiplexing capacity compared to conventional methods.

3. DISTRIBUTED TEMPERATURE SENSING USING RAMAN SCATTERING

Optical fibre distributed temperature sensors enable to monitor the temperature profile along the length of a fibre continuously. Distributed fibre optical temperature sensing (DTS) was first demonstrated in 1981 at Southampton University by testing a telecommunication cable. The original device used special fibres, which resulted in limited temperature range and covered distance, but good response time and spatial resolution [15].

Further research on Raman scattering in fibres has provided a technology to cover much longer distances and wider temperature ranges using both standard single-mode and multimode fibres [16–18]. The sensors operate on the optical time domain reflectometry (OTDR) principle, invented by Barnowski and Jensen in 1976, which was the first method for distributed fibre measurements using backward Rayleigh scattering to determine the optical loss along fibres [19].

A short laser pulse is sent along the fibre and the backscattered Raman light is detected with high temporal resolution. The intensity of the Raman light contains information about loss and temperature along the fibre whereas the time between sending the pulse and detecting the backscattered signal provides a measure of the distance along the fibre. As the DTS system is based on optical fibre technology, it can be used in a wide range of conditions, including hazardous environment and EMI intensive areas, such as power cable monitoring, fire detection in tunnels and pipeline monitoring.

3.1. Raman light scattering

Light is scattered as the pulse passes down the fibre through several mechanisms, including density and composition fluctuation (Rayleigh scattering) as well as Raman and Brillouin scattering due to molecular and bulk vibrations, respectively (Fig. 5). The effects of scattering are classified by the relation between frequencies of the incident and scattered photons.

If these frequencies or wavelengths are equal, it is called *unshifted scattering*, i.e. Rayleigh or elastic scattering. But if these frequencies differ, the term *shifted* or *inelastic scattering* is used. Examples are the Raman and Brillouin scattering, which are both temperature sensitive. In practice, the Brillouin lines are separated from the launch wavelength by only a few tens of GHz and it is impractical to separate these components from the Rayleigh signal.

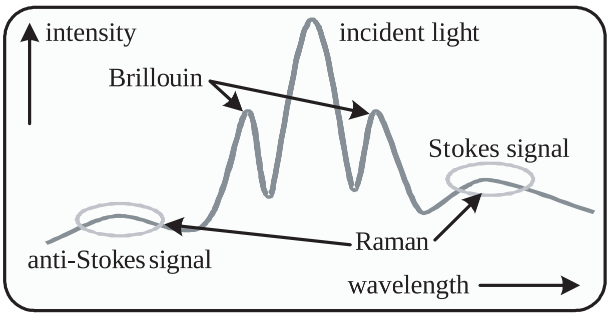

Fig. 5. Spectrum of backscattered light after pulsed illumination with a laser light source. For distributed temperature sensing the Stokes and anti-Stokes peaks are evaluated.

The Raman signal, however, is sufficiently strong and distinct to be used in temperature measurement. Here the frequency shift is proportional to the characteristic vibrational frequencies of the molecules. Photons, scattered at lower frequencies, are termed *Stokes lines* and those, scattered to higher frequencies, are termed the *anti-Stokes lines*. The longer wavelength Stokes line is only weakly temperature sensitive whereas the backscattered light at the shorter anti-Stokes wavelength increases with higher temperature.

3.2. Measurement set-up

The described tests have been conducted in an attempt to verify the ability of DTS systems to detect hotspots and thereby prove the general possibility to use DTS systems for power cable monitoring. For this purpose a measurement set-up with a 1 km multimode fibre has been realized (Fig. 6). The employed DTS system from Agilent uses the Raman scattering effect combined with OTDR and signal coding to measure the temperature along a multimode graded index optical fibre with a maximum length of 8 km. A 1064 nm YAG laser is used to send short pulses (approx. 10 ns) into the fibre, which cause backscattered signals with a spreading of approximately 40 µs and a local temperature resolution of 1 m.

To create hotspots, the fibre has been heated at different points with heating resistors at a length of 3 cm. To evaluate subsea conditions, two times 400 m were put into a climate box at 10 °C.

Another measurement set-up, delivered by the manufacturer, has been used to check and to compare the general performance of DTS systems. In this set-up, two fibre coils of about 100 m of optical fibre length were heated with four heating resistors, to produce long heating zones. The total detection length was 550 m.

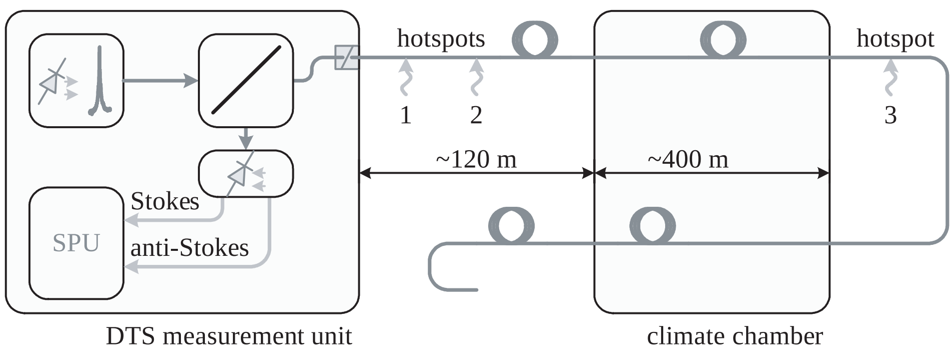

Fig. 6. Measurement set-up for local hotspot detection assessment. Large parts of the measurement fibre are coiled in a climate chamber.

3.3. Results and discussion

In the first test with the manufacturer set-up the fibre was scanned with a resolution of 1 m. Every three minutes the temperature over the fibre length was registered. The temperature signal distribution is averaged over three measurement. Figure 7 shows the heating process of the two fibre sections, from approximately 30 to 60 °C. One section is from the starting point of the fibre to 100 m, the other one from 425 to 525 m. During the whole cycle, the measured temperature has a standard deviation of 1 K. In the heated parts of the fibre, ripples can be observed due to inhomogeneous heating of the fibre loops.

During second measurements with the 1 km multimode fibre, local temperature variations have been applied to the fibre. Here the spatial resolution is an important parameter for detecting hotspots with a good location and temperature accuracy. The spatial resolution specifies the slope width of a measured step ΔT of the temperature profile. The slope width is defined as the spatial distance between the measured 10 and 90% level of the slope, with 0 and 100% being the stationary temperature levels before and after the step. The response of the DTS system to a local hotspot depends on the spatial resolution of the system (Fig. 8). If the temperature of the local heating occupies a zone, which is smaller than the spatial resolution of the DTS, the measured temperature is lower by approximately the ratio of hotspot width x to spatial resolution.

During the measurements, shown in Fig. 9, the local hotspots have been heated from the room temperature to about 65 °C. As the fibre was winded by hand on a plastic coil, the fibre was allotted irregularly on the coil, so that some parts of the fibre were located near to the cooling plates, which resulted in coldspots as can be seen in the same figure.

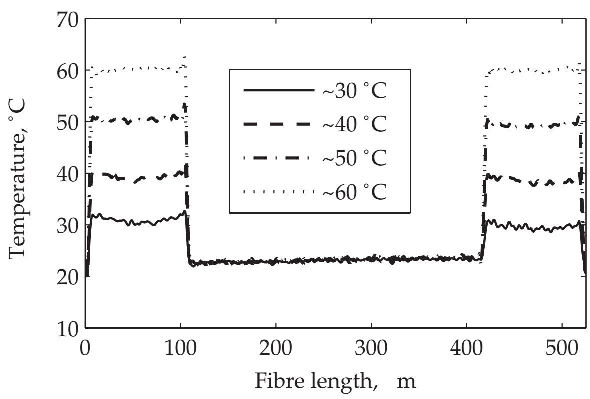

Fig. 7. Heating process of two 100 m segments of the test fibre, separated by approximately 300 m of fibre, held at room temperature.

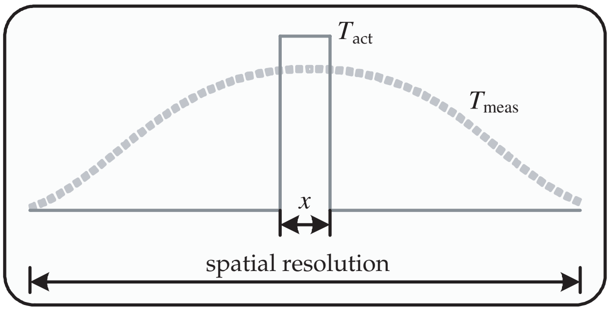

Fig. 8. Relationship between hotspot size and spatial resolution. In order to measure absolute temperatures of hotspots, these parameters have to be known.

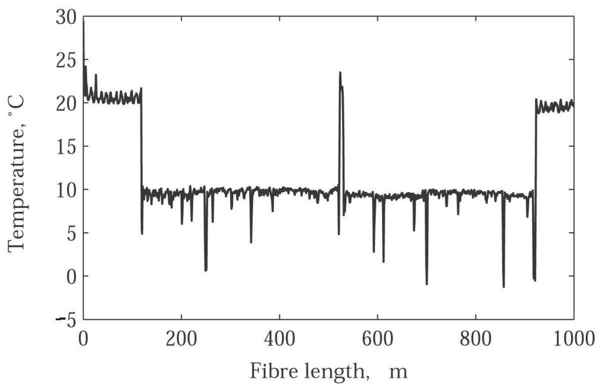

Fig. 9. Temperature distribution along the fibre during a test run. Hotspots as well as coldspots, resulting from local thermal impacts, do not appear in their full scope due to lower spatial resolution.

Figure 10 shows a zoom on the second hotspot. It can be observed that the detected temperature matches the given ratio. Hence, for hotspot detection, knowing the width, a correction factor can be estimated, otherwise the system can only register a local temperature rise without any detailed information about the width and real temperature.

Due to this fact, current system applications are limited to temperature distributions that vary little in terms of local resolution of the DTS system. However, compared to the long measurement distance, DTS systems meet the requirements for numerous applications, and research to improve the spatial resolution is continuing [20,21]. Especially for monitoring purposes of civil structures, distributed temperature sensing is already widely employed [22] as well as for power cable monitoring [23], fire detection in tunnels and downhole performance monitoring oil and gas wells.

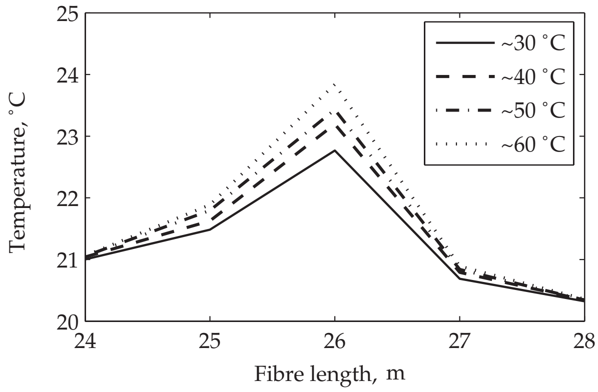

Fig. 10. Local hotspot No. 2 (see Fig. 6) during heating process. It can be seen that the measured temperature does not reflect the actual hotspot temperature.

4. TEMPERATURE SENSING WITH AN INTERFEROMETRIC PROBE

Interferometric fibreoptical temperature sensors can be divided into intrinsic and extrinsic sensor types. The principal function of interferometric sensors is the variation of the optical resonator length, e.g. geometrical length, and refraction index under the influence of the measurand. In intrinsic sensor types the necessary Fabry–Perot resonator consists of a single-mode fibre with partially transmitting fibre ends [24]. Extrinsic sensors use, e.g., a thin-film Fabry–Perot resonator, localized on the fibre end. A family of interferometric sensors for temperature, pressure and humidity has been developed in the last years at the Institute of Photonic Technology in Jena [25,26]. The benefit of spectral encoded sensor signals is high reliability and a nearly path-independent transmission along optical fibres over long distances. Depending on the resonator material, a temperature range from –200 to +1000 °C can be achieved [27].

4.1. Working principle

In Fig. 11, the principle of fibreoptical temperature measurement with Fabry–Perot transducers is illustrated. The Fabry–Perot resonator of the temperature sensor has dimensions 2×2 mm and consists of multiple thin layers with alternating high and low refraction indices. As a material with high refraction index, amorphous silicon is used. Its refraction index has a temperature dependence of about 2.8×10^{-4} 1/K. The material with low refraction index is represented by silicon dioxide.

Figure 12 shows the measured reflection spectrum of such a temperature transducer. Warming up the transducer causes a wavelength shift of the monitored

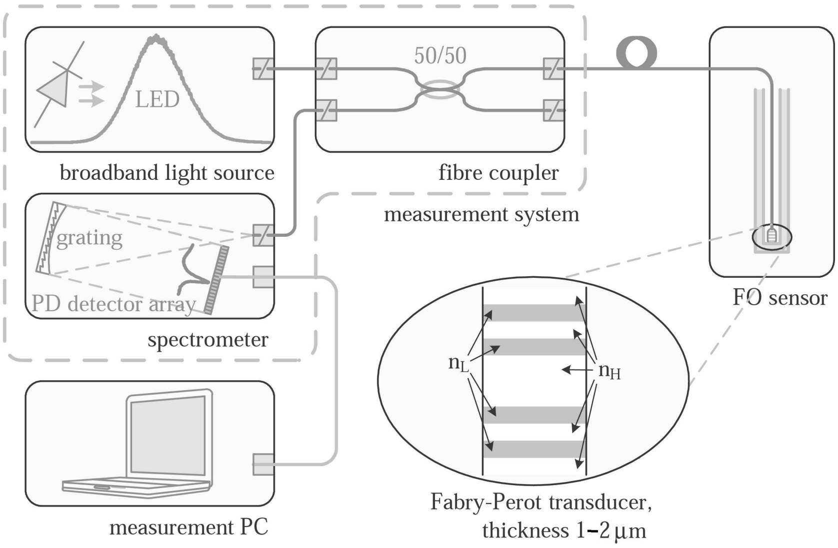

Fig. 11. Principle setup of a fibreoptical temperature measurement system with Fabry–Perot transducers.

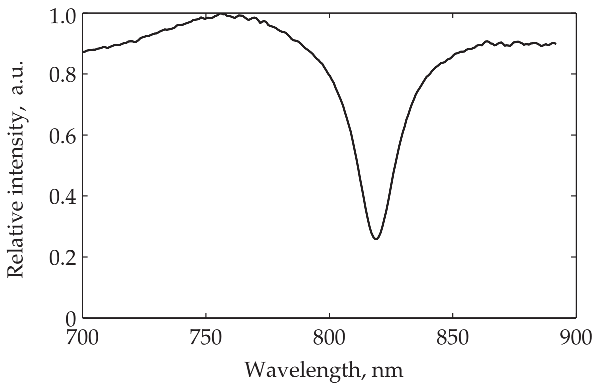

Fig. 12. Measured spectrum of a Fabry–Perot-temperature sensor with a minimum reflectivity at about 820 nm.

interference minimum to greater values. The transducer chips where laser-welded on a glass capillary. Through this capillary, the transducer and fibre are positioned. Another possibility is a deposited thin-film system on a fibre end. In this case, sensor diameters in the scale of the fibre, e.g. 200 μm for a multimode type, can be realized.

4.2. Instrumentation

For illuminating the transducer through the fibre, tungsten halogen lamps or broadband GaAlAs light emitting diodes are suitable. For sensor signal demodulation, for example a low-cost miniature optical polymer spectrometer can be used. The spectral range of these polychromators is from 700 to 900 nm with an optical resolution of 4 nm and a linear dispersion of 31.3 nm/mm. These polychromators are illuminated by a fibre bundle with a circular input and a rectangular output (70×500 μm). The photodiode array has a pixel pitch of 25 μm with a pixel height of 500 μm. By using a sub-pixel approximation algorithm, for example polynomial interpolation, a detection accuracy of 10 pm can be achieved [28]. The standard deviation of a single measurement of the interference minimum equals 3 pm. Spectral resolution and stability of the polychromator determine mainly the sensor performance.

4.3. Application

Fibreoptical temperature sensors are suitable for measurement in several application fields such as medicine or industrial process control. A fibreoptical temperature sensor was assembled for temperature measurements in gearboxes as an example of harsh environments. The sensor can withstand the aggressive oily environment inside a gearbox for typical operating temperatures up to 150 °C without any problems. The thin-film system of the used transducer is designed for a temperature range from -200 to 500 °C. Figure 13 shows the assembled temperature sensor with a sensitivity of about 0.07 nm/K (Fig. 14). Together with the polymer spectrometer, a measurement accuracy of 0.5 K can be achieved.

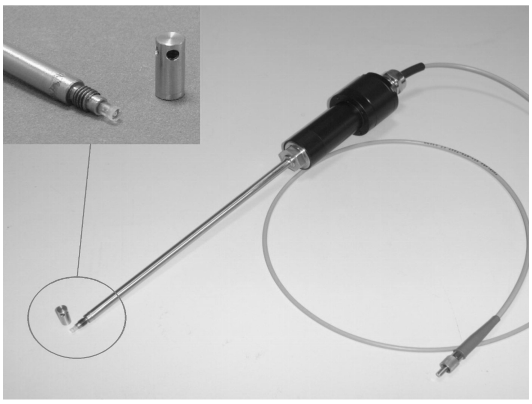

Fig. 13. Assembled fibreoptical temperature sensor for temperature measurements in a gearbox.

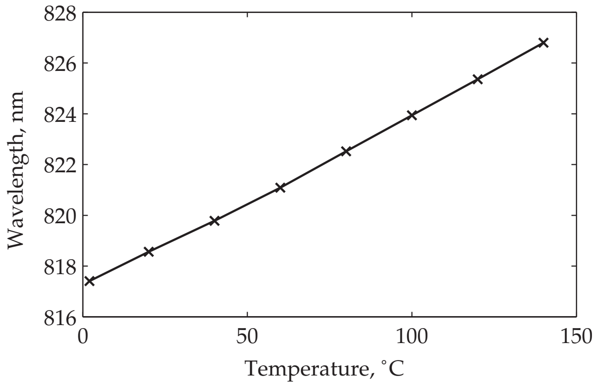

Fig. 14. Characteristic wavelength change with temperature of the assembled fibreoptical temperature probe.

5. CONCLUSIONS

Great potential for further development of fibreoptical temperature sensing is seen in applications that demand a high degree of multiplexing, distributed measurements, or measurements in harsh environments with strong electromagnetic fields or explosives.

Three main concepts of fibreoptical measurement of temperatures were explained and the technology's present status as well as some current application examples were presented. Principles of two-point shaped fibreoptical temperature sensors were exemplified, including an intrinsic one (fibre Bragg gratings) and an extrinsic probe (interferometric measurement). With Raman scattering, the most common method of distributed temperature sensing was also presented.

Fibre Bragg gratings are most suitable where many temperature measurement points are desired or where strain measurements are carried out with FBGs. In the latter case some FBGs can be used for temperature compensation purposes. With current commercial systems, resolutions of about 100 mK can be achieved.

The Fabry–Perot principle is the basis of the interferometric fibreoptical temperature probe. The realization of a temperature sensor for measurements inside a gearbox or in similarly harsh environments was described. As spectral detector, a low-cost polymer spectrometer was used. With this set-up a resolution of about 0.5 K was achieved.

Distributed temperature measurements, based on Raman scattering, were also presented. Laboratory tests with a commercial DTS system were carried out. In these tests, sub-sea conditions were simulated and applicability for pipeline monitoring was demonstrated. Typical applications of distributed temperature sensing are also in the fields of civil structures and down-hole monitoring.

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Temperatuuri mõõtmise fiiberoptiliste meetodite rakendusi

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Temperatuuri mõõtmine tööstuslikes tingimustes nõuab uusi sensoreid, milleks sobivad fiiberoptilised sensorid. On käsitletud sellise sensori loomise aluseks olevat kolme printsiipi (Braggi fiibervõred, Ramani hajumine ja Fabry–Pérot' interferomeetria) ning nende uudset rakendamist. Ehkki fiiberoptilised meetodid on leidnud senini kasutamist vaid nišitoodetes, on neil suur tulevikupotentsiaal.