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Temperature Sensing with Fibre Bragg Gratings and Application

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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.

Keywords: Optical fiber sensors, Fiber Bragg Grating, Fiber Bragg Grating Sensor

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.

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 B *i* could be used to measure quasi-distributed temperature at various locations, all connected by a single optical fibre.

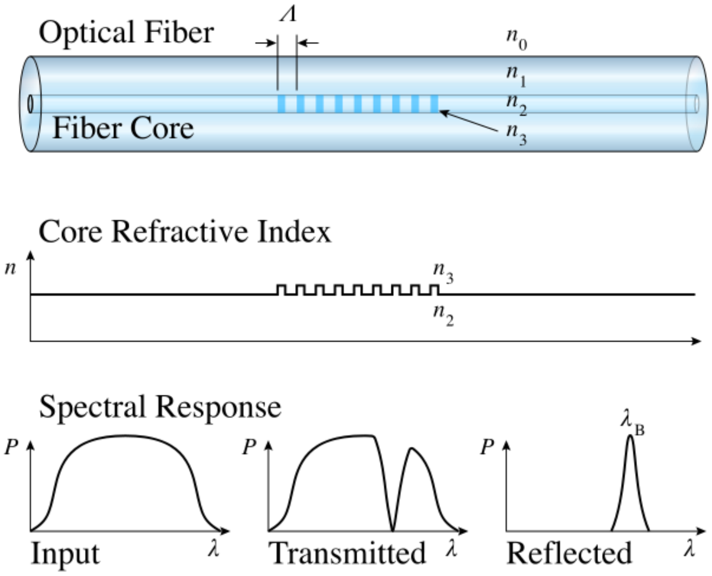

Fig: A Fiber Bragg Grating structure, with refractive index profile and spectral response

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 contradirectional 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 or temperature changes ,
- 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

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

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

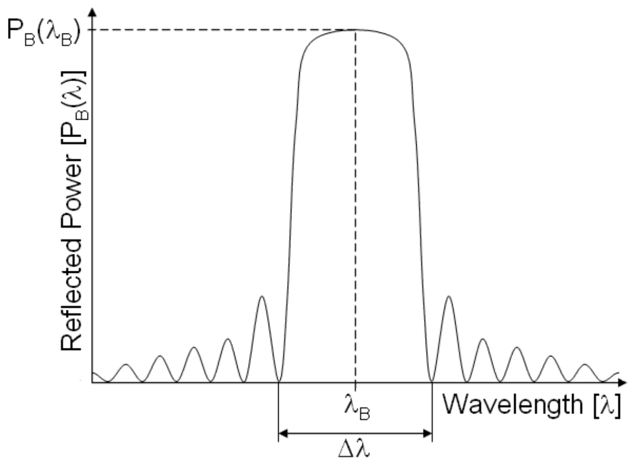

Fig: FBG reflected power as a function of wavelength

TYPES OF GRATINGS

Standard, or type I, gratings

Type I gratings are usually known as standard gratings and are manufactured in fibers of all types under all hydrogenation conditions. Typically, the reflection spectra of a type I grating is equal to 1-T where T is the transmission spectra. This means that the reflection and transmission spectra are complementary and there is negligible loss of light by reflection into the cladding or by absorption. Type I gratings are the most commonly used of all grating types, and the only types of grating available off-the-shelf at the time of writing.

Type IIA, or type In, gratings

These are gratings that form as the negative part of the induced index change overtakes the positive part. It is usually associated with gradual relaxation of induced stress along the axis and/or at the interface. It has been proposed that these gratings could be relabeled type In (for type 1 gratings with a negative index change; type II label could be reserved for those that are distinctly made above the damage threshold of the glass).

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

$$\frac{\Delta\lambda B,T}{\lambda B} = \frac{1}{\lambda B}\frac{d\lambda B}{dT} = \frac{1}{neff}\frac{\partial\, neff}{\partial T} - \frac{\partial\, neff^2}{2}(p11\ +\ 2p12)\alpha T\ + \alpha T \qquad (2)$$

Here is $\frac{\Delta\lambda B,T}{\lambda B}$ the relative change in centre wavelength per Kelvin temperature change, $\frac{\partial\, neff}{\partial T}$ is the thermooptical coefficient, $p11$ and $p12$ are Pockel's coefficients, representing the photoelastic effect and αT is the thermal expansion coefficient of the fibre material.

The thermal expansion coefficient of bare silica fibres is approximately $0.5\times\ 10^{-6}$ 1/K [5], Pockel's constants $p11$ and $p12$ 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 experimentally determined by the refractive index dependence on the temperature variation, which gives the total derivative dn=dT. If all other material parameters are known, the partial derivative $\frac{\partial\, neff}{\partial T}$ is equal to $9.7\times\ 10^{-6}$. This results in a general sensitivity of approximately $6.8\times\ 10^{-6}$ 1/K or around 10.5 pm/K at a wavelength of 1550 nm.

The mentioned coefficients depend on temperature [7,9], leading to nonlinearities 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].

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 [11]. 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 [12]. Combining these FBGs with a high-temperature coating, such as metals, makes them suitable for long-term high temperature measurements.

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 ¹m 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. 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.

REFERENCES

[1] Measures, R. *Structural Monitoring with Fiber Optic Technology*. Academic Press, Boston, 2001.

[2] Hill, K., Fujii, Y., Johnson, D. and Kawasaki, B. Photosensitivity in optical fiber

[3] waveguides: Application to reflection filter fabrication. *Appl. Phys. Lett.*, 1978, 32, 647–649.

[4] Meltz, G., Morey, W. and Glenn, W. Formation of Bragg gratings in optical fibers by a transverse holographic method. *Opt. Lett.*, 1989, 14, 823–825.

[5] Lee, B. Review of the present status of optical fiber sensors. *Opt. Fiber Technol.*, 2003, 9, 57–79.

[6] Lagakos, N., Bucaro, J. and Jarzynski, J. Temperature-induced optical phase

shifts in fibers. *Appl. Opt.*, 1981, 20, 2305–2308.

[7] Bertholds, A. and Daendliker, R. Determination of the individual strain-optic coefficients in single-mode optical fibers. *J. Lightwave Technol.*, 1988, 6, 17–20.

[8] O'Dwyer, M., Ye, C., James, S. and Tatam, R. Thermal dependence of the strain response of optical fibre Bragg gratings. *Meas. Sci. Technol.*, 2004, 15, 1607–1613.

[9] Flockhart, G. M., MacPherson,W. N., Barton, J. S., Jones, J. D., Zhang, L. and Bennion, I. Departure from linearity of fibre Bragg grating temperature coefficients. In *Optical Fiber Sensors Conference Technical Digest (OFS)*, Portland, 2002, 15, 75–78.

[10] Gupta, S., Mizunami, T., Yamao, T. and Shimomura, T. Fiber Bragg grating cryogenic temperature sensors. *Appl. Opt.*, 1996, 35, 5202–5205.

[11] Lin, G., Wang, L., Yang, C., Shih, M. and Chuang, T. Thermal performance of metal-clad fiber Bragg grating sensors. *IEEE Photonics Technol. Lett.*, 1998, 10, 406–408.

[12] Li, X., Prinz, F. and Seim, J. Thermal behavior of a metal embedded fiber Bragg grating sensor. *Smart Mater. Struct.*, 2001, 10, 575–579.

[13] Lupi, C., Felli, F., Ippoliti, L., Caponero, M. A., Ciotti, M., Nardelli, V. and Paolozzi, A. Metal coating for enhancing the sensitivity of fibre Bragg grating sensors at cryogenic temperature. *Smart Mater. Struct.*, 2005, 14, 71–76.