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Measurement of temperature and thermal gradients using fibre optic long period gratings

Frédéric J Lesage

Abstract Ultraviolet-written Long Period Fibre Gratings are demonstrated to be affective tools when measuring thermal gradients of a thermally conductive material. More specifically, variations in the thermal system of a substrate are detected through transmission spectrum responses. While it is well known that uniform temperature leads to pure wavelength shifts of the transmission spectrum minimum, observed changes in transmission loss lead to predictions of thermal gradients. Since Fourier's law of heat conduction implies that heat flux measurements of known conductive materials can be predicted with knowledge of the temperature gradient, the present work demonstrates that optical fibres may be used to develop photonic heat flux sensors. Such an advancement would have a significant impact in industries, such as building materials, in which embedded sensors are used to predict surface thermal boundary layer conditions.

1 Introduction

In the physical sciences, our capacity to measure physical phenomena dictates our ability to make scientific observations and to formulate conclusions. For this reason, there is great interest in the scientific community to improve the precision in temperature and heat flux measurements. Indeed,

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accurate accounts of thermal profiles are key in design, safety, control, and maintenance of a large array of industrial processes [1, 2]. Rather than discuss all processes involving thermal measurements, this paper focuses on the need for improved temperature and heat flux sensors for building materials. More specifically, in the construction industry deteriorating building foundations are due to premature form-work removal (or stripping) when curing structural concrete resulting in a material resistance that is inferior to that which was intended [3]. Strategies to control concrete resistance aim to measure real time curing temperature evolution by inserting a temperature sensor in the form-work before curing begins [4]. The information provided allows for adjustments to be made to the water, limestone and aggregate quantities and to pinpoint the removal time of the concrete encasing [5].

Katipamula and Brambley [6] highlight the need for building material temperature measurements for improved habitat comfort, and for more efficient building energy systems. Other needs for temperature sensors in building materials gravitate towards the detection of faulty design, energy consumption, and structural damage [7,8]. Currently, conventional temperature sensors present certain limitations. As detailed in [1], they can be fragile, be unstable over long-period use, overheat, heat the substrate, and are subject to electromagnetic interference. Furthermore, they are inconvenient over large distances [2]. The present study explores the use of fibre optics as a temperature sensor and as a heat flux sensor. The main thesis of this work is that long-period fibre gratings can be calibrated to measure simultaneously temperature and heat flux. Furthermore, the precision of the measurements relative to conventional methods is promising. This is due to the fact that the measurements rely on the degree of accuracy of wavelength and transmission spectrum measurements.

2 Background

Fibre optics are generally made of glass and have the ability to channel light over large distances with minimal loss. They are widely used in telecommunications and have more recently been used as sensors for various applications [9]. The use of fibre optics as sensors was made possible by the development of Fibre Bragg Grating (FBG), characterised by their core's periodic variations in refractive index, and by Long-Period Fibre Grating (LPFG), which feature periodic perturbations in the cladding mode. These fibres have been shown to be sensitive to temperature and deformation [10–12].

In this study, Ultraviolet Long-Period Fibre Gratings (UV-LPFG) are used to detect variations in the transmission spectrum with respect to heat flux

and temperature. As illustrated in the UV-LPG section of Fig. 1, the permutations are written into the fibre cladding and the core (such as in [13]) periodically, thereby changing the propagation modes. The result is a graphical dip in transmission spectrum representing a power loss that is sensitive to the light's energy levels (hc/λ).

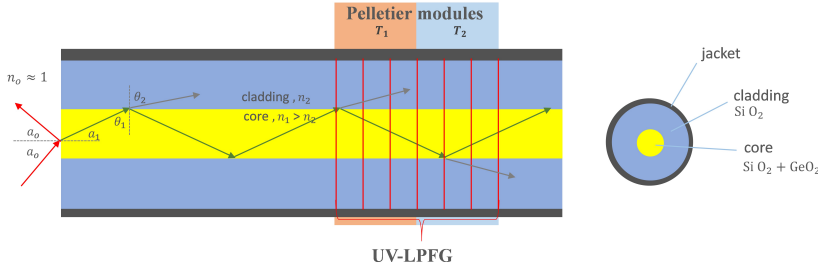


Fig. 1 Incident light refracting through the core and cladding of an Ultraviolet Long-period Fibre Grating (UV-LPG) with a thermal gradient maintained using Peltier modules.

Light propagates in the optical fibre according to Snell's law (also known as Descartes' law) which states that:

$$n_0 \sin a_0 = n_1 \sin a_1 \quad (1)$$

in which n_i represents the index of refraction of the medium i , a_0 is the incident angle from air and a_1 is the refracted angle into the core of the fibre. Refraction propagates through the fibre in which the core-cladding refraction is also determined by Snell's law such that $n_1 \sin \theta_1 = n_2 \sin \theta_2$. Total internal reflection is achieved when $\theta_2 = \pi/2$ thereby identifying the critical incident angle a_c as that for which

$$\sin a_c = \frac{1}{n_0} \sqrt{n_1^2 - n_2^2} \quad (2)$$

In this study, a UV-LPG is placed in a thermal system environment that measures its transmission spectrum with respect to temperature and to heat flux in an effort to provide the ground-work for photonic heat flux and temperature sensors.

3 Experimental Set-up

A CLS-561 light source providing 23 dBm (≈ 200 mW) with a spectral power stability of ± 0.2 dB for wavelengths ranging from 600 nm to 1700 nm provides incident light to an optical fibre. A BK Precision 9201 electric current source is used to power two thermoelectric Peltier modules that are 30 mm \times 30 mm \times 3.8 mm. The modules are used to control the thermal system acting on the fibre. An Agilent 86142B is used to measure the transmission spectrum and an Agilent 34970A is used to measure the temperature data provided by thermocouples.

Experiments are performed in which the transmission spectrum is measured for varying temperatures, temperature gradients and distances between the Peltier modules. The tested LPFG of length 5 cm exhibits a sensitivity of $d\lambda_c/dT = 0.1286$ nm/K for which λ_c is the centre wavelength corresponding to the wavelength generating the minimum in the transmission spectrum. The sensitivity is measured for a mean temperature varying over 35 °C. The experimental apparatus measures centre wavelength with an accuracy of 0.05 nm, which translates into a mean temperature accuracy of 0.4 °C. As losses and minimum power level measurements can be performed with an accuracy of 0.01 dB, UV-LPFG are used for the simultaneous measurement of temperature gradient and mean temperature by tracking the changes in transmission spectral minimum and centre wavelength.

4 Experimental results

4.1 Transmission response to temperature gradient

We consider the case in which a target mean temperature is applied to the fibre and the transmission spectrum is measured. The experiments are repeated for varying thermal gradient while maintaining the same target mean temperature. The experimental results illustrated in Fig. 2 demonstrate that an increase in temperature gradient dictates a decrease in the lower peak of the transmission spectrum and that the wavelength generating the peak is independent of temperature gradient. The temperature gradient is identified by the temperature differences (ΔT) generated by the Peltier modules since they are maintained at a fixed centre-to-centre distance of 30 mm.

Similar experimental observations were observed for mean temperatures of 10, 15, 20, 25, 30, 35 and 40 °C in which each set of experiments was conducted over the same range of temperature gradients as that of Fig. 2.

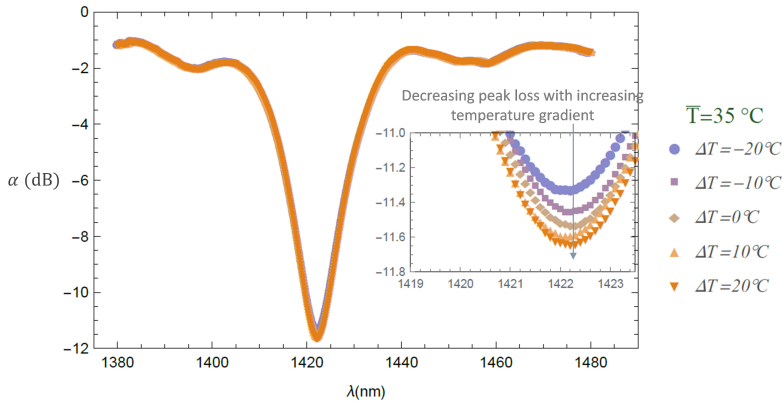


Fig. 2 Transmission spectrum with respect to varying thermal gradients (denoted ΔT) with fixed distance between Peltier modules and fixed mean temperature \bar{T} .

Figure 3 presents the measured transmission spectrum minimums (denoted α_{min}) with respect to temperature gradient for varying mean temperatures. The results show a linear dependence between transmission spectrum minimums and temperature differences. Furthermore, a curve fitting to the measured data is used to provide a predictive tool. More specifically, the following linear equation predicts the thermal gradient from transmission spectrum results for the tested optical fibre.

$$\Delta T(\alpha_{min}) = -137.1\alpha_{min} - 1577.9 \tag{3}$$

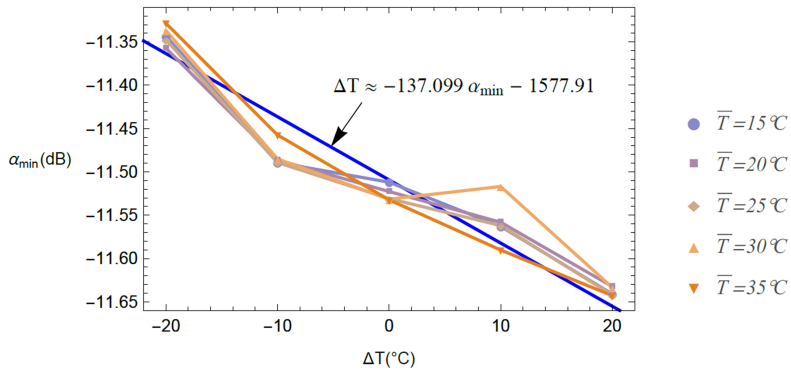


Fig. 3 Minimum transmission spectrum with respect to varying thermal gradient.

4.2 Transmission response to mean temperature

We now consider the case in which a target temperature difference is maintained for a series of experiments with varying mean temperatures. The results illustrated in Fig. 4 show that as the mean temperature increases, the lower peak of the transmission spectrum remains constant. However, the results also show the centre wavelength increasing mean temperature.

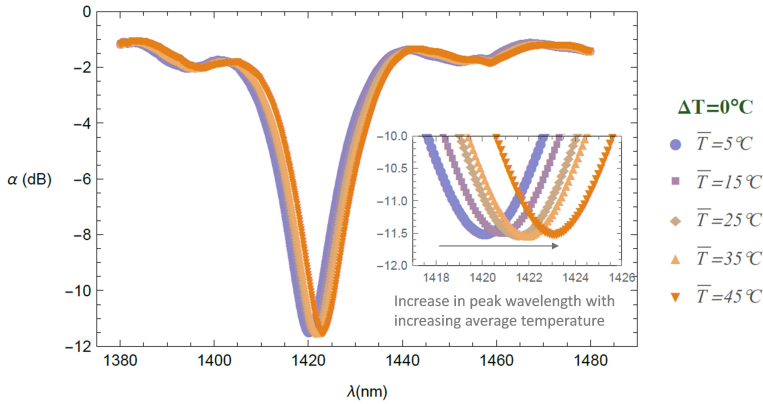


Fig. 4 Transmission spectrum with respect to varying mean temperature (\bar{T}) with fixed thermal gradient.

Similar experimental observations were observed for ΔT values of -20 , -10 , 0 , 10 and 20 $^\circ\text{C}$ in which each set of experiments was conducted over the same range of mean temperatures as that of Fig. 4.

The results illustrated in Fig. 5 show a linear relation between the centre wavelength and the mean temperature. The following linear curve fit can be used to predict the substrate's mean temperature from the transmission results for the tested optical fibre.

$$\bar{T}(\lambda_o) = 13.1\lambda_o - 18549.0 \quad (4)$$

Equations (3) and (4) imply that the transmission spectrum measurements, and more specifically, the coordinates of the peak dip in transmission, can be used to determine the mean temperature and the thermal gradient of a material over a length spanning 30 mm. The accuracy of the ΔT and \bar{T} measurements is evaluated as being within 0.34°C due to the peak transmission measurements being within 0.0001 dB.

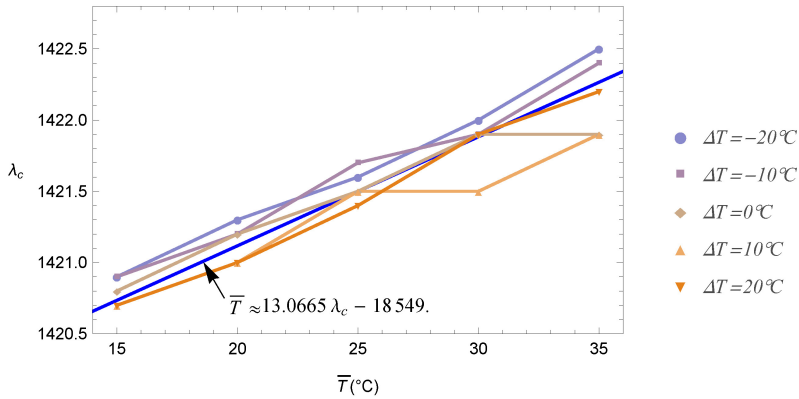


Fig. 5 Centre wavelength with respect to mean temperature

5 Conclusion

This work shows that optical fibres can be used to simultaneously measure the thermal behaviour of a substrate. It is demonstrated that the mean temperature is a linear function of the transmission spectrum's centre wavelength and that the temperature gradient is a linear function of the transmission spectrum's minimum value. Therefore, by applying Fourier's law of heat conduction, a single photonic sensor can be calibrated and used to measure the temperature and heat flux of a substrate with known proprieties. This technology has potential applications in many industries, such as combustion engines, integrated circuits and building materials since current heat flux sensors require two temperature readings resulting in a high uncertainty. Furthermore, optical fibres can be easily embedded into materials thereby providing surface boundary conditions by using the inverse heat conduction method.

Acknowledgements

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