Spectrally-resolved distributed optical fibre bolometry

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ABSTRACT

We propose a fully distributed optical fiber sensor capable of performing spectrally-resolved detection of visible light radiation. The sensor is based on monitoring the temperature change between two optical fibers with different coating colors. In our implementation, the temperature is simultaneously monitored in a black-coated fiber (which is highly sensitive to all input wavelengths) and a color-coated fiber, which basically acts as an optical stop-band filter for a certain input color. By comparing the temperature behavior attained for each fiber, it is possible to obtain information of the wavelength/color of a given optical radiation present in the environment. Suitable calibration could lead to distributed colorimetry measurements.

Keywords: Optical sensors, Rayleigh scattering, fiber bolometry, optical time domain reflectometry, distributed sensing

1. INTRODUCTION

Distributed fiber optic sensing alternatives are becoming attractive solutions in a variety of fields. They have been receiving increasing attention from areas such as civil engineering, energy, and seismology [1]. The benefits of Distributed Fiber Optic Sensors (DFOS) come from the convenient replacement of thousands of independent detectors disposed along a certain monitored element, with a single optical fiber cable and a single interrogation unit. These features enable a reduction in the overall complexity, energy consumption, and cost of the monitoring system when the number of points to control is large (in the order of thousands). Across the literature, DFOS have often shown to be capable of performing highly sensitive measurements of different physical variables (typically temperature and strain) in a wide set of applications and over large distances [2].

Recently, the appearance of more advanced optical fiber reflectometry techniques allowed to extend the application of DFOS to different areas of engineering, offering new and attractive solutions in those fields. The development of phase-sensitive optical time domain reflectometry with linearly chirped pulses (CP-ΦOTDR) has demonstrated to achieve robust, fast (kHz) and high sensitivity (mK) distributed fiber temperature measurements over distances of up to 70 km [3]. Benefitting from these features, it was recently demonstrated, for the first time, the detection of optical radiation in a distributed way, i.e. the first all fiber distributed bolometer [4]. The concept of fiber-based bolometry opens the door for the exploitation of photothermal radiation sensing applications, such as the detection of solar radiation in power line transmission or in photovoltaic fields. Following this growing interest, it emerged the idea of further exploiting the concept of fiber-based bolometry with the intent of obtaining spectral information from the light in the environment.

Here, we demonstrate the possibility of achieving distributed colorimetry using CP-ΦOTDR interrogation and fiber-based bolometry. The principle involves the temperature monitoring of two fibers with different coating colors, one operating as an optical wideband absorber (black-coated fiber), and the other acting as a wavelength-selective absorber (in our case, a color-coated fiber). The proposed system has the potential for being integrated in applications such as the monitoring of the temperature of melting steel, where the steel temperature is evaluated based on the spectral information obtained during the melting process.

2. THEORY

2.1 Fiber-based bolometry

The principle of bolometry can be implemented using optical fiber-based technology, as recently described in [4]. The core idea behind the fiber-based bolometer is that by monitoring the temperature of two optical fibers with different coatings (i.e. different absorption coefficients), the measurement of an incident irradiance, E_{inc}, can be achieved for an arbitrary external temperature, T_0. The idea is developed by using two optical fibers with different optical absorption coefficients, α_1, α_2, (and/or different heat transfer coefficients h_1, h_2), which are placed in the same environment and under the same irradiance. At the equilibrium state, in this case reached at different temperatures for fiber 1 and fiber 2, T_1, T_2, the incident radiation can then be calculated using [4]:

$$E_{inc} = (T_1 - T_0)\cdot(h_1\cdot A)/(A_{inc}\cdot\alpha_1) = (T_1 - T_0)/\text{¢}_1 \Leftrightarrow T_0 = T_1 - (E_{inc}\cdot\text{¢}_1) \tag{1}$$

$$E_{inc} = (T_2 - T_0)\cdot(h_2\cdot A)/(A_{inc}\cdot\alpha_2) = (T_2 - T_0)/\text{¢}_2 \Leftrightarrow T_0 = T_2 - (E_{inc}\cdot\text{¢}_2), \tag{2}$$

being A the heat transfer surface area, A_{inc} the absorber's area of radiation incidence, and ¢ a constant which depends on the system parameters. By replacing $T_0 = T_1 - (E_{inc}\cdot\text{¢}_1)$ in eq. 2, it is then derived that:

$$E_{inc} = (T_2 - T_1)/(\text{¢}_2 - \text{¢}_1). \tag{3}$$

This way, the measurement of a given incident irradiance E_{inc} can be achieved in an optical system by measuring the temperature difference between two fibers with different absorption coefficients, for an arbitrary external temperature T_0.

2.2 Spectral discrimination of light

In this work, we propose a method to achieve spectral discrimination of the input light based on the principle of fiber-based bolometry. It is based on the monitoring of the temperature difference between two optical fibers exposed to a given incident irradiance, E_{inc}, with the difference that, in this case, one of the fibers operates as an all-wavelength absorber in the visible range, while the other is colored, and acts as a wavelength-selective absorber (the color coating acts as a band-stop filter for that color). Therefore, the absorption coefficients α_1, α_2 of the fibers 1 and 2 are the same except for the wavelengths contained within the spectral bandwidth reflected by the colored coating. i.e.:

$$\alpha_1(\lambda) = \alpha_2(\lambda), \quad \lambda \neq [\lambda_1, \lambda_2] \tag{4}$$

where $[\lambda_1, \lambda_2]$ defines the bandwidth containing the rejected wavelengths by the band-stop optical filter (fiber 2). This idea can be achieved by implementing a black-coated fiber (with a high and constant absorption coefficient through the visible range), and a similar optical fiber but with a certain coating color (high absorption coefficient in the visible range with the exception of the specific coating color region). For equal fibers with same materials and coating thicknesses, we can also derive that $h_1(\lambda) = h_2(\lambda), \lambda \neq [\lambda_1, \lambda_2]$. Therefore, considering eq. 3 and assuming that the two fibers are placed in the same conditions and under the same incident irradiance, the temperature difference between the fibers $T_2 - T_1$ at the equilibrium state can be written as:

$$T_2 - T_1 = \begin{cases} E_{inc}(\lambda)\cdot(\text{¢}_2(\lambda) - \text{¢}_1(\lambda)), & \lambda = [\lambda_1, \lambda_2] \\ 0, & \lambda \neq [\lambda_1, \lambda_2] \end{cases} \tag{5}$$

This way, by detecting a temperature difference between a black and a colored fiber with similar features and under the same environmental conditions, the presence of an irradiance at a certain wavelength/color can be identified.

3. EXPERIMENTAL SETUP

The experimental setup used for the demonstration of the system is represented in Figure 1. Two standard fibers under test (FUT) with the same geometric and material properties and different coating colors were used as the sensing elements. For the fiber 1, FUT_1, a black coated fiber was chosen, while for the fiber 2, FUT_2, three different fibers were studied with red, green and blue coatings. All fibers had an outer diameter of 0.25 mm and an overlapping section of ~10 m which was wrapped in concentric circles with a radius of ~10 cm. The fibers were placed at the same position to ensure that they would receive the same uniform irradiance, and they were spliced together, as to achieve a single optical fiber to be monitored by the optical interrogator. Optical radiation was then applied to the FUTs, using a warm white LED lamp (with 800-1000 total lumens) and an optical filter in front, which selected the red, green or blue components of the emitted light. The values of irradiance experienced by the FUTs were measured by a radiation pyrometer, with the detector placed at the position of the FUTs.

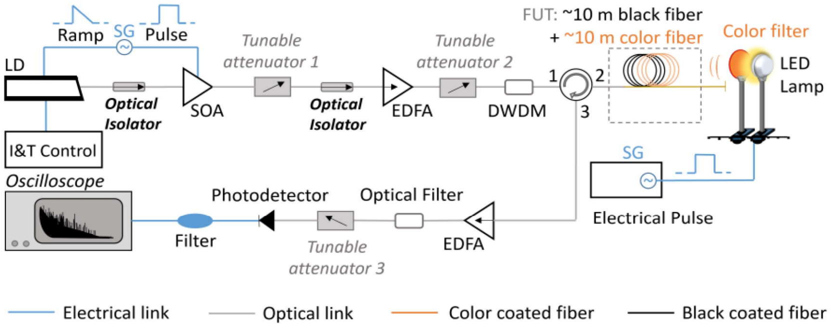

Figure 1. Experimental setup of the proposed system.

The temperature of the two optical fibers was then monitored in real-time by an optical distributed fiber temperature interrogator based on CP-ΦOTDR, which allows for high sensitivity and fast distributed measurements of temperature. Detailed information on this measurement technique can be found in [3]. The CP-ΦOTDR measurement was performed using 60 ns pulses (corresponding to 6-meter spatial resolution), linearly chirped with ≈0.3 GHz of total pulse frequency content and a detection scheme enabling a temperature resolution of ≈1 mK, with a temperature sampled at 2kHz.

4. RESULTS

To demonstrate the principle of spectrally-resolved distributed bolometry measurements with CP-ΦOTDR, visible radiation was sent to the fibers in cycles of 1 minute each (allowing them to approach a thermal equilibrium state) using three different optical filters for the input light (labelled “red”, “green” and “blue”). The sequence of irradiances applied was: (1) 0 W/m^2 (LED off), (2) 83.61 W/m^2 (red light), (3) 0 W/m^2, (4) 58.25 W/m^2 (green light), (5) 0 W/m^2, (6) 36.51 W/m^2 (blue light), (7) 0 W/m^2. The temperature behavior obtained for the three colored fibers (red, green and blue) and the black fiber is represented in Fig. 2 (a), (b) and (c). The ratio obtained between the temperature response for fibers 1 and 2, T_1 / T_2, was also characterized and is depicted in Fig. 2 (d).

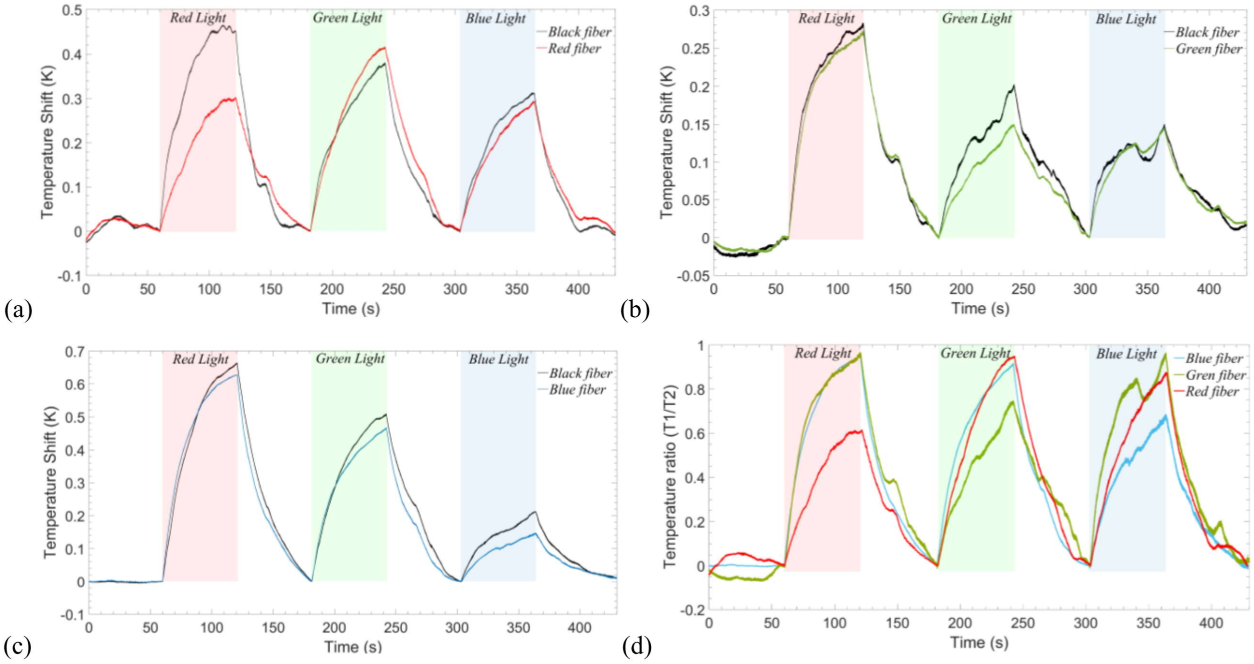

Figure 2. Temperature shift experienced by the black fiber (black line) and the (a) red fiber, (b) green fiber, and (c) blue fiber, when submitted to 1 minute of red, green and blue irradiance. (d) Ratio between the temperature change obtained for the red, green and blue fibers (red, green and blue traces, respectively), and the black fiber in each measurement.

The results in Fig. 2 show that the system has sensitivity to discriminate an optical radiation of a given color/wavelength, by detecting a temperature difference between the reference fiber (black one) and a fiber with the same coating color of the radiation. Additionally, considering eq. 5, the ratio between the temperature of the fibers T_1/T_2 at the equilibrium state should have the form $T_1 / T_2 = 1 - E_{inc}(\lambda) \cdot (\text{¢}_2(\lambda) - \text{¢}_1(\lambda)) / T_2$ when the light has the same color of fiber 2, and $T_1 / T_2 = 1$ when the radiation is of any of the other two colors. The results in Fig. 2 (d) are in accordance with the expected behavior, presenting a ratio lower than 1 when the light has the same color of the coating of fiber 2, and a ratio close to 1 in the presence of other radiation colors.

5. CONCLUSIONS

In this work, the possibility of achieving fully distributed, spectrally-resolved discrimination of optical radiation using CP-ΦOTDR interrogation has been demonstrated. The method is based on measuring the temperature difference between two optical fibers placed under the same environment. One of the fibers operates as an optical all-wavelength absorber in the visible range (a black-coated fiber in our implementation), and the other as a wavelength-selective detector (a colored fiber in our case), absorbing all wavelengths except those of the coating color. By monitoring the temperature difference between the black fiber and colored fiber, we demonstrated the possibility of having a certain spectral discrimination in the detection of external irradiance. The distributed spectrally-resolved detection of light here shown can be made to operate within the range and resolution limits already demonstrated for the temperature interrogation technique of CP-ϕOTDR: mK temperature resolutions over tens of km range, and meter-scale spatial resolutions. Moreover, an array of optical fibers with different coating colors (from red to purple) can be implemented and monitored simultaneously, in order to obtain a better spectral coverage across all the visible range.

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