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Ming Ding
University of Southampton

Pengfei Wang
Technological University Dublin, pengfei.wang@tudublin.ie

Gilberto Brambilla
University of Southampton

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A Fast-Response, High-Temperature Microfiber Coupler Tip thermometer

Ming Ding, Pengfei Wang, and Gilberto Brambilla

***Abstract*—A compact temperature sensor based on a broadband microfiber coupler tip is demonstrated. The thermometer dynamic range spans from room temperature to 1511 ºC with a response time of tens of ms. This is the highest temperature measured with a silica optical fiber device. A resolution of 0.66 ºC was achieved for a coupler tip diameter of ~12.56 µm. Better resolution can be achieved with smaller size microfiber coupler tips.**

***Index Terms*— microfiber coupler tip, fast response time, high temperature sensor, responsivity, resolution**

I. Introduction

The use of optical fibers for temperature monitoring has been widely investigated [1,2] because of their immunity to electromagnetic interference and possibility to work in contact with explosives. Fiber Bragg gratings (FBGs) [3-6] are possibly the most commonly investigated optical fiber devices for temperature monitoring, as they can reach temperatures as high as 800 ºC [7] when inscribed in telecom optical fibers. In addition, regenerated FBGs written in silica optical fibers have been shown to be capable to reliably stand 1000 ºC [8] and reach temperatures as high as 1295 ºC [9], but they often require special fibers, hydrogen loading, a cumbersome grating writing equipment working with toxic gases and post fabrication treatments.

Here, a compact thermometer based on a microfiber coupler tip (MFCT) is presented. While fused optical fiber couplers have been extensively used in optical communication because of their high performance and low cost, their initial application to temperature monitoring [10] related only to low temperatures (below 100 ºC) and resulted in low responsivity. Recently, a compact thermometer based on a ~2.5 µm MFCT (Fig. 1) was reported [11]: by measuring wavelength shifts, it measured a broad temperature interval ranging from room temperature to 1283 ºC.

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Ming Ding is with the Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ United Kingdom (phone: +44 (0)2380593143; fax: +44(0)2380593142; e-mail: md20g09@orc.soton.ac.uk).

Gilberto Brambilla is with the Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ United Kingdom (e-mail: gb2@orc.soton.ac.uk).

Pengfei Wang is with the Photonics Research Centre, Dublin Institute of Technology, Dublin Ireland and he is visiting the Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ United Kingdom (e-mail: pw3y09@orc.soton.ac.uk).

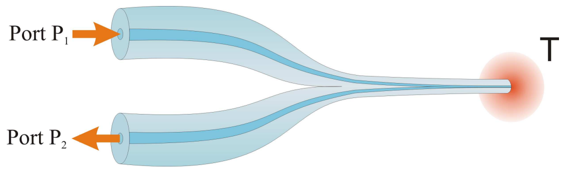

Fig. 1. Schematic of a bi-conical microfiber coupler tip (MFCT).

Although also the temperature sensor presented in this paper is still based on an MFCT and its sensing mechanism relies on the change of optical path with temperature [11], its working principle is different from that used in ref [11]: instead of measuring a wavelength shift, the intensity change is recorded at a specific wavelength, reducing the device response time and the need for expensive equipment. In addition, since the MFCT is made of silica, which softens at 1680 °C, it is predicted that it can potentially reach very high temperatures.

II. Microfiber coupler tip temperature sensor fabrication

In these experiments, a low-loss microfiber coupler (MFC) was fabricated from two standard telecom optical fibers (SMF-28, Corning, NY, USA) using the microheater brushing technique [12]. The lengths of tapered and uniform waist regions were ~25 mm and ~6 mm, respectively. The MFCT was manufactured by cutting a MFC into two equal parts at the center of the minimum waist region using a ceramic cleaver. In the MFCT, light launched from port P_1 is partially reflected by the flat surface of the tip and can be measured at port P_2.

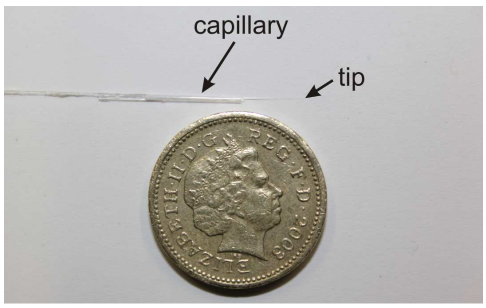

Fig. 2. Picture of a MFCT. The capillary has 600 µm outer diameter.

Fig. 2 shows a picture of the MFCT: a glass capillary was used to increase the thermometer stiffness. Two MFCTs were fabricated in the experiments: sample 1, with a 12.56 µm diameter, and sample 2, with a 4.8 µm diameter. Large diameters were chosen to ensure an adequate rigidity for the thermometer head and a wide temperature measurement range, even if this potentially resulted in multimode guidance. The broadband singlemode [13] bi-conical 2×2 MFC had transition regions designed to minimize the fraction of power in high order modes and to provide efficient power splitting of the fundamental mode at the two output ports.

III. Microfiber Coupler Tip Temperature Sensor Characterization

A. *Temperature monitoring method*

The MFCT spectral characterization was carried out using the set-up shown in Fig. 3(a), which connects a broadband light source (Fianium Ltd, Southampton, U.K.), with emission over the wavelengths range 450-1800 nm, to port P_1, and an optical spectrum analyzer (OSA) (AQ6317, Yokogawa, Japan) to port P_2. The microheater (NTT-AT, Tokyo, Japan) which is used to fabricate the MFC was also used for temperature testing, as it can reach temperatures in excess of 1500 ºC. The MFCT was inserted into the microheater center and reflection spectra were recorded at different temperatures. The microheater temperature was changed by increasing the current flowing into the microheater.

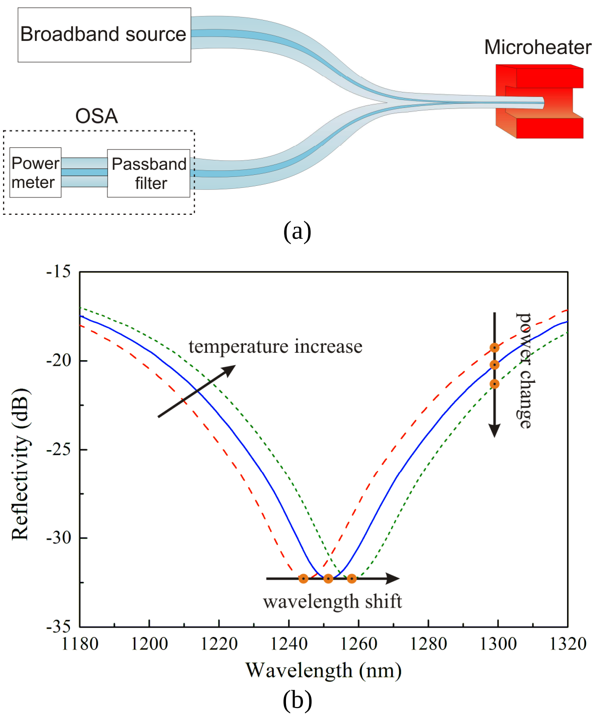

Fig. 3. (a) MFCT characterization set-up; (b) the reflection spectra of sample 1 when the temperature increases.

The reflection spectrum of sample 1 for increasing temperatures is presented in Fig. 3(b) and shows a resonance peak at the wavelength λ~1246 nm (red dash curve). When the microheater current is increased, the temperature increases and the peak redshifts to long wavelengths. Temperature monitoring can be carried out evaluating the power change over a bandwidth of 1 nm at a fixed wavelength. The OSA was used as a replacement for a passband filter and a power meter at the wavelength λ=1300 nm. When the temperature was increased, the recorded intensity at λ=1300 nm decreased.

B. *Response time*

The device response time is related to its mass and thermal properties. As the Biot number is greater than 10^3, heat loss by convection is considerably greater than that by conduction and the MFCT dynamic thermal behavior can be described by:

$$hA(T_f - T)dt = c\rho V dT \qquad (1)$$

where V and A are the volume and surface area of the heated region, h, c and ρ are the surface convection coefficient, heat capacity and density and T_f is the surrounding fluid temperature. The integration of this equation shows that the time constant (thus response time) of the device is given by:

$$\tau = \frac{c\rho V}{hA} = \frac{c\rho}{h}\frac{r}{2} \qquad (2)$$

and it is proportional to the MFCT radius r. Assuming h=418.68 W/m^{2}K [14], c=0.8 kJ/kg·K, ρ=2300 kg/m^3 and r=6.28 μm, the device response time results to be τ=13.8 ms.

The thermometer response time was measured by rapidly inserting the MFCT into the microheater; the driver current was set at ~2.00 A corresponding to T~1045 ºC (Fig. 4). The response time was obtained considering the time interval at which the intensity drop reached 1/e of its total change. For sample 1, a response time of ~16.6 ms was measured, comparable with the value obtained from equation 2.

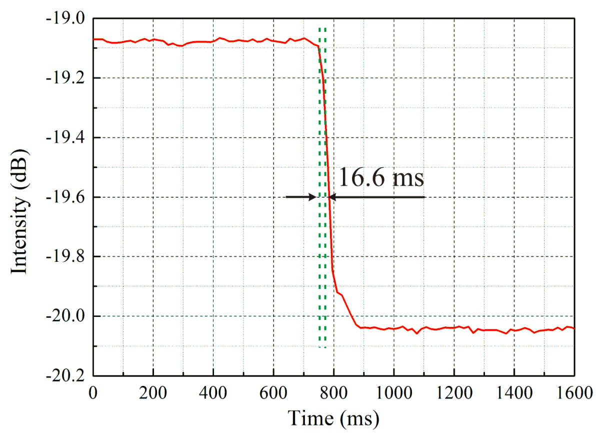

Fig. 4. Measurement of MFCT response time of sample 1: the temporal dependence of the MFCT reflected intensity was recorded for a rapid temperature change, resulting in a response time of ~16.6 ms.

C. *Dynamic range, Responsivity and Resolution*

The device temperature response was carried out using the set-up shown in Fig. 3(a). The microheater temperature was changed from 0.2 A to 3.6 A in steps of 0.2 A. Measurements were taken every 15 minutes to ensure a stable temperature. When the temperature stabilized, the MFCT was rapidly inserted into the microheater and then taken out. The intensity response is presented in Fig. 5 and it shows that the intensity dip increases for increasing currents.

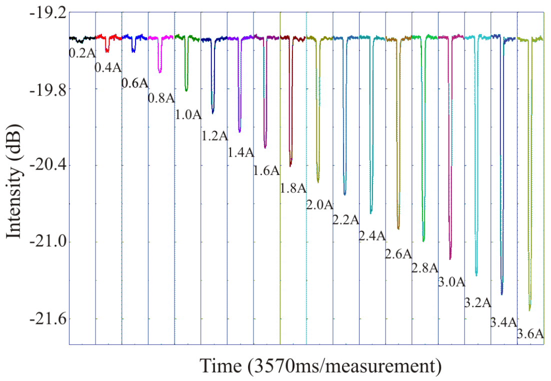

Fig. 5. Temporal intensity change for sample 1 when the tip is repeatedly inserted and taken out from the microheater at different temperatures. The temperature was changed by changing the driver current from 0.2 A to 3.6 A in steps of 0.2 A. The current I=3.6 A corresponds to T~1511 ºC.

Fig. 6 presents the relationship between the measured intensity and the microheater temperature for samples 1 and 2, which are both monotonically decreasing functions. The maximum dynamic range was achieved for sample 1, which reached T=1511ºC. The sensor responsivity *R*, defined as the change in the sensor output per unit signal change, corresponds to the curve slope in Fig. 6. Sample 1 has R~1.514×10^{-3} dB/ºC, smaller than that of sample 2 (~9.748×10^{-3} dB/ºC).

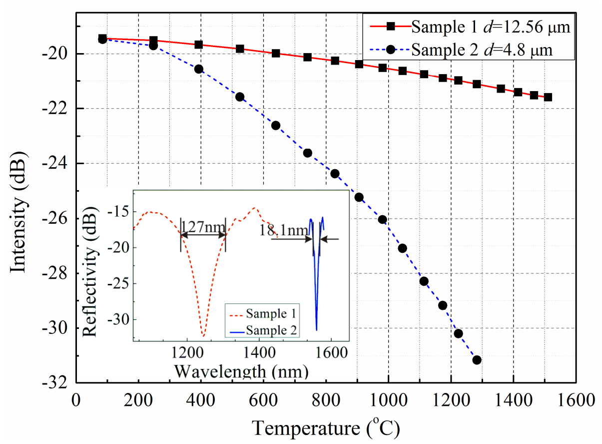

Fig. 6. Relationship between measured intensity and the microheater temperature. Inset: resonance peaks used for T measurements in sample 1 and 2, respectively.

The sensor resolution *S* is defined as the minimum temperature change that the sensor can distinguish. Since the power resolution of the OSA (and commonly of many powermeters) is of the order 10^{-3} dB, an average S~0.66 ºC was achieved in the temperature interval ~85 ºC to ~1511 ºC for sample 1; this is higher than that previously obtained measuring the peak shift [11]. Sample 2, with smaller diameter, has better resolution S~0.10 ºC but smaller dynamic range (from T~85 ºC to T~1283 ºC). The inset of Fig. 6 presents the resonance peaks used for T measurements in sample 1 and 2, respectively. In sample 1, which has a full width at half maximum (FWHM) of 127 nm, the gradient of the resonance peak is small, corresponding to a wide temperature measurement range and low *S*. On the other hand, in sample 2 a smaller diameter corresponds to a sharper resonance peak: the steep slope provides a high *S* in exchange for a smaller dynamic range.

IV. Conclusion

In summary, a compact temperature sensor which uses a MFCT for fast response and high temperature sensing has been demonstrated. The thermometer had a resolution of 0.66 ºC and wide temperature measurement range from room temperature to ~1511 ºC. To the best of our knowledge this is the highest temperature measured with a silica optical fiber device. Resolution can be improved with smaller size MFCTs. MFCT offers several advantages, including compactness, extremely high temperature measurement capabilities, fast response, easy connection with other fiberized optical components, simple fabrication and low cost. By setting a reference wavelength and measuring the intensity ratio between the two wavelengths, the sensitivity can be further improved and the error associated to the source power drift/oscillations can be minimized [15].

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