

Temperature sensing using micro-deformed looped fiber taper

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A novel fiber-optic temperature sensor device based on an optical fiber tapered loop with a micro-deformation at the taper waist section to enhance its sensitivity is presented. The taper waist diameter was selected as $10\ \mu\text{m}$, and the micro-deformation at the taper waist section enables the formation of spectral deep notches with enhanced sensitivity to external disturbances, such as temperature. Three dissimilar looped devices were fabricated to assess the effectiveness of engaging temperature disturbances ranging from 100°C to 600°C . It was found that a bi-dose function fits better the wavelength-shift response to temperature changes of the enhanced spectral notches as a function of temperature, with greater R_2 values, in contrast with a linear fitting. By using a linear fitting for the whole range of temperatures, the results show a range of average linear sensitivity from approximately $7.39\ \text{pm}/^\circ\text{C}$ to $17.07\ \text{pm}/^\circ\text{C}$. With these discoveries, the proposed device can be used as a high-temperature sensor in a wide range, which makes it attractive for practical applications. The encouraging results obtained in this article contribute significantly to the field of fiber optic high-temperature sensors and have a lot of potential to be used in industry and research.

Keywords: Optical fiber; micro-deformation; tapered fiber; temperature sensor.

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1. Introduction

Temperature sensors manufactured from fiber optics have been very useful in recent decades, in the area of physical and chemical detection. This is due to the wide variety of properties they entail, of which we can mainly list their tiny size, fast response speed, high sensitivity and ease of construction, which make them highly useful devices. Over time, many temperature sensors have been built from optical fiber, with different forms of construction, such as Bragg gratings [1,2], long-period fiber gratings [3,4], tapers [5,6], Mach-Zehnder type interferometers [7,8] and resonator type interferometers [9,10,11]. These latter devices are often constructed in shapes that include loops, knots, and rings. Whether winding the taper, creating a loop, or knot, the guiding light within the fiber recirculates within the closed cavity through a vanishing coupling at the bonding area [12]. In previous works, optical fiber sensors have been investigated to detect temperature changes that are manufactured from tapers with curvatures [13,14] and deformations [15]. In Ref. [14] a device composed of an optical fiber between two grooved plates is

used for temperature sensing. When the teeth of the plates induce a micro-bending, caused by displacement according to the temperature changes, the guided mode of single-mode fiber couples to cladding modes and modulates light loss in the fiber. All the aforementioned research has made a wide range of ways to address the problem of temperature measurement, using fiber optics and with the goal of being able to obtain temperature sensors with high sensitivity and according to particular requirements. Among the applications that require high-temperature monitoring, we have those in metal processing, advanced materials research, monitoring of engines, high-temperature turbines and industrial furnace processes. Moreover, in processes that require critical thermal control such as power generation or in the aerospace industry, we find temperature ranges ranging from 100°C to 600°C .

In this letter, we present an optical fiber looped micro-deformed tapered in a conventional SMF for temperature measurements. The micro-deformation in the optical fiber is performed by a spherical fiber end, which pushes the apex of a tapered fiber loop while both are heated in a glass processor. The average sensitivity for a micro-deformed looped

fiber taper is $7.39 \text{ pm}/^\circ\text{C}$ and $17.9 \text{ pm}/^\circ\text{C}$, within the temperature range between 100°C to 625°C and 100°C to 600°C , respectively. Analyzing the responses with the Biphasic Dose-Response function model, we obtained $R^2 = 0.98174$ and $R^2 = 0.99635$, for the same micro-deformed looped fiber taper.

2. Sensor fabrication and working principle

Vytran GPX-3400 glass processing system has been widely used for fabricating a tapered fiber on SMF-28 fiber. Tapered sections with 5mm/5mm/5mm down-taper/waist/up-taper longitudinal dimensions, and a waist diameter of $10 \mu\text{m}$ were used. Once the taper was fabricated, the taper waist was deformed to a loop. Then, to keep its shape, glued with UV adhesive in the bare section before the loop starts. Using the LZM-100 glass processor, we manufactured a spherical ball at the end of an SMF. The looped fiber was mounted on the other holder side of the LZM-100. Figure 1a) in steps 1 and 2 shows the ball lens aligned and pushing against the fiber loop inside LZM-100. Then, it is applied a CO_2 -laser pulse, and the ball is moved away after the pulse is applied (step 3 in Fig. 1a)). When the sphere ball is removed, the fiber loop is permanently micro-deformed, as shown in Fig. 1a). The last fabrication procedure was described also in a previous work [16]. Figure 2 shows the micro-deformation when a $310 \mu\text{m}$ diameter sphere was used to perform the micro-deformation. This micro-deformation was analyzed under the microscope,

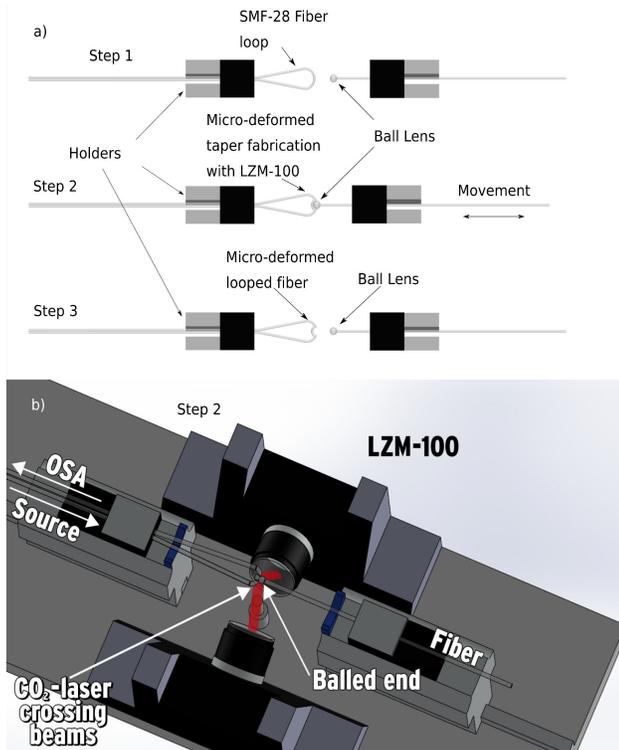


FIGURE 1. a) Manufacturing steps of the micro-deformation of a fiber loop taper. b) Diagram of the process carried out inside the LZM-100 glass processor.

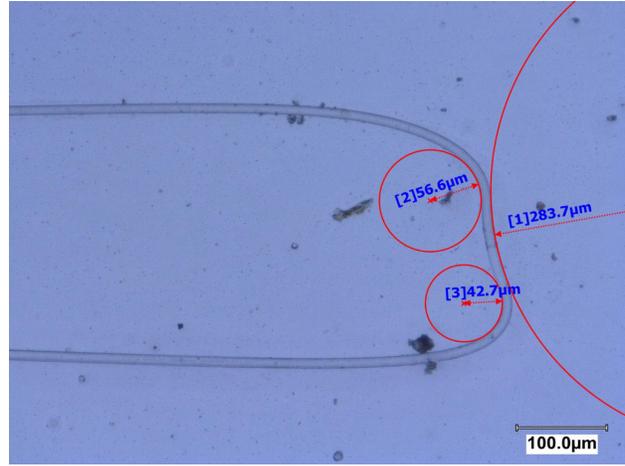


FIGURE 2. The measured optical microscope image of an optical fiber looped micro-deformed when using a spherical ball of $310 \mu\text{m}$ to generate the micro-deformation.

getting a measured deformation diameter of approximately 283 mm (see Fig. 2).

For a cladding diameter reduced from $125 \mu\text{m}$ to $10 \mu\text{m}$, the corresponding core diameter reduces to $0.332 \mu\text{m}$. For such a diameter, the core no longer supports the fundamental mode as a guided mode, it is a leak mode whose propagation is supported now by the waveguide formed between the cladding and external medium interface, in our case the air. The deformation procedure used in the device fabrication, results in a deformed section with a stress that is frozen in the structure and the bent may result in coupling to whispering gallery modes [16]. Both effects and the intrinsic thermo-optic properties of the materials that compose the fiber, allow the construction of a device to measure the temperature in a broad range.

3. Experimental results and discussion

The utilized experimental setup with the micro-deformed looped fiber taper temperature sensor is shown in Fig. 3. The experiment consists of a basic transmission setup by connecting the light source of the optical spectrum analyzer (OSA),

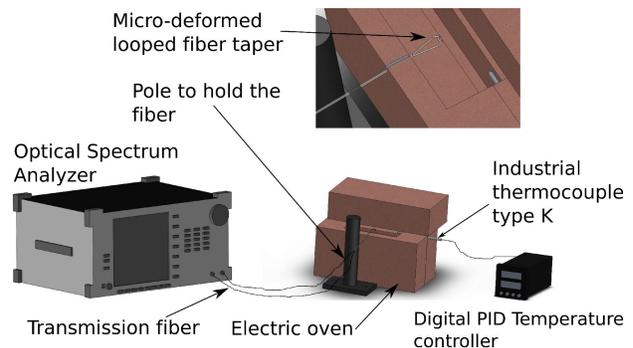


FIGURE 3. Schematic diagram of experimental setup.

TABLE I. Sensitivity and determination coefficients R^2 for linear and biphasic dose fitting corresponding to Fig. 4.

	Sens. ($^{\circ}\text{C}/\mu\text{m}$)	R^2	R^2
λ_{P1}	3.46	0.89888	0.95121
λ_{P2}	7.97	0.92461	0.98905
λ_{P3}	4.37	0.87249	0.97686
λ_{P4}	7.39	0.94374	0.98174

MS9740A, Anritsu) to one end of the micro-deformation device and the other to the OSA input. For measuring the sensitivity of the device to changes in temperature, the device is introduced in an electric oven. The temperature was varied in a range from 25°C to 600°C with 25°C of step. Every temperature step increase was monitored in real-time with a thermocouple thermometer connected to a Digital PID Temperature Controller.

Figure 4a) shows the transmission spectra of the temperature response for micro-deformed looped fiber tapers fabri-

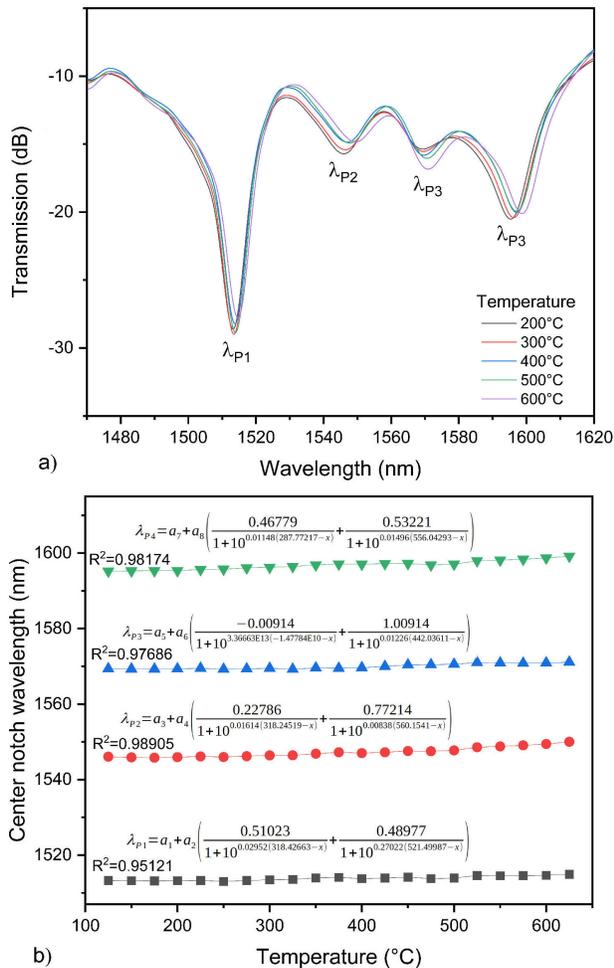


FIGURE 4. Temperature response of the micro-deformed looped fiber taper, realized by using a spherical end of $220 \mu\text{m}$ of diameter: a) Transmission spectra at several temperatures, and b) be-dose fit for every spectral notch.

cated by using spherical fiber ends of 220 nm . Figure 4b) shows the variation of the central wavelengths of the notches of Fig. 4a) as a function of temperature. The curves in Fig. 4b) were fitted by using the nonlinear fitting function “biphasic dose function”, which is part of the available nonlinear fitting functions of the OriginLab Software. Table I shows the sensitivity and determination coefficients R^2 for a linear and a biphasic dose fitting. As can be observed, the nonlinear biphasic dose reproduces with major accuracy the experimental data, in contrast with the linear fit function. Nevertheless, the linear function is accurate enough to define the sensitivity, an average, as the slope of the linear fitting curve. The peak labeled with λ_{P2} in Fig. 4a) and 4b) shows the highest sensitivity of $7.97^{\circ}\text{C}/\mu\text{m}$.

Figures 5a) and 6a) show the transmission spectra of two different micro-deformed looped tapered fibers fabricated by using spherical fiber ends of $570 \mu\text{m}$ diameter. In the first case, only two pronounced notches are observed and the variation of position of their central wavelengths as a function of temperature is shown in Fig. 5b). Again the biphasic dose function provides a better fit, however, the linear fit is accurate enough to define the average sensitivity as the slope of the linear fitting function, which in this case are $17.09^{\circ}\text{C}/\mu\text{m}$ and $14.38^{\circ}\text{C}/\mu\text{m}$ for the first and second notch wavelength peak, respectively (Table II).

For the second device fabricated with the $570 \mu\text{m}$ spherical fiber end, there are four notches whose peak wavelengths as a function of temperature are shown in Fig. 6b). In this case, as shown in Table III, the biphasic dose function is again a better fit, however, the linear fitting function is also very accurate and the greater sensitivity is observed for the second wavelength peak λ_{P2} .

The temperature sensitivity of the tapered looped micro-deformed fiber device depends on the fabrication process, *i.e.*, the dimensions of the deformation and the loop itself. Figure 7 shows the transmission spectra of the looped fiber

TABLE II. Sensitivity and determination coefficients R^2 for linear and biphasic dose fitting corresponding to Fig. 5.

Peak	Linear fitting func.		Bip. dose fitting func.
	Sens. ($^{\circ}\text{C}/\mu\text{m}$)	R^2	R^2
λ_{P1}	17.09	0.94624	0.99494
λ_{P2}	14.38	0.90753	0.99211

TABLE III. Sensitivity and determination coefficients R^2 for linear and biphasic dose fitting corresponding to Fig. 6.

Peak	Linear fitting func.		Bip. dose fitting func.
	Sens. ($^{\circ}\text{C}/\mu\text{m}$)	R^2	R^2
λ_{P1}	11.23	0.97887	0.99726
λ_{P2}	15.76	0.97166	0.99757
λ_{P3}	10.07	0.97896	0.99537
λ_{P4}	10.90	0.97999	0.99635

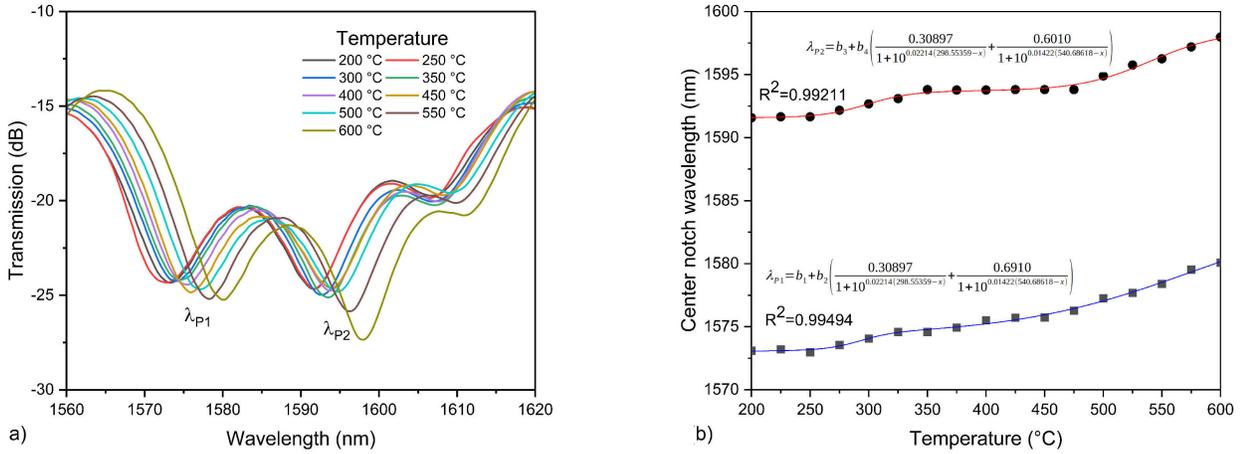


FIGURE 5. Temperature response of the micro-deformed looped fiber taper, realized by using a spherical end of 570 μm of diameter: a) Transmission spectra at several temperatures, and b) be-dose fit for two spectral notches.

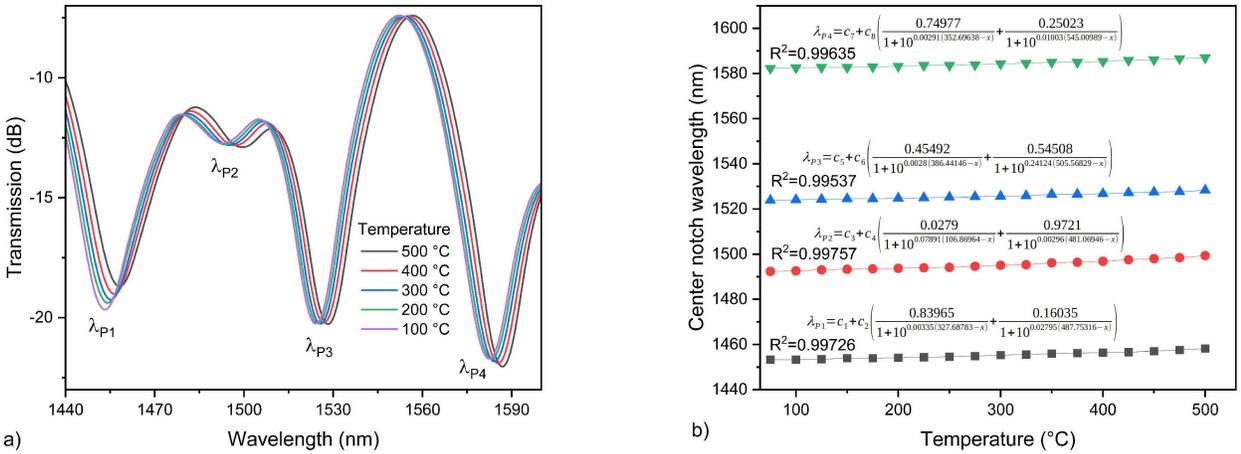


FIGURE 6. Temperature response of the micro-deformed looped fiber taper, realized by using a spherical end of 570 μm of diameter: a) Transmission spectra at several temperatures, and b) be-dose fit for every spectral notch.

taper without micro-deformation at several temperatures. As can be observed, the spectral variations are challenging to correlate with the temperature changes. However, when the micro-deformation is included in the loop, the obtained sensitivity is enhanced and, in all cases, has the same order of magnitude (3.46 – 17.09 pm/°C). On the other hand, a higher sensitivity can be obtained by changing the surrounding material, for example by encapsulating the tapered fiber device in an isopropanol-filled capillary tube [17], which also modifies the linear response range of the sensor. Usually, only the linear response range is considered as the operation range of the sensor. In fact, in most cases, we can associate different quasi-linear response ranges in the whole temperature testing range and select those with higher determination coefficients R_2 . Then in a broad temperature measurement range, from tens of °C to hundreds of °C, the response of the sensors in general will be nonlinear. The advantage of using a not ultra-sensitive sensor is that the nonlinearity is smaller, so that, a linear fitting function may result in adequate practical values. As was shown in the last section, linear fitting, in general,

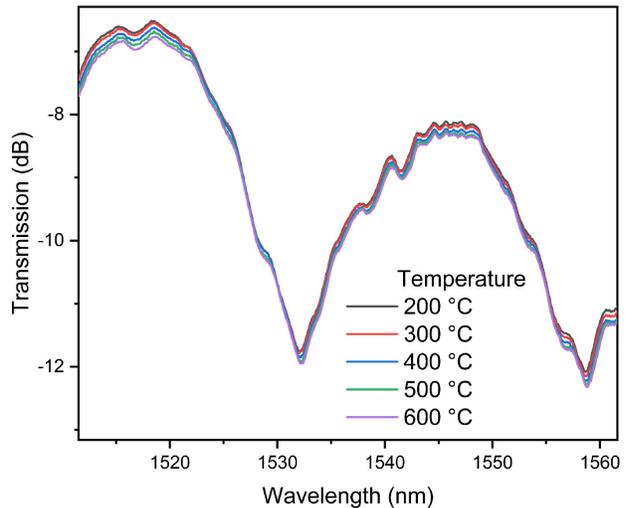


FIGURE 7. Transmission spectra of the looped fiber taper without micro-deformation at several temperatures.

results in linearity over 90%, while a nonlinear fitting with a biphasic dose function gives R^2 values close to or over 99% in most cases, in a range spanning from 100°C to 600°C, which can result in a practical device.

4. Conclusions

In conclusion, we have shown a temperature sensor based on micro-deformed looped fiber taper. The method uses a fiber optic taper that is micro-deformed. It was found that, depending on the particular geometry of the micro-deformation, sensitivities of 3.4 pm/°C to 17.09 pm/°C were obtained in

the temperature range of 100°C to 600°C. In addition, it was shown that the linear response in the whole range in most cases gives R^2 values over 90%, while the nonlinear biphasic dose function fitting gives R^2 values over 99% in most cases. Then, the response of the sensor makes it suitable for use in industrial environments and others.

Acknowledgments

Acknowledgements are presented at the end of the manuscript, before the reference section.

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