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Monitor *in situ* superconducting temperature via optical whispering-gallery mode sensors

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Abstract

In this work, we demonstrated the precise measurement and monitoring of superconductor temperature using an optical whispering-gallery mode sensor for the first time. A silica microsphere was placed into contact with a high-temperature DI-BSCCO superconductive tape (~10 cm long) to characterize superconductivity versus temperature. The electrical conductivity was measured by the 4-point probe method. The sensitivity of the WGM sensor was determined to vary from 3.6 pm K⁻¹ to 5.5 pm K⁻¹ when the temperature rose from 105 K to 150 K, which agrees well to analysis. The present instrument is small in size, fast in response, low in cost, and high in accuracy and resolution. The measurements were compared with factory specified results obtained from costly and bulky facility and an excellent agreement was found.

Keywords: whispering-gallery mode, superconductivity, critical temperature, optical sensor, *in situ* measurement

(Some figures may appear in colour only in the online journal)

1. Introduction

In the past decades, optical whispering-gallery mode (WGM) phenomenon in dielectric micro-resonators has attracted increasing attention due to distinct features of small mode volume and extremely high Q -factor [1]. Various high-tech applications based on optical WGM have been developed, e.g. biosensing and detection in molecular levels [2–6], ultra-fine temperature measurement [6–10], mechanics measurement [11, 12], optics and communications [13–17], to name a few. A vital sensing principle that was explored is resonant frequency shift. Due to high Q -factor, high-resolution measurements and ultrafine sensitivity can be realized. Pure silica resonators were demonstrated having excellent temperature measurement sensitivity at both room and cryogenic temperature regimes [10].

Superconductivity occurs when a superconductor is cooled down to below a critical temperature. This phenomenon was

discovered by Heike Kamerlingh Onnes in 1911 when he observed that at the temperature of 4.2 K, the resistance of solid mercury abruptly disappeared. To enable practical applications of superconductivity, scientists have been working for over a century to find superconductor materials that have a higher critical temperature [18, 19]. In the recent decades, ceramic material was found to have a critical temperature above 90 K [20]. Such kinds of superconductors are termed the high-temperature superconductor (HTS). Nevertheless, the operation temperature is still in the low-temperature regime. Thus, it is desirable to develop precise measurement technologies under low temperature environment.

Two typical methods were employed to demonstrate superconductivity. The first one is the Meissner effect [21]. A magnet levitating above a superconductor, which is cooled down to below the critical temperature. Persistent electric current flows on the surface of the superconductor, acting to exclude the magnetic field of the magnet (Faraday's law of induction). The second method is called the 4-point probe

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measurement [22], through which the resistance of a superconductor can be observed to drop to zero when the operating temperature is below the critical temperature. The facility used in such traditional measurements is bulky and the superconductor wire used is generally very long (~500 m) [23].

The present study aims to demonstrate a small-volume but accurate technique for determining the critical temperature and characterizing superconductivity. Here we used an optical WGM silica microsphere to determine the critical temperature with a very short superconductor tape in operation. The 4-point probe was adopted to characterize the superconductivity. We designed and built a low-temperature chamber and a cryogenic working cell to achieve a thermally stable environment between 100–150 K. The exciting laser was calibrated, and the sensitivity of the WGM temperature sensor was examined. During the test, superconductor resistance, WGM sensor resonance spectra, and thermocouple voltage were recorded simultaneously. The measurement results are compared with factory-specified data, and an excellent agreement was found. The present facility is accurate, small, cheap, fast, and portable. The measurement is *in situ* and real time.

2. Experimental setup and measurement

The experiment was performed in a small lab-made low-temperature chamber. The setup is sketched in figure 1, which consists of four main components: an optical WGM sensor, a short superconductive tape, a 4-point electrical probe system, and a cryogenic working cell. A thermocouple is also placed inside the cryogenic cell to monitor the environmental temperature.

The optical sensing system includes a 1516 nm distributed feedback laser (NEL NLK1556STG), a lens that focuses the lasing light into an optical fiber, a silica microsphere, and a taper fabricated in a small section of the optical fiber. A function generator (Agilent 33220A) is used to set a ramping with an amplitude of 3.5 V and frequency of 100 Hz. The temperature and the intensity of the laser are controlled by a laser controller (light wave LCD-3724 B).

Figure 2 sketches the lab-built cryogenic cell (about $3'' \times 4'' \times 6''$) as well as the 4-point probe arrangement. All the silica microsphere, the fiber taper, the superconductor tape, and the 4-point probe system are installed inside the working cell. The cell was enclosed by a relatively large chamber (about $1' \times 1.5' \times 2'$) which has some inlets and outlets used for multiple purposes: such as liquid nitrogen injection and inert gas purging, delivery and collection of optical and electrical signals. The cryogenic cell and low-temperature chamber were designed and built to maintain a thermally stable working space for superconductivity and to prevent frost interference at low temperature. It is necessary to purge inert nitrogen gas into the chamber for 30 min before pouring liquid nitrogen (LN2) into the cryogenic cell. This step is to suppress humidity in the working cell and chamber such that frosting caused by humidity is prevented. If humidity is retained in low-temperature condition, icing easily occurs between fiber taper and resonator coupling, either degrading the resonance of the microsphere or breaking the tiny fiber taper [24].

The cryogenic cell is made of aluminum and wrapped with a thermal insulation layer. LN2 is injected into and stored in a small reservoir beneath the cell. When 4 liters of LN2 was slowly poured into the reservoir in 20 min, the temperature in the working cell could reach to and be stabilized at about 100 K for about 10 min. A solid copper cylinder of 0.5'' in diameter is vertically inserted into the reservoir, above which another copper cylinder of 1'' in diameter has a crosscut. The cross-cut space is used to arrange the superconductor tape in one direction and the fiber taper in the cross direction. The silica microsphere is placed onto the superconductor tape and coupled to the fiber taper at the intersection. A Polydimethylsiloxane lid is put on the open cell top to prevent temperature and gas-flow fluctuations inside the cell. The cryogenic working cell cools the superconductive tape to a temperature below the factory-specified critical temperature. Another two copper rods used for aligning the superconductor tape are also inserted into the LN2 reservoir. Such an arrangement was effective in cooling down the working cell evenly.

The 4-point probe measurement is a simple apparatus for measuring electrical resistivity of a sample [22]. This technique is employed here to characterize the superconductivity. By passing an electrical current (I) through the two outer probes and measuring the voltage (V) through the inner two probes allows the determination of the tape resistivity (R). When a Kelvin connection is used, current is supplied via a pair of current leads. These generate a voltage drop across the impedance to be measured according to Ohm's law $V = IR$. In the present experiment, the voltage of a superconductive tape is tiny. Thus, a voltage amplifier is needed.

A few feet of HTS DI-BSCCO were donated by Sumitomo Electric to our laboratory. The BSCCO crystal structure contains bismuth, strontium, calcium, copper and oxygen. The ratio of these elements, Bi: Sr: Ca: Cu, is 2: 2: 2: 3. The short tape used in our measurement is shown in figure 3, together with an image of the silica microsphere. The tape is about 10 cm long, 4 mm wide, and 0.2 mm thick. It has a silver outer layer. The silver layer was removed in the places where the silica microsphere and four probes were in contact with the bare tape. The silica sphere is estimated at 525 μm in diameter. It was fused from a single-mode bare fiber (Corning SMF-28). The fiber taper was fabricated from same material via the heat-and-pull method. The sphere and tape fabrication and quality examination methods were described in detail in our previous study [7].

The optical signal was detected by a photodetector (Thorlabs PDA400) and then recorded by a digital oscilloscope (Picoscope 3206B). The bandwidth of the Picoscope is 200 MHz, and the sampling rate is 500 MS s^{-1} . The Picoscope has two input channels and a trigger input. The photodetector was plugged into channel A, and the thermocouple signal was plugged into channel B. Due to the voltage of the T-type thermocouple was very low, an amplifier (Omega Omni Amp IIB) was used. The T-type thermocouple was calibrated at freezing point (273.15 K) and boiling point (373.15 K). A reference table (N.I.S.T Monograph 175) was used to confirm the offset of the thermocouple amplifier. DAQ cards were adopted to acquire and analyze the electrical signals simultaneously.

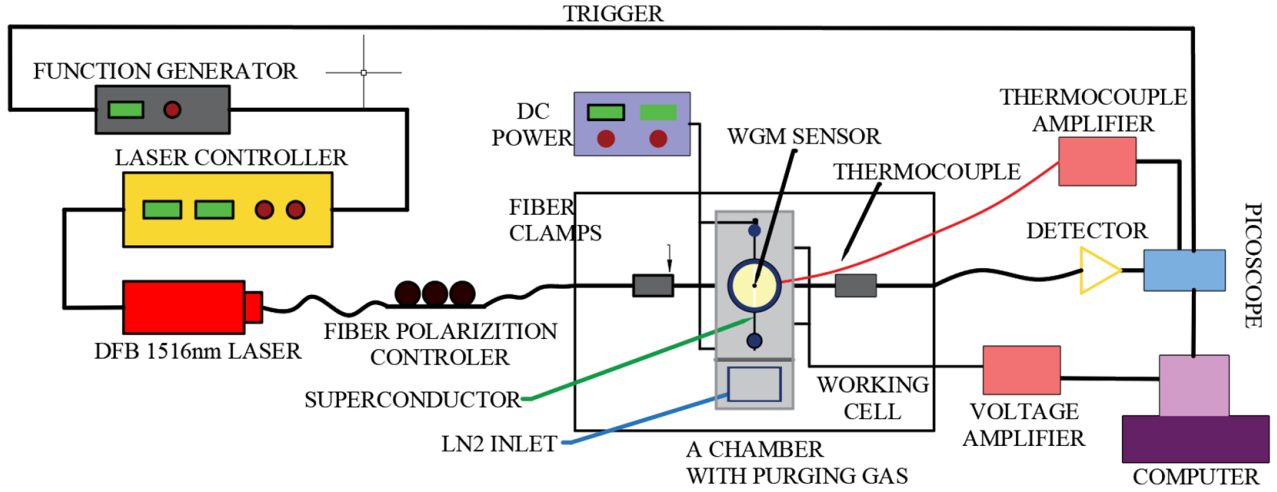


Figure 1. Experimental setup.

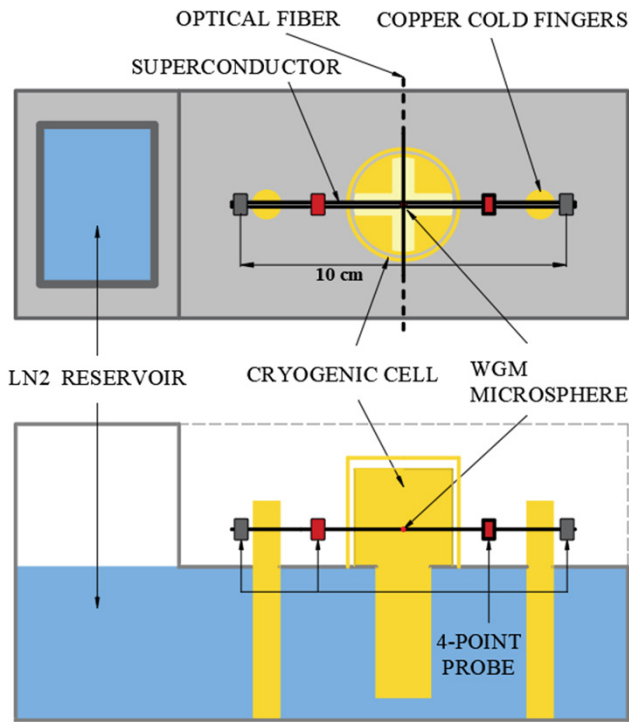


Figure 2. Sketch of the cryogenic cell and 4-point probe measurement.

3. Results and discussion

Figure 4 shows the calibration curve between the wavelength and current when the laser diode controller is at room temperature (298 K). An optical spectrum analyzer (ANDO AQ6317B) was used to calibrate the laser tuning. The resolution of the analyzer is 0.015 nm. The tunable range of the distributed feedback laser is approximately 1 nm of wavelength with applied current about 80 mA at room temperature. Repeated testing results at same temperature indicate that the laser works stably with negligible uncertainty. It should be noticed that this is a 2nd order nonlinear curve to avoid linear offset during calibration.

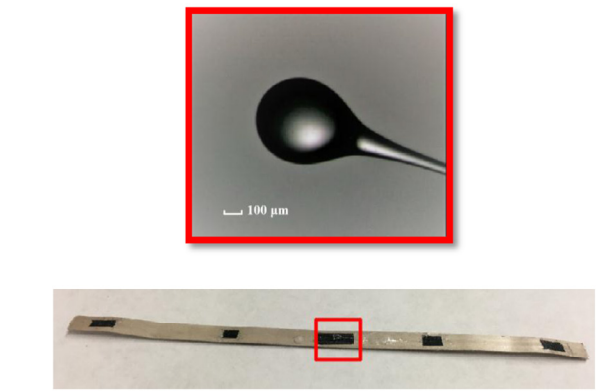


Figure 3. Photo of the HTS BSCCO tape and silica microsphere used in the present experiment.

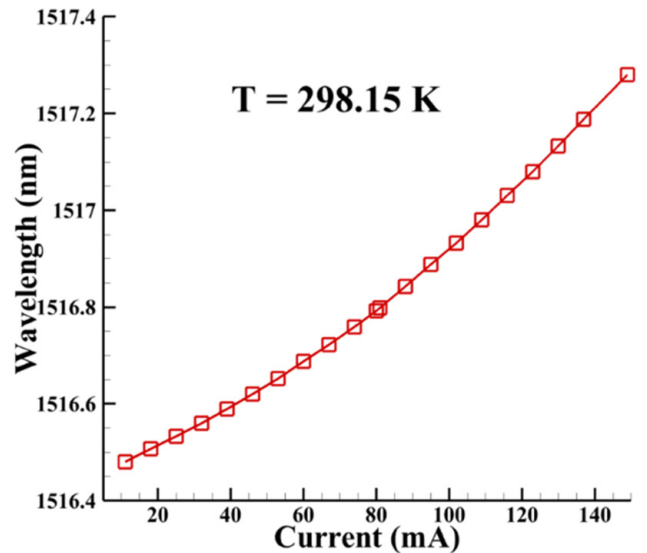


Figure 4. Calibration of the DFB laser at room temperature.

Figure 5 compares the two resonance spectra of the microsphere at 112 K and 113 K, respectively. As the temperature rises by 1°, the resonance peak (i.e. the valley in the optical fiber signal) is red-shifted by 0.0039 nm. The value of 3.9 pm

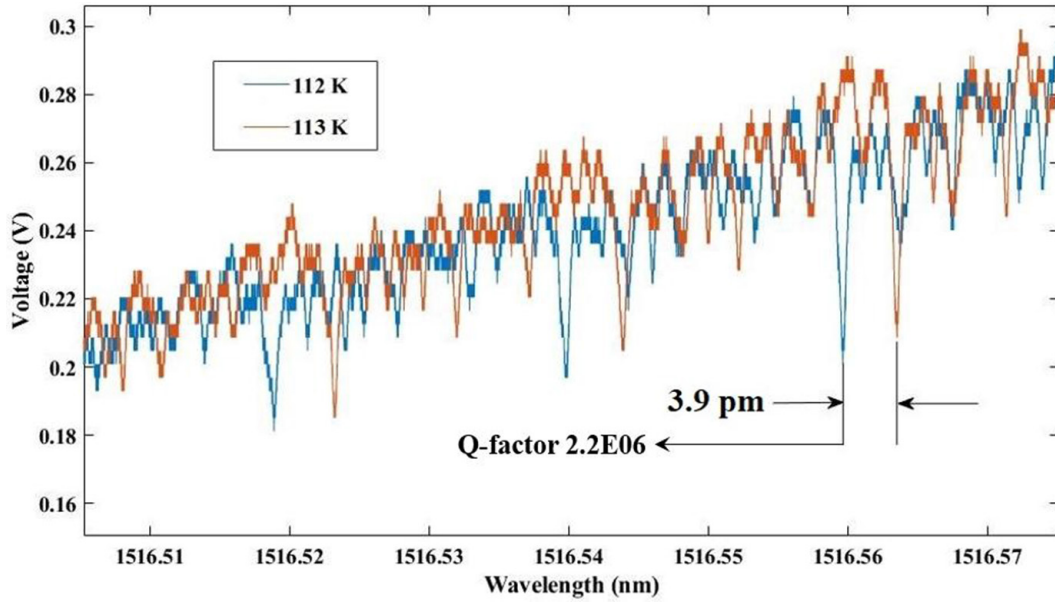


Figure 5. The measured resonance spectra at two different temperatures.

K^{-1} is the measured sensitivity of the sensor at temperature 112–113 K. Figure 6 plots the measured sensitivity of the silica microsphere in a broad low-temperature range. It is seen that the sensor sensitivity increases from 3.6 pm K^{-1} to 5.5 pm K^{-1} as temperature increases from 105 to 150 K. The sensitivity can be fitted by a quadratic equation as follows:

$$\frac{d\lambda}{dT} = (4.454 \pm 0.06) \times 10^{-5} T^2 + (3.07 \pm 0.11) \times 10^{-2} T - (0.1001 \pm 0.18). \quad (1)$$

Repeated tests were conducted and the reproducibility uncertainty is less than the sensitivity uncertainty provided in equation (1), i.e. 0.18 pm K^{-1} . As Ma *et al* [10] discussed, WGM sensor responds very fast and its sensitivity is determined by the thermal expansion coefficient, $\alpha = (dD/dT)/D$, and the thermo-optic coefficient, $\beta = (dn/dT)/n$, of the resonator material, i.e. $d\lambda/dT = (\alpha + \beta) \lambda$. Figure 6 compares the measured sensitivity with the analytical sensitivity based on the material properties of silica in the literature [25, 26]. The difference between the analysis and measurement is less than 5%. It should be mentioned that the thermo-optic coefficient in Leviton and Frey [25] was defined as dn/dT , and it should be corrected by a factor $1/n$ in the sensitivity analysis.

The Q -factor of a WGM resonator is calculated by:

$$Q = \frac{\omega_0}{\Delta\omega} = \frac{f_0}{\Delta f}, \quad (2)$$

in which $f_0 = \omega_0/2\pi$ is the resonance frequency, and Δf is the full width at half maximum (FWHM) of a resonant band. As indicated in figure 5, the Q -factor of the microsphere was measured as 2.2×10^6 at 112 K. Other measured Q -factors included 2.8×10^6 at 118.5 K and 3.5×10^6 at 125 K. The Q -factor varied in the range of $2 - 5 \times 10^6$ in this study. At room temperature, the reported Q -factor of silica microspheres could reach to the order of 10^{10} [1]. The drop of Q -factor at low temperature can be attributed to the degrading

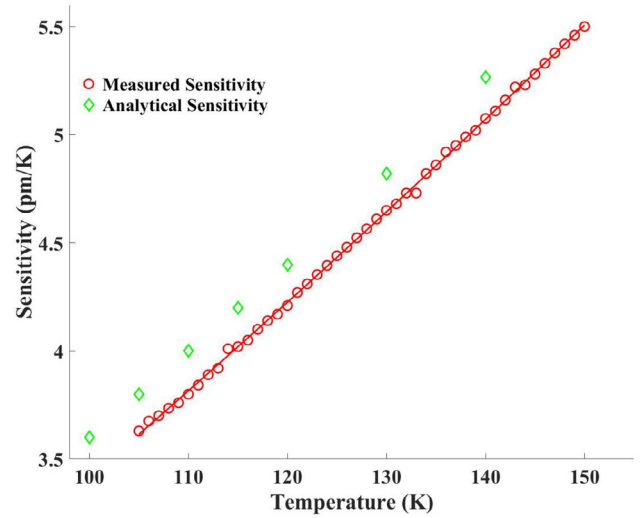


Figure 6. The measured sensitivity curve of the WGM sensor.

of the sphere quality and the loosening of coupling between fiber taper and microsphere during the cooling down process.

The temperature resolution of a WGM sensor can be calculated by [10]

$$\Delta T_{\min} = \frac{\Delta\lambda_{\min}}{d\lambda/dT}, \quad (3)$$

in which $\Delta\lambda_{\min}$ is the minimum change in wavelength measurement. $\Delta\lambda_{\min}$ depends on the data acquisition resolution defined as $(\Delta\lambda)f_s/S$. In the present measurement, the Picoscope sampling rate S is 200 MHz, the tuning range $\Delta\lambda$ of the excitation laser is 0.2 nm, and the tuning frequency f_s is 100 Hz, resulting in a small value of 1×10^{-7} nm. $\Delta\lambda_{\min}$ is also affected by another two factors, the DFB laser linewidth (2 MHz, equivalent to 0.0156 pm) and one-tenth of the WGM resonance linewidth which is defined as $\lambda/(10Q)$ and estimated around 10^{-4} nm. Thus, the resonance linewidth is

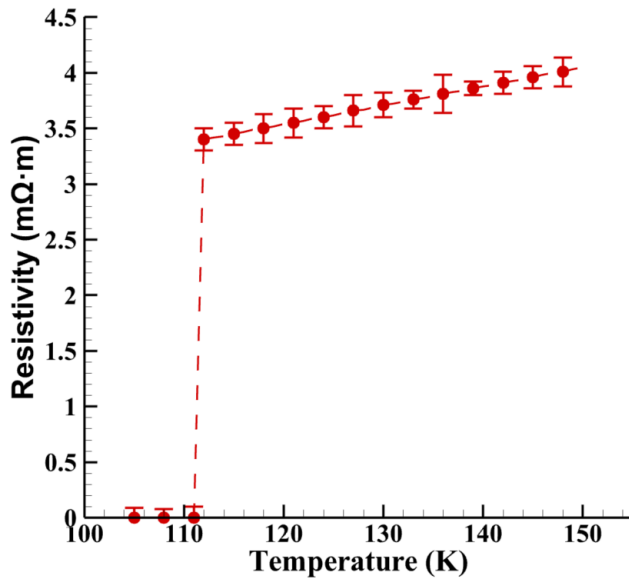


Figure 7. The variation of superconductor tape resistance versus temperature.

the major limit, and $\Delta\lambda_{\min}$ is 10^{-4} nm in the present measurement. With a sensitivity of the WGM sensor of 3.9 pm K^{-1} at 112 K, the resolution of the present critical temperature measurement is about 0.03 K and the uncertainty of the WGM sensor is then mainly affected by the calibration error, which is 0.5 K because we used a calibrated T-type thermocouple. Thus, the present WGM sensor has an accuracy ± 0.5 K. It should be mentioned that, if the sensor is to be calibrated by a highly accurate thermistor, its accuracy could reach the level of its resolution. The WGM sensor provides ultrafine resolution and sensitivity at low temperature and could be used to characterize the critical temperature of superconductivity.

We use the voltage of the superconductor tape measured by the 4-point probe to calculate the electrical resistance. Figure 7 shows the resistance variation versus temperature. It is seen that the resistance increases as the temperature rises when the temperature is above 112 K. When the temperature drops below 112 K, the resistance in the superconductor tape suddenly drops to zero. The phenomenon indicates the occurrence of superconductivity at/below critical temperature 112 ± 0.5 K. Although this value is 2 K above the factory-specified critical temperature (i.e. 110 K) [23], the current measurement has much better accuracy and smaller uncertainty. The manufacturer (Sumitomo Electric) did not directly specify measurement uncertainty; it is estimated to be ± 5 K from the resistance-temperature graph in the manual provided by the manufacturer [23].

Table 1 compares the presently measured resistances with the factory-specified data [23] at several temperatures. The difference is about 6%. The resistance uncertainty in the present measurement could be attributed to two factors: the removal of the silver layer in the tape probing locations and the minimal resistance with a short tape used (0.1 m). It should be mentioned that industrial measurement in superconductivity generally requires a bulky facility, expensive equipment, and an extremely long superconductive tape (~ 500 m). Thus,

Table 1. Comparison of data.

Current experiment		Factory specified	
Temperature (K)	Resistivity ($\text{m}\Omega \cdot \text{m}$)	Temperature (K)	Resistivity ($\text{m}\Omega \cdot \text{m}$)
115 ± 0.5	3.45 ± 0.1	115 ± 5	3.275 ± 0.1
120 ± 0.5	3.54 ± 0.16	120 ± 5	3.35 ± 0.1
130 ± 0.5	3.71 ± 0.11	130 ± 5	3.5 ± 0.1
150 ± 0.5	4.05 ± 0.15	150 ± 5	3.8 ± 0.1

the present experimental system can determine the critical temperature of superconductivity with higher accuracy, less expense, and smaller facility. Such a WGM sensing system could further be developed for on-chip sensing for monitoring superconductor temperature change as recently demonstrated by Frenkel and Guo [24] in which a polymer coated WGM microsensor was used for on-chip temperature monitoring of an electrical wire operating at low temperature.

4. Conclusions

A fused silica microsphere coupled to a fiber taper was placed onto a short superconductor tape to determine the critical temperature at the onset of superconductivity and monitor the *in situ* temperature of the superconducting tape. The occurrence of superconductivity was observed by the 4-point probe technique. The resonance quality and sensitivity of the WGM sensor were examined in the cryogenic temperature range. The measured Q -factor of the silica microsphere at low temperature is in the high order of 10^6 , degraded as compared to the extremely high orders (10^8 – 10^{10}) at room temperature reported in the literature. The sensor sensitivity is measured to vary from 3.6 pm K^{-1} to 5.5 pm K^{-1} corresponding to the temperature range from 105 to 150 K. The sensor curve can be well fitted by a quadratic expression. The resolution of temperature measurement is determined to be 0.03 K around 110 K. Via observing the superconductor resistance variation versus temperature, the critical temperature of the high-temperature DI-BSCCO superconductor is found to be 112 ± 0.5 K, close to the factory-specified value of 110 K. However, the factory specified value has a much larger measurement uncertainty. The measured resistance variation with temperature for the short (10 cm long) HTS tape also matches well to the factory-provided graph which was determined from a very long tape. The study demonstrated the WGM microsensor's feasibility and accuracy to measure and monitor the temperature of superconductor wires. The current experimental system has apparent advantages of a small device, short superconductor tape, ultrafine resolution, high accuracy, and cost-effectiveness.

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