



# **WHISPERING-GALLERY MODE SILICA SENSORS FOR SUPERCONDUCTIVE TAPE TEMPERATURE MEASUREMENT**

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## **ABSTRACT**

Optical whispering-gallery mode microsensors have been proven to measure temperature with high accuracy and sensitivity. In this work, we put a silica microsphere which is coupled to a fiber taper on a superconductive tape to characterize the electrical conductivity variation against temperature. The superconductive tape was placed inside a chilling chamber. Liquid nitrogen is used to make the air temperature in the lab-made chamber lower than the critical temperature ( $\sim 110$  K) of the high-temperature superconductor. A distributed feedback laser at 1516 nm is used to excite the resonance in the microsphere. The optical signal, particularly the resonance wavelength shifts, is recorded by a Picoscope corresponding to temperature increment. Meanwhile, a T-type thermal couple is used to calibrate the temperature data of the superconductive tape to obtain the relationship between temperature and resonance wavelength shifts. The electrical resistivity of the superconductor is measured by the 4-point probe method. The sensitivity of the optical sensor is determined by the thermal expansion and thermo-optic coefficients of the silica material. The measured sensitivities vary from 3.6 pm/K to 5.5 pm/K. The quality factor of the resonator under low temperature reaches  $2.2 \times 10^6$ . The present study has demonstrated the potential of WGM microsensors for determining the critical temperature and monitoring the temperature variation of superconductors.

**KEY WORDS:** Whispering-gallery mode, optical sensors, temperature measurement, superconductor, critical temperature, optical resonance, wavelength shift

## **1. INTRODUCTION**

In the past decades, research on optical whispering-gallery mode (WGM) phenomena in dielectric micro-resonators have been intensively studied and developed in many areas, such as molecular detection [1-3], measurement of temperature [4-7], laser stabilization [8], and miniature sensors [9,10]. Compared to traditional sensors, optical WGM sensors have the advantages of small volume and high-resolution due to high-quality (Q) factor. The WGM resonator made of dielectric material can be any circular shape that can generate total internal reflection and circulation of optical waves propagation. A major sensing principle that was explored is resonant frequency shift. Due to extremely high Q-factor, high resolution measurements and ultrafine sensitivity can be realized. Pure silica optical WGM sensors were demonstrated having good temperature measurement capability at room temperature and cryogenic regimes [7]. Because of the excellent and stable performance of the silica WGM sensor at cryogenic and low temperatures, it has a brilliant future for applications at these temperature regimes.

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 application of

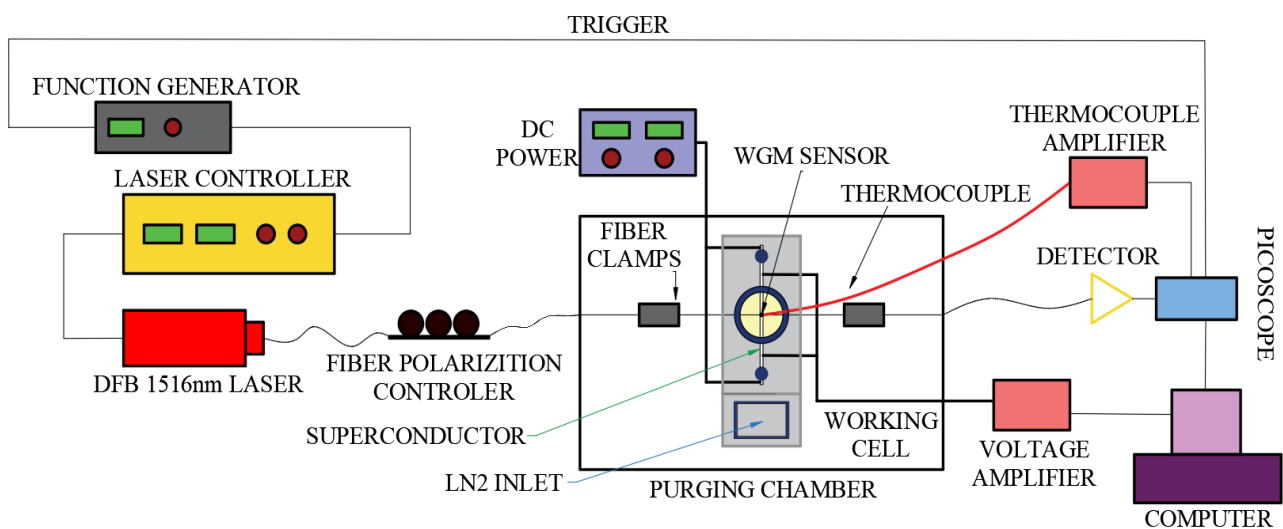
superconductivity, scientists have been working for over a century to find superconductor materials that have a higher critical temperature. In the recent decade, the ceramic material was found to have a critical temperature above 90 K [11]. Such superconductors are termed the high-temperature superconductor (HTS). Nevertheless, the operation temperature is still in the low temperature regime. If the critical temperature could be raised to room temperature, it would lead to industrial revolutions.

There are two typical methods for demonstrating superconductivity. The first one is the Meissner effect [12], a magnet levitating above a superconductor, which is cooled down to 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 method. It can be observed that the resistance of a superconductor drops to zero when the operating temperature is below the critical temperature. The facility used in the traditional measurements is bulky and the superconductor wire used is very long (up to 500 m) [13].

This study aims to demonstrate a small facility for characterizing critical temperature and monitoring temperature variation in a short, small superconductor tape. As Frenkel and Guo [14] have recently demonstrated that a polymer coated WGM microsensors can be used for on-chip temperature monitoring of electrical wires operating at low temperature. In this study, we use WGM silica microsensors to determine the critical temperature of a superconductor. Compared with other sensors, WGM silica sensors have the advantages of small size, high resolution, and stable physical properties at low temperature conditions. A cryogenic chamber is designed to achieve a thermally stable environment between 100 – 150 K. An experimental device for placing a short superconductor tape and coupling with the optical WGM sensor was built. The technology previously used to prevent the effects of frost and gas flow interference was also applied in this experiment. The laser and T-type thermocouple were calibrated before the experiment. Superconductor resistance, WGM sensor resonance spectra, and thermocouple voltage are recorded at the same time. Finally, the feasibility of using WGM sensor to observe superconductive phenomenon around critical temperature is determined.

## 2. EXPERIMENTAL SETUP

The experimental setup is shown in **Fig. 1**. There are five main components involved in this system: an optical system, purging chamber, superconductive tape with a WGM sensor, 4-point probe measurement devices, and data acquisition system.

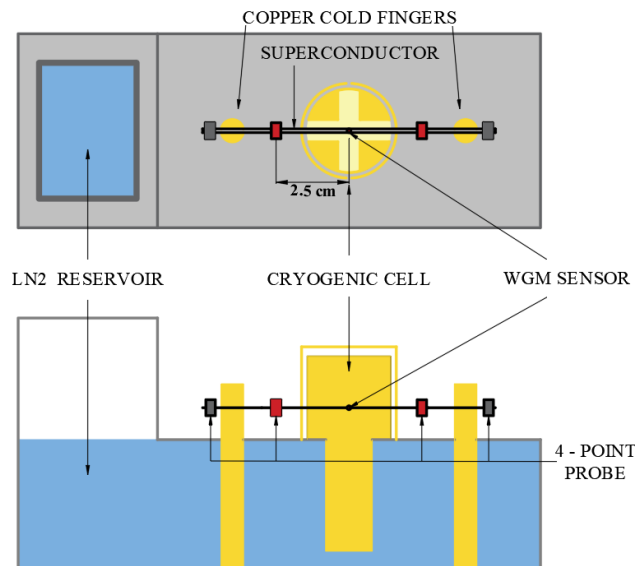


**Fig. 1** Experimental setup

The optical system includes a 1516 nm distributed feedback laser (NELNLK1556STG), a lens that focuses light into the optical fiber, and a fiber taper for exciting the WGM resonances. A function generator (Agilent 33220A) is used to set a ramping with an amplitude of 3.5 V and frequency of 100 Hz, and the temperature and the intensity of the laser are controlled by a laser controller (light wave LCD-3724 B).

The cryogenic chamber is shown in **Fig. 2** was hand-built to maintain a thermally stable space and prevent frost interference at low temperature. There are some inlets and outlets on the side of the chamber, which are used to fill liquid nitrogen, arrange fiber taper connection, thermocouple inlet and resistance measurement cables. The cryogenic cell cools the superconductive tape to a temperature below the factory-specified critical temperature. A silica microsphere is placed onto the tape and coupled to a fiber taper. The main structure of the cell is made of aluminum and covered with a thermal insulation layer. Liquid nitrogen (LN2) is poured from an inlet and stored in the small reservoir. A partially hollow copper cylinder is placed in the middle of the cell, and the hollow portion not in the reservoir used to enhance the thermal inertia and experimental environment stability is the position to place the tape and resonator. A larger hollow copper cylinder and a PDMS lid are put on the cell to prevent temperature and gas fluctuations. Two copper rods are inserted into the reservoir to align the superconductive tape.

In the present experiments, we use a short HTS tape as the object to be measured. 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 tape has a width of 4 mm, a thickness of 0.2 mm, and a length of 10 cm. As shown in **Fig. 3**, some parts of the silver layer are removed such that the silica microsphere is in contact with the bare tape. Other exposed areas will be connected to cables which are used to get current and voltage data to calculate the resistance of superconductor.



**Fig. 2** Cryogenic chamber



**Fig. 3** HTS BSCCO tape used in the experiment

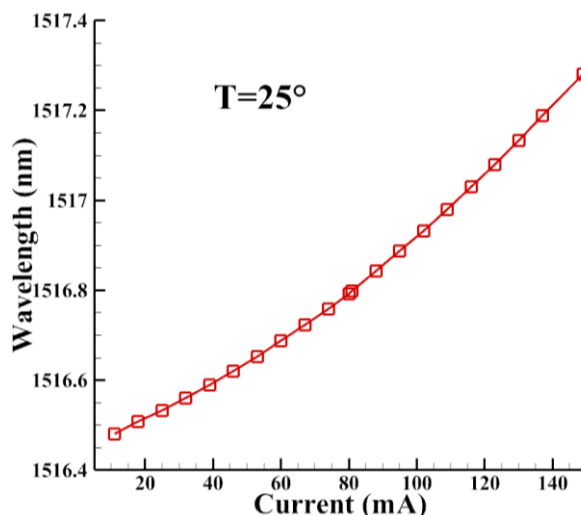
The WGM microsensors consisted of the light coupling taper, and the pure silica microsphere is placed in the middle area of the cryogenic cell. The WGM resonator is a microsphere fused from silica single-mode bare fiber (Corning SMF-28), and the diameter of the microsphere used in this study is 525  $\mu\text{m}$ . The fiber taper also used the same material and was fabricated via the heat-pull method. Specific steps of fabrication and quality examination are described in ref. [4].

The optical signal is detected by a photodetector (Thorlabs PDA400) and then recorded by a digital oscilloscope (Picoscope 3206B). The bandwidth of Picoscope is 200 MHz, and the sampling rate is 500 MS/s. The Picoscope has two input channels and a trigger input. The photodetector is plugged into channel A, and the thermocouple signal is plugged into channel B. Due to the voltage of the T-type thermocouple is very low, an amplifier (Omega Omni Amp IIB) is used. To get superconductor resistance signals simultaneously, the DAQ cards which are to plug voltage cables (National Instrument) are equipped to the computer. Waveform calibrations were done by an optical spectrum analyzer (ANDO Electronics AQ6317B), and this technique has been discussed in previous work from the authors' group [4].

### 3. RESULTS AND DISCUSSION

The purging chamber used to keep low temperature environment stability has proven feasible in our previous work [14]. When 4 liters of LN2 is slowly poured in 20 minutes, the temperature of the LN2 reservoir which is placed beneath the purging chamber can be stabilized at 100K for about 10 minutes. Then the temperature is warm up to 150 K at a rate of 1 K every 10 seconds. This capability gives us enough time to record data.

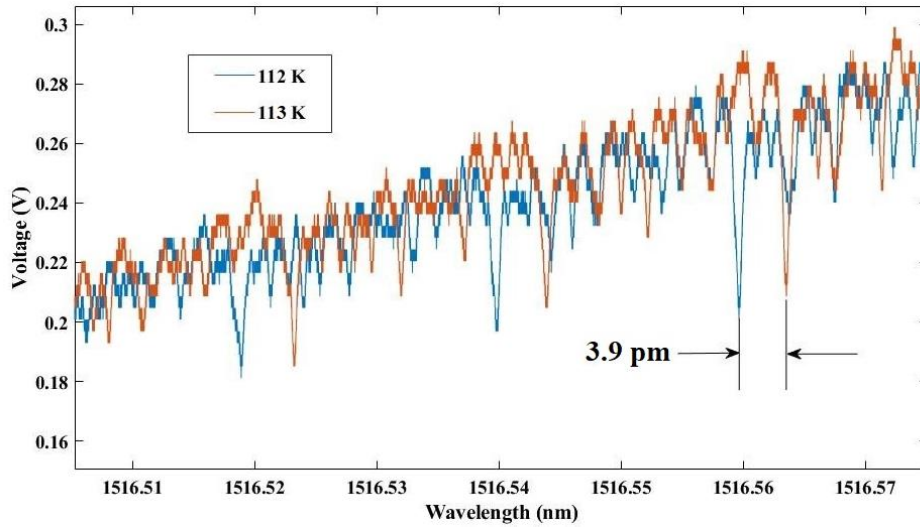
**Fig. 4** shows the curve between the laser wavelength and the current in the laser diode controller at room temperature. An optical spectrum analyzer (ANDO AQ6317B) is used to calibrate the laser tuning. The resolution of the analyzer is 0.015 nm. Repeated testing at same temperature indicates that the uncertainty is negligible. The resonance peak of optical spectra is found by a relationship with Picoscope data and the calibrated curve. Notice that it is a 2<sup>nd</sup> order nonlinear curve to avoid linear offset during the calibration.



**Fig. 4** Calibration of the DFB laser at room temperature

The present experiment is focused on the performance of a WGM sensor at cryogenic temperature, especially around superconductor critical temperature. It is necessary to fill the chamber with nitrogen gas for 30 minutes before pouring LN2. This step is to avoid the frost caused by humidity. If humidity is retained, in low temperature condition, ice will be generated between fiber taper and resonator coupling, either destroying the surface of the resonator or breaking the taper. To obtain accurate temperature data for comparison, a T-type thermocouple was

calibrated at 0 °C and 100 °C. A reference table (N.I.S.T Monograph 175) was used to confirm the offset of the thermocouple amplifier.



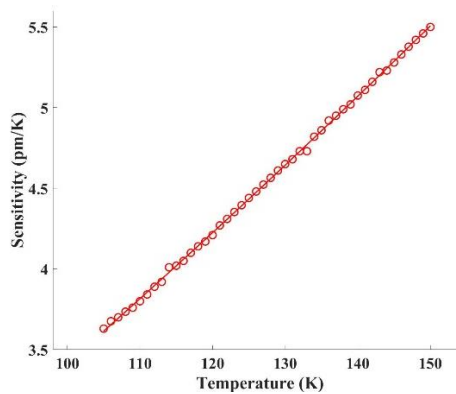
**Fig. 5** WGM resonance spectra at different temperatures

After all, preparations are completed, the system is cooled down to about 100 K. When the thermocouple signal indicates that the working environment has reached a stable state, optical signals, electrical resistance, and temperature data are simultaneously collected. To ensure thermal equilibrium of all measurement devices, data collection is done every minute.

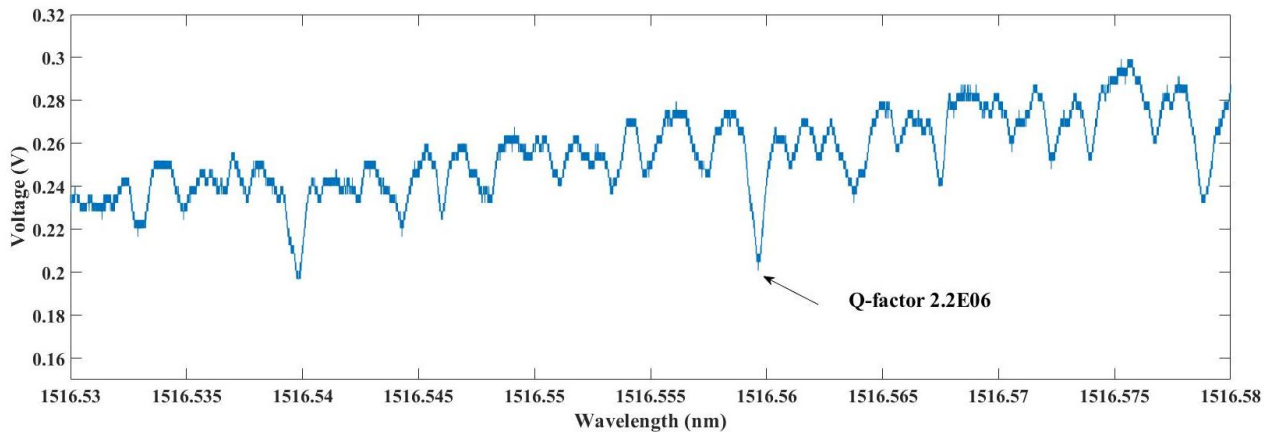
The recorded data covers a temperature range from 105 K to 150 K. **Fig. 5** shows and compares the resonance spectra at 112 K and 113 K. It can be seen from the figure that as the temperature rises, the peak generated by the resonance is red-shifted by 0.0039 nm. This distance is also defined as the sensitivity of the sensor. In **Fig. 6**, the sensitivity is measured for a wide temperature change from 105 K to 150 K. It is seen that the measured temperature sensitivity increases from 3.6 pm/K to 5.5 pm/K as temperature increases and can be expressed by a quadratic equation,

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

where  $\lambda$  is the wavelength of the laser. As Ma et al. [7] discovered, the sensitivity is determined by the thermal optical and expansion coefficients of the resonator material. These properties are temperature-dependent. The uncertainty of temperature measurement is estimated  $\pm 0.5$  K which is determined by the sum of the thermocouple, connected cables, and data acquisition system uncertainties.



**Fig. 6** The measured temperature sensitivities



**Fig. 7** Q-factor at 112K

Meanwhile, the extent of energy dissipation of WGM in the resonator is commonly expressed by the Q-factor, which is an important parameter for comparing the performance capabilities of different resonators [15]. It also determines the maximum potential resolution of the sensors as discussed by Ma et al. [7]. By Fourier transform, the Q-factor is calculated by:

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

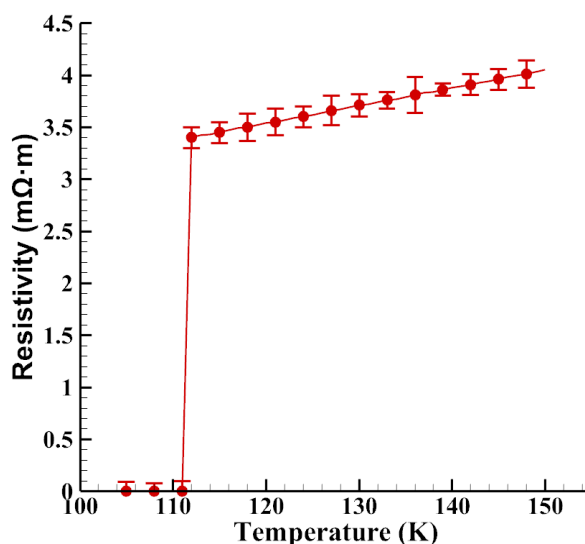
where  $f_0 = \omega_0/2\pi$  is the resonance frequency, and  $\Delta f$  is the full width at half maximum (FWHM) of the resonant band. In fact, through previous studies [7], the actually-measured value of Q-factor increases with increasing temperature. This is because of the fiber taper is pre-coupled to the WGM resonator at room temperature. During the cooling down process, the volume of the resonator becomes smaller, which causes the fiber taper tension to become smaller, and the near-field distance is changed, resulting in energy loss. At 112 K, the optical resonance spectrum for the silica microsphere used in this study is shown in **Fig. 7**, from which the Q-factor of the microsphere is measured as  $2.2 \times 10^6$ .

The temperature resolution of a WGM sensor can be calculated by [7]

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

where  $\Delta\lambda_{\min}$  is the minimum change in wavelength. The DFB laser has a laser linewidth 0.0156 pm. At 110 K and 150 K, the sensitivity is obtained by equation (1), 3.6145 and 5.5071 pm/K, respectively. So, the temperature resolution is 4.3 mK and 2.8 mK for the temperature at 105 K and 150 K, respectively.

The voltage of superconductive tape measured by the 4-point probe method is calculated by Ohm's law to get the electrical resistance of the superconductor tape. **Fig. 8** shows the resistance variation vs. temperature. It clearly shows the occurrence of superconductivity at/below  $112 \pm 0.5$  K. This value is then determined as the critical temperature. **Table 1** compares our experimental results with the superconductor material data (extracted from manual figures) provided by Sumitomo Electric [13]. The difference in critical temperature is  $1.8 \pm 0.37$  % and in resistance is 6.25 %. It is demonstrated that the present experimental system can accurately measure superconductor resistance and determine the critical temperature for a short conductor tape at cryogenic temperatures. Errors in the present experiment can be attributed to the following reasons. First, regarding the resistivity, since the superconductive tape resistance is minimal, measurement data changed when part of the surface silver is removed. Second, the difference in critical temperature is because we cannot put the WGM sensor and the thermocouple at the same point of the tape. Although the position of the thermocouple is as close as possible to the WGM sensor, it still causes a slight difference in temperature.



**Fig. 8** Resistance of superconductive tape

**Table 1** Comparison of data at critical temperature.

	<b>Current experiment</b>	<b>Factory specified</b>	<b>The difference (%)</b>
<b>Critical Temperature (K)</b>	$112 \pm 0.5$	$110 \pm 5$	$1.8 \pm 0.37$
<b>Resistivity (mΩ·m)</b>	$3.4 \pm 0.1$	$3.2 \pm 0.1$	6.25

The industrial measurement method in superconductivity is usually to cool an extremely long superconductive tape. The cost of the material is high, and the equipment facility is bulky. However, our method can be applied to on-chip sensing for dynamic monitoring. It is cost-effective, and the device is tiny and portable.

#### 4. CONCLUSIONS

A silica microsphere resonator which is coupled to a fiber taper is placed on a short superconductive tape to determine the critical temperature and monitor the occurrence of superconductivity. We built a cryogenic system to cool down the tape stably down to 100 K. Nitrogen gas is purged to avoid the frost caused by humidity before the experiment. A hollow copper cylinder is built in the chamber to prevent internal gas flow interference to optical signals. The silica microsphere is fused from a Corning SMF-28 bare fiber.

Optical results analysis shows significant resonance wavelength shifts with varying temperature. In the cryogenic temperature range, the measured silica sensor sensitivity varies between 3.6 pm/K and 5.5 pm/K, depending on the temperature. The measured Q-factor at the low temperature reaches  $2.2 \times 10^6$ . The resolution of our sensor can reach 2.8 mK at cryogenic temperatures. The superconductor resistance is measured by the 4-point probe method in the range of 105 to 150 K. From the calibrated WGM sensor, the critical temperature of the measured superconductor is found to be  $112 \pm 0.5$  K, less than 2.2% difference with the factory-specified value. The measured resistance from the 10 cm long HTS tape is  $3.4 \pm 0.1$  mΩ·m, about 6 % difference from the factory-specified value. The results proved the WGM microsensors' feasibility and accuracy to measure and monitor the temperature of superconductor tapes. The current experimental system has advantages of small devices, short superconductor tape, ultrafine resolution, high accuracy, and cost-effectiveness.

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