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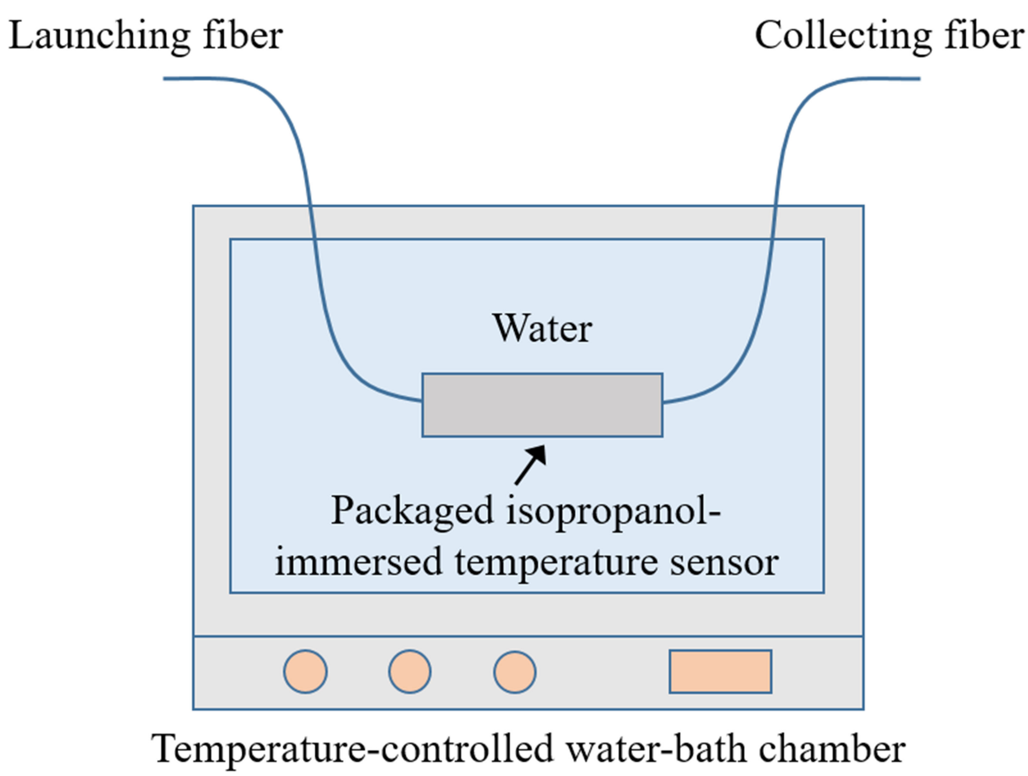

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Temperature Sensor Based on Microbottle Resonator Immersed in Isopropanol

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Abstract: Temperature measurement of an isopropanol-immersed microbottle resonator is demonstrated. The theoretical analysis indicates that the resonance wavelength blue shifts as the increase of temperature, and the temperature sensitivity increases with the decrease of resonator dimension, which are also demonstrated by experimental results. The temperature sensitivity enhancement of up to 4.6 times relative to the sensor in the air is achieved, which could be benefit from the high thermal refraction coefficient of isopropanol. Furthermore, a robust package has also been proposed to make the present sensor more practically.

Index Terms: Microresonator, temperature sensor, isopropanol.

1. Introduction

In recent years, whispering gallery mode (WGM) microresonators with high Q factor and small mode volume have attracted considerable attention, and have shown enormous potential for application in modern optics [1]–[7]. The light would be restrict in WGM microresonator while the phase matching condition is satisfied, forming resonance dips in the optical spectrum [8], [9]. Until now, various sensors based on WGM microresonators have been demonstrated since the wavelength of the resonance dip can be easily adjusted. For example, the resonant wavelength shifts with the change of the refractive index (RI) of the surrounding environment. By monitoring this shift, the detection of the RI of gas or liquid could be realized [10]–[12]. In addition, due to thermal refraction effect and thermal expansion effect, which are caused by the change of temperature, a variation of the RI as well as the dimension of the microresonator are also able to introduce a resonance wavelength shift, resulting in the realization of temperature sensing. For instance, Nemova *et al*. proposed the use of a silica microbottle resonator as a temperature sensor theoretically [13]. Guo *et al*. measured the resonance wavelength shift against temperature changes for silica beads with different diameters [14], and Xiong *et al*. demonstrated a robust temperature sensor based on packaged silica microsphere resonator [15]. However, the corresponding sensitivity of microresonators based on silica is restricted to around 10 pm/°C, which is attributed to that the thermal refraction coefficient (1.19×10^{-5}/°C) and thermal expansion coefficient (5.5×10^{-7}/°C) of this material are extremely low [16]. In order to improve the sensitivity, sensitive medium with higher thermal refraction coefficient, such as PDMS (thermal refraction coefficient of -1.0×10^{-4}/°C) or PMMA (thermal refraction coefficient of -8.5×10^{-5}/°C), has been used to cover the surface of the silica microresonator [17], [18]. However, the thickness of the sensitive medium is difficult to accurately control, and the coating process brings complicated operations.

Isopropanol is a transparent liquid with high thermal refraction coefficient (-4.5×10^{-4}/°C), and has been demonstrated as an excellent material to improve the temperature sensitivity of silica microcoupler [19]. In this paper, a packaged temperature sensor based on tapered fiber coupled microbottle resonator encapsulated in a glass tube filled with isopropanol is proposed. The sensitivity enhancement, as well as the dependence of the sensitivity on resonator dimension are discussed.

2. Theory and Simulation Analysis

Microbottle resonator (MBR) is selected for its easy fabrication and excellent package property due to that both sides of the resonator are fiber handles. As is well known, the modes in MBR could be characterized by azimuthal mode number m, radial mode number p and axial mode number q, which represented the field distributions around resonator circumference, at radial direction and along the bottle axis, respectively. Accordingly, the resonant wavelength of a MBR with maximum radius R_0 could be expressed as [20]

$$\lambda_{mpq} = 2\pi n_{eff} \left[\left(\frac{U_{mp}}{R_0} \right)^2 + \left(q + \frac{1}{2} \right) \Delta E_{mp} \right]^{-1/2} \tag{1}$$

where $U_{mp} = m + \alpha_p (m/2)^{1/3} + (3/20)\alpha_p^2 (m/2)^{-1/3}$ and $\Delta E_{mp} = 2U_{mp}\Delta k/R_0$. Δk and α_p represent the curvature of the resonator and the pth root of Airy function, respectively. n_{eff} is the effective refractive index, which could be calculated as follows for a MBR immersed in isopropanol:

$$n_{eff} = n_{silica} \cdot \eta_{silica} + n_{isopropanol} \cdot \eta_{isopropanol} \tag{2}$$

where n_{silica}, $n_{isopropanol}$, η_{silica} and $\eta_{isopropanol}$ represent the RI of silica and isopropanol, as well as the fraction of light energy traveling in the corresponding medium, respectively. The change of temperature induced the variation of the RI of both silica and isopropanol, as well as the variation of resonator dimension. The last item could be neglected as the thermal expansion coefficient of silica is much smaller than the thermal refraction coefficient of both silica and isopropanol. Furthermore, the change of thermal expansion coefficient caused by the crystal form transformation is also neglected because it always happens in temperature larger than 100 °C, which has exceed the temperature range considered in this paper. According to Eq. (1), for a specific mode of microbottle resonator, the shift of resonance wavelength λ_{mpq} affected by the temperature is proportional to the variation of n_{eff}. Thus, one can obtain

$$\frac{d\lambda}{dT} \propto \frac{dn_{eff}}{dT} = \frac{dn_{silica}}{dT} \cdot \eta_{silica} + \frac{dn_{isopropanol}}{dT} \cdot \eta_{isopropanol} \tag{3}$$

Accordingly, the change of the effective refractive index n_{eff} with temperature (effective thermal refraction coefficient for short) depends on the thermal refraction coefficients and the fraction of light energy of silica and isopropanol. As reported in Ref. [17], the effective thermal refraction coefficient, i.e., temperature sensitivity, is negative when the thickness of PDMS coated on the surface of silica microresonator is larger than 0.55 μm, let alone the silica microresonator immersed in isopropanol. Furthermore, as the dimension of the MBR increases, the confinement ability of the resonator to the light increases and $n_{isopropanol}$ decreases, resulting in a reduction of the absolute value of sensitivity.

In order to simulate the characteristic of the proposed temperature sensor, a model represents the cross-section of tapered fiber coupled microbottle resonator immersed in isopropanol was constructed and shown in Fig. 1(a). To realize the simulation of temperature variation, the RI of isopropanol under temperature range from 20 °C to 40 °C was altered, which was calculated

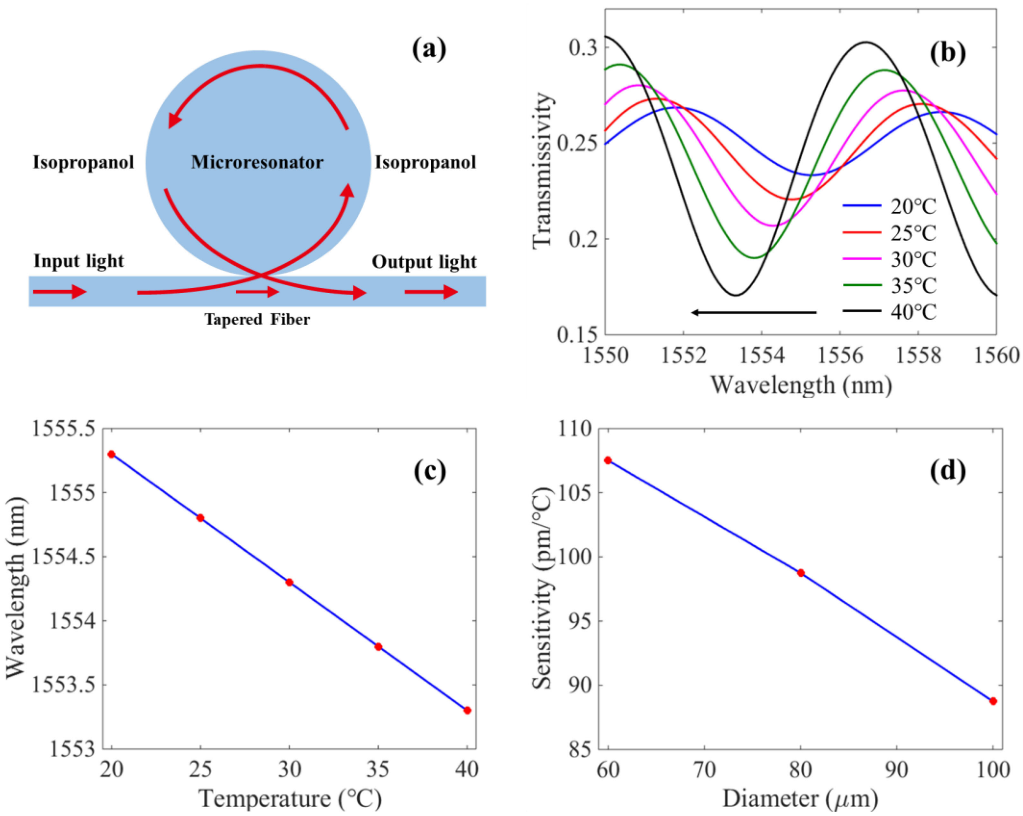

Fig. 1. (a) Schematic cross-section of tapered fiber coupled microbottle resonator immersed in isopropanol. (b) Resonance spectra of microbottle resonator immersed in isopropanol under different temperature with $R_0 = 40$ μm. (c) The relationship between the resonant wavelength and the temperature. (d) Temperature sensitivity as a function of maximum diameters of microbottle resonator.

according to the thermal refraction coefficient and the known RI under 25 °C, while the thermal effect of microresonator was neglected. A tapered optical fiber with diameter of 1 μm was used to couple light evanescently into and out of the microresonator. The RI of the silica microresonator and tapered fiber were fixed at 1.444, and the distance between them was set to zero to provide a stable arrangement.

The model was defined, solved, and analyzed using the commercial software COMSOL 5.3 Multiphysics which is based on Finite Element Method (FEM). The 2-D simulation model is selected to reduce the calculation time and the burden of computer, on the basis that it is adequate for the analysis. The port boundary was set at the input and output of the tapered fiber. The continuity boundary condition was employed as the interior boundaries, and the perfectly matched layer (PML) boundary condition was introduced to avoid back reflection from the exterior boundaries. Simulation were run with a controlled mesh size to make efficient use of computer memory.

Fig. 1(b) exhibits the simulation result of the microbottle resonator with diameter of 80 μm under different temperature, i.e., different RI of isopropanol. As the increase of temperature, the resonance wavelength blue-shift due to the negative effective thermal refraction coefficient. Simultaneously, the resonance getting stronger which could be attribute to the increased RI difference between the resonator and isopropanol. The linear fitting results illustrated in Fig. 1(c) indicate that the temperature sensitivity for a resonator with diameter of 80 μm is 98.75 pm/°C. Furthermore, according to Fig. 1(d), the temperature sensitivity decreases with the increase of maximum resonator diameter, which has been predicted theoretically.

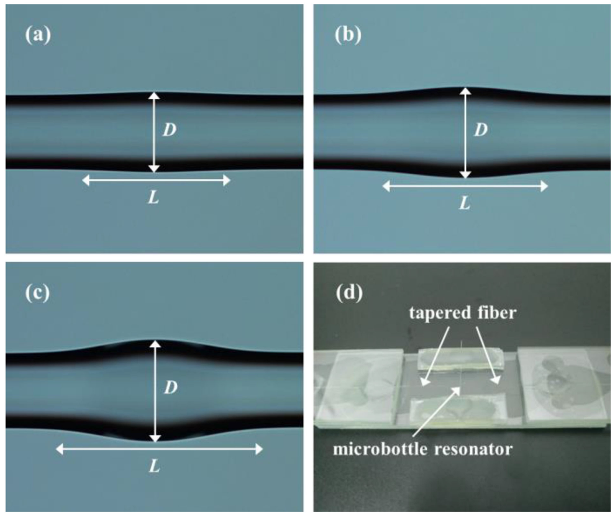

Fig. 2. Microbottle resonators with (a) D = 137 μm, L = 235 μm, (b) D = 155 μm, L = 285 μm, (c) D = 175 μm, L = 355 μm. (d) Tapered fiber coupled microbottle resonator glued to glass slide.

3. Experimental Results

The microbottle resonator is fabricated by using a soften and compress method with a fiber splicer (Filter S178C, Japan). A short section of continuous single mode fiber (SMF-28, Corning, USA) was adopted and several time splicer actions were exploited on a small region to prepare a bottle microresonator [21]. Different splicer action times could be executed to fabricate resonators with different dimensions. Figs. 2(a) to (c) indicate the microbottle resonator with maximum diameters D of 137 μm, 155 μm, 175 μm, and bottle length L of 235 μm, 285 μm, 355 μm by using 2, 4, 7 times splicer actions, respectively. Smaller or larger resonator diameter is not considered as 137 μm is close to the dimension of single mode fiber, and diameter larger than 175 μm would induce a reduction of quality factor and the sensitivity. The microbottle resonator was characterized by a tapered fiber which was fabricated utilizing the flame brushing technique [22]. By using AB glue (DP460), the ends of the tapered fiber were glued to a fixing component made by glass slide, while the center part is suspended. With the help of microscope and translation stages, the suspended part of tapered fiber was then positioned perpendicular to, and in physical contact with the resonator to provide a robust coupling and a stable transmission. After that, the fiber handles of bottle microresonator were also glued to the glass slides, as shown in Fig. 2(d). Finally, the glass slide was sealed into a glass tube filled with isopropanol by using AB glue, and a packaged isopropanol-immersed temperature sensor was obtained.

Fig. 3 displays the schematic of the temperature sensing experiment based on isopropanol-immersed silica microbottle resonator. Light from a tunable laser (TLB-6728) is coupled into microbottle resonator via the tapered fiber connected with a launching fiber, and the output light is incident into a photodetector (PD, New Focus 1811-FC) via collecting fiber. The resonance spectrum is monitored and recorded by a digital oscilloscope connected with PD. The packaged isopropanol-immersed temperature sensor, as well as the connecting fibers are immersed in water. The temperature of water is adjusted and stabilized by a temperature-controlled water-bath chamber.

The temperature measurements of tapered fiber coupled silica microresonator in the air is investigated initially to make a reliable reference as it has been investigated by various research groups. The fixing component exhibited in Fig. 2(d) is put into an oven with a thermocouple, and the spectrum is recorded when the temperature is steady. Figs. 4(a) to 4(e) draw the transmission spectra of resonator with $R_0 = 155$ μm and $L = 285$ μm under temperature range from 20 °C to 40 °C with an interval of 5 °C. The intrinsic Q factor of the bottle resonator in the air was calculated to be

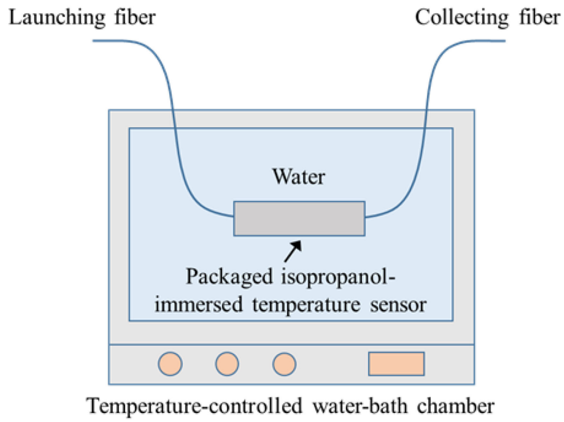

Fig. 3. Experimental setup for temperature sensing based on isopropanol-immersed microbottle resonator.

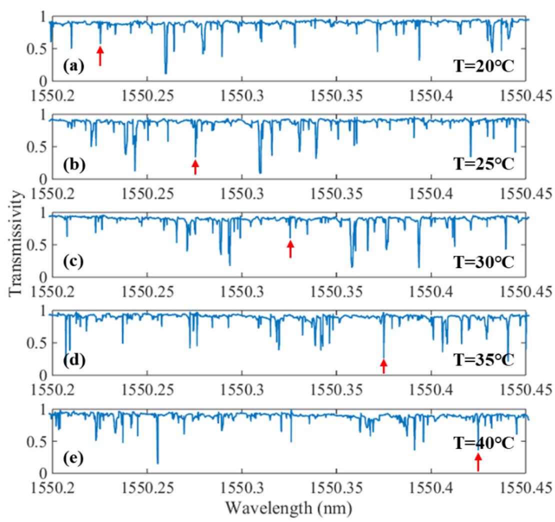

Fig. 4. Transmission spectra of resonator in the air under temperature range from 20 °C to 40 °C.

$\sim$2.4 $\times$ 10^6 by measuring the full width at half maximum (FWHM). As the increase of temperature, the resonance wavelength shows a red shift which could be attribute to the positive value of both thermal refraction coefficient and thermal expansion coefficient of silica. The calculated sensitivity is 10.4 pm/°C according to the linear fitting, which is in the same order of magnitude with the reported temperature sensors based on silica microresonator [13]–[15].

The spectral characteristics of the packaged isopropanol immersed temperature sensor based on the same microbottle resonator is depicted in Fig. 5. Due to the small RI contrast between silica and isopropanol, it is difficult for resonator to confine light, leading to an increase of scattering loss and a reduction in Q factor of about two orders of magnitude. A blue shift of resonance wavelength is observed as temperature increased, which is different from the results in the air. Furthermore, a temperature sensitivity of 48 pm/°C is obtained, which is about 4.6 times higher than that in the air.

In order to demonstrate the relationship between sensitivity and resonator diameter experimentally, the temperature response of isopropanol-immersed temperature sensor with different resonator dimensions are tested. According to Fig. 6, the temperature sensitivity of 61 pm/°C, 48 pm/°C, and 22 pm/°C were obtained for microbottles with maximum diameter of 137 μm, 155 μm and 175 μm, respectively. Thus, it could be concluded that the resonator with a larger diameter

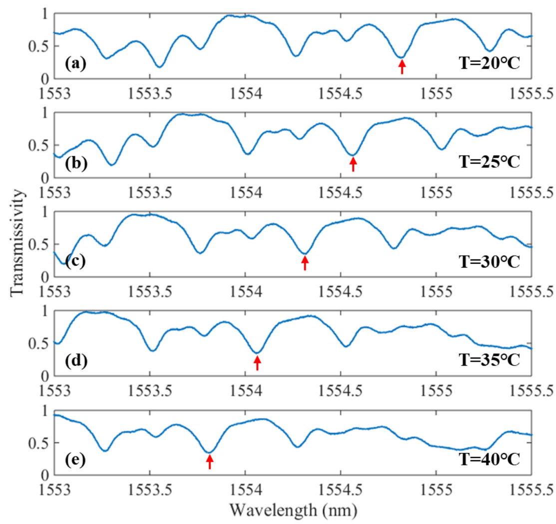

Fig. 5. Transmission spectra of resonator immersed in the isopropanol under temperature range from 20 °C to 40 °C.

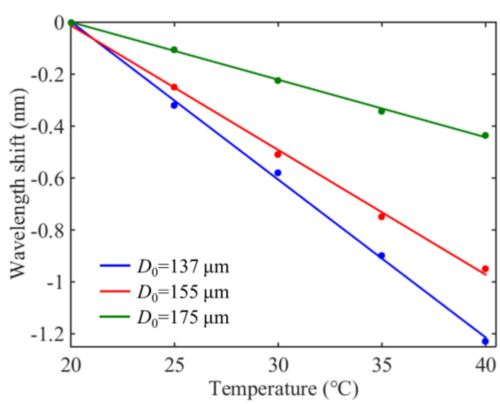

Fig. 6. The relationship between the resonant wavelength shift and the temperature of microbottle resonators with different dimensions.

has a smaller temperature sensitivity, which is coincident with theoretical result. Furthermore, the average relevant coefficient in linear fitting is 99.7%, indicated an excellent linearity dependence of resonance wavelength shift on temperature change.

The figure of merit (FOM), a parameter to evaluate the comprehensive performance of a sensor, is defined as the ratio between the sensitivity (S) and the full width at half maximum (FWHM) [23]:

$$\mathrm{FOM} = \frac{S}{\mathrm{FWHM}} \tag{4}$$

The FOM of the temperature sensor based on isopropanol-immersed WGM microresonator is calculated to be 0.33 according to the maximum sensitivity of 61 pm/°C and Q factor of 10^4. Benefit from this high Q factor, FOM achieved in this paper is higher than that of temperature sensor based on isopropanol-sealed microfiber coupler, whose FOM is 0.13 [19]. Reliable accuracy measurement is impossible and not made due to the fact that the accuracy of the thermocouple used in our water-bath chamber is unknown. Furthermore, the measurement resolution ($\Delta T_{\min}$) is estimated as 0.24 m°C according to $\Delta T_{\min} = \Delta\lambda_{\min}/(d\lambda/dT)$, and $\Delta\lambda_{\min} = 0.015$ pm is the spectral resolution of experiment system.

4. Conslusion

In this paper, a WGM temperature sensor based on microbottle resonators embedded in isopropanol was demonstrated both theoretically and experimentally. Maximum temperature sensitivity of 61 pm/°C and FOM of 0.33 were achieved experimentally, which could be attribute to the high thermal refraction coefficient of isopropanol and high Q factor of WGM microresonator. Additionally, limited by the narrow temperature control range of water-bath chamber we used and the boiling temperature of isopropanol, a wider temperature range has not been achieved in current paper, which could be solved in future work by using a new water bath with temperature control range lower than 0 °C, and using other liquids with higher boiling point and high thermal refraction coefficient. The sensor proposed in this paper possesses a simple fabrication process, and reveals advantages of excellent sensing performance and practicability.

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