An improved Y_2O_3-ZrO_2 waveguide-fiber-optic sensor for measuring gas flow temperature above 2000℃

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ABSTRACT

Although Y_2O_3-ZrO_2 fiber-optic sensor has been developed for contact measurement of temperature higher than 2000℃, its performance is not as good as that of sapphire fiber-optic sensor below 1900℃ due to the large optical loss of the Y_2O_3-ZrO_2 fiber. In order to improve the Y_2O_3-ZrO_2 fiber-optic sensor for ultra-high-temperature applications, in this work, based on a newly developed rectangular Y_2O_3-ZrO_2 single-crystal waveguide with much lower optical loss, an improved Y_2O_3-ZrO_2 waveguide-fiber-optic sensor has been developed. The sensor has been tested up to near 2300℃, we estimate that, the improved sensor has similar performance as the sapphire fiber-optic sensor in accuracy and resolution, except the disadvantage of relatively short waveguide. In addition, in this work, instead of the previous volatile and toxic BeO-coated probe, we use a multi-ions-doped sensor head, which is much stable and safe.

Key words: Y_2O_3-ZrO_2 single crysta waveguide, high temperature, fiber-optic sensor, multi-doped sensor head, gas flow

1.INTRODUCTION

Radiation-based high-temperature fiber-optic sensors, especially the sapphire fiber-optic sensor, have been widely used due to their special advantages of high accuracy, fast response, intrinsic immunity to electromagnetic interference and long life time[1, 2]. However, the melting point of the sapphire crystal fiber, 2045℃, limits the sensor to be used beyond 2000℃(1900℃ in practical use)[3]. In order to extend the working temperature of fiber-optic sensors above 2000℃, two years ago, we had tentatively developed an Y_2O_3-ZrO_2 (Y_2O_3 stabilized ZrO_2) single crystal fiber-optic sensor for contact measurement of temperature above 2000℃ [4]. Although it had been successfully operated up to 2300℃, its accuracy was much lower than the sapphire fiber-optic sensor because of the low transmissivity and small diameter of the Y_2O_3-ZrO_2 fiber, and its long-time performance was also limited by the volatility and toxicity of the BeO ceramic head(used as the probe element) at high temperature.

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Aiming to obtain high-quality Y_2O_3-ZrO_2 fibers or waveguides with optical losses as low as or even lower than sapphire fibers, recently, we have successfully developed rectangular Y_2O_3-ZrO_2 single crystal optical waveguides by precisely polishing as-grown cubic Y_2O_3-ZrO_2 single crystal bars. These waveguides show optical losses as low as sapphire fibers (e.g. 0.03dB/cm at wavelength of 900nm), and their mechanical strengths are higher than Y_2O_3-ZrO_2 fibers. In addition, these waveguides can be easily made with large cross-sections (e.g. 1.2mm×1.2mm), indicating they can transmit much more radiation signals.

In this paper, based on these waveguides, we demonstrate an improved Y_2O_3-ZrO_2 waveguide-fiber-optic sensor for measuring gas flow temperature above 2000℃. Meanwhile, instead of the volatile BeO-coated head, a multi-doped sensor head with much higher stability had been developed. The sensor had been experimentally evaluated up to near 2300℃, we estimate that the improved sensor possesses much better performances than the previous fiber-optic sensor for temperature above 2000℃.

2.CONFIGURATION OF Y_2O_3-ZRO_2 WAVEGUIDES-FIBER-OPTIC SENSOR

2.1 The sensor system

The configuration of the sensor system is shown in Fig.1. The sensor consists of three parts: the sensor head, the optical waveguides and the signal processing system. The sensor head is a thermal emission source fabricated on the waveguide end by multi-doping absorption ions. The waveguides include a rectangular Y_2O_3-ZrO_2 single crystal optical waveguide for transmitting signals under high temperature and a silica fiber working under low temperature. The signal processing system includes a beam splitter, two sets of band-pass filters, photodetectors, amplifiers and A/D converters, and a single-chip microcomputer.

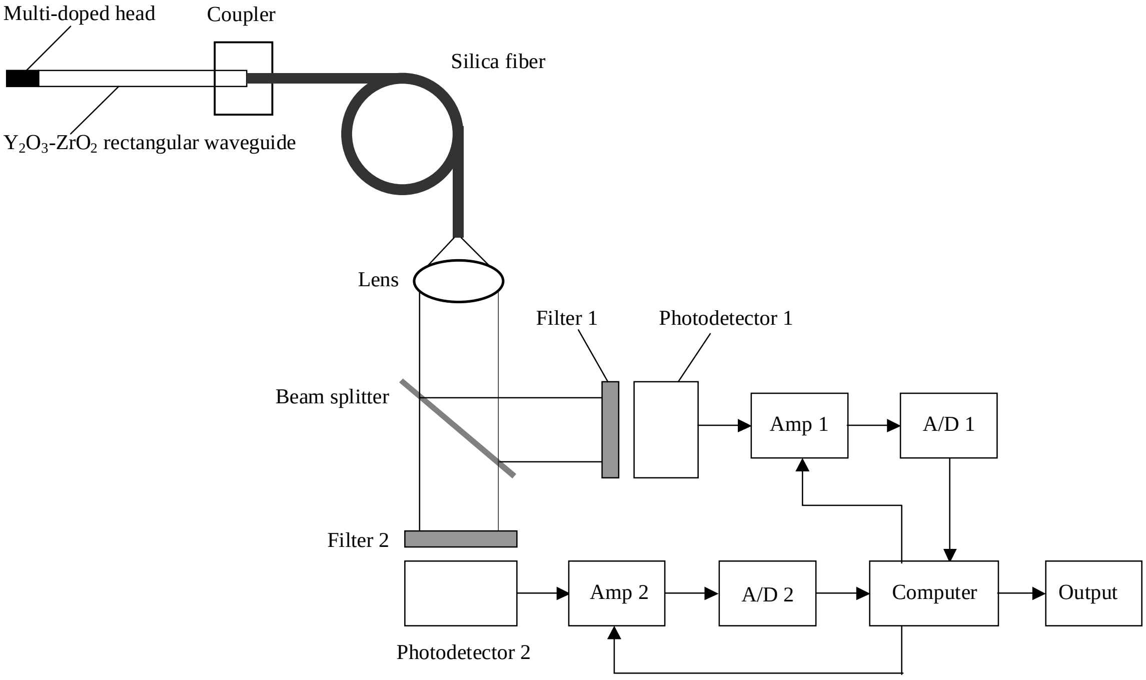

Figure1: Configuration of the Y_2O_3-ZrO_2 waveguide-fiber-optic sensor system

When placed in high temperature, the sensor head emits thermal radiation signal, which transmits through the rectangular Y_2O_3-ZrO_2 waveguide and then couples into the long flexible silica fiber. The output of the silica fiber is focused by a lens and then sent to a beam splitter, at which it is split into two and sent to a couple of filters, then the two filtered signals are detected, amplified and A/D converted separately until they are sent to a computer, where the ratio of the two signals is obtained and processed into temperature information, final temperature data are thus provided.

2.2 Rectangular Y_2O_3-ZrO_2 waveguide and circular silica fiber

The rectangular Y_2O_3-ZrO_2 waveguide we used here is fabricated by polishing the bars of as-grown Y_2O_3-ZrO_2 single crystals, it is 55mm in length and 1.1mm×1.2mm in cross-section, the optical loss of the waveguide is about 0.16dB at wavelength of 900nm, the transmission spectrum of the waveguide within 800-1000nm is shown in Fig.2, which means that the waveguide can transmit more than 95% of the radiation signals at our detecting wavelengths((λ_1=820nm, λ_2=940nm). The detailed fabrication and properties of rectangular Y_2O_3-ZrO_2 waveguides are described in another paper submitted to this conference [5].

In order to receive more output radiation signals from the rectangular Y_2O_3-ZrO_2 waveguide, here we use a large-diameter large-NA(numerical aperture) silica fiber, the core diameter of the fiber is 0.8mm, the NA of the fiber is about 0.3. The fiber length is 2m, and the transmission loss is lower than 0.10dB around 900nm, indicating an optical transmissivity of 98%.

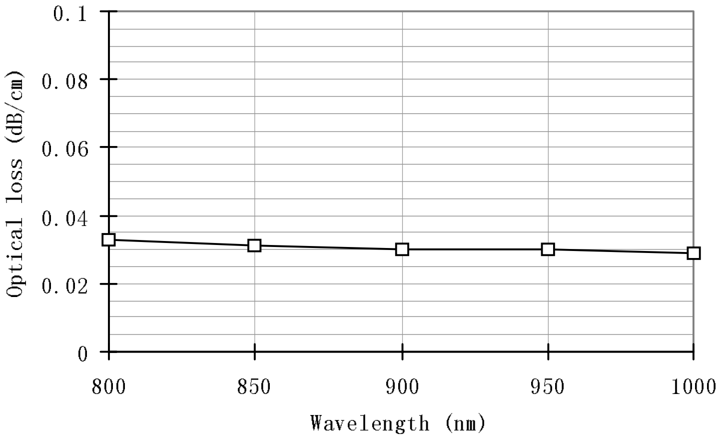

Figure 2: Wavelength-dependent optical loss of the Y_2O_3-ZrO_2 waveguide within 800-1000nm

The coupling of a rectangular waveguide with a circular fiber with small diameter and different refractive index may be inefficient or even impossible when the number of guiding modes is small. Fortunately, in radiation-based fiber-optic sensing systems, in order to obtain radiation signals strong enough for accurate measurements, transmission fibers(or waveguides) with relatively large diameters(or widths) are usually used. For Y_2O_3-ZrO_2 waveguide we developed here, the number of guiding modes can be estimated as [6]

$$M_R \approx \frac{\pi}{4}\left(\frac{2d}{\lambda_0}\right)^2 NA^2, \qquad (1)$$

where d is the average width of the near-square cross-section, λ_0 is the wavelength in vacuum, $NA=(n^2-n_0^2)^{1/2}$, the numerical aperture of the waveguide, and n_0=1 in air. At λ_0=900nm, n=2.1, for the waveguide we used here, d ~1.1mm, $M_R \sim 8.8 \times 10^6 >> 1$. For circular fibers, the number of modes is [6]

$$M_C \approx \frac{4V^2}{\pi^2}, \qquad (2)$$

where the V-parameter of the fiber is $V = 2\pi\left(\frac{a}{\lambda_0}\right)NA$, and a is the core radius of the fiber. For a 800μm-diameter slica fiber with $NA=0.3$(At $\lambda_0=900nm$) and $a=0.40mm$, $M_C \sim 2.8\times10^5 >> 1$. Since both the M_R and the M_C are much larger than 1, the rectangular waveguides are easy to couple with a large-diameter silica circular fiber. In this work, the coupling efficient measured is about 20%, the loss mainly comes from two factors: one is the Fresnel reflection on the end-faces of the waveguides and fiber, the other is that the cross-section of the silica fiber is smaller than that of the waveguide, a certain part the radiation signals is lost beyond the fiber reception area. However, even with the 20% coupling coefficient, the radiation signals we obtained is much larger than that of zirconia fiber sensing system [4] and still larger than sapphire fiber sensing system[7] in our previous work.

2.3 The doped sensor head

In our previous work, we used a BeO coated fiber head as the sensor head, although it works at that work, the volatility of the BeO at high temperature limited the lifetime of the probe, and the toxicity of the BeO vapor also adds limitations on its fabrication and applications. In this work, we use a multi-ions doped Y_2O_3-ZrO_2 ceramic tip as the sensor head. It was fabricated as following: the ions were firstly mixed in forms of Nd_2O_3, Er_2O_3 and Cr_2O_3 together with a certain amount of Y_2O_3 and ZrO_2 in powders with concentrations of 11.5at.% Nd^{3+}, 12.0at.% Er^{3+} and 1.5at.% Cr^{3+}. Homogenously mix the powders and press them in form of a rod, and then grow the rod onto the end of the Y_2O_3-ZrO_2 waveguide by LHPG(laser heated pedestal growth) system in our lab. The ceramic tip is a cylinder with diameter of about 1.35mm and length of 2.2mm. The transmission spectrum of the doped head is shown in Fig.3, which shows that, within the range of 300-1200nm, the absorption of the doped head is higher than 98%, indicating a high emissivity in this band(covers the detection wavelengths of 820nm and 940nm) when it is placed in high temperature. Since the doped tip is non-toxic, it is much safer in fabrication and application. In addition, unlike BeO-coated tip, the ions in the ceramic tip is not only doped in the surface of the tip, but homogeneously doped inside the whole tip, so even the tip volatilize slowly at high temperature, the blackbody-like sensor head remains, which greatly prolongs the lifetime of the sensor head, and meanwhile, enhances the stability of the sensor.

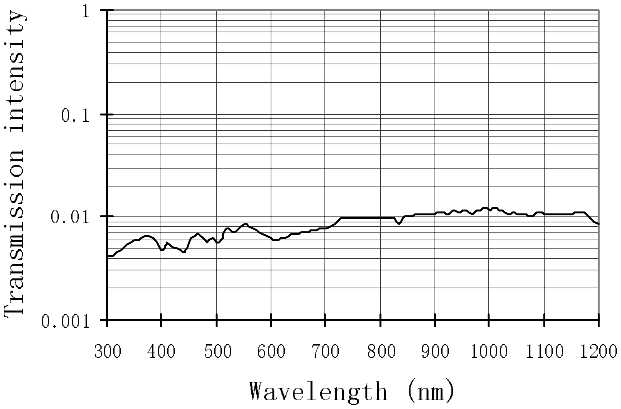

Figure 3: Transmission spectrum of the multi-doped sensor head

2.4 Signal processing system

The signal processing system is the same as that of two-band sapphire fiber-optic sensors. The two photodetectors(same photocells) are narrow-band filtered with neighbouring central wavelengths (λ_1=820nm, λ_2=940nm) and same bandwidth($\Delta\lambda_1=\Delta\lambda_2=\Delta\lambda$=30nm). When the signals output from the two photodetectors have been amplified by amplifiers, they are converted by A/D converters and sent to the computer where they can be divided by each other to produce the ratio.

Generally, the emission of pure Y_2O_3-ZrO_2 waveguide(pure Y_2O_3-ZrO_2 single crystal) is much weaker than that of the doped head, and the doped end can be approximately treated as a blackbody cavity with emission constant $\varepsilon \sim 1$. Signal intensities of the two detection bands are:

$$I_1(T) = \varepsilon_1 R_1 U_1 \int_{\lambda_1 - \frac{\Delta\lambda_1}{2}}^{\lambda_1 + \frac{\Delta\lambda_1}{2}} E_b(\lambda, T)\, d\lambda \qquad (3)$$

$$I_2(T) = \varepsilon_2 R_2 U_2 \int_{\lambda_2 - \frac{\Delta\lambda_2}{2}}^{\lambda_2 + \frac{\Delta\lambda_2}{2}} E_b(\lambda, T)\, d\lambda \qquad (4)$$

$$E_b = C_1 \lambda^{-5} \left(e^{C_2/\lambda T} - 1\right)^{-1} \qquad (5)$$

Where C_1 is the first radiation constant, C_2 is the second radiation constant; R_1, R_2 are the photo-electric responses of photodetectors; U_1 and U_2 are transmissivities of the waveguide and silica fiber at the two detection wavelengths. When the two filters have the same bandwidth of $\Delta\lambda$ and their central wavelengths(λ_1, λ_2) are close together, the ratio of the signals produced by the two photodetectors can be written as [3]

$$R(T) = K \frac{\int_{\lambda_1 - \Delta\lambda/2}^{\lambda_1 + \Delta\lambda/2} \lambda^{-5} \left(e^{c_2/\lambda T} - 1\right)^{-1} d\lambda}{\int_{\lambda_2 - \Delta\lambda/2}^{\lambda_2 + \Delta\lambda/2} \lambda^{-5} \left(e^{c_2/\lambda T} - 1\right)^{-1} d\lambda} \qquad (6)$$

where K is a constant, λ is the wavelength(in m) and T is the temperature of the sensor head (in K).

In computer, the ratio $R(T)$ obtained by Eq.(6) is compared with a calibrated data map and final temperature information is thus obtained. Limited by the performances of the photodetectors and amplifiers, the accuracy and resolution of the sensor is mainly determined by the magnitude of the radiation signals in Eq.(3) and Eq.(4), generally, the larger the $I_1(T)$ and $I_2(T)$, the higher the accuracy and resolution of the sensor. Therefore, a strong radiation and a high efficient signal transmission waveguide is very helpful to increase the performance of the sensor.

4.EXPERIMENTAL TEST OF THE SENSOR

Since the sensor is developed for gas flow measurement, in our work, in order to simulate the high-temperature gas flow, we remold an alcohol blowtorch by add a stainless-steel nozzle(it is able to survive higher temperature than the original copper nozzle) and an alumina ceramic tube to blow pure oxygen as shown in Fig.4. With this modification, the blowtorch can provide temperature higher than 2300 ℃, and the temperature can be controlled by the rate of the oxygen flow.

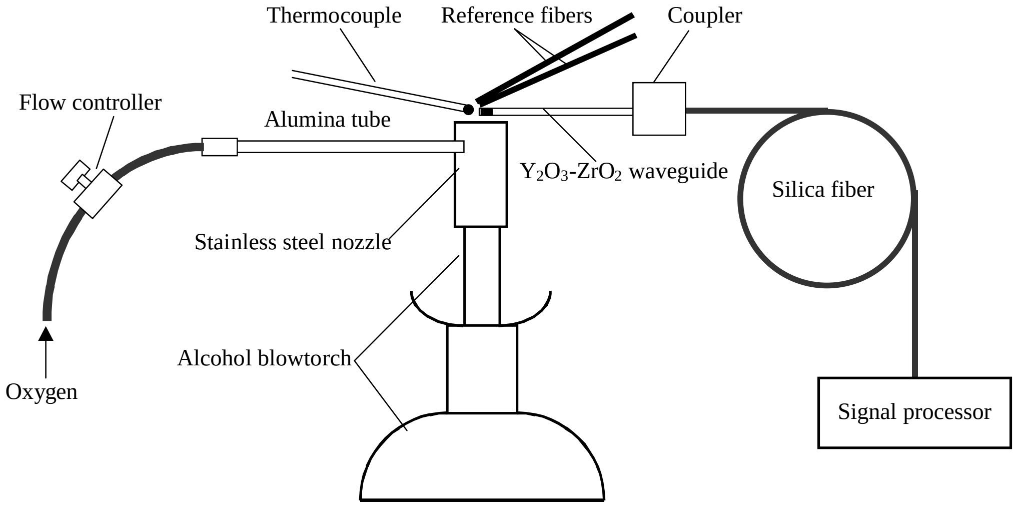

Figure 4: Experimental test system of the Y_2O_3-ZrO_2 waveguide-fiber-optic sensor

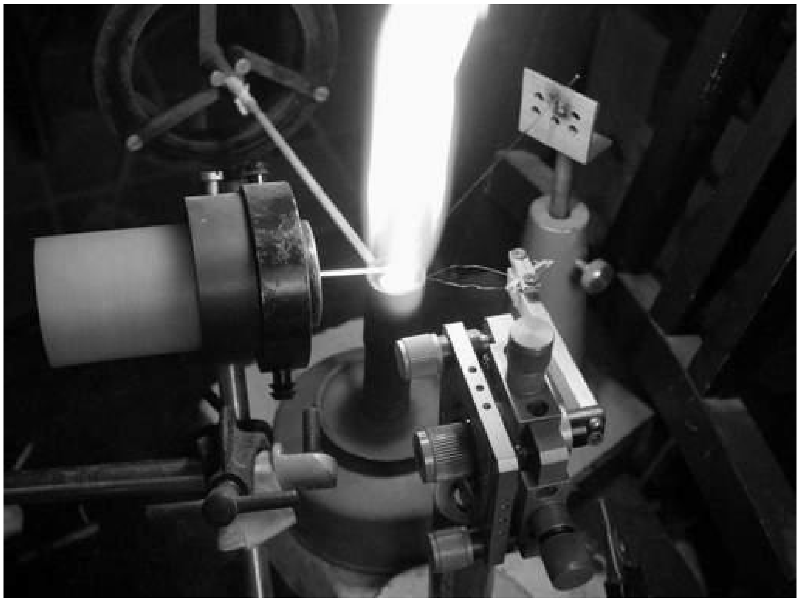

Figure 5: Photo of the real test system for Y_2O_3-ZrO_2 waveguide-fiber-optic sensor with references of thermocouple and single-crystal fibers

The experimental test system of Y_2O_3-ZrO_2 waveguide-fiber-optic sensor is shown in Fig.4. First, placed the waveguide sensor head on the top of the nozzle together with two reference fiber(sapphire fiber and YAG fiber) and a thermocouple at almost the same place of the doped waveguide head. The thermocouple we used here was a WRe_3-WRe_{25} thermocouple with wire diameter of 0.5mm and tip diameter of 1.2mm; the reference sapphire fiber was 0.98mm-diameter and 150mm-length, the YAG fiber was 0.95mm-diameter and 150mm-length. The test was carried out as following: Ignited the alcohol blowtorch as usual, when the flame became stable, gradually turned on the oxygen flow, the temperature rised with the increasing of oxygen flow. In the test, the YAG fiber melted first, then the sapphire fiber melted, the thermocouple was burn out at temperature of about 2100℃(given by the roughly calibrated sensor), a photo of the test is shown in Fig.5. Record the temperature data given by the sensor and the thermocouple, together with melting points of the reference fibers, the results are shown in Fig.6. In Fig.6, the temperature given by the waveguide sensor is used as a standard data calibrated by the melting point of YAG fiber(1930℃) with deviation of zero(in fact, it is not the standard data, but others can not bear temperature higher than 2100℃, so we select it as standard for comparison with others). Test results show that, the deviation between sensor and thermocouple is within 5%, and the temperatures obtained by the melting points of sapphire fiber(2045 ℃) is also less than 5% difference with that obtained by the sensor. The deviation seems large, however, since the flame of blowtorch was not very steady, a certain temperature gradient existed inside the flame, and the thermocouple and the reference fiber tips were not placed exactly at the same place as the sensor head, resulting in the large deviation in Fig.6, but it is not the accuracy of the sensor. In fact, the radiation signal intensities $I_1(T)$ and $I_2(T)$ in Eq.(3) and Eq.(4) we obtained in this system are almost two times higher than that of sapphire fiber-optic sensor at the same temperature. Therefore, at least, the Y_2O_3-ZrO_2 waveguide-fiber-optic sensor has the same accuracy and resolution as sapphire fiber-optic sensors, which is 0.2%(accuracy) and 1℃(resolution) in our previous work when using the same photodetectors and the same signal processing system[7]. In contrast, the accuracy of our previous Y_2O_3-ZrO_2 fiber-optic sensor is 1.5%(1200-1600 ℃) and 4% (1600-2300℃). In addition, the sensor head had been tested for more than three times at temperature higher than 2200℃ (estimated data), no damage could be found on the doped sensor head and the waveguide.

The thermal response time of the sensor had also been measured at temperature of about 2000℃, the average response time of three tests was 2.2s. A faster response could be obtained when using a taped head with smaller size.

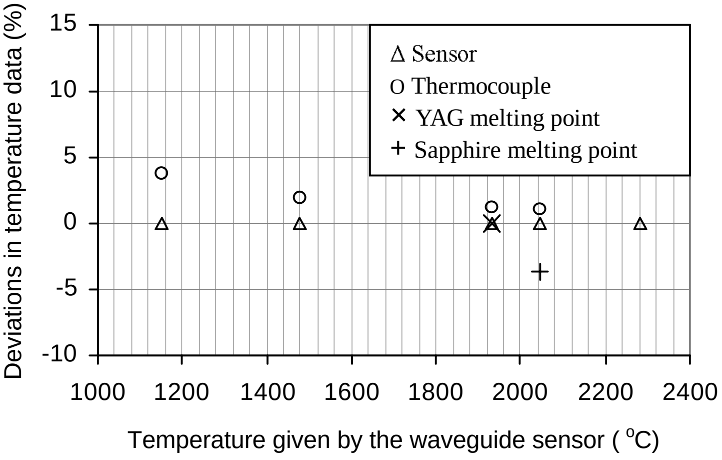

Figure 6: Test results of the Y_2O_3-ZrO_2 waveguide-fiber-optic sensor with references of thermocouple and single-crystal fibers

5.CONCLUSIONS

In conclusion, an Y_2O_3-ZrO_2 waveguide-fiber-optic sensor has been developed for contact measurement of temperature higher than 2000℃, based on a rectangular Y_2O_3-ZrO_2 single-crystal waveguide with much lower transmission loss than that of previously used Y_2O_3-ZrO_2 fiber, together with a multi-ions doped sensor head. The sensor had been successfully operated near 2300℃, from the radiation signal intensity obtained by the photodetector, we estimated that the accuracy and resolution of the sensor is better than 0.2% and 1℃ separately, which is much better than that of the previous Y_2O_3-ZrO_2 fiber-optic sensor. In addition, instead of toxic and volatile BeO-coated head in previous system, we used a multi-doped sensor head, which is non-toxic and much more durable when working at high temperature.

However, limited by the lacking of time and accurate calibration equipment at high temperature, the sensor we developed in this work had not been well calibrated and tested. Meanwhile, for practical applications, the length of the Y_2O_3-ZrO_2 waveguide is too short, although it can be relied by a long sapphire fiber, we recommend fabricating long Y_2O_3-ZrO_2 waveguide without a sapphire fiber. With these in mind, in our further work, we'll contrive to fabricate long high-quality Y_2O_3-ZrO_2 waveguides, and develop a well-calibrated Y_2O_3-ZrO_2 waveguide-fiber-optic sensor that is more suitable for practical measurement of high-temperature gas flow.

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