Sensors and Actuators A 232 (2015) 99–102

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Fabrication of high-temperature temperature sensor based on dielectric multilayer film on Sapphire fiber tip

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ARTICLE INFO

Article history:
Received 10 December 2014
Received in revised form 8 May 2015
Accepted 22 May 2015
Available online 27 May 2015

Keywords:
Optical coatings
High-temperature
ZrO_2 / Al_2O_3 / ZrO_2 (ZAZ) three-layer film
Sapphire fiber

ABSTRACT

A high-temperature temperature sensor based on dielectric ZrO_2 / Al_2O_3 / ZrO_2 (ZAZ) three-layer film structure on sapphire fiber tip with potential for low-cost batch production was fabricated. A fiber optic high-temperature sensor based on the principle of Fabry-Perot structure is proposed. The ZAZ three-layer film sensing element was deposited on the tip of a polished sapphire fiber using physical vapor deposition (PVD). Due to exceptionally small size, the as-prepared temperature sensor based on sapphire fiber tip can be used as an embedded sensor in harsh environments. And experimental result shows that the sensor based on sapphire fiber has a very high correlation with environment temperature; the correlation coefficient was measured to be 99.79%. The sensitivity of temperature reaches 1.8×10^{-5} /°C when the environment temperature changes from 100.9 °C to 1111.0 °C.

1. Introduction

During the past decades, optical fiber high-temperature temperature sensors had been explored including fiber Bragg gratings [1–2], Fabry–Perot Interferometers (FPIs) [4–11] and blackbody radiation for its advantages such as miniature design, electromagnetic immunity and durability to harsh environments. However, those sensors based on fiber Bragg grating and blackbody radiation do not have the advantages of miniaturization, simple configuration and low cost. Although FPI high-temperature sensors fabricated by micro-structured [7–9] and chemical etching fibers [10] are developed due to their unique advantages such as high resolution, simple configuration and low cost, such sensors also have many problems in the practical applications as a result of complex and fragile structure.

In this work, a method for miniature optical fiber high-temperature temperature sensor based on multilayer thin film deposited on tip of a sapphire fiber was introduced. Generally, the selection of multilayer materials is quite critical. An ideal high temperature sensitive material must possess higher melting point, low optical absorption, similar coefficient of thermal expansion and physical and chemical stabilization under high temperature. Among all the appropriate materials, Al_2O_3 possesses good mechanical property at room temperature, high melting point, and ZrO_2 is a new kind of structural material with excellent physical and chemical properties [9,12–14]. More importantly, Al_2O_3 and ZrO_2 have similar coefficient of thermal expansion under high temperature around 1000 °C [15]. The reason why these two kinds of material were used to fabricate multilayer thin film is not only their physical and chemical properties but also its optical indices which are shown in Fig. 1. From Fig. 1 the refractive index difference between Al_2O_3 and ZrO_2 can be clearly observed. According to Fresnel's law, the reflectance at interface can be approximated for the case of normal incidence:

$$R = ((n_{Al_2O_s} - n_{ZrO_2})/(n_{Al_2O_s} + n_{ZrO_2}))^2 \tag{1}$$

where R is the corresponding reflection coefficients of the interface of ZrO_2/Al_2O_3 and n is the refractive index. Due to optical indices difference, the Fabry-Perot interferometer architecture is accessible. The greater the refractive index difference is, the greater the reflected light intensity is. Hence, the Interference spectrum of sensor is easy to be extracted and determined

2. Sensors fabrication and principle

In this work, the sensing head was prepared by depositing three layers of $ZrO_2/Al_2O_3/ZrO_2$ (ZAZ) dielectric materials through physical vapor deposition (PVD) on the tip of a sapphire fiber. The thickness of ZrO_2, Al_2O_3 and ZrO_2 (ZAZ) is 283, 1396 and

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http://dx.doi.org/10.1016/j.sna.2015.05.017
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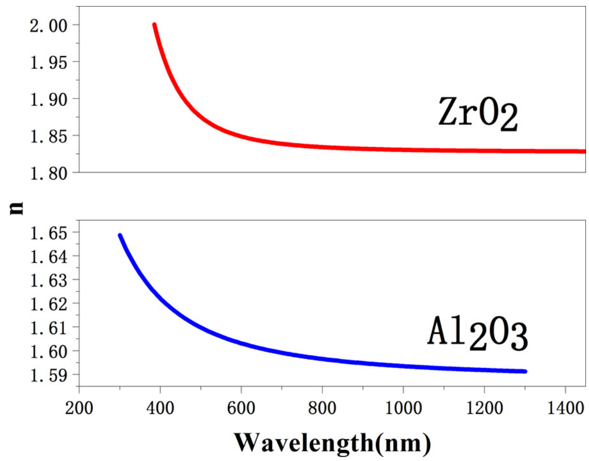

Fig. 1. Refractive index of ZrO_2 and Al_2O_3 at different wavelength.

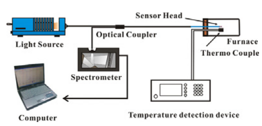

Fig. 2. Optical interrogation system for measurement of temperature.

283 nm respectively. Before deposition, sapphire fiber tips and sapphire wafers were cleaned by an ultrasonic cleaner and then rinsed in alcohol, acetone and deionized water for three times, to remove possible surface contamination. After thin film deposition and thermal annealing, the sensor was put into the high temperature furnace for sensing characterization. As shown in Fig. 2, the measurement system consists of a miniature broadband tungsten halogen lamp TLS (HL-2000, Ocean Optics), a k-type thermocouple, miniature fiber optic spectrometer (Ocean Optics, USB-2000, wavelength resolution: 0.3 nm), a 3 dB multimode optical fiber coupler (OC). With the increase of surrounding temperature, refractive index and the thickness of the deposited oxide films will increase due to thermo-optic and elastic-optic effect. This will result in the change of optical path difference (OPD) of the thin film interferometer along with the shift of interference spectra. Therefore, when the surrounding temperature increases, the thicknesses of the deposited oxide films ΔL will increase which result in the shift of the optical path difference (OPD) of the thin film, it can be described by the following equation [3,4]

$$\frac{\mathrm{OPD}(T)}{\mathrm{OPD}(T_0)} = \frac{2n(T)d(T)}{2n(T_0)d(T_0)} \approx (a_n + a_d)(T - T_0) \tag{2}$$

where a_n and a_d is the 1st-order thermal coefficients for the refractive index and the physical thickness respectively.

In turn, the change in OPD results in a shift of the peak wavelength and the peak position λ_m can be derived as follows [5,6]:

$$\lambda_m(T) = \frac{2n(T)d(T)}{m - \frac{\varphi_0}{2\pi}}, \mathrm{OPD} \equiv 2\mathrm{nd} \tag{3}$$

where n and d is the equivalent refractive index and the physical thickness of $ZrO_2/Al_2O_3/ZrO_2$ (ZAZ) dielectric film respectively.

When temperature changes on the thin film, λ_m shall shift accordingly, as is derived by material properties of the thin-film as follows [5,6]:

$$\begin{aligned} \frac{\Delta\lambda}{\lambda} &\equiv \frac{\lambda_m(T') - \lambda_m(T')}{\lambda_m(T)} = \frac{2n(T')d(T') - 2n(T')d(T')}{2n(T)d(T)} \\ &\approx \left(1 + \alpha'_d \Delta T\right)(1 + \alpha'_n \Delta T) - 1 \\ &= \left(\alpha'_d + \alpha'_n\right)\Delta T + \alpha'_d \alpha'_n \Delta T^2 \end{aligned} \tag{4}$$

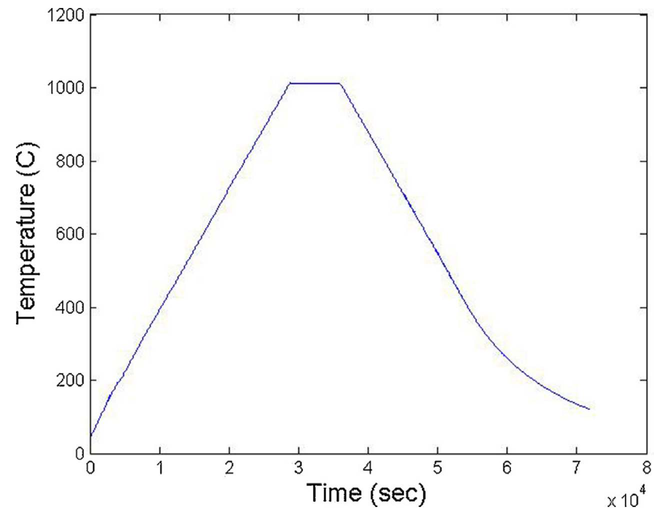

Fig. 3. Temperature calibration curve at different time.

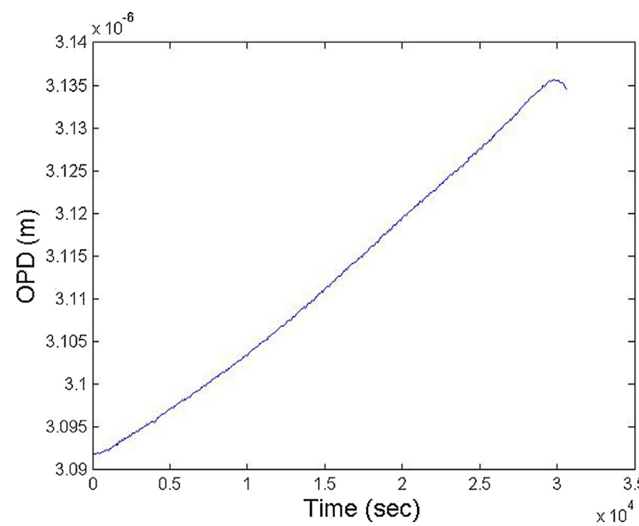

Fig. 4. The variation in OPD at different time.

where α'_d is the equivalent linear thermal expansion coefficient of $ZrO_2/Al_2O_3/ZrO_2$ (ZAZ) dielectric film and α'_n is the equivalent linear temperature coefficient of the refractive index of the film.

Thus, the increase of surrounding temperature will result in the shift of interference spectra according to Eqs. (3) and (4), and therefore the correlation of temperature change with interference spectra shift also can be maintained. In this paper, environmental temperature can be acquired in a real time by monitoring the drift of reflected interference fringe and using valleys-tracking method at different temperature levels.

3. Experimental results and discussions

Before calibration, the sapphire fiber tip sensor was annealed at 400 °C, 600 °C and 800 °C, each for at least 2 hours to stabilize the thin film. As calibration, the thin film sensor was then heated from 100.9 C to 1111.0 °C at 2 °C/min, kept at 1111.0 °Cfor 10 h and then cooled down to room temperature. The reference measurements were taken using a k-type thermocouple (shown in Fig. 3). Fig. 4 shows the variation in OPD at different time which has very similar evolution trend with Fig. 3. It indicates the variation in OPD has correlation with temperature change and the sensors is suitable for high temperature measurement up to 1111.0 °C. The