Optical Fiber-Top Microcavity Sensor for CO_2 Detection

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ABSTRACT

In this paper, we present a miniature fiber-optic CO_2 sensor by in-situ printing of a special polymer Fabry-Pérot (FP) microcavity on the end face of standard single-mode optical fiber. A photo-crosslinkable poly(ionic liquid) (PIL) with high CO_2 adsorption capability was employed to fabricate the polymer optical microcavity via an optical 3D μ-printing technology. Experimental results show that the optical CO_2 microsensor has very high sensitivity and fast response time and thus is very promising for environment and exhaust gas monitoring applications.

Keywords: fiber-optic sensor, CO_2 sensor, optical microfabrication

1 INTRODUCTION

Carbon dioxide (CO_2) is one of the most popular gases, which is not only vital to life on earth but also a widely adopted industrial material as well as notorious green-house gas [1-4]. For instance, the concentration of CO_2 plays a key role in controlling the quality of agri-food [5-7], and CO_2 concentration above 4% is dangerous to life and health according to the U.S. Occupational Safety and Health Administration [8]. Thus, there are the needs to monitor and measure CO_2 concentration in many daily-life and industrial applications.

The most commonly used technique for CO_2 sensing is based on infrared detectors [9, 10]. These detectors have fast response time but are bulky and costly which make them unsuitable for many CO_2 monitoring applications. Although electrical sensors provide a low-cost and simple solution, they are usually not suitable for remote sensing due to their susceptibility to electromagnetic interference and flammability concerns [11-13]. Fiber-optic sensors have become a very appealing solution because of their small size and immune to electromagnetic interference [3, 14].

Here, we present a new type of fiber-optic CO_2 sensor based on a polymer Fabry–Pérot (FP) cavity fabricated on the end face of a standard single-mode optical fiber, as shown in Fig. 1. A photo-crosslinkable poly (ionic liquid) (PIL) with strong CO_2 adsorption ability [15-17] was synthesized and then printed on the top of optical fiber by using an home-built *in-situ* optical printing technology to form an FP cavity for CO_2 sensing. Experimental results show such a miniature fiber-optic sensor has wide detection range and relatively fast response time for CO_2 detection.

2 RESULTS AND DISCUSSION

In the experiments, 1-vinylimidazole (monomer) and 2,2-azobisisobutyronitrile (initiator) were dissolved in dimethylsulfoxide (DMSO) solvent and then polymerized at 90 ^{o}C for 24 hours to produce poly(1-vinylimidazole). The polymer was further quaternized in the presence of 1-allyl bromide at 90 ^{o}C to obtain a photo-crosslinkable PIL, i.e. poly(1-allyl-3-vinylimidazolium bromide). The

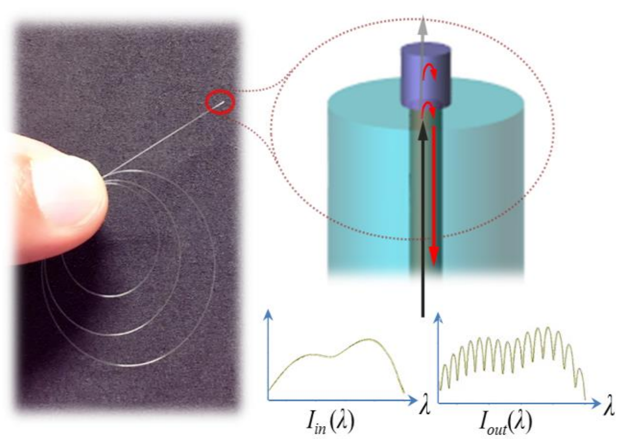

Figure 1. Schematic diagrams of the optical fiber end-face microcavity CO_2 sensor and the spectra of the sensor's input and output.

photo-crosslinkable PIL and photoinitiator (Irgacure 2959) were dissolved in deionized water (DI water) and then deposited on the end face of an optical fiber by using a dip-coating process. The thickness of the polymer on the fiber end-face can be adjusted by controlling the viscosity of the polymer solutions. The optimized weight concentrations of PIL and Irgacure-2959 are 30 wt% and 5 wt%, respectively, for the fabrication of the FP mircrocavity sensor. A home-built optical 3D μ-printing platform, as described in our previous works [18, 19], was then used to pattern the photo-crosslinkable PIL into microstructures for device fabrication. The intensity of the UV light used for optical patterning is 160.33 mW/cm^2. The total exposure time is around 30 s. The exposed micropatterns were developed in ethanol for about 5 minutes.

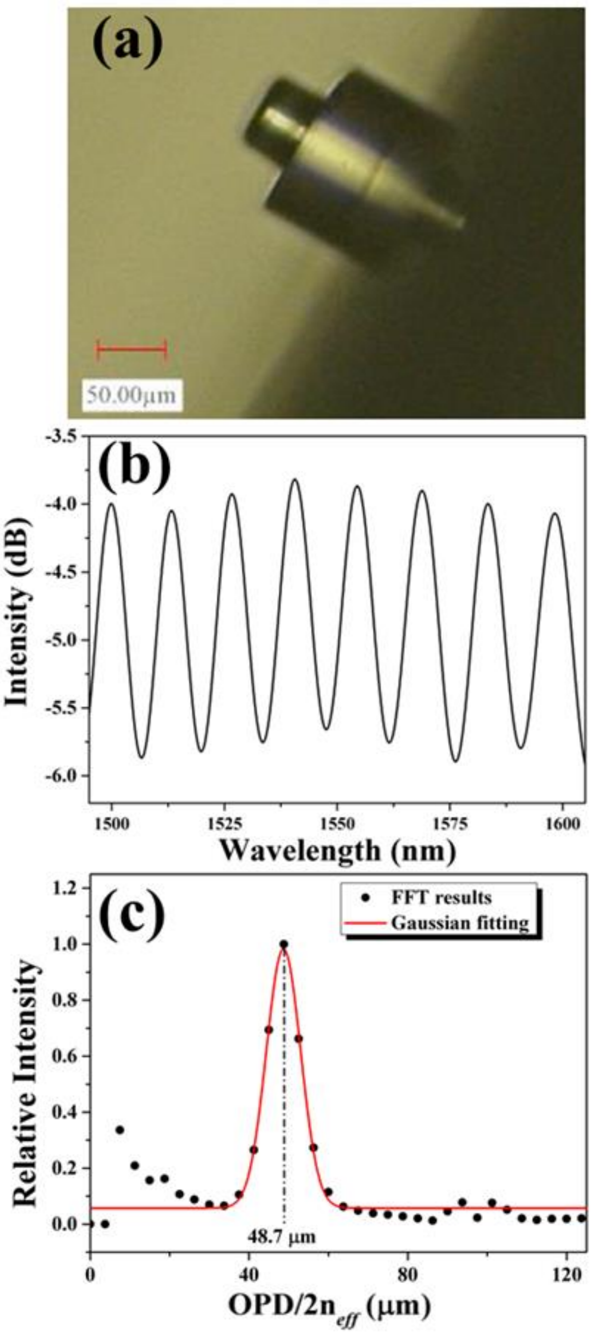

Figure 2. (a) Optical microscopic image of the PIL F-P microcavity sensor fabricated on the end face of an optical fiber. (b) Reflection spectrum of the F-P microcavity. (c) Calculated FFT result of the reflection spectrum.

Figure 2 (a) shows the polymer microdevice fabricated on the end face of a standard single-mode fiber (SMF), whose outer diameter is 125 μm. One can see that the surface of the PILs microdevice was very smooth and the whole device was well aligned in the center of the optical fiber. As the refractive indexes of silica glass and PIL are different, an F-P microcavity was then formed by the two partially reflective mirrors at the silica glass/PIL and PIL/air interfaces. The measured reflection spectrum of the fiber-top F-P microcavity is shown in Fig. 2 (b). The free spectral range (FSR) of the spectrum is about 20.3 nm. With the Fast-Fourier transform (FFT) and Gaussian fitting, the length of the microcavity is numerically calculated as ~48.7 μm, as shown in Fig. 2 (c), which agrees well with the value measured by using an optical microscope.

It is known that the fringe of the reflection spectrum of an F-P microcavity depends on the effective optical path of the cavity, i.e. the product of the refractive index and the length of the cavity, and the wavelengths of its spectral peaks can be written as

$$\lambda = 2n_{e_{ff}} L / m \, , \qquad (1)$$

where n_{eff}, L, and m are the effective refractive index of PIL,

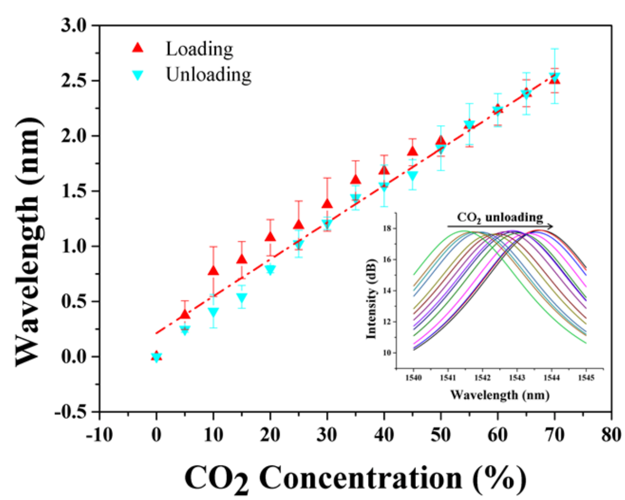

Figure 3. Response of the fiber-optic CO_2 sensor to loading and unloading of CO_2 gas. The inset shows the spectra shift with respect to the change of CO_2 concentration.

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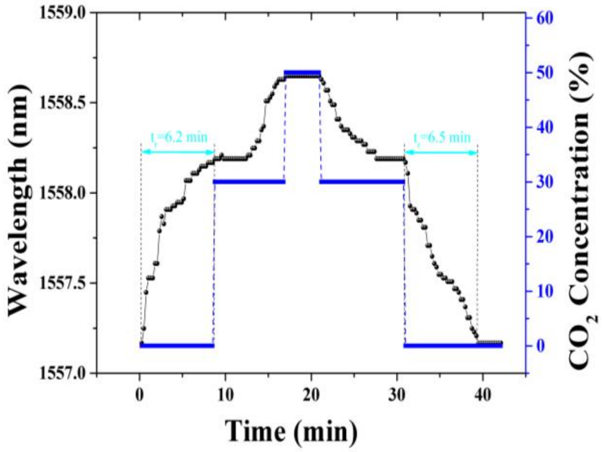

Figure 4. Dynamic response of the fiber-optic CO_2 microsensor based on PIL F-P cavity. The response time is about 6.5 minutes.

the length of the F-P cavity, and the order of fringe, respectively. When the PIL absorb CO_2 molecules, the refractive index of PIL will change due to volume expansion and refractive index change, resulting in reflection spectrum shift of the F-P cavity. Therefore, the shift of the spectral peak in the reflection spectrum can be used to measure the concentration of CO_2 gas. The influence of the cavity length is negligible in our case upon adsorption of CO_2 gas.

The fiber-top microcavity sensor was tested inside a cylinder gas chamber. With two flow regulators, the sample gas of different concentrations was generated through mixing pure CO_2 gas and pure nitrogen of different flow-rate ratios at atmospheric pressure. The sample gas flowed into the gas chamber at the same speed in all the experiments.

Figure 3 shows the response of the fiber-optic F-P microcavity sensor to loading and unloading of CO_2 gas. It can be seen from Fig. 3 that the wavelength increases with loading CO_2 gas, while decreases with unloading it. The sensor shows good reversibility with increase and decrease the concentration of CO_2 gas, with a little hysteresis due to the chemical sorption. The sensitivity of the sensor is 34.92 pm/%, according to the linear regression. Moreover, the sensor can measure the concentration of CO_2 gas from 0% to 75%

Figure 4 shows the result of a cycling test for characterization of the dynamic response of the fiber-optic CO_2 microsensor. One can see that the response time of the CO_2 microsensor is around 6.5 minutes, which is much faster than that previously reported PIL CO_2 sensor (which is about 30 minutes [20]). The fast response time of the CO_2 microsensor is attributed to its small size achieved by optical microfabrication process.

3 CONCLUSIONS

A novel fiber-optic CO_2 sensor has been fabricated by using an own-synthesized photo-crosslinkable PIL material. With the in-house optical 3D µ-printing platform, the PIL has been *in-situ* micropatterned on the end face of a standard single-mode optical fiber to form an optical microcavity sensor for CO_2 detection. Experimental results have revealed that the sensor has a wide detection range from 0 to 70% with the sensitivity of 35 pm/%. In particular, the sensor has a relatively fast response time of 6.5 minutes due to the small size of the device. It is believed that such a miniature fiber-optic CO_2 sensor has great potential in environment and exhaust gas monitoring applications.

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