Optical fiber sensors based on Fabry-Perot multilayer coatings

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The combination of fiber optics with nanostructure technologies offers great potential for the realization of novel sensor concepts. Miniature optical fiber sensors based on the Fabry-Perot (F-P) structure are presented. The transducer deposited on the fiber end face is multilayer coating consisting of a stack of nanoporous dielectric TiO_2 and MgF_2 films of optical thickness $\lambda/4$, forming a F-P filter with a typical reflection minimum at about 1300-nm wavelength. The reversible adsorption and desorption of water molecules in the porous films depend on water vapor, which would shift the reflected minimum wavelength of the F-P filter. Therefore, the humidity sensing is correlated with the central wavelength change of the F-P filter. A 14-nm shift in central wavelength is observed when the relative humidity increases from 0 to 100%. The central wavelength response to relative humidity is 0.9969 in linearity, which means that the proposed F-P thin-film sensor is very promising as a relative humidity sensor.

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Optical sensors are widely used in mechanical, chemical, and environmental applications as well as in civil structure health monitoring[1−5]. In such systems, highly reliable, compact, and inexpensive wavelength monitors are required. A promising solution is based on the wavelength-dependent transmission of spectral passive filters. Thin-film Fabry-Perot (F-P) interferometers are well accepted as narrow bandpass filters[6,7]. In optical sensor applications, F-P filters are employed in combination with photodiodes to detect sensor signals that are illuminated by white light sources or tunable lasers.

We have proposed thin-film F-P filters directly coated on fiber end faces to achieve a novel type of optical fiber sensors. The layer design of the F-P filters and their deposition process are optimized to realize a large cavity layer thickness and a porous layer microstructure, as shown in Fig. 1. The principle of such thin-film F-P sensor is that a porous multilayer is sensitive to environmental variation. Water absorption and desorption will result in a refractive index change in the cavity layer, and elastic modulation of layer thickness will occur when exposed to ultrasonic vibration. In both cases, the optical thickness of the F-P cavity layer will change; therefore, the characteristic wavelength of the thin-film F-P will shift, which is simulated and demonstrated in Fig. 2. By monitoring the reflected wavelength variation from the coated fiber end face, one can extract the impacting factor such as humidity content, which causes reversible water absorption and desorption, or ultrasonic frequency, which causes an elastic modulation of the layer thickness. In other words, humidity or ultrasonic frequency can be correlated with the shift in characteristic wavelength of the thin-film F-P sensor.

All tested fibers were cleaved. The tension of the cleaving device was adjusted as low as possible to achieve a mirrorlike fiber end face. The quality of the cleaved end faces was investigated using atomic force microscopy. The root mean square (RMS) roughness of the fiber end face was about 0.3 nm. After cleaving, the fiber end faces were subjected to a multistep cleaning procedure before deposition in order to achieve coatings with the highest quality.

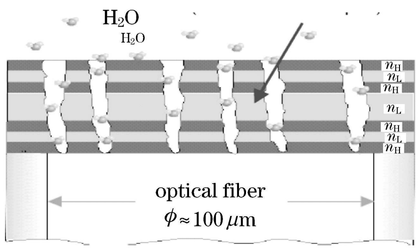

Fig. 1. Design of the F-P structure with porous thin-film layers.

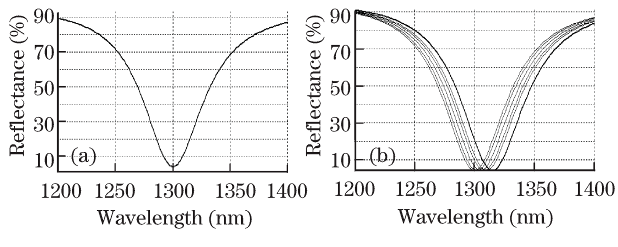

Fig. 2. (a) Central wavelength of the designed F-P structure at 1300 nm and (b) its wavelength shift due to water absorption and desorption.

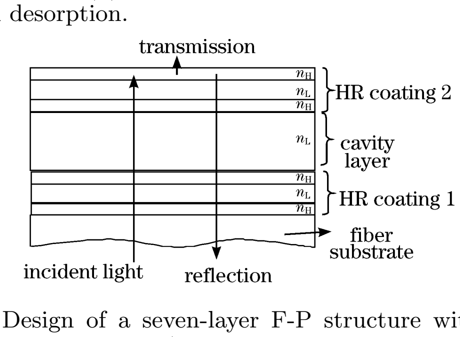

Fig. 3. Design of a seven-layer F-P structure with porous TiO_2 and MgF_2 layers (the cavity layer is 8 L, HR: high reflection).

Thin-film F-P filters containing multiple $\lambda/2$ spacers and different numbers of $\lambda/4$ reflector layers were deposited directly on the fiber end faces. The designed stack formula was (HL) H 8L H (LH), where H indicates high-index and L indicates low-index layers. A very thick cavity layer was deposited with the aim to improve sensitivity because a thicker cavity layer would have a stronger response to humidity or ultrasonic frequency change as a sensing material and transducer.

The F-P multilayer was coated on a fiber end face, which was mounted into a silicon tube with a diameter of 2 mm. A BESTECH depositing system was used to prepare these thin films. The system is specially designed for optical fiber coating and is equipped with electron (e)-beam evaporation and radio frequency (RF) sputtering sources. It has a turbo pump and allows a basic vacuum pressure down to 10^{-9} mbar. The fiber end faces were coated with dielectric layer stacks consisting of TiO_2 and MgF_2, which were well suited as high and low index materials for e-beam evaporation. Meanwhile, two 10×10 (mm) Si pieces were used as monitoring samples to characterize the deposited layer later. The deposition rate is about 0.5 nm/s. A total of seven layers with a stack design of 1H 1L 1H 8L 1H 1L 1H, as shown in Fig. 3, were realized with the initial characteristic wavelength centering at 1300 nm.

The setup of the humidity characterization system is schematically shown in Fig. 4. Light is coupled to the optical fiber with F-P multilayer coating on the end face. This F-P sensor element was located in a humidity chamber, where relative humidity could be tuned and monitored. The optical response of the filter coatings was analyzed by an optical spectrum analyzer (OSA) with a minimum resolution of 0.1 nm. The filter was illuminated over a broad spectral range provided by a white light source. During relative humidity characterization, the reflected wavelengths were collected with the optical spectrum analyzer. The measured data were recorded and sent to the computer for further data treatment.

An important property of the dielectric coatings on fiber end faces is the adhesion of the coating on the surfaces. The fiber end face should be free of impurities, especially organic materials, before the fiber is coated, and the surface should have a mirrorlike quality and a sharp edge[8,9]. Another key issue is the correct selection of materials that form the layer structure.

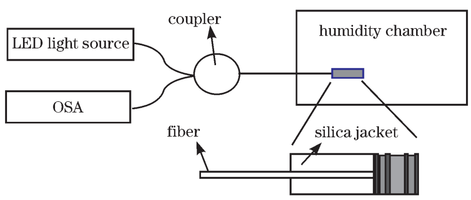

Fig. 4. Setup configuration of the F-P thin-film optical fiber sensor for humidity measurement.

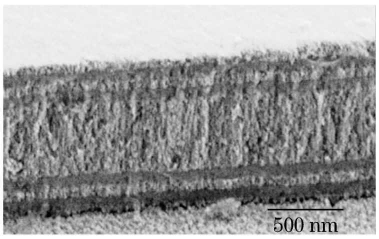

Fig. 5. Image of the deposited F-P microstructure.

From the optical point of view, the layer stack of the F-P filter would start with a TiO_2 layer on the fiber substrate. However, the TiO_2 layer tends to grow as a columnar structure. The thermal expansion coefficient of TiO_2 is one order of magnitude higher than that of fused silica. Thus, the layer is brittle and tends to break under thermal influence along the columns. The adhesion of TiO_2 coating on the fused silica fiber is low, and the coating can easily become delaminated by mechanical as well as thermal stress. To increase the adhesion of the F-P multilayer on the fiber end face, firstly, a buffer layer of SiO_2 is deposited, followed by the first stack layer of TiO_2. The buffer layer has nearly the same refractive index as the fiber bulk but has a softer structure. Under mechanical stress, the SiO_2 layer shows a ductile behavior. Figure 5 shows a fiber end face coated with a F-P filter consisting of seven stack layers. It can be concluded that the coating is well attached to the fiber surface, and the interface between the coating and the fiber can be clearly seen. The coating surface appears smooth on top but strongly columnar on the side.

The proposed F-P thin-film optical fiber sensor was tested for humidity measurement. The relative humidity was set at different points ranging from 0 to 100%, and then the reflected light was collected with the OSA and recorded. The measurement is shown in Fig. 6. From the results, one can find that the reflected central wavelength of the designed F-P thin-film sensor shows red-shift when the relative humidity increases. A 14-nm shift in central wavelength can be concluded when the relative humidity increases from 0 to 100%. The red-shift in the central wavelength can be explained by the refractive index change of the cavity layer due to water absorption.

At the beginning, the relative humidity is 0, which means that there exists no water in the chamber; therefore, the effective refractive index of the cavity layer is calculated with the MgF_2 bulk material and air as the material in the porous structure. However, when the relative humidity increases, water exists in the chamber and therefore penetrates into the porous structure. The effective refractive index here should be calculated with water as the material in the porous structure. Because water has a higher refractive index than air, the effective refractive index of the cavity layer increases and therefore results in an increase in optical length in the cavity

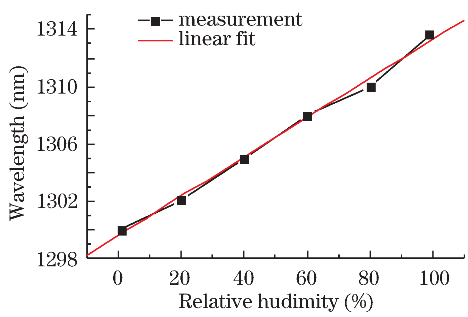

Fig. 6. Measurement of the central wavelength shift at different relative humidities.

layer. The central wavelength also shifts to a longer wavelength due to the increase in optical length in the cavity layer.

The central wavelength response to relative humidity is quite positive. The linearity is 0.9969, which means a nearly linear response. This means that the proposed F-P thin-film sensor is good enough in sensing performance as a relative humidity sensor.

In conclusion, miniature optical fiber sensors based on the F-P structure are proposed and demonstrated. The transducer deposited on the fiber end face is multilayer coating consisting of a stack of nanoporous dielectric TiO_2 and MgF_2 films of optical thickness $\lambda/4$, forming a F-P filter with a typical reflection minimum at about 1300-nm wavelength. The reflected central wavelength of the designed F-P thin-film sensor shows a redshift when the relative humidity increases. A 14-nm shift in the central wavelength can be observed when the relative humidity increases from 0 to 100%. The redshift in the central wavelength can be explained by the refractive index change in the cavity layer due to water absorption. In the case of relative humidity, the effective refractive index should be calculated with water as the material in the porous structure. The central wavelength response to relative humidity is 0.9969 in linearity, which means a nearly linear response. The proposed F-P thin-film structure on the optical fiber end face is very promising in sensing performance as a relative humidity sensor.

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