Sensors and Actuators B 194 (2014) 180–184

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

Sensitivity-enhanced Michelson interferometric humidity sensor with waist-enlarged fiber bitaper

Pengbing Hu [a,b], Xinyong Dong [a], Kai Ni [a], Li Han Chen [b], Wei Chang Wong [b], Chi Chiu Chan [b,*]

[a] Institute of Optoelectronic Technology, China Jiliang University, Hangzhou 310018, China
[b] Division of Bioengineering, School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore 63754, Singapore

ARTICLE INFO

Article history:
Received 13 June 2013
Received in revised form
13 November 2013
Accepted 20 December 2013
Available online 27 December 2013

Keywords:
Fiber-optic sensors
Michelson interferometer
Fiber-optic humidity sensor
Waist-enlarged bitaper

ABSTRACT

A fiber-optic humidity sensor composed of a chitosan-coated, waist-enlarged bitaper-based Michelson interferometer (WEBMI) is proposed and experimentally demonstrated. Humidity changes interference pattern of the sensor head through refractive index of the chitosan coating thus relative humidity level can be determined from corresponding wavelength shift. The achieved sensitivity is further enhanced by more than 5 times, from 26 pm/%RH to 135 pm/%RH, by reducing the fiber cladding thickness and oxidizing the chitosan film. Experimentations show that the measurement is fully reversible and repeatable with fast response and recovery time of ∼5 s and 3 s, respectively.

1. Introduction

Humidity is one of the most commonly concerned environmental parameters. Monitoring and control of humidity are very important in a diverse range of fields, such as food processing, pharmaceutical, structural monitoring and electronics processing [1,2]. In recent years, fiber-optic humidity sensors have been studied widely due to their many advantages such as compact size, high sensitivity, good resistance to chemical corrosion and insusceptibility to electromagnetic interference. According to the sensing mechanisms and structures, fiber-optic humidity sensors can be classified as fluorescence and absorption spectroscopic-based sensors [3,4], evanescent field sensors [5,6], in-fiber grating sensors [7,8] and interferometric sensors [9–12]. Because of the phase detection method used in fiber interferometric sensing scheme, it is easy for them to realize high sensitivity and accurate measurement. So far, many fiber-optic interferometric sensors have been reported based on Sagnac [13], Fabry–Perot [14], Mach–Zehnder [15,16] or Michelson configurations [17–19]. Among them, Michelson configuration shows great convenience in applications owing to its unique reflective operation mode. However, to our knowledge, there are few investigations carried out on fiber-optic Michelson interferometer-based humidity sensing.

Fiber-optic interferometric humidity sensors usually employ hygroscopic materials whose refractive index and/or thickness change with environmental humidity level due to the swelling and deswelling effects. Chitosan, as one of the most abundant polysaccharides in nature, can be easily turned into hydrogel of high elasticity when dispersed in diluted organic acids such as acetic acid. Owing to its good film-forming ability, non toxicity, biocompatibility and favorable chemical resistance property, chitosan is widely explored in environmental and biochemical fields such as drug delivery, food packaging, and human health [20]. All these factors make it a good choice as a coating material for humidity sensing.

In this paper, a humidity sensor with a chitosan-coated, waist-enlarged bitaper-based fiber-optic Michelson interferometer is studied. Waist of the fiber bitaper is enlarged rather than reduced (as shown in conventional fiber bitapers), so that the bitaper not only couples light between core and cladding modes to realize interference, but also possesses higher mechanical strength than conventional ones. Humidity changes interference pattern of the Michelson interferometer through refractive index of the chitosan coating thus relative humidity (RH) level can be determined from corresponding wavelength shift. Moreover, improvement of sensitivity by 5-times is achieved by reducing the fiber cladding's thickness and oxidizing the chitosan film.

* Corresponding author. Tel.: +6567904822.
E-mail address: eccchan@ntu.edu.sg (C.C. Chan).

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http://dx.doi.org/10.1016/j.snb.2013.12.081

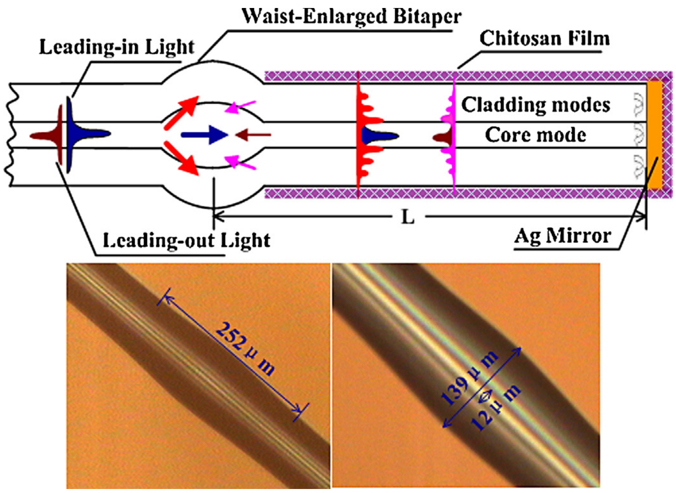

Fig. 1. Schematic diagram of the proposed WEBMI-based humidity sensor. The inset (a) and (b) are microscope photos of the waist-enlarged bitaper with different magniscales.

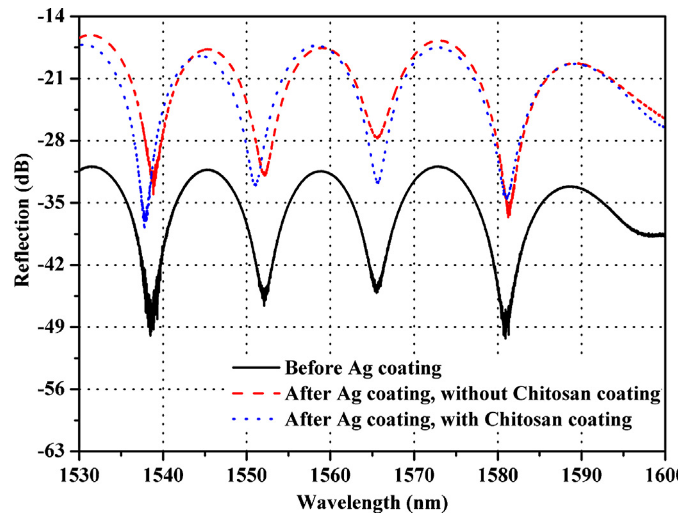

Fig. 2. Interference patterns of the sensor before and after silver/chitosan coating.

2. Sensor design and principle

The proposed humidity sensor is schematically shown in Fig. 1. It is formed by a waist-enlarged bitaper-based Michelson interferometer (WEBMI) coated with the hydroscopic chitosan. The WEBMI is formed between the bitaper and a silver mirror at the fiber end. The mode-coupling ratio mainly depends on the length and waist diameter of the bitaper. When the leading-in light propagating in the fiber core encounters the waist-enlarged bitaper, several cladding modes are excited due to the expanded fiber core. Both the core and cladding modes travel in the fiber and are reflected at the silver coated fiber end and re-combine in the bitaper region to interfere with each other. The corresponding interference pattern is therefore generated and measured by using an optical spectrum analyzer (OSA).

Assuming that only one linearly-polarized cladding mode is dominantly excited by the bitaper [21,22], thus the accumulated optical phase difference induced by the different effective refractive indices of the core and cladding modes can be expressed by,

$$\Delta\varphi = \frac{4\pi}{\lambda}(n_{\text{cladding}} - n_{\text{core}})L \quad (1)$$

where n_{core} and n_{cladding} are the effective refractive indices of the core and cladding modes respectively, λ is the operation wavelength and L is the length of the interferometric cavity. The interferometric pattern reaches its dip at the resonant wavelengths satisfying $\Delta\varphi = (2k+1)\pi$, here k is an integer.

When humidity changes refractive index of the chitosan coated on the surface of the WEBMI, $\Delta\varphi$ will be changed because n_{cladding} is a function of surrounding refractive index. Therefore the dip of the interferometric pattern will change in wavelength according to the variation in relative humidity. The corresponding wavelength shift can be simply described as,

$$\delta\lambda = \frac{4\delta n_{\text{eff}}(\text{RH})L}{2k+1} \quad (2)$$

where $\delta n_{\text{eff}}(\text{RH})$ is the humidity-induced variation in the effective index difference between the core and the cladding modes, i.e. $\Delta(n_{\text{cladding}} - n_{\text{core}})$.

3. Experimentations and discussions

3.1. Fabrication of humidity sensor

In order to build up a WEBMI, the fusion splicer (Sumitomo Electric, Type 36) was set to manual mode. The primary splicing parameters, i.e. overlap, splicing fusion time and arc discharge were specially set to 80 μm, 0.62 s and 52 steps, respectively. During the fusion splicing process, tips of the fibers were softened and then pushed together with relatively further traveling than their original distance, leading to the formation of a gradually enlarged bitaper [16]. The maximum diameters of the core and the cladding for the bitaper were ~12 and 139 μm, respectively. And the bitaper length was ~252 μm, as shown in the insets of Fig. 1. The insertion loss induced by the fusion bitaper was ~6 dB. Then the fiber was cleaved at 2-cm to the bitaper and a silver layer was last deposited on the fiber's end to increase its reflectivity.

For RH measurements, a layer of chitosan was coated onto the surface of the WEBMI. The chitosan solution was prepared by dissolving proper amount of chitosan powders in 0.1 M sodium chloride in 4% acetic acid solution for overnight stirring at room temperature. The resultant solution with a concentration of 1% was filtered and adjusted to about pH 1.7, where the formative film is more flexible and thicker [23,24]. The prepared WEBMI was then dip coated into the solution with a withdrawing speed of 30 mm/min by using a dip coater. The coating process was repeated several times to ensure good smoothness and few defects in the formed chitosan film. The coated WEBMI was exposed in the air overnight until it was partially dehydrated before an experiment. All the reagents used were purchased from Sigma–Aldrich.

Fig. 2 shows the measured interference patterns of the WEBMI sensor before and after silver/chitosan coating. Before any coating, the maximal extinction ratio reaches ~20 dB over the spectrum range from 1530 nm to 1600 nm, but the spectral intensity owing to 4% Fresnel reflection is very low. After silver coating, its spectral intensity was markedly increased by ~15 dB without any change in its spectral shape. In addition, a blue shift was observed in the interference pattern after chitosan coating due to the high refractive index of the coating film.

3.2. Sensing characteristics

To characterize response of the sensor to ambient RH, the sensor was placed into a lab-made sealed chamber, as shown in Fig. 3. The