Optics & Laser Technology 74 (2015) 16–19

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Humidity sensor based on optical fiber attached with hydrogel spheres

Zhi Feng Zhang, Yilei Zhang*

School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798 Singapore, Singapore

ARTICLE INFO

Article history:
Received 3 March 2015
Received in revised form
13 May 2015
Accepted 14 May 2015
Available online 2 June 2015

Keywords:
Fiber optic sensor
Humidity sensor
Hydrogel

ABSTRACT

This paper reports a new type of intensity-based fiber optic humidity sensor formed by solidifying mini hydrogel spheres on bare fiber cores. Upon variation of relative humidity, the refractive index of hydrogel spheres changes and leads to the intensity change of the transmitted light through the fiber. The dependence of the transmission ratio on the refractive index, size, number and separated distance of hydrogel spheres is simulated and optimized by using commercial software program TracePro. Simulation results suggest great dependence of the transmission ratio on the refractive index change of hydrogel spheres compared to even-thickness coating, because the spherical geometry is much more effective to couple light out of the fiber core. For example, the transmission ratio of the fiber core attached with a single hydrogel sphere in diameter of 2 mm could be reduced to 9% by changing refractive index of hydrogel while 2 mm coating could only achieve 87% for the same fiber core. Larger spheres reduce transmission as expected for longer coupling length. Increasing sphere number also cut transmission but the magnitude become minimal for four and more spheres. Preliminary experimental studies were carried out and demonstrated the idea of the sensor.

1. Introduction

Fiber optic sensing of relative humidity has been extensively studied and there have been a great number of proposed methods [1]. Sensing relative humidity is critical in various applications including food storage, climate monitoring, and chemical process [2]. Among various sensing methods of relative humidity, fiber optic based ones is preferred in many situations because of their minimal size, immunity to electromagnetic interference, and remote sensing capability. Though a large number of sensing schemes have been reported in literature, there is still a need for low-cost sensors, including both the fabrication and operation cost [3].

Intensity type of fiber optic sensors are the low-cost options compared to those based on the fiber Bragg grating [4], the surface plasmon resonance [5], photonic crystal fibers [6] etc. Those intensity based fiber optic sensor for humidity sensing are normally fabricated by coating hydrogels on the etched fibers. Agarose [7–10] and polyvinyl alcohol are the two most commonly used hydrogels and both silica fibers [7] and polymer optical fibers [11] are adopted previously. It had been demonstrated that agarose coated fiber core is sensitive to relative humidity due to refractive index change of the agarose hydrogel depending on the environment humidity [12]. The intensity of the transmitted light decreased at lower relative humidity.

This paper reports a new type of fiber optic humidity sensor which is also based on hydrogel coated optical fiber. Rather than coating the bare optical fiber core with an even-thickness coating, the reported sensor exploit hydrogel spheres on the fiber core. Its performance is firstly studied by commercial optical engineering software TracePro, which has been a powerful optical engineer tool and successfully applied in sensor design [13–16].

2. Simulation

The sensing performance of the sensor is simulated by TracePro. The fiber model is built based on the fiber patch cable (Thorlabs M28L02) used in experiments, which has a silica core in diameter of 400 μm and a TEQS™ cladding in thickness of 12.5 μm. The refractive index of the fiber core is set to be 1.4517 (pure silica at 625 nm). The refractive index of the cladding is calculated to be 1.40 based on the specified numerical aperture of 0.39. The refractive index of the hydrogel sphere is changed from 1.40 to 1.51. Design parameters including the sphere size, number, and separation distance are investigated.

3. Experiment

Protective layers of a segment of a fiber patch cable (Thorlabs M28L02) are removed by appropriate tools and the cladding is

* Corresponding author. Tel.: +65 6790 5952.
E-mail address: ylzhang@ntu.edu.sg (Y. Zhang).

http://dx.doi.org/10.1016/j.optlastec.2015.05.006
0030-3992/

burnt by flame to obtain bare fiber core. To avoid fiber break, the patch cable is fixed on an aluminum block. Then one or more drops of PEGDMA (Poly(ethylene glycol) dimethacrylate, average molecular weight 750, ALDRICH) hydrogel mixed with 0.5 wt% curing agent is dipped onto fiber core by using a micropipette. Hydrogel droplets are crosslinked for 30 s by a UV lamp (UV Flood, Epoxy & Equipment Technology Pte Ltd). Fig. 1 shows a typical sensor and hydrogel spheres and the spheres are not perfectly spherical due to the influence of gravity and surface tension. Humidity sensing tests are done in a temperature and humidity chamber (ESPEC North America Inc., SH-240). The temperature is maintained at 30 °C for all tests while the relative is set to 90% for two hours, then 80% for one hour, 70% for one hour etc. A fiber coupled LED (Thorlabs, M625F1) is used as the light source and a spectrometer (StellarNet, Silver-NOVA spectrometer) is used to measure the relative intensity of the transmitted light at 631 nm. Transmission ratio is calculated by dividing the relative intensity to that of 90% RH. The PEGDMA was selected because it has a refractive index of 1.465 which is the refractive index for hydrogel spheres that leads to lowest transmittance.

4. Results and discussion

Fig. 2 shows simulated light rays that travel through a single hydrogel sphere attached on a section of fiber core, illustrating the working principle of the sensor. Light travels in the fiber from the left to the right end. The refractive index of the hydrogel is higher than that of the original fiber cladding and hence some light rays refract into the hydrogel sphere. Because of the spherical geometry, refracted light rays have very small incident angle at surface of the front side of the hydrogel sphere and therefore refract again out of the sphere leading to light loss. This is the main reason that spheres are more effective in coupling light out of the fiber core and accordingly high sensitivity of the proposed sensor. As the refractive index of the hydrogel sphere is changed due to varied humidity, the transmission of light will change accordingly.

Simulated transmittance of hydrogel spheres coated fibers is shown in Figs. 3–5. Fig. 3 shows the transmittance of the fiber with a single hydrogel sphere as the refractive index of the hydrogel is increased from 1.40 to 1.51. For all sphere sizes, the transmittance starts to sharply decrease above refractive index of 1.43, and reaches a lowest transmittance around 1.46 and then gradually increases. The size of spheres dramatically influences the transmittance. As the diameter of the sphere increases from 0.6 mm to 2 mm, the lowest transmittance decreases from 62.9% to 9.0%. As a comparison, a uniform coating in thickness of 15 μm and length of 2 mm is included in the figure, which only leads to a lowest transmittance of 86.9%. While a single sphere of 2 mm is capable of reducing transmittance to 10%. Evidently, hydrogel spheres are much more effective in coupling out light from the fiber than the coating, suggesting higher sensitivity of sensors based on spheres.

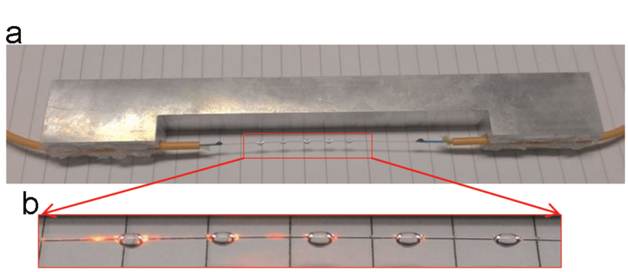

Fig. 1. Photo of a fabricated sensor with five hydrogel spheres attached on a section of fiber core. (a) The whole sensor; (b) detail view of five spheres with light input from left side. Bright spots away from hydrogel spheres along fiber core are due to slight damage to the core surface during fabrication.

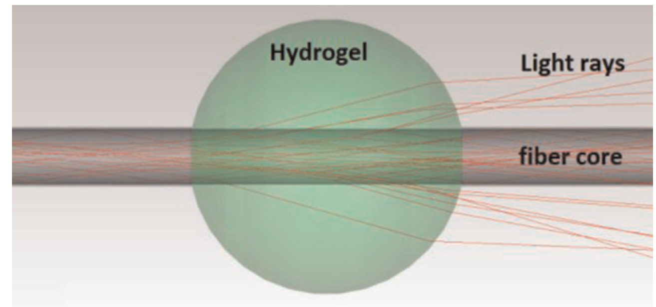

Fig. 2. Illustration of light rays that travel through a single hydrogel sphere in diameter of 2 mm and with a refractive index of 1.45. It should be noted that light loss occurs not only at the hydrogel sphere but also along fiber surface after the sphere, though the magnitude along the fiber is lower than that at the spheres.

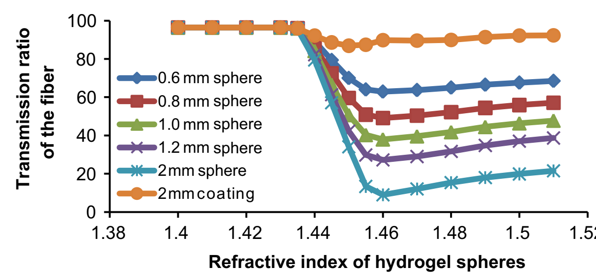

Fig. 3. Dependence of transmittance on the refractive index and size of a single hydrogel sphere.

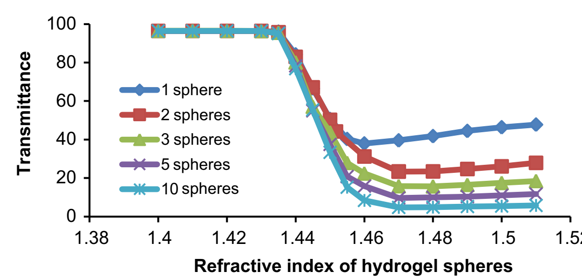

Fig. 4. Dependence of transmittance on the refractive index and number of hydrogel spheres in diameter of 1 mm.

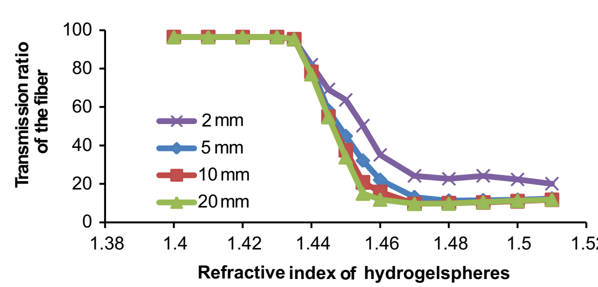

Fig. 5. Dependence of transmittance on the refractive index and separation distance of hydrogel spheres (five spheres in diameter of 1 mm).

Fig. 4 illustrates the influence of sphere number on the transmittance of sensing fibers. Expectedly more spheres lead to lower transmittance. For a single sphere, the lowest transmission occurs when the refractive index of the hydrogel is 1.46. For multiple spheres, this critical value of refractive index increases slightly. However, the accumulated transmission for N spheres is higher