Modeling and simulation of a polymer optical fiber humidity sensor for the skin microenvironment

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Abstract: A polymer optical fiber (POF) humidity sensor to monitor the humidity of a skin microenvironment of wounds without removing the wound dressing is modelled by ray tracing based on Monte Carlo simulation. To produce the sensor, a sensitive zone is made by removing the cladding from a segment of POF and mesoporous SiO_2 nanoparticles are deposited layer-by-layer. In this paper, there is a report that applied the ray tracing model to simulate POF humidity sensor characteristics and compared the experimental results that have been reported earlier. This sensor which is based on plastic optical fiber was easily fabricated and could be used for real-time humidity monitoring of wound status.

Keywords: polymer optical fiber, humidity sensor, ray tracing, relative humidity

1. Introduction

Control of humidity in many fields, such as industry, medical facilities, farming and the home environment, is becoming very important. Therefore, the development of a low-cost humidity sensor with fast response is very much required. An overview of fiber-optic-based methods for humidity sensing is given in [1]. Compared to their glass counterparts, they are less costly and easier to handle. POF humidity sensor (POFHS) has been proposed [2]. The various accurate methods of multimode fibers modal analysis are exploited. For example, the method that relies on solving power flow equations was described in [3–6]. In this paper, there is a report that applied the ray tracing model to simulate POF humidity sensor characteristics and compared the experimental result that has been reported in [2].

2. The structure of POF humidity sensor – an overview

Commercial fiber ESKA SK-10 (by Mitsubishi Rayon Co., Ltd.) was used to build the sensor. This multimode (step index) polymer fiber has the polymethyl-methacrylate resin core with the diameter of 240 μm. Its index of refraction is 1.49 and numerical aperture is 0.5. Its core is cladded in a 5 μm fluorinated polymer. The optical fiber of the humidity sensor is specially sensitized by precision machining into the cladding of a selected fiber segment. This removed the cladding and a portion of the fiber core along a selected fiber segment as illustrated in Fig. 1.

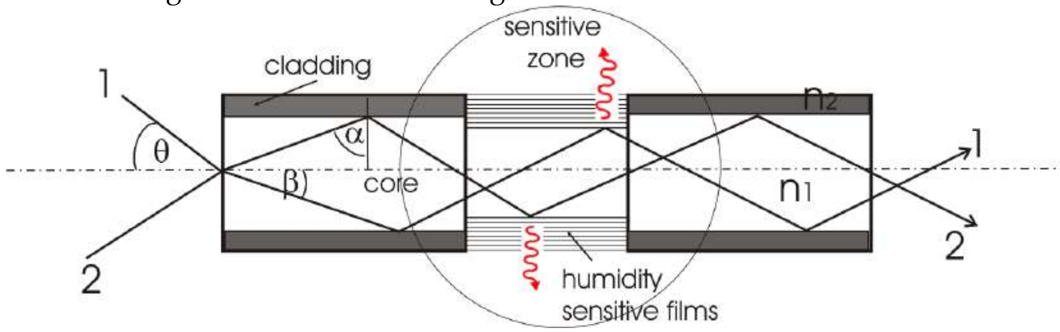


Figure 1. POFHS structure and the light propagation along the sensitive zone of the POF.

Once the cladding and a part of the core are removed, a film sensitive to humidity is deposited using the LbL method. It consists of SiO_2 mesoporous nanoparticles (SNOWTEX 20L, 40–50 nm diameter, Nissan Chemical, Japan). They were deposited with poly(allylamine hydrochloride) (PAH) to form a PAH/SiO2 hydrophilic material. This combination provided a higher sensitivity to humidity [7]. The deposition of the PAH/SiO_2 layers was in three stages [8]. The resulting cut-out of POF cladding/core introduced light transmission loss that is related to relative humidity.

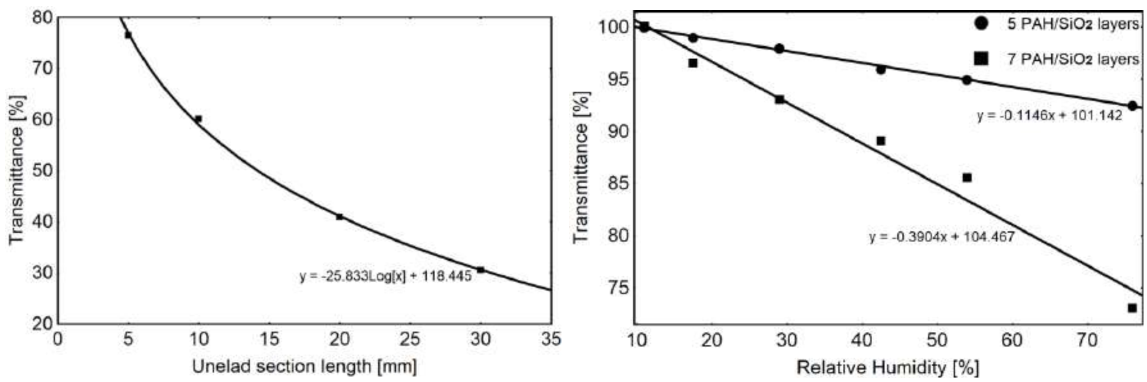
3. Modeling by three-dimensional ray tracing

Using Monte Carlo (MC) simulation, the basic idea is to trace rays propagating along the fiber that has the sensitised zone. Using MC more than 10^6 random directions for many input rays were generated. Each such launch is traced as it propagates along the POF until either contributing to a radiation loss or reaching the output fiber end. Rays radiated through the sensitive zone represent a modulation loss induced by the sensor – for the particular level of relative humidity taken as a reference. At different humidity, the ratio of this light loss to that in the sensitive zone at the reference humidity level is then calculated (under equal other conditions). The magnitude of this relative loss characterises the device sensitivity for the particular set of the sensitive zone's features, chiefly the zone length, depth and the number/type of deposited layers. Because it would be difficult to optimise these multiple sensor-features experimentally, a computer optimisation is performed by ray tracing. Further ray trajectories with distance from the input fiber-end are traced by the method described previously [9, 10].

3. Results

The important part of the simulation is to trace rays as they propagate along the sensitized zone of the multimode POF (ESKA SK-10 multimode POF, Mitsubishi Rayon

Co. Ltd. with the core diameter of 240 μm, 1.49 core refractive index and 5 μm thick fluorinated polymer cladding; NA = 0.5). A 125 mW point source was situated at a distance of 100 μm from the input fiber end. The axial location at the start of the zone is specified as an input parameter $z = z_1$ along the fiber axis. The zone is rough, and the depth of the zone is fixed. The sensing region's lengths of 5, 10, 20 and 30 mm were modelled for the core diameter reduced to 190 μm. The condition for total reflection was examined for each ray at every reflection. The program recorded the outcomes. If a ray reached the sensitized zone, its transmission loss was also recorded. To compare the interaction of the evanescent wave with different lengths of the sensitive zone, the transmittance at the wavelength of 611 nm was calculated as a function of the length of the unclad section of the POF. The transmittance is simply calculated as the ratio $(P_{out}/P_{in}) \times 100\%$ where P_{out} is the total optical power at the end face of the fiber, and P_{in} is the total initial power at the fiber origin.



(a) (b)

Figure 2. (a) Transmittance vs. the length of the unclad section of the, (b) Transmittance vs. relative humidity. The curves of a POFHS coated with five and seven PAH/SiO_2 layers.

Figure 2(a) shows transmittance as a function of the number of PAH/SiO_2 layers deposited. The hydrophilic mesoporous films are deposited layer by layer on the unclad central region of the POF. The light intensity change in the interaction of the evanescent wave with the hydrophilic film is calculated as well. Figure 2(b) shows the calculations with POFHS coated with five and seven PAH/SiO2 layers. Calculations are for the wavelength of 611 nm for both sensors (190 μm core diameter and 30 mm length of the sensitive region).

3. Conclusions

Plastic fibers' use as sensors often requires not much more than basic (inexpensive) devices such as light emitting and photodiodes. In this paper, a three-dimensional analysis of light propagation through the optical fiber humidity sensor is reported. The sensor characteristics are simulated in order to analyze and compare the experimental results. All major cases that may appear when light interacts with the device's sensitive zone have been considered. This simulation includes different lengths of the sensitive zone of the POF. In the computer experiment, the penetration depth of the evanescent wave and its interaction with the hydrophilic film is related to the light loss that reaches the sensitized region. The refractive index of PAH/SiO_2 layers was altered, and the fiber transmittance was calculated as a function of relative humidity. These results are in good agreement with previous experimental results [2]. This new approach for humidity sensing is potentially extremely helpful for providing improved monitoring of wound status. If successful it will be of increased benefit for patients and offers the potential to allow a better understanding about the process of wound healing itself.

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