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A planar low-cost full-polymer optical humidity sensor

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Abstract

We present an all-polymer optical humidity sensor, based on a 1 mm plastic optical fiber (POF) with a U-bend, cladded with poly(N,N-dimethylacrylamide) (PDMAA) in the sensing region. The cladding changes its scattering properties on absorption of environmental humidity, thus modulating the transmitted optical power through the sensor. We explain the working principle of the sensor and show experimental results regarding scattering behavior of the cladding material and sensitivity to sudden humidity changes. We also propose a planar layout suitable for application to a hot embossing or lamination process for large-scale fabrication.

Keywords: Polymer waveguides, polymer optics, planar systems, humidity sensor, evanescent wave sensor

1. Introduction

The measurement of environmental humidity is essential in a multitude of applications, ranging from automated climate control [1] in office environments, over the production and storage of food [2] or electronics [3] to compensation tasks in sensing applications sensitive to humidity as, e.g., for piezoresistive sensors [4]. With the ongoing effort to investigate the feasibility of plastic optical sensors for structural health monitoring (SHM)

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applications [5] the need for parallel measurement of environmental relative humidity (RH) arises to enable compensation of water absorption into the polymer systems. In case of the often utilized polymethylmethacrylate (PMMA), the water absorption can exceed 1.5 vol%, depending on temperature and humidity [6], thus influencing e.g. strain measurement by swelling of the sensor material itself.

Polymer optical strain sensors for SHM are most often based on the measurement of mechanical deformation, either by utilizing a fiber bragg grating in a polymer optical fiber [7] or an embedded waveguide, by applying other techniques such as optical frequency domain reflectomety (OFDR) [8], or by evaluating the coupling efficiency between two waveguides arranged vis-à-vis to each other over an elongation area designed according to the measurement range required [9]. The main advantages of such polymer-optical systems lie in the comparatively high elasticity with nondestructive elongations of up to 5 % (as compared to 0.5 % for glass-optical fiber sensors) [10] and the fundamental compatibility to high-throughput manufacturing processes like hot embossing [11] or lamination [12], thus reducing the overall unit costs.

Humidity measurement with plastic optical fiber (POF) or glass optical fiber coated with functional claddings has been demonstrated using metal salt compounds [13], agarose gel [14] and polyvinyl alcohol as cladding material [15] among others. The mode of operation of these systems relies either on a change of absorption wavelength [13], of the cladding refractive index [14,15] or of the scattering behavior [16] upon absorption of environmental humidity. The underlying principle of the humidity sensor presented here also utilizes the change of scattering in the sensing cladding deposited on a POF which increases with increasing moisture absorption leading to a decline in transmitted power through the system. The cladding material is a hydrogel coating based on poly-dimethylacrylamid (PDMAA). This material is deposited by dip coating in this case and then crosslinked via UV irradiation which triggers a C,H insertion reaction between UV active benzophenone (MABP) groups incorporated in the polymer in adjacent chains. At the same time anchoring of the layer to the polymeric substrate is achieved through the same reaction.

In future, the cladding material can basically be deposited by spray coating using a process as described in [12]. This ensures a good compatibility of the production process to lamination techniques and paves the way to the production of combined polymer waveguides (e.g. used as displacement sensor) and humidity sensors for integrated humidity compensation in a single production line. Here, we demonstrate the fundamental functional capability of the proposed system using a 1 mm U-bent unclad POF and the aforementioned cladding material and describe a way to manufacture the sensor using techniques already presented [12].

2. Humidity Measurement with Evanescent Wave Sensors

The principle of humidity measurement with the evanescent wave method is based on attenuation of the evanescent field of an optical beam in the sensing region either by optical absorption or scattering. The evanescent field in the case of total internal reflection in an optical waveguide is the part of the field transmitted through the optical boundary, decreasing exponentially with increasing radial distance from the fiber optical axis. Although it does not transport energy away from the reflection point on the boundary, attenuation of the evanescent field leads to attenuation of the wave reflected back into the waveguide core. Since the functional principle of macroscopic optical fibers such as 1 mm POF can be satisfyingly described by total internal reflection, such a POF coated with an attenuating material would show increased attenuation of the transmitted light.

Besides the sensitivity of the attenuation to humidity changes, the penetration depth d_p of the evanescent field into the cladding is the main factor defining the overall sensitivity of the sensor. Since d_p rises with decreasing beam angle θ, see Fig. 1a) for the basic sensor geometry, it is desirable to use a multimode fiber for light guiding and to excite as many higher order modes as possible in the sensing region. Often the numerical aperture (NA) in cladded waveguides is small and, therefore, only lower order modes are present in the sensing region. The sensing region itself has a lower critical angle $\theta_s<\theta$ between beam ray and interface normal and, thus, a higher NA, due to the missing cladding or due to the sensing cladding having a much lower refractive index n_S than the cladding everywhere else on the fiber. To excite higher modes in the sensing region, most often sensors of this type are bent in a 180° configuration, thus increasing the beam angle and, therefore, the penetration depth. A comprehensive investigation of this principle is given in [17]; in this work, only a short summary of the mechanism is given.

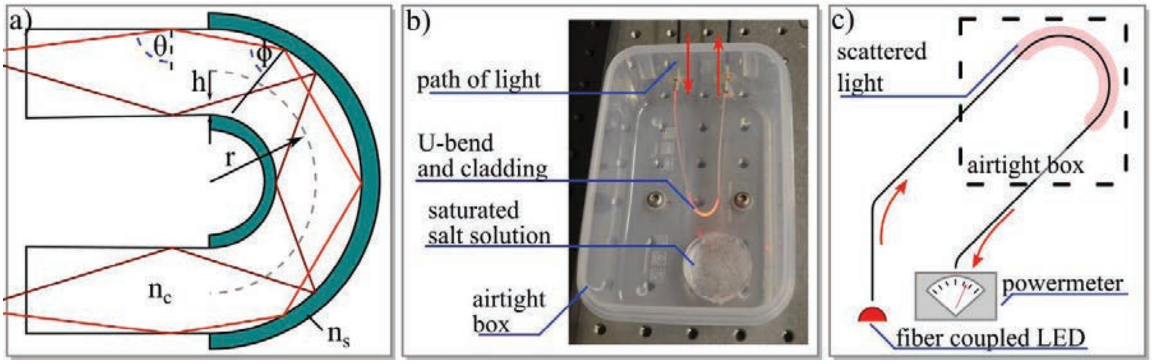

Fig. 1 a) Path of light inside the U-bend. Two examples for light beams propagating through the U-bend are shown schematically by the bright red and dark red lines. b) Experimental setup for systematic humidity measurements. The box can be closed with an airtight lid, allowing the humidity to rise to the level buffered by the saturated salt solution. c) Schematic of the experimental setup, path of light indicated by the red arrows.

If illuminated with a light source with isotropic intensity distribution in radial direction, i.e. exhibiting a flat-top intensity profile, the power in the waveguide will also be isotropically distributed over all modes or beam angles $\theta_s < \theta < 90°$. On entering the U-bend, the angle between the surface normal and the beam, denoted as ϕ, is depending on several factors as illustrated in Fig. 1 a). Firstly, the beam can pass the U-bend by being reflected on both the inner and the outer interfaces or it can pass the U-bend by being reflected only on the outer interface. Secondly, ϕ depends on the beam angle θ before entering the bend, on the beam height h relative to the optical axis and on the bend radius r. Calculating the new reflection angles ϕ in the bend for all beam angles and heights gives a new contact angle distribution of the beam rays in the fiber of $\phi = f\left(\theta, h, r\right)$ that ultimately leads to a new power distribution inside the fiber and, due to the geometrical constraints in the fiber, to increased energy in the evanescent field of the fiber.

With the increased amount of energy entering the cladding, the evanescent wave sensor can sensitively detect small changes of, e.g., the cladding attenuation or the cladding refractive index, for example, by monitoring the transmission losses. In our sensor approach, we exploit the change of the optical scattering properties of the cladding for humidity measurement, see below.

3. Experimental Setup and Sensor Performance

3.1. Experimental Setup

The experimental setup consists of a short piece of PMMA POF with a U-bend of radius $r = 5$ mm. The U-bend is coated with the PDMAA-*co*-MABP polymer and fixed inside a box with an airtight lid, shown in Fig. 1b). Together with the sensor, a petri dish with a saturated salt solution is positioned inside the box, which allows to adjust the relative humidity inside between 11.4 % and 85.1 % at a temperature of 20 °C by using lithium chloride and potassium chloride saturated salt solutions, respectively.

Incoherent light from a Thorlabs® M625F1 High Power LED is coupled into the sensor and the transmitted power is monitored using a Thorlabs® PM200 Powermeter together with a Thorlabs® S151C fiber coupled photodiode detector. The environmental humidity outside the box is measured with a Testo® 608-H1 thermo-hygrometer. Each measurement starts with a closed lid of the box, the inside humidity is, therefore, fixed by the saturated salt solution. When the lid is lifted, the relative humidity drops/rises to room relative humidity, simulating an approximate step function to be detected.

An additional experimental setup was conceived to determine if a change in the scattering properties of the PDMAA coating occurs when the environmental humidity changes. For this purpose, coherent and collimated light at 632 nm is launched from a 3 mW HeNe-Laser onto a coated PMMA substrate and the resulting beam intensity and waist diameter in the far-field is recorded using an Ophir® 620U beam profiler, see Fig. 2.

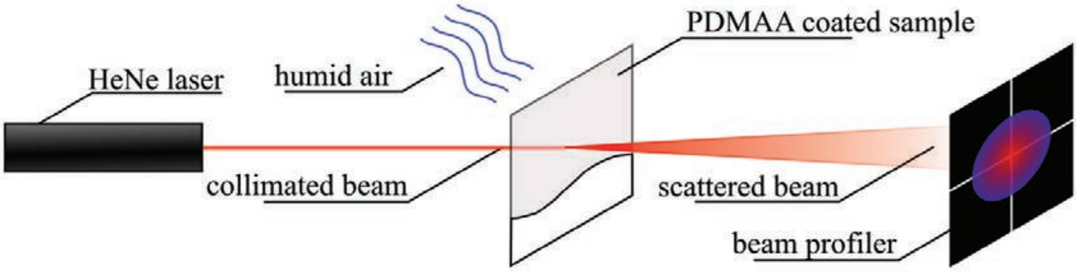

Fig. 2 Experimental setup for the characterization of the scattering properties of the PDMAA coating. The collimated beam from a HeNe laser is scattered by the coated PMMA plate and the beam width is measured with a beam profiler.

The intensity measured with the beam profiler is integrated to a ‘total counts’ value, indicating the power arriving at the CMOS sensor of the profiler. A change in the scattering properties should, therefore, increase or decrease the measured power for decreasing or increasing number of scattering events or decreasing or increasing beam waist diameter, respectively.

3.2. Results and Discussion

The results of the humidity measurements using the setup in Fig. 1 are shown in Fig. 3. The graph shows measured data from three experiments, roughly an hour apart, where the lid of the box is finally lifted. Consequently, the humidity around the sensor drops from 85.1 % to room relative humidity which was 23.4 % during all experiments. It can be observed for the blue and red curves that the transmitted LED power rises with decreasing humidity, thus, indicating a decrease in cladding attenuation. The simultaneous increase in the cladding refractive index n_S which can be assumed for decreasing water content should, in contrast, lead to a decline in transmitted power due to the resulting lower NA. This indicates that the effect of the absorbed humidity on the optical attenuation is by far larger than the change of the refractive index of the cladding.

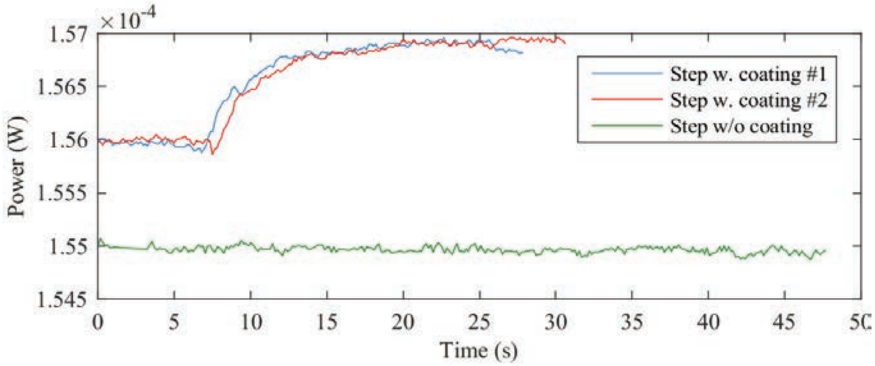

Fig. 3 Different recorded power curves for the relative humidity varying from 85.1 % to 23.4 %. The red and blue curves show the reaction of the same sensor to lifting the lid after the humidity inside the box reached a stable value of 85.1 %. The green curve shows the reaction of an uncoated POF. In each experiment the lid of the box was lifted at around 7 s of measurement time.

For comparison, the experiment was repeated with another POF without cladding, green curve in Fig. 3. It can be observed that this sensor shows a signal dominated by random noise only and the transmitted power does not increase. For each experiment, the lid of the airtight box was lifted after around 7 s of measurement time.

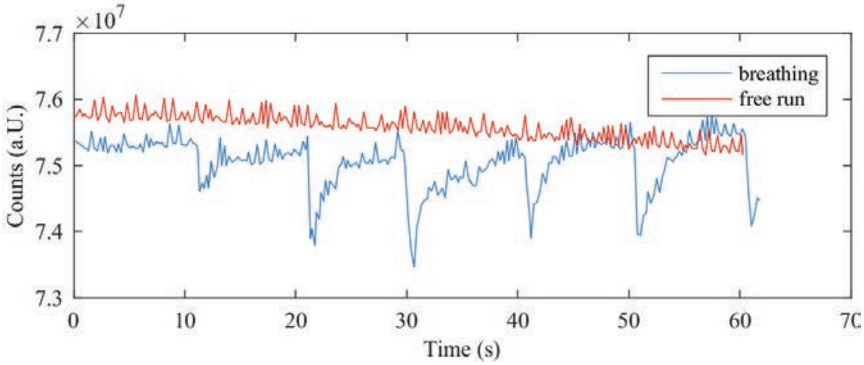

Fig. 4 Integrated CMOS counts over time showing the coated PMMA plate while exposed to human breath (blue) and while measuring the environmental humidity in air (red). Each decrease in counts in the blue curve indicates a breathing event on the substrate.

To verify the change in the scattering properties we carried out the measurements using the setup depicted in Fig. 2. Figure 4 shows the integrated CMOS counts over time when the sensor was exposed to human breath and, for comparison, the corresponding signal when the sensor was exposed to environmental air. In the first case the measurement curve shows a clear drop in integrated power for each breath event followed by a rise until the integrated counts reach the initial level again. This rise is mainly dictated by the relative humidity of the environment. The measurement on air does not show this behavior. The slight offset between the two curves originates from a drift in the output power of the HeNe laser.

4. Planar-Optical Humidity Sensor Approach

While the demonstrated prototype of the sensor uses a rather bulky 1 mm standard POF it is in principle possible to switch to a planar design, using solely lamination and spray coating techniques.

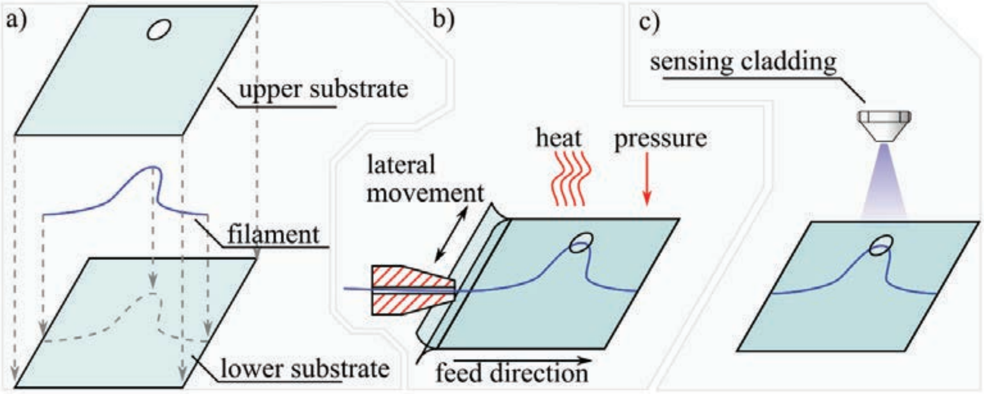

Fig. 5 Schematic of the production process for a planar sensor system, using a combination of lamination and spray coating techniques. The system consists of three layers: a) One core filament and two substrate layers that can be laminated using pressure and heat, b). The sensing cladding layer can be applied by spray coating through an opening in the top substrate layer, c).

Figure 5 shows a schematic of such a production process in detail. The sensor consists of three layers, Fig. 5 a): a standard foil substrate, a core filament, later serving as waveguide inside the two substrate layers, and a superstrate with an opening to be placed where the filament shows the smallest bend radius. The substrate can be laminated in a hot-roll laminator, see Fig. 5 b), while a guiding nozzle moves the filament that is fed between the substrate layers, thus creating the required wave-like filament pattern. In a last step, Fig. 5 c), the sensing cladding can be spray coated onto the sensor blanks and after end facet preparation the humidity sensor is ready for use.

The benefit of the proposed approach is its applicability to roll-to-roll processes, thus enabling direct mass-production of planar all-polymer sensor devices. The working principle in this case is not expected to differ too much from the presented U-bend humidity sensor, although the achievable sensitivity will depend on the materials used. For this design, we propose to use a COP filament as the waveguide and PMMA as substrate. As, in general, individual calibration of each sensor is not feasible for low-cost sensor systems an estimate of the sensor performance can be implemented by careful evaluation of achievable precision and repeatability of the manufacturing process.

5. Outlook and Conclusions

In this work, we demonstrated a prototype optical sensor for relative humidity measurement solely based on polymer materials. The sensor can detect humidity changes in the range between 24 % to 85 % relative humidity at 20 °C environmental temperature. It shows a rise time of approximately 5 seconds, which lies in the range of other fiber optic humidity sensors as reviewed in [6]. The sensor is easy to manufacture and only requires a 1mm PMMA POF in U-shape configuration and dip-coating to apply the sensing polymer.

While the measurements for the characterization of the sensor principle were carried out with a 1 mm POF, we ultimately aim for a planar humidity sensor compatible with hot embossing or lamination production technologies. We recently showed that it is possible to fabricate polymer-optical waveguides by utilizing a lamination process, a COP filament as core, and a PMMA foil as cladding material. Since the process relies solely on spray coating and lamination technologies it is well suited for larger-scale production of the demonstrated humidity sensor. In more detail, the sensing polymer could be applied by spray coating and the resulting sensing waveguide could then be laminated between two PMMA substrate foils, one with an opening allowing to establish contact between the coated filament and the surrounding.

In the next step, we plan to produce the proposed sensors both by lamination and by hot embossing to evaluate and compare the performance of both implementations. In a second step, we plan to integrate the humidity sensor with polymer-optical strain sensors on a single substrate to allow for humidity-compensated optical strain measurement.

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