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Colorimetric gas sensors based on optical waveguides made on plastic foil

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Abstract

We report on the realization of a low-cost polymeric optical waveguide made on a plastic foil and used for colorimetric gas detection. Low-temperature processes have been used for the realization of polymeric micro-mirrors and the depositions of the chemochromic reagent on PET foil. The planar waveguide configuration aims at improving the transducer sensitivity and simplifies its fabrication. Indeed, the device is currently produced by standard microfabrication techniques but its configuration and the materials involved make the sensor compatible with large scale and low-cost fabrication techniques. The operation of the optical transducer was applied to a colorimetric gas sensor and validated for the detection of ammonia.

Keywords: Optical waveguide; Plastic foil; PET; Colorimetric gas detection; Micro-mirror; Ammonia

1. Introduction

Optical transducers targeting the detection of gases have gained interest since it can provide better sensitivity and selectivity than other gas sensing techniques. One trend in the field is the development of low-cost devices to enlarge their field of application with the development of selective and low-cost colorimetric gas sensors [1]. However, in a typical configuration the optical measurements are performed in a transmission mode with a limited optical path. We have therefore considered a waveguide configuration in order to increase the gas sensitivity of such sensing devices. However, the optical transducers are relatively expensive due to the precise alignment required with the use of a light source and a spectrometer coupled with fiber optics [2,3] or the use of a laser [4]. Moreover, despite their high sensitivity, such optical transducers are bulky and power consuming and for these reasons not suitable for the development of low-cost and low power consuming devices.

A significant decrease in manufacturing cost may be achieved with the use of plastic substrates and appropriate manufacturing techniques. We present here a transducer concept based on an optical waveguide made of a PET foil combined with surface mount device (SMD) optical components developed for colorimetric based gas sensors. Its planar configuration makes it compatible with large scale fabrication processes, such as roll to roll, hot embossing or

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inkjet printing, targeting their fabrication at low cost. The inherent ability of the PET as substrate to guide light was used to simplify the fabrication of the device. The application of the optical transducer for gas detection was demonstrated with the deposition of a colorimetric film sensitive towards ammonia [5].

2. Experimental

2.1. Principle of operation

The optical transducer is based on the combination of SMD photonics devices with a planar optical waveguide (Fig. 1). The light propagates in the latter by total internal reflection due to its higher refractive index than the surrounding media. The light coupling between the light source, the waveguide and the light detectors (one reference and one for the measurement) was ensured by micro-mirrors formed on the PET foil. The transducer was designed in a planar configuration and realized in polymeric materials to make it more cost effective. The optical waveguide developed here aimed at colorimetric gas sensing. It is based on the variation of the light absorption in the evanescent field of a colorimetric film deposited on the plastic foil and sensitive to a specific gas to be detected.

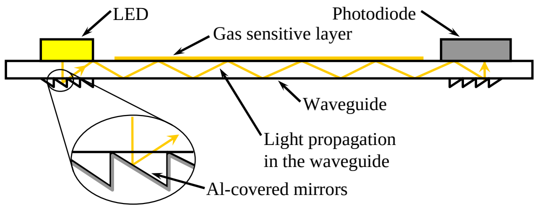

Fig. 1: Cross-sectional schematic of the transducer. A LED was used as light source. The light intensity that reaches the photodiode (i.e. the sensor response) depends on the absorption of light in the evanescent field going along the colorimetric film in presence of the gas to be detected.

2.2. Technical realization of the transducer

The optical waveguides were cut out of a 100 or 250 µm thick optically clear PET foils (Melinex® 506 from DuPont) or made out of standard glass microscope slides, the latter used for the validation of the fabrication of the micro-mirrors and to compare the optical losses with the PET-based devices. Waveguides of two different lengths, 23 and 46 mm, were fabricated to investigate the influence of this parameter on the light losses and gas sensing performances. The fabrication was based on low-temperature processes to be compatible with the materials involved. Micro-mirrors coupled the light in and out of the waveguide (Fig. 2). They were patterned in an UV-curable optically clear epoxy resist with a PDMS mold. An aluminum layer, 300 nm-thick to achieve a proper step covered edge, was deposited by e-beam evaporation through a shadow mask on some waveguides to investigate its influence on light reflection on the mirrors. Figure 3 shows the technical realization of the waveguide on a PET foil.

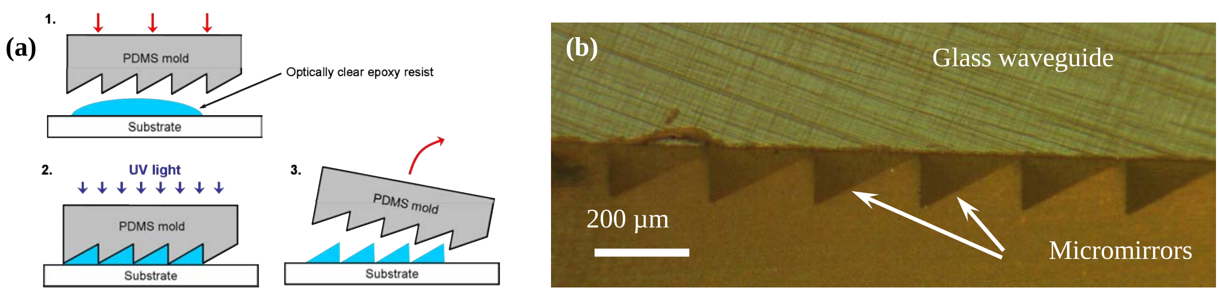

Fig. 2: (a) Patterning of a UV-curable resist. A droplet of resist was dispensed on the substrate (1) before molding it with a PDMS part (2). The resist was polymerized by UV light before removing the mold (3). (b) Cross-sectional picture of the micro-mirrors patterned on glass slide.

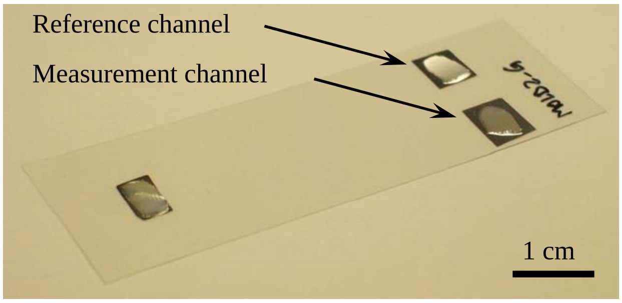

Fig. 3: Optical picture of a PET optical waveguide with micro-mirrors covered with 300 nm of aluminum.

2.3. Characterization of the transducer

First, the light intensity reaching the detector was measured for all the fabricated waveguides with the photonic devices used for gas measurements. A SMD LED (SML-012DTT86AA from Rohm) and standard SMD photodiodes (BPW34 from Osram, λ_{max} = 850 nm) were selected. The length of the waveguide and its thickness were investigated to determine the most suitable configuration in term of reduction of the optical losses. The influence of Al on the mirrors on the light coupling was also evaluated. Finally, gas measurements were performed with a custom-made gas mixing system. A colorimetric film sensitive to NH_3 composed of a pH indicator (bromophenol blue) embedded in a PMMA polymeric matrix and a plasticizer [5] was deposited by spin-coating onto the waveguide. A yellow LED (λ_{max} = 590 nm, 100 mcd) was used as light source since the variation of the light absorption of the film sensitive to NH_3 was the highest at such wavelengths. The colorimetric sensor was placed in a gas cell of 15 x 30 x 90 cm^3. The gas sensor was exposed to concentrations of NH_3 ranging from 20 down to 5 ppm, which was the minimum reachable with the gas mixing station at our disposal.

3. Results and discussion

Figure 4 presents the light coupling using the micro-mirrors. Optical losses in the waveguide including the micro-mirrors were between 2 and 7.5 dB depending on the design. The shortest and thickest waveguides exhibited the lowest losses. With thicker waveguides, better light coupling was achieved, leading to a higher intensity reaching the photodiodes. The addition of Al on the micro-mirrors slightly increased the optical losses by absorption while total internal reflection occurred when the mirrors were left uncovered. 46 mm long PET waveguide of 250 µm in thickness with uncovered micro-mirrors exhibited optical losses of about 3 dB.

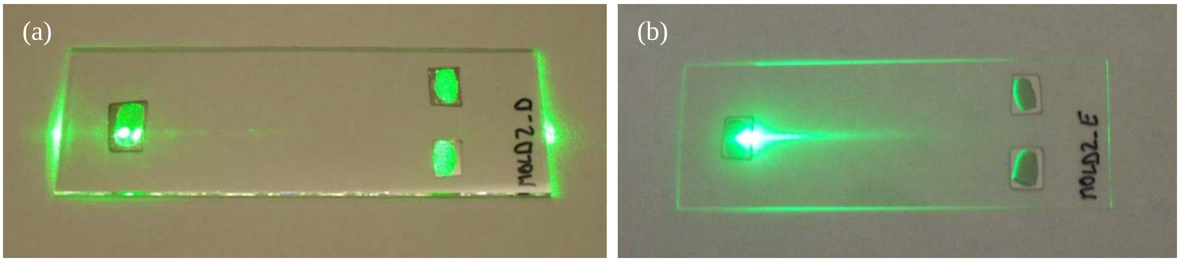

Fig. 4: Optical picture of 25 x 70 mm (a) glass and (b) 100 µm thick PET waveguides. Light from a laser was applied to the left mirror and came out of the measurement and reference channels on the right, which showed the proper optical operation of the device.

The operation of the plastic optical transducers for colorimetric gas detection was validated under NH_3 (Fig. 5). Fairly high sensitivity of the system towards NH_3 was reached, which confirm the suitability of the optical transducer developed for this particular application. The slow response time was due to the colorimetric film.

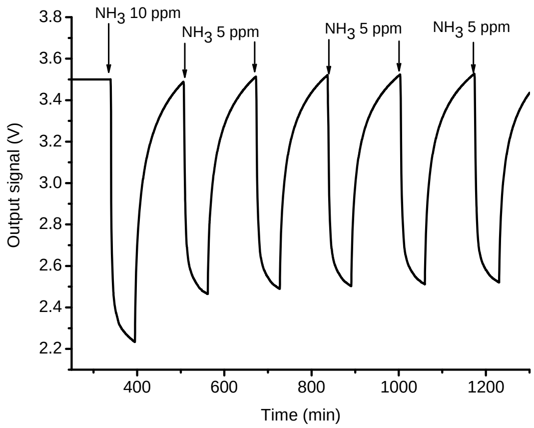

Fig. 5: Gas measurement performed with the colorimetric sensor consisting in a 250 µm thick PET foil with uncovered mirrors when exposed to different concentrations of NH_3. The measurement was carried out in synthetic air with about 50% of relative humidity and a gas flow of 500 ml/min.

4. Conclusion

A polymeric optical waveguide based on PET foils has been presented. It combined low-cost materials with low temperature fabrication targeting large scale fabrication. The light losses according to the material and waveguide length have been investigated. They were of about 3 dB for a 46 mm long waveguide of 250 µm in thickness made of PET. Its ability of being used for gas sensing has been demonstrated in combination with an ammonia sensitive colorimetric film. Despite its low response time due to the sensing film, the device exhibited a good sensitivity towards NH_3 and we are currently investigating the limit of detection reachable with an optimized sensor configuration.

Other gases such as O_2 or CO_2 for instance could be potentially detected by changing the chemochromic film, which further widen the application field of such transducers. We are looking at their potential fabrication using the hot embossing techniques and we are also considering PEN as substrate to further reduce the cost.

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