Recent Progress in Advanced Humidity Sensors

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Abstract. The measurement and control of humidity is imperative for a variety of applications. We present our significant advances in humidity sensing with different classes of sensors, which includes colorimetric indicators, humidity-based touchless control, ultra-fast point humidity sensors, and fully distributed humidity sensors.

1. Introduction

Water is a precious resource which connects every aspect of life. The world has a global water crisis involving water loss. There are 844 million people living without access to safe water [1], and 1 million deaths per year due to water, sanitation and hygiene-related diseases. Yet, billions of treated water are lost every day due to leaking pipes in the United Kingdom and Australia alone [2, 3]. Saving this large quantity of lost water can benefit society and save lives.

On the other hand, water in unwanted places can lead to problems. As a result, it is of great value to monitor water along underground/building water pipelines; inside ships and submarines; along undersea tunnels; along roads, aircraft runways and railway racks; along electrical power lines; and inside nuclear power stations.

Similarly, moisture generated from high relative-humidity (RH) is damaging to various environments. As such, it benefits the economy to monitor the RH inside grain storage rooms; inside wood treatment chambers; within timber buildings; across forests and botanic gardens; within paint/coating manufacturing lines; inside museums and hospital rooms; and outside aircrafts.

We report our progress in developing advanced humidity sensors to solve the aforementioned problems, which is a multi-disciplinary effort by photonics, sensing and material-science experts.

2. Discussions

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We have recently exploited polyelectrolyte multilayer (PEM) coatings based on layer-by-layer-assembled poly(diallyldimethylammonium) (PDDA) and poly(styrenesulfonate) (PSS) to develop state-of-the-art humidity sensors. Although this particular type of PEM coating has been known and extensively used for decades in applications such as sensors [4], anti-reflection coatings [5], anti-fouling surfaces [6] and superhydrophobic surfaces [7], its enabling properties when deployed as a thin film have been previously overlooked.

When a PEM coating is only a few hundred nanometers thick, thin-film interference between the material interfaces (air-polymer and polymer-silicon substrate) give rise to selective spectral filtering that outputs a uniform color. We have investigated the optical properties under different levels of relative humidity (RH), as illustrated in Figure 1(a). While the number of bilayers change the starting color of the thin film, exposure to RH enables it to cycle through a spectrum of colors. The underlying mechanism is adsorption of water vapor, followed by absorption of water, which produces refractive-index change and swelling. As much as 56% thickness change and 0.15 RI change were observed [8]. The response time was only ~35 ms, which places it amongst the fastest humidity sensors in the literature [9]. A more accurate RH readout can be achieved by using 3 or more coating strips shown in Figure 1(b) with different initial thicknesses, such that the combined set of colors is translated into a RH reading.

As the next step forward, we paired the PEM coating with laser interrogation to provide automated and precise measurements of RH. The wavelength shift for a 0-100% change in RH is 305 nm [8], which would yield an ultra-low detection limit of $6.6 \times 10^{-3}\%$RH when a 20 pm wavelength resolution
spectrometer or optical spectrum analyzer is used. It was found that when the substrate surface was treated with amino groups rather than piranha solution, the resulting sensitivity is higher [8], as shown in Figure 2.

We also explored humidity-based touchless control in novel applications such as access for people with disabilities, portable device input, and a new class of electronic toys. A demonstration sensor module is shown in Figure 1(c), which could be miniaturised by several orders of magnitude. This direction was not possible before due to the lack of combined speed, sensitivity and uniformity.

To push the lower limit of response time for finding new applications in process control, touchless keypads, water-hazard safety mechanisms, respiratory analyzers, and atmosphere monitoring, we coated a single bilayer of PEM coating on a bent fiber taper shown in Figure 1(d). The result is the shortest-ever response time of ~3 ms from a humidity sensor [10], and one order of magnitude faster than the previous report of ~30 ms [11].

The first-ever practical (i.e. non-bending mechanism) fully distributed humidity sensor based on an all-fiber design has recently been demonstrated (i.e. under peer review), as shown in Figure 3. This is the key to solving the aforementioned problems of water leakage and moisture monitoring. Owing to the high optical-loss of the specialized optical fiber used (>3 dB/m), short-range monitoring (e.g. up to 10 m) can be enhanced through optical switches to multiplex multiple branches for a larger spatial-coverage.

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