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Humidity and pressure sensor based on internal reflection

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Received 22 October 2013; accepted 27 January 2014; posted 3 February 2014 (Doc. ID 199944); published 5 March 2014

A low-cost humidity and pressure optical sensor, based on the internal reflection phenomenon, is presented. It takes advantage of the phase difference acquired by s- and p-polarized light undergoing internal reflection to generate an easily detectable minimum in the reflected profile, in a position corresponding to the critical angle. The apparatus presents good sensitivity to relative humidity changes above 70% and a response time below one second. The same device is also capable of measuring changes in pressure and can be used as a vacuum gauge between 1 and 1000 mbar. © 2014 Optical Society of America

OCIS codes: (280.0280) Remote sensing and sensors; (120.5475) Pressure measurement.

http://dx.doi.org/10.1364/AO.53.001591

1. Introduction

Humidity sensors have been widely applied in a variety of fields as agriculture, medicine, textiles, food storage, human comfort, industrial processes, and others [1,2]. Their working principle usually relies on the changes of some physical parameter of a material shaped in the form of a thin film, as it is exposed to variations in the humidity of the surroundings. Regardless of the techniques used to probe these films, which can be of electrical [3,4], acoustical [5,6], or optical [7–9] nature, this approach has the obvious drawback that the sensing material has to be synthesized and deposited as a thin film. Besides, it can age and have its performance degraded if a long lasting operation is desired. Therefore, it is of great interest to develop methods that can sense the humidity in a direct way, without the need of a humidity-sensing thin film material. Moreover, if the sensor is of an optical nature it can, in principle, have a better performance than their electrical counterpart as it would be less sensitive to electromagnetic interference.

An optical parameter that depends on the humidity of a gas is the refractive index (RI), but its change under the usual environmental conditions is very small; thus, to measure it one usually needs complex, although sensitive, interferometric techniques [10,11]. An alternative approach to measure the RI with appreciable accuracy was recently introduced for liquids and is based in detecting the critical angle, \( \theta_c \), of the total internal reflection [12]. The critical angle depends on the refractive indices of two media according to \( \sin \theta_c = n_1/n_2 \), and if one of them is kept constant (for instance, using an optical glass to provide \( n_2 \)), it will depend only on the RI \( n_1 \) of the surrounding medium, which in the present case is moist air. However, since the RI of air changes only by about \( 10^{-6} \) when the humidity goes from 0% to 100% [13], the critical angle measurement would not be sensitive because it is limited to RI variations of the order of \( 10^{-5} \) [12]. Even though, the silica-based glass surface is hydrophilic and, owing to the adsorption of water molecules, there is an average RI that can be measured by critical angle technique.
Another important type of sensor is the one that monitors primary vacuum as it is widespread for processes involving drying, distillation, and degasification in the food industry, packaging, kinescopes, lamps, refrigeration, air conditioning, plating equipment, vacuum flasks, vacuum smelting and refining of metals, and so on. Diaphragm vacuum gauges are particularly suitable for pressure measurements up to high vacuum, regardless of the gas type [14]. They measure the elastic deformation of a membrane, which is a result of different forces acting on its two sides. What differs in membrane-based sensors are the different approaches to detect the deformation. These include capacitance, mechanical and piezoelectric transducers, among others.

The present work reports on a device based on the detection of changes in the critical angle for the measurement of relative humidity (RH) and pressure. The internal reflection occurs in a high RI semi-cylindrical glass lens, whose base is in contact with the air to be measured. The principle responsible for the RH sensing is the dependence of $\theta_c$ on the average RI due to the water molecules adsorption while for pressure sensing, $\theta_c$ depends directly on the RI of air because this changes linearly with the pressure [13]. The critical angle can be determined by a simple inspection of the light pattern reflected by the system, as explained in [12]. The device has no moving parts, is rugged, inexpensive, user friendly, and compact. As a RH sensor, it operates for high humidity, presenting a sensitivity level and response time suitable for respiratory sensing and dew point determination. As a vacuum monitor, it was shown to be useful in the range from 1 to 1000 mbar, proving to be competitive with similar devices, such as Baratron capacitance manometers and diaphragm-based mechanical gauge sensors. Although our measurements were carried out under primary vacuum conditions, there are no impediments for the sensor to be used at pressures higher than atmospheric.

2. Experiment

In the setup shown in Fig. 1, the curved surface of a semi-cylindrical lens automatically produces a range of different angles incident on its base. This geometry, recently used to measure the RI of liquids [12], results in a magnification of the laser beam in the plane of incidence that increases the sensitivity. The same geometry was also used in a high-sensitivity optical humidity sensor based on a thin dielectric planar waveguide [15]. The semi-cylindrical lens has a typical radius on the order of 10 mm and is made of flint glass (Schott, SP10), with RI around 1.7. A crown glass, or fused silica, could also be employed with similar results. As a light source, we used a 5 mW, low-cost 532 nm laser pointer, whose position was chosen such that the beam forms an angle of about 36° with the normal, which is the critical angle for the flint glass used. The curved surface of the semi-cylindrical lens generates a range of angles ($\pm 2^\circ$, depending on the diameter of the laser beam) around this value, providing the conditions for a differential device. The laser light passes through a low-cost plastic linear polarizer, with transmission axis at 45° and with the vertical such that the components parallel (p-polarization) and perpendicular (s-polarization) to the plane of incidence have equal amplitudes. The light impinges normally to the cylindrical surface to minimize astigmatism. An analyzer, with the transmission axis parallel to that of the input polarizer, is used to project these components and make them to interfere, giving rise to a dark stripe in the transmitted profile.

To understand the origin of the dark stripe at $\theta_c$, we consider the Fresnel reflection coefficients for s- and p-polarized plane waves, given by [16]

$$r_s = \frac{\cos \theta - \sqrt{n^2 - \sin^2 \theta}}{\cos \theta + \sqrt{n^2 - \sin^2 \theta}},$$

$$r_p = \frac{-n^2 \cos \theta + \sqrt{n^2 - \sin^2 \theta}}{n^2 \cos \theta + \sqrt{n^2 - \sin^2 \theta}},$$

where $\theta$ is the angle of incidence and $n = n_1/n_2 < 1$ is the relative RI of the sample ($n_1$) with respect to the semi-cylindrical lens ($n_2$). Figures 2(a) and 2(b) show the modulus and phase differences of these coefficients, respectively. The analyzer projects the two orthogonal polarization components to a common transmission axis, after which they interfere and give rise to the intensity pattern:

$$I = I_0(|r_s|^2 + |r_p|^2 + 2|r_s||r_p|\cos \varphi),$$

shown in Fig. 2(c), with $\varphi$ being the phase difference between the two polarization components. In other words, our device is a sort of a two-beam interferometer, where each beam corresponds to a different polarization. For $\theta$ smaller than the Brewster angle, $\varphi = 0$, Eq. (3) becomes $I = I_0(|r_s| + |r_p|)^2$, which is approximately constant as $\theta$ varies. For $\theta$ between the Brewster angle and the critical angle, $\varphi = \pi$ and Eq. (3) becomes $I = I_0(|r_s| - |r_p|)^2$, varying significantly as $\theta$ increases because the p-wave amplitude increases rapidly above the Brewster angle. Exactly the critical angle $|r_s| = |r_p| = 1$ and the intensity
vanishes, leading to the dark band in the transmitted profile. For $\theta \geq \theta_c$, the amplitudes remain equal to 1, but there is an extra phase difference produced by total internal reflection \[16\]. This causes the intensity to rise again. From another viewpoint, the polarization of the light reflected in the lens base rotates by $\pi/4 + \alpha$, where \(\tan \alpha = |r_p|/|r_s|\), because, above the Brewster’s angle, the $p$-component acquires a phase $\pi$ and changes its signal. At $\theta_c$, $|r_s| = |r_p|$, meaning that the polarization rotates exactly by $90^\circ$ and the light is blocked by the analyzer. Below the critical angle, $|r_s| \neq |r_p|$, the polarization rotates by an angle different from $90^\circ$ and some fraction passes through the analyzer while above the critical angle, $|r_s| = |r_p|$, but the additional phase difference, due to the total internal reflection, allows the light to be transmitted through the analyzer again, leaving a dark stripe at $\theta_c$, as seen in the theoretical curve (c) of Fig. 2, and in the experimental pattern of Fig. 3(a).

The intensity transmitted through the analyzer is detected by an inexpensive CCD monochrome linear sensor (Sony ILX554B) with a microcontroller. However, with the purpose of visualizing the profile of the reflected light, we also used a low-cost Web camera and image software with a personal computer. The CCD linear array (or Web camera) is positioned symmetrically to the laser pointer and its distance to the focal point, shown in Fig. 1, can be adjusted as a way of changing the responsivity of the sensor by covering a different number of pixels in the CCD. The only moving part is the laser holder that is used to center the reflected profile in the CCD linear array. After such tuning, the assembly should not be readjusted to avoid losing the calibration. Actually, our device is of the differential type and the RI of the sample is determined by the measurement of the critical angle variation and not by its absolute value, which would require an accurate goniometer. This means that the critical angle has to be calibrated against another type of sensor prior to use.

As shown by the Web camera image depicted in Fig. 3(a), a dark stripe appears in the reflected light profile, as already reported in \[12\]. Note that, to compare Figs. 3 and 2(c), one has to multiply the latter by the finite laser transverse profile, which reduces the effective field of view. As discussed earlier, the dip occurs at the critical angle and moves left or right as the gas humidity or pressure changes. In Fig. 3(a), the laser beam was attenuated to show the actual profile, but this may not be the best choice for the measurement because the borders of the pattern are not regular and may introduce noise to the intensity profile acquired. This can be seen in Fig. 3(b), where the Web camera was replaced by the CCD linear array. To mitigate this problem one can work with a higher laser power to saturate part of the image, as in Fig. 3(c), and measure a better defined minimum. Therefore, the operating principle of this RH sensor relies on determining the position of the minimum of Fig. 3(c) as the humidity or pressure changes.

To verify the performance of this apparatus as a RH sensor, we used a homemade humidity chamber, kept at atmospheric pressure (~900 mbar) and

![Image](image_url)
constant temperature (22°C). Prior to the measurements, the semi-cylindrical lens was boiled in ethanol to remove any residual dirt. A partial view of the chamber and the gas flow system is shown in Fig. 4(a). Each humidity value was achieved by controlling the flux ratio between dry nitrogen gas and moist nitrogen gas, which was obtained by bubbling nitrogen gas inside water contained in an interconnected vessel. We used a commercial probe (average accuracy of about 1.5% below 90% RH) to calibrate the pixel number corresponding to the minimum shown in Fig. 3(c) as a function of RH. Since this chamber takes a few minutes to adjust its RH, the sensor's response time was characterized by blowing moist gas directly onto the lens base for a given period of time and then letting the system evolve to ambient RH for the same time. However, because the valve that switches the flux of moist gas has to be opened manually, the fastest time that can be measured in our setup is estimated to be of the order of one second.

The performance of the pressure sensor was verified by placing the semi-cylindrical lens inside the Pyrex bell jar shown in Fig. 4(b), seated on top of an inox flange with two outputs. One of them was used to evacuate the system with a mechanical vacuum pump, while the other was connected to a diaphragm vacuum gauge (DIAVAC DV 1000) to calibrate the pressure.

3. Results and Discussion

Figure 5 shows the pixel number corresponding to the position of the dip obtained in static (slow) RH measurements. The first fact to be noticed is that the device responds only to RH above 70%, which makes it unsuitable as a general purpose humidity sensor. Even though, it may be useful in applications such as respiratory sensing and dew point determination. As already mentioned, the reason for this behavior at low RH is the negligible variation of the RI of air at this range. The response above 70% can be understood as a consequence of water molecules being gradually adsorbed on the prism surface [17].

For the Fresnel reflection coefficients to be meaningful, the medium specified by $n_1$ (adsorbed water) should have a thickness on the order of a quarter wavelength, and this only occurs for a fairly large number of water monolayers deposited. This is the opposite of what happens in the optical humidity sensor based on a thin dielectric planar waveguide, which is more sensitive to the first monolayer formed [15]. In the present case, there is a detectable response only for high humidity values, which lead us to the conclusion that lower RH can only be accessed by using a humidity-sensing thin film on the prism base.

Another point to be noticed is the nonlinearity of the response to RH. As shown by the solid line in Fig. 5, it follows an exponential growth function, which is a behavior common to most humidity sensors. Once all optical components are fixed, a curve like that of Fig. 5 is stored in the microcontroller and used to convert pixels to RH. Such a calibration curve is achieved with a commercial device, which limits the accuracy to that of the sensor used for the calibration procedure. In our setup, for instance, we used a device whose accuracy was of about 1.5% below 90% RH and, therefore, we end up with the same accuracy. On the other hand, sensitivity is determined by the accuracy that the pixel corresponding to the minimum of Fig. 3(c) is found. The microcontroller was programmed with the centroid method [18], providing an accuracy of 0.1 pixel. An
analysis of Fig. 5 leads to the conclusions that, in the range 70%–80% RH the total peak variation is about 2.5, meaning an average of 4% RH per pixel, which results in a sensitivity of 0.4% RH. However, between 80% and 90% RH, the total peak variation is more than 25, resulting in an average sensitivity of 0.04% RH.

We also measured the sensor’s response time subject to rapid variations of humidity, by blowing moist air at the base for about 30 s and then exposing the system to the ambient humidity (≈45% RH). The result depicted in Fig. 6(a) shows a fast sensor, which could be used to measure respiration. To be sure about this point, we carried out measurements in a time scale compatible with breathing and, as shown in Fig. 6(b), we could verify the possibility of this type of application. Moreover, to detect respiration or dew point, one just needs a small area photodetector placed at the dip position and the CCD linear array would not be necessary.

Figure 7 shows the results obtained for primary vacuum sensing. The lower abscissa corresponds to the value obtained with the mechanical diaphragm vacuum gauge while the upper abscissa gives the value of the RI of air, obtained from Ref. [13]. No hysteresis is observed when the pressure decreases and increases and the deviation of the experimental points with respect to a straight line is due to the reading of the DIAVAC vacuum gauge, which has an analog dial with pointer. As our refractometer has an accuracy of 10^{-6} in units of RI, it is possible to measure pressures down to 1 mbar. This operation range is of interest to industry, especially for food packaging. Thus, the device can be competitive with other similar devices, such as capacitance manometers of the Baratron type, and mechanical or piezoelectric diaphragm sensors.

4. Conclusion

We introduced a simple humidity and pressure optical sensor, based on the internal reflection of a light beam. Since it uses just glass as the sensing material, it is quite reliable and does not age. As a humidity sensor, it was shown to be sensitive and fast above 70% RH, allowing its use for dew point detection or as a breathing sensor for monitoring chronic obstructive pulmonary disease, acute respiratory depression, and apnea. In these applications, where the quantitative determination of RH is not necessary, the apparatus can be even simpler because the linear CCD can be replaced by a small area detector. It was also shown to be quite reliable as a primary vacuum pressure gauge between 1 and 1000 mbar, but this range can be straightforwardly extended to several atmospheres because the refractive indices increase and become easier to measure.

The present study was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

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