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Measuring CO_2 concentration with a Fabry–Perot based bolometer using a glass plate as simple infrared filter

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ABSTRACT

Recently, Fabry–Perot IR-absorbing structures have been proven suitable as low cost detectors in non-dispersive infrared (NDIR) gas-sensors for measuring diluted gases (e.g., CO_2) in a pure nitrogen (N_2) atmosphere. To identify the monitoring capability of the devised prototype system in ambient air, the cross-sensitivity to other gases, mainly water vapor, has to be explored. The absorption coefficient associated with the individual infrared absorbing bands of water vapor is small compared to that of CO_2; however, the atmospheric concentration of vapor much is higher. To improve the impact of CO_2 absorption compared to other gases a new method using a normal glass plate as infrared filter is introduced. The presented theoretical and experimental analysis investigates the achievable response to CO_2 as well as the resulting cross-sensitivity for absolute humidity, where also the dependence of the characteristics on the temperature was considered. In particular a model for the bolometer is combined with ray tracing simulations for a connected sample chamber yielding the response of the entire IR-absorption sensor system, which is compared with measurements.

1. Introduction

In [1] we demonstrated the feasibility of a stack consisting of a bolometer and a non-symmetric Fabry–Perot absorber-structure as infrared detector. The absorbing mechanism of such a Fabry–Perot based detector (see Fig. 1) is based on constructive and destructive interference in the spacing layer within the two metal mirrors. For absorbing a selected wavelength λ (referring to the wavelength in the corresponding medium) in resonance, the thickness of the spacing layer d has to fulfill the relation:

$$d = (2 \cdot m + 1)\frac{\lambda}{4}$$

Here m represents the order of the interference. This yields an antinode of the electric field at the (very thin and thus partially transparent) top metal mirror where the main part of the absorption takes. For our detectors we chose the first interference order (representing a $3\lambda/4$ structure) using germanium (index of refraction $n \approx 4$) as material for the spacing layer, and selected the wavelength of the main CO_2 absorption peak (around 4.26 μm) as target area. This yields the following thickness of the spacing layer:

$$d = \frac{(2 \cdot 1 + 1)(4.26\ \mu m/4)}{4} = 800\ \ nm$$

This novel detector was tested in an NDIR gas sensor system [2] for measuring the CO_2 concentration in a pure N_2 atmosphere. The fundamental setup of the detector is depicted in Figs. 1 and 2 (see [1] for the design properties of the detector layers and the basic building blocks of the total sensor system). The resulting spectral response of the total sensor system depends, besides the properties of the absorber-structure, on the temperature [3] and the emissivity [4] of the IR-emitter material (we use a commercial broadband IR-source). To apply this detector concept to real-world measurements in air, it is essential to identify infrared absorption of other atmospheric gases close to the used absorption wavelength of CO_2 (around 4.26 μm) [5]; the most distinctive absorption bands in the mid infrared are given in Fig. 3. Based on the fact that the majority of the atmospheric gases either have a very low concentration in the environment (e.g., N_2O or CO) or a very low ability to absorb infrared radiation (e.g., homonuclear diatomic molecules like N_2 or O_2 [6]) the influence of all these gases can be neglected for low cost sensors.

Even though water vapor has also a very small IR absorption coefficient, it has a very high atmospheric concentration, which means that its influence cannot be ignored. To illustrate possible cross-sensitivities, in Fig. 4 a comparison of a simple estimation for

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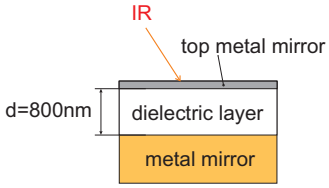

Fig. 1. Non-symmetric Fabry–Perot structure for gas measurement: the two mirrors and the dielectric layer of the infrared absorbing structure are shown. The thickness of the dielectric layer (Ge) is optimized for measuring CO_2 representing a $3\lambda/4$ structure.

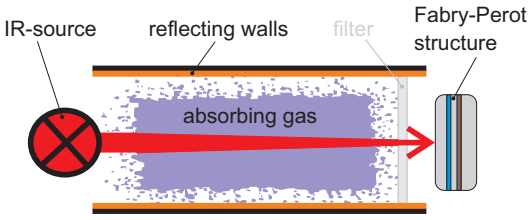

Fig. 2. The image illustrates the basic building blocks of a NDIR gas sensor with a bolometer as IR-detector (the additional filter is optional).

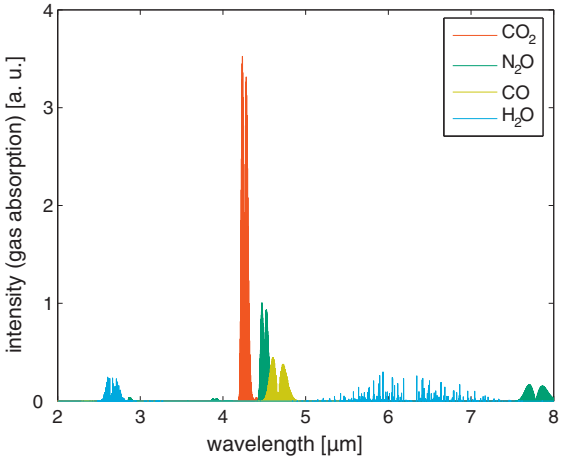

Fig. 3. This picture demonstrates the major molecule absorption bands in the mid infrared [5].

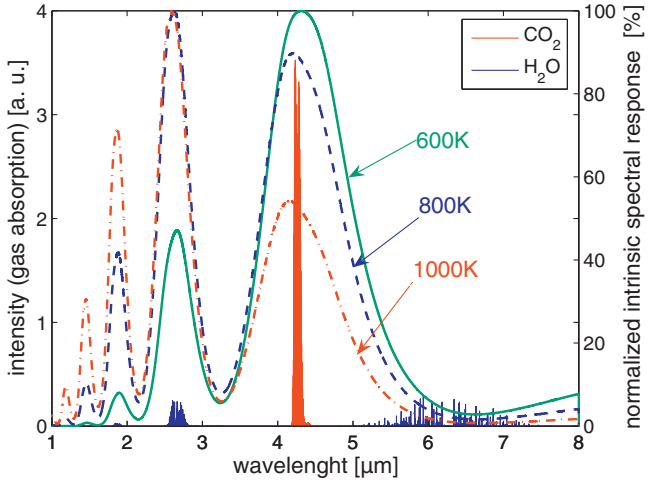

Fig. 4. Normalized intrinsic spectral response of the sensor system for three different IR-source temperatures in comparison to the infrared absorbing spectra of CO_2 and H_2O.

the resulting normalized intrinsic spectral response of the sensor system (without an absorbing gas) [1] to the infrared absorption spectra of CO_2 and H_2O is shown for three different IR-source temperatures (600 K, 800 K and 1000 K). Note that the total detector signal corresponds to the area below the spectral response curve (see also our previous work [1]). Gas absorption leads to a decrease of the total detector signal. The sensitivity to gas absorption is larger, if the system's spectral response is pronounced in the wavelength-region where the specific absorption occurs (in our case the region around 4.26 µm for CO_2). As shown in Fig. 4, the peak in the system response located at the main absorption region of the target gas is moving to smaller wavelengths with increasing temperature and thus the sensitivity of the total detector response to CO_2-based IR-absorption is reduced.

Finally we would like to note that the impact of the spurious cross-sensitivity to water vapor is intimately linked to the temperature dependence of absolute humidity, i.e. to the number of infrared-absorbing H_2O molecules in the optical path of the sensor. In this context, the maximum possible number of vapor molecules which can be dissolved in air rise with increasing temperature is a very relevant parameter. The maximum fraction of water molecules in air is described by the mole fraction $x_{H_2O,\,sat}$ in saturated air [7], which in turn can be calculated from the ratio of the saturation vapor pressure for a defined ambient temperature e_{H_2O} (computable e.g., with [8]) to the total air pressure p:

$$x_{H_2O,\,sat} = \frac{e_{H_2O}}{p}$$

In Fig. 5 the increase of the maximum number of dissolvable H_2O molecules in air with rising temperature is depicted.

2. Modified system design

As a simple method to improve the response for CO_2 measurement with a Fabry–Perot based bolometer we propose the utilization of a glass plate as infrared filter. The used glass plate at the same time reduces the unwanted cross-sensitivity for water vapor.

Standard glasses feature a sharp infrared transmission edge at about 5 µm; i.e. longer infrared wavelengths will be absorbed. For our research, glass substrates from Schott [9] with a thickness of 0.3 mm were used. In Fig. 6 the measured infrared transmission characteristics (FTIR measurements) of this particular glass substrate is specified in connection to the infrared

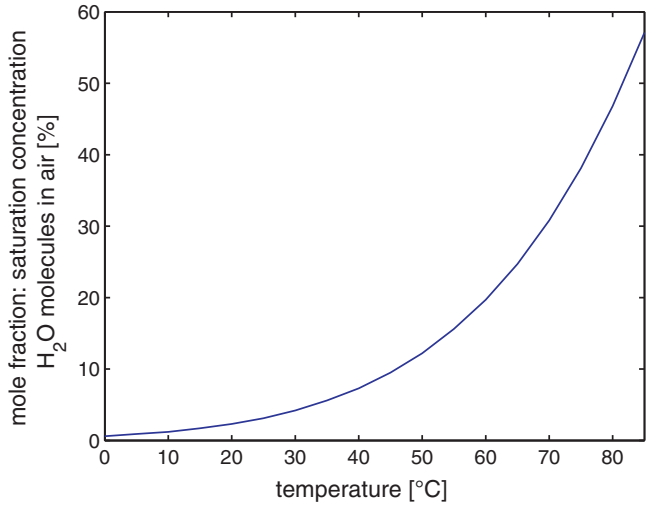

Fig. 5. The temperature dependent mole fraction in saturated air yields the maximum number of dissolvable water molecules in air.