A Microwave System for Relative Humidity Measurement

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Abstract

This paper deals with a microwave hygrometer that is based on the sensitivity of air permettivity to humidity. The hygrometer embeds a microwave generator which feeds two different channels. A channel is a holed waveguide, whose permettivity depends on the air humidity, while the other channel is insensitive to the air humidity. The output signals of the two channels are suitably combined in order to obtain the corresponding phase angle, which depends on the permettivity of the air inside the holed waveguide and therefore on the air humidity. Two possible implementations of the proposed principle are described which permit one to obtain an uncertainty of a few percentage of relative humidity in the humidity range of 10 %RH *to* 90 %RH *and in the temperature range of* 5 °C *to* 40 °C, *but with different costs and complexities. The main characteristics of the proposed sensor are a fast response, a low sensitivity with respect to air pollution and the absence of hysteresis phenomena.*

1. Introduction

In recent years industry as well as research and calibration laboratories have increased the demand for humidity measurements. Such a trend is motivated by the necessity to achieve improvements in the final product or in the provided service: this requires a better measurement and control of the environmental quantities and, hence, of the humidity.

Several humidity sensors are nowadays commercially available that are based on the sensitivity of electrical parameters of hygroscopic substances to humidity [1-4]. Such sensors offer low-uncertainty at good prices, but their hysteresis is comparable to the uncertainty and their behaviour could become unpredictable after exposure to air pollution.

Alternatively, sensors that rely on the propagation of electromagnetic waves can be employed to avoid the aforementioned drawbacks [5]. Such sensors are based on the sensitivity of the air permettivity to the humidity, hence no water vapour diffusion is required in hygroscopic substances. In this situation no hysteresis phenomena are expected and the sensor exposure to air pollution does not impair the performance. Furthermore, the response time of the hygrometer to humidity changes is expected to be very small.

In this paper two different hygrometers that are based on a microwave interferometer system are described and the expected performance is reported.

2. Operating principle

The air relative permettivity ε_r is a function of temperature T, relative humidity h and pressure P (see appendix):

$$\varepsilon_r = f_\varepsilon(T, h, P) \tag{1}$$

Figure 1 shows the ε_r behaviour in the temperature range of 5 °C to 40 °C and in the humidity range of 10 %RH to 90 %RH at a pressure of 101 kPa. The figure shows that the ε_r change is of about $4 \cdot 10^{-4}$ in the considered ranges and that the sensitivity of ε_r to the humidity ($2 \cdot 10^{-6}$ %RH^{-1} @ 20 °C, 50 %RH) is comparable to the

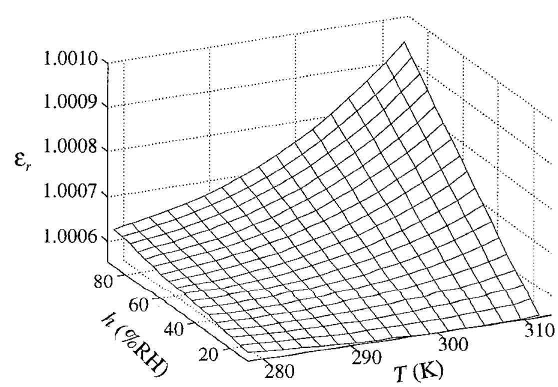

Fig. 1. Theoretical behaviour of air relative permettivity.

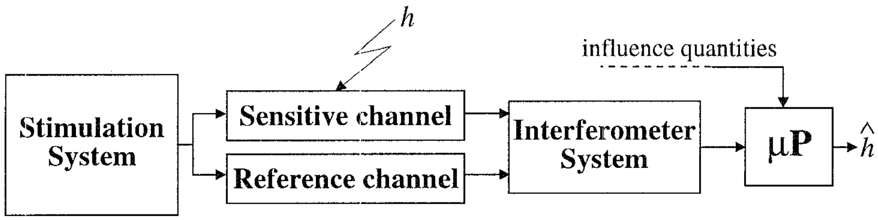

Fig. 2. The principle scheme of the proposed sensor.

sensitivity to the temperature ($3.5 \cdot 10^{-6}$ °C^{-1} in the same conditions). The sensitivity of ε_r to the pressure is of about $1 \cdot 10^{-9}$ Pa^{-1}, therefore pressure effects are negligible for pressure changes of up to some kilopascal.

It is hence possible to indirectly obtain the humidity of the air by measuring its temperature and permettivity:

$$h = f_{\varepsilon}^{-1}(\varepsilon_r, T) \quad (2)$$

Pressure measurements have to be carried out if pressure changes greater than some kilopascal are expected.

The air permettivity can be obtained by measuring its effect on the amplitude of a microwave signal that propagates through a holed waveguide. However, the permettivity changes in the considered temperature and humidity ranges are not large enough to be easily detectable in this way. For this reason it is convenient to detect the phase of a microwave signal by means of an interferometer system.

Such a solution requires another signal that acts as a reference for the signal that propagates through the waveguide and can be implemented by means of the system shown in figure 2. A stimulation system excites the holed waveguide (sensitive channel) and a reference channel by means of the same signal. The electrical length of the holed waveguide depends on the air permettivity that, in turn, depends on the humidity h. The output signals of the two channels are sent to an interferometer system in order to obtain a quantity that is related to the difference between the electrical length of the two channels. A microprocessor acquires such a quantity and the other relevant influence quantities and then estimates the relative humidity.

Two sensors based on the principle scheme of figure 2 are here proposed that basically differ from each other as far as the reference channel and the interferometer system are conceived. One sensor employs a coaxial cable as a reference channel (SWH: Single Waveguide Hygrometer - figure 3), while the other employs a sealed waveguide (TWH: Twin Waveguide Hygrometer - figure 7).

2.1 The Single Waveguide Hygrometer (SWH)

The block scheme of the SWH is shown in figure 3: the stimulation system, which is made up of a microwave generator coupled to a power splitter, excites a holed waveguide that acts as a sensitive channel and a coaxial cable that acts as a reference channel; the interferometer system is a simple mixer, whose output is a DC voltage that depends on the difference between the two channel electrical-lengths. The electrical length of the coaxial cable is insensitive to the humidity, while that of the holed waveguide is related to the air permettivity and to the physical length of the waveguide, which changes according to the temperature. The microprocessor acquires the

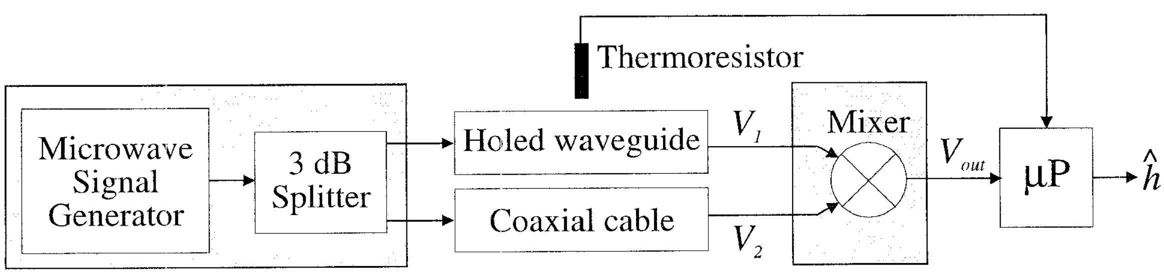

Fig. 3. The block scheme of the Single Waveguide Hygrometer.

outputs of the mixer and of a temperature sensor (thermoresistor) and then estimates the relative humidity.

The mixer output voltage V_{out} can be expressed as:

$$V_{out} = V_1 \cdot V_2 \cdot \cos\varphi \quad (3)$$

where

V_1, V_2 are the amplitudes of the signals at mixer input;

φ is the phase angle between the two signals at mixer input.

The electrical length of the coaxial cable can be considered constant if it is not subjected to large temperature changes. In this situation V_{out} only depends on V_1 and φ that, once the system parameters (dimensions, working frequency, etc.) are fixed, mainly depend on the air permettivity and on the waveguide physical dimensions that, in turn, depend on the temperature:

$$V_{out} = V_2 \cdot V_1(\varepsilon_r, T) \cdot \cos[\varphi(\varepsilon_r, T)] = f_V(\varepsilon_r, T) \quad (4)$$

From equation (4) it is possible to express the air permettivity as:

$$\varepsilon_r = f_V^{-1}(V_{out}, T) \quad (5)$$

By replacing the previous equation in equation (2), the air relative humidity can eventually be obtained as:

$$h = f_\varepsilon^{-1}[f_V^{-1}(V_{out}, T)] \quad (6)$$

An SWH prototype has already been completed and tested [6]. The prototype employs a brass circular waveguide that has a length of about 35 cm and a diameter of about 13 mm and works at a frequency of 16.4 GHz.

The theoretical behaviour of the prototype voltage output, obtained by means of a simulation, is shown in figure 4. One should note that the sensitivity of V_{out} to the humidity is greater at high temperatures because of the greater amount of water vapour that is required to obtain a certain humidity level. This means that at high temperatures it is possible to obtain a better uncertainty than that obtained at low temperatures.

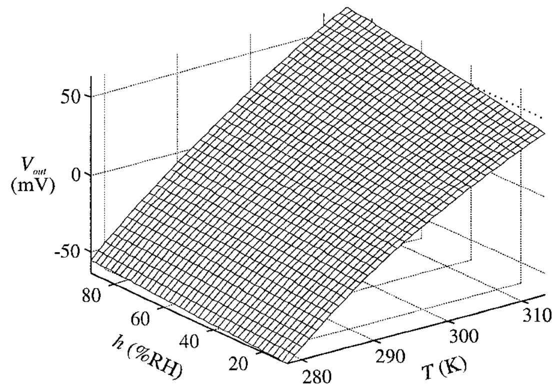

Fig. 4. Expected voltage output of the Single Waveguide Hygrometer.

The expected standard uncertainty of the SWH prototype in the humidity range of 10 %RH to 90 %RH and in the temperature range of 5 °C to 40 °C is of a few percentage of relative humidity, provided that the temperature and voltage output are measured with a standard uncertainty that, in the worst case (@ 5 °C, 10 %RH), is of 0.04 °C and $1 \cdot 10^{-3}$ respectively. The SWH performance also depends on the frequency stability of the signal generator, which should be better than 10^{-5} to maintain the above stated uncertainty.

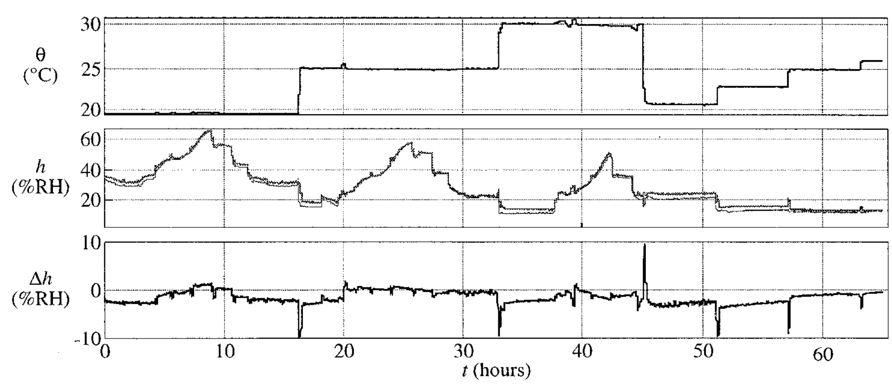

Fig. 5. An example of results obtained with the SWH. The thin line is the output of a reference humidity sensor; the thick line is the SWH output.

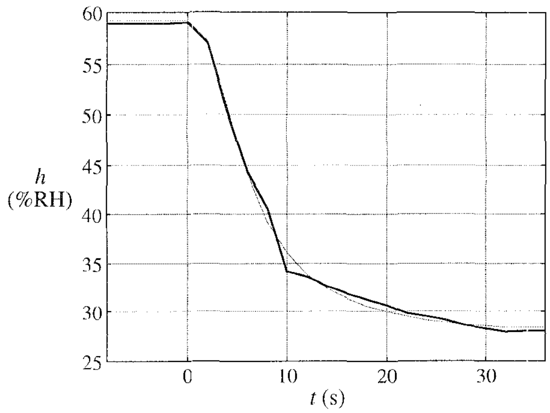

Fig. 6. The outputs of the SWH (thick line) and of a reference humidity sensor (thin line) during a fast humidity change.

A preliminary characterisation of the SWH prototype has been performed by employing a climatic chamber, which allows one to set the temperature and humidity, and by comparing the SWH output with that of a solid-state humidity sensor.

The results of an experimental test at variable temperature and humidity are shown in figure 5 as an example. The top trace represents the temperature, which is measured by means of a thermoresistor; the middle trace indicates the output of the SWH (thick line) and that of the reference humidity sensor (thin line); the bottom trace is the difference between the reference and the SWH outputs. The experimental standard deviation of such a difference in a series of similar tests was of less than 3 %RH.

Figure 6 shows the results of a dynamic test that has been performed during a fast humidity change. Such a result permits one to estimates a response time of less than 10 s. However, the response time of the SWH could be lower than 10 s, since the estimated response time is that of the climatic chamber. A better dynamic characterisation of the SWH therefore requires a faster climatic chamber.

2.2 The Twin Waveguide Hygrometer (TWH)

The TWH employs the same stimulation system as the SWH (see figure 7), but both the reference channel and the interferometer system are different.

The reference channel is a sealed waveguide that has the same nominal dimensions of the holed waveguide.

The TWH interferometer system is made up of a splitter, a quadrature directional coupler and two mixers in order to mix the waveguide output signals, both in phase and in quadrature. Hence the mixer outputs V_q and V_p can be expressed as:

$$V_q = V_1' \cdot V_2' \cdot \sin\varphi \;;\; V_p = V_1'' \cdot V_2'' \cdot \cos\varphi \tag{7}$$

where

V_1', V_2'
are the signal amplitudes at the inputs of mixer A;

V_1'', V_2''
are the signal amplitudes at the inputs of mixer B;

φ
is the phase angle between the two signals at mixer inputs.

Attention has been paid to the design of the interferometer system in order to have the same signals at the two mixer inputs, i.e. in order to have:

$$V_1' = V_1'' = V_1 \;;\; V_2' = V_2'' = V_2 \tag{8}$$

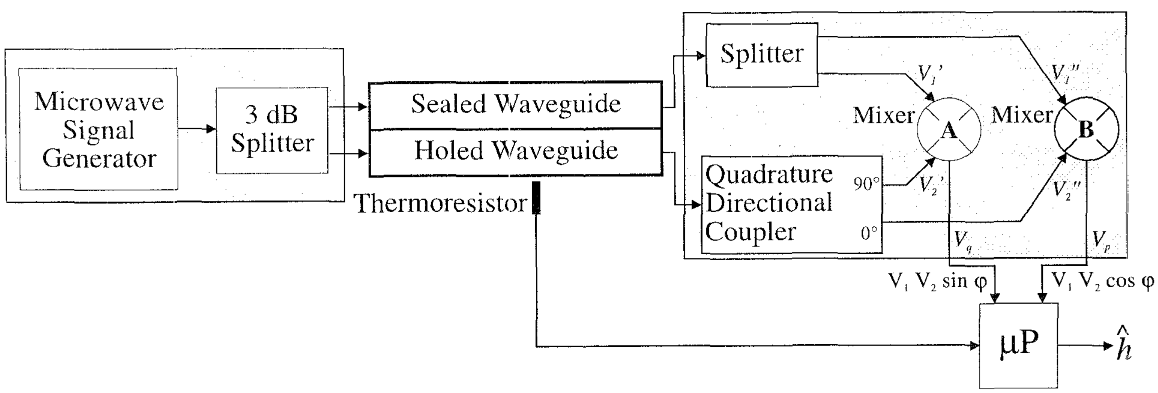

Fig. 7. The block scheme of the Twin Waveguide Hygrometer.

The microprocessor acquires the mixer outputs and computes the ratio between V_q and V_p so that the phase angle φ can be obtained:

$$\tan\varphi = \frac{V_1 \cdot V_2 \cdot \sin\varphi}{V_1 \cdot V_2 \cdot \cos\varphi} = \frac{V_q}{V_p} \quad (9)$$

This simple procedure makes the signal amplitude effects negligible and allows one to obtain a parameter that depends on the difference between the electrical lengths of the two waveguides. These electrical lengths are related to the physical length of the waveguides, which changes with the temperature, and to the air permettivity. Thermal dilatation effects also become negligible if the waveguides are at the same temperature, have the same nominal lengths and are made of the same material. Therefore, the phase angle φ changes according to the air relative permettivity inside the two waveguides:

$$\varphi = f_\varphi(\varepsilon_{rH}, \varepsilon_{rS}) \quad (10)$$

where

ε_{rH} is the air relative permettivity inside the holed waveguide;

ε_{rS} is the air relative permettivity inside the sealed waveguide.

Furthermore, if the sealed waveguide contains dry air the corresponding permettivity is constant, since the volume inside the sealed waveguide is constant (see appendix), so that equation (10) becomes:

$$\varphi = f_\varphi(\varepsilon_{rH}) \quad (11)$$

and hence it is possible to express the air permettivity as:

$$\varepsilon_{rH} = f_\varphi^{-1}(\varphi) \quad (12)$$

By combining the previous equation with equations (2) and (9), the relative humidity is eventually obtained as:

$$h = f_\varepsilon^{-1}\left[f_\varphi^{-1}\left(\frac{V_q}{V_p}, T\right)\right] \quad (13)$$

The TWH the authors have designed is based on two WR-90 waveguides obtained from a single aluminium block. In such a way the two waveguides can be considered isothermal and their behaviour towards the temperature can be considered the same. The waveguides have a length of about 40 cm and the working frequency is of 9 GHz. The temperature measurement is carried out by means of a thermoresistor.

Figure 8 shows the theoretical behaviour of the phase angle φ in the humidity range of 10 %RH to 90 %RH and in the temperature range of 5 °C to 40 °C. One should note that the behaviour of φ is very similar to the behaviour of the air relative permettivity (see figure 1). This is due to

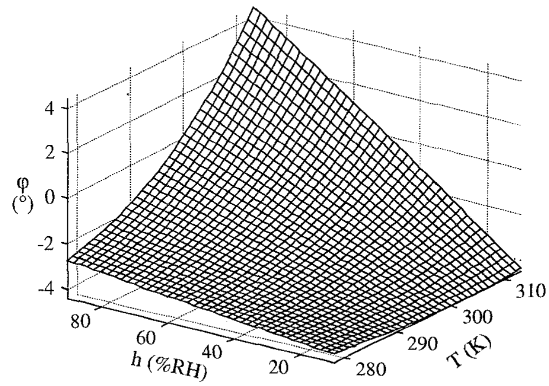

Fig. 8. Expected phase output of the Twin Waveguide Hygrometer.

the insensitivity of φ to the signal amplitude and to the compensation of the temperature effects on the waveguide dimensions that results from the use of the twin waveguides.

If the voltage measurement uncertainty is the same as that of the SWH (about $1 \cdot 10^{-3}$), a humidity standard uncertainty of a few percentage of relative humidity can be expected if the temperature is measured with a standard uncertainty that, in the worst case (@ 10 %RH, 5 °C), is of 0.1 °C. The use of the TWH also permits one to relax the frequency stability specification of the signal generator, which should be better than 10^{-3}.

The reduction in the frequency specification with respect to the SWH is of two orders of magnitude, while that in the temperature uncertainty is of about twice. This happens because only the temperature effects on the physical dimensions of the twin waveguides is compensated, while the sensitivity of the air relative permettivity to the temperature does not change.

The TWH is not yet completed; at the moment the authors are working on a waveguide set-up that embeds the sensitive and reference channels, the splitter that divides the input signal and the splitter and the quadrature directional coupler of the interferometer system, in order to greatly simplify the system assembly.

3. Conclusions

A microwave hygrometer that is based on the sensitivity of air permettivity to humidity has been described in this paper. Two possible versions of the sensor have been proposed which have been referred to as Single Waveguide Hygrometer (SWH) and Twin Waveguide Hygrometer (TWH). The SWH is based on a simple assembly, but requires severe specifications for the temperature sensor and the signal generator. On the contrary, the TWH assembly is more complex, but allows one to relax the specification of the temperature uncertainty and the frequency stability.

The main characteristics of the proposed microwave hygrometer compared to traditional humidity sensors are a fast response time and the absence of hysteresis phenomena, as no water vapour diffusion is required in hygroscopic substances. Furthermore, a long maintenance-free interval is expected, since a possible exposure of the sensor to air pollution does not affect its characteristics.

The SWH has already been completed and tested and the obtained results have shown the effectiveness of the measurement principle. The TWH has been designed, but the waveguide set-up that embeds the sensitive and reference channels and part of the interferometer system is not yet completed.

Appendix

The air relative permettivity ε_r can be expressed as [7]:

$$\varepsilon_r = 1 + A \cdot \frac{P}{T} + B \cdot \frac{\rho_w}{T} + C \cdot \rho_w \tag{14}$$

where
- P is the atmospheric pressure;
- T is the absolute temperature;
- ρ_w is the density of the water vapour in the air;
- A, B, C are three constant parameters, whose value are $1.552 \cdot 10^{-6}\ \mathrm{K\,m^2/N}$, $3.456\ \mathrm{K\,m^3/kg}$ and $-76.57 \cdot 10^{-6}\ \mathrm{m^3/kg}$ respectively.

In order to express ε_r as a function of the relative humidity h, the relationship between the water vapour density ρ_w and h has to be employed.

The water vapour density is defined as the ratio between the mass of the water vapour and the volume that contains such a mass, so that ρ_w can be expressed as:

$$\rho_w = \frac{x_w \cdot M_w}{v} \tag{15}$$

where
- x_w is the molar fraction of the water vapour in the air;
- M_w is the molar mass of the water vapour;
- v is the molar volume of the air.

The molar volume of the air is simply obtained as:

$$v = Z \cdot \frac{R \cdot T}{P} \tag{16}$$

where
- R is the universal gas constant;
- Z is the compressibility factor of the air [8].

The molar fraction of the water vapour is instead calculated as:

$$x_w = \frac{h \cdot f \cdot P_{sv}(T)}{P} \tag{17}$$

where
- h is the relative humidity;
- P_{sv} is the saturated water vapour pressure that is a known function of temperature T;
- f is a correcting factor which takes the difference of behaviour of the humid air from that of a perfect gas into account [8].

The relationship between ρ_w and h can be determined by combining equations (15), (16) and (17). By replacing such a relationship in equation (14) the relative air permettivity can be eventually expressed as a function of the relative humidity, temperature and pressure.

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