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A temperature and humidity synchronization detection method based on microwave coupled-resonator

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ABSTRACT

This article proposes a novel temperature and humidity synchronization test method based on the U-shaped microwave resonator technology. U-shaped microwave resonator have been manufactured using the U-shaped microwave probe by studying the high quality factor, which was deponed on the length, distance of gap and radius of tungsten filament. Based on this U-shape microwave probe, the resonance frequency shift was using to detect the temperature and relative humidity with the sensitivity of 38 kHz/°C and 10.3 kHz/%RH, respectively. Meanwhile, the humidity can be detected by the resonance intensity with the signal noise ratio (SNR) of 100. Based on it, the temperature and relative humidity can be synchronization detected using the U-shaped microwave resonator. It proves a high sensitive, low-cost, ease of fabrication technologies.

1. Introduction

Temperature and humidity detection technologies play a key roles in various fields, such as atomic/quantum/molecular/condensed matter physical scientific experiment environment control, aeronautics and astronautics devices running environment control, industrial production process monitoring, biological tissue living environment control and agricultural planting management [1–5].

The temperature and humidity detection technologies based on different working principles has been studied for several decades and have many reports. However, there were fewer reports about method for the temperature and humidity synchronization detection. Generally, it is difficult to detect the humidity signal from the temperature with the high SNR because of the temperature effect of the most of humidity sensing materials [6–10]. Hence, the main synchronization detection technologies was assembled with two sensing elements. One of the element was used to sensing temperature and another one was to sense relative humidity.

In addition, the microwave technology to detect the relative humidity have gained extensive attention, due to the metal sensing elements without the temperature effect. Meanwhile, the microwave resonator can detect the temperature signals based on the dielectric effect and electron spin effect with the high-quality factors and signal-noise ratio [11–13].

Hence, this paper proposed a temperature and humidity synchronization test method based on U-shape microwave resonator. By simulate the quality factor of microwave resonator to design the length, distance of gap and radius of U-shape structures. And, fabricated the U-shape microwave probe based on the tungsten filament. In the experiment, the resonance frequency intensity have been used to detect the humidity, and the resonance frequency shift have been used to calculate the temperature. The relative humidity and temperature can be synchronization detected. And, the conclusion have been demonstrated in the temperature and humidity mixing environment, and the sensitivity can up to 38 kHz/°C for the temperature and 10.3 kHz/%RH for the relative humidity.

2. Prepare for the experiment

U-shape microwave probe was fabricated by using the tungsten filament with the diameter of 1.0 mm and the length of 72 mm. And the changes in the length of tungsten filament have a function of temperature can be express as: $\Delta l = 4.5 \times 10^{-6} \times l \times \Delta C$.

The U-shape microwave coupled-resonant was made by coupling the microwave cavity and the U-shape microwave probe. The

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microwave cavity was connected to vector network analyzer (VNA, Agilent N5224A) by the coaxial cable (LMR-SW540, Pasternack Company) with the diameter of 2.2 mm and the length of 30 cm. The shield layer of coaxial transmission line was made of seamless aluminum, and center layer was made by the copper materials with the impedance of 50 Ω. The whole structures have been packaged by the ordinary glass tube.

The relative humidity environment was created by the saturated salt solution prepared by the lithium chloride, potassium acetate, magnesium chloride, potassium carbonate, sodium bromide, potassium iodide, sodium nitrate, potassium chloride, potassium nitrate. Temperature was testing in the home-made temperature controlling system (TCS) with the accuracy of 0.1 °C.

3. Results and discussion

3.1. Methods of detection

Fig. 1a show the synchronization testing schematic of temperature and relative humidity using the U-shape microwave probe. As in Fig. 1a shows, the U-shape microwave resonator was made with the air at the gap of U-shape probe and the U-shape metal structure. The microwave signals (generated by the vector network analyzer) was coupling transferred into U-shape microwave resonator by the coupling area, and resonated at a certain frequency in the U-shape microwave resonator. The certain resonance frequency was as a function of the dielectric constant of air at the gap, which was determined by the temperature and the relative humidity. While, the resonance intensity of microwave signals was determined as a function of the amounts of water molecules in air depended by the air humidity. That is, the relative humidity can be detected by the resonance intensity. And the temperature can be calculated by the resonance frequency drift without the frequency drift created by the relative humidity. Based on this method, the temperature and relative humidity can be synchronous tested.

The synchronous testing model have been equivalent to be the resistance R, inductance L, capacitance C (namely RLC) circuit model as shown in Fig. 1b. The coupling area was working as the inductance L. The air at the gap can be equivalent as the parallel model of resistance R and capacitance C by the electromagnetic interaction theory and the transmission line theory [14].

By the transmission line theory, the resistance *R*, capacitance *C*, inductance *L*, and conductivity *G* of our equivalent model can by calculated as [15,16]:

$$R = \frac{1}{2\pi\sigma_l d} \tag{1}$$

$$C = \frac{\pi\varepsilon_0\varepsilon_p}{\ln\left[\frac{b}{2a}+\sqrt{\left(\frac{b}{2a}\right)^2-1}\right]} \tag{2}$$

$$L = \frac{\mu_0}{\pi}\ln\left[\frac{b}{2a}+\sqrt{\left(\frac{b}{2a}\right)^2-1}\right] \tag{3}$$

$$G = \frac{\pi\sigma_p}{\ln\left[\frac{b}{2a}+\sqrt{\left(\frac{b}{2a}\right)^2-1}\right]} \tag{4}$$

Where, ε_p was the dielectric constant, σ_l was the DC conductivity, ω was the microwave frequency, the *d* was the skin depth of transmission line, σ_p was the environment medium conductivity, ε_0 was the initial dielectric permittivity of environment. a was the diameter of transmission line, and the d was the distance of the gap.

Therefore, from Eqs. (1)–(4), the resonant frequency of the U-shape microwave resonantor was:

$$f = \frac{1}{4l\sqrt{LC}} = \frac{c}{4l\sqrt{\varepsilon_p}} \tag{5}$$

In this work, U-shape microwave probe was open at the end and the RLC circuit can be calculated by the transmission line theory as:

$$R_{eq} = Z_0\frac{1-e^{-2\alpha l}}{1+e^{-2\alpha l}} \tag{6}$$

$$L_{eq} = \frac{\pi Z_0 e^{-2\alpha l}}{2\omega_r\left(1+e^{-2\alpha l}\right)} \tag{7}$$

$$C_{eq} = \frac{2\left(1+e^{-2\alpha l}\right)}{\pi Z_0\omega_r e^{-2\alpha l}} \tag{8}$$

Where, Z_0 was the characteristic impedance, the propagation constant γ was given by the attenuation constant α and the phase constant β (the propagation equation was expressed as $\gamma = \alpha + j\beta$). *l* was the equivalent length and ω_r was the resonant frequency of the transmission line as: $\omega_r = 2\pi f_r = \pi/2l(LC)^{1/2} = c/4l\sqrt{\varepsilon_r}$. ε_r was the dielectric constant of transmission line.

Therefore, the resonant frequency of the U-shape microwave resonantor was:

$$f = \frac{1}{4l\sqrt{LC}} = \frac{c}{4l\sqrt{\varepsilon_{p+}\varepsilon_r}} \tag{9}$$

The dielectric constant of air at the gap was as a function of temperature and the relative humidity was [17]:

$$\frac{\varepsilon_p-1}{\varepsilon_p+2} \approx \sum_i \rho_i A_i + \rho_w\left(A_w+\frac{B_w}{T}\right) \tag{10}$$

Where, ρ_i and A_i were the molar density and the molar polarizability in the air ($i = N_2, O_2, Ar$). ρ_w was the molar density of water vapor, and T was the absolute humidity. A_w and B_w were the Debye constants.

Based on the above model, the resonance frequency was as a function of temperature and relative humidity. The two parameter can be detected, but cannot calculate respectively. In this work, the microwave intensity attenuation effect on moisture have been study to detect the relative humidity. The relative humidity can be accurately detected, and the temperature can be calculated by removing the factor of relative humidity. The microwave intensity attenuation effect on moisture can be expressed as [18]:

$$\alpha(z) = 4.343\frac{0.6\pi}{\rho_w\lambda}\mathrm{Im}\left(-\frac{m^2-1}{m^2+2}\right)\rho_w \tag{11}$$

Where, *m* was refraction index of moisture, ρ_w was the water content (was the molar density of water vapor). When the spread distance was a fixed value, the microwave intensity attenuation approximation was determined as a function of the relative humidity:

$$\alpha(z) = 4.343\frac{4\pi\times 10^{[0.0122(291-T)-1]}}{\lambda^2}\rho_w \tag{12}$$

Where, *T* was absolute temperature, λ WAs the microwave wavelength. The saturation humidity *F* at 40 °C was 51.2 g/m^3, $\rho_w = Y_1 \times F \times 100\%$, Y_1 was the relative humidity.

3.2. Design and fabricate the U-shaped coupled-resonant probe

By the synchronization test model of temperature and humidity, the measurement system have been made based on the U-shaped resonance probe as shown in Fig. 2a. The microwave signals was transmitting into the microwave cavity and coupling into the