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Highly sensitive open-ended coaxial cable-based microwave resonator for humidity sensing

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ABSTRACT

A novel portable open-ended hollow coaxial cable resonator (OE-HCCR) is proposed and demonstrated for direct relative humidity (RH) measurements without the assistance of any humidity-sensitive material. The sensor is fabricated from a homemade hollow coaxial cable platform that provides ease of modification and improved robustness. The microwave cavity resonator is a metal post-coupled open-ended coaxial resonator, which includes two highly-reflective reflectors, i.e., the metal post and the metal plate-backed open end of the coaxial line. The gap distance between the metal plate and the open end is defined by a circular spacer. By simple one-step adjustments of the thickness of the spacer, the RH measurement sensitivity of the OE-HCCR can be greatly enhanced. The device physics is discussed; numerical calculations and experimental investigations are conducted to verify the sensitivity enhancement of the OE-HCCR for RH sensing. Due to the increased sensitivity, this is the first report of an open-ended coaxial line that is able to directly sense gaseous analyte, to the best of our knowledge. The proposed OE-HCCR with the sensitivity enhancement has the potential for highly sensitive chemical sensing combined with functional materials.

1. Introduction

Relative humidity (RH) sensing is of significant importance in various laboratory and industrial applications such as electronic device manufacturing, food processing, medical storage, pharmaceutical manufacturing, and chemical gas purification [1]. Various techniques have been demonstrated for RH sensing, including conventional mechanical dial hygrometers, electrical approaches, and more recently, fiber-optic configurations. In a typical mechanical hygrometer, a hygroscopic material is used as the sensing element, manifesting itself as a change in length or shape under a humidity variation. The length or shape change is then magnified by a mechanical mechanism and transferred to an indicator dial. The electrical sensors work based on measurements of RH-induced changes in the capacitance of a capacitor due to changes in a dielectric material [2], the impedance of a conductive material, or the dielectric property of a hygroscopic material [3,4]. Fiber-optic RH sensors have been extensively investigated recently due to their unique advantages such as high sensitivity, immunity to electromagnetic interference, and capabilities for remote sensing and multiplexing. Various optical fiber micro-structures and different types of optical fibers combined with humidity-sensitive materials have been demonstrated for RH sensing such as grating structures, interferometers, and specialty fibers [5–7]. The working principle of fiber-optic RH sensors is based on the humidity-sensitive material induced secondary effects (e.g., due to expansion/contraction of the material under different RH) on the fiber sensing region, e.g., variations of refractive index and local strain. The secondary effects will subsequently result in spectrum shifts or intensity variations of the optical fiber sensors. Tapered optical fibers were also reported for direct RH sensing based on infrared spectroscopy where water exhibits a strong absorption peak near 2-μm waveband so that no humidity-sensitive material was needed [8,9]. However, the tapered optical fiber-based RH sensors are fragile due to the reduced fiber diameters and require extreme caution in sensor handling and installation. The majority of these reported RH sensors rely on the use of a humidity-sensitive material as the transducing element, where the material is generally required to be sensitive over a large range of RH, stable over time under thermal cycling, chemical inert in the presence of various chemical species in the ambient environment, and preferably exhibit good response and recover speed [3,5,10]. Therefore, the selection of a suitable humidity-sensitive material for sensor construction is rather difficult and challenging.

Taking advantage of the large contrast in permittivity between air and water in the microwave domain, several microwave sen-

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sors were demonstrated for direct humidity sensing without the use of humidity-sensitive materials, such as U-shaped resonator [11], substrate integrated cavity resonator [12,13], and a miniaturized double-folded substrate integrated cavity resonator [14]. Open-ended coaxial probes are another type of microwave device that has been extensively used for the determination of electromagnetic properties of materials in the past fifty years [15,16]. A bulky dielectric material in liquid or solid phase covering the open end modifies the fringing electric field, and the complex permittivity of the material can be determined by analyzing the complex reflection coefficient of the coaxial line. However, open-ended coaxial probes have not been demonstrated for direct gaseous vapor sensing due to their low dielectric sensitivity.

Recently, mimicking the optical fiber in-line interferometers, we proposed a series of novel in-line coaxial cable-based devices, including the coaxial cable Bragg grating [17], the coaxial cable Fabry-Perot interferometer [18], and the coaxial cable Fabry-Perot resonator [19–22], which have been successfully demonstrated for sensing applications in harsh environments (e.g., large strain 5% and 1000 °C) [17,23]. Compared to fiber-optic sensor counterparts, the coaxial cable-based sensors presented here are robust, able to withstand harsh environments, and exhibit a large dynamic range, but with relatively low measurement resolution. Very recently, we reported a new microwave sensing scheme in an extrinsic configuration, i.e., the open-ended hollow coaxial cable resonator (OE-HCCR) [24]. The OE-HCCR integrated the strength from two different arenas, the open-ended coaxial line technique and interferometry. Similar to the fiber-optic extrinsic Fabry-Perot interferometer, the OE-HCCR was explored for displacement measurements, offering nanometric displacement resolution within an operational range of 0.1 mm.

In this paper, we report a novel OE-HCCR-based portable hygrometer that is capable of directly measuring RH without the assistance of any humidity-sensitive material. More importantly, the measurement sensitivity can be further enhanced by simple one-step adjustments of the sensor structure. The underlying physics that explains the function of the device was studied, and the capability for sensitivity enhancement was numerically investigated and experimentally verified. We demonstrated that both the resonance frequency and resonance depth of the OE-HCCR responded to variations of RH with high sensitivity. The fast response of the sensor was also demonstrated by monitoring human exhaled breaths.

2. Sensor design and measurement principle

A schematic and an example of the reflection spectrum of the proposed OE-HCCR hygrometer are shown in Fig. 1. The OE-HCCR was fabricated from a homemade hollow coaxial cable. The radii of the inner conductor (a) and outer conductor (b) (indicated in Fig. 1(a)) were 3 and 7 mm, respectively. The characteristic impedance of the hollow coaxial line was calculated to be 50.8 Ω. Meanwhile, this design geometry also makes the homemade cable capable of being connected to a commercial coaxial cable (e.g., RG-58/U) via a standard SMA to N-type adapter. A cylindrical stainless-steel post was welded within the hollow coaxial line 75 mm away from the open end. The radius of the metal post was 1.5 mm. The metal post created a short circuit between the inner conductor and the outer conductor, resulting in a high reflection (e.g., ~80 %) of the electromagnetic wave (EM) traveling inside the cable. Combined with the open end, which provides a total reflection of the EM wave, a microwave cavity resonator is formed. A metal plate with thorough holes was fixed to the open end using a set of machine screws. The open end was sealed using water-proof epoxy. The gap distance, as indicated in Fig. 1(a), is determined by the thickness of the circular spacer. According to transmission line theory, the reflection spectrum of the resonator, in magnitude, can be calculated by:

$$M=\sqrt{\frac{\Gamma_1^2-2\Gamma_1\Gamma_2e^{-\alpha 2d_0}\cos(\delta-\phi_1-\phi_2)+\Gamma_2^2e^{-\alpha 4d_0}}{1-2\Gamma_1\Gamma_2e^{-\alpha 2d_0}\cos(\delta-\phi_1-\phi_2)+\Gamma_1^2\Gamma_2^2e^{-\alpha 4d_0}}} \tag{1}$$

where ϕ_1 and ϕ_2 are the phase reflection coefficients of the metal post and the open end, respectively; Γ_1 and Γ_2 are the magnitudes of the two corresponding reflection coefficients; d_0 is the physical length of the microwave cavity resonator, i.e., 75 mm; and, α is the transmission loss of the cable. Fig. 1(b) is a plot of the numerically-calculated reflection coefficient in magnitude of the OE-HCCR with air filled in the gap when d was set to 1 mm. Two resonance frequencies were observed within the 3 GHz-observation bandwidth, including the fundamental and the 2nd harmonic resonances. According to Eq. (1), the resonance frequencies of the OE-HCCR, where the phase-matching condition is satisfied, can be expressed as [24]:

$$f_{res}=\frac{c(2m\pi+\phi_1+\phi_2)}{4\pi d_0} \tag{2}$$

where c is the speed of light in vacuum; m is a non-negative integer denoting the resonance order.

Since the working principle of the RH sensor is based on the modification of ϕ_2 (as discussed later), we will focus on mathematically deriving ϕ_2; ϕ_1 can be determined by a full-wave simulation, e.g., by ANSYS HFSS [19]. Employing equivalent circuit modeling, ϕ_2 can be calculated by:

$$\phi_2=-2\tan^{-1}(\omega Z_0 C) \tag{3}$$

where f is the frequency of the EM signal; Z_0 is the characteristic impedance of the cable (i.e., 50 Ω); C is the capacitance at the open end and is given by [25]:

$$\begin{aligned}C=\varepsilon_r\Bigg\{&\frac{2\varepsilon_0}{[\ln(b/a)]^2}\int_a^b\int_a^b\int_0^\pi\frac{\cos\phi' d\rho d\rho' d\phi'}{\sqrt{\rho^2+\rho'^2-2\rho\rho'\cos\phi'}}\\&+\frac{4\varepsilon_0}{[\ln(b/a)]^2}\sum_{n=1}^{\infty}\int_a^b\int_a^b\int_0^\pi\frac{\cos\phi' d\rho d\rho' d\phi'}{\sqrt{\rho^2+\rho'^2+4n^2d^2-2\rho\rho'\cos\phi'}}\Bigg\}\\=k\varepsilon_r\end{aligned} \tag{4}$$

where ε_0 and ε_r are the vacuum permittivity and relative permittivity of the gaseous analyte in the gap defined by the open end and the metal plate, respectively; k denotes a linear coefficient. As can be observed from Eq. (4), the capacitance (C) is determined by the gap distance (d) and relative permittivity (ε_r) of the gas filled in the gap; for a given d, C is linearly proportional to ε_r. Therefore, a change in ε_r results in a variation of C, and the variation of C changes the phase reflection coefficient of the open end (i.e.,ϕ_2), resulting in a variation of the phase-matching condition and manifesting as a shift in the resonance frequency. Therefore, by monitoring the resonance frequency shift, the variation of ε_r can be determined. Taking advantage of the fact that water has a large permittivity in the microwave domain (e.g., ~80 at 20 °C), a small change in RH (i.e., a change in the relative amount of water vapor in the air) results in a relatively large variation of permittivity of the vapor. It was reported that the dielectric change per unit change in RH was 0.0002/RH at 30 °C and 1 atm [13]. Consequently, the proposed microwave resonator has the potential to directly measure variations in RH without the assistance of a hygroscopic material. More importantly, the sensitivity can be further enhanced based on a novel sensing scheme, as discussed below.

In our recent study [24], we demonstrated that the fringing capacitance increases exponentially as the gap distance (d)

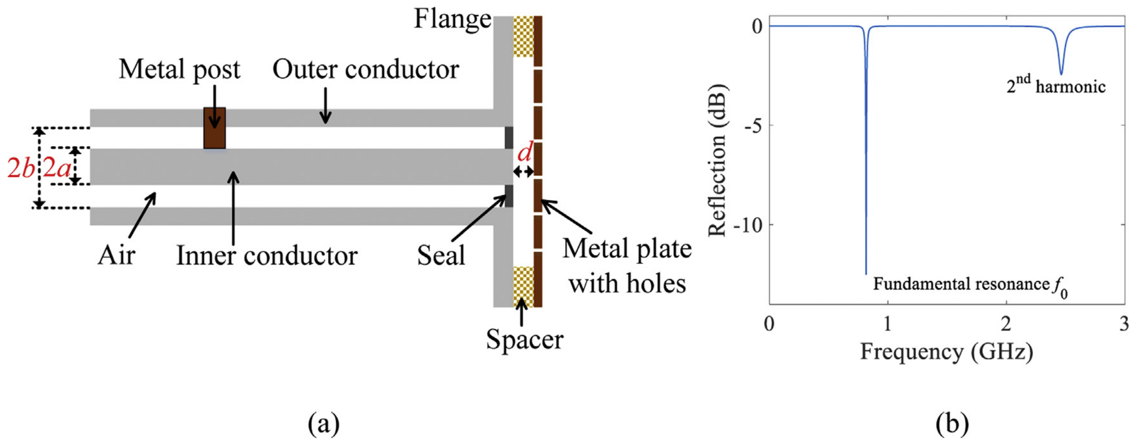

Fig. 1. The proposed OE-HCCR hygrometer. (a) Schematic of the hygrometer. The gap distance *d* separates the endface of the central conductor from the surface of the metal plate. (b) Calculated reflection spectrum of the hygrometer where the gap was filled with air and *d* was set to 1 mm. The fundamental resonance frequency was determined to be 817 MHz.

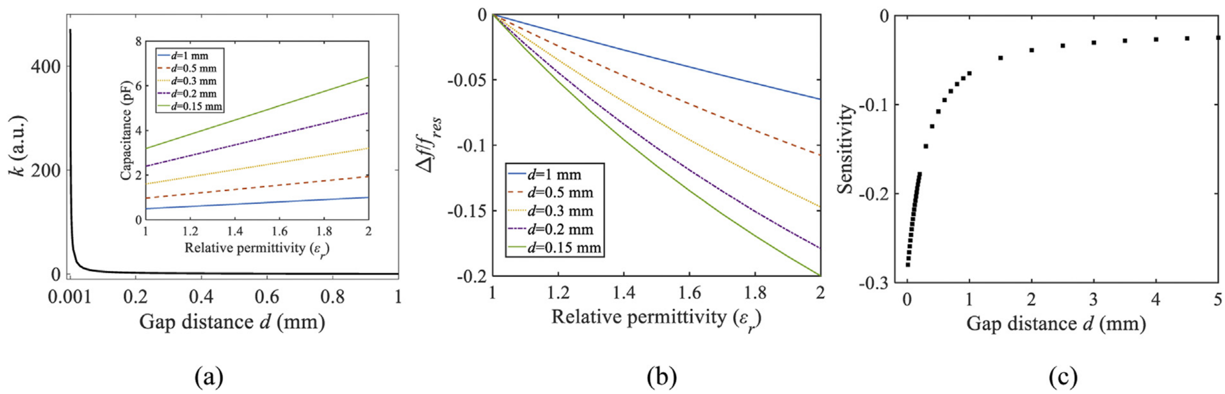

Fig. 2. Numerical investigations of the sensitivity enhancement of the OE-HCCR. (a) The dependence of the linear coefficient on the gap distance *d*. The inset shows the capacitance as a function of ε_r for five different values of *d*. (b) The relative change in resonance frequency (i.e., frequency shift/initial resonance frequency) as a function of ε_r for five different values of *d*. (c) The calculated dielectric measurement sensitivity with respect to the gap distance. In the calculation, the relative permittivity of the gap medium increased from 1 to 1.5, and the corresponding relative shifts in resonance frequency were calculated. The dielectric sensitivity was then obtained by differentiating the relative shift in resonance frequency with respect to the change in the relative permittivity of the gap medium.

decreases for a given ε_r (e.g., 1) of the material in the gap. Therefore, as *d* decreases, the linear coefficient *k* in Eq. (4) increases exponentially, indicating that the fringing capacitance will have a greater dependence on ε_r, thus higher sensitivity for measuring variations of ε_r. Numerical calculations of the OE-HCCR were conducted to verify our expectations, as presented in Fig. 2. Fig. 2(a) shows the dependence of the linear coefficient *k* on the gap distance *d*; the inset presents the capacitance *C* as a function of ε_r for five different values of *d*. As expected, the slope (i.e., *k*) increases exponentially as *d* decreases. Fig. 2(b) includes the plots of numerically calculated relative changes in the fundamental resonance frequency (i.e., $\Delta f/f_{res}$, the shift in resonance frequency/initial resonance frequency) as a function of ε_r for five different values of *d*. The absolute value of the slope, i.e., measurement sensitivity (the relative change in resonance frequency/variation of ε_r) increased as *d* decreased. The exponential relationship between the calculated sensitivity and the thickness of the spacer *d* is shown in Fig. 2(c). As can be seen, the absolute value of the sensitivity to the relative permittivity of the material in the gap increased exponentially as *d* decreased from 5 mm to 0.01 mm. Therefore, the sensitivity for measurements of humidity by the OE-HCCR hygrometer can be enhanced by simple one-step adjustments of the thickness of the spacer, i.e., the gap distance *d*; the smaller the gap distance, the larger the measurement sensitivity.

3. Experimental results and discussion

The response of a prototype OE-HCCR hygrometer under controlled conditions was investigated by placing the sensor in an environmental chamber (electro-tech systems, MODEL 5506), where the RH could be manually adjusted and monitored by a commercial hygrometer in real-time. A portable VNA (Anritsu MS46121B) was employed as the interrogator, which was configured with sampling points of 5000, an intermediate frequency (IF) bandwidth of 1 kHz, and an observation bandwidth of 20 MHz. In the experiment, the RH inside the chamber was increased from 40 % to 80 % in steps of 10 %, and the corresponding responses of the sensor were recorded at each setting of the RH. Fig. 3 includes the measured reflection spectra of the prototype hygrometer for different settings of the RH when *d* (the thickness of the spacer) was set to 1, 0.5, 0.3, and 0.1 mm. The reflection spectrum shifted to the lower-frequency region as *d* decreased from 1 mm to 0.1 mm, which matched well with our previous study [24]. For each setting of *d*, the reflection spectrum shifted to the lower frequency as the RH increased from 40 % to 80 %, consistent with increases in ε_r due to the water component of the humidified air. More importantly, the magnitude of the shift of the reflection spectrum increased as *d* decreased, indicating that the sensitivity to variations in the RH increased as *d* decreased, as expected. The fundamental resonance frequency obtained for the prototype device when *d* was set to

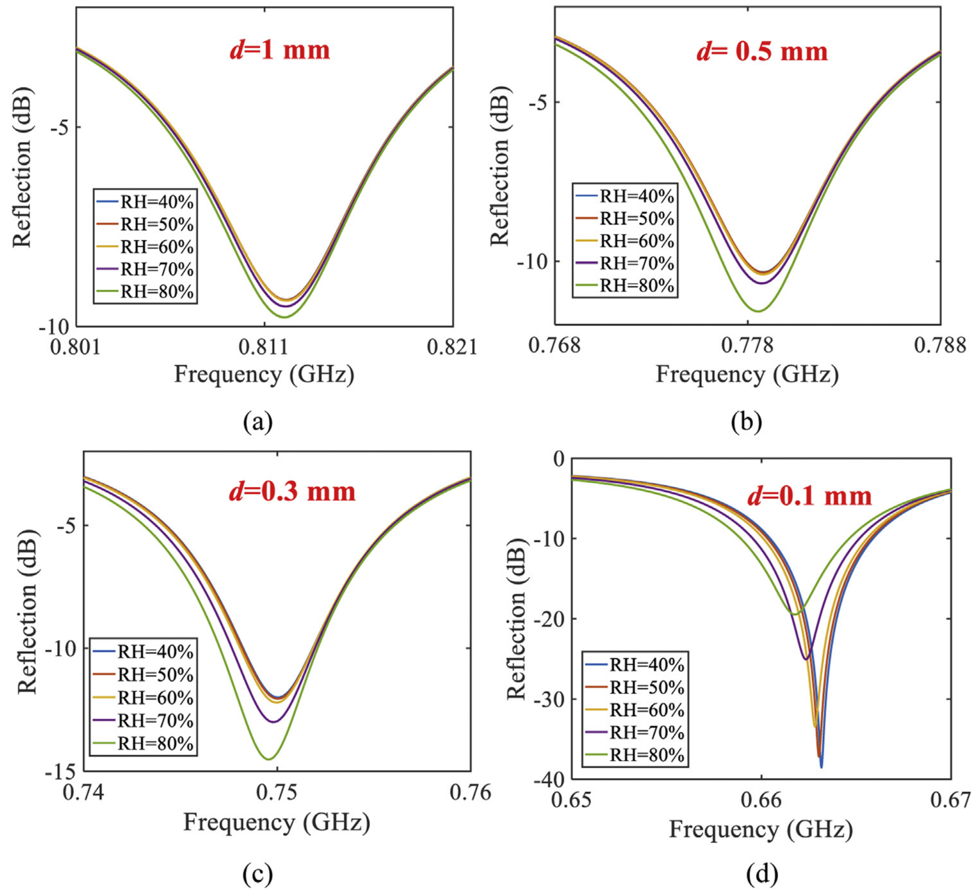

Fig. 3. Measured reflection spectra centered at the fundamental resonance frequency for different settings of the RH in the range 40 %–80 % when *d* (the thickness of the spacer) was set to (a) 1 mm, (b) 0.5, (c) 0.3 mm, and (d) 0.1 mm.

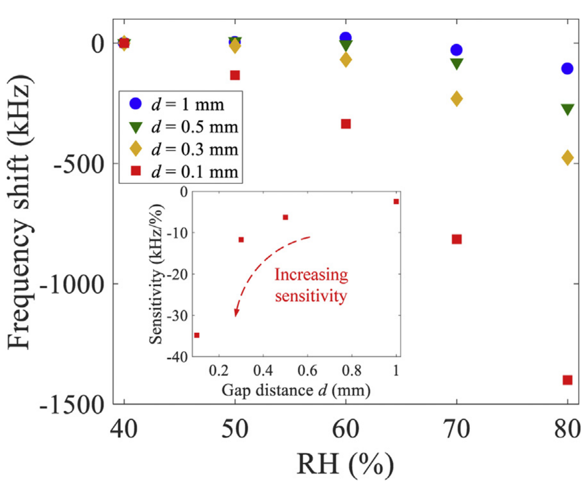

Fig. 4. Shift in the fundamental resonance frequency as a function of the RH for four different settings of *d* (1, 0.5, 0.3, and 0.1 mm). The inset shows the dependence of the average frequency sensitivity (frequency shift/variation in RH) of the OE-HCCR hygrometer on the gap distance *d*.

1 mm was approximately 812 MHz, which matched well with the numerical prediction of approximately 817 MHz.

Fig. 4 plots the shift in resonance frequency as a function of the RH for four different settings of *d*. When *d* was set to 1 mm, the resonance frequency first increased by approximately 10 kHz as the RH increased from 40 % to 60 %, and then decreased by about 120 kHz as the RH increased from 60 % to 80 %. We believe that the non-monotonic phenomenon is due to the low sensitivity and resolution under this setting of *d* (i.e., 1 mm). The environmental chamber employed in the experiment has an RH control uncertainty of ±2.5 %, which might contribute to the non-monotonic response of the sensor. The errors introduced in the determination of the resonance frequency from the recorded spectrum might also play a role in the recorded non-monotonic response. Therefore, sensitivity enhancement for the sensor is necessary. As can be observed in Fig. 4, as *d* decreased, the magnitude of the shift in resonance frequency increased, and monotonic relationships were obtained for all other settings of *d* (i.e., 0.5, 0.3, and 0.1 mm). The inset in Fig. 4 presents the dependence of the average frequency sensitivity (frequency shift/variation of RH) on the gap distance *d*. A more than tenfold sensitivity enhancement was realized as *d* decreased from 1 mm to 0.1 mm. Although a nonlinear relationship was revealed, the prototype device could be employed for RH sensing after proper calibrations. Since no hygroscopic material was used in the sensor construction, the long-term stability and repeatability of the proposed hygrometer are ensured. In addition, the all-stainless-steel structure makes the sensor capable of measuring RH at elevated temperatures.

Apart from monitoring RH-induced shifts in resonance frequency, changes in the resonance depth of the reflection spectra were also investigated. According to Fig. 3, as *d* was set to 1, 0.5, and 0.3 mm, the resonator was over coupled, and the resonance depth increased as the RH increased. As *d* decreased down to 0.1 mm, the resonator became critically coupled with a resonance depth of ∼40 dB, and the resonance depth decreased as the RH increased, indicating that the resonator evolved from critical coupling to loose coupling [24]. The reason for this evolution is that the magnitude of the effective reflection coefficient of the open end decreased as the RH increased and became smaller than that of the metal post. A detailed analysis of the coupling states of the resonator can be found in our previous work [24]. Fig. 5 plots the absolute change in the resonance depth of the microwave resonator as a function of the RH for four different settings of *d*, according to the reflection spectra shown in Fig. 3. Monotonic relationships were obtained for all four different settings of *d*. Interestingly, the absolute change in resonance depth also increased as *d* decreased. The inset in Fig. 5 shows the average resonance depth sensitivity (absolute change in resonance depth/variation of RH) as a function of the gap distance *d*. A more than fiftyfold improvement was observed as *d* decreased from 1 mm to 0.1 mm. Therefore, the evolution of the resonance depth could also be employed as a parameter for monitoring variations in the RH.

We also expect a fast response from the proposed RH sensor (i.e., real-time sensing) since no humidity-sensitive material was used in the sensor design. The response time was investigated by employing the hygrometer for monitoring human exhaled breaths. Fig. 6 presents the investigation results. The experimental setup is illustrated in Fig. 6(a), where a fan was placed in front of the sensor to enhance the circulation in the sensing chamber of the hygrome-

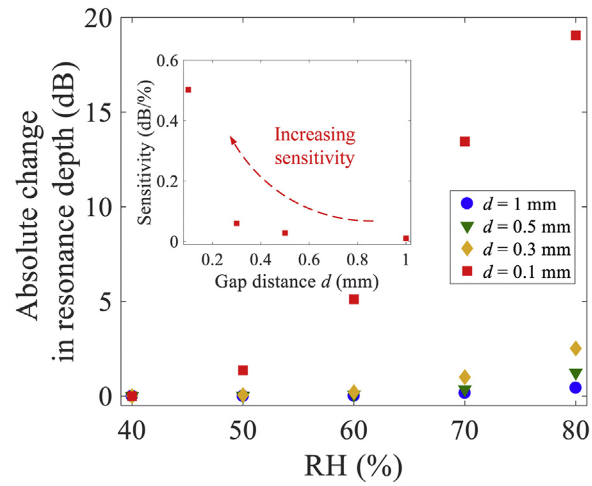

Fig. 5. Absolute change in the resonance depth of the fundamental resonance as a function of the RH for four different settings of *d* (1, 0.5, 0.3, and 0.1 mm). The inset shows the average resonance depth sensitivity (absolute change in resonance depth/variation in RH) of the hygrometer as a function of the gap distance *d*.

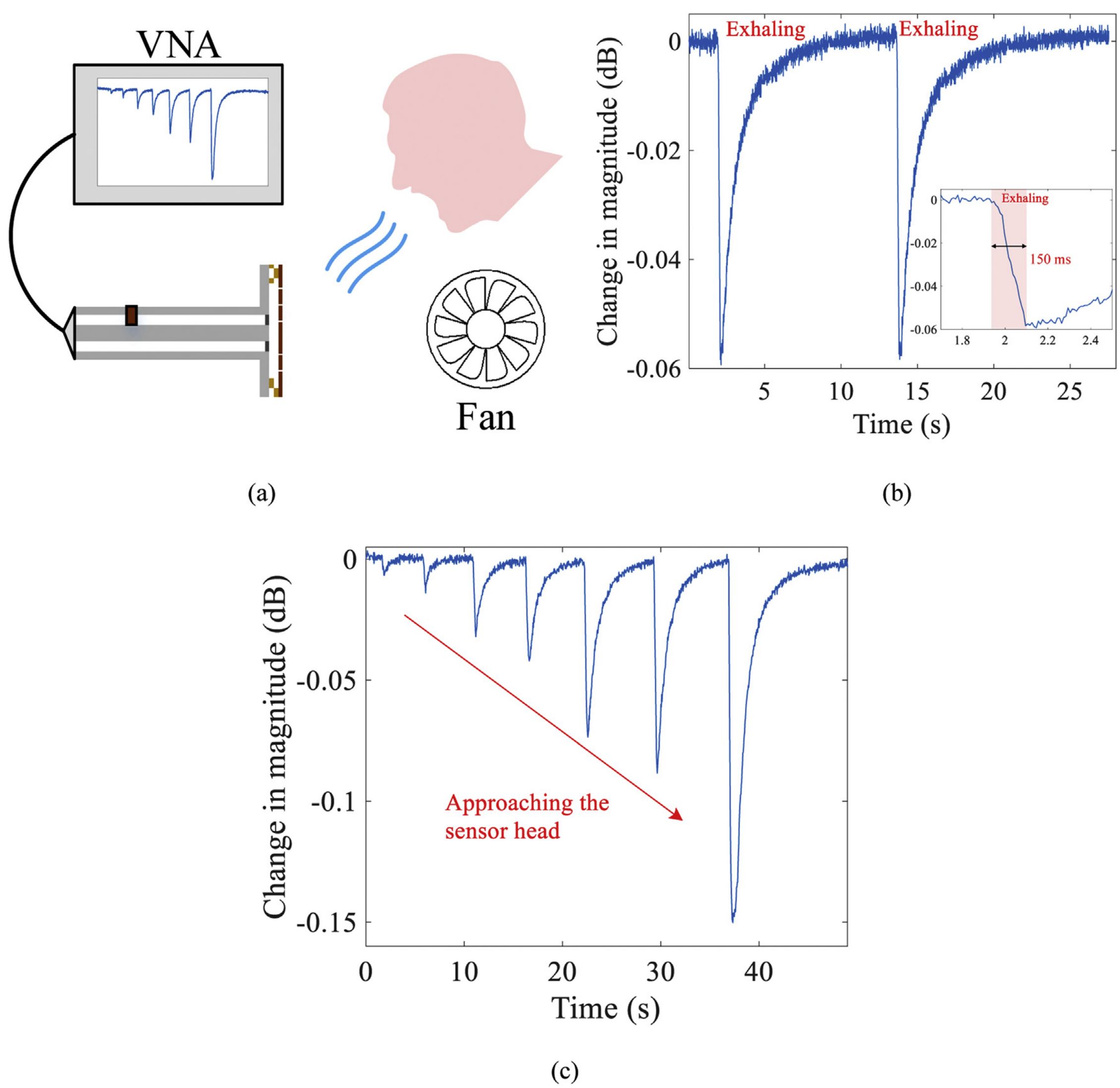

Fig. 6. Investigation of the response and recovery times of the OE-HCCR hygrometer. (a) A schematic diagram of the experimental setup used to demonstrate the response and recovery times of the OE-HCCR hygrometer. (b) Measured responses of the sensor to two successive human breaths. The inset presents an enlarged view of the response curve centered at ~2.1 s showing the fast response time of the sensor. (c) The measured responses of the sensor as the volunteer exhaled into the sensor probe head at seven different distances away from the sensor head, from 40 cm to 10 cm in steps of 5 cm.

ter. The gap distance between the open end of the coaxial cable and the metal plate was set to 0.3 mm, where the OE-HCCR resonated at ~750 MHz (see Fig. 3(c)). To obtain a rapid update rate from the interrogator (i.e., the VNA), a CW-frequency mode was used and the operating frequency was set to 747 MHz. The magnitude reflection coefficient at the operating frequency was monitored in real-time. Fig. 6(b) shows the measured response of the hygrometer when a volunteer exhaled into the sensor head twice. The inset presents an enlarged view showing the response time of the sensor. As the moist air from exhaled breaths reached the chamber of the sensor, the reflection magnitude decreased; as the humid air flowed out of the chamber (due to the airflow driven by the fan), the reflection magnitude recovered. The response time was determined to be ~150 ms, while the recovery time was found to be ~7 s. The relatively long recovery time can be explained by the process of evaporation of the water molecules in the chamber of the sensor. We expect that an improved circulation system can be designed to further decrease the recovery time of the sensor, for example, by engineering an outlet port on the OE-HCCR, which can be driven by a vacuum. The response and recovery times of the OE-HCCR hygrometer are ultimately limited by the flow rate of the analyte of interest. The unique feature of the proposed OE-HCCR hygrometer, which does not use a humidity-sensitive material, makes it extremely suitable for monitoring variations of RH of flowing gas in real-time. In fact, the development of a human breath analyzer based on an improved OE-HCCR is ongoing in our lab. Fig. 6(c) shows the response of the sensor when a volunteer exhaled into the sensor at different distances away from the sensor probe head. As the volunteer kept approaching the sensor head, larger changes in the magnitude were recorded because more water molecules entered into the chamber.

4. Conclusion

To summarize, we proposed, fabricated, and tested a novel portable OE-HCCR hygrometer for highly sensitive RH measurements without the assistance of a hygroscopic material. A metal post-coupled open-ended coaxial resonator was engineered from a homemade hollow coaxial line. A gap was introduced at the metal plate-backed open end using a spacer and was used as the chamber for the gaseous analyte (e.g., moist air). Numerical calculations demonstrated that the resonance frequency of the resonator was highly sensitive to changes in permittivity of the analyte that filled in the gap. Importantly, the dielectric sensitivity of the OE-HCCR could be enhanced by only decreasing the gap distance. Taking advantage of the large permittivity of water vapor in the microwave frequency domain, the OE-HCCR sensor device was employed for direct measurements of RH. The experimental demonstrations show that both the resonance frequency and resonance depth of the developed resonator had a great dependence on variations of the RH. Also, it was experimentally demonstrated that the sensitivity of the device for RH sensing could be further enhanced by adjusting the gap distance between the open end and the metal plate. In addition to humidity measurements, the demonstrated OE-HCCR sensor device with sensitivity enhancement could be developed further for detection of trace chemical vapors and employed for biochemical sensing applications when combined with functional films (e.g., an electronic nose) [26].

CRediT authorship contribution statement

Chen Zhu: Conceptualization, Methodology, Writing - original draft, Software, Validation, Investigation, Writing - review & editing. **Rex E. Gerald:** Software, Validation, Investigation, Writing - review & editing. **Jie Huang:** Conceptualization, Methodology, Writing - original draft, Software, Validation, Investigation, Writing - review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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