POSTPRINT VERSION. The final version is published here :
Benleulmi, A., Boubekeur, N. et Massicotte, D. (2019). A Highly Sensitive Substrate Integrated Waveguide Interferometer Applied to Humidity Sensing. IEEE Microwave and Wireless Components Letters (Vol. 29, p. 68-70).
doi: 10.1109/LMWC.2018.2882302

A Highly Sensitive Substrate Integrated Waveguide Interferometer Applied to Humidity Sensing

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***Abstract*—This letter presents a new generation of radio-frequency interferometric sensors. Herein, an original, simple and monolithic interferometer based on substrate integrated waveguide technology is introduced for the first time. In order to demonstrate its potential for measurement applications, the proposed structure has been studied as a humidity-sensing element. Its detection principle is based on the variation of the effective dielectric constant of a sensitive branch due to the variation of the humid air dielectric constant. The sensitive characteristics of the structure have been investigated in the range of 20%–70% relative humidity. An analytical model that predicts the frequency shift and estimates the humidity level is proposed. The substrate integrated interferometer can be used in many measurement applications such as dielectric material characterization and environmental detection.**

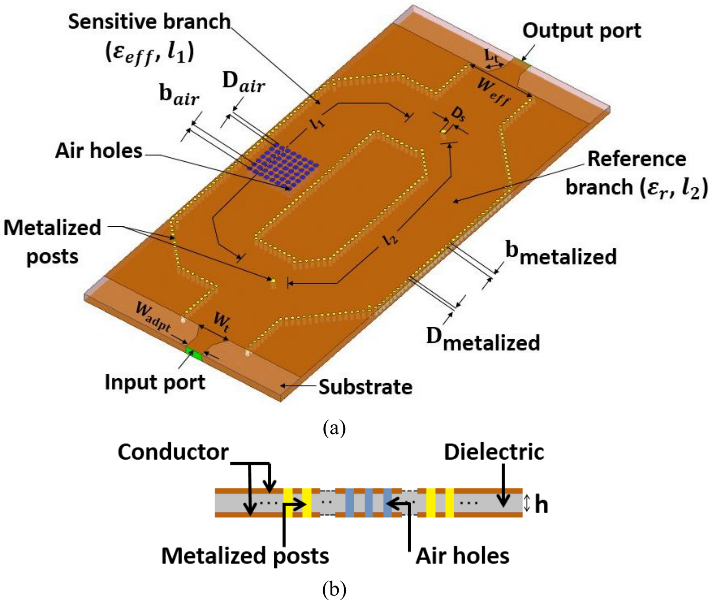
***Index Terms*—Interferometer, Radio-Frequency, Passive, Sensor, Substrate Integrated Waveguide (SIW).**

I. INTRODUCTION

OVER the last few years, there has been a spike in the interest in substrate integrated waveguide (SIW) components for measurement applications. Indeed, the use of SIWs for the development of sensors presents a very promising option due to their advantages in terms of good electrical properties, compactness and low cost [1].

Several SIW structures have been demonstrated for the characterization of dielectric materials [2], [3] as well as the detection and monitoring of physical quantities such as hydrogen and humidity [4], [5]. The measurement techniques employed by these structures are mainly the resonance and the transmission/reflection methods. Typically, cavity resonators are used in sensing applications that rely on high accuracy. However, their efficiency is quite limited for wideband measurements; for the latter, the second approach is often used despite its low accuracy. Thus, the applied measurement technique is usually chosen based on the requirements of the intended application.

Radio-frequency (RF) interferometry presents another attractive technique for sensing applications that require high sensitivity, fine resolution, fast speed and accuracy [6]. Fundamentally, it relies on a process of phase variation detection and waves' superposition. At optical wavelengths, interferometric sensors have been widely investigated for various applications such as biological and chemical sensing [7]. By exploiting different technologies and architectures, RF interferometers have also been extensively demonstrated for many applications such as small displacements measurement [8] and dielectric spectroscopy [9]. The development of interferometric sensors using SIW technology has never been investigated despite the good-sensing capabilities of the substrate integrated sensors. In this context, a new class of SIW sensing elements is demonstrated and presented in this letter. An original substrate integrated interferometric sensor is introduced for the first time. The proposed structure is investigated for relative humidity (RH) sensing without using a sensitive layer in order to demonstrate its potential for measurement applications. Its sensitivity is compared with that of the SIW cavity resonators introduced in [5]. The SIW interferometer combines the advantages of both the SIW technology and the interferometry technique. Therefore, it presents a highly sensitive, passive and compact measurement solution. Additionally, the new device reduces the measurement errors related to the dielectric properties variations by exploiting a differential approach and also simplifies the phase measurement of the SIW phase shifter presented in [4] so that the detected physical quantity can be instantly mapped on the frequency.



(a)

(b)

Fig. 1. (a) The 3-D structure of the substrate integrated interferometer. (b) Side view of the dielectric and metalized posts.

Manuscript received October 1, 2018; revised November 2, 2018; accepted November 14, 2018. This work was supported in part by funding from the Natural Sciences and Engineering Research Council of Canada (NSERC) and in part by software equipment from the Canadian Microelectronics Corporation (CMC).

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II. THEORETICAL MODEL

The basic structure of the interferometer consists of two distinct branches connected on each side to a built-in power divider/combiner. Fig.1 shows the conceived SIW interferometric sensor. The sensitive branch, enabled by the introduction of the air holes, has an effective dielectric constant ε_{eff} and a length l_1 as attributes. Analogously, the reference branch has a length l_2 and a relative dielectric constant ε_r (the substrate dielectric constant). The operation principle can be summarized into three major steps: the division of the input signal into two probing signals, the propagation of each probing signal through a branch of the interferometer, and finally the combination of the two probing signals at the output port.

The phase difference between the two branches at a frequency f is given by

$$\Delta\varphi(f) = |\beta_1(f)l_1 - \beta_2(f)l_2| \qquad (1)$$

where β_1 and β_2 are the phase constants of the sensitive branch and the reference branch, respectively.

At the interferometer's operation frequency, the signals from the two branches have a destructive interference, i.e., a phase difference of 180°. Hence, for the TE_{10} mode, equation (1) can be written as

$$\left| \sqrt{\left(\frac{2\pi f_0\sqrt{\varepsilon_{eff}}}{c}\right)^2 - \left(\frac{\pi}{W_{eff}}\right)^2}\, l_1 - \sqrt{\left(\frac{2\pi f_0\sqrt{\varepsilon_r}}{c}\right)^2 - \left(\frac{\pi}{W_{eff}}\right)^2}\, l_2 \right| = \pi \qquad (2)$$

where c denotes the speed of electromagnetic waves in vacuum, f_0 is the operation frequency, and W_{eff} is the effective width of each branch [1]. The effective permittivity of the sensitive branch changes depending on the humid air dielectric constant and its variation can be estimated by the Maxwell-Garnett (MG) mixing rule [2]

$$\varepsilon_{eff} = \varepsilon_r + 3v\varepsilon_r \frac{\varepsilon_r(H)-\varepsilon_r}{\varepsilon_r(H)+2\varepsilon_r-v(\varepsilon_r(H)-\varepsilon_r)} \qquad (3)$$

where v is the volume fraction of the sensitive region, and $\varepsilon_r(H)$ is the dielectric constant of moist air given by [10]

$$\varepsilon_r(H) = 1 + \frac{211}{T}\left(P + \frac{48P_s}{T}H\right) \times 10^{-6} \qquad (4)$$

where T is the absolute temperature (K), P is the pressure of moist air (mmHg), P_s is the pressure of saturated water vapor (mmHg), and H is the relative humidity (%).

Equations (2)–(4) show that the operation frequency f_0 varies according to the relative humidity percentage. In fact, the permittivity of humid air is proportional to the relative humidity level. Therefore, the variation of the RH percentage changes the effective permittivity of the sensitive branch, which causes the operation frequency shift. The variation of the pressure and temperature can also affect the frequency shift, however, their effect is less important [5].

TABLE I
DESIGN PARAMETERS VALUES FOR THE SIW INTERFEROMETER [MILLIMETER]

W_{eff}	$D_{metalized}$	D_{air}	D_s	$b_{metalized}$	b_{air}	W_{adpt}	W_t	L_t
13.66	0.6	0.9	0.94	1	1.2	3.38	6.5	2.5

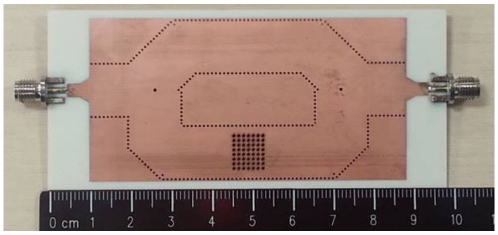


Fig. 2. The manufactured SIW interferometric sensor.

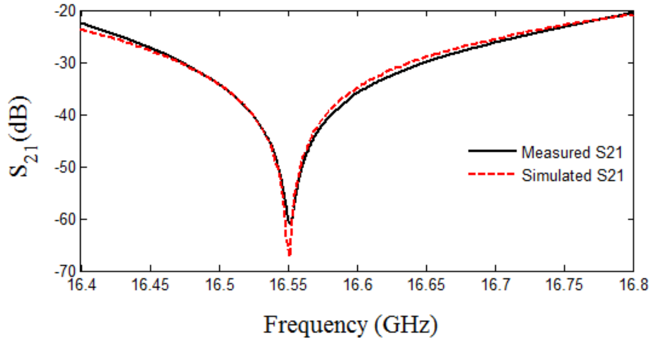
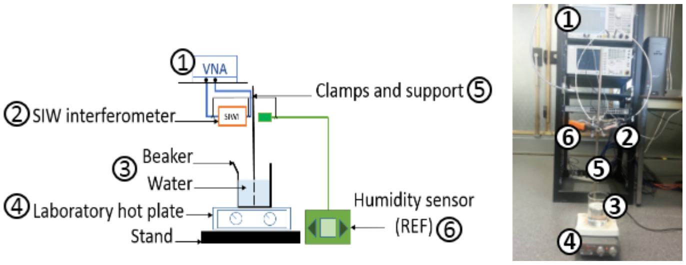


Fig. 3. Simulated and measured S_{21} modulus at 20% RH.

III. DEVICE STRUCTURE AND EXPERIMENTAL VALIDATION

The SIW interferometer was designed and simulated using HFSS [11]. The considered dimensions are shown in Table I. The proposed structure operates at the frequency of 16.55 GHz and the used substrate is Rogers 4003C (ε_r= 3.55, tan δ = 0.0023, h = 1.524 mm). Fig. 2 shows the built SIW interferometric sensor. A comparison between the simulated and measured S_{21} modulus of the device at 20% RH is shown in Fig. 3. The obtained simulation result is in accordance with the measured S_{21}.

The sensitive characteristics of the proposed interferometer were tested experimentally for T = 30 °C in the range of 20%–70% RH using the experimental setup presented in Fig. 4. The tests were carried out within this humidity range in order to avoid the accumulation of water molecules with a very high dielectric constant (~70) in the functionalized region at higher relative humidity percentages. In fact, water condensation would cause an important change in the effective dielectric constant of the sensitive branch and consequently a significant frequency shift. Fig. 5 shows the measured S_{21} modulus at 20% and 70% RH in the frequency range of 16.4 GHz to 16.8 GHz. According to this figure, the structure is ascertained to be sensitive to the variation of the relative humidity percentage as the operation frequency shifted by 7.1 MHz. The corresponding



(a) (b)

Fig. 4. (a) Scheme of the used measurement setup. (b) Its picture.

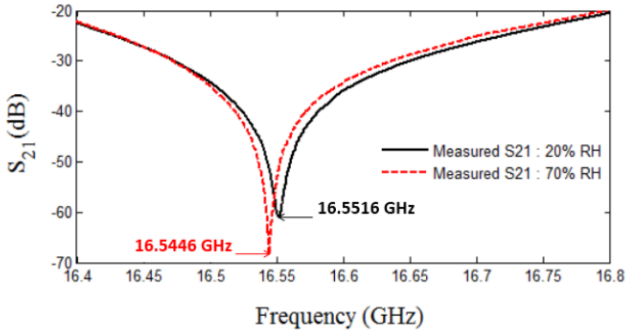


Fig. 5. Measured S_{21} modulus at 20% and 70% RH.

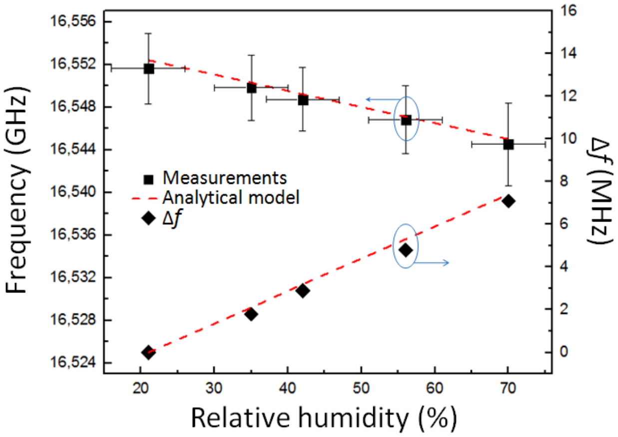


Fig. 6. Sensitivity characteristics of the SIW interferometer for the TE_{10} mode: (Left axis) the measured and calculated operation frequency as a function of the humidity level variation. (Right axis) operation frequency variation.

effective quality factor, defined as $Q_{eff} = f_0/\Delta f_{3dB}$, is 2.4×10^3 at 20% RH. The experiment was repeated three times under the same experimental conditions to test the measurements repeatability and identify their errors. The frequency shift was estimated analytically using the proposed analytical model. Fig. 6 shows the numerical results for the TE_{10} mode of the estimated frequency shift together with the measurement results at different relative humidity levels. As shown in this figure, the measurement results agreed well with the proposed model and the structure exhibited a sensitivity of 142 kHz/RH from 20% to 70% RH. The repeatability tests showed a coherence between the different measurements with a maximum frequency shift under 4 MHz. Table II presents a comparison between the sensitive characteristics of the proposed interferometer and the SIW cavity resonators introduced in [5] for the same experimental conditions (T = 30 °C and P = 760 mmHg) and propagation mode (TE_{10} mode). As shown in Table II, the proposed sensor has the smallest sensitive region and the highest sensitivity; by using the proposed analytical model, this result was verified with an estimation of the device's sensitivity at around 4 GHz. Therefore, the SIW interferometer is very convenient for measurement applications that involve the use of small volumes of materials and require high sensitivity. Concerning the total dimensions of the sensor, it was reported in [4] that a way to reduce significantly the size of a SIW sensor would be through the use of slow-wave SIWs [12].

TABLE II
COMPARISON BETWEEN THE SIW INTERFEROMETER AND CAVITY RESONATOR

Structure	Operation frequency [GHz]	Sensitive region dimensions [mm×mm]	Sensitive region surface [mm²]	Overall size [cm×cm]	RH range [%]	Sensitivity [kHz/RH]
SIW resonator	4.15	28.2×28.2	795	5. 1 ×3.9	0-80	101
	3.6	8.7×8.7	75.7	5. 1 ×3.9		9.35
SIW interferometer	16.55	8.1×9.3	75.3	9.8× 4.6	20-70	142

IV. CONCLUSION

A new generation of RF interferometric sensors has been introduced in this paper with a SIW interferometer for measurement applications. The developed structure has been demonstrated for relative humidity measurement and exhibited a sensitivity of 142 kHz/%RH in the range of 20%–70% RH. An analytical model that predicts this sensitivity has been proposed and validated experimentally. Finally, it is important to mention that the SIW interferometer as a new class of SIW sensing elements presents a more reliable and a better solution for applications such as dielectric materials characterization and gas sensing.

REFERENCES

[1] K. Wu *et al.*, "The substrate integrated circuits—A new concept for high-frequency electronics and optoelectronics", in *Proc. TELSIKS*, Serbia and Montenegro, vol.1, pp.3-10, 2003.
[2] J. D. Barrera and G. H. Huff, "Analysis of a variable SIW resonator enabled by dielectric material perturbations and applications," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 1, pp. 225–233, Jan. 2013.
[3] K. Saeed *et al.*, "Substrate integrated waveguide cavity resonators for complex permittivity characterization of materials," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 10, pp. 2340–2347, Oct. 2008.
[4] A. Benleulmi *et al.*, "Substrate Integrated Waveguide Phase Shifter for Hydrogen Sensing," *IEEE Microw. and Wireless Compon. Lett.*, vol. 26, no. 9, pp. 744-746, Sept. 2016.
[5] H. El Matbouly *et al.*, "Passive Microwave Substrate Integrated Cavity Resonator for Humidity Sensing," *IEEE Trans. Microw. Theory Techn.*, vol.63, no.12, pp.4150-4156, Dec. 2015.
[6] Nguyen, C and Kim, S, *Theory, Analysis and Design of RF Interferometric Sensors,* Springer Science+Business Media, New York, NY, USA, 2012.
[7] K. Kim and T. E. Murphy, "Porous silicon integrated Mach-Zehnder interferometer waveguide for biological and chemical sensing," *Opt. Express,* vol. 21, no. 17, pp. 19488-19497, 2013.
[8] A. Thansandote *et al.*, "Microwave interferometer for measurements of small displacements, " *IEEE Trans. Instrum. Meas.*, vol. IM-31, no. 4, pp. 227-232, Dec. 1982.
[9] Y. Cui and P. Wang, "The Design and Operation of Ultra-Sensitive and Tunable Radio-Frequency Interferometers," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 12, pp. 3172-3182, Dec. 2014.
[10] J. Fraden, *The Handbook of Modern Sensors: Physics, Design and Application,* 3rd ed. New York, NY, USA: Springer, 2003, pp. 393–399.
[11] ANSYS HFSS, Release 18. [Online]. Available: http://www.ansys.com/Products/Electronics/ANSYS-HFSS
[12] A. Niembro-Martín *et al.*, "Slow-Wave Substrate Integrated Waveguide", *IEEE Trans. Microw. Theory Tech.*, Vol. 62, No. 8, pp. 1625-1633, Aug. 2014.