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Design and Implementation of SIW Cavity Oscillators for Humidity Sensing Applications

Seyed Ehsan Mohsir
Department of Electrical Engineering
Ferdowsi University of Mashhad
Mashhad, Iran
eh.moshir@mail.um.ac.ir

Mojtaba Joodaki[1,2]
[1]*Department of Electrical Engineering*
Ferdowsi University of Mashhad, Mashhad, Iran
[2]*Department of Computer Science & Electrical Engineering,*
Jacobs University Bremen, Bremen, Germany
joodaki@um.ac.ir

***Abstract*— This paper presents the design and implementation of an oscillator-based humidity sensor. The designed oscillator consists of a SIW cavity resonator connected to a negative resistance oscillator. The sensing principle is based on an oscillation frequency shift caused by permittivity change of the humid air. Oscillation frequency of the oscillator is 3.917GHz and phase noise at 100 KHz offset from carrier is less than -94 dBc/Hz. Sensor's output shows linear characteristics in the range of 10%-85% relative humidity. The oscillator-based sensor can be used in radio frequency applications like IOT where the sensor needs to be wireless, low cost and with a simple manufacturing process.**

***Keywords*— substrate integrated waveguide, microwave oscillators, humidity sensor, oscillator-based sensors.**

I. Introduction

In recent years, the demand for wireless, low cost and low profile environmental sensors in different applications are growing unprecedented. Environmental sensors are widely used in applications such as Internet of Things (IoT), air quality control systems, detection of harmful agents and monitoring air quality in vehicles and houses.

Different humidity sensing techniques including, dielectric response of carbon nanotubes [1], film depositions on SAW resonators [2], and a transmission line coated with sensitive materials [3] are reported previously.

The oscillator-based sensors are used in various applications like gas sensors [4], metal detection sensors [5] and electrochemical mass detection [6]. Typically the resonator of an oscillator-based sensor is sensitive to a specific parameter. Any change in that parameter would change the oscillation frequency of the oscillator. The output of the oscillator can be applied to a frequency counter [7] or an antenna [8] to form a wireless sensor. Microwave sensors have also attracted attention in recent years due to the properties such as fast response, high accuracy, low cost and the ability to work in noisy environment [9]. Different displacement, alignment and rotation microwave sensors based on transmission line loaded by a resonator have been reported in [10], [11].

In this paper, a low cost oscillator-based humidity sensor based on the SIW cavity resonator proposed in [12] is designed, fabricated and tested. In section II the design procedures of the SIW cavity and oscillator are presented. SIW cavity is designed and simulated using a 3D electromagnetic software. The designed oscillator is a negative resistance oscillator. Noise and long term frequency stability play an important role in the performance of oscillator-based sensor, so the oscillator should be designed to have the best phase noise and stability performance.

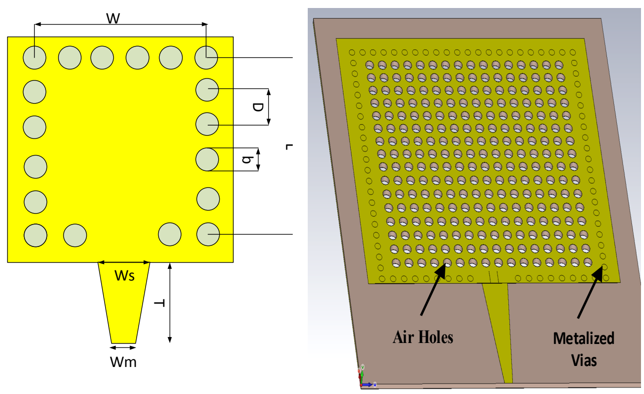
Section III involves the measurement and testing of the oscillator-based sensor. In this section output power, phase noise and other parameters of the oscillator is measured. Moreover, sensor is tested under different humidity and temperatures. The results show that the sensor sensitivity is good and is capable of humidity measurements in the range of 10%-85%.

II. Structure of Sensor and Oscillator Design

A. Principle of Humidity Sensing Using SIW Cavity Resonators

A SIW structure consists of two rows of metallic holes on a substrate. The distance between the two rows will determine the frequency band inside SIW. Due to the similar performance of SIW structures and rectangular waveguide, SIW structures can be used as resonant cavity in TEm0 mode. Fig .1a shows an SIW cavity. According to [13] leakage is negligible if:

$$\frac{D}{b} < 2.5 \qquad \frac{w}{D} > 8 \qquad (1)$$



(a) (b)

Figure. 1. SIW cavity resonator: (a) A simple SIW cavity; (b) SIW cavity for humidity sensing proposed by [12]

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Also, the resonance frequency of a SIW resonator can be found using (2).

$$f_{R,mn} = \frac{c}{2\sqrt{\varepsilon_{r,eff}}}\sqrt{(\frac{m}{W_{eff}})^2 + (\frac{n}{L_{eff}})^2} \quad (2)$$

Where W_{eff} and L_{eff} are approximately equal to:

$$L_{eff} = L - \frac{D^2}{.95b} \qquad W_{eff} = W - \frac{D^2}{.95b} \quad (3)$$

As can be seen in (2), by changing the $\varepsilon_{r,eff}$ of the substrate the resonance frequency of cavity will change. It is suggested by [13] that adding air holes in the middle of cavity would sensitize the SIW cavity to humidity. Fig .1b presents the SIW cavity structure proposed in [12] for humidity sensing. The relation between humidity and air permittivity is as follows [13]:

$$\varepsilon_r = 1 + \frac{211}{T}\,(P + \frac{48P_s}{T}\,RH) \times 10^{-6} \quad (4)$$

Where P is the pressure of air in mmHg, T is temperature in Kelvin, P_s is the pressure of saturated water vapor in mmHg, and RH is humidity percentage. The effective permittivity of the SIW cavity is a function of ε_r of substrate and air permittivity. It should be noted that by adding air holes into the SIW cavity the resonance frequency of the cavity would be slightly different from (2).

In order to investigate the characteristics of the cavity, a 3D electromagnetic simulation (CST) is performed. Fig .2 shows the results of the simulation. The simulation was done under room temperature and 20% humidity. The simulated quality factor of the SIW resonator is 420. Microstrip to SIW transition designed using 3D simulation to have the lowest return loss. Detailed geometrical values of SIW cavity are given in Table I.

TABLE I. GEOMETRICAL PARAMETERS OF SIW CAVITY RESONATOR

Parameter	value	Parameter	value
D	1.5 mm	W	31.4mm
b	0.6 mm	L	31.4mm
T	12.1mm	Ws	5.25mm
Wm	1.13mm	AirHole	1.2mm

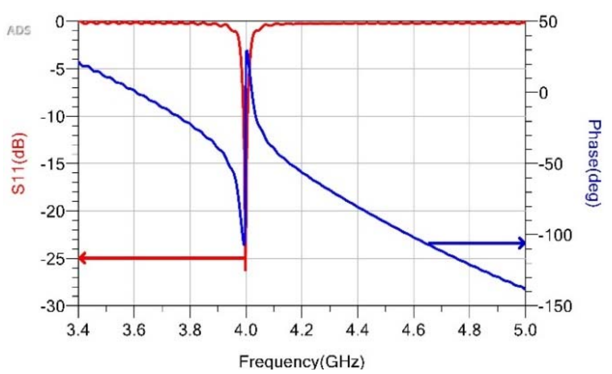


Figure. 2. Magnitude and phase of S11 for the SIW cavity resonator of Fig. 1b.

B. Oscillator Design

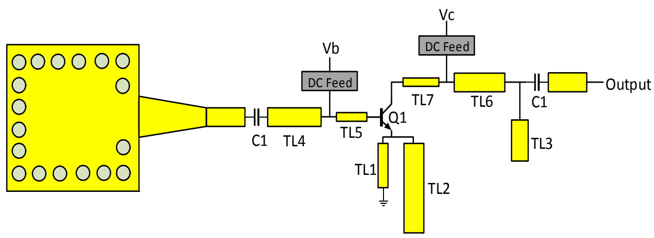
The topology of the oscillator which is a negative resistance oscillator (NRO) is shown in Fig. 3a. The emitter of Q1 is connected to the ground by transmission line TL1. An open circuit stub (TL2) is also connected to the emitter of Q1 acting as a capacitor to increase the instability of the transistor in the desired frequency band. SIW cavity is connected to the base of the active device. The collector of Q1 is connected to the output which in this case is an SMA connector. The oscillator-based sensor can be wireless, simply by replacing SMA connector with an antenna. Bias network consists of a quarter wavelength transmission line connected to a radial stub. The quarter wavelength line should be designed with special care to have same resonance frequency with the SIW resonator.

In linear analysis, two conditions need to be satisfied in order to have a stable oscillation:

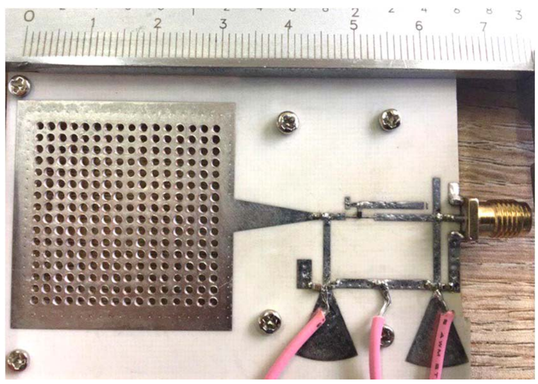
$$R_L + R_{out} < 0 \quad (5)$$

$$jX_L + jX_{out} = 0 \quad (6)$$

TL3 is added in parallel with the output to satisfy (5). C1 and C2 are DC blocking capacitors. It is important to ensure that these two conditions are only satisfied with the desired oscillation frequency. Keysight ADS software is used for designing and optimizing of the oscillator. Detailed values of the oscillator parameters are listed in Table 2.



(a)



(b)

Figure. 3. Oscillator-based humidity sensor: (a) Schematic of the circuit; (b) Photograph of implemented oscillator

Fig. 3b shows the proposed oscillator-based humidity sensor. The sensor oscillator is fabricated on a RO4003 Rogers substrate with h=508 um and ε_r=3.55. The active device used in the oscillator is Infineon BFR740L3RH. This transistor is a low cost and low noise silicon germanium heterojunction bipolar transistor. Superior low frequency noise performance of SiGe devices makes them a suitable option for designing oscillators.

TABLE II. GEOMETRICAL AND CIRCUIT PARAMETERS OF OSCILLATOR

Parameter	value	Parameter	value
L1	1.1mm	L4	1.8mm
W1	650um	W4	1100um
L2	9.6mm	L5	1.8mm
W2	1100um	W5	350um
L3	3.1mm	L6	9mm
W3	1100um	W6	1100um
L7	1.8mm	W7	350um
C1	100nF	C2	100nF

III. MEASUREMENT AND RESULTS

A. *Measurement of the Oscillator Parameters*

The implemented oscillator was first measured in terms of parameters such as oscillation frequency, output power, power of second and third harmonics and phase noise. The measurement was performed with a spectrum analyzer (NEX1 NS-132). Fig. 4 shows the output of the oscillator. The oscillation frequency of the oscillator is 3.918 GHz. The output power is 9.38 dBm. Second and third harmonics are well below the first harmonic. It should be noted that the connector used in measurement has 0.5 dB attenuation at 4 GHz. It is seen that the resonance frequency of the SIW resonator and the oscillation frequency of the oscillator are slightly different, which is due to the nonlinearities on the active device.

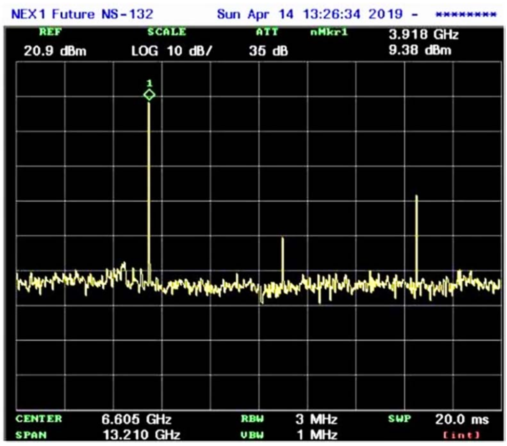


Figure. 4. The output spectrum of the proposed oscillator

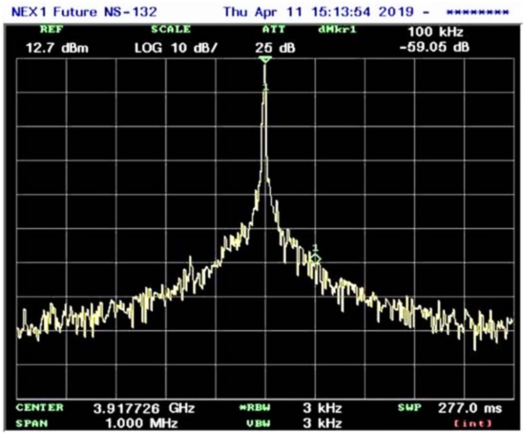


Figure. 5. Phase noise performance of the oscillator

Fig. 5 shows the phase noise performance of the oscillator. The phase noise can be found using equation (7).

$$\mathrm{L_{corr}}(f_m) = L_{meas}(f_m) - 10\log(RBW) + 1.5 \qquad (7)$$

Where $\mathrm{L_{corr}}$ is the phase noise in dBc/Hz, $\mathrm{L_{meas}}$ is measured single-sideband noise at a given offset and RBW is the resolution bandwidth of measurement in Hz. Using (7) the phase noise is calculated -94 dBc/Hz and -124 dBc/Hz at 100 kHz and 1 MHz offset from the carrier.

B. *Experimental Results for Oscillator-Based Humidity Sensor*

The oscillator-based humidity sensor is experimentally tested using a humidity chamber. In order to deliver the humidity to the chamber ambient air is used. During the test temperature and humidity of the chamber are monitored using two different sensors. The temperature of the chamber is 25°C during the test. Measurements are recorded after 5 min delay in order to stabilize the humidity level. In order to investigate the long term stability of the oscillator, measurement is repeated one day after the first measurement. Fig .6 shows the results of the measurement of the oscillator-based humidity sensor. The maximum linear variation of the oscillation frequency is recorded at 82% humidity. Where oscillation frequency is changed 7 MHz. The measured sensitivity of the sensor is 100 KHz/RH.

Fig. 7 shows the results of the oscillation frequency when the temperature is changed from 5°C to 50°C. In this measurement, the humidity is fixed to 25%. Fig. 7 shows that the sensor is not sensitive to temperature.

The performance of the oscillator-based sensor is compared to other microwave humidity sensors in Table 3. It should be noted that most of the microwave humidity sensors use sensitive materials to sense the humidity, while this sensor uses no sensitive material and is fabricated with planar PCB technology.

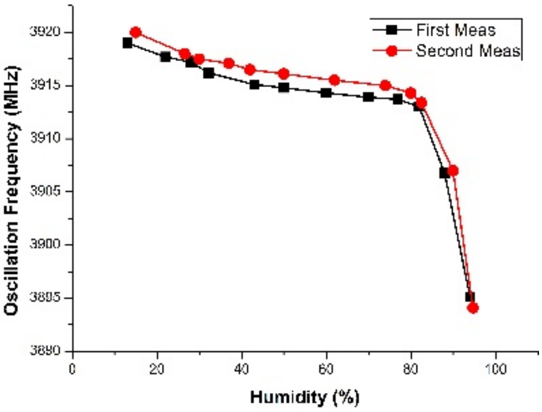


Figure. 6. Measured oscillation frequency versus humidity

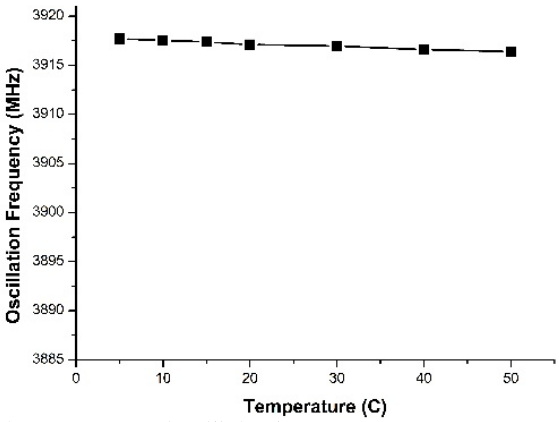


Figure. 7. Measured oscillation frequency versus temperature

TABLE III. PERFORMANCE COMPARISON OF HUMIDITY SENSORS

Ref	Technology	Sensing Method	RH Range	Sensitivity	Sensitive Material
[14]	U-shaped Coupled Resonator	Resonant Frequency Shift	20-90%	10.3 kHz/RH	No
[15]	QMSIW Resonator	Resonant Frequency Shift	0-80%	36.5 kHz/RH	No
[2]	SAW Resonator	Resonant Frequency Shift	15-59%	89.34 kHz/RH	Yes
[16]	SIW Resonator	Resonant Frequency Shift	11-96%	197 kHz/RH	Yes
This Work	SIW Resonator Oscillator	Oscillation Frequency Shift	10-80%	100 kHz/RH	No

IV. CONCLUSION

In this paper, a microwave oscillator-based humidity sensor is presented. The proposed sensor can be used in wireless microwave environmental sensing. The presented oscillator-based sensor oscillates at 3.9 GHz, the output power of the oscillator is 10dBm and has a good phase noise performance. Tests show that the sensor output is linear for humidity ranges of 10%-80%. The sensor can be easily implemented on different substrates and the oscillation frequency can be modified based on the application.

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