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Simultaneous Resolution and Dynamic Range Improvement in Microwave Phase-Variation Displacement Sensors

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ABSTRACT

In this paper, a reflective-mode phase-variation microwave displacement sensor is proposed. It consists of a reader, a one-port microstrip line terminated with a matched load, and a movable resonator (etched in an independent substrate), which exhibits three different resonance frequencies, two of them in low frequency range and close to each other, and the third one at a higher frequency. The sensing mechanism is based on the motion of the resonator along the microstrip line, with a small airgap in between. The phase of the reflection coefficient at the three resonance frequencies of the resonator is recorded at the input port of the reader. As a result, the motion of the movable resonator can be characterized. The phase of the reflection coefficient at the two lower frequencies is used to enhance the dynamic range, while the phase at the higher frequency improves sensor resolution.

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1. INTRODUCTION

In many industrial, medical, and laboratory systems, the use of linear or angular displacement/velocity sensors is vital and, according to the needs and conditions of any of these applications, the proper type of sensor differs. Thus, different types of displacement/velocity sensors, like optical, microwave, and magnetic have been proposed by researchers [1-11]. In [1], rotary encoders which are one of the most widely used displacement sensors have been discussed while magnetic and Hall-effect sensors are presented in [4-8]. On the other hand, some microwave displacement sensors are introduced in [9-11] which are a clue to show the interest of the researchers in this technology for sensor realization. The advantages of microwave sensors over other sensor types are their low cost and their robustness in harsh environments, besides being implementable in printed circuit board (PCB) technology.

One method for sensing the displacement/velocity in microwave sensors is based on measuring the changes in the amplitude or phase of the reflection or transmission coefficient in a reader (typically a transmission line) by moving a planar resonant element on top of it [12-23]. Some of these cited works are related to the displacement sensors for smaller dynamic ranges like [12-14] and some others like [15,16] are electromagnetic encoders which allow detecting displacements in higher dynamic ranges but lower resolution. In one of the authors' recent work, a linear displacement sensor suitable for breath rate monitoring, based on the measurement of the phase of the reflection coefficient of the reader line, has been presented [24]. In that sensor, resolution cannot be improved without sacrificing the dynamic range and by increasing the resonance frequency of the resonator, i.e., the frequency of operation. By increasing the frequency (decreasing the wavelength) of the feeding signal, the resolution improves, but the dynamic range decreases. So, a trade-off between resolution and dynamic range exists in that sensor. After the mentioned work, two other works have been carried out in order to address this issue. In [25] by working simultaneously with two different frequencies and utilizing two resonators rather than one, it is demonstrated that the sensor exhibits better resolution, without decreasing the dynamic range. On the other hand, in [26], a sensor based also on measuring the phase of the reflection coefficient was proposed, but the reader in that sensor consists of two microstrip lines (rather than one), and the movable part includes two resonators tuned at closely spaced frequencies. By using this method, the input dynamic range (which is normally limited to the half-wavelength at the working frequency) can be dramatically enhanced without degrading the resolution. In this paper, we combine the two previously mentioned ideas in order to improve the dynamic range and resolution of the sensor simultaneously. As an explanation, we used three working frequencies, two of them in lower frequencies and close to each other, to enhance the dynamic range of the sensor based on what proposed in [26] and the third working frequency, much higher than the two first, to be able to improve the resolution of the sensor based on what presented in [25]. The compactness of the sensor was also improved, by using a single microstrip line in the reader (instead of two lines in [26]) and a single resonator in the movable part which can resonate in all the three considered working frequencies.

This proposed microwave displacement sensor has potential applications in space technology, particularly in precision positioning systems. The ability to characterize motion with enhanced dynamic range and high resolution makes it suitable for tracking the displacement of critical components in satellites, space probes, and robotic arms used in space applications.

The paper is organized as follows. The proposed displacement sensor and its working principle are presented in Section II. In Section III, the sensor is validated both at simulation level and experimentally. In Section IV, the resolution and dynamic range of the proposed sensor is compared with that of other displacement sensors. Finally, the main conclusions are highlighted in Section V.

2. SENSOR CONCEPT AND WORKING PRINCIPLE

As mentioned in the introduction, a displacement sensor based on retrieving the phase of the reflection coefficient of the reader line was published in [24]. That sensor consists of a (static) reader and a movable (resonator) part. The reader in that sensor is a simple 50-Ω microstrip line terminated with a matched load. A resonator etched/printed on a separate dielectric substrate is able to move on top of the reader with a small air gap between them along the microstrip axis. A single frequency harmonic signal is injected to the input port of the reader with a frequency identical to the resonance frequency of the resonator on the movable part. Thus, the injected signal is reflected at the transverse plane where the resonator is placed (on top of the microstrip line), and the phase of this reflected signal depends on the distance between the resonator and the input port of the reader. Therefore, by reading this phase, the position of the resonator can be retrieved. Note that in this kind of sensors, based on the phase of the reflection coefficient, the dynamic range of the sensor is limited to a half wavelength at the working frequency, since, after this range, the phase cyclically repeats. On the other hand, the resolution of this type of sensor is related to the least amount of detectable phase for the system and the amount of phase change versus displacement. Obviously by working at higher frequencies the resolution will improve because the same amount of displacement makes higher phase change in higher frequencies. However, this strategy causes a reduction in the sensor dynamic range due to decrease in the wavelength.

In [25], the resolution was improved without decreasing the dynamic range in these sensors. To achieve this goal, two resonators were etched on the movable substrate. One of these resonators was tuned to a low frequency, so that by reading the phase of the reflection coefficient at that frequency, an acceptable dynamic range (given by the half wavelength of the signal at that frequency) was achieved. The second resonator, tuned to a higher frequency, was used to enhance the resolution of the sensor by measuring the phase of the reflection coefficient at its resonance frequency. It is worth mentioning that, with this method, two harmonic signals with frequencies equal to the resonance frequencies of the resonators must be injected to the input port of the reader.

In [26], the dynamic range was increased without considering lower frequencies (since this would result in a degradation of the sensor resolution). The proposed structure in [26] consists of a reader with two independent 50-Ω microstrip lines terminated with matched loads. The substrate of the movable part contains two resonators etched on it, each one moving on top and along the axis of the reader microstrip lines. The dimensions of the resonators were chosen in a way that their resonance frequencies were close spaced. Therefore, in each phase cycle caused by the displacement of the resonators on top of reader, there is a small difference between the phase of the reflection coefficient read in the two reader ports (the phase cycle for the higher frequency is slightly lower than the other). As a result, even though the phase of the reflection coefficient repeats cyclically for both line by displacing the resonators on top of the reader, the phase difference between them differs for each cycle, until a total displacement equivalent to the minimum common multiple (MCM) of the half wavelength at both frequencies is achieved. By using this method, comprehensively discussed in [26], the dynamic range of the sensor was increased considerably without degrading the resolution.

In this work, we combine the two previously mentioned methods in order to improve simultaneously the resolution and the dynamic range of the sensor, avoiding the use of two microstrip lines in the reader. By this means, the resulting sensor is more compact. The reader consists of a unique 50-Ω microstrip line terminated with a matched load. The movable part consists of a microwave substrate with a single resonator (made of two back-to-back connected C-shaped loops) etched on it. This movable part displaces along the microstrip line axis on top of it with a small airgap between them. The resonator exhibits three resonance frequencies which are of our interest. Two of them (f_A, f_B) are closely spaced and relatively small (suitable for the method presented in [26] to increase the dynamic range). The third frequency (f_C), at higher frequencies, is suitable for enhancing the resolution [25]). So, by injecting a multiple-frequency signal containing all these three frequencies, the phase of the reflection coefficient can be used to detect the displacement and position with precise resolution and long dynamic range. A perspective view of the sensor's structure is shown in Fig. 1.

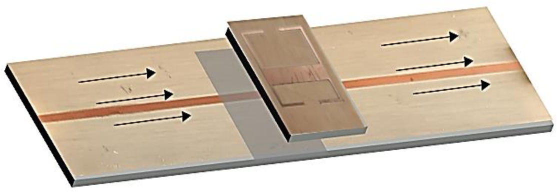

Fig. 1. Perspective view of the proposed reflective-mode phase-variation displacement sensor.

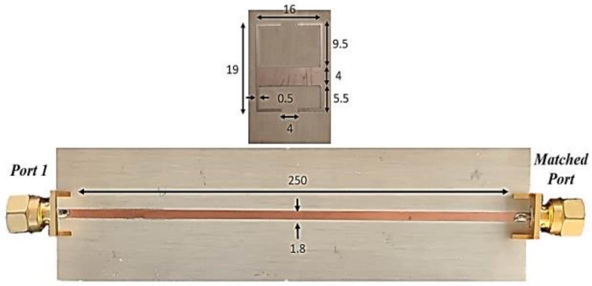

Fig. 2. Photograph of the fabricated reader and resonators with their dimensions in mm.

3. FABRICATION, MEASUREMENT, AND RESULTS

To validate the method, the proposed sensor, consisting of the reader (static part) and the resonator (movable part) has been designed, simulated, and fabricated on the *I-Tera MT40* substrate with dielectric constant $\varepsilon_r = 3.38$, thickness $h = 0.76$ mm, and loss tangent tanδ = 0.0028. The airgap between the reader and resonator has been considered to be $g = 0.2$ mm. To implement a 50-Ω microstrip line in this substrate, the width of the line is set to $W = 1.8$ mm. The frequencies of interest in this work, in which the resonator causes a strong reflection are considered to be $f_A = 3.0$ GHz, $f_B = 3.7$ GHz, and $f_C = 9.1$ GHz. The corresponding wavelengths are approximately $\lambda_A = 6.0$ cm, $\lambda_B = 4.8$ cm, and $\lambda_C = 2.0$ cm. As a result, according to [26], the sensor dynamic range is approximately $4\lambda_A/2 = 5\lambda_B/2 = 12$ cm. On the other hand, the resolution of the sensor is determined by the phase changes at f_C. To clarify this, we can consider that the smallest phase difference that can be detected by our measurement setup is 5º. So, the obtainable resolution for f_A, f_B, and f_C are 0.42 mm, 0.33 mm, and 0.14 mm respectively. Thus, the resolution of the whole system is given by the smallest value (at f_C), namely, 0.14 mm. The structure and dimensions of the reader and resonator can be seen in Fig. 2.

A set of electromagnetic simulations was carried out using the *ANSYS HFSS* commercial software. The magnitude of the reflection coefficient when the resonator is placed on top of the reader line is depicted in Fig. 3. It can be appreciated that the signal at the considered frequencies, f_A, f_B, and f_C, is significantly reflected back to the input port (i.e., the return loss is close to 0dB at these frequencies).

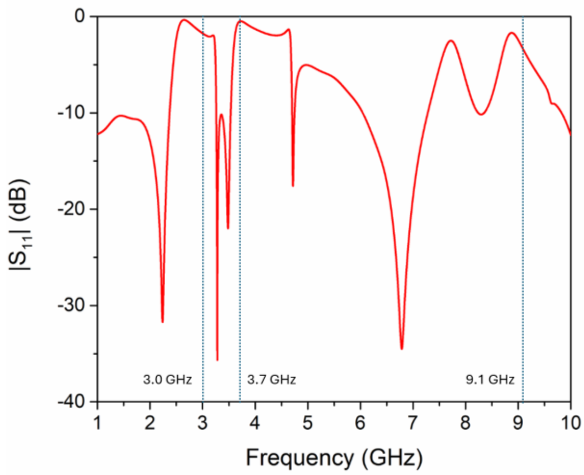

Fig. 3. Magnitude of the reflection coefficient versus frequency inferred from electromagnetic simulation.

In Fig. 4, the phase of the reflection coefficient at the considered frequencies inferred from electromagnetic simulation is depicted, whereas the measured phases are shown in Fig. 5. The measurement has been carried out on the fabricated prototype by using the vector network analyzer (VNA) *Keysight FieldFox N9950B*. Note that the discrepancies between simulation and measurement results are related to fabrication tolerances and to the fact that it is difficult in practice to keep exactly the same condition as in simulation. By inspection of Figs. 4 and 5, it follows that by using the phase of the reflection coefficient at two lower frequencies, the displacement and position can be appreciated at least in a range of $4\lambda_A/2 = 5\lambda_B/2 = 12$ cm, as mentioned before. On the other hand, after determining the position of the sensor with low resolution using the phase of the reflection coefficient at f_A and f_B, the phase at f_C provides the position with high resolution and accuracy. It is worth noting that the vertical distance between the resonator and the reader must be in a range that in which there is enough coupling between the resonator and the reader's line to have enough reflected signal in working frequencies. So, the airgap can be chosen any value in the mentioned range but once we select the amount of airgap, it should be kept constant during the measurement because changing the airgap can lead to alteration of the resonance frequencies. Another point to consider is that the resonator must move along the microstrip line's axis and misalignment from the line's axis can lead to wrong outputs.

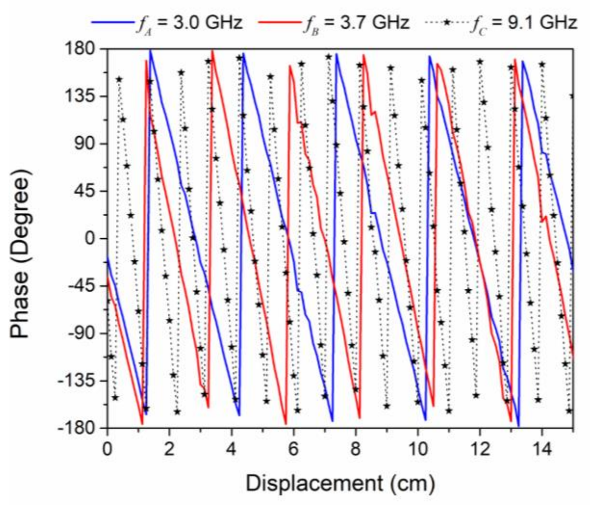

Fig. 4. Variation of the phase of the reflection coefficient with the displacement as inferred by electromagnetic simulation.

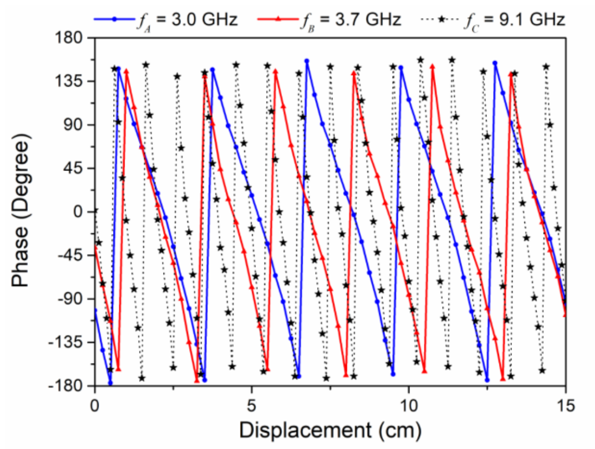

Fig. 5. Variation of the phase of the reflection coefficient with the displacement as inferred from measurement.

4. COMPARATIVE ANALYSIS

To have a perspective of goal achievements in this work, we compare the resolution and dynamic range of the sensor presented in this work with its counterparts in Table I. Comparing to the three preceding works by the authors [24-26], both resolution and dynamic range have been improved in this work simultaneously. In [23] the resolution is very good due to the highly sensitive structure of the sensor, but the dynamic range is small. In other cases which are based on frequency [12,13] or magnitude [17,18] variation, although good resolutions have been reported, the dynamic range is limited, and these sensors can only be used in sub-cm or sub-mm displacement scenarios.

Table 1. Comparison of various linear displacement sensors

Ref.	Resolution (mm)	Dynamic range (cm)
[12]	0.03	0.4
[13]	< 1	0.3
[17]	< 0.2	0.1
[18]	< 0.1	0.07
[23]	0.016	0.5
[24]	0.61	4.4
[25]	0.29	6.2
[26]	5	<14
This Work	**0.14**	**12**

5. CONCLUSION

In conclusion, in this paper, a planar microwave displacement sensor based on phase measurements has been presented and validated. The sensor consists of the reader line, a one-port matched line terminated with a matched load (the static part), and a planar resonant element (made of two back-to-back connected C-shaped loops etched on a movable substrate) exhibiting three resonances. The resonator has been designed such that two resonances (those exhibiting the lower frequencies and present in the low frequency range) are closely spaced, the third resonance being present at a significantly higher frequency. Displacement measurement is based on retrieving the phase of the reflection coefficient at the three frequencies as the movable resonator displaces along the line axis at short vertical distance (0.2 mm in this work). It has been demonstrated that by using the phase of the reflection coefficient measured at the lower frequencies, the dynamic range of the sensor can be enhanced (12 cm in the fabricated prototype), whereas resolution improvement (0.14 mm in the reported sensor) is determined by the phase measured at the higher frequency. In summary, this paper has presented a displacement sensor that combines the ideas of two previous realizations, one focused on resolution improvement, and one devoted to dynamic range optimization. The result has been a sensor where both performance indicators (resolution and dynamic range) have been simultaneously optimized. The sensor exhibits also good linearity and can be applied in scenarios where cm-scale measurements are needed, e.g., motion control, structural health monitoring, servomechanisms, automotive industry, etc.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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