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RESEARCH ARTICLE

Inclination Sensor With a Wide Angle Measurement Range Using Half-Wavelength Microstrip Resonator

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ABSTRACT In this article, a new inclinometer concept based on an angular half-wavelength microstrip resonator is presented. The inclinometer has a wide dynamic range of 84° (B142°) which can be extended to 180° through a simple modification. The inclinometer is composed of a microstrip transmission line resonator on printed circuit board and a second transmission line on an overlapping circuit board that rotates according to the inclination angle. As the inclination angle changes, the overall length of the resonator varies and leads to resonance frequency shift, which is transformed into inclination variation. The sensor measurements results determined the sensitivity of the sensor as 0.384 mm/° and the resolution as 0.035°. The proposed sensor is also quite simple, cost-effective, compact, and robust.

INDEX TERMS Inclinometer, inclination, tilt sensor, sensor, half wavelength, resonator, dynamic range, resolution, sensitivity, 3D printing, microwave sensor, tilt angle measurement.

I. INTRODUCTION

An inclination sensor or inclinometer is a device to measure an object's position angle change relative to a reference vector in the Earth's gravitational field or its magnetic field. Inclination measurement has been increasingly in demand in many applications including, but not limited to, industrial machine alignment, navigation systems in cars and ships, and prediction of natural disasters such as earthquakes [1], [2], [3], [4], [5], [6], [7]. In addition, inclination angle monitoring has a significant importance in the process of building civil infrastructures such as roads, tunnels, bridges, and buildings. Another area where tilt angle is one of the key parameters that should be measured is robotics. An inclination sensor can be mounted on an infrastructure being built or on the moving parts of a robot and the inclination of that part can be monitored or controlled using a processing wireless network connected to the sensor.

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Different types of inclinometers have been reported using electric contact [8], micro-electro-mechanical method [1], electrolytes [2], capacitance method [9], transmission line resonators [3], [4], [7], and fiber optics [5], [6], [10], [11], [12], [13], [14]. Most of the fiber-optic (FO) inclinometers fall into one of two types: Extrinsic Fabry-Perot Interferometers (EFPI) or Fiber-Bragg-Grating (FBG) sensors. EFPI inclinometers are designed based on two-rope suspended pendulums as tilting elements. The length of the Fabry-Perot cavity changes with shifting the tilt angle [5], [14]. In FBG-based inclinometers, the shift in tilt angle causes a variation in strain applied to the FBGs, which in turn shifts the resonance wavelength [6], [10], [11], [12], [13]. Fiber-optic inclinometers typically have low transmission loss, high accuracy and high sensitivity but they are not always an option when the application involves harsh environments where robust construction and durability are also required, as well as having a costly interrogation system [3], [4], [7].

Coaxial cables offer higher durability compared to optical fibers, making them a promising candidate to implement inclinometers. In [3] and [7], coaxial cable inclinometers mimicking optic-fiber EFPIs have been explored. In [3], a metal mass block, suspended in proximity to the open end of a hollow coaxial cable in parallel, is used to make a pendulum structure. Applying inclination to the pendulum leads to modification in the phase reflection coefficient at the open end. In [7], a hollow coaxial cable Fabry–Perot resonator (HCC-FPR) is implemented, using a metal post that shorts the inner conductor and the outer conductor of the HCC as the first reflector, and air–water interface as the second reflector. These inclinometers are robust and have a high measurement resolution, but they have a large size and more importantly, a limited angle measurement range. The capacitive inclinometers explored in [9] and [4] have a relatively higher dynamic range, but their measurement resolution is not studied. Mechanical inclinometers can also detect very slight inclinations but have limited angle measurement range and resolution [6].

In this work, an inclinometer based on an angular microstrip half-wavelength resonator (MHWR), consisting of a fixed and an overlapping mobile part, is proposed. When the inclinometer is tilted, the length of the resonator and consequently, its resonance frequency changes. The use of Microstrip technology allows for the design of an straightforward inclinometer that is both sturdy and capable of integration, making it compatible with planar structures and requiring only basic readout electronics. Furthermore, it is more compact, lighter, and less expensive than the previously discussed inclinometers that relied on optical or coaxial cable technology. Additionally, the suggested sensor has a high sensitivity and resolution, and it has a broad dynamic inclination angle measurement range. The sensor that is being suggested has the ability to identify the direction of inclination along a single axis, indicating whether the inclination is applied in a positive or negative direction. The paper is organized as follows: the resonator design method is first explored, the required experimental setup and measurement results are discussed, and a discussion and comparison with other inclinometers are carried out.

II. INCLINOMETER DESIGN PRINCIPLE

Half-wavelength resonators have been used in several different microwave sensors [15], [16], [17], [18]. They are used to implement an inclination sensor in this work. In this section, the design principle for the angular half-wavelength resonator and its resonance frequency correlation to the circular sector angle is first discussed. The resonator is then used as the sensing element in an inclinometer setting.

A. RESONATOR DESIGN

The layout of the resonator used for the proposed inclinometer is illustrated in Fig. 1. It is an open-ended half-wavelength microstrip line resonator shaped in a circular path. The resonator is designed on RO4003C substrate, with a dielectric constant (ε_r) of 3.38 B1 0.05, loss tangent of 0.0027, copper cladding thickness t of 34 um, and a dielectric thickness h of

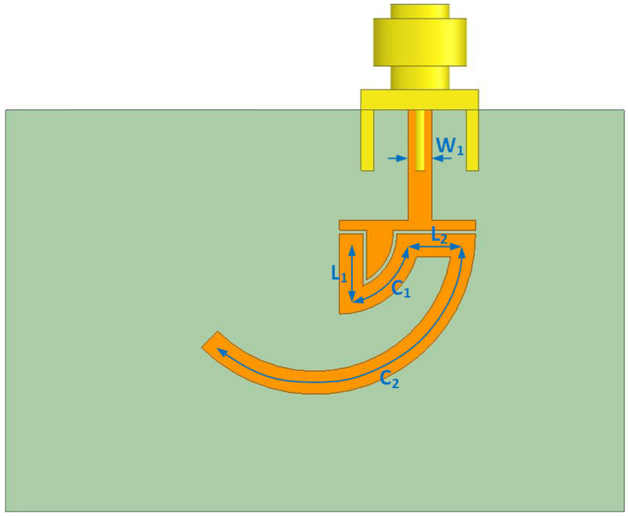


FIGURE 1. Layout of the utilized half wavelength resonator, C_1 is a 90° circular sector line and C_2 is a θ° circular sector line.

0.81 mm. The width of the half-wavelength resonator and the input line, W_1, is chosen 1.76 mm to make a 50 Ω microstrip line.

A coupling structure is used to measure the resonant frequency of the variable resonator. The shape and dimensions of the coupling structure are chosen such that a strong coupling as well as a high quality-factor is maintained.

Considering the total length of the resonator as $L_1 + C_1 + L_2 + C_2$, the resonance frequency of the half-wavelength resonator is given by 1 [19].

$$f_n = \frac{nc}{2(L_1 + C_1 + L_2 + C_2)\sqrt{\varepsilon_{eff}}} \tag{1}$$

where c is the speed of light, ε_{eff} is the effective permittivity of the substrate, and n is an integer representing the resonant mode.

If we consider C_1 as a 90° section of a circle with a radius of L_1 and C_2 as a θ° of a larger circle with a radius of $L_1 + L_2$, the resonance frequency can be written as

$$f_n = \frac{nc}{2(L_1 + \frac{\pi}{2}L_1 + L_2 + \theta(L_1 + L_2))\sqrt{\varepsilon_{eff}}} \tag{2}$$

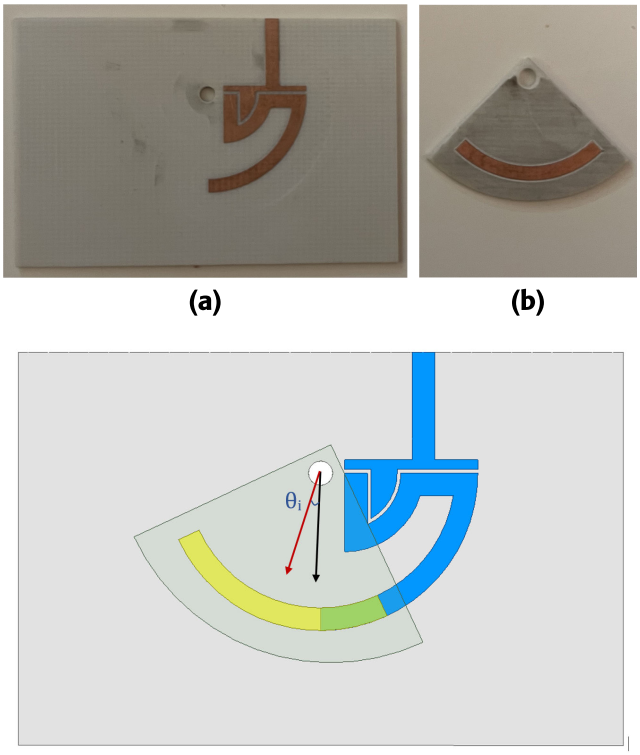
where θ is the section angle of the outer circular part of the resonator. The resonance wavelength is then given as a linear function of θ

$$\lambda_n = \frac{2}{n}(L_1 + \frac{\pi}{2}L_1 + L_2 + \theta(L_1 + L_2)) \tag{3}$$

It can be observed from Equation 3 that the angle of the outer circular section, denoted by θ, establishes the resonance wavelength. By calculating the resonance frequency, we can determine the corresponding wavelength and utilize it as a sensing component in an inclinometer.

B. INCLINATION SENSING MECHANISM

The inclinometer consists of two parts, a fixed and a sliding (moving) part that overlap, as shown in Fig. 2. The use of



(c)

FIGURE 2. **Proposed inclinometer; (a) fabricated fixed part, (b)fabricated moving part, and (c) the overlapped schematic at a given inclination angle θ_i to the left ($\theta = 135°+ \theta_i$); in case of inclination to the right, θ_i would be negative. The blue line shows the fixed part, the yellow line shows the moving part, and the green section indicates the overlapped area.**

overlapping structures in microwave sensing has found use in other applications such as the measurement of cracks in structures [20]. In Fig. 2, the sector angle θ of the fixed part is 90°. Another 90° of microstrip line with the same width is made on the same substrate (without ground copper layer) as the moving part. The moving part is placed on top of the fixed resonator using a bolt at the hole made at the top center. When the inclinometer is not tilted, half of the moving line overlaps with the fixed line and the other half adds to the θ, making it 135° in total ($\theta_i = 0$, $\theta = 135°$). Fig. 2 (c) illustrates the overlapped design at a given inclination angle θ_i, with the area of overlap indicated by the green section.

By inclining the sensor to the left by θ_{iL}, the overlapping section gets smaller and the total sector angle will increase to $\theta_0 + \theta_{iL}$ and if the sensor is inclined to the right by θ_{iR}, the overlapping section gets larger and the total sector angle will decrease to $\theta_0 - \theta_{iR}$. Thus, in accordance with equation 2, tilting the sensor towards the left or right will result in a decrease or increase in the resonance frequency, respectively. The magnitude of the reflection coefficients at the input port for the sensor inclined by different θ_i angles are compared to that of the uninclined sensor in Fig. 3. Negative θ_i represents an inclination to the right and positive θ_i means an inclination to the left is applied. The resonance frequency shifts caused by the inclination can be seen in the presented S_{11} plots.

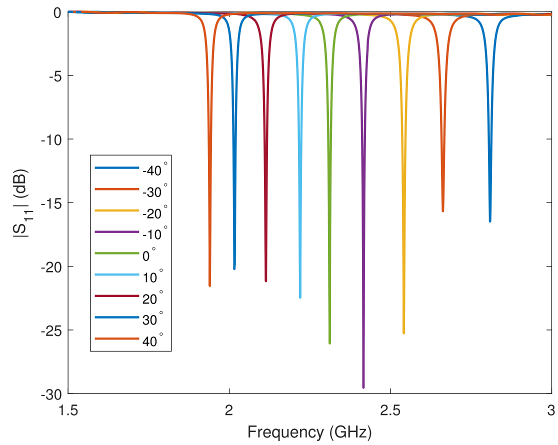


FIGURE 3. **Magnitude of the measured reflection coefficient of the sensor inclined by different θ_i angles.**

III. MEASUREMENT PROCESS

A. INCLINATION MEASUREMENT SETUP

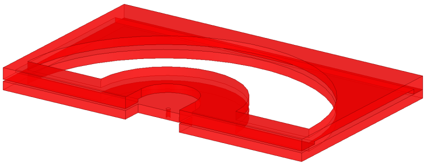
To characterize the performance of the proposed inclinometer, a customized experimental test setup was developed. The experimental arrangement secures the sensor in a vertical position with respect to the inclination plane that needs to be gauged, and permits the sliding component to rotate freely along the surface inclination. Fig. 4 shows the proposed setup for inclination angle measurement. A 3D printer was used to create the setup, which securely houses the fixed part and features a circular path for the moving part to rotate within. This path is created by leaving a small air gap in the structure, slightly larger than the height of the moving part, allowing for free movement through inclination.

The sliding part is held in the structure using a nylon bolt and nut. The bolt needs to be tightened so that the sliding and fixed parts are touching each other with as little space as possible, but not so tight that the sliding part can't move easily. Since the moving part is like a pendulum moving with only gravity force, using a comparably heavy weight connected to the sliding part using a thread is useful. It allows the sliding part to move more easily when the bolt is tight.

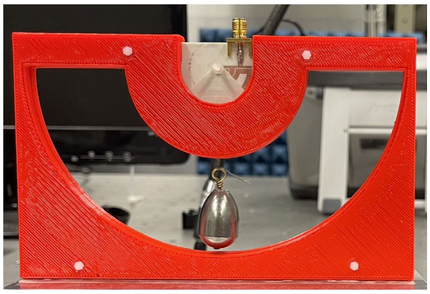
B. EXPERIMENTAL RESULTS

The response of the inclinometer to large inclination variation is first tested. The experimental setup used to measure the inclinometer is illustrated in Fig. 5. The inclinometer is placed on a surface that is supported by two points, with one of the points positioned on a vertical translation stage on one side. The inclination is applied by adjusting the height of the support point on one side of the surface using the translation stage. In the experiment, inclination angles (θ_is) in the range of −42° to +42° with 10° steps are applied. For each setting, the reflection coefficient at the input port (S_{11}) is measured with a vector network analyzer (VNA) and the resonance frequencies are recorded.

Fig. 6 shows the resonance wavelength of the sensor as a function of the inclination angle. The lengths of the microstrip



(a)



(b)

FIGURE 4. Inclination measurement setup; a) 3D printed model, b) fabricated 3D printed model used in the setup.

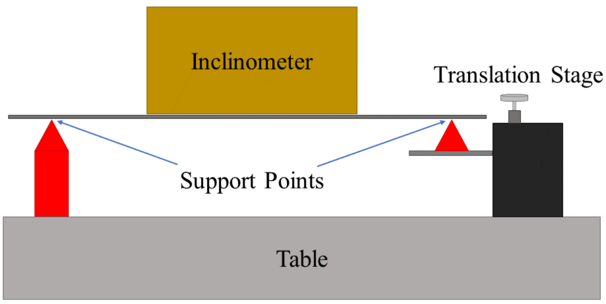


FIGURE 5. Schematic of the experimental setup; translation stage changes the height of the right support point.

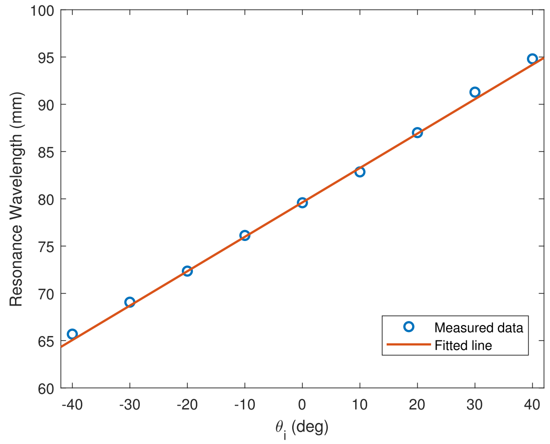


FIGURE 6. Resonance wavelength of the inclinometer as a function of applied inclination in large angle variation experiment.

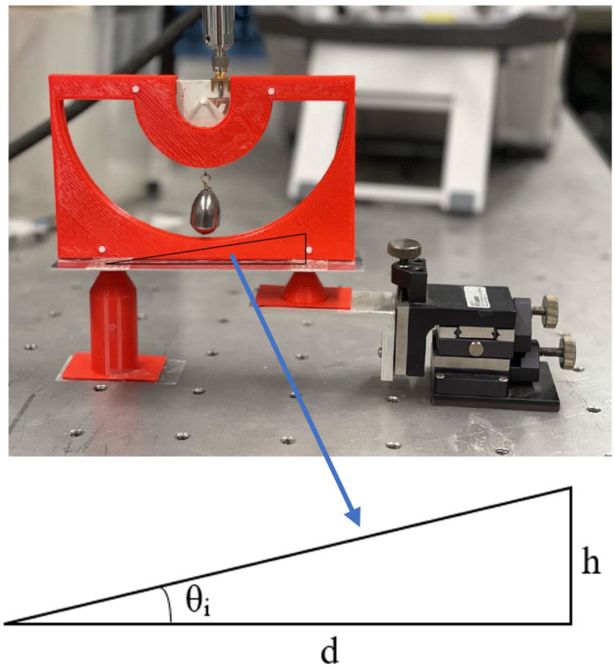


FIGURE 7. Experimental setup for resolution evaluation.

lines (L_1 and L_2) in the fabricated prototype of the sensor are chosen such that it resonates around 2.4 GHz when it is not inclined ($\theta_i = 0°; \theta = 135°$). As the applied inclination angle changes from $-42°$ to $+42°$, the resonance wavelength increases, as expected from 3. The linear curve fitting the measured data is found as $\lambda = 0.384\theta_i + 79.6$ where λ is in mm and θ_i in degrees. Thus, the measurement sensitivity is determined to be 0.384 mm/°.

To measure the resolution of the inclinometer, another test is carried out. As shown in Fig. 7, a setup like Fig. 5 but with 500MIS precision XYZ micropositioner from Quater research and development company is used, so that small variations in tilt angle can be applied. The distance between the two support points (d) is 100 mm and by every turn of the screw on the positioner, the height of the right support pin (h) changes by 0.32 mm. The inclination angle shift can be calculated as $\theta_i = \tan^{-1}\frac{h}{d}$, equal to 0.183° change for every turn of the screw.

The inclinometer is initially set at approximately 0° and the inclination is increased to 1.83°, in steps of 0.183° and the S_{11} for each angle setting is measured 6 times, every 5 minutes, in 25-minute time spans. The recorded data of all measurements are shown in Fig. 8. The inset in Fig.8(a) represents the deviation of the resonance wavelength in the 6 series of measurements. The inclinometer's sensitivity results in a resolution of 0.035° when the maximum deviation of resonance wavelength in the 11 angle settings is taken into account, which was found to be 0.0136 mm. The resonance wavelength versus inclination angle data and the curve fitting the data are also shown in Fig. 8(b). The linear curve fitting the measured data can be defined as $\lambda = 0.396\theta_i + 78.92$ where λ is in mm and θ_i is in degrees, so the sensitivity in small scale inclination variation is 0.396 mm/°, which matches closely with the large inclination variation sensitivity.

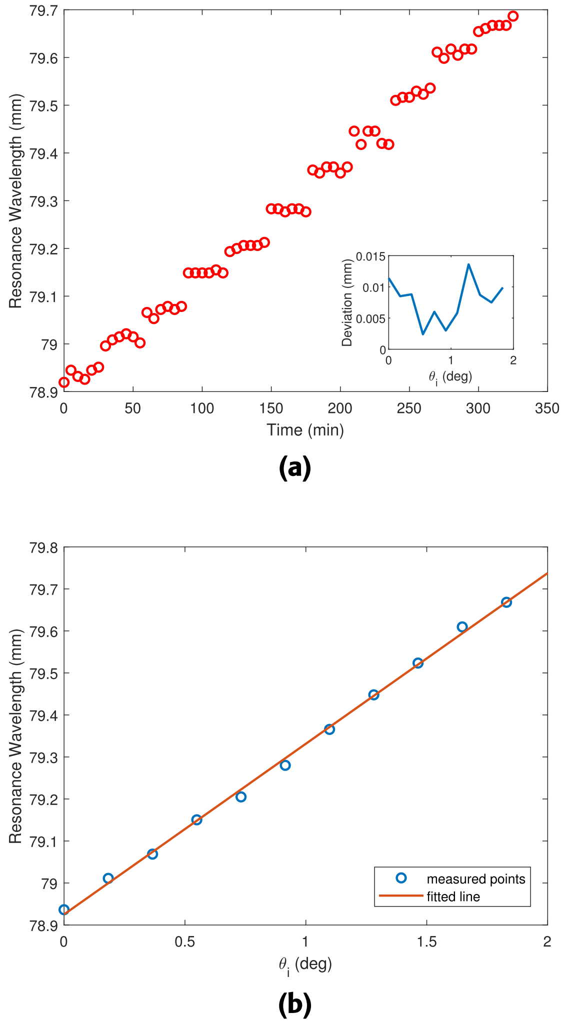


FIGURE 8. Response of the inclinometer to small variations of inclination angle; a) resolution test result: six measurements were recorded for each setting of the tilt angle and the inset shows the obtained deviations of the resonance wavelength for the eleven different angle settings, b) resonance wavelength as a function of inclination angle.

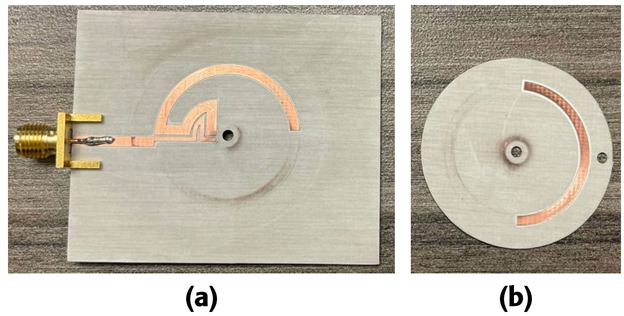


FIGURE 9. Fabricated prototype of the second sensor with wider angle measurement range; a) Fixed part, b) Moving part.

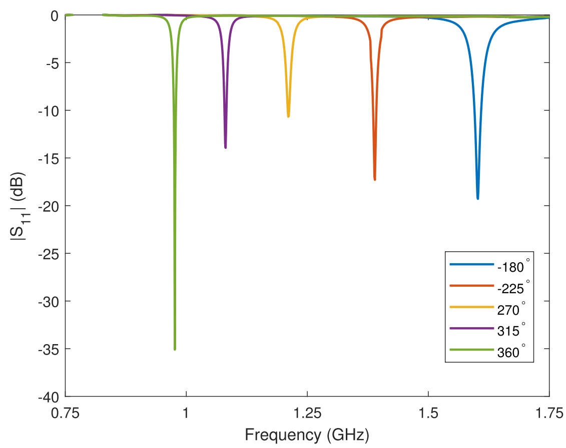


FIGURE 10. Magnitude of measured reflection coefficient of the second sensor with different sector angle θs.

IV. DISCUSSION AND COMPARISON TO OTHER INCLINOMETERS

The proposed sensor can measure any inclination in the wide dynamic range of $-42°$ to $+42°$. However, it is possible to further increase the dynamic range through a simple modification in the geometry of the fixed and moving parts. The sensor with an extended range was fabricated and is shown in Fig. 9. The length of the fixed half wavelength resonator is increased to a 180° sector angle. The length of the transmission line in the moving part is also increased to 180° and the geometry of the moving substrate is extended into a full circular disk. The coaxial launcher and coupled-line feed are repositioned to allow the sliding part to freely move above the fixed resonator.

The sensor is measured in different angle settings using a VNA and the recorded reflection coefficients are shown in Fig. 10. As expected, the resonance frequency is decreasing as the inclination is applied and the outer circular path sector angle is increasing. The measured resonance wavelength as a function of the section angle of the outer circular part and the linear curve fitting the measured data, which is found as $\lambda = 0.43\theta + 35.38$ (λ in mm and θ in degrees), is shown in Fig. 11. The fitted curve can measure the inclination angle with less than %0.24 error referenced to the measured value.

In Table 1, the proposed inclinometer in this work is compared to the prior inclinometers presented in the recent literature. The resolution of our inclinometer is close to the optical FBG based inclinometers presented in [13] and [10], but it has a higher sensitivity to the inclination variation and can measure a wider range of tilt angles. In [3], [5], and [7], inclinometers that use optical, hollow coaxial cable, and transmission line Fabry-Perot techniques are described to have excellent resolution, but they have an extremely limited angle measurement range. No exact resolution data is given for the capacitive inclination sensor presented in [9], but our sensor outperforms it in terms of sensitivity and dynamic range. Converting the sensitivity of our sensor to relative sensitivity as $\Delta\lambda/\lambda$ will result in a relative sensitivity of approximately %0.48, which is higher than the sensitivity of the sensor in [9]. The sensor proposed in this study can also serve as a rotation sensor, with sensitivity comparable to that of recently developed rotation sensors such as the one

TABLE 1. Comparison of the performance of the inclinometers reported in literature and the proposed work.

	Sensor Configuration	Resonance Wavelength or Frequency	Dynamic Range	Sensitivity	Resolution
[13]	FO-FBG	1550 nm	-35° to 35°	0.00282 nm/°	0.013°
[10]	FO-FBG	1550 nm	0° to 8°	NM	0.006°
[5]	FO-EFPI	NM	-0.48° to 0.48°	1.05 mm/°	$5.7*10^{-7°}$
[3]	HCC-FPR	800 MHz	0° to 7.2°	350 MHz/°	$6.3*10^{-6°}$
[7]	HCC-FPR	290 mm	-7.5° to 10°	11.15 mm/°	$4.3*10^{-40°}$
[9]	Capacitive	NM	-20° to 20°	%0.1/°	NM
THIS WORK	MHWR	79 mm	-42° to 42°	0.384 mm/°	0.035°

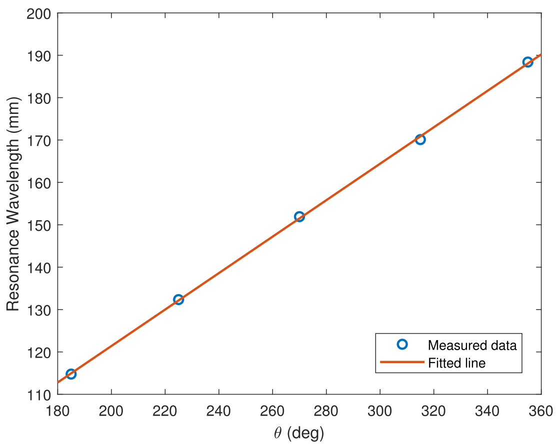


FIGURE 11. Resonance wavelength of the second sensor as a function of section angle of the outer circular part.

discussed in [21], which has a sensitivity of approximately 0.11%. In addition to the acceptable resolution and high sensitivity, the dynamic range of the presented inclinometer is significantly large, and it has been proven that it can get even larger with some modifications. Furthermore, the proposed sensor in this paper is quite simpler than all the other inclinometers in the literature and unlike some of the prior inclinometers, it can detect the direction of the inclination in B1x direction, as well. It is also very lightweight and small-sized, and its fabrication process and interrogation system are more cost-effective than the others.

V. CONCLUSION

An inclinometer designed based on an angular half-wavelength microstrip line resonator is presented. The inclinometer is composed of two parts, one fixed and one movable. When the inclinometer is tilted, the two parts can overlap and cause a change in the length of the resonator. The resonator length variations correspond to its resonance frequency variations, allowing us to measure the inclination angle. The proposed inclinometer is robust, simple, cost-effective, and small, and it can detect inclination angle with a relatively high resolution and a high sensitivity. It also has a large dynamic range compared to the other inclinometers presented in recent literature and the sensor has the flexibility to be modified in order to get a larger dynamic range of up to 180°. It can also be further improved to measure inclination angle in any direction, rather than a single B1x direction.

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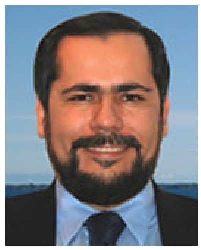

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