01 Jan 2023

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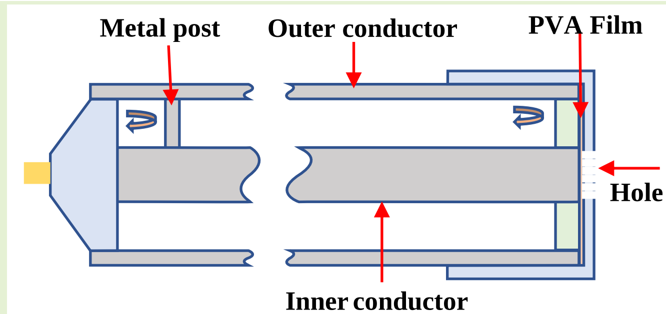
Recommended Citation

J. Guo et al., "Embeddable Soil Moisture Content Sensor based on Open–end Microwave Coaxial Cable Resonator," *IEEE Sensors Journal*, Institute of Electrical and Electronics Engineers, Jan 2023.
The definitive version is available at https://doi.org/10.1109/JSEN.2023.3266665

Embeddable Soil Moisture Content Sensor based on Open–end Microwave Coaxial Cable Resonator

Jing Guo, Yan Tang, Yongji Wu, Chen Zhu and Jie Huang, Senior *Member, IEEE*

***Abstract*—In this paper, we propose and demonstrate a novel corrosion-resistant, embeddable open-end coaxial cable soil moisture sensor. This microwave resonator is constructed using two reflectors along the coaxial line. The first reflector is a metal post at the signal input end, short-circuiting the inner conductor to the outer conductor. The second reflector comprises a welded metal plate parallel to the open-end of the coaxial line, maintaining a fixed gap. A moisture-sensitive Polyvinyl Alcohol (PVA) film is inserted into this gap. The resonance frequency of the open-end coaxial cable resonator is highly dependent on the fringe capacitance, which varies with soil moisture levels. As such, tracking resonance frequency changes allows for correlation with soil moisture fluctuations. We provide a detailed discussion of the embeddable open-end microwave coaxial cable resonator (EOE-MCCR) mathematical model and a proof of concept for soil moisture measurement. The demonstration experiments investigate soil moisture content ranging from 4% to 24%. The prototype device exhibits a soil moisture measurement sensitivity of 0.76MHz/% for soil moisture between 4% and 10%, and 1.44MHz/% for soil moisture between 10% and 24%. The soil moisture sensor presented here is robust, easy to manufacture, chemically resistant, low-cost, and suitable for long-term applications and potential industrial uses. This innovative sensor is ideal for sensing applications in harsh environments, advancing the field of chemical trace sensing.**



***Index Terms*—Open-end Coaxial Cable, Soil Moisture, Microwave Resonator.**

I. Introduction

Soil moisture content plays an essential role in geophysical fields [1], agricultural production [2], soil remediation engineering [3], and groundwater contaminant removal engineering [4]. Not only does soil moisture influence the soil's geophysical properties, but it also impacts the rate at which contaminants are transferred to groundwater. Contamination in soil contributes to groundwater pollution via the infiltration process. [5]. Precisely evaluating the transfer of contaminants from soil to groundwater is crucial for both remediation and protection of groundwater resources. Moreover, vadose zones remain poorly understood due to their complex geophysical properties, which hinder the acquisition of essential information such as soil water content and soil porosity.

Scientists around the globe are diligently striving to create various sensing applications and devices for measuring soil water content, which is relevant to agricultural production and overall human well-being. Numerous sensing technologies have been developed, such as the traditional gravimetric method [6], Gamma-ray transmission [7], Neutron Scattering [8], capacitance [9, 10], seismic waves [4] and dielectric methods [6, 11, 12].

Soil water content is a fundamental property of soil, defined as the proportion of water to soil quantity. Mass soil-water content represents the ratio of water mass to the mass of dry soil containing water. Meanwhile, volumetric soil-water content refers to the ratio of water volume to the total soil volume. [13]. The conventional method for determining water content in soil is the gravimetric method, which also establishes the definition of soil moisture. Gravimetric soil water content is the mass of water in the soil, calculated by the difference between the wet and dry soil. The dry soil can be obtained by heating the soil to 105 °C in an oven. [14]. The gravimetric method, being simple and straightforward, serves as the standard approach for calibrating and comparing new techniques. However, this method can be time-consuming and labor-intensive [6], and it is not a cost-effective choice for real-time monitoring.

The cosmic gamma-ray transmission method relies on a radioactive source to emit gamma-rays, and the energy transmitted through the soil, received by a probe, indicates the soil's moisture content. Celik et al. used this method to rapidly obtain volumetric water content in soil without a drying process [7]. However, safety concerns and high costs associated with

Manuscript received Month DD, YYYY; revised Month DD, YYYY; accepted Month DD, YYYY.

Research reported in this publication was supported by the Roy A Wilkens Professorship Endowment.

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gamma rays limit its practical application.

Kumar et al. developed a planar antenna sensor based on capacitive principles to monitor the complex reflection coefficient of soil samples, providing real-time measurement of soil moisture content [9]. The capacitance varies with the soil's water content, causing a resonant frequency shift in the measurement. They designed single and dual resonant frequency antennas for comparison and determined that soil moisture could be measured at microwave frequencies between 0.4 and 2.45GHz. Despite offering a novel method for measuring soil moisture, the antenna sensor faced corrosion challenges in the measurement environment, particularly in contaminated soil. Coating the antenna with weather-resistant materials significantly increases its service life.

Another method for measuring soil moisture content is the neutron probe, which emits low-level radiation in the form of neutrons when inserted into the ground [8]. These neutrons enter the soil and collide with various atomic ions. Fast neutrons lose the most energy and decelerate quickly when they collide with hydrogen atoms. The neutron flux density depends on the water content in the surrounding soil, with more water content resulting in more neutrons scattered back at the device [15]. Establishing the relationship between the slow neutron cloud density and water molecules allows the neutron meter to determine soil moisture content. The neutron probe is a non-destructive testing method that enables continuous monitoring at fixed locations with high measurement accuracy. However, neutron instruments are expensive compared to most other methods and require government registration due to radiation-related health hazards [16].

Linneman et al. proposed a model that connects changes in compressional seismic wave velocity to soil stress conditions for monitoring soil moisture in vadose zone sediments [4]. Factors like soil density affect elastic wave propagation in the vadose zone. According to the semi-empirical model, elastic wave velocity is related to soil water content, porosity, and degree of saturation [17]. The seismic wave velocity method offers an integrated tool for monitoring soil moisture conditions and contaminant transport rates, which are crucial for determining remedial strategies. However, for small-scale soil site investigations, this method is too expensive compared to other techniques.

Table 1: Comparison of common use soil moisture sensor techniques

Measurement Principle	Application requirements, range(m)	Measured parameter	Response time	Cost (USD)	Resolution	Sensitivity	Operation Frequency	Advantage	Disadvantage
Gravimetric Technique [6, 13]	Lab required, any depth	Soil water content	24 h	~ 400	0.01%	NA	NA	Easy to implement, accurate results	Time consuming, destructive test
Neutron probe [15, 18-20]	In-situ, 0.1–0.3 m	Neutron scattering	1-2min	~10,000	±1%	0.703-1.085 m/m θ	NA	Fast response Nondestructive	Health risk, high cost
Capacitive technique/FDR [21-23]	In situ, Lab, <1m, operating frequency up to 1GHz	Dielectric constant	30s	100-4000	±1 to ± 3%	0.02-0.03m^3/m^3 θ	~MHz	Fast response, non-destructive	Not good response in high saline soils
Resistive sensor [21-23]	In-situ, Lab, 0.1-0.3m	Electrical resistance	2-3h	5-30	±1 to 2%	0.02-0.09 ohm θ	~KHz	Cost effective	Time consuming
Commercial sensor (Campbell,CS616) [24]	In situ, Lab, <0.3m, operating frequency up to 1GHz	Dielectric constant	30s	~200	0.1%	Not Reported	Not Reported	Fast response, non-destructive	Not good at deep range measurement
Proposed method	In situ, Lab, 0.365m, operating frequency 1.0-1.06GHz	Dielectric constant	30s	~50	±1.51*10^{-4}%	1.44MHz/%	1.04-1.09GHzz	Non-corrosion, high resolution, high stability, low cost	Single point method
Note: NA-Not Applicable; θ- Soil Moisture Content									

None of the aforementioned methods simultaneously provide cost-effectiveness, ease of manufacturing, high measurement sensitivity, and long-term service. The advantages and disadvantages of current state-of-the-art soil moisture sensors are presented in Table 1.

Dielectric methods are widely developed since soil dielectric properties are significantly affected by water content [3, 11]. Researchers have created structures that utilize the dielectric properties of moist soil to measure water content, such as Time Domain Reflectometry (TDR) [25-27], Frequency Domain Reflectometry (FDR) [28-30], coaxial probes [13, 14] and microwave ring resonators [12].

TDR sensors use parallel metal rods as transmission lines. A voltage is applied to the rods and reflected back to the sensor for analysis. Time Domain measurements are based on changes in soil dielectric properties, with the electromagnetic wave propagation velocity determined by dielectric permittivity. The travel time of the reflected signal can be directly correlated with changes in soil moisture content. TDR offers non-destructive, in situ monitoring of soil water content but faces challenges when applied to high saline soils or soils with high bulk electrical conductivity or high attenuation. Some challenges have been addressed by coating dielectric materials [27] or designing insulated probes [28].

FDR, similar to the capacitive working principle, uses swept frequency to collect data over a wide range of frequencies. It

typically uses an oscillator to propagate an electromagnetic signal through a metal or other waveguide [29]. Soil moisture is determined by the difference between the output wave and the reflected back wave frequency, caused by changes in soil dielectric permittivity. FDR is accurate and flexible but requires calibration for different soil types. Additionally, FDR sensors demand careful installation to avoid air gaps between the sensor and soil [30, 31].

The coaxial probe method, proposed and applied in [32] measures the reflection coefficient variation between the probe and the medium. It is suitable for in-situ dielectric measurements with uncertainty ratios under 3.3% for a wide range of relatively complex dielectrics. You et al. developed a handheld microcontroller-based soil moisture reflectometer using monopole probe sensing technology [26]. The system operates from 1.35 to 1.95 GHz and measures volumetric and gravimetric moisture content in various soil types. The reflectometer polynomially calibrates the reflected voltages and soil moisture content. However, due to soil heterogeneity, the probe's point signal property cannot accurately represent real moisture.

A microwave ring resonator sensor for measuring soil water content was first proposed by Kamal Saramandi. The ring resonator utilized dielectric properties of soil in the measurement and was constructed to be used in portable devices [12]. Then et al developed a microwave sensor system operating from 2.2 GHz to 4.4 GHz, and can measure the change of soil dielectric constant with different soil water concentrations ranging from 0% to 26%. A soil sample placed on the microstrip ring resonator sensor measures the reflected voltage and converts the magnitude of return loss, S11.The calculated return loss is then correlated with soil moisture [33]. This kind of planar method can solve the point signal disadvantage of microwave probe sensor; however, the material of strip is easily affected by slight environmental variations such as temperature, soil composition, and soil pH.

Microwave resonator sensors have been studied for their excellent precision and high sensitivity in relation to moisture content [33, 34]. Water's tendency to absorb microwave energy offers a direct approach to develop a microwave device for measuring moisture content. Coaxial cable probes and microwave ring resonator technology are reliable methods for obtaining soil moisture. However, both methods still have unsatisfactory aspects, as previously mentioned.

This paper outlines the novel sensor device's working principles and presents experimental results for soil moisture measurements. The soil moisture sensor is designed with corrosion resistance, real-time measurement, and on-site monitoring in mind. The innovative fixed-contact interface design makes this sensor more stable and reliable for solid-state applications. Notably, the fabrication of the EOE-MCCR platform only involves traditional standard metal machining, welding, polishing, and cutting procedures, which are low-cost processes. As a result, the EOE-MCCR can be easily mass-produced. The all-metal structure also provides high mechanical robustness and enhances the device's stability in various environments. The fabrication of the EOE-MCCR moisture sensor device simply involves combining an EOE-MCCR platform with a thin layer of PVA film. A new Polyvinyl alcohol (PVA) diaphragm-assisted planar embeddable open-end microwave coaxial cable resonator (EOE-MCCR) is employed to achieve these goals. This technology enables soil moisture content monitoring based on the resonator's frequency domain characteristics. The sensor's working principle depends on the sensitivity of the fringe capacitance to the open-end coaxial cable material. Variations in PVA's dielectric properties caused by differential moisture can be accurately captured by the resonating coaxial line structure. The results show the high sensitivity of the EOE-MCCR-based device for soil moisture sensing. The measurement also demonstrates that sensitivity can be easily adjusted. The novel device's soil moisture measurement resolution was investigated, revealing a resolution of 0.76MHz/% for soil moisture from 4%-10%, and 1.44MHz/% for soil moisture from 10%-24%. The soil moisture sensor also accurately monitored soil moisture levels over a two-week period, demonstrating its feasibility. The soil moisture sensor described in this work is robust, easy to manufacture, chemical resistant, low-cost, and suitable for long-term industrial applications. The fabrication of the MCCR sensor platform only involves traditional standard metal machining, welding, polishing, and cutting procedures, which are low-cost processes, allowing for easy mass production. The all-metal structure provides high mechanical robustness and improves the device's stability in different environments.

The paper is organized with an introduction to soil moisture characteristics and commonly used monitoring methods in Section I, the sensor design theory in Section II, the working principle and sensor design, experimental setup, and results in Sections III and IV respectively. Sect. V provides conclusions for the sensor design.

II. Theory

The embeddable soil moisture sensor capitalizes on the significant difference in dielectric permittivity between dry soil and water in the microwave domain. Moisture content greatly influences dielectric properties, with the dielectric constant of water typically being much higher than that of dry soil. The soil system consists of three phases: solids, water, and air. Generally, water has a dielectric constant of 80, leading wet soil to have a permittivity within that range. In comparison, dry soil has a permittivity of 4, and air is 1 [26]. As a result, the dielectric constant of wet soil heavily depends on water content, and changes in moisture content substantially determine the dielectric constant of the sample.

In this article, the embeddable open-end microwave coaxial cable resonator (EOE-MCCR) designs are based on the principles of prior work completed by the authors. Microwave sensing encompasses the spectrum range from approximately 1 cm to 1 m in wavelength. Long-wavelength microwave radiation can penetrate materials and is not susceptible to scattering, unlike optical wavelengths. This property enables microwave energy detection under various environmental conditions, offering potential real-time sensing capabilities. Coaxial cable waveguides are primarily used at frequencies in the microwave range. Huang et al. proposed a microwave coaxial cable Fabry-Perot Interferometer and demonstrated its ability as a strain measurement platform. [35]. Due to the long signal transmission distance and durability of material components, coaxial cable-based sensor devices provide an

emerging solution for high-temperature, harsh environments. Open-ended coaxial cable waveguides have been extensively researched and commercialized for dielectric spectroscopy at microwave frequencies. The working principle of open-ended coaxial probes relies on the fringe capacitance's dependence on the complex permittivity of the material in front of the open end. The complex permittivity correlates with the coaxial line's reflection coefficient in both magnitude and phase. A detailed analysis of the resonator's working principles can be found in the authors' previous work [34, 36, 37].

The working principle of the previous works is based on these three key findings:

1) The fringe capacitance experiences an exponential increase as the gap distance decreases for a given permittivity, ε_r, of the material in the gap.

2) The measurement sensitivity rises as the gap distance diminishes.

3) For a specific gap distance, the fringe capacitance is linearly proportional to ε_r.

These three conclusions led to the discovery that by associating the resonance frequency with the dielectric constant of the medium between the metal plate and the open end, the resonator can be utilized for sensing applications in harsh environments. However, the original sensor structure needed modification to enhance resonator performance in a soil environment. A notable advantage of the EOE-MCCR structure is that it does not depend on the gap distance to sense soil moisture content, setting it apart from Extrinsic Fabry-Perot Interference (EFPI). The sensor treats the open end of the coaxial cable, the cavity medium, and the metal plate (fixed interface) as a single unit. When the gap is filled with different dielectric materials, it functions as a capacitor. As the gap distance or the medium's dielectric in the cavity changes, the fringe capacitance changes accordingly, leading to variations in the second reflector's reflection coefficient. The design employs a fixed gap distance within an ideal range, enabling better soil moisture sensing through the dielectric properties.

Polyvinyl alcohol (PVA) film was chosen as a suitable material with the necessary moisture sensitivity for detecting moisture content. PVA film readily absorbs and releases water, and most importantly, it quickly establishes equilibrium. It also demonstrates a good response time and recovery speed. Additionally, PVA is a chemically inert material, preventing corrosion due to soil acidity or alkalinity.

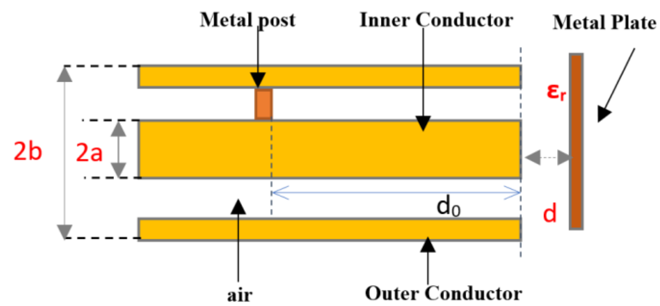
III. Working Principle and Sensor design

The working principle and sensor design for the EOE-MCCR are outlined in the following sections.

A. Working Principle of the EOE-MCCR

A diagram of the EOE-MCCR is displayed in Fig 1. The EOE-MCCR consists of two reflectors positioned along the coaxial cable line. The first reflector, a cylindrical metal post, connects the inner conductor to the outer conductor, causing a high reflection of the electromagnetic wave traveling within the cable. The hollow coaxial cable's open end, combined with an external parallel conducting metal plate surface and a dielectric (PVA film) sandwiched between them, acts as the second reflector in the resonating structure, contributing additional reflection. These two reflectors create the microwave cavity resonator. The metal plate featuring holes is welded to the hollow coaxial cable's exterior. A precisely tailored PVA thin film fills the gap, perfectly matching the hollow coaxial cable's diameter and serving as the moisture-sensitive element.

As previously stated, when the gap distance remains constant, the dielectric constant of the second reflector changes, leading to a shift in the fringe capacitance and causing variations in the second reflector's reflection coefficient in both magnitude and phase. The change in the reflection coefficient's phase results in a shift in the resonance frequency reflection spectrum of the EOE-MCCR. By connecting soil moisture parameters to the resonant frequency shift, the resonator can function as a soil moisture sensor.



(a)

Fig. 1 a) Schematic illustration of EOE-MCCR terminated by a metal plate with a medium gap distance (d) from the open end of the coaxial line. The inner and outer conductor diameters are 2a and 2b, respectively. The metal post serves as the first reflector, and the open end serves as the second reflector. ε_r represents the relative permittivity of the medium in the gap.

The incoming microwave signal is partially reflected by the metal post, while the transmitted part continues to travel to the open end and reflects at the coaxial line's open end. As per prior work, the electromagnetic (EM) wave reaching the open end is nearly entirely reflected. Multiple reflections between the two reflectors create a resonance pattern in the EOE-MCCR's reflection spectrum.

Based on the transmission line theory, the resonator's magnitude reflection spectrum can be calculated by [18]:

$$M = \sqrt{\frac{\Gamma_1^2 - 2\Gamma_1\Gamma_2 e^{-\alpha 2d_0}\cos(\delta - \varphi_1 - \varphi_2) + \Gamma_2^2 e^{-\alpha 4d_0}}{1 - 2\Gamma_1\Gamma_2 e^{-\alpha 2d_0}\cos(\delta - \varphi_1 - \varphi_2) + \Gamma_1^2\Gamma_2^2 e^{-\alpha 4d_0}}} \quad (1)$$

where Γ_1 and Γ_2 are the magnitude of the reflection coefficients of the metal post and the open end, respectively; α signifies the coaxial cable's transmission line loss; d_0 is the physical length of the microwave cavity resonator; δ is the round-trip phase delay between two partially reflected waves of the EM signal; and φ_1 and φ_2 are the phase reflection coefficients of the two corresponding reflection coefficients. The EOE-MCCR was designed for practical microwave coaxial cable transmission line applications, so the equivalent circuit is not a realistic model for this case. Future research could utilize the equivalent circuit to provide theoretical parameter information.

According to Eq. (2), the EOE-MCCR's resonance frequencies, where the phase-matching condition is met, can be expressed as:

$$f_{res} = \frac{c(2m\pi+\varphi_1+\varphi_2)}{4\pi d_0} \quad (2)$$

where c is the speed of light in vacuum and m is a non-negative integer representing the resonance order. Notably, the gap length d shown in Fig. 1 between the coaxial cable's endface and the external metal plate is not the Fabry-Perot cavity, which distinguishes it from traditional EFPI. Importantly, the phase term φ_2 associated with the second reflector of the EOE-MCCR strongly depends on the dielectric constant ε_r when the gap distance is fixed. This lays foundation of the proposed configuration as a sensing platform. According to equivalent circuit theory, the calculation of φ_2 is:

$$\varphi_2 = -2\tan^{-1}(\omega Z_0 C) \quad (3)$$

where ω is the angular frequency of the EM input signal; Z_0 is the characteristic impedance of the cable (50Ω); and C is the fringe capacitance at the open end and is given by [34]:

$$C = \frac{2\varepsilon_0\varepsilon_r}{[\ln(b/a)]^2}\int_a^b\int_a^b\int_0^\pi \frac{\cos\varphi' d\rho d\rho' d\varphi'}{\sqrt{\rho^2+\rho'^2-2\rho\rho'^2\cos\varphi'}} + \sum_{n=1}^{\infty}\int_a^b\int_a^b\int_0^\pi \frac{\cos\varphi' d\rho d\rho' d\varphi'}{\sqrt{\rho^2+\rho'^2+4n^2d^2-2\rho\rho'\cos\varphi'}} = k\varepsilon_r \quad (4)$$

where ε_0 and ε_r are vacuum dielectric and relative dielectric of the medium in the gap; ρ and ρ' denote the radial direction, and φ' denotes the azimuthal direction; d is the gap distance; and the k denotes a linear coefficient. From Eq. (5), it can be observed that, when d is a fixed number, the fringe capacitance 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. Thus, by tracking the resonance frequency shift, the variation of ε_r can be determined.

It is known that water has a dielectric constant of 80, which is significantly higher than the dielectric constant of dry soil. Changes in moisture content will cause permittivity to change, affecting fringe capacitance. Now it can be seen that the φ_2 varies from the initial setting. Consequently, the change in moisture content will lead to the resonance frequency shift. This phenomenon lays the groundwork for the capability of the EOE-MCCR for soil moisture sensing and the unique feature of user-configurable sensitivity of the PVA-film assisted EOE-MCCR soil moisture sensor device. It is worth noting that the device's measurement sensitivity can be adjusted simply by changing the gap distance. Based on the aforementioned equations, changes in moisture content cause a resonance frequency shift. By tracking the reflection spectrum shift, soil moisture content can be accurately determined.

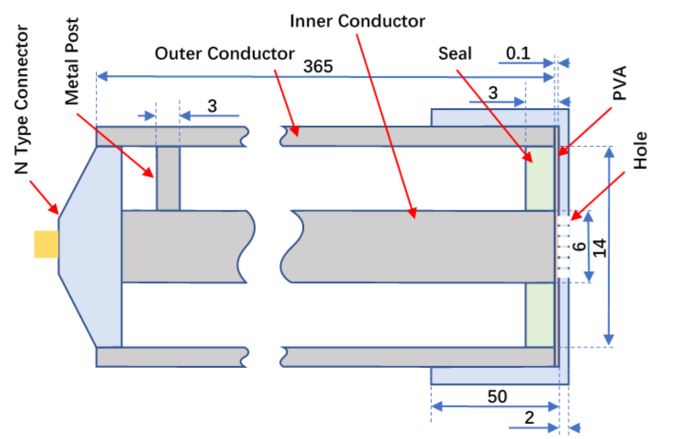
B. Sensor Design

Utilizing a combination of a full-wave analytical solution and a full-wave simulation package, we assessed the underlying physics of the sensor in terms of sensitivity, signal strength, and more. The full-wave simulation offers a solid engineering understanding of the sensor physics, enabling the development of optimal sensing solutions for monitoring soil moisture. Fig 2 displays the EOE-MCCR structure details, with the resonator structure created between the first reflector (metal post) and the second reflector (open-end of the coaxial cable). The sensor's parameters include a length of 365mm, inner and outer conductor diameters of 6mm and 14mm, respectively, and a metal post diameter of 3mm. The gap distance is set at 0.1mm, with a thin 0.1 mm PVA film directly placed in the gap to detect moisture changes. The metal post, located 35mm from the input end in the input signal direction, was welded parallel to the outside of the hollow coaxial cable. Two Teflon washers support the inner conductor, while a stainless-steel 40 mesh screen was mounted over the open end to prevent soil particle interference and protect the PVA film from damage. When a microwave input signal with frequency f and phase δ is incident upon the EOE-MCCR opening, the input signal will be partially reflected by the metal post due to the significant impedance mismatch, resulting in a high reflection point for the EM wave traveling within the coaxial cable. The transmitted signal will continue to travel to the PVA and the open end, reflecting back into the hollow coaxial cable. Multiple reflections then occur between the two reflectors, leading to a resonance pattern in the EOE-MCCR's reflection spectrum.

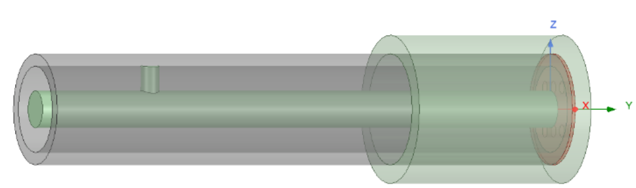
Fig.2 Cross-sectional schematic of the EOE-MCCR, with inner and outer conductor diameters of 6mm and 14mm, respectively. The metal post is 35mm away from the input end. A PVA film is inserted into the gap as a soil moisture element. Unit: mm.

C. Simulation

Full-wave simulations using ANSYS HFSS were utilized to examine the response of the proposed moisture sensor to water



content variations. Fig. 3(a) displays the simulation schematic diagram of the EOE-MCCR model constructed in HFSS. The resonator structure is formed between the first and second reflectors. The sensor's parameters include L=365mm, d=0.1mm, 2a=6mm, 2b=14mm, and a metal post diameter of 3mm. The conducting material is stainless steel, with a 35mm distance between the metal post and the input end face.



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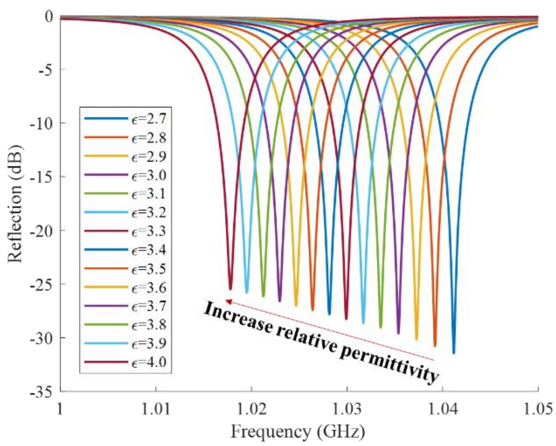

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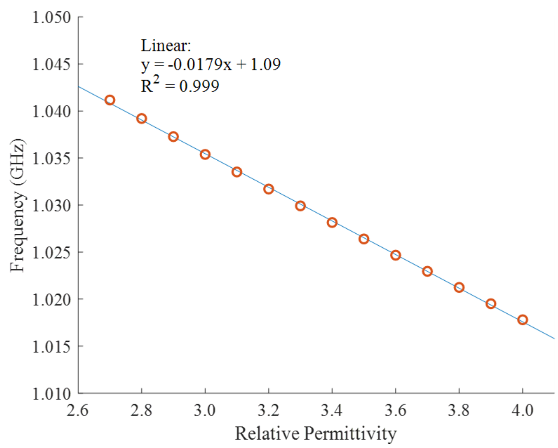


(c)

Fig. 3 Investigation of the proposed moisture sensor using full-wave simulations. (a) Full-wave simulation schematic. (b) Evolution of the reflection spectrum as the relative permittivity increases. (c) Calculated resonance frequency of the sensor as a function of applied relative permittivity.

As the relative permittivity changed from 2.5 to 4.0, the corresponding phase reflection coefficient φ_2 decreased, and the resonant frequency shifted to the left. The simulated calculation results are presented in Fig. 3. Fig. 3(b) illustrates the reflection spectrum shifting to the lower frequency region as the relative permittivity increased. Fig. 3(c) depicts the resonance frequency as a function of the relative permittivity. A linear relationship between resonance frequency shift and relative permittivity was obtained for this sensor. The absolute value of the slope, i.e., measurement sensitivity (the relative change in resonance frequency/variation of ε_r), is -0.0179. The full-wave simulations confirm that the proposed configuration can be employed for sensing moisture content applied to the device with a linear response.

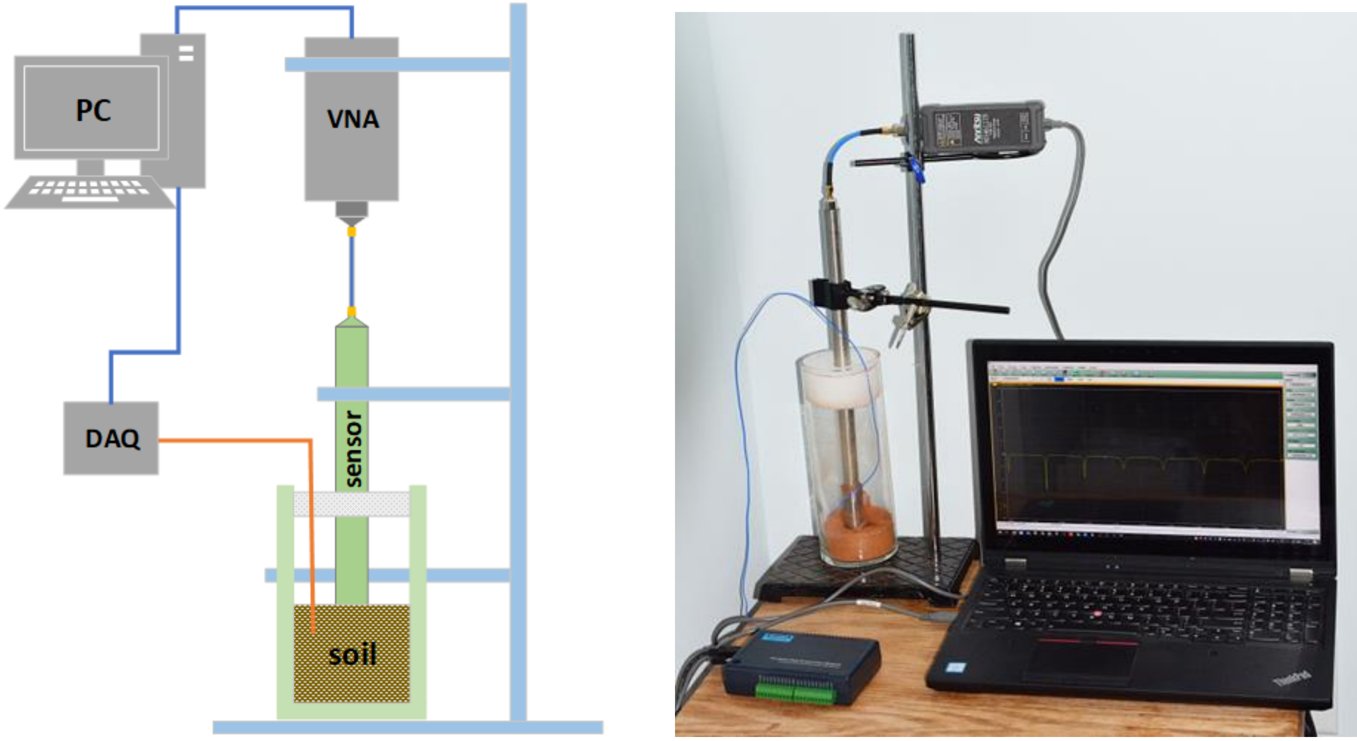
IV. Experiment and Data Analysis

To evaluate the proposed EOE-MCCR concept, a prototype resonator was designed, fabricated, and tested for soil moisture measurements. The sensor was based on a custom-made hollow coaxial cable. Fig. 4 presents an image of a prototype EOE-MCCR and a schematic of a basic application using the prototype EOE-MCCR. Fig. 4(a) displays a photograph of the EOE-MCCR device fabricated from a stainless-steel tube and welded metal plate. The prototype EOE-MCCR device's fabrication involved traditional metal welding and cutting techniques, which are cost-effective processes. The all-metal structure also offers high mechanical robustness and enhanced chemical resistance, allowing the sensor to be embedded in damp soil. The inner conductor and outer conductor diameters of the microwave coaxial cable were designed to be 6mm and 14mm, respectively, resulting in a characteristic impedance of approximately 50.8 Ω. This design enables the homemade cable end to be compatible with a standard N-type connector. Through the connector, the resonator can connect to a vector network analyzer (VNA, Anristu 46121B), which also functions as a signal source and detector. Other parameters used in the prototype fabrication were the same as those used in the previously discussed simulation.

The experimental setup for the soil moisture measurement demonstration is schematically depicted in Fig.4(b). A Plexiglass cylinder with a height of 350 mm and an internal diameter of 64 mm was utilized to hold the soil column. A known volume of water was injected into the soil column. Data acquisition, recording, and processing were accomplished by a personal computer connected to the VNA. The VNA was also configured to measure the amplitude reflection spectrum.

The prototype soil moisture sensor's response to water content variations at room temperature (24°C) was demonstrated. Natural soil samples were collected from a local yard at a depth of 50 cm to avoid plant roots and insects in the surface soil. The soil was then dried at 105°C for 24 hours in an oven. Next, the soil was screened with a size 40 sieve to remove large particles, separated into 11 sample batches weighing 50g each. Water volumes starting at 1ml, with 1ml increments, were added to the 11 samples, corresponding to moisture content ranging from 4% to 24%. The samples were placed in a stable temperature environment for 24 hours. Each sample was then measured for 1 hour to obtain stable data.

(a)

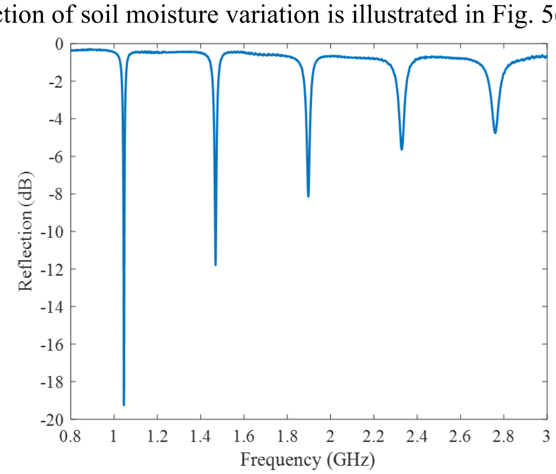


(b) (c)

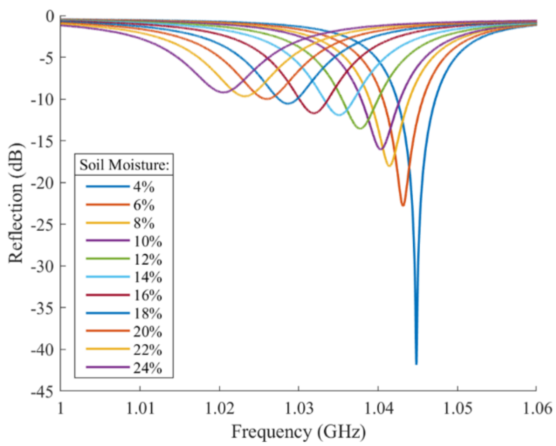
Fig. 4 (a) Photograph of the prototype device. (b) Experimental setup used to test the soil moisture response of the EOE-MCCR. (c) Actual experimental setup.

Fig. 5(a) displays the amplitude reflection spectrum of the EOE-MCCR sensor in the frequency range from 800 MHz to 3 GHz. Due to the two highly reflective reflectors, multiple resonant frequencies are visible, indicating a resonant phenomenon. The original reflection spectrum encompasses the fundamental and higher-order modes within the observation bandwidth. Discrete resonance frequencies at 1.01 GHz (fundamental resonance frequency) and 1.42 GHz (second resonance frequency) were detected. The resonance frequencies and the various resonance depths align well with the simulation outcomes. The other high-order resonant frequencies are discernible and can be utilized for sensing applications. Considering the fringe contrast of the resonant frequency dip, the 1.0-1.1 GHz range can be employed as the working bandwidth due to its high signal-to-noise ratio (SNR). This observation is logical because the reflectivity of the two reflectors becomes unbalanced as the frequency increases. A downward trend of the reflection spectrum was observed because of the high transmission loss of the commercial coaxial cable in the high-frequency region. The small periodic ripples are attributable to the multiple reflections at port 1 of the VNA and the interface between the commercial cable and the EOE-MCCR, caused by a minor impedance mismatch. The high transmission loss in the high-frequency area of the commercial coaxial cable results in a downward trend of the reflection spectrum, as demonstrated in Fig. 5(a).

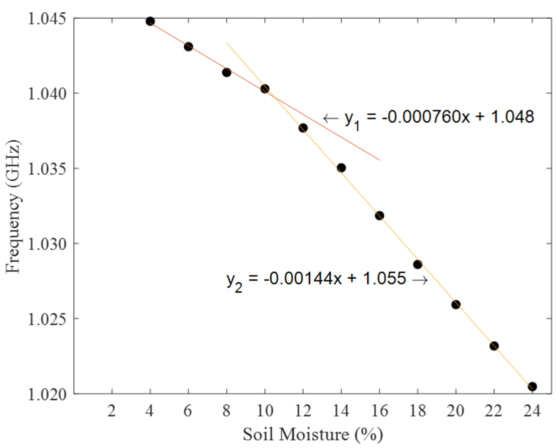
Fig. 5(b) features the measured response of the prototype sensor device to water content variations ranging from 4% to 24% to showcase the sensor's moisture sensing ability. In the experiment, a total water volume of 11ml in 1ml increments was added to the samples, corresponding to a total soil moisture change from 4% to 24% in 2% steps. Fig. 5(b) displays the measured reflection spectra centered at the fundamental resonance frequency with an increasing soil moisture profile and a fixed gap distance of the sensor. It is evident that the reflection spectrum shifts to lower frequencies as the soil moisture rises. This trend was also observed in the model and simulation results. As the applied soil moisture increased, the PVA absorbed water and reached equilibrium, causing an increase in the relative permittivity between the PVA film and the open-end face of the coaxial line. The changes in relative permittivity led to a fringe capacitance change, resulting in a shift of the resonance frequency of the EOE-MCCR, as anticipated in Fig. 3. The resonance frequency of the sensor as a function of soil moisture variation is illustrated in Fig. 5(c).



(a)



(b)



(c)

Fig. 5. Soil moisture response of a prototype EOE-MCCR sensor device. (a) Measured reflection spectrum of the sensor device. (b) Recorded reflection spectra of the sensor during increasing soil moisture. (c) Resonance frequency response as a function of soil moisture during increasing soil moisture. The linear curve fit model for the measured data set is shown. The measurements were conducted over a range of soil moisture levels from 4% to 24%.

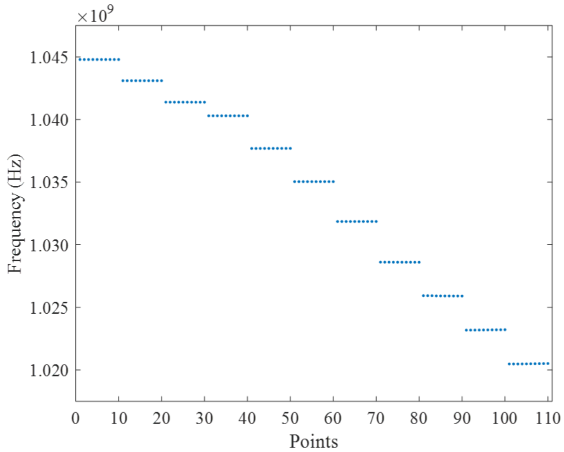
The measurements and theoretical prediction results align well overall. Two linear curve fits were applied to the data sets, revealing linear relationships with equations as: y_1=-0.000760x+1.047 and y_2=-0.0144x+1.055. R-square values for y_1 and y_2 are 0.9905 and 0.9991, respectively. The measurement sensitivity (change in resonance frequency/change in soil moisture) of the EOE-MCCR was determined to be 0.76MHz/% for soil moisture from 4%-10%, and 1.44 MHz/% for soil moisture from 10%-24%. There are two regions of moisture measurement results because bonding water effects are stronger than free water effects when soil moisture is lower than 10%. The results show that the PVA diaphragm-equipped EOE-MCCR can be used as a soil moisture sensor with good sensitivity and linear responses.

As discussed earlier, the soil moisture sensitivity of the PVA-film assisted EOE-MCCR device increases exponentially as the gap distance between the PVA film and the open-end face of the coaxial line decreases. This unique feature suggests that the proposed device has significant potential for detecting minute moisture changes with high resolution. An experiment based on soil moisture changes was conducted to demonstrate this high resolution. In the experiment, a total water volume of 11ml in 1ml increments was added to the samples, corresponding to a total soil moisture change from 4% to 24% in 2% steps. For each soil moisture setting, ten reflection spectra from the sensor were recorded. From the stair-step curve, the sensor responded well to small increments of moisture. The maximum standard deviation obtained from the measurements was determined to be 114.9 Hz, as shown in Fig 7 (a). Given the measurement sensitivity of 0.76 MHz/% for soil moisture from 4%-10%, and 1.44 MHz/% for soil moisture from 10%-24%, the resolution of the EOE-MCCR device was estimated to be 1.51×10^{-4}*% and* 7.97×10^{-5}%, respectively. Therefore, the measurement resolution is 1.51×10^{-4}% for this device. In comparison to traditional commercial and newly investigated soil moisture sensors' resolution data, the high resolution of the proposed prototype demonstrates that the EOE-MCCR has the potential to improve the resolution of soil moisture sensors.

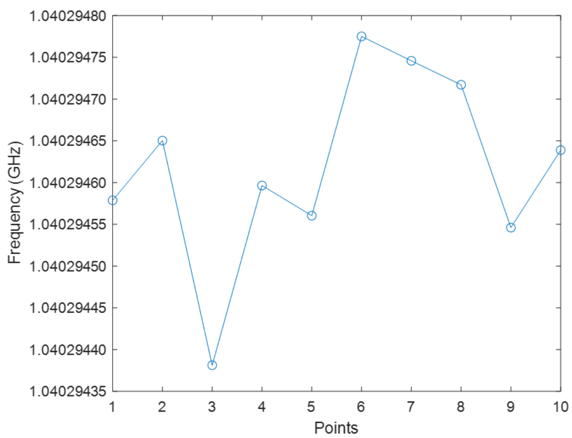
The stability of the proposed PVA-film assisted soil moisture sensor was also examined. A 150-minute experiment was conducted by placing the sensor in a temperature-controlled container to maintain the temperature at 25 °C and eliminate environmental interferences. The results are shown in Fig. 7. The frequency uncertainty was found to be 640 Hz in the current laboratory setting. Compared to the work band within 1.04×10^9 Hz, the small standard deviation of 114.9 Hz of the soil moisture sensor indicates excellent stability of the sensor.

To validate the practicality of the proposed soil moisture sensor based on the EOE-MCCR, an experiment measuring water distribution was conducted. The sensor was placed in a 125 g dry soil sample, and 20 ml of water was injected to observe the entire process of water diffusion at room temperature for two weeks. Fig. 8 depicts the measured trend as soil moisture gradually increases and reaches a stable level in two days. The graph provides information about the soil water diffusion process, which is crucial in contaminated soil remediation and groundwater pollution protection. The experiment also demonstrates that the prototype sensor has long-term applicability in real-world scenarios. From the long-term observation, it was also discovered that temperature changes do impact soil moisture levels. In the experiment, when the temperature increased, condensation formed on the cylinder's shell, thereby decreasing the soil moisture level. This occurred because the temperature inside the cylinder was higher than the outside temperature. Conversely, when the temperature decreased, the condensation dissipated back into the soil. Since this is a sealed container, the soil moisture maintains a balance.

In conclusion, the proposed EOE-MCCR soil moisture sensor demonstrates good sensitivity, linear response, high resolution, and excellent stability. The prototype's high resolution and practicality in real-world scenarios show that it has the potential to improve the performance of soil moisture sensors. Moreover, the experimental results provide valuable insights into soil water diffusion processes, which are essential for contaminated soil remediation and groundwater pollution protection. The sensor's ability to maintain a moisture balance in various temperature conditions further highlights its suitability for a wide range of applications.



(a)



(b)

Fig.6. Sensitivity and response of the prototype soil moisture sensor. (a) The sensor's response to small variations of soil moisture, where ten measurements were recorded for each soil moisture setting. (b) The maximum variability of 114.9 Hz was observed for ten measurements of the resonance frequency obtained from measurement points 30-40, indicating high precision of the proposed sensor.

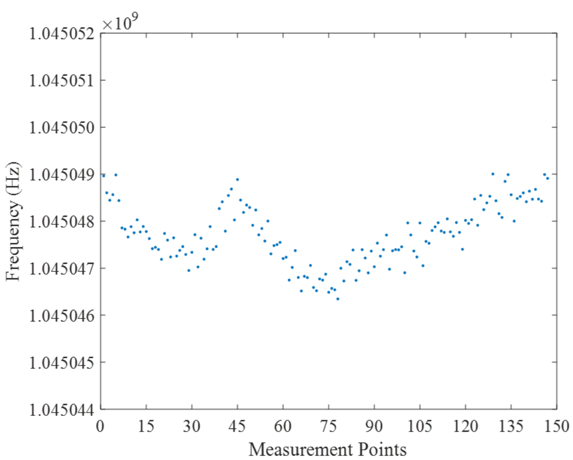


Fig.7 Stability test of the proposed PVA-film assisted soil moisture sensor. The sensor was placed in a temperature-controlled container at 25 °C for 150 minutes to eliminate environmental interferences. The frequency uncertainty was found to be 640 Hz, indicating excellent stability of the sensor.

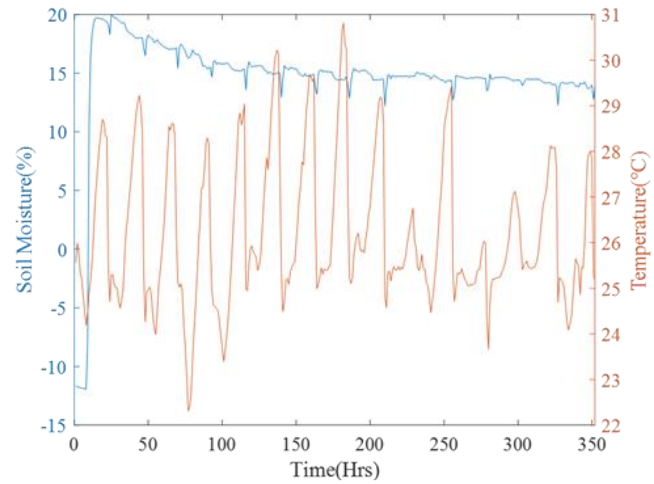


Fig.8 Long-term observation of soil moisture changes in response to water injection. A total of 20 ml of water was added to 125 g of soil, resulting in a gradual increase in soil moisture content that stabilized at approximately 16%.

V. Conclusion

The development of open-end coaxial cable soil sensors aims to offer a more precise, non-invasive, and cost-effective approach for measuring soil moisture. The innovative design of these sensors allows for direct embedment in solid-phase environments. Through theoretical analysis, simulations, and obtained measurement results, this study confirms that PVA film-assisted open-ended hollow coaxial cable resonators are an outstanding choice for applications necessitating highly sensitive soil moisture measurements. Furthermore, the proposed method can be applied to permittivity measurements of materials in other contexts. A strong linear relationship between the sensor response and changes in soil moisture content was observed. Capitalizing on water's high permittivity in the microwave frequency range, the EOE-MCCR sensor device was utilized for direct soil moisture measurements. By monitoring the resonance frequency of the coaxial cable resonator, the differential soil moisture applied to the PVA film could be determined. Numerical calculations revealed the resonance frequency of the resonator to be highly sensitive to permittivity changes. The novel device exhibited high measurement sensitivity, reaching 0.76 MHz/% for soil moisture ranging from 4% to 10% and 1.44 MHz/% for soil moisture between 10% and 24%. Besides soil moisture measurements, the demonstrated EOE-MCCR sensor device with enhanced sensitivity could be further developed for detecting trace chemical contaminants in soil using functional films.

Acknowledgment

J.H. is grateful for support from the Roy A. Wilkens Professorship Endowment.

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