ISSN:3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.2.1.P357

Sensing Depth Analysis of Open-Ended Coaxial Probes at Different Input Powers and Frequencies

Guifeng Yang [1, a], Shaohua Zhou [2, b], Hui Huang [3, c], and Jianhua Yang [1, d] *

[1] School of Automation, Northwestern Polytechnical University, Xi'an 710129, China;

[2] School of Integrated Circuits, Zhongyuan University of Technology, Zhengzhou 450007, China.

[3] Beijing Xinchen Technology Co., Ltd, Beijing 100029, China.

[a] yangguifeng@mail.nwpu.edu.cn, [b] zhoushaohua@zut.edu.cn, [c] huanghui@xinchenkeji.cn,

[d] yangjianhua@nwpu.edu.cn

Abstract. The open-ended coaxial probe has been widely used to measure the permittivity of different materials. Input power and frequency are two important factors that affect the sensing depth of an open-ended coaxial probe. Existing studies in the literature on the effect of input power and frequency on the sensing depth of probes are mainly qualitative studies of the effect of frequency variation on the sensing depth of open-ended coaxial probes at a particular input power. However， the central prerequisite for accurate sample preparation is precise knowledge of the magnitude of the sensing depth of an open-ended coaxial probe at any input power and at any frequency. In this paper, the effect of frequency (0.5 GHz to 20 GHz) and input power (-20 dBm to 20 dBm) variations on the sensing depth of an open-ended coaxial probe is investigated for the first time from an experimental point of view using methanol as an example. Then, the theoretical formula for the sensing depth size of the open-ended coaxial probe is given by fitting to the experimental data, and its validity is proved by experimental verification. The experimental results show that the sensing depth of the open-ended coaxial probe for methanol does not exceed 2 mm in the frequency range of 0.5 GHz to 20 GHz and the input power range of -20 dBm to 20 dBm.

Keywords: Open-ended coaxial probe, sensing depth, frequency, input power, permittivity.

1. Introduction

The open-ended coaxial probe method has been widely used to measure the permittivity of different materials due to its simplicity in sample preparation and its ability to provide broadband, non-invasive and non-destructive measurements[1]-[6]. The open-ended coaxial probe method requires that the reflection coefficient of the sample under test be the same as that of a sample that fills the entire half-space. Therefore, it is necessary to accurately determine the minimum thickness of the sample [3][7][8][9]. The minimum thickness of the sample is determined by the sensing depth of the probe, which is defined as the minimum distance between the bottom of the probe and the sample boundary [6][8]. Input power and frequency are two important factors that affect the sensing depth of an open-ended coaxial probe [3][4][7][8][10] [11][12][13]. Many researchers have investigated the effect of input power and frequency on the sensing depth of the probe.

David L. Gershon et al. investigated the electric field induction of open-ended coaxial probes in the 0.3-6 GHz frequency range, and showed that the strength of the electric field beneath the probe depends on the magnitude of the input power, but the exact magnitude of the input power is not given in the paper [3]. Ching-Lieh Li et al. analyzed the distribution of electromagnetic waves in the frequency range of 0.3-4 GHz in an open-ended coaxial probe and in the material under test by means of a theoretical model, and the results of the study showed that the strength of the electric field under the probe also depended on the magnitude of the input power, but the specific magnitude of the input power was still not given [4]. Emily Porter et al. investigated the size of the tissue area measured below the probe in the frequency range of 300 MHz - 8.5 GHz and showed that the effective sensing depth below the probe is also dependent on the amount of input power [14]. Paul M. Meaney et al. analyzed the sensing depth of open-ended coaxial probes at 2 GHz and

ISSN:3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.2.1.P357
4 GHz frequencies, and the results of the study showed that the sensing depth of open-ended coaxial probes decreases with increasing frequency [15]. Ali Farshkaran et al. investigated the effect of frequency variation on the sensing depth of an open-ended coaxial probe in the range of 1 GHz to 8 GHz, and the results of the study showed that the sensing depth of an open-ended coaxial probe decreases with increasing frequency [13]. Cemanur Aydinalp et al. analyzed the relationship between the sensing depth of open-ended coaxial probes and frequency variation in the range of 0.5 GH to 20 GHz, and the results of the study similarly showed that the sensing depth of open-ended coaxial probes decreases with the increase in frequency [9].

In summary, the current research in the literature on the effect of input power and frequency on the sensing depth of probes focuses on the effect of frequency change on the sensing depth of open-ended coaxial probes at a particular input power. And none of these studies gave quantitative findings, but only analyzed and discussed the effect of input power and frequency on the sensing depth of open-ended coaxial probes from a qualitative point of view. As mentioned before: the preparation of the minimum thickness sample directly affects the measurement of the material's permittivity. In turn, the sensing depth of the open-ended coaxial probe is a key factor in determining the minimum thickness of sample preparation. Therefore, an accurate knowledge of the relationship between the sensing depth of the open-ended coaxial probe and the variation of frequency and input power becomes a key factor governing the accurate measurement of the material dielectric constant by the open-ended coaxial probe method.

In this paper, the effect of input power (-20 dBm to 20 dBm) and frequency (0.5 GHz to 20 GHz) variations on the sensing depth of an open-ended coaxial probe is quantitatively analyzed and discussed for the first time from an experimental point of view using methanol solution as an example. The experimental results show that the sensing depth of the open-ended coaxial probe for methanol does not exceed 2 mm in the frequency range of 0.5 GHz to 20 GHz and the input power range of -20 dBm to 20 dBm. On this basis, the theoretical formulas for the sensing depth of an open-ended coaxial probe are given and experimentally verified in this paper in the input power range of -20 dBm to 20 dBm and in the frequency range of 0.5 GHz to 20 GHz, at any input power and at any frequency point. The theoretical formula for the sensing depth of open-ended coaxial probes given in this paper can provide an effective guide for the accurate preparation of samples.

2. Discussion and Analysis of Experimental Results

2.1 Sensing Depth of Open-Ended Coaxial Probes at Different Frequencies at 0 dBm.

The measurement system used in this paper is shown in Fig. 1, which is mainly composed of a vector network analyzer (R&S ZVA40) and a 2.2-mm open-ended coaxial probe (MEMF-C1203, Beijing Xinchen Technology Co., Ltd.). Methanol as a typical material is often used as an object of study for material permittivity measurements based on open-ended coaxial probes [2][8][17][18][19]. In this paper, methanol (permittivity = 37) is also chosen to analyze the effect of input power and frequency variations on the sensing depth of an open-ended coaxial probe.

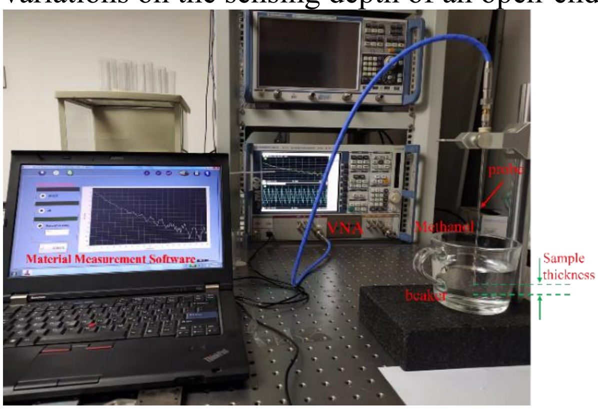

Fig. 1 Measurement Systems

ISSN:3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.2.1.P357

The frequency and input power were first set to 2 GHz and 0 dBm, respectively. The probe is then inserted into the beaker containing the material and the distance between the end of the probe and the bottom of the beaker is further determined; this distance is the sample thickness of the material being measured, as shown in Fig 2. Changes in the thickness of the sample cause a change in the dielectric constant of the sample being measured. The minimum thickness of the sample is determined to obtain the sensing depth of the probe. In this paper, the thickness of the samples was set from 0mm to 5mm in 0.2mm steps. The results of the variation of the dielectric constant of methanol with the thickness of the sample at 2 GHz and an input power of 0 dBm are shown in Fig. 2.

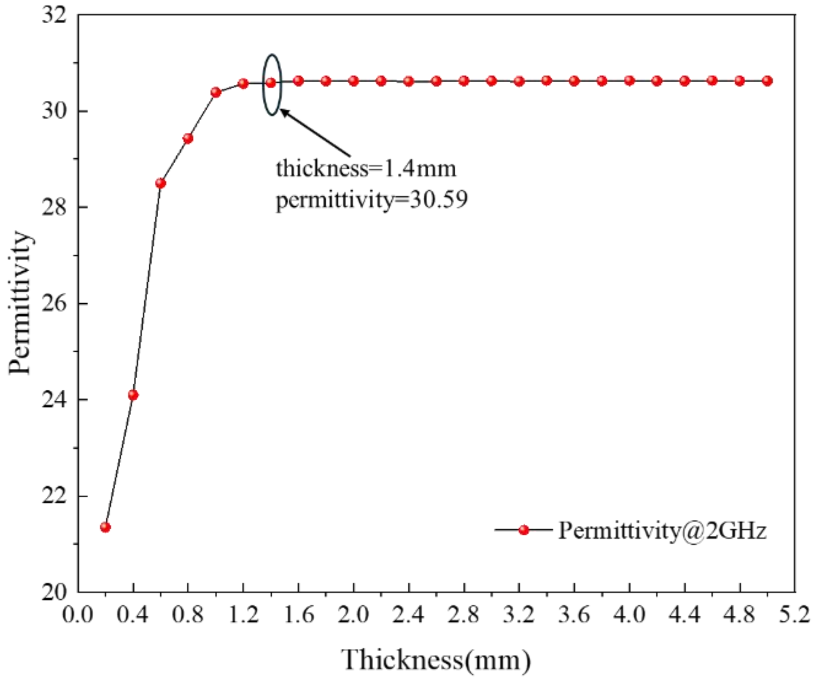

Fig. 2 Permittivity of methanol with different thicknesses

The sensing depth of an open-ended coaxial probe is defined in the literature as the thickness of the sample when the probe no longer senses the influence of non-target regions [20]. In order to more realistically reflect the sensing depth of the open-ended coaxial probe, 10% of the sample thickness is often used as an artificial incremental perturbation [21]. Therefore, for methanol, the open-ended coaxial probe has a sensing depth of 1.6 mm at a frequency of 2 GHz and an input power of 0 dBm.

Table 1 gives the sensing depths of the open-ended coaxial probe at different frequencies in the range of 0.5 GHz to 20 GHz for an input power of 0 dBm.

Table 1. Sensing depth of open-ended coaxial probes at -20 dBm for five typical materials.

Serial Number	Frequency	Sensing Depth(mm)
No.1	0.5GHz	1.8
No.2	2GHz	1.6
No.3	5GHz	1.6
No.4	10GHz	1.5
No.5	15GHz	1.4
No.6	20GHz	1.3

2.2 Sensing Depth of Open-Ended Coaxial Probes at Different Frequencies with Input Power in the Range of -20 dBm to 20 dBm.

ISSN:3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.2.1.P357

Table 2. Sensing depth of the probe at different frequencies and powers.

Power \ Frequency	0.5 GHz	2 GHz	5 GHz	10 GHz	15 GHz	20 GHz
-20 dBm	1.6	1.5	1.5	1.4	1.2	1.1
-10 dBm	1.7	1.5	1.6	1.4	1.3	1.2
0 dBm	1.8	1.6	1.6	1.5	1.4	1.3
10 dBm	1.9	1.8	1.7	1.6	1.5	1.3
20 dBm	2.0	1.9	1.8	1.7	1.6	1.5

In the previous subsection, we analyzed the sensing depth of the open-ended coaxial probe at 0 dBm for different frequencies. This subsection gives the sensing depth of the open-ended coaxial probe at different frequencies for input powers in the range of -20 dBm to 20 dBm, as shown in Table 2.

Based on the data in Table 2, using the polynomial function and combining it with the least squares function, the following equation can be obtained.

$$depth = c + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + b_1y + b_2y^2 + b_3y^3 + b_4y^4 + b_5y^5 \quad (1)$$

Where, $depth$ is the sensing depth, x is the frequency, and y is the input power.

$c = 1.87567 \pm 0.03681$

$a_1 = -0.21475 \pm 0.04909$

$a_2 = 0.06422 \pm 0.0183$

$a_3 = -0.00835 \pm 0.00258$

$a_4 = 4.60862E-4 \pm 1.50602E-4$

$a_5 = -9.0408E-6 \pm 3.08424E-6$

$b_1 = 0.00134 \pm 48111.96651$

$b_2 = 8.33333E-5 \pm 2.54168E-4$

$b_3 = 9.78019E-5 \pm 601.39958$

$b_4 = -6.78794E-21 \pm 5.65517E-7$

$b_5 = -1.95604E-7 \pm 1.2028$

The fitting results based on Eq. (1) are given in Fig. 3. It can be seen that the sensing depth of the open-ended coaxial probe decreases with increasing frequency and increases with increasing input power. The sensing depth of the open-ended coaxial probe in the range of -20 dBm to 20 dBm at different frequencies (0.5 GHz to 20 GHz) does not exceed 2 mm.

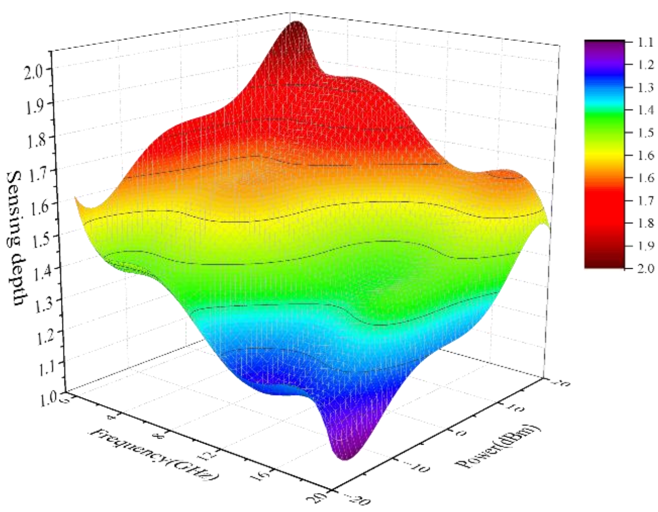

Fig. 3 Predictions of open-ended coaxial probes at different input powers and frequencies.

ISSN:3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.2.1.P357

Equation (1) gives the theoretical formula for the sensing depth of an open-ended coaxial probe at different input powers (-20 dBm to 20 dBm) and different frequencies (0.5 GHz to 20 GHz). In order to prove its effectiveness, experimental validation is carried out in this paper and the results are shown in Table 3. A comparison of the theoretical calculations based on Eq. (1) and the actual measurements is given in Table 3.

Table 3. Theoretical calculation results and actual measurement results based on Eq. (1)

Frequency(GHz)	Power(dBm)	Experimental value	Projected value	Error
0.5	-18	1.6	1.52	5.0%
0.5	-8	1.7	1.76	3.5%
0.5	8	1.8	1.73	3.9%
0.5	18	2.0	1.91	4.5%
2.5	-18	1.5	1.45	3.3%
2.5	-8	1.5	1.53	2.0%
2.5	8	1.8	1.75	2.8%
2.5	18	1.9	1.86	2.1%
7.5	-18	1.4	1.36	2.9%
7.5	-8	1.5	1.43	4.7%
7.5	8	1.6	1.66	3.7%
7.5	18	1.7	1.75	2.9%
12.5	-18	1.4	1.34	4.3%
12.5	-8	1.4	1.37	2.1%
12.5	8	1.5	1.42	5.3%
12.5	18	1.6	1.57	1.9%
17.5	-18	1.2	1.17	2.5%
17.5	-8	1.3	1.24	4.6%
17.5	8	1.4	1.36	2.9%
17.5	18	1.5	1.43	4.7%
20.0	-18	1.1	1.13	2.7%
20.0	-8	1.3	1.34	3.1%
20.0	8	1.3	1.41	8.5%
20.0	18	1.5	1.46	2.7%

From Table 3, it can be seen that the maximum error between the theoretical calculation results based on Eq. (1) and the actual measurement results is 8.5%, which is in line with the 10% error requirement and the tolerance requirement in practical testing [21]. This shows that the theoretical formula (1) given in this paper for the sensing depth of an open-ended coaxial probe at different input powers (-20 dBm to 20 dBm) and different frequencies (0.5 GHz to 20 GHz) is valid.

3. Conclusion

In this paper, the effect of input power (-20 dBm to 20 dBm) and frequency (0.5 GHz to 20 GHz) variations on the sensing depth of open-ended coaxial probes is quantitatively analyzed for the first time from an experimental point of view. And the theoretical formulas for the sensing depth of open-ended coaxial probes at different input powers and different frequencies are given. The results of this paper will provide effective theoretical guidance for the accurate preparation of samples and the accurate measurement of material permittivity.

ISSN:3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.2.1.P357

References

[1] Dilman I, Akinci M N, Yilmaz T, et al. A method to measure complex dielectric permittivity with open-ended coaxial probes[J]. IEEE Transactions on Instrumentation and Measurement, vol.71, pp.1-7, 2022.

[2] Mirbeik-Sabzevari, Amir, and Negar Tavassolian. "Characterization and validation of the slim-form open-ended coaxial probe for the dielectric characterization of biological tissues at millimeter-wave frequencies." IEEE Microwave and Wireless Components Letters, vol.28, no.6, pp.85-87, Jan. 2017.

[3] Gershon, David L., et al. "Open-ended coaxial probe for high-temperature and broad-band dielectric measurements." IEEE transactions on microwave theory and techniques, vol.47, no.9, pp.1640-1648, Sep.1999.

[4] Li, Ching-Lei, and Kun-Mu Chen. "Determination of electromagnetic properties of materials using flanged open-ended coaxial probe-full-wave analysis." IEEE Transactions on Instrumentation and Measurement, vol.44, no.1, pp.19-27, Jan.1995.

[5] Fallahi, Arya, Sina Hashemizadeh, and Niels Kuster. "On the dielectric measurement of thin layers using open-ended coaxial probes." IEEE Transactions on Instrumentation and Measurement, vol.70, pp.1-8, 2021.

[6] Bakhtiari, Sasan, Stoyan I. Ganchev, and Reza Zoughi. "Analysis of radiation from an open-ended coaxial line into stratified dielectrics." IEEE Transactions on Microwave Theory and Techniques, vol. 42, no.7, pp.1261-1267, Jul.1994.

[7] Folgerø, Kjetil, et al. "Combined thickness and permittivity measurement of thin layers with open-ended coaxial probes." Sensors, vol.19, pp.1765, Aug. 2019.

[8] Hagl, Dina M., et al. "Sensing volume of open-ended coaxial probes for dielectric characterization of breast tissue at microwave frequencies." IEEE Transactions on Microwave Theory and Techniques, vol.51, no.4, pp. 1194-1206, Apr.2003.

[9] Meaney, Paul M., et al. "Open-ended coaxial dielectric probe effective penetration depth determination." IEEE transactions on microwave theory and techniques, vol.64, no.3, pp.915-923, Mar.2016.

[10] De Langhe, Pascal, Luc Martens, and Daniël De Zutter. "Design rules for an experimental setup using an open-ended coaxial probe based on theoretical modelling." IEEE transactions on instrumentation and measurement, vol.43, pp.810-817, Jun.1994.

[11] Porter, Emily, and Martin O'Halloran. "Investigation of histology region in dielectric measurements of heterogeneous tissues." IEEE Transactions on Antennas and Propagation, vol.65, pp.65541-5552, Oct.2017.

[12] Aydinalp, Cemanur, et al. "Characterization of open-ended coaxial probe sensing depth with respect to aperture size for dielectric property measurement of heterogeneous tissues." Sensors 22.3 (2022): 760.

[13] Farshkaran, Ali, and Emily Porter. "Coaxial Probe-based Measurements of Biological Tissues: Inaccuracies in Sensing Volume when Calculated from Sensing Radius and Sensing Depth." 2021 International Conference on Electromagnetics in Advanced Applications (ICEAA). IEEE, pp.110-113, 2021.

[14] Porter, Emily, et al. "Modeling of the dielectric properties of biological tissues within the histology region." IEEE Transactions on Dielectrics and Electrical Insulation, vol.24, no.5, pp.3290-3301, May.2017.

[15] Products-and-material measurement, Xinchen technologies, Accessed: February 14th. [Online]. February 28th http://www.xinchenkeji.cn/clcltj.

[16] Belhadj-Tahar, Nour-eddine, Olivier Meyer, and Arlette Fourrier-Lamer. "Broadband microwave characterization of bilayered materials using a coaxial discontinuity with applications for thin conductive films for microelectronics and material in air-tight cell." IEEE Transactions on Microwave Theory and Techniques, vol.45, no.2, pp.260-267, Feb.2013.

[17] Hagl, Dina M., et al. "Sensing volume of open-ended coaxial probes for dielectric characterization of breast tissue at microwave frequencies." IEEE Transactions on Microwave Theory and Techniques, vol.51, no.4, pp. 1194-1206, Apr.2003.

ISSN:3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.2.1.P357
[18] Otto, G. P., and W. C. Chew. "Improved calibration of a large open-ended coaxial probe for dielectric measurements." IEEE Transactions on Instrumentation and Measurement, vol.40, no.4, pp.742-746, Apr.1991.

[19] Berube, D., F. M. Ghannouchi, and P. Savard. "A comparative study of four open-ended coaxial probe models for permittivity measurements of lossy dielectric/biological materials at microwave frequencies." IEEE Transactions on microwave Theory and Techniques, vol.44, no.10, pp.1928-1934, Oct.1996.

[20] Meaney, Paul M., et al. "Open-ended coaxial dielectric probe effective penetration depth determination." IEEE transactions on microwave theory and techniques, vol.64, pp.915-923, Mar.2016.

[21] Baker-Jarvis, James R., et al. "Measuring the permittivity and permeability of lossy materials: Solids, liquids, metals, and negative-index materials." (2005).