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Shanghai University Doctoral Dissertation (2000)

A Study on Finite Flange Open-ended Coaxial Probe and Its Application to Electromagnetic Properties Characterization of Curved Surfaces High Loss Coating Materials

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Shanghai University Press

· Shanghai ·

上 海 大 学

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答辩委员会对论文的评语

该博士论文研究用开口同轴测量探头对曲面高损耗材料涂层进行非破坏性测量其电磁特性（ε、μ）的理论和相应测量技术。有耗材料涂层非破坏性测量问题是近年来微波工程中急待解决的关键问题，论文选题具有重要实用价值和理论意义。

论文采用了适应性很强的时域有限差分法(FDTD)对同轴开路探头和被测曲面材料进行建模，在此基础上分别研究了以下问题。

1. 探头法兰尺寸对测量平面样品的结果影响，并和无限大法兰假定下的分析法求解结果进行比较，以此检验通常无限大法兰假定的近似程度。

2. 不同曲率的凸面和凹面材料和法兰之间的空隙对测量结果的影响。发现凹面空隙的影响远大于凸面间隙的影响。这一规律对实际工作具有一定的指导意义。

3. 针对凹面材料测量，提出一种改进型开口同轴探头。理论分析和实际测量证实了该种探头结构比目前通用的探头具有更高的测量精度。

以上研究成果具有创新意义和实际应用价值，已引起国际学术同行的重视和肯定。由于学习时间限制，上述改进型探头还存在带宽窄等问题有待进一步深入研究。

论文概述清楚，层次分明，计算正确，结果合理。已达到博士学位论文水平，从论文可见，作者已具有较好的基础知识和专业知识。具有独立从事科学研究能力。

答辩中回答问题基本正确，经无记名投票一致同意通过该博士论文答辩，并建议授予工学博士学位

答辩委员会表决结果

经答辩委员会表决，一致通过该同学的论文答辩，并建议授予工学博士学位。

答辩委员会主席：李征帆

2000年10月10日

摘 要

鉴于开口同轴探头技术对材料电磁参数测量的广阔前景，始自 80 年代初期，人们对其开展了广泛的研究，但只限于测量平板和平面涂敷材料。对于用开口同轴线测量曲面介质材料如微波吸收涂料的技术，长时期来一直没有得到解决，这是因为在同轴探头法兰和测试材料之间存在着空气隙问题。由于实际应用中日益受到关注，所以，分析研究这些被测材料弯曲表面对测量结果的影响是非常必要的。

本文研究了用有限法兰开口同轴探头测量弯曲表面高损耗涂料(凹面和凸面)的电磁特性(包括复介电常数和磁导率)。由于时域有限差分法（FDTD）对处理复杂边界条件非常有用，本文首先应用 FDTD 对探头和被测材料进行建模，分析了探头法兰的直径对测量平面材料的精确度影响；一般来说，合适的法兰尺寸随被测材料的电磁参数，样品厚度和工作频率而变化；如果法兰尺寸满足$(D/2-b)\geqslant(1-1.5)\lambda_m$，则法兰可被认为无限大。

接着研究了用标准开口同轴探头测量曲面材料时空气间隙的影响。因此，利用标准同轴探头测量凹面材料即使大的表面曲率半径也是很不适合的，而对凹曲面材料利用标准同轴探头进行测量对精度没有很大影响（除非小的曲率半径）。第二方面的研究是提出一种改进型结构的开口同轴探头技术。它是基于在标准同轴探头的内导体末端加载一块环状贴片，连同内导体伸入至探头法兰和被测材料的空气隙中，本文详细分析和研

究了所加载的环状贴片尺寸的影响。由FDTD理论建模和实验结果表明，这种改进结构对提高反射系数测量精度有着重要的作用。运用该种改进探头，对数种不同曲率半径的涂敷材料进行了计算和测试，其结果与文献符合的很好。理论和初步实验证明该技术能适用于曲面材料电磁特性的测量，尤其是非破坏性的测量。

关键词 开口同轴探头，弯曲表面材料实验，复合介电常数，磁导率，空气间隙，FDTD

Abstract

The open-ended coaxial probe technique has been extensively studied due to its potential for materials characterization. Since the initial investigation in early 1980s, most of the research work done with respect to open-ended coaxial probe technique was, however, limited to measure complex permittivity of dielectric materials with planar surface. For testing materials with curved surfaces, using of open-ended coaxial probe remains to be uncovered after a long period of time debating in the reach society. The problem lies in the air gaps between the probe with its finite dimension of the flange and the material under test by which the flange size could lead much uncertainty to the measured data. Therefore, analysis the influences of these curvature surfaces on measurement accuracy and develop a new configuration of coaxial probe are necessary since the characterization of materials with curved surfaces such as microwave absorbing coatings on metallic structures gave received considerable interest in practice.

In this thesis, utilization and development of finite flange open-ended coaxial probe for electromagnetic properties (both complex permittivity and permeability) are studied. The finite-difference time-domain (FDTD) technique, that is very applicable to the boundary problem, is employed for modeling the probe loaded with the materials under test. The influence of probe flange diameter on measurement accuracy of materials with planar surface is first analyzed. The results have shown that a flange size varies, in general, with the EM-paramefers of the sample under test, sample thickness and the operating frequency.

We found that a flange dimension of (D/2-b) larger than (1-1.5) λ_m can be considered for the practical purpose to be an infinite.Then we focus on curved surface materialsmeasurement technique. The first step is related to an uncertainty analysis to specify the errors created due to the gaps between the standard open-ended coaxial probe and samples of concave surface is more serious on the measurement than that between the probe and samples of convex surface. Therefore, use of standard coaxial probe for concave surface materials measurement is highly not suitable even for large radii, while for convex surface materials there is no serious problem except for small radii.

The second aspect is related to a new configuration of open-ended coaxial probe proposed for concave surface materials testing. The inner conductor or the standard coaxial probe is extended throughout the air gap between the probe and surface of material under test. A ring patch is embedded at the terminal of the conductor in contact with the material under test. The performance of the modified coaxial probe is studied as a function of flange diameter, sample radii and patch dimensions. The FDTD modeling and experimental results indicate that a patch with appropriate dimensions plays an important rule on improving reflection coefficient measurement accuracy. The modified coaxial probe has been used to measure electromagnetic properties of several microwave-absorbing materials coated on concave surface prototype boxes of different radii. The deduced ε^* and μ^* values are relatively in good agreement with the published data. It has been demonstrated that the technique is suitable for nondestrutive testing of curved surfaces coating materials and other cases where it would be difficult to fit the material under test with standard coaxial probe.

Key Words Open-ended coaxial probe, curvature surfaces materials testing, complex permittivity, permeability, air gap, FDTD

CONTENTS

Chapter 1
Introduction

With the advances in the instrumentation and computer control and data processing, microwave measurement techniques for materials characterization have been widely developed, and considerable efforts are made both in theory and technology to further improve the measurement accuracy. Different measuring methods with different frequency range have been employed, depending upon the particular requirements, the experimental conditions and the nature of the material under test. The most significant advances have been made in nondestructive testing technique, because it allows the material to be measured in its raw form, in-situ and on-line applications. This chapter presents an overview of the development of microwave measurement techniques for materials characterization with emphasizing on open-ended coaxial probe technique since it has proven to be a powerful tool for nondestructive measurement of a wide range of materials.

1.1 Recent Trends of Microwave Dielectric Measurement Techniqnes

As well known, the dielectric data are required on a large variety of materials for many industrial, scientific, and medical applications of microwave. It has aroused considerable interests for many years in developing measurement techniques to characterize EM parameters of materials quickly, accurately, and conveniently[1-4]. Some major trends of microwave dielectric measurement can be summarized [5-7]:

• The test frequency range has been extended from MW to MMW and SMW;

• Materials under study include low-loss/ high-loss;

• Automation and wide band are desired; and

• The test samples are no longer restricted to a closed waveguide/ resonator and open-ended-coaxial probe technique receives extensive interest.

The last trend has its important significance. During the period of 1950s~1970s, the typical microwave measurement methods were cavity method and waveguide method[1,8]. In these methods, it is necessary to insert the sample into the cavity or hollow guide, and machine the sample so as to fit the waveguide or resonator cross section with negligible air gaps. This requirement limited the measurement frequency range, accuracy, and unfavors the applications of the technique in nondestructive and on-line testing. In early 1980s, with the advance in EM theory and computational electromagnetics, numerous new techniques of measurement such as free space method[9-13] and open-ended coaxial/waveguide method have been developed.

The use of open-ended coaxial probes for nondestructive measurement of materials has been widely studied because they offer a relatively small interrogation area and possess wide band characteristics. To sum up, the coaxial probe measurement technique has such advantages [5, 6]:

- Lessening some restrictions on sample preparation
- Operation in a broad range of frequencies.
- Suitable for nondestructive and in-vivo testing
- Suitable for dielectric measurement at high/low temperature
- Compatibility with frequency-domain and time-domain techniques, in addition to the more common single-frequency and sweep technique
- Simplifying testing equipment

This technique was initially proposed by S.S. Stuchly *et al.*[6] and used to measure the dielectric properties of biological tissues at radio and microwave frequencies. Soon afterwards, it was found applications in microwave engineering and microwave nondestructive applications for dielectric properties measurements. In most of these applications, the material under test is often considered to be infinite thick. However, Xu and co-workers and Ganchev [14,15] have shown that this assumption is not always hold true and open-ended coaxial probe has been extended for measurement of the dielectric materials of finite thickness or thin-sheet sample. This measurement technique has important applications in the industrial characterization of different materials. Wide frequency range of measurement is a remarkable feature of open-ended coaxial probe technique. However, at the initial stage of practical use of open-ended coaxial probe, the frequency of the measurement of both reflection and resonator methods were restricted to the frequency range below 4 GHz [16,17]. This is due to the influence of higher order mode excitation at the open end of the probe and radiation losses at higher frequencies. Xu *et al.*[18] have analyzed the influence of higher order modes excitation and radiation loss effects and gave a concise expression by which the probe has been used successfully up to 11 GHz. Misra *et al*[19] measured the complex permittivity of methanol up to 18 GHz using the model of Marcuvitz [20] which was approximated by series expansion. Soon afterwards, Wei *et al.*[21] developed a technique by which the test frequency was expanded up to 20 GHz.

One of the critical elements in dielectric properties measurements using an open-ended coaxial probe, is making a good contact between the probe and the material under test. In practice, still the problem of air gaps influence on measurement accuracy, in particular solid materials, constitute a major contribution to the total measurement errors due to lack of correction for probe lift-off. This problem becomes more serious when thin-sheet materials are involved. It has been shown that the surface roughness of the sample significantly influences measurement accuracy[22,23]. Therefore, at the initial stage, this technique was suitable only for measuring the permittivity of liquids or semi-liquid such as biological tissue. Baker-Jarvis *et al.*[24] have analyzed the influence of an air gap that may exist between planar surface sample and the probe on the reflection coefficient using an analytical approach. The results have shown that the air gaps on the order of fraction of a millimeter strongly influence the measurements.

We should mention that most of the research work done in the past with respect to open-ended coaxial probe was limited to measure the complex permittivity of dielectric materials. Because in above research works, $\mu=1$ is usually assumed, for some absorbing materials used in modern military system or in electromagnetic