A new technique using the multi-port annular slot antenna for the measurement of complex permittivity is developed. The benefit of this new technique is that a two port network can be used on a planar device. The forward case of measuring $S_{21}$ is combined with a simple but effective calibration technique to compensate for the feed network. The validity of the method is confirmed by using methanol and ethanol, which are commonly used reference materials, for comparison between expected and measured results.

Introduction

The measurement of dielectric constants has many applications especially in the emerging field of biological imaging [1] and cancer detection [2]. In order to be successful in these applications a well defined model of the electrical characteristics is required. It is with this in mind that we develop a new method of complex permittivity characterization using the annular slot antenna.

There are currently several methods by which the complex permittivity of a material can be accurately determined, each with its drawbacks and benefits [3]. A popular method for measuring permittivity is the waveguide method. The material is inserted into a waveguide section and the transmittance is measured through the material to find the dielectric constant [4]. However, this method can be problematic since the material must be excised from its source as well as having errors introduced by windows used to contain liquids. An alternate method that is well developed is the use of a coaxial cable [5]. In this method the open end of a semi-rigid coax is terminated by the material under study and can be performed without excision. The reflected signal is used to extract the
value of complex permittivity. The drawback of this method is that there is only one unknown variable that can be solved for, the reflection coefficient, and it is not suitable for solving permittivity and permeability simultaneously.

We have developed a new method based on the annular slot that has the benefits of both of the above methods. It can have two or more ports such that the transmitted signal as well as the reflected signal can be used in the determination of permittivity. The material does not need to be excised, since the device is planar, but is placed on top of it. Unlike other planar devices [6] the feed network for the ports are completely isolated from the material under examination.

Theory

The geometry for the device is shown in Fig. 1. It is a circular slot with a mean radius a=0.25 inches and a slot width of 2W=12mils. The feeds to the device are 50 ohm microstrip lines printed on the bottom. The material under study is located on top of the device and is assumed to be of infinite extent. The electromagnetic modeling follows that of Tong et. al. [7] and the notation is consistent. This formulation gives the impedance of a port as well as the mutual impedance between any two ports as the summation of azimuthal modes. The impedance is given as

$$Z_{jk} = \frac{2Z_0(2W)^2}{\pi} \sum_{m=-\infty}^{\infty} \frac{\exp[jm(\varphi_j - \varphi_k)]}{K_m}$$

where the azimuthal modes are given by the susceptance

$$K_m = \int_0^\infty \left[ \bar{Y}_{r}\left( g_{m+1}(\beta) + g_{m-1}(\beta) \right)^2 + \bar{Y}_{im}\left( g_{m+1}(\beta) - g_{m-1}(\beta) \right)^2 \right] \beta d\beta.$$  

There are singularities in the integrand of (2) which can be handled very easily by using analytical substitutions as outlined in [8]. Once the singularities are removed any standard numerical routine can be used for the integration. Most materials have some loss tangent that is frequency dependent. This is accommodated by allowing the permittivity to have complex values. The permittivity $\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$ is substituted directly into the formulation.

The circuit is fabricated on a Rogers Duroid 4350B substrate that has a dielectric constant of 3.48 and is 20mils thick. To account for this, the free space wavenumber $k_0$ is modified by substituting it with the effective propagation constant $k_{eff}$ found by performing an analysis on an infinite length slotline of the same dimensions [9]. Fig. 2 shows the effective dielectric constant from which

$$k_{eff} = \sqrt{\varepsilon_{eff} k_0}$$

The validity of this type of approximation is shown in [10].

Measurements

Methanol and ethanol were used as the study materials since they have well known characteristics. The Debye equation was used to determine the expected complex permittivity of the materials. Their expected Z-parameters were directly found from the above analysis, using 20 modes, and converted to S-parameters. The feed network is
calibrated by using a reference material to find a correction factor which is then applied to the unknown materials S-parameters [6].

\[
\zeta = \frac{S_{\text{simulated, ref}}}{S_{\text{measured, ref}}}
\]  

(4)

is found for the reference and then applied to

\[
S_{\text{material}} = \zeta S_{\text{measured}}
\]

(5)

to find the S-parameters with the correct phase and amplitude. This calibration scheme assumes that the errors are predominantly multiplicative in nature. This assumption appears reasonable since the feedline, excluding vias and transitions, is a 50ohm microstrip transmission line and the only correction that is required is an adjustment in the phase delay of the output. Ethanol was used as the reference material for this experiment. Fig. 3 shows the corrected value of \(S_{21}\) for methanol compared to its simulated value, and its phase.

Fig. 3  Comparison of the simulated and measured parameter \(S_{21}\) for methanol, for amplitude(top) and phase(bottom), using ethanol as the reference material.

The difference in S-parameters between the simulated and measured data is within several percent in both the phase and the amplitude for the bandwidth shown. It is very accurate for the lower frequencies but it begins to deviate from the predicted value at the higher frequencies. In this frequency range the size of the device is less than a half
wavelength so there will be no phase ambiguities in the determination of the dielectric constant from the S-parameters. Additionally, the device is a poor radiator at these frequencies so it was not necessary to use time domain gating to deal with reflections of a propagating signal from the upper surface of the material under study. This device can be viewed as two parallel slotted transmission lines. However, the slotline is not a TEM type of transmission line and it will begin to radiate when the wavelength gets short relative to its total length. For higher frequencies it will be necessary to take into account the shape of the material, the finite nature of the ground plane, as well as the discontinuities in the feed line.

Conclusion

A new method for measuring complex permittivity based on the annular slot has been presented. It has the benefits of a two port measuring device, without the need to excise material from its source, which is accomplished by isolating the feed network. The device has been successfully verified in the 1-5GHz range and will be useful in the characterization of biological materials. It will be further investigated for optimization by adding circuit elements at discrete locations on the slot.

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References: