NON DESTRUCTIVE RESONANT TECHNIQUE FOR THE MEASUREMENT OF COMPLEX PERMITTIVITY

- THEORETICAL ANALYSIS AND EXPERIMENTAL RESULTS -

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Abstact

A simple non-destructive method to measure the complex permittivity of materials is described. It uses an iris terminated resonant section of waveguide in contact with the metal-backed sample. A numerical analysis of the structure permits one to relate the measured resonance characteristics to the sample permittivity

Introduction

The increasing use of microwaves for industrial testing procedures has recently generated a strong need for accurate non-destructive techniques for the measurement of permittivity at microwave frequencies. Material properties such as moisture content and local inhomogeneities are often important factors which can be evaluated and controlled quite efficiently with microwaves. Most classical methods to measure dielectric material properties require cutting and machining of samples to close tolerances[1]. Besides the cost and delays necessary for such operations, these techniques are quite unsuited for on line control of industrial processes.

Other methods were more recently developed for this purpose. They rely basically on the external perturbation of the resonant characteristics of a cavity by placing the material to be tested near a coupling aperture[2]. However such techniques were used so far to provide comparative measurement information on the permittivity based on measurement of known reference samples.

The purpose of this paper is to present a technique where the measured quantities can be directly related to the unknown permittivity, using an accurate theoretical analysis of the electromagnetic field distribution in the measurement structure.

Principle of the method

The basic experimental setup is described in Fig. 1: a resonant rectangular waveguide section is terminated by a large thin metallic flange containing a rectangular opening symmetrically located with respect to the waveguide axes. This flange is placed in firm contact to the slab of material to be tested, which is in turn backed by a flat metal plate. One measures the resonant frequency and Q-factor of the resulting waveguide cavity.

The usefulness of this principle of measurement is evidenced by the strong dependence of the resonant cavity parameters upon the permittivity, which appears in Figs. 5 and 6.

In order to predict theoretically these resonance parameters and, consequently, to find a direct relationship between them and the slab permittivity, a theoretical analysis of the fields in the cavity must be carried out. It is therefore necessary to determine the equivalent admittance presented by the aperture at the waveguide end, which illuminates the metal-backed dielectric sheet.

Theoretical analysis

Let us consider the structure of Fig. 1, where the rectangular waveguide is assumed to propagate only the dominant TE_{10} mode. The theoretical approach presented here for the calculation of the equivalent admittance of the open-ended waveguide is similar to the one used in [3] and [4]., where the waveguide was simply cut at its end without any iris.

In the waveguide, the magnetic hertzian potential can be written

$$\Pi_{m1}=\frac{1}{k_1}\left(e^{-k_1 z}-\rho e^{+k_1 z}\right)\sin\frac{\pi x}{a}+\sum_{i=2}^{\infty}\alpha_i \sin\frac{m_i\pi x}{a}\cos\frac{n_i\pi y}{b}e^{k_i z} \qquad (1)$$

where $k_i^2=(m_i\pi/a)^2+(n_i\pi/a)^2$ and $k=\omega\sqrt{\varepsilon\mu}$. m_i and n_i are the mode indices ($m_1=1$, $n_1=0$), a and b the dimensions of the waveguide cross section and ρ the reflection coefficient of the dominant mode. In the dielectric slab, we have

$$\Pi_{m2}(x,y)=\frac{1}{2\pi}\int_S f(x',y')\, G\, dx'\, dy' \qquad (2)$$

where the integration is taken over the flange aperture (a',b'). The unknown function f is found to be the transverse electric field in the aperture plane. G is the Green's function valid for the dielectric slab and can be written

$$G=\frac{e^{-jk_r r_0}}{r_0}+\sum_{n=1}^{\infty}\frac{e^{-jk_r r_n}}{r_n} \qquad (3)$$

with $r_n^2=(x-x')^2+(y-y')^2+(2nh)^2$ and $k_r=k\sqrt{\varepsilon_r}$. By applying the continuity condition of the electric and magnetic fields at the reference plane z=0, we find the expression for the aperture admittance

$$Y=\alpha\frac{1}{D^2}\int_S\int_S f(x,y)\, f(x',y')\, H\, dx\, dy\, dx'\, dy' \qquad (4)$$

with $\alpha = jab/2k_1$ and $D = \int_S f(x,y) \sin \frac{\pi x}{a} dx\, dy$.

S is the flange aperture (a',b')and H a dyadic function depending on the Green's function and the chosen waveguide modes.

This expression is variational with respect to the unknown function f[3]. A Rayleigh-Ritz type of approximation can be used. The unknown function is therefore expanded as a series of trial functions corresponding to the modes existing in a waveguide of a',b' cross section:

$$f(x,y) = \sum_{i=1}^{N} A_i \sin \frac{m_i \pi x}{a'} \cos \frac{n_i \pi y}{b'} \qquad (5)$$

The problem reduces then to a matrix equation with the coefficients A_i as unknowns. Solving this equation and replacing (5) into (4), the admittance and the coefficient of reflection for the open ended waveguide is found.

Knowing this coefficient, the characteristics of the resonant cavity can be computed. Actually the cavity may be represented by Fig. , where Y is the open-ended admittance, Y_c the characteristic admittance of the rectangular waveguide for the dominant TE_{01} mode and Y_{iris} the equivalent admittance of the coupling iris. The admittance of the whole cavity is Y_{in}. One has

$$Y_c = \frac{1}{\omega\mu} \sqrt{(\omega/c)^2 - (\pi/a)^2} \qquad (6)$$

and Y_{iris} is given by Marcuvitz[6] for an iris with a symmetric circular aperture. The resonant characteristics are obtained from the basic condition

$$\mathrm{Im}(Y_{in}) = 0 \qquad (7)$$

at resonance $\omega = \omega_r$. The Q factor is then computed from the two half power frequencies f_1 and f_2 :

$$1/Q_L = (f_1 - f_2)/f_r \qquad (8)$$

Experimental verification

As a test for the validity of the method described here experiments were performed. First, for the simple case of an iris terminated waveguide radiating into free space, the reflection parameters (VSWR and phase shift ϕ with respect to short circuit placed on the flange) are presented in Fig.3. Then in Fig.4, the same parameters are given for a practical case (h=0.95 cm, Perspex : $\varepsilon_r = 2.56$, $\tan\delta = 0.0008$). In both cases, the agreement is quite satisfactory.

Based on the above theoretical considerations, calculations were also performed to determine the resonance characteristics of an iris terminated waveguide structure loaded with Perspex slabs of different thicknesses. The results are compared with experimental data (Fig.5). The correspondance between theory and experiments is satisfactory in view of the fact that in the analysis the waveguide and the coupling structures are assumed to be lossless. Experimental results for a resonator loaded with metal backed highly lossy dielectric slabs are presented in Fig. 6.

Actual calculations of an unknown permittivity using the measured resonance characteristics can be made, for instance, by means of computer generated charts.

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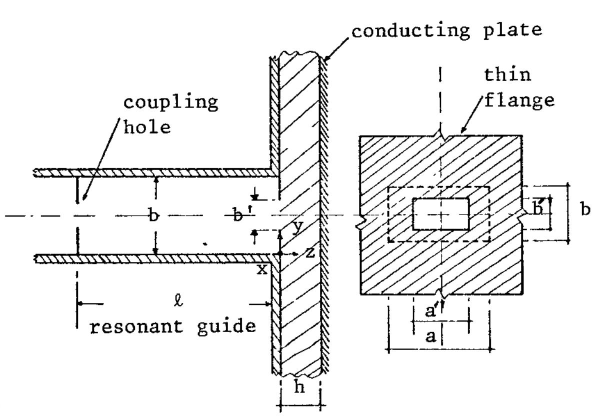

Fig. 1 Basic measurement structure.

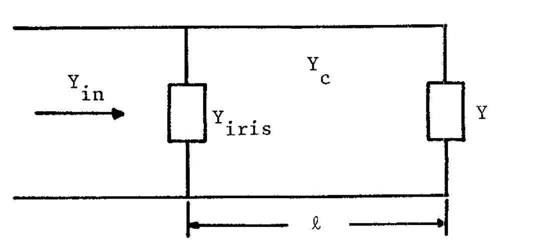

Fig. 2 Equivalent circuit of the waveguide cavity.

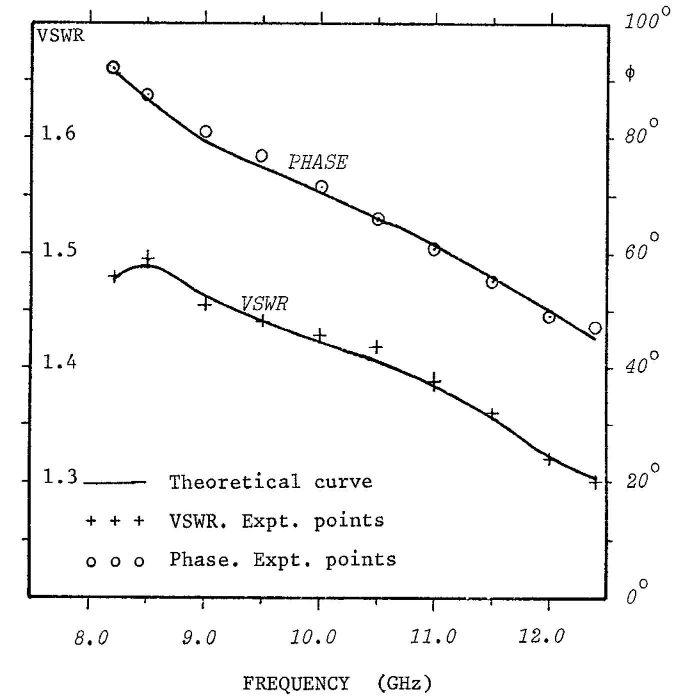

Fig. 3

Reflection characteristics of a rectangular iris radiating into free space.
(Iris: $a' = 17.90$ mm , $b' = 10.16$ mm)

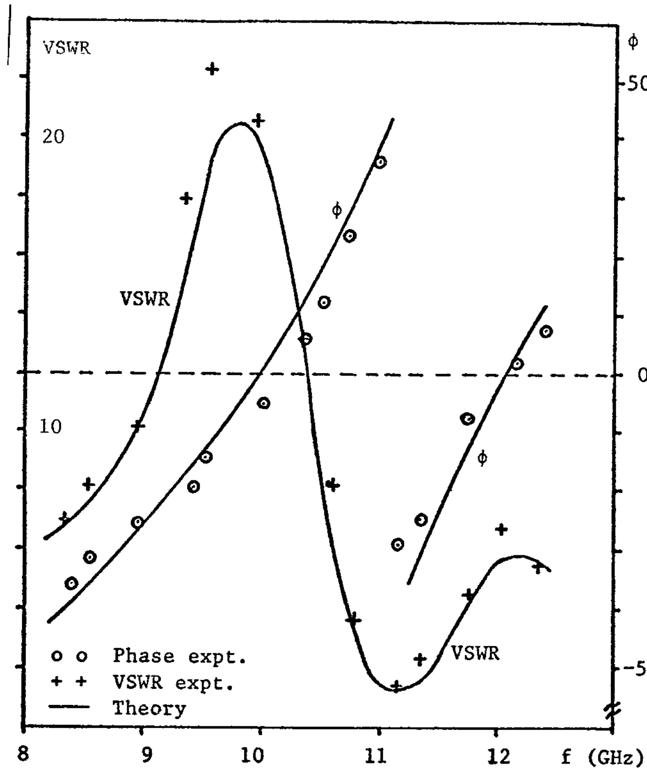

Fig.4

Reflection characteristics of a rectangular iris loaded with a lossless dielectric slab.
(Perspex: $\varepsilon_r = 2.56$, $\tan\delta = 0.0008$
Iris: $a' = 17.90$ mm , $b' = 10.16$ mm)

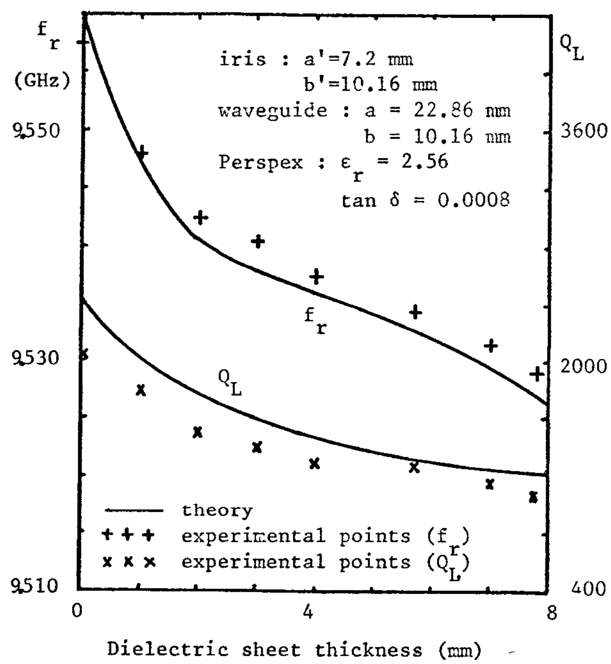

Fig. 5 Resonant parameters of the cavity loaded with Perspex sheets.

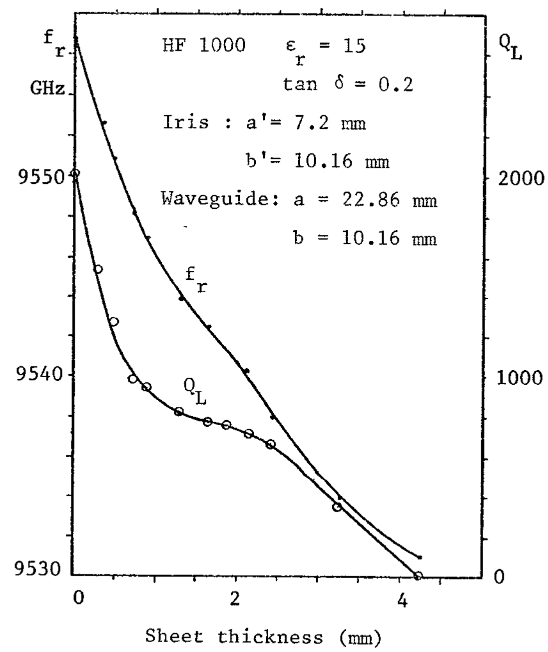

Fig. 6 Measured resonant parameters of loaded cavity with lossy dielectric sheets (HF 1000).