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Design of a Grooved Circular Cavity for Dielectric Substrate Measurements in Millimeter Wave Region

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SUMMARY A grooved circular cavity is designed for the millimeter wave measurements of dielectric substrates. The grooves are introduced to separate the degenerate TE_{01p} and TM_{11p} modes in circular cavities. A rigorous mode-matching method is used to investigate the influence of grooves on both the TE_{01p} and TM_{11p} modes. The dimensions of the grooves are determined from the numerical results. Comparative experiments of circular cavities with and without grooves validate the design method.

key words: *dielectric substrate measurement, cut-off circular waveguide method, millimeter wave*

1. Introduction

Rapid progress of microwave and millimeter wave circuits requests cheap and low-loss dielectric materials. We have proposed the cavity resonator method [1], [2] and the cut-off circular waveguide method [3], [4] to measure the complex permittivities of low-loss dielectric substrates. In these methods, it is needed to separate the degenerate TM_{11p} mode from the TE_{01p} mode, because the dimensions and relative conductivity σ_r of the circular cavity can be measured from the TE_{01p} modes. Here $\sigma_r = \sigma/\sigma_0$ is the effective relative conductivity including influence of oxidation and roughness of the copper surface, σ is the conductivity, $\sigma_0 = 58 \times 10^6$ S/m is the conductivity of the standard copper. Moreover, the degenerate TM_{11p} mode affects these measurements, especially relative conductivity measurement.

The study of the degenerate TE and TM modes has been presented in [5], [6]. However, these studies were not performed by the rigorous analysis.

In this paper, a grooved circular cavity is designed for the millimeter wave measurements of dielectric substrates. The grooves at the both ends in a circular cavity are introduced to separate the degenerate TE_{01p} and TM_{11p} modes. The TE_{01} mode is cut off in a radial waveguide constituted by the grooves; hence the resonant frequency of the TE_{01p} mode is affected little by the grooves. On the other hand, the TM_{11p} mode propagates forth and back in the grooves; hence the resonant frequency of the TM_{11p} mode is affected significantly. A rigorous mode-matching method is used to investigate the influence of grooves on both the TE_{01p} and TM_{11p} modes. The dimensions of the grooves are determined from the results calculated numerically. The measured results validate the design method.

2. Analysis

A cross sectional view of a circular cavity with diameter D and height H is shown in Fig. 1. The circular cavity is cut into two parts in the middle of the height for clamping a dielectric plate sample. At both upper and lower ends of the cavity, grooves with depth d_g and width w are cut at both ends of the cylinder for separating the degenerate TE_{01p} and TM_{11p} modes. The cavity with these grooves can be viewed as coaxially cascaded circular waveguides with different diameters [7], [8]. Then electromagnetic (EM) fields in each of these circular waveguides are expressed by series of incident and reflected normal modes of the respective circular waveguide. At the step-junction between two neighboring circular waveguides with different diameters, the EM boundary conditions are applied. As a result, the generalized scattering matrix of the incident and reflected normal modes including higher order modes is obtained at the step-junction. By combining the generalized scattering matrices at each of the step-junctions, and using the EM boundary conditions at the top and bottom of the cavity, we get finally the eigenvalue ma-

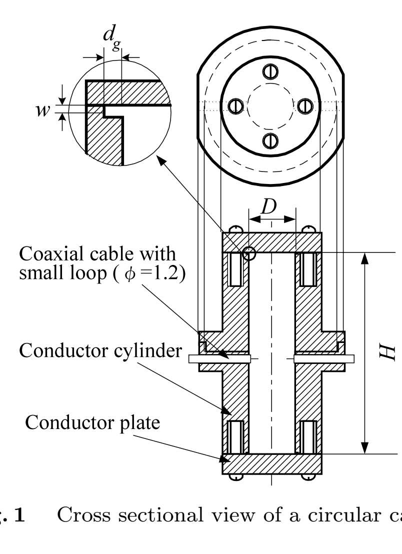

Fig. 1 Cross sectional view of a circular cavity.

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trix equation for calculating the resonant frequencies and field distributions of different resonant modes.

In addition, the unloaded Q_u of the TE_{01p} modes can be calculated from a simple equation for a circular cavity without grooves, because the grooves constructed the radial waveguide do not almost affect to the fields distributions of the TE_{01p} modes.

3. Design of the Cavity

3.1 Determination of the Diameter and Height of the Circular Cavity without Grooves

For the circular cavity as shown in Fig. 1, but without grooves, the resonant frequencies f_0 are calculated by

$$\left(\frac{f_0 D}{c}\right)^2 = \frac{1}{4}\left(\frac{pD}{H}\right)^2 + \left(\frac{j_{nm}^{(\prime)}}{\pi}\right)^2 \tag{1}$$

where c is the velocity of light, and j_{nm} and j'_{nm} are the m-th root of the n-th Bessel function of the first kind and its differential, respectively. Also, j'_{nm} is for the TE_{nmp} modes and j_{nm} for the TM_{nmp} modes.

At first, the ratio D/H were chosen as 0.294 from Fig. 2, so that unwanted modes do not appear near the degenerate TE_{01p} and TM_{11p} modes. Then the value of D is chosen as 7.0 mm so that the resonant frequency of the TE_{011} mode becomes approximately 50 GHz. Thus, the value of H is determined to be 23.8 mm.

3.2 Control of the Degenerate TM_{11p} Modes

We need to suppress the degenerate TM_{11p} mode and to separate from the TE_{01p} mode, because the dimension and relative conductivity of a circular cavity are measured by using the TE_{01p} mode. This is realized by the position of the excitation, the plane of small loop of coaxial cable and the grooves machined at both ends of the cylinder as shown in Fig. 1.

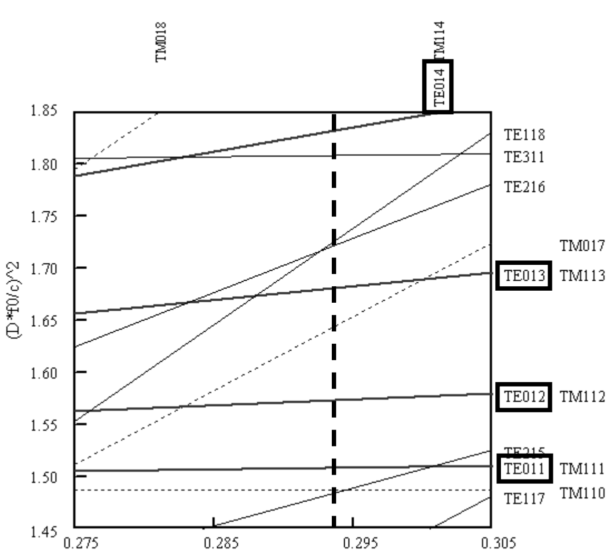


Fig. 2 The mode chart for a circular cavity.

3.2.1 The Position of Excitation

The position of the excitation is investigated to suppress the degenerate TM_{11p} modes in consideration the electromagnetic field distributions of the circular empty cavity. The electromagnetic fields of the TE_{01p} and TM_{11p} modes are shown in Fig. 3.

At first, we consider the case of exciting the H_r-components at $z = \pm H/2$ and $r = D/4$ by a pair of coaxial cables with small loops at their top ends. In this case, the both modes are excited and the degenerate TM_{11p} modes cannot be suppressed, because the both modes have the H_r-components at the conductor plates of the both cylinder ends.

Secondly, we consider the case of exciting the H_z-components at $z = 0$ and $r = \pm D/2$. In this case, the degenerate TM_{11p} modes are not excited because this mode doesn't have the H_z-component at the middle of the cylinder wall. However, the TE_{01p} modes are not also excited by the same reason where mode number p is even. We determine the position of the excitation at $z = -0.5$ mm to excite all TE_{01p} modes.

3.2.2 Determination of Groove Size

The degenerate TM_{11p} modes are suppressed if the each plane of the small loop of the coaxial cables is vertical to z-axis perfectly. However, it is difficult to realize this condition, practically. The grooves are introduced to separate the degenerate TE_{01p} and TM_{11p} modes in circular cavities. The field distributions of the TE_{011} and TM_{111} modes of the grooved circular cavity are shown in Fig. 4. To compare the filed distributions of these

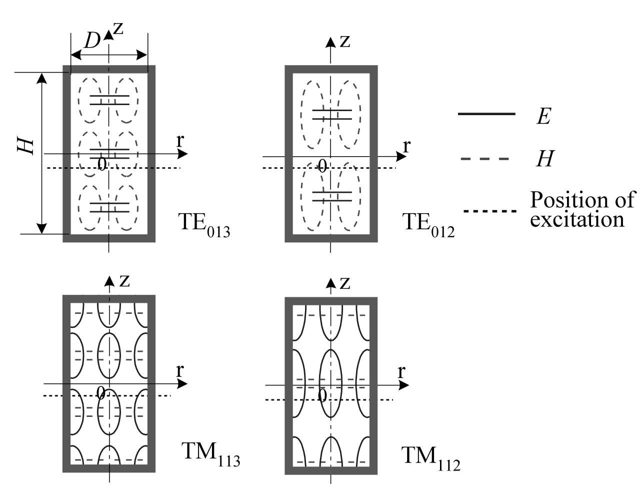


Fig. 3 The field distributions of the TE_{01p} and TM_{11p} modes of the circular cavity.

modes at $z = \pm H/2$, the TE_{011} mode does not have the electric fields. However, the TM_{111} mode has the E_z-component. Therefore, the degenerate TM_{11p} modes are separated from the TE_{01p} modes by the grooves machined at both ends.

The resonant frequencies of the TE and TM modes are calculated by a computer program developed based on the mode-matching method described in Sect. 2.

At first, we check the convergence of the solution with number of expansion modes N. When D=7.0 mm, H= 23.8 mm, d_g=0.2 mm and w=0.2 mm, the calculated resonant frequencies for the TE_{011} and TM_{111} modes are shown in Fig. 5. It is seen that the solution converges to the sixth effective figure when $N = 25$.

Secondly, the f_0 values for the TE_{01p} and TM_{11p} modes were calculated as functions of d_g and w. The calculated results are shown in Fig. 6, where the values of f_0 changed by grooves are normalized by the values of f_n without grooves, and d_g and w are normalized by D and H, respectively. As the d_g and w values are increased, the f_0 value of the TM_{11p} mode is decreased

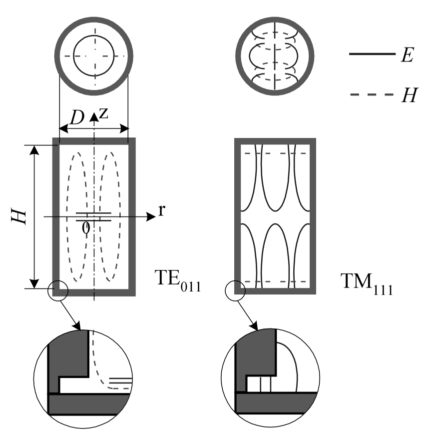
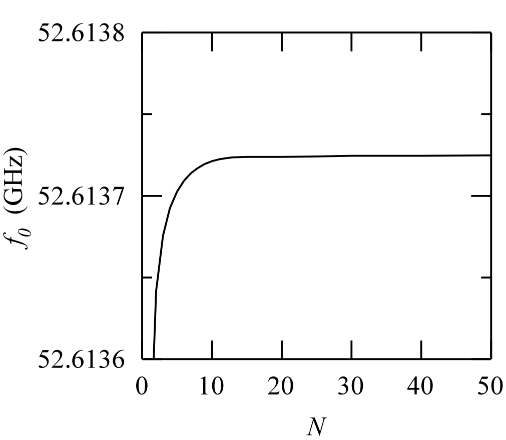
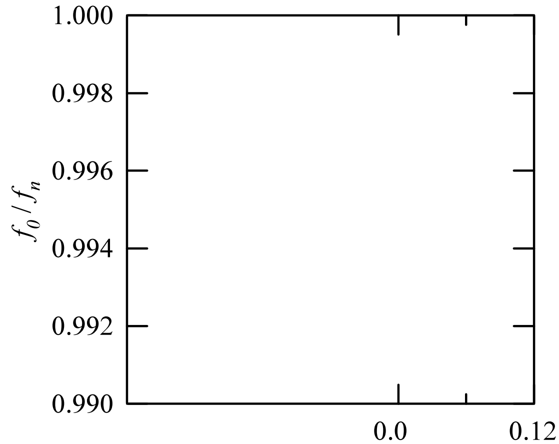
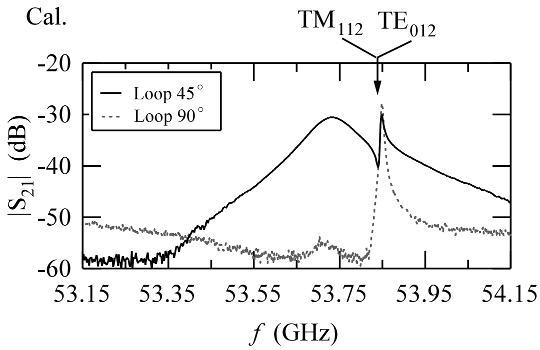


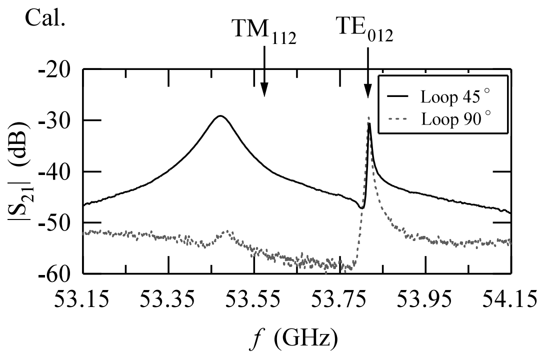
Fig. 4 The field distributions of the TE_{011} and TM_{111} modes of circular cavity with grooves.




1.000
0.998
0.996
0.994
0.992
0.990
f_0 / f_n
0.0
0.12



(a) Cavity without grooves



(b) Cavity with grooves of $d_g = 0.6\,\mathrm{mm}$, $w = 0.15\,\mathrm{mm}$

Fig. 8 Frequency response measured for the TE_{012} and TM_{112} modes of the circular cavity and the resonant frequencies calculated by mode-matching method.

Table 1 Comparison between calculated and measured f_0 values for the TM_{112} mode.

Cavity Type & Dimension (mm)	Calculated f_0 (GHz)	Measured f_0 (GHz)	Error (%)
No groove	.847	3. 33	2

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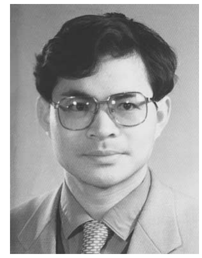

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