Measurements of Dielectric Properties near 100GHz Using a Reflection-Type Hemispherical Open Resonator

Hao Li*, Q.S.Zhang, Ying liu, Liusha Yang
University of Electronic and Science Technology of China, Chengdu, Sichuan610054, China
*Contact: lihao_uestc@126.com, phone +15908175447

Abstract—**As low loss dielectric materials play an important role in application for microwave devices. To obtain their dielectric properties, Based on both theoretical analysis and numerical simulation by a 3-D finite element electromagnetic code, HFSS, two reflection-type hemispherical open resonators are designed to excite TEM0030 mode at 94.7GHz and TEM0055 mode at 100.5GHz.In contrast with two ports measurements, the system with only one coupling hole was directly connected to a W-band vector network analyser (VNA) provide a simple method. Calculating through the VNA measured port reflection coefficient (S11) resonant curve can get dielectric properties. The automated measurement system has addressed several key technologies of how to determine precision value of cavity length and how to choose correct solution from a lot of solutions. The certified measurement system after a series of checking is used to measure sapphire. Lots of measurement results show that the standard deviation of measurement error is less than 0.154% in permittivity and 20.42% in loss tangent. Meanwhile, some experimental summaries on the open resonator technique are provided. Software that controls the measurement system is developed and it improves the testing efficiency greatly.**

INTRODUCTION

Low loss dielectric materials are the key of millimeter-wave vacuum electronic devices (VEDs) components like input-output window, helix support rods, cavity loss-buttons, Therefor, precisely measurements of dielectric materials become important especially in high frequency-band. Lots of measurement techniques have been developed such as the closed cavity method [1], the open resonator technique [2], the free space method [3] and so on. Owing to great advantages of high Q value, good single mode performance and high measurement accuracy, the open resonator technique has been proved to be the most powerful tool in measuring loss tangent and dielectric permittivity of low loss dielectric material in millimeter wave, submillimeter wave and THz wave regime.

Generally, the open resonators can be divided into two types. One of them is the confocal type which often is built with two symmetric concave mirrors and two ports. The other one is the hemispherical type, which is composed of a concave mirror, a plane mirror and one port. Due to the traits of two ports, dielectric properties are measured through simulation of the transmission coefficient (S21).Unfortunately, the coefficient always would be too small to precisely obtain because of its high sensitive to input signal even with the change in noise level would make the coefficient great changes. In addition, vector network analyzer (VNA), scalar network analyzer, spectrum analyzer, and power meter are used to construct the measurement system. The complexity of confocal open resonator system brings lots of system errors .Thus, Compared to the complex system [4]-[6], we choose the simple one- hemispherical open resonator system which just consists of a reflection-type hemispherical open resonator ,a VNA and the sample. To a large extent decreasing of the numbers of measurement instruments will reduce influence of system errors.

In this paper, the design method of reflection-type open resonator is presented. And the measurement system is constructed well. The measurement system is introduced in the next sections briefly. In section II a design methodology of the measurement system is described. In section III, construction of the system, measurement procedure and results are discussed .In section IV, the work is concluded for this paper.

DESIGN OF REFLECTION-TYPE HEMISPHERE RESONATOR

A reflection-type hemispherical open resonator, as shown in Fig.1,which consists of a hemispherical concave mirror, a plane mirror and a coupling aperture. Through connecting coupling aperture with a standard rectangular waveguide, the electromagnetic energy of TE_{01} mode in the input waveguide is coupled to the coupling hole to excite operation modes (Gauss beam modes $TEM_{p,l,q}$).Since the fundamental modes ($TEM_{0,0,q}$) have smaller Gauss beam radius, smaller Gauss beam divergence and more energy distribution than high-order modes, $TEM_{0,0,q}$ is used for our measurement system. The coupling aperture is placed exactly the center of the concave mirror so that $TEM_{p,l,q}$ are easily obtained.

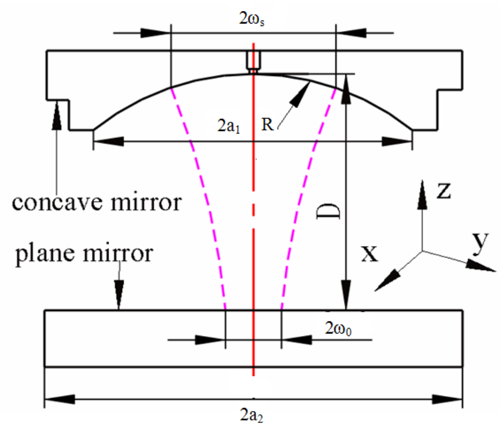


Fig 1 Schematic of open refleciton-type resonantor

A. Design theory

The scalar theories of openresonator are well established in many literatures such as [7-8].As the fundamental modes, the $TEM_{0,0,q}$ resonant modes are excited in the open resonator and the resonator frequencies of the empty resonator are obtained from

$$f_0 = c/(2D)\left[q+1+\frac{1}{\pi}\arctan\sqrt{D/(R-D)}-\frac{1}{\pi}\arctan(\frac{1}{kR})\right]^{-1} \quad (1)$$

Where R is the curvature radius of the spherical mirror, D is the cavity length, q represents the axial modal orders corresponding with $TEM_{0,0,q}$ mode , c is the velocity of the light and k is the free space wavenumber. The Gauss beam radius is expressed by

$$w(z) = w_0\sqrt{(1+(2z/kw^2{}_0)^2)} \quad (2)$$

$$w_0 = \sqrt{\lambda\sqrt{D(R-D)}/\pi} \quad (3)$$

Where λ is the wavelength. w_0 is the Gauss beam radius at the plane mirror It should be noted that , in order to enhance accuracy of the measurement results , w_0 is much less than the sample radius. The unloaded quality is given by

$$Q_0 = 1/[1/(\frac{D}{2\delta_c}\frac{1}{(1-1/(k\sqrt{D(2R-D)}))})+ 1/(\frac{2\pi D}{\lambda\alpha_d}\frac{1}{(1-(2p+l+1)/(k\sqrt{D(2R-D)}))})] \quad (4)$$

where δ_c means the penetration depth of the silver surface, k represents wave number of free space. Diffraction loss is expressed by $\alpha_d = \exp(-2D_s/w_d{}^2)$ and D_s is the diameter of the spherical mirror, w_d is the Gauss beam radius at the concave mirror.

When a sample is placed on the plane mirror, the resonator frequency will shift to lower frequency fsdue to the dielectric permittivity and the bandwidths will become boarder due to the dielectric loss tangent. The permittivity is obtained through the following equations [9-12]

$$\frac{1}{n}\tan(nkt-\phi_t) = -\tan(kd-\phi_d) \quad (5)$$

Where $\phi_t = \arctan\left(\frac{t}{nz_0}\right)-\arctan\left(\frac{t}{nkR_1(t)}\right)$,

$\phi_d = \arctan\left(\frac{d'}{z_0}\right)-\arctan\left(\frac{1}{kR}\right)-\arctan\left(\frac{t}{nz_0}\right)-\arctan\left(\frac{t}{kR_2(t)}\right)$

$R_1(t) = t+\frac{n^2 z_0{}^2}{t}$, $R_2(t) = \frac{R_1(t)}{n}$, $k = \frac{2\pi f_s}{c}$, $z_0 = \sqrt{d'(R-d')}$,

$d' = d+\frac{t}{n}$, $d = D-t$, t is the thickness of the sample, and $n = \sqrt{\varepsilon'}$ is the refraction index of the sample. In addition, the loss tangent can be expressed by

$$\tan\delta = \frac{1}{Q_s}\frac{2nk(t\Delta+d)}{2nkt\Delta-\Delta[\sin 2(nkt-\phi_d)]} \quad (6)$$

In which

$$\frac{1}{Q_s} = \frac{1}{Q_{LS}}-\frac{1}{Q_{00}}\frac{D(\Delta+1)}{2(d+t\Delta)} \text{ and}$$

$$\Delta = \frac{n^2}{n^2\cos^2(nkt-\phi_t)+\sin^2(nkt-\phi_t)}$$

Q_{LS} denotes the loaded quality factor of the resonator containing the sample, and Q_{00} means the Qfactor of the empty resonator.

B. Goal of the design

Based on the theories presented above, a reflection-type hemisphere open resonator is designed. In order to maintain the repeatability, accuracy, reliability and stability of our measurement system, a few factors are took into consideration. First, Gauss beam radius should be as small as possible to improve the resolution; Secondly, loss must be low and Q_{00}should be as large as possible; thirdly,electromagnetic field in the resonator should be as pure as possible and the whole system could be easy to installation and debugging. In our system, a design goal is made: 85GHz$<f_s<$105GHz,$Q_0>9\times10^4$,$\omega_0<$4.5mm.

C. Design procedure

A Matlab optimized code has been written to search the basic parameters according to equation (1)-(4).Based on the code, several groups values of *R, D, q* are obtained ,which satisfy the design goal above. Some other factors should be obeyed during design process: First, the mode-spacing (*MI*) between operation mode and parasitic mode should be as large as possible. Second, Spherical surface should fit the Gauss beam phase front should be as well as possible. To decrease the loss of fundamental mode, the diameter of mirror should be as large as possible. However, decreasing the mirror can suppress the loss of parasitic mode. Thus, tradeoff should be made to decide the diameter of the sphericalmirror ($2a_1$) and the one of the plane mirror ($2a_2$). After considering these factors, table1 gives optimized parameters of measurement system. Fig.2 gives the theoretical electrical field distribution of the working mode and parasitic mode. As we can see from the figure, the fundamental mode has a smaller waist radius and more centralized field distribution. From eq(4),three kinds of quality coefficient are showed in table2.Q_d, Q_r, $Q_o$respectively, correspond to the diffraction loss L_d , mirror surface resistance loss L_r ,and the total loss of the resonator

L_t.Fig.3 is showed that the designed spherical curve has a good agreement with the operation mode.

Table 1 Structure parameters and electrical parameters for hemispherical resonator

R(mm)	D(mm)	a_1(mm)	a_2 (mm)	q	$f_{0\_Th.}$ (GHz)	$Q_{0\_Th.}$ (10^5)	w_0(mm)	*MI* *(MHz)*
55	49.8	70	90	30	94.5	11.9	4.03	610
90	84.4	70	90	55	101.1	20.3	4.20	559

Table 2 Three kin*ds* of quality coefficient

Mode(q)	50	51	52	53	54	55
f[GHz]	91.307	93.012	94.858	96.634	98.409	10.019
$Q_d\times10^4$	2.23	2.51	2.81	3.14	3.52	3.95
$Q_r\times10^5$	9.86	8.89	8.04	7.29	6.62	6.03
$Q_0\times10^5$	2.00	2.02	2.04	2.05	2.07	2.09

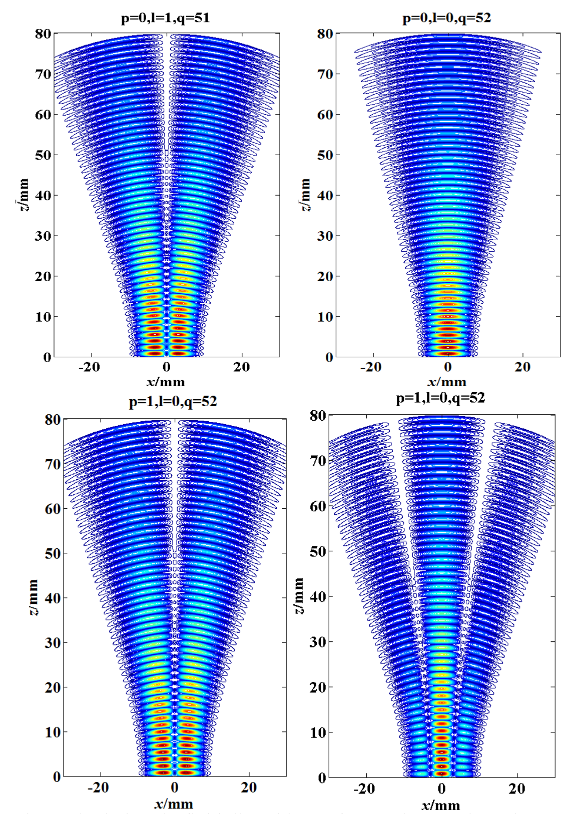
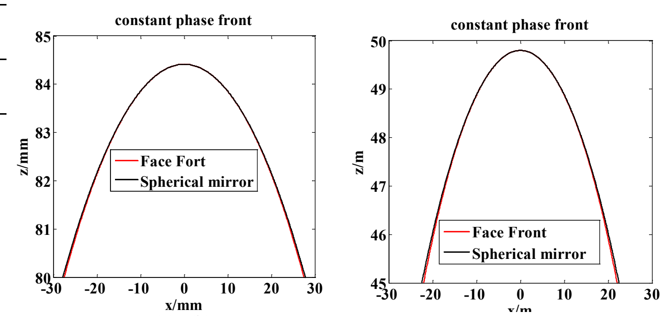


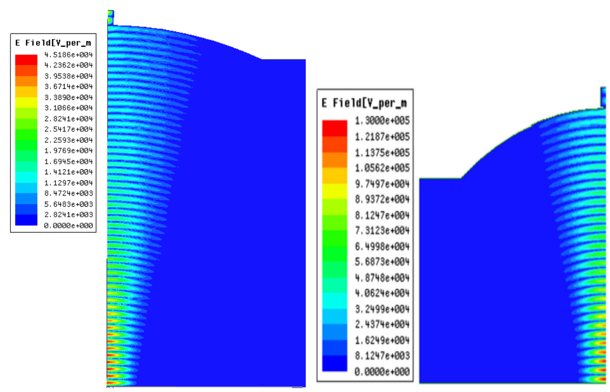
Fig 2 Theoretical electric field distrubiton of operation mode and parasitic modes

Few of references have mentioned about the influence of the coupling hole in open resonator system. Just in [13,14], the whole open resonator system with the hole can be analyzed using the equivalent circuit. In this paper, with the usage of 3-D analysis tool ANSYS HFSS, the coupling aperture diameter(Φc) and depth (dc) are analyzed. The simulated electronic field distribution is shown in fig.4. The number of axial field peaks is 31 for TEM_{0030} and 56 for TEM_{0055}, which agree well with theoretical analysis.Compare theoretical analysis about simulation analysis, there is a relativity large difference in upload quality Q_0, Mainly because of the neglect of coupling loss in the theoretical method .Fig.5denotes the reflectioncoefficient$S_{11.}$ According to the simulated performance parameters and considering the actual fabrication level and cost, trade-off is made to decide the final dimensions of the coupling hole: h_c=0.2mm; Φ_c=0.9mm.



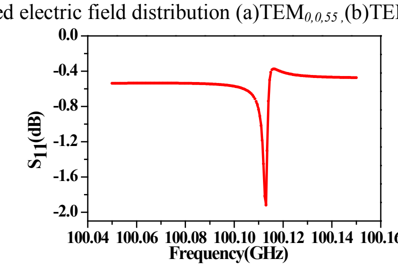
(a) (b)

Fig 3 Face front of the operation mode(a)$TEM_{0,0,55}$,spherical mirror radius(R)84.414mm (b)$TEM_{0,0,30}$,spherical mirror radius$R$=55mm.

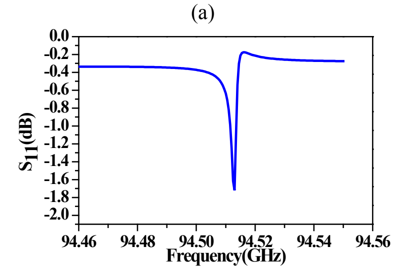


(a) (b)

Fig 4 Simulated electric field distribution (a)$TEM_{0,0,55}$,(b)$TEM_{0,0,30.}$



(a)



(b)

Fig 5 Resonant curve of HFSS simulation (a)$TEM_{0,0,55}$,(b)$TEM_{0,0,30.}$

D. System construction and measurement

In several references, lots of materials such as copper, bronze, and aluminum, are used as body mirrors in measurement system. In this work, body mirrors are both made of K9 optical glass coated silver film. Compared to metal mirrors, it is more convenient to decrease surface roughness to avoid the Gaussian Beam scattering out of the resonator. In addition, curvature radius of the spherical mirror can be better processed.

Several steps have been made to obtain the final mirror.

Step 1 ： The rectangle waveguide hole and coupling aperture are punched using ultrasonic wave punching machine at the center of mirrors. A kind of locating device is used to keep the center of rectangle hole, coupling aperture and spherical mirror be coaxial.

Step 2： Mirrors are polished with optical method and chemical silver .The thickness of the silver film is about five times of the skin depth at resonant frequency, which can prevent the microwave escape form the mirror surface.

Step3: Indium is used to connect the glass waveguide aperture and the external metal rectangle waveguide located on the upper surface of the spherical mirror.

Agilent N5247A vector network serves as I/O signal separation device in this work. The measurement system is connected to VNA with a spectrum extension module through E-face bend waveguide.

To improve the measurement accuracy, the sample should be well prepared by keep the following tips. First of all, the radius of the sample should be large enough to prevent the influence of diffraction of at specimen edge. Secondly, the sample should be flat enough and without spur at its edge. At last, thickness over entire surface of the sample should be uniform.

The measurement procedure of the system is presented as follows:

Step 1: TRL method is used for calibration of VNA with the help of WR-10 waveguide kit.

Step 2:We identify operation mode ($TEM_{0,0,q}$) of the measurement system. Search for resonant frequency using a piece of paper with low-loss material on it .When the paper is put on the center of the plane mirror, the peak of operation mode would disappear or be extremely weakened. Then substitute resonant frequency (f_{00}) of operation mode into eq.(1) ,we can determine the accurate cavity length (D) . After obtaining the whole mechanical parameters, empty resonant quality (Q_0) also can be calculated with the help of eq.(4)

Step 3: Put the sample on the center of the plane mirror. The resonant frequency (f_{os}) would shift and use the same method in step2 to find operation mode. Then record fos and calculate the unload quality (Q_{OS}) with sample.

Step 4: obtain permittivity and loss tangent of the sample through eq.(4) and eq.(6).

E. Measurement results

The electrical parameters and measured results of permittivity and loss-tangent are shown in Table 3. Quality factor value and resonant frequency of the resonator without and with sample were all recorded or calculated through the resonant curves. The permittivity of the sample can be solved numerically using above equation.Compared to record measurement results [15], the standard deviation of measurement error is less than 0.154% in permittivity and 20.42% in loss tangent.

Table 3 Comparison of measured results with other record results

Parameter	This work	IAP
ε_r/f(GHz)	9.40/92.1206	9.4/140
$\tan\delta\times10^4/f$(GHz)	1.8/92.1206	1.7/90

F. Conclusion

Two reflection-type open resonant measurement system have been designed in this paper. One of them is constructed well and the other one is in our plan. Although measurement results have a good agreements with the record results, a smaller Gauss beam radius of the open resonator is also needed to measurement the distribution of the dielectric Properties of the low loss materials.

REFERENCES

B. B.Yang , S. L. Katz, K. J. Willis,etal,A high-Q Terahertz resonator for the measurement of electronic properties of conductors and low-loss dielectrics. IEEE Trans. Terahertz Science and Technology. 2 (4), 449-459, 2012

G.X.Shu, Y.Luo,Q.S.Zhang, Millimeter Wave Measurement of the Low-Loss Dielectricin Vacuum Electronic Devices with Reflection-TypeHemispherical Open Resonator. J Infrared MilliTerahz Waves , 2015 36:556 – 568

J. J. Choi, Dielectric measurements of CVD diamonds at millimeter wavelength using a Fabry-Perot open resonator. Int.JInfrated and Millimeter waves. 26(10). 1427-1436, 2005

Y. F. Gui, W. B. Dou, K. Yin, and P .G .Su, Open resonator system for automatic and precise dielectric measurement at millimeter wavelengths. Int.JInfrated and Millimeter waves. 29, 782-791, 2008

T. M. Hirvonen, P. Vainikainen, A. Lozowski, and A. V. Raisanen, Measurement of dielectrics at 100GHz with an open resonator connected to a network analyzer. IEEE Trans.Instrum. Meas. 45(4), 780–786 , 1996

P. Coquet, T. Matsui, and M. Kiyokawa, Measurements of low loss dielectric materials in the 60 GHz band using a high-Q gaussian beam open resonator, IMTC'94, pp.1265–1268, May 10–12, 1994.

C. R. Jones, J. Dutta, G. F Yu and Y. C. Gao, Measurement of Dielectric Properties for Low-Loss Materials at Millimeter Wavelengths.J Infrared MilliTerahz Waves.32,838-847, 2011

F. R. Cui, Z. X. Luo, F. Ji, B. J. Hu, and S. I. Lai. Quasi optical resonator for measuring surface resistance and its distribution of high temperature superconductor film. Int.JInfrated and Millimeter waves.20(6), 1037-1045 , 1999

M. N. Afsar, H. Y. Ding, A novel open-resonator system for precise measurement of permittivity and loss-tangent. IEEE Tran.Instrum. Meas. 50(2), 402-405, 2001

M. N. Afsar, H. Y. Ding, K. Tourshan, A new 60GHz open resonator technique for precision permittivity and loss tangent measurement. IEEE Trans. Instrum. Meas. 48(2), 626–630, 1999.

R. G. Jones. Precise dielectric measurements at 35GHz using an open microwave resonator. Proc.IEE. 123(4), 285-290, 1976

J. Xia, C. H Liang, The calculation for the Q factor of an electromagnetic open resonator. Journal of Electronics. 17(1), 103-107, 1995

R. K. Mongia and R. K. Arora, Equivalent circuit parameters of an aperture coupled open resonator cavity. IEEE Trans. Microwave Theory Tech. 41, 1245-1250, 1993

Guofen Yu, JyostnaM.Dutta, Charles R.Jones, The Influence of a Coupling Film on Ultra-Low-LossDielectric Measurement Using an Open Resonator ,J Infrared MilliTerahz Waves (2011) 32:935 – 942,2011

R. Heidinger, "Dielectric measurements on sapphire for electron cyclotron wave systems," J. of Nucl.Mat. 212–215, 1101–1106, 1994