A Quasi-optical resonator with new coupling method and parasitic-mode-suppressing in 110 ~ 170GHz

Jin Cheng, YunPeng Zhang, JiaWei Long and En Li✉

In this paper, a quasi-optical resonator with new coupling method and parasitic-mode-suppressing in 110~170GHz is proposed. The coupling of THz quasi-optical resonator in this paper is realized by PCB substrate processing and pressurized flange. At the same time, the parasitic mode is effectively suppressed by slitting the plane mirror to reduce the influence on the main mode during the test. And fused quartz sample was tested to verify the feasibility of the system for complex dielectric testing of materials in 110~170GHz.

Introduction: Microwave dielectric materials are widely used in military and civilian industries such as electronic communications, radar detection and biomedicine due to their strong penetration and large information capacity. The dielectric properties of microwave dielectric materials are the basis for the integration and development of microwave technology. In the terahertz(THz) frequency range, the open resonator has been widely used in the dielectric constant test of materials due to its advantages of high Q value, no peripheral metal loss and convenient test [1-2]. In this paper, a new coupling method of quasi-optical resonator is designed in the form of coupling plate processed by PCB substrate and pressurized flange in the 110~170GHz frequency band. Also, the parasitic mode is suppressed by plane mirror slotting, and the dielectric properties of broadband materials in THz frequency band are tested. It is of great significance to characterize the dielectric properties of dielectric materials related to frequency.

Design of the system: The quasi-optical resonator is developed from the optical Fabry-Perot interferometer and consists of two mirrors. There are two forms of quasi-optical resonator. The first form is that the reflector is composed of two spherical mirrors, and the sample is loaded in the middle of them. The second form is to replace a spherical mirror with a plane mirror, and the sample is loaded on the plane mirror. For the convenience of placing sample and parasitic mode suppression, the second form is adopted in this paper. The structure diagram is shown in Fig.1. R_0 is the radius of curvature of the spherical mirror, and D is the length of the quasi-optical resonator.

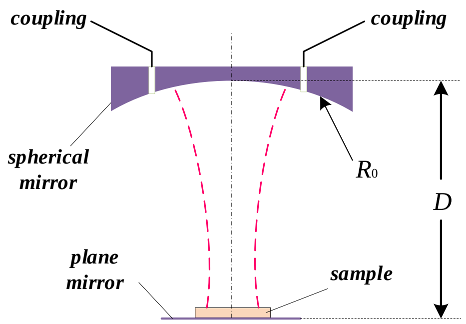


Fig. 1 *Semi-symmetric quasi-optical resonator structure diagram*

The common coupling methods of quasi-optical resonator are single-port coupling and double-port coupling. Single-port coupling generally requires additional correction. The dual-port coupling is often used in low frequency, because the coaxial line can be used for ring coupling at low frequency, and in the THz frequency band, the coaxial line cannot be used for ring coupling due to process constraints. Therefore, this paper uses the processing of PCB substrate for hole coupling to realize the weak coupling of THz resonant resonator, and this method can realize the adjustment of coupling amount. The structure diagram is shown in Fig.2. The spherical mirror is a profile view, the coupling plate is processed by Rogers5880 substrate, and the copper coating is carried out. And in order to better coupling effect, the pressurized flange is used to give certain pressure. The standard waveguide is connected to the pressurized flange and connected to the spread spectrum module.

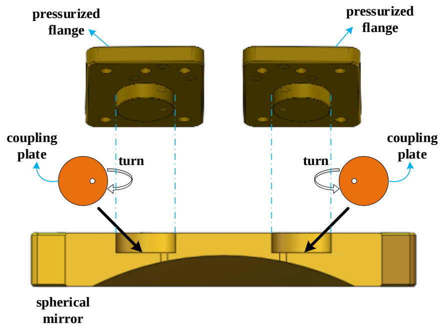
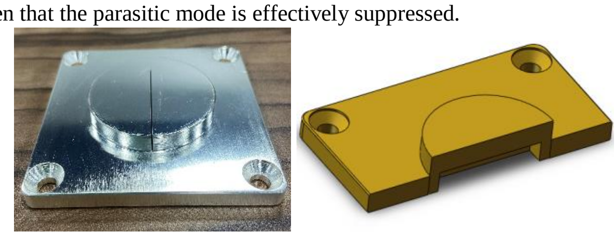


Fig. 2 *The method of PCB coupling plate and pressurized flange assembly diagram*

Under broadband frequency measurement, in addition to the main mode TEM00q, there are more interference parasitic modes in the quasi-optical resonator. Some interference parasitic modes are distributed around the fundamental mode, which will cause a bimodal shape in the spectrum. Therefore, it is necessary to consider suppressing them. Because the resonator surface current distribution of different modes is different. And the surface current distribution of the TEM_{00q} mode on plane mirror is distributed along the diameter direction, while the surface current distribution of the non-TEM_{00q} is not satisfied. Considering that the slits on the resonator can cut off the surface current distribution [3-4], so the current path of some parasitic modes can be cut off by slitting along the diameter direction in the plane mirror, to achieve the purpose of suppressing the parasitic mode, as shown in Fig.3. And The comparison of the suppression effect is shown in Fig.4 around 113.7GHz. It can be seen that the parasitic mode is effectively suppressed.

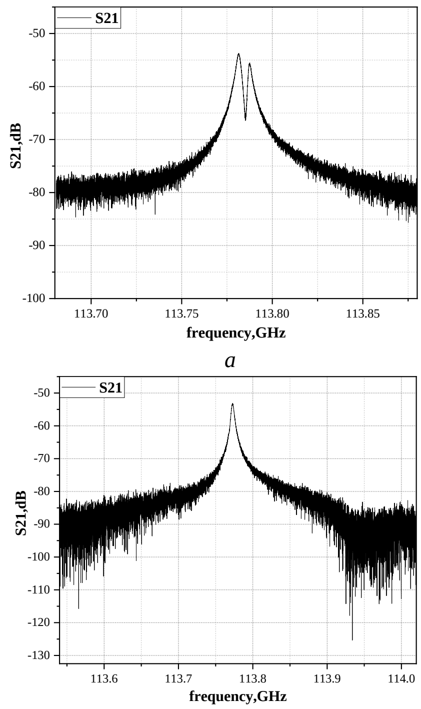


a *b*

Fig. 3 *The structure of slotted plane mirror*

a Photograph of plane mirror with slit

b Model profile view



a *b*

Fig. 4 *Comparison of plane mirror slit suppression effects*

a Plane mirror without slit

b Plane mirror with slit

Measurement principle: For the open resonator, the field in the quasi-optical resonator propagates in the form of Gaussian beam. And good measurement theories and methods have been established in many literatures [5-7]. The expression of fundamental mode TEM_{00q} of empty resonator is:

$$f=\frac{c}{2D}\left(q+1+\frac{1}{\pi}\arctan\left(\left(\frac{D}{R_0-D}\right)^{1/2}\right)\right) \tag{1}$$

Where D is the length of the quasi-optical resonator, R_0 is the radius of curvature of the spherical mirror, q is the mode number of TEM_{00q} and c is the speed of light.

When a sample with a thickness of t is placed on the plane mirror, the resonant frequency becomes f_s, which satisfies:

$$\frac{1}{n}\tan\left(nkt-\Phi_t\right)=-\tan\left(kd-\Phi_d\right) \tag{2}$$

Where:

$$\Phi_t=\arctan\left(\frac{t}{nz_0}\right) \tag{3}$$

$$\Phi_d=\arctan\left(\frac{d''}{z_0}\right)-\arctan\left(\frac{t}{n^2z_0}\right) \tag{4}$$

$$d=D-t \tag{5}$$

$$z_0=\sqrt{d''\left(R_0-d''\right)} \tag{6}$$

$$d''=d+\frac{t}{n^2} \tag{7}$$

Where $k=2pi/f_s$ is the wavenumber and $n=\sqrt{\varepsilon_r}$ is the refractive index of the sample. Thus, the relative permittivity ε_r of the sample can be determined. And because of the phase mismatch on the surface of the sample, it is necessary to use error correction for the thickness of the sample, and the reduction of the measurement quality factor of the resonator containing the sample is directly related to the loss tangent of the sample [7-9], so there are:

$$\tan\delta=\frac{1}{Q}\frac{(d+t\Delta)}{\left\{\Delta t-\left(\frac{1}{2k}\right)\sin 2\left(kd-\Phi_t\right)\right\}} \tag{7}$$

where

$$\Delta=\frac{n^2}{n^2\cos^2\left(nkt-\Phi_t\right)+\sin^2\left(nkt-\Phi_t\right)} \tag{8}$$

$$\frac{1}{Q}=\frac{1}{Q_L}-\frac{1}{Q_0}\frac{D(\Delta+1)}{2(t\Delta+d)} \tag{9}$$

So, the loss tangent of the sample can be calculated by measuring the resonator Q_0 value without sample and Q_L value with sample.

Results: As shown in Fig.5, we established a test system at 110 ~ 170GHz frequency, which D = 69mm, R_0 = 74mm. This system consists of vector network analyser(VNA), quasi-optical resonator, rectangular waveguide, coupling device and displacement platform.

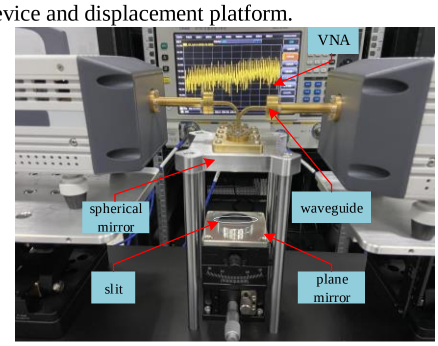


Fig. 5 *Photograph of test system*

Based on the above system, we test the fused quartz, and the complex permittivity results are shown in Fig.6. It can be seen that the measured relative permittivity at room temperature is basically consistent with the CRC data[8](@9.4GHz)3.81,and the literature[1](@36.18G) 3.825, the error is within 2 %. The loss tangent is basically in the range of 4E-04 to 7E-04, comparing with 3.18E-04[1](@36.18G). The difference in the loss tangent is slightly larger. This is because a part of the energy is lost after the plane mirror is slotted, resulting in a decrease of the resonator quality factor, which in turn affects the lower limit of the measurable loss tangent range.

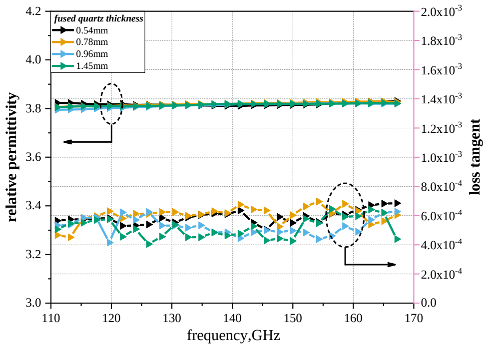


Fig. 6 *Complex permittivity measurement results of fused quartz with different thickness*

Conclusion: This paper presents a quasi-optical resonator with new coupling method and parasitic-mode-suppressing in 110~170GHz. And applied to the measurement of complex permittivity of materials in a wide-frequency range. The typical sample test results were in good agreement with the data published in the literature. And this coupling method can easily adjust the coupling amount of the resonator, which provides convenience for the test of the complex permittivity of the THz band material.

Acknowledgment: This work was supported by the National Natural Science Foundation of China under Grant No. U2241241.

One or more of the Figures in this Letter are available in colour online.

Jin Cheng, YunPeng Zhang, JiaWei Long and En Li (National Engineering Research center of Electromagnetic Radiation Control Materials, School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, People's Republic of China)

✉ E-mail: lien@uestc.edu.cn

References

1 Shu, G.X., Luo, Y., Zhang, Q.S. et al. Millimeter Wave Measurement of the Low-Loss Dielectric in Vacuum Electronic Devices with Reflection-Type Hemispherical Open Resonator. J Infrared Milli Terahz Waves 36, 556–568 (2015). https: //doi.org/10.1007/s10762-015-0160-x

2 H. Chen, H. Chen, W. Che, S. Zheng, X. Xiu and Q. Xue, "Review and Modification of Permittivity Measurement on Open Resonator for Transparent Material Measurements at Terahertz," in IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 11, pp. 9144-9156, Nov. 2020, doi: 10.1109/TIM.2020.2998565.

3 Yu CY, Li E and Guo GF, "Dielectric Characterisation of Small Samples Using Broadband Coaxial Cavity," in Electronics Letters, vol. 53, pp. 1316-1318, Sept. 2017. https://doi.org/10.1049/el.2017.2492

4. Zhang YP, Li E , Zhang J , et al. A broadband variable-temperature test system for complex permittivity measurements of solid and powder materials[J]. Review of Scientific Instruments, 2018, 89(2):024701. https://doi.org/10.1063/1.4993507

5 R. G. Jones, Precise dielectric measurements at 35 GHz using an open microwave resonator. Proc. Inst. Elec. Eng. 123, 285–290 (1976) Apr. DOI: 10.1049/piee.1976.0067

6 A. L. Cullen and P. K. Yu, "The accurate measurement of permittivity by means of an open resonator," Proc. of the Royal Society London, vol. 325, pp. 493–509, 1971. https://doi.org/10.1098/rspa.1971.0181

7 T. M. Hirvonen, P. Vainikainen, A. Lozowski and A. V. Raisanen, "Measurement of dielectrics at 100 GHz with an open resonator connected to a network analyzer," in IEEE Transactions on Instrumentation and Measurement, vol. 45, no. 4, pp. 780-786, Aug. 1996, doi: 10.1109/19.516996.

8 Shackelford, J F, and Alexander, W. CRC materials science and engineering handbook. Third edition. United States: N. p., 1999. Web.