Invited paper

Study on radiation parameter measurement of terahertz source based on bolometer radiometer

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Abstract: Terahertz radiation characteristics of blackbody are theoretic basic of detecting terahertz radiation, and also the key of how to calibrate and measure terahertz sources. Terahertz radiation characteristics of blackbody are analyzed, and terahertz bolometer radiometer is built, then the terahertz radiance of blackbody, which temperature range is (223～323) *K*, are tested by bolometer radiometer. Furthermore, the radiance of folded waveguide traveling-wave tube is tested. The results show that the method which can test terahertz radiation parameter of terahertz source is provided.

Key words: Terahertz source measurement, Radiation blackbody, Terahertz bolometer radiometer

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1. Introduction

All objects can emit terahertz radiation when molecules vibrate. Terahertz radiation characteristics of blackbody are the theoretic basic of detecting terahertz radiation. Terahertz blackbody can be used with standard terahertz source, and provide value trace ability for many kinds of terahertz sources. PTB has studied on terahertz radiation in 2009, and developed the terahertz source measurement system in which blackbody is used as a standard radiation source [1-3]. At the same time, using thermal detectors, such as pyroelectric array detector and bolometer, to build terahertz imaging systems are studying. Otherwise, measuring terahertz radiation parameter of terahertz sources correctly is the key of how to calibrate and measure terahertz sources [4-6]. So, it is necessary to solve the problem how to measure the terahertz radiation of terahertz sources.

In this paper, terahertz radiation of blackbody characteristics are analyzed, and bolometer radiometer is built, then the terahertz radiation and radiance power of blackbody, which temperature range is (223～323)K, are tested. And then, the radiance of folded waveguide traveling-wave tube is tested.

2. Terahertz radiance characteristics calculation methods of blackbody

Terahertz radiance of blackbody which temperature range is (15～623)K is showed in Fig.1. Infrared radiation is much higher than terahertz radiation when the blackbody temperature upraises. So, it is difficult to filter infrared radiation when terahertz radiation is measured. Theoretically, the peak value wavelength of blackbody which temperature of (3～100)K is (30～3000)μm, but the terahertz radiance is extremely weak, so it is very difficult to detect. The higher the blackbody temperature is, the stronger the terahertz radiance and radiation power are. Radiation of blackbody whose temperature range is (223～323)K is higher than that whose temperature range is (3～100)K by two orders of magnitude for the higher signal-to-noise, and the gap is not very big comparing to the infrared radiation. The infrared radiation of blackbody in (223～323)K is easier to throw off by filter in the terahertz radiation testing. So it is furthermore appropriate with blackbody in (223～323)K for the radiation parameter measurement of Terahertz.

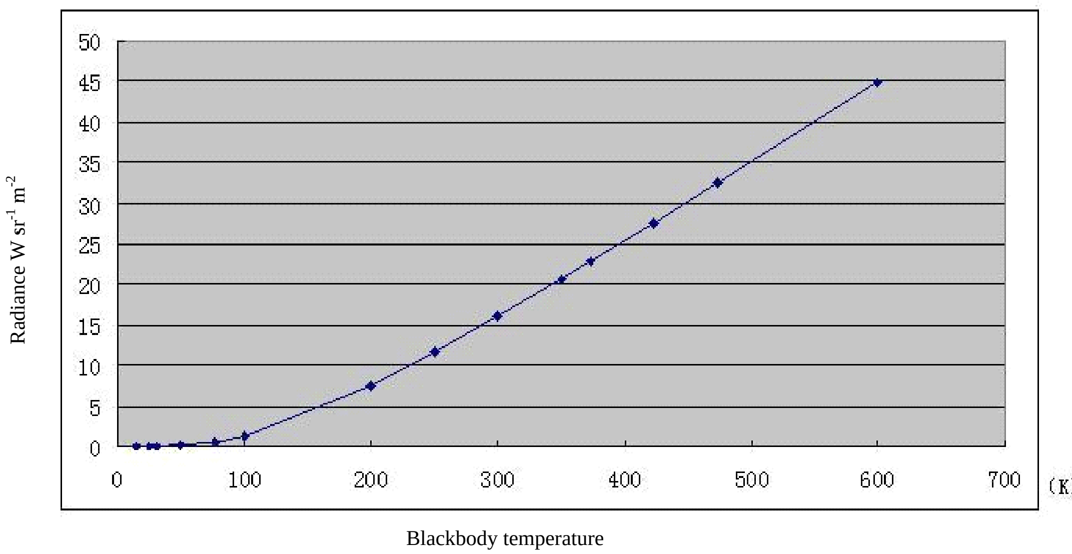

Fig. 1 Radiance distributing of different temperature blackbody in terahertz waveband

The terahertz radiation characteristics of the blackbody are analyzed, and then normal temperature blackbody having appropriate temperature is chosen as standard terahertz source. According to Plank's law, radiance of standard terahertz blackbody is calculated by function 1, and radiation power is calculated by function 2.

$$L = \varepsilon \cdot \int_{\lambda_1}^{\lambda_2} \frac{2hc^2}{\lambda^5} (e^{\frac{hc}{\lambda kT}} - 1)^{-1} d\lambda \qquad W \cdot sr^{-1} m^{-2} \tag{1}$$

$$\Phi = \varepsilon \cdot A \int_{\lambda_1}^{\lambda_2} \frac{2\pi hc^2}{\lambda^5} (e^{\frac{hc}{\lambda kT}} - 1)^{-1} d\lambda \qquad W \tag{2}$$

Here, ε is the emissivity of blackbody, A is sampling facular area when blackbody calibrated, $h = 6.6256 \times 10^{-34} J \cdot s$, $c = 2.997925 \times 10^{8} m \cdot s^{-1}$, $k = 1.38054 \times 10^{-23}$ J/K , $\lambda_1 = 30\mu m$, $\lambda_2 = 1000\mu m$, and T is blackbody temperature, that is to say $L_1 = L_2$.

The measurement principle of terahertz radiation parameter is:

Blackbody is stand by Lambertian, so radiance in any direction is equal. According to radiance conversation law, transmission loss can be ignored when closed beam transmits in the same medium, and source's radiance is equal to detector sink's.

In consideration of the loss, energy transmission transmittance of imaging system in terahertz waveband is τ, and then the illumination and radiation power, which is focused on detector photosensitive surface after the Cassegrain system.

Radiation cavity diameter of terahertz blackbody is 28*mm*, and the sampling spot diameter of Cassegrain system to blackbody is 20*mm*. In the measurement process, part of blackbody radiation enters the optical system and then is incepted by the detection system. Blackbody radiation is modulated into square wave by chopper. When chopper is turning to a certain frequency, radiation of terahertz variable temperature blackbody and liquid nitrogen blackbody are reflected into detection system by turns in a period. Thereby, blackbody radiation incepted by detection in a period is half of pre-modulated, that is to say radiation power is reduced twice.

Radiation power which is produced by blackbody is converged by the optical systems, the response voltage value of detection is described by function 3:

$$U = \Phi \cdot R = \frac{\varepsilon \cdot A \cdot R \cdot M_0 \cdot \tau_0 \cdot \tau_f \cdot D_i^2}{8b^2} \tag{3}$$

Here, M_0 is the radiant exitance of blackbody in terahertz waveband to be tested, R is the responsibility of detector, Φ is the radiation power incepted by detector in detection system, ε is the actual emissivity of blackbody, L_0 is radiance of blackbody, τ_0 is energy transmittance of terahertz optical system in terahertz waveband, τ_f is transmittance of filter in terahertz waveband, D_i is diameter of exit pupil, and b is image distance.

The Cassegrain system characteristics are: diameter of entrance pupil is 150*mm*, central shield coefficient k is 0.425, and image distance is 380.7*mm*. Because there is a shield in the central in the Cassegrain system, equivalent diameter of exit pupil D_E can be calculated by function 4 when analyzing system energy transfer.

$$D_E = \sqrt{D_1^2 - D_2^2} \tag{4}$$

After calculating, the equivalent diameter of entrance pupil is 133.7*mm*, and diameter of exit pupil can be calculated by the formula $D_{\mathrm{i}} = \beta^* D_E$.

Radiation power and radiance of terahertz sources to be tested is described by function 5:

$$L_1 = \frac{V_1 - V_0}{V_T - V_0} \cdot L_T \tag{5}$$

Here, L_1 is radiance of terahertz sources to be tested respectively, L_T is radiance of standard terahertz sources (standard variable temperature blackbody) respectively, V_1 is measured voltage of terahertz sources to be tested, V_T is measured voltage of standard terahertz sources, V_0 is measured voltage of reference blackbody refrigerated by liquid Nitrogen.

3. Measurement on terahertz radiation parameter of blackbody

Terahertz radiometer of bolometer is showed in Fig. 2 for terahertz radiation characteristics measurement, which includes the source system, optics system, detection system, vacuum low background channel and software. The optics system is composed of the flat-mirror, chopper, Cassegrain system, terahertz narrowband filter group, and bolometer light cone coupling system. The chopper is circumvolved by controller, and radiation signals from terahertz and reference signals from blackbody refrigerated by liquid Nitrogen is inducted in optics system by turns.

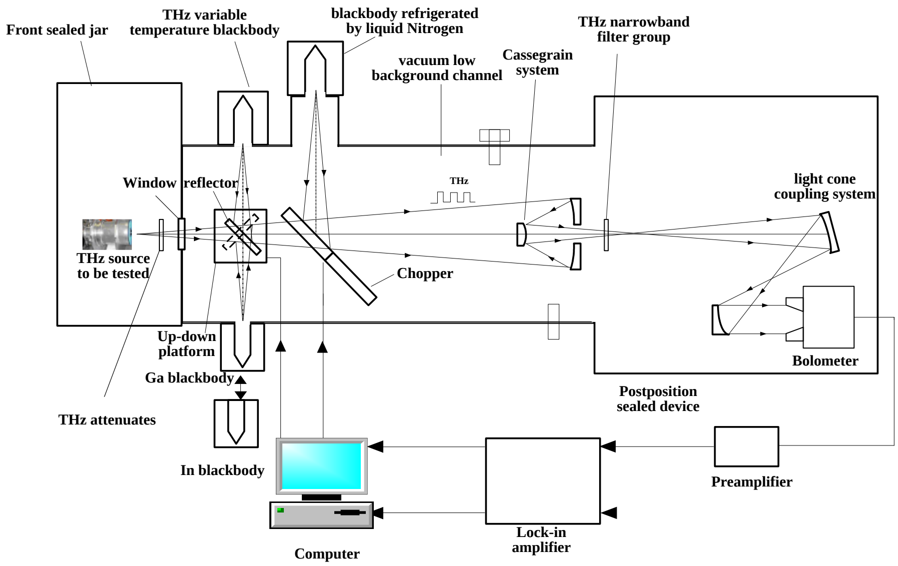

Fig. 2 Terahertz radiometer of bolometer

3.1 Terahertz radiometer of bolometer detection system

Terahertz bolometer detection system is showed in Fig. 3, which includes the bolometer system, low noise preamplifier, chopper and lock-in amplifier. The bolometer system includes the bolometer, high density cuneiform window, light cone, liquid Helium container, liquid Nitrogen container, Dewar, vacuum valve and molecular pump group.

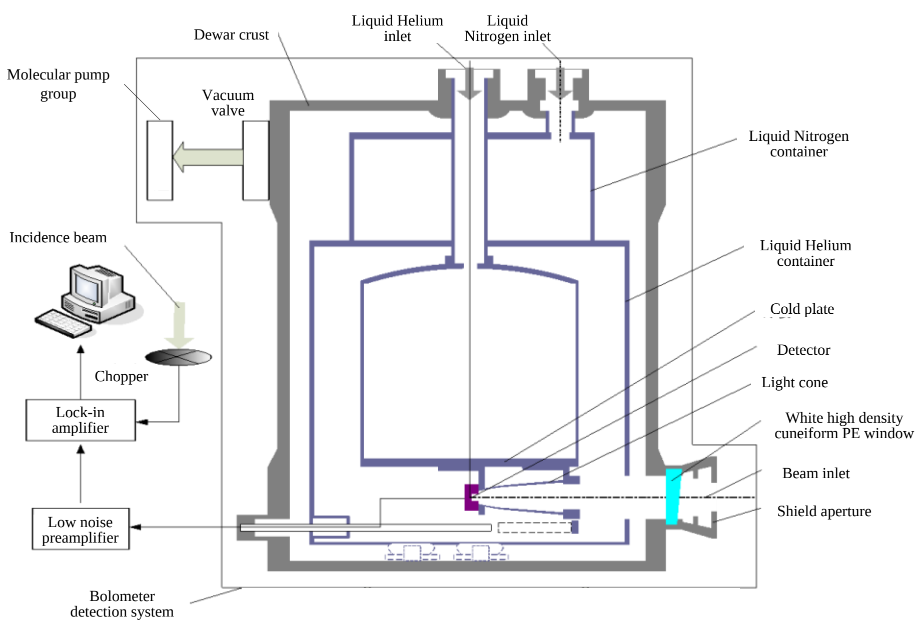

Fig. 3 Terahertz bolometer detection system

Bolometer detector includes heat-sensitive detection element made by doped silicon and diamond absorber whose size is 2.5*mm*. Operation principle of bolometer is: if the terahertz radiation arrive the detector, the temperature will rise, and then the resistance value will change, so voltage changes can be measured by amplifying circuit. The bolometer is fixed in liquid Helium Dewar. Its operation temperature is 4.2*K*, so the background thermal noise can be decreased. For modulated by chopper, resistance value changes will correspond to the incidence radiation power changes [14-16].

3.2 Measurement on calibration factors

Average voltage values from bolometer are showed in table 1, and the calibration factors are showed in table 2.

Tab. 1 Testing average voltage values

Blackbody temperature （*K*）	Testing average voltage values（*mV*）					
	(97.9～116.3)μm	(176.4～230.6)μm	(264.0～354.3)μm	(525.6～662.0)μm	(814.5～1224.9)μm	(2708.3～3430.6)μm
223	60.547	39.649	36.563	51.884	100.185	172.538
233	64.922	41.255	37.905	53.561	104.730	179.994
243	67.358	42.640	38.437	55.526	109.127	187.632
253	70.557	43.822	39.795	57.373	113.648	195.008
263	74.655	44.861	41.199	59.204	117.188	202.638
273	76.416	46.631	42.725	61.228	121.705	212.281
283	80.261	48.401	44.922	63.599	125.794	218.934
293	78.674	50.354	40.081	65.796	133.180	222.108
303	81.421	51.758	47.607	67.871	134.156	233.155
313	82.825	52.307	48.950	69.214	137.269	234.986
323	85.876	54.711	50.720	73.534	141.786	245.667

Tab. 2 Calibration factors of bolometer

Blackbody temperature (*K*)	Calibration factors					
	(97.9～116.3)μm	(176.4～230.6)μm	(264.0～354.3)μm	(525.6～662.0)μm	(814.5～1224.9)μm	(2708.3～3430.6)μm
223	2.993005	1.213259	0.484493	0.03902	0.007088	0.00009
233	3.101177	1.377332	0.495652	0.038637	0.00743	0.000089
243	3.18137	1.40478	0.500852	0.038826	0.007675	0.000089
253	3.222024	1.402807	0.504162	0.039537	0.007674	0.000089
263	3.275443	1.426365	0.509862	0.040097	0.007858	0.000091
273	3.324819	1.440037	0.513022	0.039386	0.007878	0.000091
283	3.320378	1.433209	0.51174	0.039618	0.007781	0.000091
293	3.46645	1.449581	0.508666	0.040044	0.007694	0.00009
303	3.490437	1.456061	0.514575	0.039936	0.007728	0.000091
313	3.553267	1.474354	0.51891	0.041097	0.007913	0.000091
323	3.642582	1.473954	0.521277	0.040836	0.00792	0.000092
average	3.324632	1.413794	0.507565	0.03973	0.007694	0.000090
standard deviation	0.198587	0.073023	0.010726	0.000778	0.000246	0.000001

In measurement process, calibration factors average value are used as calibration coefficient in corresponding terahertz waveband. From the table 2, the maximum value of relative measurement error in terahertz waveband is 8%. When the terahertz source is tested, calibrating factor is chosen from table 2 corresponding to the terahertz waveband which the terahertz source lies in.

4. Test on terahertz radiance of blackbody and terahertz source

The terahertz blackbody temperature range is (223～323)*K*, in which some special temperature points are chosen. Then seven pieces of filters are placed in the light path in turn. In here, the filter which central wavelength is 105.1μm corresponds to the waveband (97.9～116.3) μm; the filter which central wavelength is 199.5μm corresponds to the waveband (176.4～230.6) μm; the filter which central wavelength is 301.3μm corresponds to the waveband (264.0～354.3) μm; the filter which central wavelength is 584.8μm corresponds to the waveband (525.6～662.0) μm; the filter which central wavelength is 978.4μm corresponds to the waveband (814.5～1224.9) μm; the filter which central wavelength is 3041.7μm corresponds to the waveband (2708.3～3430.6) μm.

Measurement results of radiance and radiation power when the variable blackbody temperature range is (223～323)K are showed in table 3 .

Tab. 3 Measurement results of radiance (unit: W sr^{-1} m^{-2})

Blackbody temperature （K）	(97.9～116.3)μm	(176.4～230.6)μm	(264.0～354.3)μm	(525.6～662.0)μm	(814.5～1224.9)μm	(2708.3～3430.6)μm
223	1.891×10^{-1}	5.228×10^{-2}	1.790×10^{-2}	2.004×10^{-3}	7.770×10^{-4}	1.559×10^{-5}
233	2.035×10^{-1}	5.548×10^{-2}	1.845×10^{-2}	2.109×10^{-3}	8.028×10^{-4}	1.623×10^{-5}
243	2.146×10^{-1}	5.808×10^{-2}	1.927×10^{-2}	2.162×10^{-3}	8.428×10^{-4}	1.663×10^{-5}
253	2.651×10^{-1}	6.049×10^{-2}	2.021×10^{-2}	2.267×10^{-3}	8.718×10^{-4}	1.244×10^{-5}
263	2.347×10^{-1}	6.345×10^{-2}	2.102×10^{-2}	2.382×10^{-3}	9.204×10^{-4}	1.834×10^{-5}
273	3.462×10^{-1}	6.706×10^{-2}	2.198×10^{-2}	2.416×10^{-3}	9.562×10^{-3}	1.906×10^{-5}
283	2.568×10^{-1}	6.848×10^{-2}	2.276×10^{-2}	2.519×10^{-3}	9.795×10^{-4}	1.980×10^{-5}
293	2.733×10^{-1}	7.164×10^{-2}	2.339×10^{-2}	2.629×10^{-3}	9.990×10^{-4}	2.008×10^{-5}
303	2.838×10^{-1}	7.372×10^{-2}	2.449×10^{-2}	2.705×10^{-3}	1.036×10^{-3}	2.119×10^{-5}
313	2.935×10^{-1}	7.779×10^{-2}	2.540×10^{-2}	2.848×10^{-3}	1.086×10^{-3}	2.137×10^{-5}
323	3.075×10^{-1}	7.861×10^{-2}	2.632×10^{-2}	2.915×10^{-3}	1.225×10^{-3}	2.260×10^{-5}

After Analyzing the data in table 3, we know that, the standard deviations of radiance and radiation power when the variable blackbody temperature range is (223～323)K are less than 1.5%.

When the waveband is (97.9～116.3) μm, the trend of terahertz radiance and radiation power as the blackbody temperature changing are showed in Fig. 4.

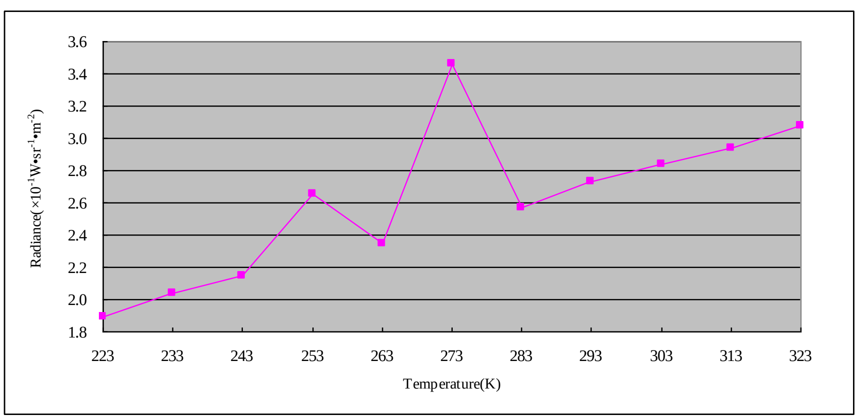

Fig. 4 The trend of terahertz radiance as the blackbody temperature changing

A terahertz folded waveguide traveling-wave tube which output power is 0.22*THz* and wavelength is 1363*nm*, when the duty ratio is 99%, the radiance is tested. The calibrating factor chosen from table 2 is 0.007694. Its terahertz radiance is showed in table 4.

Tab. 4 Terahertz radiance of folded waveguide traveling-wave tube

The number of measurements	Radiance (10^3 W sr^{-1} m^{-2})
1	1.157
2	1.150
3	1.139
4	1.121
5	1.176
6	1.180
Average value	1.154
Experimental standard deviation	0.022

5. Conclusions

Using the contradistinctive measurement method between the standard terahertz source and terahertz source to be tested, terahertz radiance of many kinds of terahertz sources which have broad waveband and great dynamic range are calibrated. A measurement model on how to measure the terahertz radiation of low-temperature and normal-temperature is established. A radiation subsection detection program which is based on spectral filtering method is proposed. Multiple temperature points of variable blackbody terahertz radiation are tested, and then the average values are gotten. In this way, the radiation parameterof terahertz source to be tested can be calibrated. Terahertz radiance of folded waveguide traveling-wave tube is tested, and the results reach a rather highly degree, which the experimental standard deviation is 0.022.

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