The Systematic Optimization Designs for the Microwave Wide Band Blackbody Calibration Target's Electromagnetic and Thermal Characteristics

Nian feng[1] , Wang Wei[1,2] , Huang Peikang[2]

[1]National Key Laboratory of Metrology and Calibration Technology, P.O.Box:3930, Beijing, 100039, China. Email: nianfeng@m165.com
[2] The Second Academy of China Aerospace Science&Industry Corp. P.O.Box:3930, Beijing, 100039, China. Email: zdsys@203.com

Abstract

The systematic optimizations to the microwave wide band blackbody calibration target applied for the microwave radiometer's pre-launch calibrations are researched with its electromagnetic and thermal characteristics based on the Kirchhoff's law, the sub-grid finite difference time domain（FDTD）method and the thermal analysis. Optimization results indict that round wedge is better than the square one, the best ratio for height to bottom radius is 4:1 for the wide band application, and the absorbing material's gradual thickness coating and multilayer coating are helpful to guarantee the uniform distribution of surface temperature with a higher emissivity.

1. Introduction

The microwave wide band blackbody calibration target is one of the key instruments to calibrate the microwave radiometer's linearity and sensitivity by outputting a standard microwave brightness temperature. However, how to emit a standard microwave brightness temperature with a higher precision for a blackbody calibration target in a microwave wide band is not easy to be realized, which is decided by the blackbody's two important parameters: the brightness temperature emissivity and its surface physical temperature. A qualified microwave wide band blackbody calibration target should have an emissivity near to 1 at all its working frequency band and have a smallest amount of temperature gradient along its wedge [1,2].

By now, the radar cross section（RCS）measurement is adopted as a substitute to the directly measurement method in evaluating the blackbody's emissivity based on the Kirchhoff's law that an object with higher heat absorbing ability should also have higher heat emissivity. Due to the high cost of manufacturing a blackbody, it becomes necessary and feasible to carry out an optimization simulation on the blackbody's key parameters such as the ratio of height to bottom radius of the wedges, the shape of square wedges compared with round wedges, the multilayer coating and thickness gradual coating of absorbing material. The simulation of the blackbody's RCS belongs to an electrically large size problem, so a FDTD method with sub-grid technology is preferred to decrease the staircase effect in modeling the wedges to a more precise level. Another merit from FDTD is that this time domain method can output a wideband RCS information with only once calculation compared with the frequency domain method such as the multilevel fast multipole algorithm （MLFMA）.

The other difficult problem is the temperature gradient along the wedges, which is not easy to be measured with uncontact measurement method at a precision <0.1K from 80K to 330K (the requirement of temperature variable blackbody calibration target) by now. So the extreme value of the temperature gradient along the wedge has to be analyzed on theory to evaluate the uncertainty of the microwave standard brightness.

2. Basic Theories

2.1 The Basic Theory of Optimizing Normal Emissivity with Backward RCS

The Kirchhoff's law of thermodynamics indicts that in the thermodynamics equilibrium state, a real blackbody calibration target with strong emissivity also has a strong absorbing ability which means the real blackbody's emissivity equals to its absorbing rate.

$$\varepsilon_{\lambda,\theta} = a_{\lambda,\theta} \tag{1}$$

In which $\varepsilon_{\lambda,\theta}$ is the monocolour directional emissivity of a real blackbody at certain direction θ at wavelength λ; And $a_{\lambda,\theta}$ is the monocolour directional absorbing rate of a real blackbody at certain direction θ at wavelength λ [3].

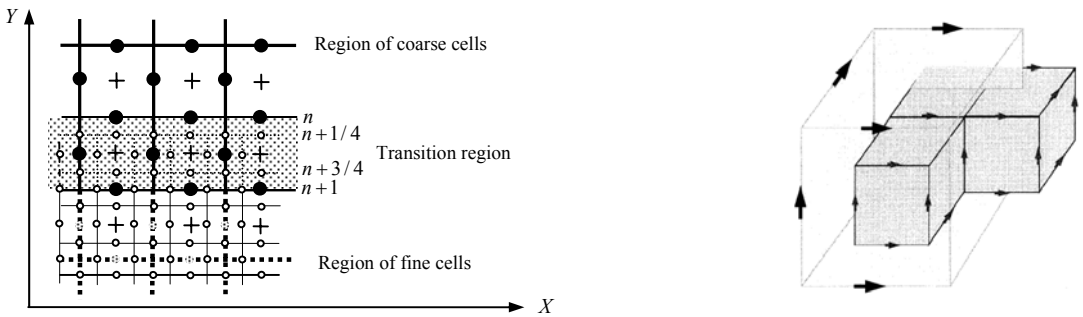
The blackbody calibration target uses its normal direction vertical to the antenna of the radiometer under calibration. So the normal emissivity should be adopted to evaluate the performance of the blackbody calibration target. From (1), the normal emissivity equals to the normal absorbing rate and the normal absorbing rate has the following relationship with the blackbody's backward RCS σ_{Backward}.

$$a_{\lambda,\theta=\text{Normal}} \propto 1-\sigma_{\text{Backward}} = 1-4\pi R^2 \frac{\left|E_{s\ \text{Backward}}\right|^2}{\left|E_{i\ \text{Backward}}\right|^2} \tag{2}$$

In which R is the distance from observation position to the calibration target; $E_{s\ \text{Backward}}$ is the backward scattering field; $E_{i\ \text{Backward}}$ is the normal incident field. So reducing the backward RCS of the blackbody calibration target becomes the optimizing target to design an approximately ideal blackbody with emissivity near to 1.

2.2 The FDTD Method with Sub-cell Technology Bridging Over the Dielectric Boundary

Because the thin layer of absorbing material coating on the metal wedge will lead to serious staircase errors in conventional FDTD method, the FDTD method with sub-grid technology is recommended. The dimension of the fine cell is 1/2 of the coarse cell. In Fig.1 (a) the grey part shows the transition region between the fine cell and the coarse cell and In Fig.1 (b) shows the 3 dimension distribution of the sub-cells and the coarse cells [4].



(a) (b)

Figure.1 Transition region between fine cells and coarse cells in sub-grid FDTD method

Besides the calculation precision can be increased especially for the wedge part when coating thin layer of absorbing material, the adoption of sub-grid FDTD can also reduce the calculation quantity greatly than simply applying the fine cells in entire calculation region.

3. The Simulation Results

The real blackbody calibration target developed now in BIRMM is shown in Fig.2, and based on this design, the optimization simulation models with 5×5 wedge array are constructed with sub-grid FDTD method as shown in Fig.3. The optimization processes are divided into three stages:

(1) The optimization to wedge shape: square wedge vs. round wedge with different H/w as shown in Fig.4;

(2) The optimization to different thickness t of absorbing material coating layer as shown in Fig.4;

(3) The optimization to gradual thickness coating as Fig.5(a), multilayer coating as Fig.5(b) and the combination of (a) and (b) as Fig.5(c).

Figure.2 A real blackbody calibration target

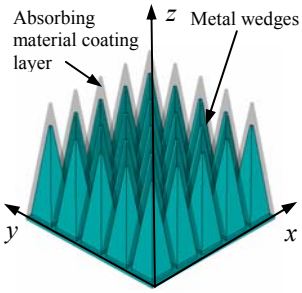


Figure.3 5×5 square wedge array

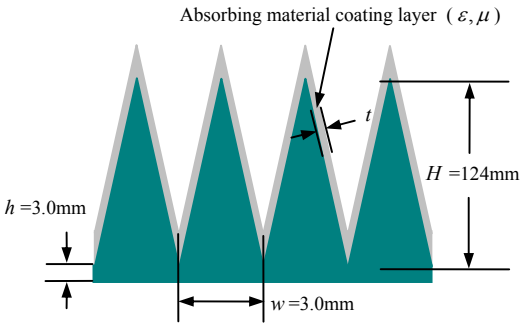


Figure.4 The sectional view of square wedge array of Fig.2

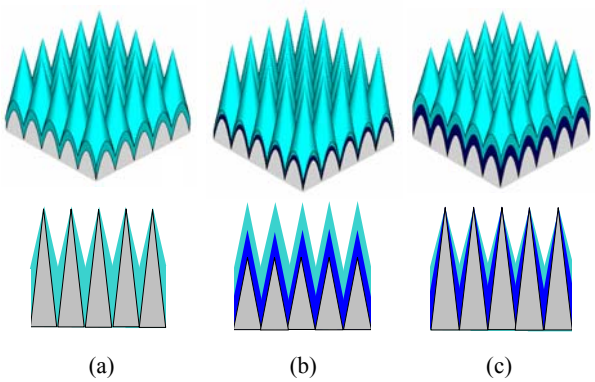


Figure.5 The optimization to absorbing coating layers

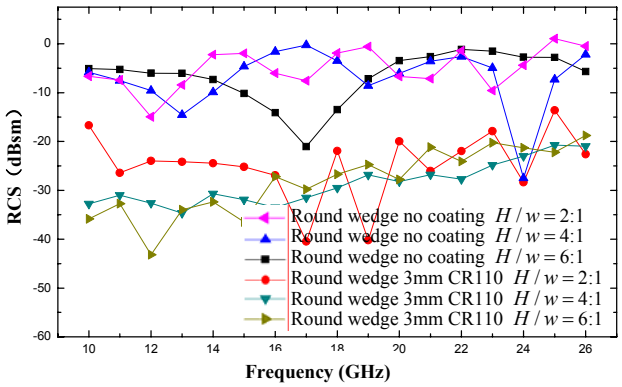


Figure.6 The RCS optimization of H/w for round wedge

Fig.6 shows that H/w=4:1 is the better proportion to realize a relatively lower and stable RCS in a wideband (CR11X is the absorbing material from Emerson & Cuming Inc.). And compared with the square wedge in Fig.7, round wedge has a lower RCS which can also be explained from the current distribution on the surface of the metal wedge in Fig.8.

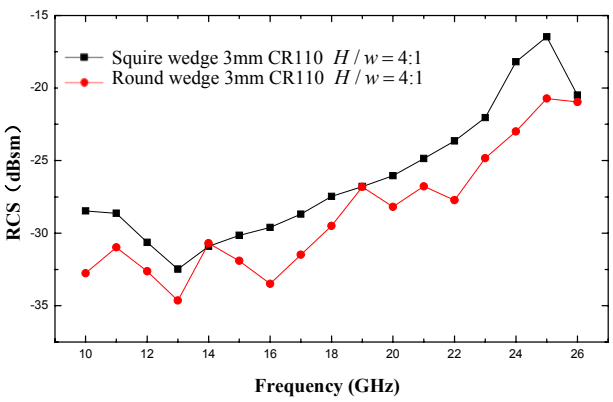
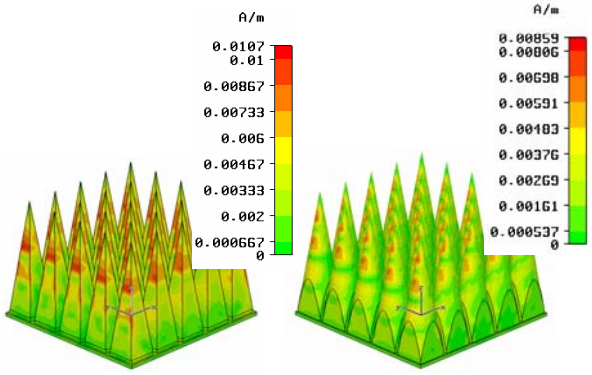


Figure.7 The RCS comparison of squire and round wedge



(a) Square wedge (b) Round wedge

Figure.8 Comparison of square and round wedge The current distribution c

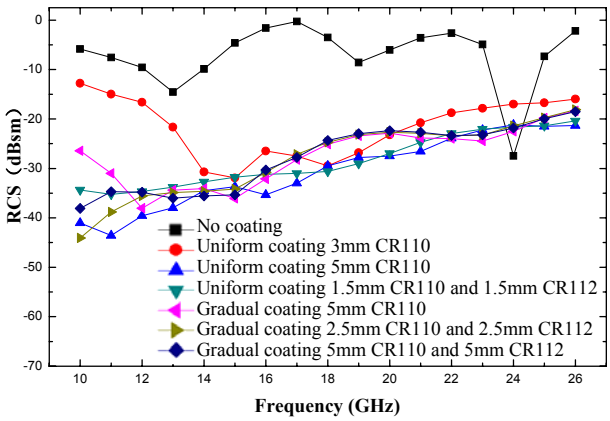
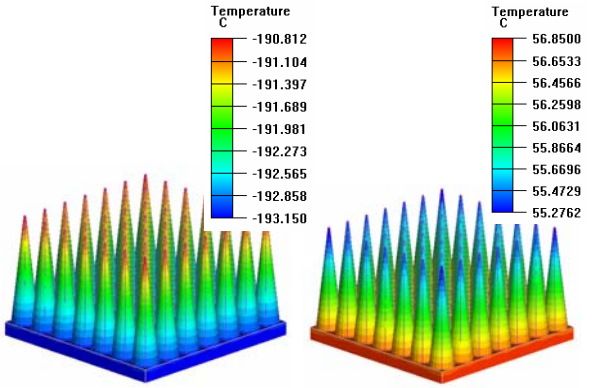


Fig.9 The optimization to absorb coating layers



(a) 80K blackbody / 293K ambient (b) 330K blackbody / 293K ambient

Fig.10 The theory extreme value of temperature gradient

Fig.9 shows that the multilayer coating (1.5mm CR110 (outer layer) and 1.5mm CR112 (inner layer) is better than the single layer same thickness coating, the gradual coating 5mm CR110 in form of Fig.5(a) has a smaller RCS value than the uniform coating 3mm CR110 and a similar RCS value compared with the uniform coating 5mm CR110 which indicts that this type of coating can realize a uniform temperature gradient while having a higher emissivity, the multilayer coating combined with the gradual thickness coating can realize a more lower RCS. So the gradual coating 2.5mm CR110 (outer layer) and 2.5mm CR112 (inner layer) will be the relatively better optimized design to meet both the electromagnetic and the thermal requirements for the blackbody calibration targets in a wide frequency band. Because the electromagnetic optimization is decided by the low frequency side for the blackbody, these optimization advices are also useful to be applied in the higher frequency band. Fig.10 shows the theory extreme value of temperature gradient (blackbody is 80K and 330K respectively radiating to ambient 293K under vacuum conditions) with the round wedge at H/w=4:1 which can provide a reference to evaluate the uncertainty of the blackbody's microwave brightness standard.

4. Conclusions

The systematic optimization simulations for the blackbody calibration targets were carried out by BIRMM. The key optimization results shows that a round wedge shape with proportion H/w=4:1 will be more suitable to be treated as the basic design to develop the blackbody. Besides these, cases of multilayer coating, gradual thickness coating and the combination of both technologies are also simulated, which shows that these changes will also increase the performance of the blackbody's electromagnetic and thermal characteristics. Finally based on the thermodynamic analysis the extreme value of the temperature gradient along the round wedges are evaluated which provide a reference to define the uncertainty of the blackbody's microwave brightness standard. Now the certification experiments are prepared in BIRMM to develop a more qualified blackbody calibration targets from 10GHz to 90GHz with an emissivity $e \geq 0.999$ for the construction of a microwave brightness temperature standard.

5. References

1. J Randa, A E Cox, D K Walker, "Proposal for development of a national microwave brightness temperature standard," 2006 IEEE International Geoscience and Remote Sensing Symposium Digest(IGARSS-2006) Denver, CO, U.S.A，Aug. 2006.

2. D M Jackson, A J Gasiewski, "Electromagnetic and thermal analyses of radiometer calibration targets," 2000 IEEE International Geoscience and Remote Sensing Symposium (IGARSS-2000), Proceedings. 24-28 July 2000.

3. R Siegel and J Howell. "Thermal radiation heat transfer, 4th ed," New York:Taylor and Francis, 2002.

4. M Okoniewski, E Okoniewska, M A Stuchly. "Three-dimensional subgridding algorithm for FDTD," Antennas and Propagation, IEEE Transactions on. March 1997 pp.422-429.