IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 12, 2019, accepted March 23, 2019, date of publication March 27, 2019, date of current version April 10, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2907704

GO/PO Method for the Terahertz Scattering Computation of Objects With Multiple Small-Scale Grooves

X. MENG[1], L. X. GUO[2], (Senior Member, IEEE), C. L. DONG[2], AND Y. C. JIAO[1]

[1]National Key Laboratory of Antennas and Microwave Technology, Xidian University, Xi'an 710071, China
[2]School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710071, China

Corresponding author: X. Meng (mengxxidian@126.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61701378, and in part by the Foundation for Innovative Research Groups of the National Natural Science Foundation of China under Grant 61621005.

ABSTRACT In this paper, the Geometric Optics (GO)/Physical Optics (PO) method is improved to analyze the terahertz (THz)-wave scattering characteristics of objects with multiple small-scale grooves, where the grooves are of the same size. For the traditional GO/PO method, when the number of grooves reaches dozens or even hundreds, the existence of a large number of redundant intersection tests will be a main limitation to calculate the electromagnetic (EM) scattering in THz band. Therefore, in order to solve this problem, the scattered field from one of the grooves is computed using the GO/PO method and extended to obtain the scattered field of the other grooves according to their dimensional information. In this way, the computation load is effectively reduced. To demonstrate the validity of our method, the results are compared with those of MLFMM, traditional GO/PO method and experimental data. A good agreement is achieved. Meanwhile, the runtime of our method is compared with that of traditional GO/PO method, where the computational time is greatly saved. Furthermore, the scattering characteristics of objects with multiple small-scale grooves in THz band is studied. The simulation results show that the small-scale grooves will have a great effect on EM scattering characteristics in THz band.

INDEX TERMS THz, EM scattering, GO/PO method, objects with multiple small-scale grooves.

I. INTRODUCTION

In recent year, a significant progress has been made in the THz science and technology [1]–[4], which also promoted the wide application of THz radar in many fields. Exploration of the THz scattering characteristics will contribute to the development of THz radar systems and has become a hot research field.

THz wave is a kind of electromagnetic wave, whose frequency range is 100GHz-10THz. In such high frequencies, the micro-structure will have a great impact on the EM scattering behavior of objects. Thus, it is necessary to investigate the EM scattering characteristics of objects with micro-structures. As is known that there is a wide variety of micro-structures, and different types of micro-structure will exhibit different EM scattering properties. In this paper, we focus our study on the scattering of objects with multiple small-scale grooves, where the grooves are of the same size.

As is known that many solutions have been developed to solve EM scattering problems of objects. Generally speaking, the computational accuracy of numerical methods is high, but its calculation process is complicated. In order to meet the demands of THz scattering computation, there is a high request for the computing capacity when adopting numerical methods. Meanwhile, because of the limitation of computational memory and time, it is difficult for a single computer to undertake such calculation task. Therefore, the high-frequency methods have been widely used for the study of THz scattering characteristics of objects. For example, the physical optics (PO) method has been employed to calculate the Radar Cross Section (RCS) of perfectly electrical conducting (PEC) objects in THz band [5], where the exact integration of polygon surfaces is obtained with independence of frequencies through properly manipulating to the double integration appeared in PO. In addition, the THz scattering characteristics of the coated object with a rough surface is analyzed based on the modified PO method in [6]. However, since PO method only takes the

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Zhao.

first-order scattering into consideration, its computational accuracy is low when dealing with the scattering of complex objects. Instead, the ray-based high-frequency method is a good choice, such as GO/PO method [7]–[9] or Shooting and Bouncing Rays (SBR) method [10]–[12]. Cui *et al.* [13] investigated the EM scattering characteristics of PEC targets in the THz frequency range through the use of ray-based high-frequency EM techniques. In this paper, GO/PO method is employed to study the THz scattering characteristics of objects with multiple small-scale grooves, where the multi-path scattering is calculated based on the principle of GO, and the scattered field is obtained by the PO.

For the ray-based high-frequency method, if no acceleration technique is adopted to speed up the ray tracing part, the computational time will be too long to tolerate, especially in the THz band. Kd-tree [14], [15], and Oct-tree [16], [17], which are based on adaptive space division, have been two commonly used ray tracing acceleration techniques. They provide an efficient way to reduce the intersection tests between the ray and facets. Therefore, the computational time needed to trace each ray is greatly reduced. On the other hand, with the significant improvement of computer hardware, Graphics Processing Units (GPUs) has been utilized to improve the computational efficiency of ray tracing process in EM scattering problems [18]–[21]. With the adoption of GPUs, the rays are traced in parallel fashion, which can save the total computational time.

In this paper, Oct-tree is chosen to improve the efficiency of GO/PO method, where the code is executed in CPU serial model. However, when deal with the scattering of objects with multiple small-scale grooves, although the computational efficiency of ray tracing has been improved with the use of Oct-tree, there still exists a large number of redundant intersection tests for the traditional GO/PO method.

The computational time will become a main concern with the continuous increase in the frequency and groove number. For this reason, the GO/PO method is further improved to meet the demand of THz scattering of objects with multiple small-scale grooves. Here, the scattered field from one of the grooves is computed and extended to obtain the scattered field from the other grooves according to their dimensional information. Therefore, the computational capability can be greatly improved without calculating the ray path in the other grooves. In current version, the computational load doesn't increase with the number of grooves, and the total CPU time is reduced. Our method provides an efficient way to investigate the THz scattering characteristics of objects with multiple small-scale grooves. It also establishes a good foundation for GPU implementation in our future work.

To demonstrate the validity of our method, the simulation results are compared with those of MLFMM, traditional GO/PO method and experimental data. A good agreement is achieved. Meanwhile, the runtime is compared with that of traditional GO/PO method, where the computational time is greatly saved. In the end, the scattering characteristics of objects with multiple small-scale grooves at THz frequencies is computed, and the effect of groove structure on the THz scattering characteristics has been analyzed.

II. EM SCATTERING FROM OBJECTS WITH MULTIPLE SMALL-SCALE GROOVES

With the combination of ray tracing, GO/PO method can handle the multiple scattering behavior. Therefore, it is very suitable for the EM scattering prediction of objects with multiple small-scale grooves. In this section, we focus on the efficient implementation of GO/PO method for EM scattering from objects with multiple small-scale grooves.

A. IMPLEMENTATION OF GO/PO METHOD

For the GO/PO method, the initial rays are launched from incident direction at first, where each initial ray tube consists of three corner rays, as shown in Fig. 1.

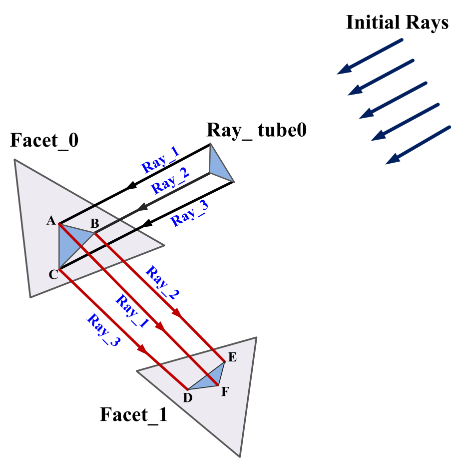


FIGURE 1. **Multiple bounces in the GO/PO method.**

First of all, the central ray of each ray tube is traced according to the principal of GO. An initial ray tube is considered invalid for EM computation if its central ray is sheltered by the triangular facets. In the contrast, if the central ray is not sheltered, it means that this ray tube is responsible for EM scattering.

Then the intersections between the three corner rays and the triangular facet are calculated to obtain the lighted area. It should be noted that if any of the three corner rays doesn't intersect with the triangular facet, the ray tube is considered invalid and discarded. As illustrated in Fig. 1, Ray_1, Ray_2 and Ray_3 intersect Facet_0 at A, B and C, respectively. Therefore, the illuminated area of the initial ray tube is ABC. Correspondingly, the first-order scattered field of Ray_tube0 is computed based on PO, which can be expressed as

$$\vec{E}_s(\vec{r}) = jkZ_0 \frac{e^{-jkr}}{4\pi r} \int_{ABC} \hat{k}_s \times \left[\hat{k}_s \times \vec{J} + \frac{1}{Z_0} \vec{M} \right] e^{jk\hat{k}_s \cdot \vec{r}'} ds \quad (1)$$

where $\vec{E}_s(\vec{r})$ is the far-scattered field, $\vec{r}$ is the position vector of observation point, $\vec{J} = \hat{n} \times \vec{H}$ and $\vec{M} = -\hat{n} \times \vec{E}$ are the electric and magnetic equivalent current densities of the object surface, respectively. $\hat{n}$ is the normal vector of scattering facet, $\vec{r}'$ is the position vector of the illuminated area. k is the wavenumber and $\hat{k}_s$ is the direction of scattered wave vector. Z_0 is the wave impendence in free space.

Next, the reflected ray rube reradiates as a secondary EM source. Similarly, the central ray is traced to find the intersected triangular facet, and the three corner rays to determine the illuminated area. According to GO theory, the incident electric field for the secondary intersection is

$$\vec{E}(\vec{r}_2) = \bar{\Gamma} \cdot \vec{E}(\vec{r}_1)\, e^{-jkr} \tag{2}$$

where $r = |\vec{r}_2 - \vec{r}_1|$ is the distance between the first and second intersections, and $\vec{r}_1$ and $\vec{r}_2$ are the first and second intersection, respectively. $\vec{E}(\vec{r}_1)$ and $\vec{E}(\vec{r}_2)$ represent the incident electric field at $\vec{r}_1$ and $\vec{r}_2$.$\bar{\Gamma}$ is the planar reflection coefficient matrix.

All the ray tubes are traced and the scattered field are calculated until they don't intersect with any triangular facet. In the end, the total scattered field is the summation of scattered field from each ray tube.

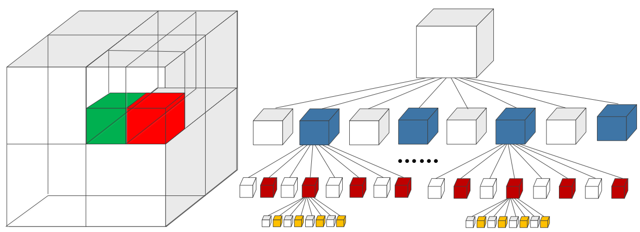


FIGURE 2. Oct-tree structure.

In this paper, the well-known Oct-tree structure is used to accelerate the ray tracing process. As shown in Fig. 2, the Oct-tree structure begins with the object space that is the smallest cubic volume containing the entire object structure. The Oct-tree can be constructed by recursively subdividing the cube into eight child cubes [17]. Triangular facets of object are stored in the related child cube. During the ray tracing process, a ray usually starts from root nodes to intra child nodes until finding the leaf nodes. The illuminated surface elements in the leaf nodes are determined by occlusion judgment.

B. IMPROVED GO/PO METHOD FOR EM SCATTERING FROM OBJECTS WITH MULTIPLE SMALL-SCALE GROOVES

In this paper, we aim at the EM scattering from objects with multiple small-scale grooves in THz band, as shown in Fig. 3.

Obviously, tracing the multiple bounces in groove structure is the most time-consuming part. Although Oct-tree has been used to speed up the ray tracing, if we strictly calculate the scattered field from each groove like the traditional GO/PO method, the computational time will become too long to tolerate with the continuous increase in the frequency and groove number. Therefore, the GO/PO method is further improved to meet the demand of efficient EM scattering prediction of objects with multiple small-scale grooves in THz frequencies.

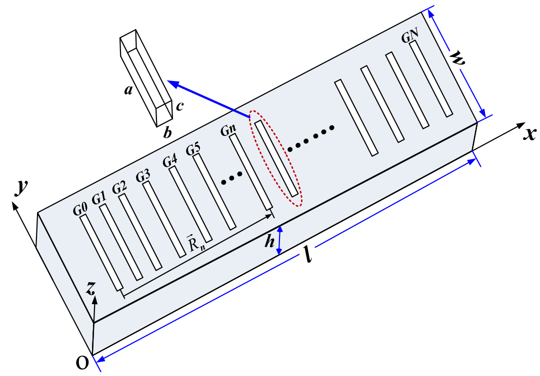


FIGURE 3. Object with multiple surface grooves.

As presented in Fig. 3, l, w and h represent the length, width and height of object, respectively. There are a series of grooves *G0*, *G1*, *G2*...... *GN* on object surface. All the grooves are of the same size, where a, b and c represent the length, width and height, respectively. According to the geometrical feature, the ray tube in each groove structure propagates in the same way. Therefore, it invoked us to find a convenient way to compute the EM scattering from the multiple surface grooves. Here, the scattered field from one of the grooves is calculated and extended to obtain the scattered field of the other grooves based on their dimensional information.

Without loss of generality, we take the first groove *G0* as an example. The scattered field from each ray tube in *G0* is calculated based on the GO/PO method at first. Let $\vec{R}_n = \vec{r}_n - \vec{r}_0$, where $\vec{r}_0$ and $\vec{r}_n$ are the center of *G0* and *Gn*, respectively. As ray paths in *Gn* is the same with those of *G0*, the scattered field from the same ray path in *Gn* can be obtained as following,

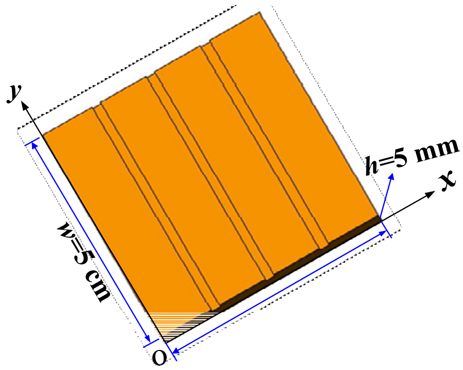
$$\begin{cases} \vec{E}_{sn}(\vec{r}) = \vec{E}_{s0}(\vec{r})\, e^{-j\vec{k}_i \cdot \vec{R}_n} \cdot e^{j\vec{k}_s \cdot \vec{R}_n} = \vec{E}_{s0}(\vec{r}) \cdot Q_n \\ Q_n = e^{-j\vec{k}_i \cdot \vec{R}_n} \cdot e^{j\vec{k}_s \cdot \vec{R}_n} = e^{j(\vec{k}_s - \vec{k}_i)\cdot \vec{R}_n} \end{cases} \tag{3}$$

where $\vec{E}_{s0}(\vec{r})$ and $\vec{E}_{sn}(\vec{r})$ are the scattered electric field from *G0* and *Gn*, respectively. Q_n represents the phase difference of scattered field caused by the relative displacement between *Gn* and *G0*.

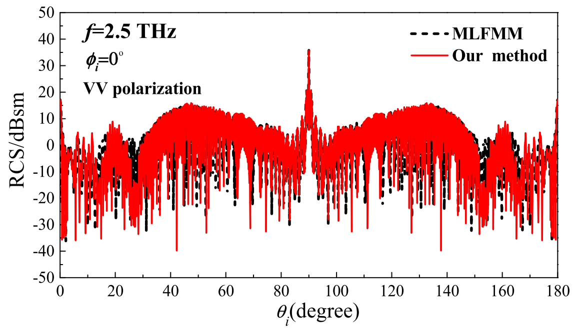
In the end, the scattered fields from all the grooves and the other component of object are summed to obtain the total scattered-field.

III. RESULTS AND DISCUSSION

The EM scattering characteristics of objects with multiple small-scale grooves in THz band is studied in this section. All the models are PEC objects. Our simulations by GO/PO method are executed on a personal computer with an Inter(R) Core(TM) i5-6500 3.2 GHz CPU and 8G main memory. Programs are built and run under the Windows 7 32-bit operating system. The CPU implementation is built with Microsoft Visual Studio 2015.



(a)



(b)

FIGURE 4. Backscattering RCS of an object with three grooves. (a) Simulation model. (b) Simulation results.

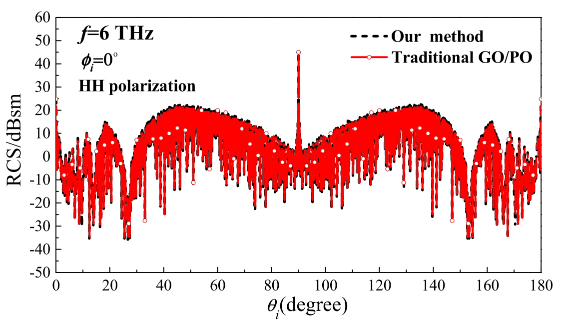


FIGURE 5. Comparison with traditional GO/PO method.

A. VALIDATION

Firstly, an object with three grooves is chosen to test the validity of the improved GO/PO method in this paper. The model is presented in Fig. 4(a), whose length, width and height are $l = 5$ cm, $w = 5$ cm and $h = 5$ mm, respectively. In addition, the size of each groove is $a = 5$ cm, $b = 2$ mm, $c = 1$ mm. The backscattering RCS at the frequency of 2.5 THz is studied and compared with the simulation result obtained by MLFMM, as shown in Fig 4(b). The incident angle varies from 0° to 180°, and the angular resolution is set as 0.1°. The incident azimuth angle is $\phi_i = 0°$(xoz plane). VV polarization is considered. As depicted in Fig. 4(b), a good agreement is achieved, and the efficiency of our method for EM scattering of the object with multiple surface grooves in THz frequency is verified.

TABLE 1. Runtime comparison.

Traditional GO/PO(s)	Our method(s)	Speedup ratio
6962.032	2003.958	3.474×

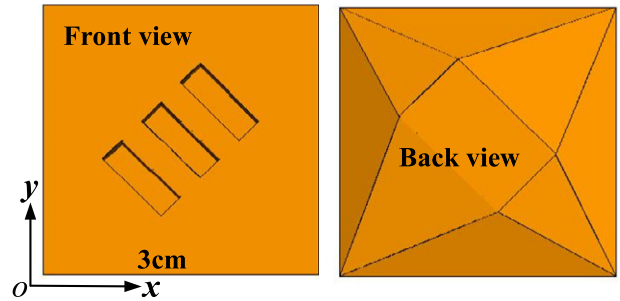


FIGURE 6. Simulation model.

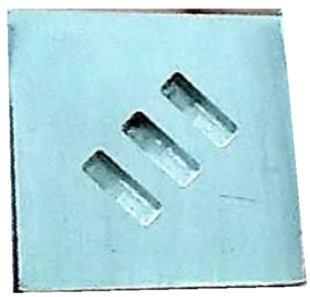


FIGURE 7. Real model for measurement.

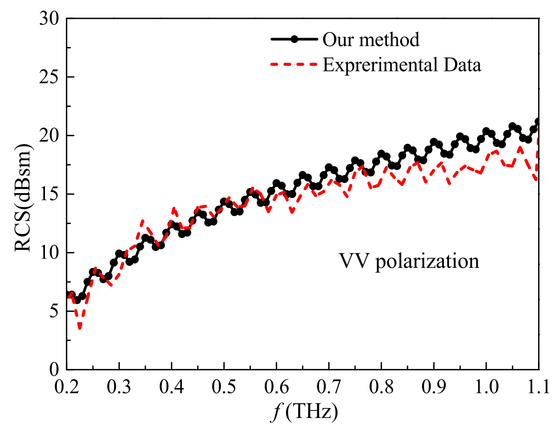


FIGURE 8. Bistatic RCS of an object with three grooves.

To further verify the efficiency of our method, the simulated backscattering RCS and runtime performance of our method are compared with those of traditional GO/PO method, as shown in Fig.5 and TABLE 1. The model is presented in Fig.4 (a). The frequency of incident wave is $f = 6.0$ THz. HH polarization is calculated. The other parameters are the same as those in Fig. 4. It should be noted that the computational time in TABLE 1 is the total CPU time for 1801 degrees.

Simulated results by our method and the traditional GO/PO method show a good agreement in Fig.5. Moreover,

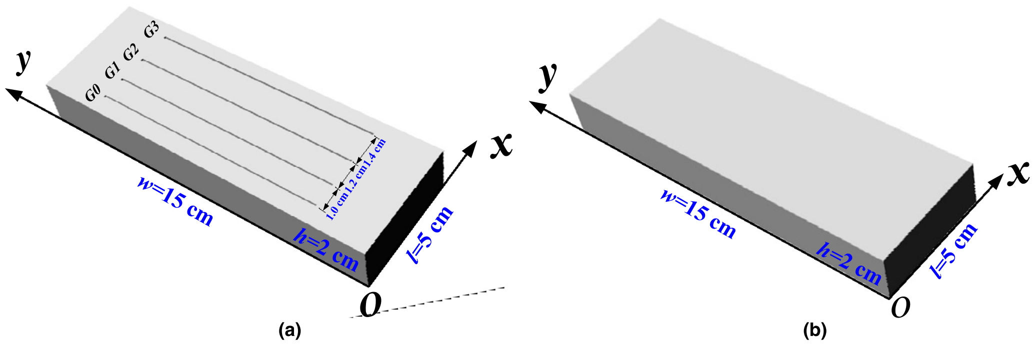


FIGURE 9. Objects with and without small-scale grooves. (a) With grooves. (b) Without grooves

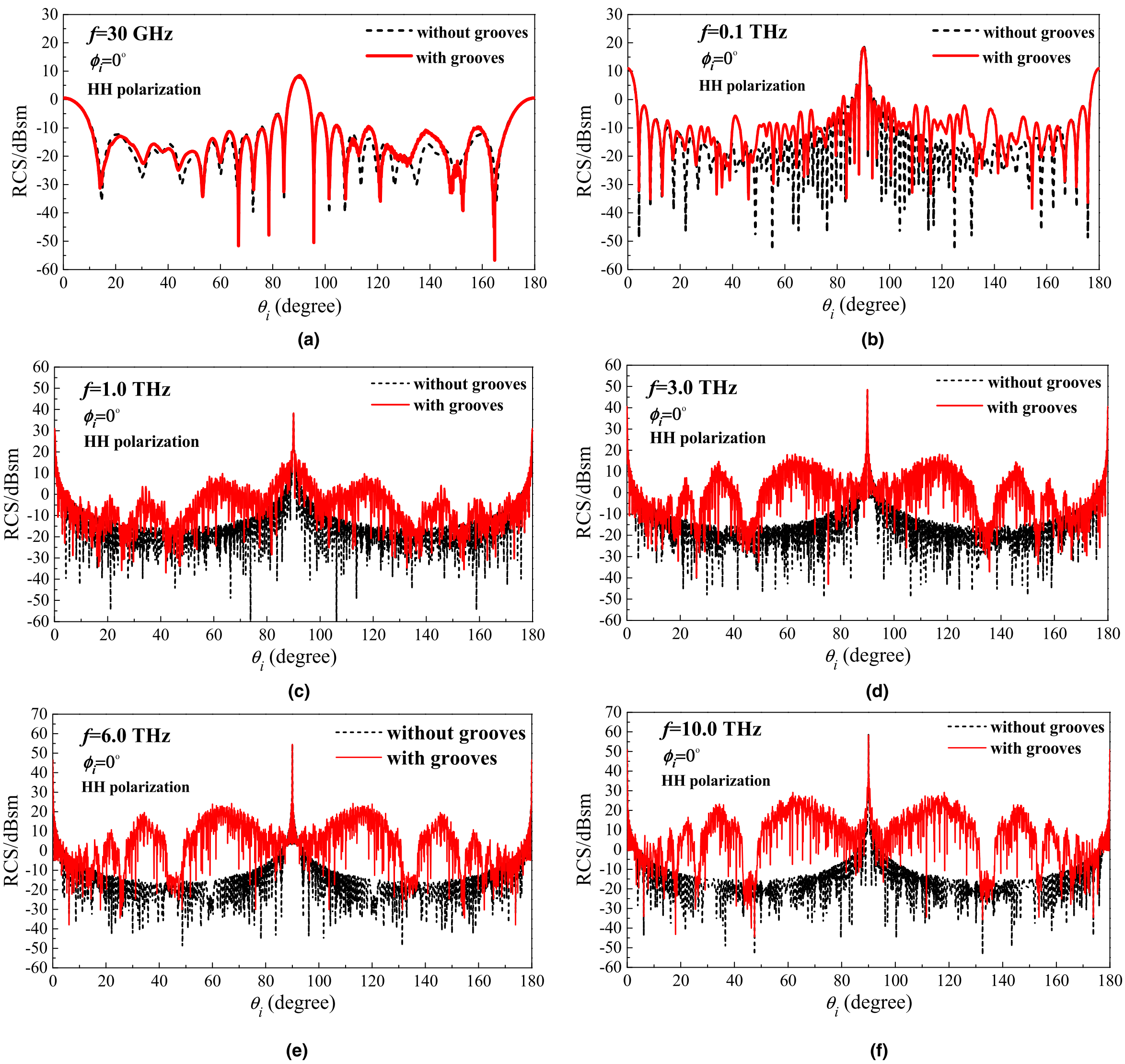


FIGURE 10. Objects with and without small-scale grooves backscattering RCS of objects with and without grooves. (a) $f = 30$ GHz. (b) $f = 0.1$ THz. (c) $f = 1.0$ THz. (d) $f = 3.0$ THz. (e) $f = 6.0$ THz. (f) $f = 10.0$ THz.

the computational time of our method is much shorter than that of the traditional GO/PO method, where the speedup ratio is 3.474. Therefore, the efficiency of our method for the THz scattering computation from objects with multiple small-scale grooves is further demonstrated.

Moreover, a different model with three grooves is utilized, which is 3 cm in length and width. The size of each groove is 9 mm * 3 mm * 3 mm. The bistatic scattering RCS for different frequencies is investigated, and the simulation result is compared with the experimental data

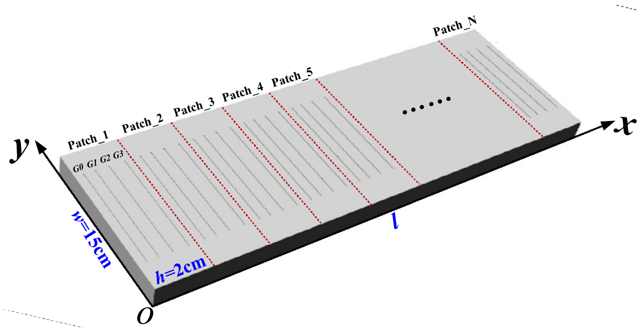


FIGURE 11. Simulation model of object with multiple small-sale grooves.

in Fig. 8. The simulation model and real model are presented in Fig. 6 and Fig. 7, respectively. The frequency varies from 0.2 THz to 1.1 THz. In addition, the incident and scattered angle are $\theta_i = \theta_s = 3.25°$, and the incident and scattered azimuth angle are $\phi_i = \phi_s = 0°$. VV polarization is considered.

As shown in Fig. 8, the bistatic scattering RCS calculated by our method is well consonant with the experimental data. It should be noted that the simulation results still have a certain difference with the experimental data, especially for the high frequencies. This is mainly caused by the fact that the experimental results are highly susceptible to the measurement environment. In addition, the modeling error and the measurement system error will also result in the difference between the simulation results and experimental data.

B. THz SCATTERING FROM OBJECTS WITH MULTIPLE SMALL-SCALE GROOVES

Fig. 9 shows the objects with and without grooves, which are 5 cm, 15 cm and 2 cm in length, width and height. In Fig.9 (a), there are four grooves on the object surface, and the interval between two neighbouring grooves is different. The size of each groove is 10 cm * 1 mm * 1 mm. The backscattering RCS of objects with and without grooves is compared to study the effect of small-scale groove structure on EM scattering, as shown in Fig. 10. Here the backscattering RCS at 30 GHz (microwave band) is calculated for reference in Fig. 10(a). The incident angle θ_i is 0° to 180°, and the angular resolution is 0.1°. The incident azimuth angle is $\phi_i = 0°$(xoz plane). HH polarization is considered.

As presented in Fig.10, it is obvious that the small-scale grooves have a significant effect on EM scattering characteristics in THz band. In Fig. 10(a), the backscattering RCS of object with grooves is similar to that of object without grooves at the frequency of 30 GHz in microwave band. It indicates that the groove structure has a little influence on EM scattering results when its size is much smaller than the wavelength of incident wave. In the contrast, backscattering RCS of objects with grooves differs greatly from that of object without grooves at THz frequencies, as shown in Fig.10(b) ∼ Fig.10(f). Especially in Fig.10(c) ∼ Fig. 10(f), compared with object without grooves, a noticeable enhancement of backscattering RCS is observed for incident angle $\theta_i = 20° \sim 70°$ and $\theta_i = 110° \sim 160°$ when there exists the groove structure. This is mainly benefiting from the strong

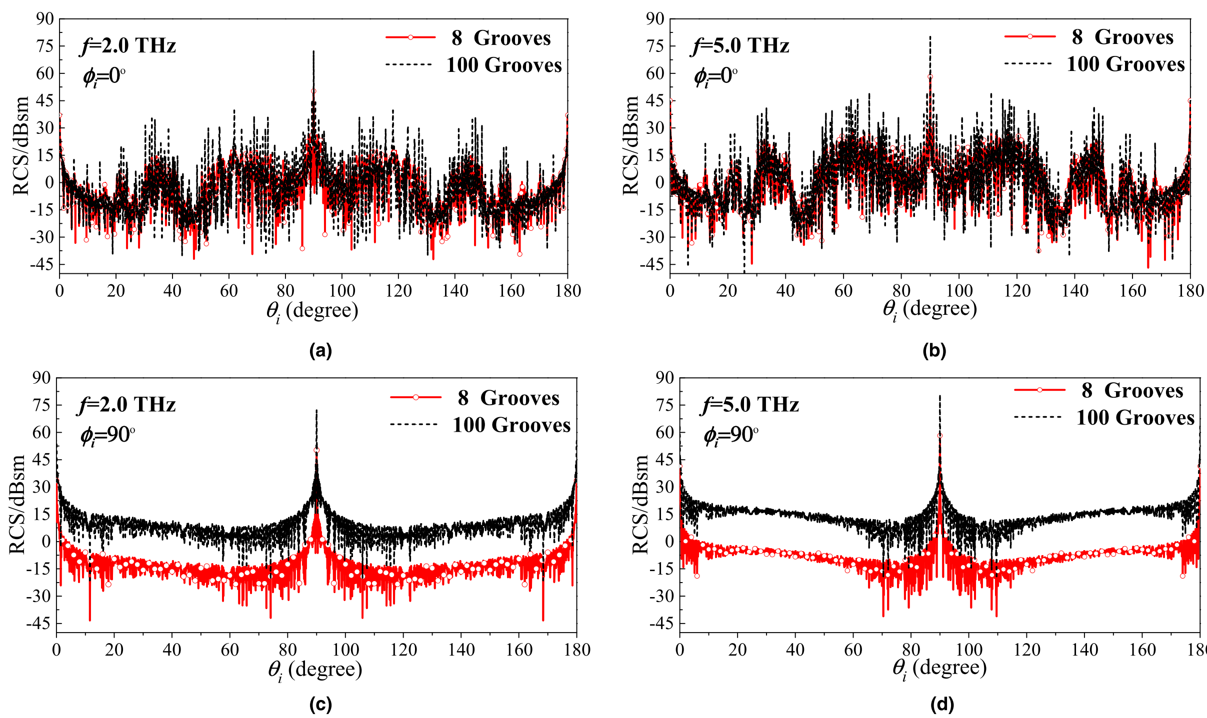


FIGURE 12. Backscattering RCS of objects with different number of multiple small-sale grooves. (a) $f = 2$ THz, $\phi_i = 0°$ (b) $f = 5$ THz, $\phi_i = 0°$ (c) $f = 2$ THz, $\phi_i = 90°$ (d) $f = 5$ THz, $\phi_i = 90°$.

scattering echoes from the multi-path in the groove. In a word, the small-scale groove will affect the EM scattering characteristics of objects greatly in THz band when its size is much larger than the wavelength of incident wave.

To further explore the influence of groove number on EM scattering characteristics in THz band, the object with multiple small-scale grooves, as shown in Fig.11, is constructed for calculation. Its width and height are 15 cm and 2 cm, respectively. The upper surface consists of a set of patches, and the profile of each patch is the same as that in Fig. 9(a). Assume that N and N_G represent the number of patches and grooves, respectively. Then, the length of object is related to the number of grooves and patches, which can be expressed as $l = N^*5\text{cm} = (N_G/4)^*5\text{cm}$.

Backscattering RCS of objects with 8 and 100 small-scale grooves has been simulated at frequencies of 2THz and 5THz, as shown in Fig. 12. HH polarization is considered. Both the incident azimuth angle $\phi_i = 0°$ (xoz plane) and $\phi_i = 90°$ (yoz plane) are calculated.

In Fig.12(a) and Fig.12(b), we observed that the trend of backscattering RCS is greatly influenced by the number of grooves in the case of incident azimuth angle $\phi_i = 0°$ (xoz plane). The main reason is that phases of scattered field from different patches are different for the incident azimuth angle $\phi_i = 0°$. However, when the incident azimuth angle $\phi_i = 90°$(yoz plane), it is obvious that $\vec{k}_i$ is perpendicular to $\vec{R}_n$. In this case, the phase difference of scattered field between *Gn* and *G0* is equal to zero ($Q_n = 0$). The scattered field from all the patches has the same phase. Therefore, a constant trend is observed in the backscattering RCS for different number of grooves in Fig.12(c) and Fig.12(d). Meanwhile, it is found that the backscattering RCS increased with the quantity of groove in the case of incident azimuth angle $\phi_i = 90°$.

IV. CONCLUSION

In this paper, the GO/PO method is adopted to analyze the EM scattering characteristics of objects with multiple small-scale grooves in THz band. In order to improve the computational efficiency, only the scattering from one of the grooves is calculated. Then the EM scattering from the other grooves can be obtained according to their dimensional information. Therefore, the computational capability can be greatly improved without calculating the ray path in the other grooves. Meanwhile, the computational load doesn't increase with the number of grooves, and the total CPU time is reduced. Our method provided an efficient way to investigate the THz scattering characteristics of objects with multiple small-scale grooves. It also establishes a good foundation for GPU implementation in our future work.

The validity of our method is demonstrated by comparing with the results of MLFMM, traditional GO/PO method and experimental data. Using the improved GO/PO method, the backscattering RCS of objects with and without grooves at THz frequencies is further studied. It indicates that the small-scale grooves have a great impact on THz scattering characteristics. Meanwhile, the influence of groove number on THz-wave scattering is discussed. Simulation results show that the trend of backscattering RCS changes with the number of grooves in the case of $\phi_i = 0°$. While it has the same trend for different number of grooves with $\phi_i = 90°$. In general, the improved GO/PO method has the ability for the EM scattering computation of objects with multiple small-scale grooves in THz band.

REFERENCES

[1] K. Moon, E. Jung, M. Lim, Y. Do, and H. Han, "Terahertz near-field microscope: Analysis and measurements of scattering signals," *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 1, pp. 164–168, Sep. 2011.

[2] Q. Jing, D. Liu, and J. Tong, "Study on the scattering effect of terahertz waves in near-surface atmosphere," *IEEE Access*, vol. 6, pp. 49007–49018, 2018.

[3] I. N. Dolganova, K. I. Zaytsev, S. O. Yurchenko, V. E. Karasik, and V. V. Tuchin, "The role of scattering in quasi-ordered structures for terahertz imaging: Local order can increase an image quality," *IEEE Trans. THz Sci. Technol.*, vol. 8, no. 4, pp. 403–409, Jul. 2018.

[4] G. Sundberg, L. M. Zurk, S. Schecklman, and S. Henry, "Modeling rough-surface and granular scattering at terahertz frequencies using the finite-difference time-domain method," *IEEE Trans. Geosci. Remote Sens.*, vol. 48, no. 10, pp. 3709–3719, Oct. 2010.

[5] X. J. Zhong, T. J. Cui, Z. Li, Y. B. Tao, and H. Lin, "Terahertz-wave scattering by perfectly electrical conducting objects," *J. Electromagn. Waves Appl.*, vol. 21, no. 15, pp. 2331–2340, 2007.

[6] H.-Q. Hua, Y.-S. Jiang, and Y.-T. He, "High-frequency method for scattering from coated targets with extremely electrically large size in terahertz band," *Electromagnetics*, vol. 35, no. 5, pp. 321–339, 2015.

[7] W.-F. Huang, Z. Zhao, R. Zhao, J.-Y. Wang, Z. Nie, and Q. H. Liu, "GO/PO and PTD with virtual divergence factor for fast analysis of scattering from concave complex targets," *IEEE Trans. Antennas Propag.*, vol. 63, no. 5, pp. 2170–2179, May 2015.

[8] T.-Q. Fan and L.-X. Guo, "OpenGL-based hybrid GO/PO computation for RCS of electrically large complex objects," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 666–669, 2014.

[9] J. X. Li, M. Zhang, and P. Wei, "Combination of GO/PO and PTD method for EM scattering and SAR image simulation from complex targets," in *Proc. IEEE Int. Symp. Antennas Propag.*, Jul. 2018, pp. 2467–2468.

[10] H. Ling, R.-C. Chou, and S.-W. Lee, "Shooting and bouncing rays: Calculating the RCS of an arbitrarily shaped cavity," *IEEE Trans. Antennas Propag.*, vol. 37, no. 2, pp. 194–205, Feb. 1989.

[11] T.-Q. Fan, L.-X. Guo, B. Lv, and W. Liu, "An improved backward SBR-PO/PTD hybrid method for the backward scattering prediction of an electrically large target," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 512–515, 2016.

[12] Y. B. Tao, H. Lin, and H. J. Bao, "Adaptive aperture partition in shooting and bouncing ray method," *IEEE Trans. Antennas Propag.*, vol. 59, no. 9, pp. 3347–3357, Sep. 2011.

[13] Z. Li, T. J. Cui, X. J. Zhong, Y. B. Tao, and H. Lin, "Electromagnetic scattering characteristics of PEC targets in the terahertz regime," *IEEE Antennas Propag. Mag.*, vol. 51, no. 1, pp. 39–50, Feb. 2009.

[14] M. Hapala and V. Havran, "Review: Kd-tree traversal algorithms for ray tracing," *Comput. Graph. Forum*, vol. 30, no. 1, pp. 199–213, 2015.

[15] S. Popov, J. Günther, H.-P. Seidel, and P. Slusallek, "Stackless KD-tree traversal for high performance GPU ray tracing," *Comput. Graph. Forum*, vol. 26, no. 3, pp. 415–424, 2007.

[16] A. S. Glassner, "Space subdivision for fast ray tracing," *IEEE Comput. Graph. Appl.*, vol. 4, no. 10, pp. 15–24, Oct. 1984.

[17] K. S. Jin, T.-I. Suh, S.-H. Suk, B.-C. Kim, and H.-T. Kim, "Fast ray tracing using a space-division algorithm for RCS prediction," *J. Electromagn. Waves Appl.*, vol. 20, no. 1, pp. 119–126, 2006.

[18] P.-B. Wei, M. Zhang, W. Niu, and W.-Q. Jiang, "GPU-based combination of GO and PO for electromagnetic scattering of satellite," *IEEE Trans. Antennas Propag.*, vol. 60, no. 11, pp. 5278–5285, Nov. 2012.

[19] Y. Tao, H. Lin, and H. Bao, "GPU-based shooting and bouncing ray method for fast RCS prediction," *IEEE Trans. Antennas Propag.*, vol. 58, no. 2, pp. 494–502, Feb. 2010.

[20] C. Y. Kee and C.-F. Wang, "Efficient GPU implementation of the high-frequency SBR-PO method," in *Proc. IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 941–944, 2013.
[21] C. Y. Kee, C.-F. Wang, and T. T. Chia, "Optimizing high-frequency PO-SBR on GPU for multiple frequencies," in *Proc. IEEE 4th Asia–Pacific Conf. Antennas Propag.*, Jun. 2015, pp. 132–133.

X. MENG received the B.S. degree in electronic information science and technology and the Ph.D. degree in radio science from Xidian University, Xi'an, China, in 2011 and 2017, respectively.

Her research interests include electromagnetic scattering from electrically large complex objects and rough sea surface, and GPU high-performance computing in remote sensing and computational electromagnetics.

L. X. GUO received the M.S. degree in radio science from Xidian University, Xi'an, China, and the Ph.D. degree in astrometry and celestial mechanics from the Chinese Academy of Sciences, China, in 1993 and 1999, respectively.

From 2001 to 2002, he was a Visiting Scholar with the School of Electrical Engineering and Computer Science, Kyungpook National University, South Korea. He was a Visiting Professor with d'Energetique des Systemes et Precedes (LESP), University of Rouen, France, and the Faculty of Engineering and Physical Sciences, University of Manchester, U.K. He is currently a Professor with Xidian University. His research interests include electromagnetic wave propagation and scattering in complex systems, computational electromagnetics, and fractal electrodynamics.

Dr. Guo is a Senior Member of the Chinese Institute of Electronics (CIE) and a Fellow of the Physics Institute of Shaanxi Province, China.

C. L. DONG received the B.S. degree in electronic information science and technology from Xidian University, Xi'an, China, in 2015, where he is currently pursuing the Ph.D. degree in radio science with the School of Physics and Optoelectronic Engineering.

His research interests include the areas of computational electromagnetics, and the electromagnetic scattering characteristics of the rough surface and the target.

Y. C. JIAO received the B.S. degree in mathematics from Shanxi University, Taiyuan, China, in 1984, and the M.S. degree in applied mathematics and the Ph.D. degree in electrical engineering from Xidian University, Xi'an, China, in 1987 and 1990, respectively, where he is currently a Professor.

In 1990, he joined the Institute of Antennas and EM Scattering, Xidian University. He was a Visiting Priority-Area Research Fellow of the University of Tsukuba, Tsukuba, Japan. From 1997 to 1998 and from 1999 to 2000, he was a Research Associate with The Chinese University of Hong Kong, Hong Kong. In 2002, he was a Research Fellow of the City University of Hong Kong, Hong Kong. In 1996, he was supported by the Japan Society or the Promotion of Science. His current research interests include antenna array, antenna design, computational electromagnetics, optimization algorithms and applications, and evolutionary computation.