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Integral staggered point-matching method for millimeter-wave reflective diffraction gratings on electron cyclotron heating systems

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HIGHLIGHTS

- The integral staggered point-matching method for design of polarizers on the ECH systems is presented.
- The availability of the integral staggered point-matching method is checked by numerical calculations.
- Two polarizers are designed with the integral staggered point-matching method and the experimental results are given.

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ABSTRACT

The reflective diffraction gratings are widely used in the high power electron cyclotron heating systems for polarization strategy. This paper presents a method which we call "the integral staggered point-matching method" for design of reflective diffraction gratings. This method is based on the integral point-matching method. However, it effectively removes the convergence problems and tedious calculations of the integral point-matching method, making it easier to be used for a beginner. A code is developed based on this method. The calculation results of the integral staggered point-matching method are compared with the integral point-matching method, the coordinate transformation method and the low power measurement results. It indicates that the integral staggered point-matching method can be used as an optional method for the design of reflective diffraction gratings in electron cyclotron heating systems.

1. Introduction

Owing to short wavelength of the millimeter-wave and the submillimeter-wave, gratings in optics are widely used in these two frequency regions as antennas, sub-devices in amplifiers, filters, polarizers, and so on [1–4]. When used as polarizers, an important application of gratings is in the high power and long pulse electron cyclotron heating (ECH) systems, where the available sources are gyrotrons and the output waves are linearly polarized with power from a few hundred kilowatts up to one megawatt [5,6]. For plasma heating and current drive with electron cyclotron waves, not only linearly polarized but also elliptically polarized waves are needed for high efficient coupling between waves and plasma [7]. To realize various polarizations, reflective diffraction gratings (RDGs) with high power capability are normally installed in such systems for polarization strategy [3,4,8–10].

The schematic of a RDG for modulating polarization of a wave on the ECH system is shown in Fig. 1 [9]. The RDG is a periodic-metallic-groove grating and different polarization of the reflected wave can be obtained by rotating the grating (Fig. 1(a)). For a RDG with a fixed incident angle, the polarization characteristic is mainly determined by the shape, depth, and period of grooves (Fig. 1(b)). Normally, nonrectangular grooves without sharp edges are used to improve the power capability of a RDG for high power ECH systems, especially the systems in the megawatt level [3,9].

For solution of the problem in Fig. 1, various rigorous numerical methods, such as the integral point-matching method (IPMM) [11], the coordinate transformation method (C-method) [12], and the rigorous-coupled-wave analysis [13], have been developed in the past few decades. Among these methods, the IPMM is one of the most attractive and useful method for design of polarizers in the ECH systems [3,4]. The basic idea of the IPMM is as follows [11]:

(1) Considering the Maxwell equations and the boundary conditions of the grating, integral equations can be obtained;

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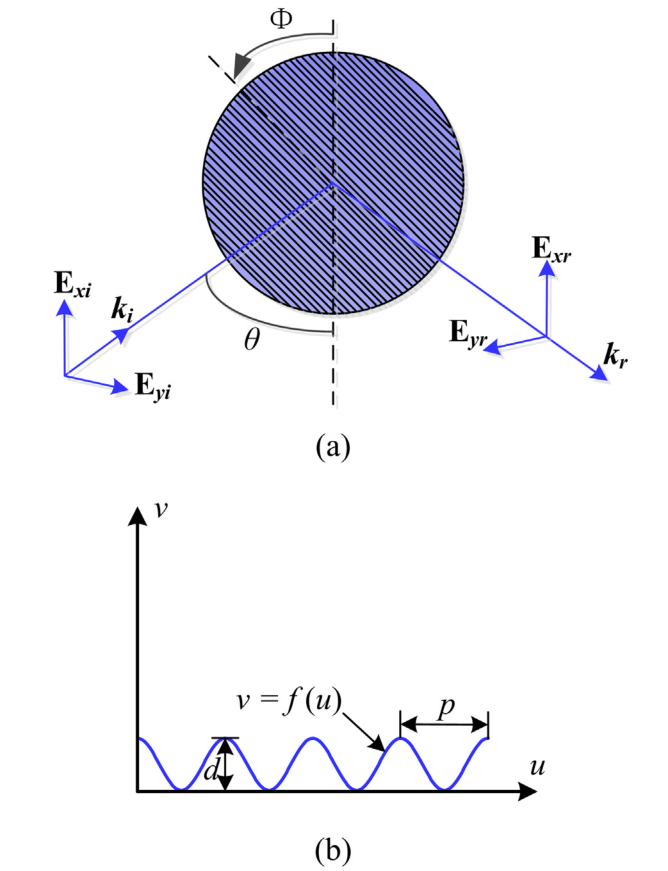

Fig. 1. Schematic of a reflective diffraction grating. (a) The coordinate system. θ and Φ are the incident angle of the wave and the rotation angle of the grating; ($\mathbf{E}_{xi}$, $\mathbf{E}_{yi}$) and ($\mathbf{E}_{xr}$, $\mathbf{E}_{yr}$) are electric field components of the incident and reflected waves; $\boldsymbol{k}_i$ and $\boldsymbol{k}_r$ are the wave vectors, the direction of grooves is parallel to $\mathbf{E}_{xi}$ at $\Phi = 0$. (b) Parameters of grooves for wave polarization. The shape of grooves is defined by $v = f(u)$; d and p are the depth and period of grooves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2) Discretizing the integral equations on the grating profiles with the point-matching method and linear equations related to the diffraction efficiency can be obtained;
(3) Solving the linear equations with numerical calculation tools, and getting the relationship between the reflected wave and the incident wave.

Although the process of the IPMM has been proved to be rigorous, the convergence problems [11] sometimes may confuse the users, especially those who are not familiar with the integral method and incorrect results will be obtained. In addition, tedious calculations [11] should be done to remove the convergence problem, which makes the use of this method become difficult for the millimeter wave (MMW) researchers.

To make the IPMM more accessible to those who only need to use this method for design, the integral staggered point-matching method (ISPMM) is proposed in this paper. In Section 2, the basic idea of the ISPMM and the difference between the IPMM and ISPMM are given. We show the numerical calculation results and compare the results with the C-method in Section 3. Finally, the experimental results are presented in Sec. 4 and conclusions are briefly summarized in Section 5.

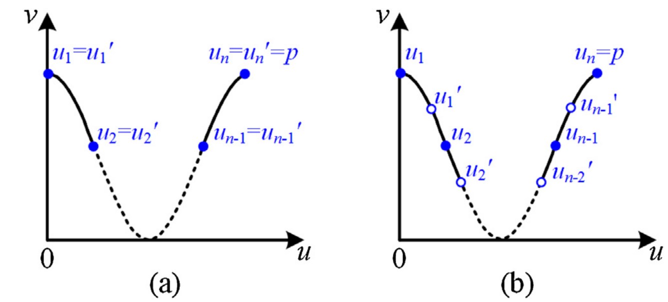

Fig. 2. Principle of the integral point matching method (left) and the integral staggered point-matching method (right). u_j for $1 \le j \le n$ and u_r' for $1 \le r \le n$ are the discrete points for numerical calculation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Theory

2.1. Integral equations

For the grating in Fig. 1, the incident wave should be firstly decomposed to two kinds of modes for calculation of diffraction coefficients [11]: (1) the TE polarization mode without a magnetic component in the direction of grooves; (2) the TM polarization mode without an electric component in the direction of grooves. Then using the basic theory of integral method, we can derive a set of equations for these two modes [3,11]

$$A_{hm} = \int_0^p \frac{\varphi_m(u)c_m}{2ip\beta_h} \exp\left[-i\alpha_h u - i\beta_h f(u)\right] du, \tag{1}$$

$$\varphi_m(u) = 2\varphi_{0m}(u) + 2\int_0^p N_m\left(u, u'\right)\varphi_m\left(u'\right) du' \tag{2}$$

$$\varphi_{0m}(u) = d_m \exp[ik_e u \sin\theta_e - ik_e f(u)\cos\theta_e], \tag{3}$$

$$N_m(u, u') = \frac{1}{2p}\sum_{l=-\infty}^{+\infty} \begin{array}{l} \left\{sign[f(u) - f(u')] - \alpha_n f'(g_m)/\beta_n\right\} \\ \times \exp(i\alpha_l(u - u') + i\beta_l|f(u) - f(u')|) \end{array}. \tag{4}$$

Here $m = 1$ and 2 correspond to the TE and TM polarization mode respectively; $f(u)$ is the shape function of grooves as shown in Fig. 1 and $f'(u) = \partial f(u)/\partial u$; h is an integer and A_{hm} is the hth diffraction coefficient; $c_1 = 1$, $d_1 = -ik_e\,[\cos\theta_e + f'(u)\sin\theta_e]$, $g_1 = u$ and $c_2 = ik_e\,[\beta_h - \alpha_h f'(u)]$, $d_2 = 1$, $g_2 = u'$; *sign* $(x > 0) = 1$, *sign* $(x < 0) = -1$ and *sign* $(0) = 0$. The parameters θ_e, k_e, α_h and β_h are defined as

$$k_e = 2\pi\sqrt{1 - (\sin\theta\sin\Phi)^2}/\lambda, \tag{5}$$

$$\cos\theta_e = \cos\theta/\sqrt{1 - (\sin\theta\sin\Phi)^2}, \tag{6}$$

$$\alpha_h = k_e\sin\theta_e + 2\pi h/p, \tag{7}$$

$$\beta_h = \sqrt{k_e^2 - \alpha_h^2}. \tag{8}$$

where λ is the wavelength; the definition of θ and Φ is shown in Fig. 1.

Once the incident angle θ, the rotation angle Φ, the shape function $f(u)$ and the frequency of the wave are known, the diffraction coefficients can be obtained by solving Eqs. (1)–(2).

2.2. Integral staggered point-matching method

As seen in Eqs. (1)–(2) for the calculation of diffraction coefficients, Eq. (2) should be firstly solved. Eq. (2) is a Fredholm integral equation [11] and cannot be directly solved by analytical method. The basic idea of IPMM for solving Eq. (2) are shown in Fig. 2(a), where Eq. (2) is written at n points and the integral part in the right