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Polarizers with non-rectangular grooves for high power millimeter waves

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Abstract

Polarizers with non-rectangular grooves are studied in high power millimeter wave transmission lines for electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) of fusion plasmas. The groove shape is important for determining the polarization parameters and avoiding arc breakdown in the system. A low-power measurement has been carried out for several polarizers with different groove depths. The polarization characteristics experimentally measured are in good agreement with numerical results in which the actual groove shape is taken into account. The polarizers are designed and applied to different frequencies of ECH/ECCD systems. Favorable results have been obtained in high-power transmission up to 500 kW, 0.2 s.

Keywords: High power millimeter wave; Polarizer; Non-rectangular groove; Electron cyclotron heating and current drive

1. Introduction

Polarizers are assembled in high power millimeter wave transmission lines to obtain the desired polarization for electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD). A grooved mirror can work as a polarizer both in the HE11 mode waveguide and quasi-optical transmission lines. Universal polarizers have been proposed for a Gaussian beam propagating through free space using two or three mirrors, that is, combinations of smooth and grooved mirrors can give arbitrary polarization [1]. Kopp et al. [2] have solved Maxwell's equations using finite difference method to obtain the near and far field distribution of waves in front of rectangular or sinusoidal grooved mirrors in the perpendicular incident case. The grooved mirror can work as a polarizer also in the HE11 mode waveguide transmission line when installing it on a miter-bend. Doane [3] has investigated the performance

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of rectangular grooved mirrors in a waveguide line, and has shown that his experimental results are in good agreement with the plane wave theory when the waveguide is oversized ($D/\lambda \gg 1$, where D is waveguide diameter and λ is wavelength).

The polarization parameters such as rotation and ellipticity are obtained once the phase shift between the field components parallel and perpendicular to the grooves, and the mirror rotation angle are given. The phase shift is a function of groove parameters of pitch, depth and shape. For rectangularly grooved mirrors, it is simply calculated by expanding the fields into the Fourier components [4]. However, the rectangular groove is not suitable for high power application, because the electric field is enhanced at the edge of the metallic groove surface, leading to a high possibility of electrical arc breakdown. The rounding of the groove or the sinusoidal shape is preferable for avoiding the arc breakdown in the transmission line of high power ECH. However, modification of the groove gives rise to a change in the phase shift between the modes, making it hard to predict the performance. Also it is not easy to manufacture the ideally designed shape especially for the higher frequency (short wavelength) case, since the groove shape has more fine structure.

In this paper, non-rectangularly grooved polarizers in a high power millimeter wave transmission line are studied. Several kinds of grooved mirrors have been manufactured and tested. Low power measurements of the polarization are compared with numerical calculation results in which the actual groove shape is taken into account. Following the low power measurement results, we have designed and manufactured the polarizers for the ECH and ECCD system with different frequencies on several fusion devices. High power transmission results in the plasma experiment are also shown. The organization of this paper is as follows. The geometry of the polarizer is described in Section 2. The low power experiments and numerical calculations are shown in Section 3. Application of the polarizers to ECH/ECCD systems is shown in Section 4. Conclusion is given in Section 5.

2. Geometry

Geometry of the system is illustrated in Fig. 1. The incident wave is assumed to be linearly polarized. The direction of the incident wave is determined by the angle ψ. The angles, θ and ϕ, are the spherical coordinates, and the grooved mirror is rotatable around the normal axis of the mirror by the angle, Φ. The plane of incidence is perpendicular to the plane of the polarizer. The linearly polarized incident wave can be changed into the elliptically polarized reflected wave by the grooved mirror. The polarization of the reflected wave is characterized by the rotation angle, α, and the ellipticity, β, of the ellipse. To determine the relation between the incident and reflected waves,

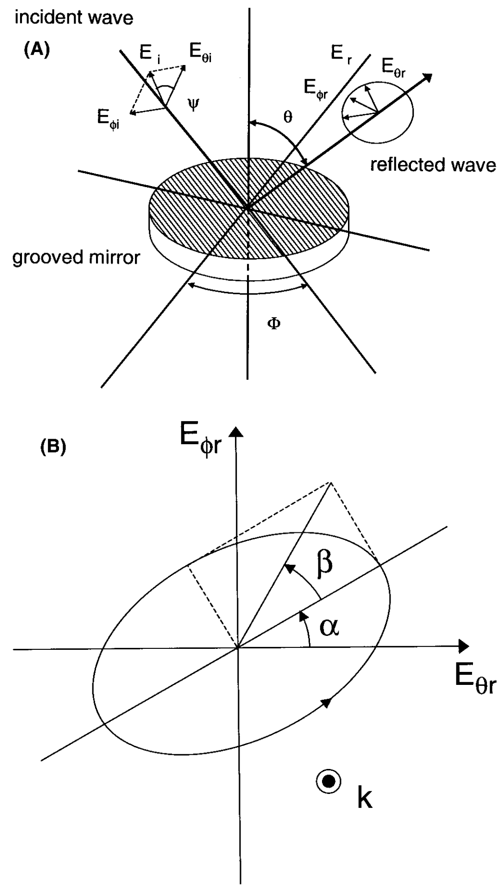

Fig. 1. Schematic view of polarizer, and incident and reflected waves (a) whole geometry and (b) rotation α and ellipticity β of reflected wave.

the incident field is decomposed into two orthogonal modes, the TE- and TM-like modes, respectively. The magnetic field of the TE-like mode does not have a component in the groove direction, and the electric field of the TM-like mode does not have a component in the groove direction. The TM-like mode penetrates into the grooves, while the TE-like mode is reflected at the surface, leading to a phase shift between them. The relation between the incident and reflected waves is given as

$$\begin{pmatrix} E_{\theta r} \\ E_{\phi r} \end{pmatrix} = E_0 \begin{pmatrix} \cos\psi & \cos(2\xi+\psi) \\ -\sin\psi & \sin(2\xi+\psi) \end{pmatrix} \begin{pmatrix} \cos(\tau/2) \\ i\sin(\tau/2) \end{pmatrix} \quad (1)$$

where the suffix, r, denotes the reflected wave. The parameter, ξ, is given by $\xi = \tan^{-1}(\tan\phi \cdot \cos\theta)$, and satisfies the relation, $E_\theta \sin\xi + E_\phi \cos\xi = 0$, for the TM-like mode. The phase difference, τ, between the TE- and TM-like modes has the same definition as in [5]. When we define the phase shift between $E_{\theta r}$ and $E_{\phi r}$ as δ, then the angles, α and β, of the reflected wave are obtained by solving

$$\tan 2\alpha = \tan 2\gamma \cdot \cos\delta \quad (2)$$

$$\sin 2\beta = \sin 2\gamma \cdot \sin\delta \quad (3)$$

where $\gamma = \tan^{-1}(E_{\phi r}/E_{\theta r})$, $-90° \leq \alpha \leq 90°$, $-45° \leq \beta \leq 45°$. If $\delta > 0$, the rotation is left-handed, and if $\delta < 0$, the rotation is right-handed. More details are written in [4].

3. Performance of a single grooved mirror

The phase shift is a function of the groove parameters and the mirror rotation angle. The groove is characterized by the period, p, the depth, d, and its shape. Several types of grooved mirrors are manufactured to investigate the effect of groove shape. Fig. 2 shows the shape of grooves. The shape is measured by a replica method conventionally utilized for the metallic surface measurement. The period is fixed as 0.48λ, which satisfies the condition, $p < \lambda/(1 + \sin\theta \cdot \cos\phi)$, that is, only the zeroth-order mode is propagating. The depth has a wide range from

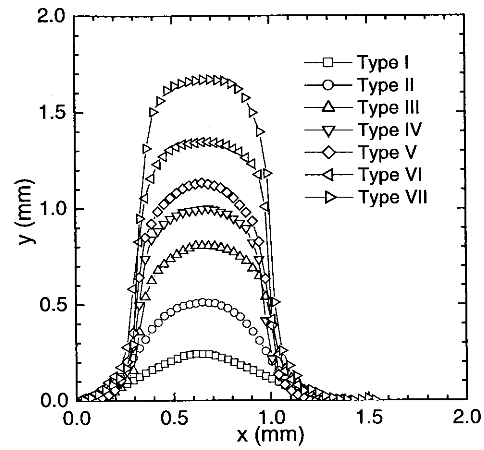

Fig. 2. Measured groove shapes. The pitch is the same, $P = 0.48\lambda$, for all the grooves.

0.086 to 0.527λ. Here λ is 2.82 mm ($f = 106.4$ GHz). The rounding of the top edge makes the TE-like mode penetrate into the groove, while rounding the bottom edge makes the TM-like mode less penetrate into the groove, becoming smaller with an increase of rounding.

Low power measurements have been performed in the HE11 mode transmission system to measure the polarization parameters. In the low power experiment, we use the same transmission components as in the high power measurement such as straight waveguides and miterbends. Details of the low power test are described in [6]. Because the waveguide is highly oversized for the HE11 mode, $D/\lambda = 22.5$, a plane reflector can be used at the miterbend. A grooved mirror is easily installed on the miterbend by replacing the flat mirror. The grooved mirror is rotatable with an accuracy of 0.1°, which is enough to measure polarization parameters. The miterbend has an elliptical opening in the back, and the grooves in the circular mirror fully covers this opening. The polarization parameters are measured by rotating a crystal diode setting on a two-dimensional scanning and rotatable system. The detected signal is a sinusoidal function of the detector rotation angle. The rotation angle, α, is estimated by the shift of the peak position, and the ellipticity is estimated by $\beta = \tan^{-1}(\sqrt{I_{max}/I_{min}})$ where I_{max} and I_{min} are the maximum and minimum signal amplitudes, respectively.

Fig. 3 shows the examples of polarization parameters as a function of the mirror rotation angle. The type III mirror works almost as a circular polarizer, because the ellipticity is high, 38°, at $\Phi = 60$ and 120°. On the other hand, the type V mirror works as a linear polarizer, because the 90° rotation of the incident wave can be made with small ellipticity at $\Phi = 55$ and 125°. With combination of both mirrors, we would expect a wide polarization parameter range. It is also confirmed that the reflecting beam profile is nearly Gaussian regardless of the mirror rotation angle, and the cross polarization is less than 20 dB in the whole region. The $1/e$ power radius of radiating beam is 29.6 mm at the distance $z = 800$ mm, which is close to the theoretical value using a far-field approximation, 28.8 mm [7].

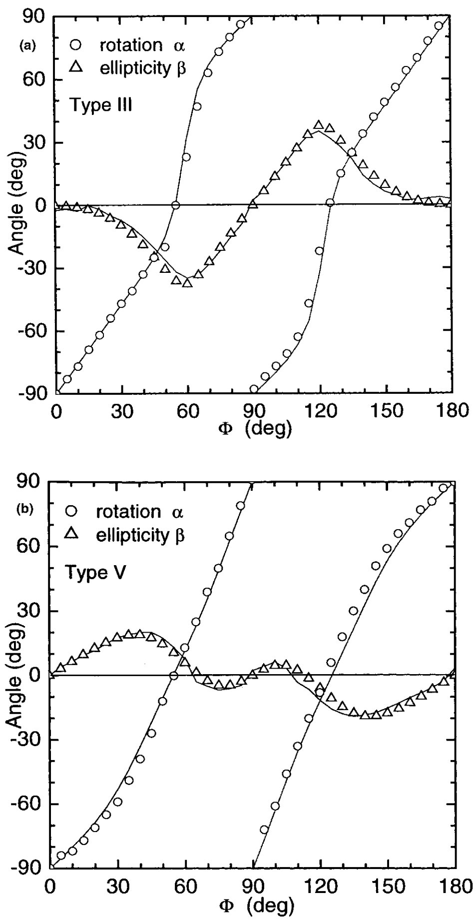

Fig. 3. Dependence of rotation angle and ellipticity on mirror rotation angle (a) type III, $d = 0.286\lambda$ and (b) type V, $d = 0.402\lambda$. The circles and triangle symbols denote the measured rotation angle and ellipticity, respectively. The solid curve denotes numerical calculation results.

For polarizer designs, we compare the experimental data to the numerical results obtained by using the integral method developed in vector theories of diffraction gratings [8]. Waves reflected by a grooved mirror are expanded into a series of plane waves with their coefficients being obtained by solving two integral equations derived for TE- and TM-like modes. Thus we have the phase difference, τ, in Eq. (1) between the fundamental TM- and TE-like modes of reflected waves for arbitrary groove shape. First, we consider the case of the plane of incidence being normal to the groove. The field function of reflected waves, $F(x, y)$, is written in the form,

$$F(x, y) = \sum_{-\infty}^{\infty} B_n \phi_n(x, y) \quad (4)$$

where

$$\phi_n(x, y) = \exp(ik_{xn}x + ik_{yn}y)$$

$$k_{xn} = k \sin\theta + \frac{2n\pi}{p} \quad (5)$$

$$k_{yn} = \sqrt{k^2 - k_{xn}^2}$$

k is the wave number, θ the angle of incidence, x and y are the coordinates perpendicular and parallel to the grooves on the mirror surface, respectively, and n has a range $-\infty < n < +\infty$. The function, F, gives the wave electric field for the TE mode and the magnetic field for the TM mode. The coefficients, B_n, are obtained for these modes as a integral function including the groove shape function [6]. The field calculation can also be carried out for the case that the plane of incidence is not normal to the grooves by using the theorem of invariance [8], i.e. by replacing the wavelength, λ, with $\lambda_e = \lambda/\cos\Lambda$, and the angle of incidence, η, with $\eta_e = \cos^{-1}(\cos\eta/\cos\Lambda)$, where Λ is the angle between the incident wave vector and the plane normal to the mirror and the grooves, i.e.

$$\Lambda = \cos^{-1}\{\sqrt{1 - (\sin\eta\cos\iota)^2}\} \quad (6)$$

with ι being the angle between the grooves and the plane of incidence. We have the coefficients,

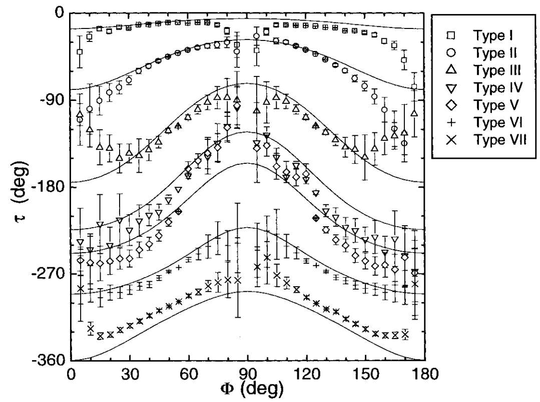

Fig. 4. Phase difference as a function of polarizer rotation angle. The solid lines correspond to the numerical calculation results.

B_0^{TE} and B_0^{TM}, of the fundamental TE and TM modes, respectively, and obtain the phase difference as $\tau = \arg(B_0^{\mathrm{TE}}) - \arg(-B_0^{\mathrm{TM}})$. Solid curves drawn in Fig. 3 show the numerical results, where the groove shape data shown in Fig. 2 are used to calculate the phase differences. We see that the results are in good agreement with the experimental data.

We also compare the phase difference between the experiment and calculations, which is important for determining the polarizer performance. Fig. 4 shows the phase difference as a function of the mirror rotation angle. The experimental and theoretical results of all types of grooved mirrors are plotted. With an increase of groove depth, the phase difference becomes more negative. The dependence on the polarizer rotation angle is similar to that of the rectangularly grooved mirror, but the absolute value is smaller. The deviation from the calculation is large when Φ is around 0, 90 and 180°. This is because small measurement errors less than 1° in Φ, α and β give rise to a big error in the phase difference there. The deviation may also attribute to the roughness of groove surface, 50–0.02λ, related to the machining accuracy. However, the phase difference is found to be in good agreement between them for all type of mirrors at $\Phi = 45°$ where the error is rather small. This indicates that the polarizer performance can be calculated from the developed numerical code including the actual grooved shape without performing low power measurement.

4. Application to ECH/ECCD systems

Following the low power measurement results and the comparison with the numerical results, we have designed and manufactured the polarizers for ECH/ECCD systems on fusion devices. The applied ECH/ECCD systems are listed in Table 1. The frequency range is relatively wide from 28 to 106.4 GHz.

The polarizer is used in the Heliotron E helical device for studying profile control, wave propagation and absorption. The 106.4 GHz ECH system has 500 kW RF power and 0.2 s pulse length [9]. A grooved mirror has been installed on a miter-bend in the HE_{11} mode waveguide transmission system. The insertion loss has been measured by comparing the RF power with and without the polarizer. The measurement result shows that the insertion loss is about 2%, and the transmitted power is found to have a weak dependence on the groove direction. Beam pattern measurements are

Table 1
Parameter list of ECH and ECCD systems and manufactured grooved mirrors

Frequency (GHz)	Power (kW)/pulse length (s)	Peak power density (kW cm^{-2})	Transmission line	Groove shape	Plasma device
28	200/0.04	52.0	Waveguide	Sinusoidal	H-1NF
53.2	200/0.1	52.0	Waveguide	Roundly edged rectangular	Heliotron J
89.6	180/0.03	10.5	Quasi-optics	Sinusoidal	WT-3
106.4	500/0.2	130.0	Waveguide	Roundly edged rectangular	Heliotron E

made with an infrared camera at the last waveguide mouth. The measured radiated beam shape is circularly Gaussian, and the $1/e$ beam radius is close to the analytical value $0.455a$, where a is the waveguide radius. There is no clearly visible distortion in the Gaussian beam shape even when rotating the polarizer. The transmission line with the polarizer works well in the atmospheric pressure.

The polarizer is applied for ECH plasma experiment on Heliotron E in order to study effects of the magnetic shear on ECH launching condition [10,11]. The electron cyclotron wave can be controlled from the O-mode to X-mode, and the electron temperature in the core plasma is shown to change from 1 to 2 keV, depending on the propagating modes. The dependence of the deposited power density in the core plasma on the polarization rotation angle is in good agreement with a numerical calculation result including the magnetic shear effect. This indicates that the polarizer works in the same manner as in the low power test.

A waveguide transmission line is designed and now under construction for 28 GHz ECH on the H-1NF heliac device. The groove mirror is assembled on a miterbend in the same manner as Heliotron E. Fig. 5 shows the calculated polarization parameter range using the two grooved mirrors with different groove depth. We have measured the polarization using a single mirror and confirmed that it agrees with the numerical results. A wide range of polarization is available by choosing the groove depth properly. It is possible to control the rotation angle, α, arbitrarily with keeping the ellipticity, β, constant, and vice versa.

The polarization system has also been designed and manufactured for 89.4 GHz ECH/ECCD experiment at the WT-3 tokamak. It is assembled into the quasi-optical transmission line. The required polarization condition is that the ellipticity should be ranged from -37 to $+37°$, while the long axis of ellipse is kept perpendicular to the magnetic field of WT-3 tokamak plasma. Two grooved mirrors are used to obtain such desirable polarization parameters. The diameter of mirrors is 300 mm, the pitch of grooves is 0.54λ (1.80 mm), and the depth is 0.24λ (0.80 mm) and 0.40λ

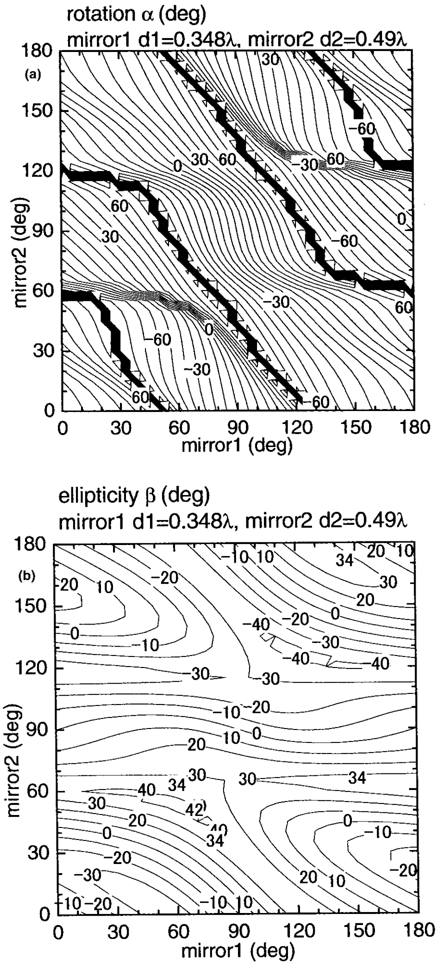

Fig. 5. Range of polarization parameters using two groove mirrors (a) rotation angle, α, and (b) ellipticity, β. The groove depth is 0.348λ and 0.49λ ($\lambda = 10.71$ mm) for first and second mirrors, respectively.

(1.34 mm) for first and second mirrors, respectively. The incident angle is set as 45° for both mirrors. The polarization parameters are measured in low power test by varying the mirror rotation angles systematically. The measurement results show that the polarizers works well as expected. These polarization parameters are also confirmed in the high power test using 89.6 GHz gyrotron source. No breakdown problem happens at any combination of mirror rotation angles. The ECCD experiment using this system is described in [12].

5. Conclusions

Polarizers with nonrectangular grooves have been studied in high power millimeter wave transmission line for ECH and ECCD experiments. The groove shape is important for determining the polarizer's performance and avoiding the arc breakdown in the transmission line. The deviation from the rectangular or sinusoidal shape affects the phase difference between the TE-like and TM-like modes, leading to a hard prediction of polarization performance. Several grooved mirrors with different groove depth and shape have been manufactured and tested in the low power (mW) measurement. A numerical code has been developed taking into account the actual groove shape. The calculation results are in good agreement with the low power measurement results. Since this numerical code is applicable to any grooved shape and millimeter range of frequencies, we can expect to design the future polarizer without experimental measurement.

Following the low power measurement results, we have designed the polarizers and applied to some ECH/ECCD systems in fusion devices. No arc breakdown is observed in both HE11 mode waveguide and quasi-optics systems within the available power and pulse length up to 500 kW and 0.2 s. The insertion loss is estimated to 2%, and is weakly dependent on the mirror rotation angle. Polarization control experiments have successfully performed in Heliotron E and WT-3. The polarizers will also be used for the plasma experiment on H-1NF and Heliotron J in the near future.

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