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Optimized design of polarizers with low ohmic loss and any polarization state for the 28 GHz QUEST ECH/ECCD system

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Abstract

In a high-power long-pulse millimeter-wave transmission line for electron cyclotron heating and current drive (ECH/ECCD), the ohmic loss on the grooved mirror surface of polarizers is one of the important issues for reducing the transmission loss. In this paper, the ohmic loss on the mirror surface is evaluated in simulated real-scale polarizer miter bends for different groove parameters under a linearly-polarized incident wave excitation. The polarizers with low ohmic loss are optimally designed for a new 28 GHz transmission line on the QUEST spherical tokamak. The calculated optimum ohmic loss is restricted to only less than 1.5 times as large as the theoretical loss for a copper flat mirror at room temperature. The copper rounded-rectangular grooves of the polarizers were relatively easy to make smooth in mechanical machining and the resultant surface roughness was not more than 0.15 μm, which is only 0.38 times as large as the skin depth. The combination of the designed elliptical polarizer and the polarization rotator can also realize any polarization state of the reflected wave.

Keywords: Polarizer, Miter bend, Millimeter-wave transmission, Electron cyclotron heating and current drive
PACS: 42.25.Ja, 42.79.Dj, 52.50.Sw, 52.55.Fa, 84.40.Az

1. Introduction

Effective power absorption of an electron cyclotron (EC) wave into a plasma requires an appropriate setting of the EC wave polarization. The desired polarization can be obtained with polarizers with a grooved mirror surface installed at miter bends in a transmission line [1]. In a high-power long-pulse transmission line, a polarizer must satisfy highly efficient coverage of any polarization state, high-power tolerance, and low ohmic loss. In the previous work [2], polarizers optimized for any polarization state were successfully realized and installed on the electron cyclotron heating and current drive (ECH/ECCD) system for the Large Helical Device. The groove shapes for an elliptical polarizer ($\lambda/8$ type) and a polarization rotator ($\lambda/4$ type) for a transmission line were optimally designed using an integral method in the vector theories of diffraction gratings [2, 3, 4, 5], so that the efficiency to realize any polarization state was maximized [2]. Here, λ denotes the wavelength in free space propagation. The next step is to achieve both requirements for polarizers, i.e., (i) maximizing efficiency to realize any polarization state and (ii) minimizing ohmic loss on the grooved mirror. One must select the polarizer with the lowest ohmic loss from a set of polarizers that can realize any polarization state. In addition, the polarizer grooves should be machined smoothly so that the surface roughness is as small as possible, because it is reported that surface roughness larger than the skin depth increases the ohmic loss on the mirror [6]. At present, the effect of the surface roughness is not taken into account in simulation studies for the ohmic loss on the grooved mirror. In that context, the feasible groove shape must be proposed in consideration of machining processes.

In this work, as shown in the following two sections, polarizers not only with any polarization state but also with low ohmic loss were optimally designed and successfully fabricated for the new 28 GHz ECH/ECCD system of the QUEST (Q-shu University Experiment with Steady-State Spherical Tokamak) at Kyushu University [7]. The new 28 GHz system including the new polarizers and a new launcher enables the performing of steady-state ECH/ECCD experiments using electron Bernstein waves in over-dense plasmas.

2. Numerical calculations

In order to evaluate the ohmic loss on the grooved mirror surface of polarizers, a polarizer miter bend is simulated on a real scale using COMSOL Multiphysics with its rf (radio frequency) solver [8], which is a commercial FEA (finite element analysis) software easy to learn and handle. Figure 1 shows a CAD model of a real-scale polarizer miter bend for a 28 GHz 63.5-mm waveguide transmission line. The incident wave of the HE_{11} mode with an arbitrary polarization (e.g., E-plane polarization or H-plane polarization) is excited at the miter bend inlet. A perfectly matched layer (PML) is artificially set on the miter bend outlet so that the reflected wave from the grooved mirror can be fully absorbed in the PML, thereby preventing further undesirable reflection into the simulation box. The size of triangular meshes on the grooved mirror surface is set as

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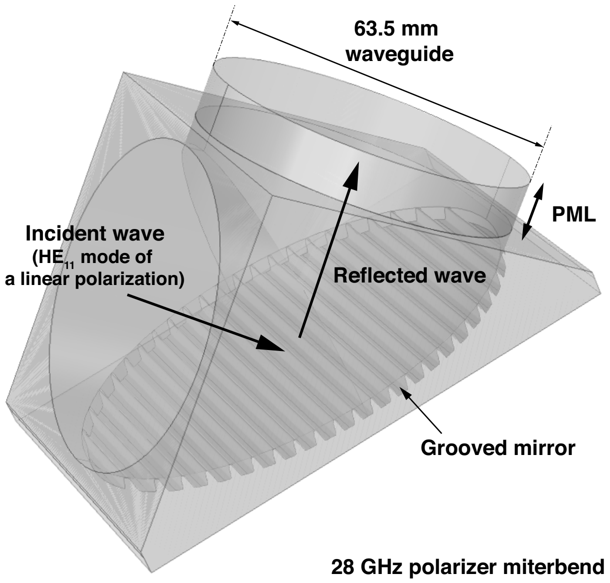

Figure 1: Simulated real-scale 28 GHz polarizer miter bend on the COMSOL software. The waveguide diameter is 63.5 mm. The perfectly matched layer (PML) is artificially installed so that the reflected wave from the grooved mirror can be absorbed in the PML.

follows: the maximum element size of 0.2 mm, the minimum element size of 0.01 mm, the maximum element growth rate of 1.3, the curvature factor of 0.1, and the resolution of narrow regions of 1. The size of tetrahedral meshes in the miter bend space is set as follows: 2 mm, 0.01 mm, 1.5, 0.1, and 1. Assuming the impedance boundary condition on the surface of the grooved mirror made of ideal copper enables the calculation of the ohmic loss due to the induced surface currents on the grooved mirror. In order to examine the impact of the groove shape along with the incident polarization on the ohmic loss, simulations are performed with the following groove shape, which is proposed by Plaum *et al.* [9], that is $y' = d\exp(-(a_c x'/p)^4)$, where x' is the length perpendicular to the groove direction on the mirror surface, y' is the length normal to the mirror, p is the groove period, d is the groove depth, and a_c corresponds to the duty ratio in the case that a groove shape is rectangular, respectively. This expression is considered to fulfill low ohmic loss and no sharp edges to prevent arcing [9]. When the groove depth is effectively $\lambda/4$, the E-plane ohmic loss becomes the lowest in the groove shapes with identical a_c and p, although the desired polarization can be achieved by the combination of an elliptical polarizer and a polarization rotator whose groove depths are effectively $\lambda/8$ and $\lambda/4$, respectively.

Figure 2 shows 28 GHz rf field distribution in the simulated polarizer whose groove parameters are as follows: $a_c = 6$, $d = 0.286\lambda$, and $p = 0.374\lambda$. One can see that the incident wave with E-plane polarization is reflected at the bottom of the grooves, while the incident wave with H-plane polarization is reflected at the top of the grooves, which gives rise to a phase difference between the two modes of the reflected wave and the different ohmic loss on the grooved mirror. Figure 3 shows the relative ohmic loss as a function of the incident polarization

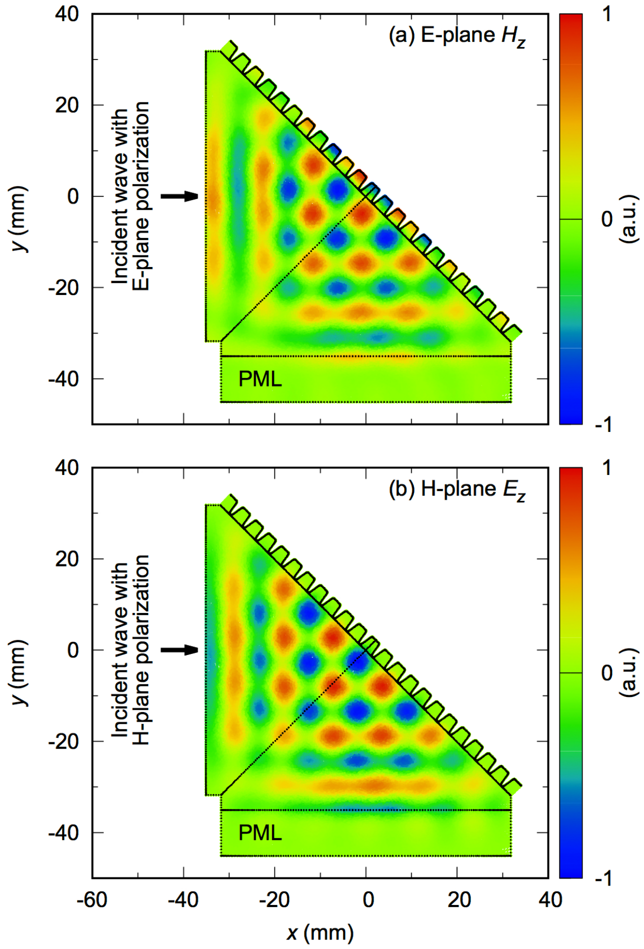

Figure 2: 28 GHz rf field distribution on the plane of incidence at $z = 0$ in a simulated polarizer miter bend in the cases of (a) incident E-plane polarization and (b) incident H-plane polarization, respectively. Groove parameters are as follows: $a_c = 6$, $d = 0.286\lambda$, and $p = 0.374\lambda$.

angle α_i under linear polarization, where $\alpha_i = 0°$ represents E-plane polarization and $\alpha_i = 90°$ represents H-plane polarization. The plotted ohmic loss is normalized by the theoretical ohmic loss for normal incidence of a copper flat mirror at room temperature, i.e., $P_L = 4R_s/Z = 4\sqrt{\pi\mu f/\sigma}/\sqrt{\mu/\varepsilon}$, where R_s is the surface resistance, Z is the characteristic impedance, μ is the permeability, f is the frequency, σ is the conductivity of the mirror material, and ε is the permittivity. The groove parameters are the same as in Fig. 2 for the COMSOL analysis and for the referenced FDTD (finite difference time domain) analysis [9]. It is noted that the normalization cancels the dependence of the ohmic loss on frequencies for flat mirrors. For a miter bend in which the incidence angle is 45°, the theoretical ohmic loss on the flat mirror is represented by $P_L/\cos 45°$ for E-plane polarization and $P_L \cos 45°$ for H-plane polarization. The results indicate that the ohmic loss for the COMSOL analysis is comparable with that for the reference [9], and that the grooves increase the ohmic loss as compared to the flat mirror. The ohmic loss in the case of arbitrary α_i can be expressed using the ohmic loss of E-plane polarization $P_{0°}$ and that of H-plane polarization $P_{90°}$ by $P_{\alpha_i} = P_{0°}\cos^2\alpha_i + P_{90°}\sin^2\alpha_i$.

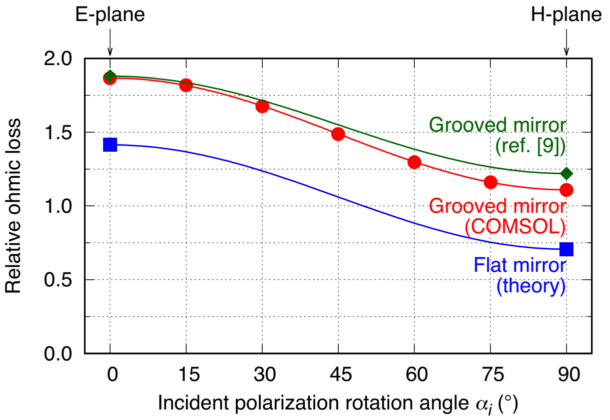

Figure 3: Relative ohmic loss as a function of the incident polarization rotation angle α_i. The ohmic loss is normalized by the theoretical ohmic loss for normal incidence of the flat mirror. Groove parameters are the same as in Fig. 2 for the COMSOL analysis and for the referenced FDTD analysis [9].

Then the averaged loss for this range of polarization is given by $(P_{0^\circ} + P_{90^\circ})/2$, which can be utilized as a criterion for choosing a low-loss polarizer, as shown below.

Figure 4 shows ohmic loss evaluated on the mirror surface as a function of (a) d/λ for $a_c = 10$ and as a function of a_c for (b) $d = 0.25\lambda$ and for (c) $d = 0.35\lambda$, respectively. The ohmic loss normalized by the input power at the miter bend inlet is shown in the left ordinate, while the relative ohmic loss using the same normalization as Fig. 3 is shown in the right ordinate. The groove period p is fixed at $p = 0.5\lambda$, which satisfies that higher-order modes of the reflected wave are suppressed. As shown in Fig. 4(a), although the ohmic loss for the E-plane polarization is minimum at around $d/\lambda \sim 0.35$, which is an effective depth of $\lambda/4$ at the incident angle of 45°, the averaged ohmic loss has a relatively flat profile for d/λ, which provides a high degree of freedom in designing the groove depth for an elliptical polarizer and a polarization rotator. By using the calculations for realizing any polarization state [2], $d = 0.25\lambda$ and $d = 0.35\lambda$ are suitable for the elliptical polarizer ($\lambda/8$ type) and the polarization rotator ($\lambda/4$ type), respectively. Figures 4(b) and (c) indicate that the minimum averaged ohmic loss can be obtained in $a_c = 6$ for both the polarizers. The minimum averaged loss is restricted to only less than 1.5 times as large as the theoretical averaged loss.

3. Polarizers for the 28 GHz QUEST ECH/ECCD system

The above-mentioned ohmic loss analyses for the exponential-shape grooved mirror surface are suitable for examining the dependencies of the ohmic loss on groove depths and duty ratios.

It was found, however, that a rounded-rectangular shape was easier to make by mechanical machining than the exponential shape in terms of surface roughness. Thus, good surface roughness at the top and the bottom of the grooves as small as $R_q = 0.08$-0.15 μm, which was restricted to be 0.20-0.38 times of the skin depth, was achieved with the rounded-rectangular shape. Here, R_q denotes root mean squared surface roughness,

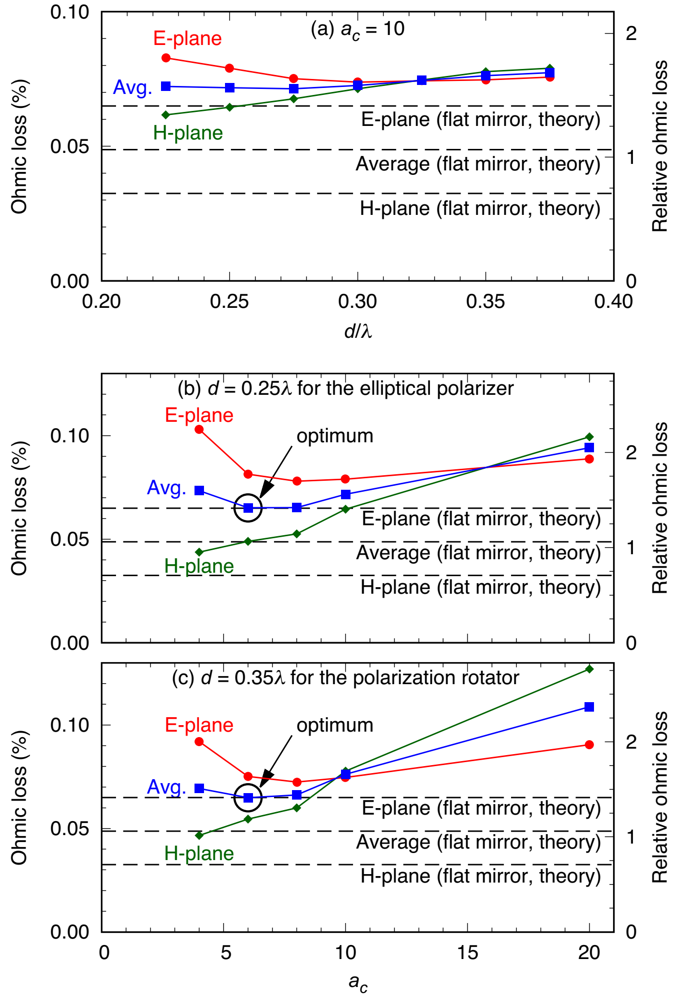

Figure 4: Ohmic loss evaluated on the mirror surface normalized by the input power (the left ordinate) and normalized by the theoretical ohmic loss for normal incidence of the flat mirror (the right ordinate) as a function of (a) d/λ for $a_c = 10$ and as a function of a_c for (b) the elliptical polarizer ($d = 0.25\lambda$) and (c) the polarization rotator ($d = 0.35\lambda$), respectively. The groove period p is fixed at $p = 0.5\lambda$.

which were measured using a standard surface roughness tester (Mitutoyo Surftest SJ-400). The polished surface prevents the increase in the ohmic loss on the grooved mirror from the calculated ohmic loss without the effect of the surface roughness, because surface roughness larger than the skin depth increases the ohmic loss on the mirror [6, 10]. Moreover, as shown in Table 1, no clear difference is found in the calculated ohmic loss on the mirror surface between the two types of groove shapes. Figure 5 shows rounded-rectangular-shape polarizers with a smooth surface, which were successfully fabricated in our machine shop. An inner radius cutter with a radius of 0.7 mm was utilized to make the rounded edges of the grooves, while the milling machine with a square end mill with a diameter of 3.0 mm ran back and forth to make the grooves. The groove parameters for the elliptical polarizer and the polarization rotator are the same as shown in Table 1. It is noted that the requirements for the machining accuracy and surface roughness are much stricter for fusion experiments with the commonly used 140 GHz or 170

Table 1: Comparison of the ohmic loss on the mirror surface between exponential-shape grooves and rounded-rectangular-shape grooves. The groove period is $p = 0.5\lambda$. The duty ratio for the rounded-rectangular-shape grooves is the equivalent of $a_c = 6$, i.e., $(2/a_c)(\ln 2)^{1/4}$.

Groove depth (shape)	E-plane	H-plane	Average
0.25λ (exponential)	0.081%	0.049%	0.065%
0.25λ (rounded rectangular)	0.090%	0.048%	0.069%
0.35λ (exponential)	0.075%	0.055%	0.065%
0.35λ (rounded rectangular)	0.076%	0.052%	0.064%

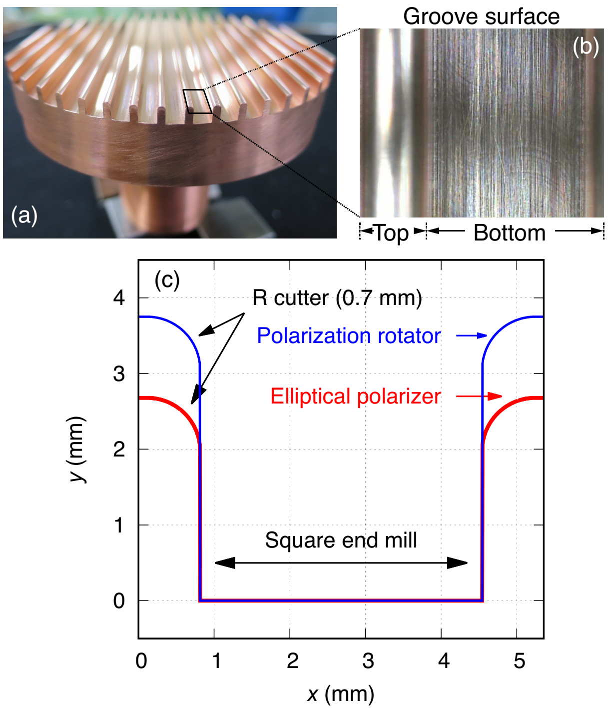

Figure 5: (a) Photo of the fabricated polarization rotator by mechanical machining, (b) a part of the mirror surface observed with a microscope. The surface roughness R_q is 0.08-0.15 μm at the top and the bottom of the grooves. (c) Design of the groove geometry for the elliptical polarizer and the polarization rotator. The groove parameters are the same as in Table 1.

GHz higher than 28 GHz.

Figure 6 shows the calculated relationship between a linearly-polarized incident wave and an elliptically-polarized reflected wave from the combination of the optimally-designed two polarizers. For this calculation, the planes of incidence for both the polarizers are set identical and the direction of the incident wave polarization for the first polarizer, i.e., the elliptical polarizer, is set perpendicular to the plane of incidence. The calculation method is experimentally validated in the previous work [2]. The results indicate that the efficiency to realize a given polarization state is more than 99.88%. Thus, it is concluded that any polarization state can be realized.

4. Conclusions

The ohmic loss on the grooved mirror surface was evaluated in the simulated real-scale polarizer miter bend by changing incident polarizations and groove parameters. The polarizers with low ohmic loss for the new 28 GHz ECH/ECCD system on the QUEST were optimally designed. The designed polarizers also satisfy the condition that any polarization state can be realized. The rounded-rectangular grooves, whose surface can be relatively easy to smooth by mechanical machining, have comparable ohmic loss with the designed exponential-shape grooves. Thus, the polarizers with the rounded-rectangular grooves were successfully fabricated.

Acknowledgments

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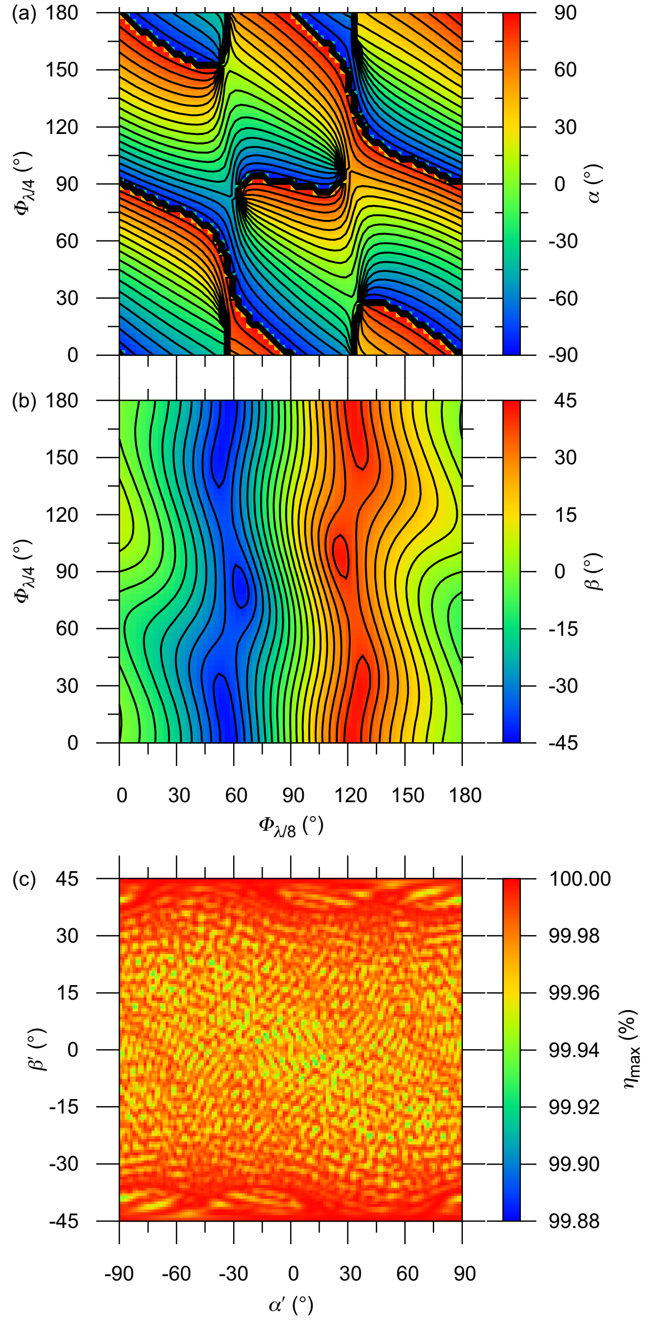

Figure 6: Polarization states of the reflected wave under a linearly-polarized incident wave; (a) the polarization rotation angle α and (b) the polarization ellipticity β as a function of the polarizer rotation angles $(\Phi_{\lambda/8}, \Phi_{\lambda/4})$ for the combination of the optimally designed elliptical polarizer and the polarization rotator, as described in Fig. 5, and (c) the maximum efficiency η to realize a given polarization state (α', β'), where $\eta = \cos^2(\alpha-\alpha')\cos^2(\beta-\beta') + \sin^2(\alpha-\alpha')\sin^2(\beta+\beta')$.