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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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HIGHLIGHTS

- Ohmic loss was calculated on the grooved mirror surface in simulated polarizers.
- Polarizers with a low ohmic loss feature were optimally designed for 28 GHz.
- Smooth rounded-rectangular grooves were made by mechanical machining.
- The designed polarizers can realize all polarization states.

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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.

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 (λ/8 type) and a polarization rotator (λ/4 type) for a transmission line were optimally designed using an integral method in the vector theories of diffraction gratings [2–5], 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

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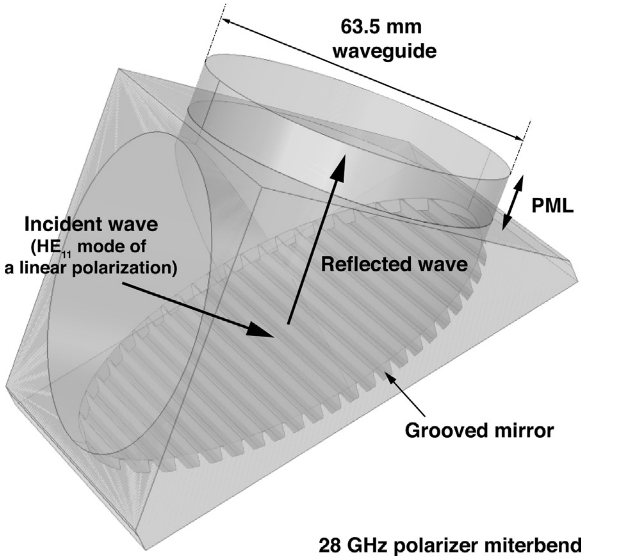

Fig. 1. Simulated real-scale 28 GHz polarizer miter bend on the COMSOL software. The waveguide diameter is 63.5 mm. The perfectly matched layer (PML) is artificially installed so that the reflected wave from the grooved mirror can be absorbed in the PML.

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. Fig. 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 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.

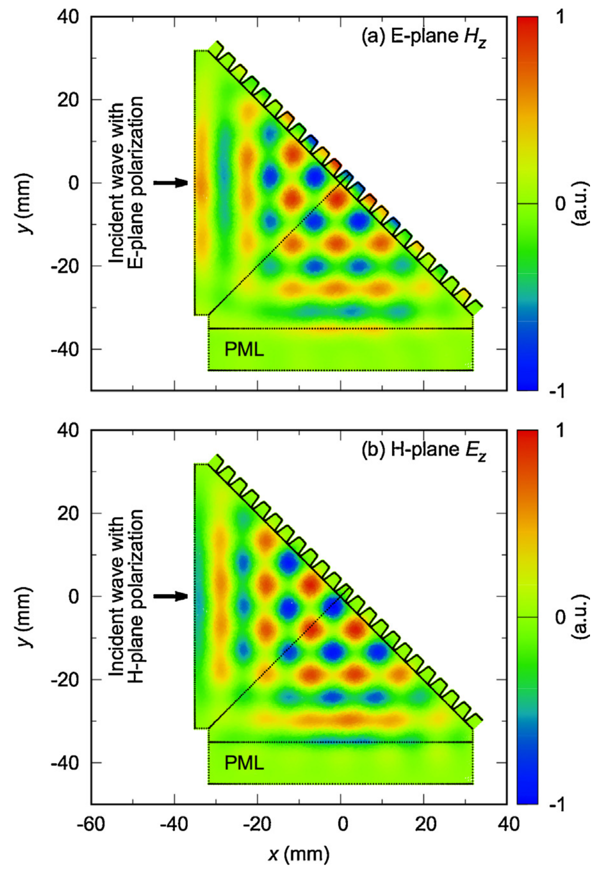

Fig. 2. 28 GHz rf field distribution on the plane of incidence at $z = 0$ in a simulated polarizer miter bend in the cases of (a) incident *E*-plane polarization and (b) incident *H*-plane polarization, respectively. Groove parameters are as follows: $a_c = 6$, $d = 0.286\lambda$, and $p = 0.374\lambda$.

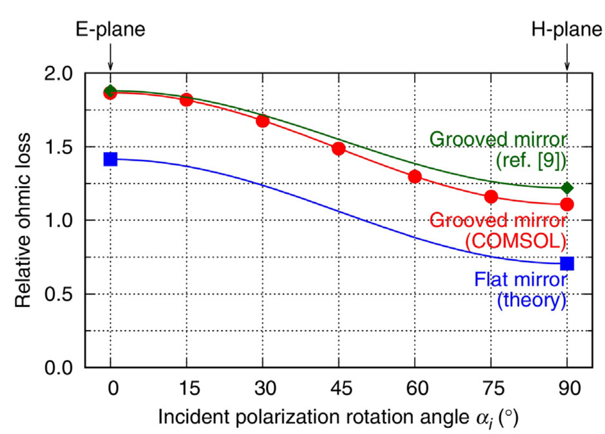

Fig. 3. Relative ohmic loss as a function of the incident polarization rotation angle α_i. The ohmic loss is normalized by the theoretical ohmic loss for normal incidence of the flat mirror. Groove parameters are the same as in Fig. 2 for the COMSOL analysis and for the referenced FDTD analysis [9].

Fig. 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