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Development of Polarizers for a Mega-Watt CW ECH Transmission Line
メガワット定常ECH伝送系における偏波器の開発

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We have designed polarizers with non-rectangular grooves for a mega-watt long-pulse millimeter-wave transmission line (TL) of the electron cyclotron heating system in the Large Helical Device. The aim of this study is to increase the standoff voltage for the dangerous arc discharge around the edge of the groove and to decrease the power loss on the surface by reducing the surface roughness due to the machining process. The groove shape of $\lambda/8$- and $\lambda/4$-type polarizers for an 82.7 GHz TL is optimally designed in an integral method developed in the vector theories of diffraction gratings so that the efficiency to realize any polarization state can be maximized. The dependence of the polarization states on the combination of the two polarization angles ($\Phi_{\lambda/8}$, $\Phi_{\lambda/4}$) is examined experimentally in a low-power test with the newly developed polarization monitor. The results show that the measured polarization characteristics are in good agreement with the calculated characteristics.

1. Introduction

Electron cyclotron heating (ECH) is widely used for magnetic confinement fusion experimental devices, and is considered one of the promising heating sources for future reactors. Effective power absorption of the EC beam into a plasma requires an appropriate setting of polarization of the injected millimeter (mm) wave, so that the wave can couple to electromagnetic waves at the plasma boundary, which results in excitation of pure ordinary or extraordinary mode at the resonance layer. The desired polarization can be achieved by grating polarizers installed at the miter bends in a mm-wave transmission line (TL) [1]. In MW long-pulse mm-wave TL on the Large Helical Device (LHD), ITER, or future reactors, the polarizer must satisfy highly efficient coverage of all polarization states, high-power tolerance, and low-loss features. The polarizer fabricated by conventional wire-electro discharge machining is considered to have a problem in power loss due to the surface roughness of the mirror and may affect a high power steady-state operation. Another problem is the electric field concentration at the edge of the grooved mirror that can cause arc discharge and disable further operation of the gyrotron.

To improve the above issues, new polarizers with rounded shape at the edge of the periodic groove surface are designed and fabricated by machining for the TLs of the LHD ECH system. An integral method is adopted to calculate the polarization characteristics of the reflected wave from the diffraction gratings with an arbitrary periodic groove shape [2,3]. Then, the groove shape of $\lambda/8$- and $\lambda/4$-type polarizers for an 82.7 GHz TL on the LHD was designed so that the realizable polarization states cover as widely as possible by optimizing the depth and width of rectangular corrugation with fixed pitch and round edge curvature. The manufactured polarizers were tested in a low-power test stand with the newly developed polarization monitor, where the dependence of the polarization states on the combination of the two polarizer rotation angles ($\Phi_{\lambda/8}$, $\Phi_{\lambda/4}$) were examined. The measured polarization was compared with the numerical calculated results.

2. Polarizer design

We designed the polarizers with rectangular shape rounded at the edge of the periodic grooves. Since the combination of $\lambda/8$- and $\lambda/4$-type polarizers with conventional rectangular grooves generates any polarization state, equalizing the phase difference τ of each type of the rounded-rectangular-grooved polarizers with that of the rectangular-grooved polarizers as much as possible can maximize the efficiency to realize any polarization state. The wavelength λ is 3.628 mm for 82.7 GHz, though the polarizer performance is determined by d/λ, where d is the groove depth. The edge of the groove surface is chamfered roundly with a 0.35 mm inner radius cutter. The period p is fixed at 1.8 mm, which satisfies the condition $p < 0.586\lambda$. The duty ratio is also fixed at $(1.8 - 1.0)/1.8 = 0.444$. The grooves are made by a 0.8 mm square end mill. The round shape, the period, and the duty ratio are preliminarily determined by choosing the cutting tools for machining, and then the groove depth is optimized by this analysis. We chose the groove depths of $d = 0.24\lambda$ as the $\lambda/8$-type polarizer and of $d = 0.37\lambda$ as the $\lambda/4$-type polarizer because of similarities of the τ charactestics to those with the rectangular grooved polarizers. The surface roughness of the grooves fabricated by machining is approximately five times better than that by wire-electro discharge machining.

3. Low power test

The polarization parameters of the manufactured polarizers are measured in a newly developed low-power test stand, as shown in Fig. 1, and compared with the numerically calculated data obtained in the previous section. The linearly polarized wave enters the combination of the $\lambda/8$- and $\lambda/4$-type polarizers and their incident and reflected angles are set 45 deg., respectively. Each polarizer is mounted on a rotating stage that can rotate from 0 deg. to 180 deg. at a speed of 2.5 deg./s. The elliptically polarized wave received with a circular corrugated horn antenna is divided into two orthogonal linearly polarized waves by an orthomode transducer. Using harmonic heterodyne detection with a common local oscillator, the two intermediate frequency signals with a down-converted frequency of 50 MHz are directly acquired by a fast digitizer with a field programmable gate array (FPGA). Fast Fourier transform into the signals at every nearly 100 ms enables us to calculate the amplitude ratio and the phase difference almost in real time.

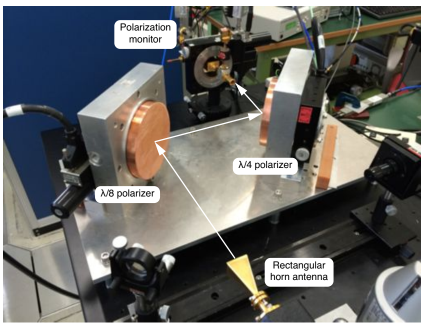

Fig. 1. Low power test setup. The polarization monitor with a fast digitizer with an FPGA is newly installed.

Figure 2 shows the dependence of polarization parameters (α, β) on the polarizer rotation angles ($\Phi_{\lambda/8}$, $\Phi_{\lambda/4}$) of the manufactured polarizers, where α denotes the rotation angle of the major axis of the polarization ellipse and β the ellipticity. The minimum value of the efficiency η to realize a polarization state is 99.6%, which indicates that almost all of the polarization states are realized. Since the polarization performance is nearly identical with that of the rectangular-grooved polarizers, β can be changed almost only by rotating the $\lambda/8$-type polarizer, while α can be changed almost only by rotating the $\lambda/4$-type polarizer with β fixed, which results in easy setting of a polarization state. Degree of coincidence between the calculated polarization parameters and the measured ones can be evaluated quantitatively by using η again. The measured polarization parameters are in good agreement with the calculated parameters at a rate of over 88%. The measurement error analysis shows that η is lower at larger $\delta\eta$, where β is large but not enough for circularly polarized waves and α changes rapidly.

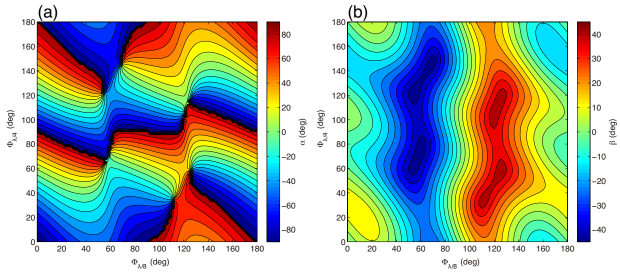

Fig. 2. Dependence of polarization parameters (a) α and (b) β on the polarizer rotation angles $\Phi_{\lambda/8}$ and $\Phi_{\lambda/4}$ of the manufactured polarizers.

4. Conclusion

Polarizers with rounded rectangular grooves were fabricated by machining by optimally designing the groove shape, in particular, the groove depth with the integral method developed in the vector theories of diffraction gratings. We obtained the polarizer performance nearly identical to that of polarizers with rectangular grooves that can realize almost all polarization states, which was confirmed in a low-power test with the newly developed real-time polarization monitor.

Acknowledgments

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