Grating Polarizers at 170 GHz for ECRH Systems: Low Power Tests and Simulations

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For an ECRH system to be efficient, the microwave power, e.g., neo-classical tearing modes (NTMs) and sawteeth [1-5], controlling the magneto-hydrodynamic (MHD) instabilities for plasma heating and current drive experiments, and also for Plasma Science and Fusion Center, Massachusetts Institute of Technology, U.S. Department of Energy.

The elliptical polarization produced by a pair of sinusoidally profiled miter-bend grating polarizers has been measured experimentally and found to be in excellent agreement with theory. The polarizers were designed to be used at 170 GHz in the miter bends of a 63.5 mm corrugated metallic waveguide for creating the arbitrary elliptically polarized microwave beam needed for Electron Cyclotron Resonance Heating of plasma. Using a vector network analyzer to generate a linearly polarized HE_{11} incident mode, each polarizer was individually tested to measure the rotation \( \alpha \) and ellipticity \( \beta \) of the elliptically polarized reflected microwave beam as a function of the grating rotation angle. The grating polarizers were then tested together to measure the elliptical polarization as a function of the angles of the combination of the two polarizers arranged sequentially on the transmission line. The map of the ellipticity vs. grating angles agreed very well with numerical simulations using HFSS. Numerical simulations show that up to eight combinations of rotation angles of the two grating polarizers can provide the same ellipticity but with varying ohmic loss, thus allowing the choice of settings to minimize the ohmic loss, a necessary consideration to minimize heating effects in megawatt power level systems.

Index Terms—Gratings, polarization, microwave measurements, phase measurements, Gaussian beams, corrugated waveguides

I. INTRODUCTION

ELECTRON Cyclotron Resonance Heating (ECRH) systems in fusion experiments are specifically designed for plasma heating and current drive experiments and also for controlling the magneto-hydrodynamic (MHD) instabilities e.g. neo-classical tearing modes (NTMs) and sawteeth [1-5]. For an ECRH system to be efficient, the microwave power must be launched into the plasma at the cyclotron resonance frequency of plasma electrons and must be elliptically polarized in a specific orientation with respect to the magnetic field inside the vessel. The microwave power generated from a megawatt-level gyrotron is linearly polarized in the form of a Gaussian beam which is transmitted to the launchers using either a system of specialized overmoded corrugated waveguides [2,6,7], or, quasi-optically in free space using mirrors [8,9]. This linear polarization can be converted to any arbitrary elliptical polarization state prior to the launchers by a pair of reflection grating polarizers (called simply “gratings” in this paper), inserted in the corrugated waveguides in a 90° bend (also called a miter bend) [10]. The pair consists of a polarization rotator and a circular polarizer. At normal incidence these would have grating depths of \( \lambda/4 \) and \( \lambda/8 \) respectively, where \( \lambda \) is the wavelength of the microwave radiation. These grating depths must be adjusted for the 45° angle of incidence in the 90° miter bends. The field reflected from a periodic grating can be solved using a generalized space harmonic formalism [10-14] where the field components can be treated along and perpendicular to the grooves or using finite difference time domain (FDTD) [15,16] analysis, or, by using the vector theory of diffraction gratings developed in [17]. Doane [10] first presented the low power test results of grating polarizers inserted in waveguide miter-bends. The measured intensity variation was accurately predicted using plane wave theory. However, predicting the polarization properties in detail of a pair of grating polarizers requires an additional set of measurements of the phase of the reflected field from the grating polarizers. Further investigations are needed to generate the full polarization map from the combined setup consisting of two grating polarizers, a polarization rotator and a circular polarizer, separated by a section of corrugated waveguide. In the megawatt power level transmission lines at ITER or similar large fusion experiments, it is imperative that the polarization rotator be optimized to achieve a full range of polarization states with minimal ohmic losses or mode conversion in a miter bend in order to prevent thermal damage to the transmission lines and gratings and to achieve higher efficiency [6,7,11,18-20]. We note that Saigusa et. al. [21] built and tested a single grating miter-bend to create the required elliptical polarization and minimize the ohmic loss by reducing the number of miter bends. Our work follows a convention approach using two grating polarizers in miter bends. To examine all these issues, we have employed the
commercial software High Frequency Structure Simulator (HFSS) to solve for the field reflected by a sinusoidal groove profile. The advantage of using HFSS is that it can solve for any arbitrarily shaped groove profile in a general case.

The purpose of this paper is to compare theoretical and experimental results for a pair of grating polarizers with sinusoidal groove shapes. These gratings were fully assembled with motorized rotation capability in the 63.5 mm diameter corrugated waveguide miter-bends, which are built by General Atomics (GA) to operate at 170 GHz [11]. Low power tests were performed extensively to examine all polarization states. An arbitrary elliptical polarization state is defined by two parameters, ellipticity ($\beta$) and rotation ($\alpha$) of the major axis of an elliptically polarized wave. Roughness observed in the fabrication process by wire-electro discharge machining or in direct CNC machining.

Another critical issue associated with the performance of such miter-bend grating polarizers is mode conversion as the grating is rotated to achieve the required elliptical polarization. We experimentally examined the mode conversion to higher order linearly polarized (LP) modes [19,20,22,24-26] by measuring the radiated field from the corrugated waveguide aperture and thereby measuring the mode contents in the corrugated waveguide with respect to the grating rotation angle.

This paper is organized as follows: Section II gives a brief description of the polarizers and their numerical simulations to examine the grating behavior. Section III reports on the experimental procedure used to measure the polarization characteristics in low-power tests and their comparison with numerical results. Ohmic loss simulations are discussed in Section IV. In Section V, the experimentally measured mode conversion is discussed followed by our conclusions in Section VI.

II. POLARIZER: DEFINITION AND NUMERICAL SIMULATIONS

A general schematic of the geometry of configuration showing the incident and reflected electric field components is given in Figure 1(a). We specialize to 90 degree miter-bends, for which the angle of incidence ($\theta$) and reflection is 45°. The grating can be rotated by an angle $\Phi$ in the XY plane. The incident field vector $E_i$, when linearly polarized for the H-plane configuration, is represented by $E_{\text{hi}}$ and when polarized for the E-plane configuration is represented by $E_{\text{ei}}$. The subscripts $i$ and $r$ indicate incident and reflected fields, respectively. At the grating surface the incident field is divided into components parallel and perpendicular to the groove orientation. The electric field perpendicular to the plane of incidence ($E_{\text{fast}}$ or TE-mode) is reflected at the top surface of the grating while the field component parallel to the plane of incidence ($E_{\text{slow}}$ or TM-mode) [10] penetrates to the bottom and gets reflected at the bottom surface. This induces a phase shift (\(\tau\)) between the two reflected components and hence gives rise to the resultant elliptical polarization. For an ideal case of rectangular shaped grooves with normal incidence ($\theta=0^\circ$), when the phase shift $\tau = \pi/2$, which corresponds to a groove depth of $d = \lambda/8$, the resultant polarization is circular and the grating is referred to as a circular polarizer. When $\tau = \pi$, corresponding to a groove depth of $d = \lambda/4$, the resultant polarization is linear and the grating is referred to as a polarization rotator. For a $\theta = \pi/4$ incidence angle, as in the case of a miter-bend, the groove depths scale as $d/\cos(\pi/4)$. However, for groove shapes other than rectangular e.g. sinusoidal (as is the case in our analysis) or trapezoidal, the depth is further optimized to achieve all desired polarization states. An arbitrary elliptical polarization state is defined by two parameters, ellipticity ($\beta$) and the orientation of the ellipse’s major axis ($\alpha$). These are defined in Figure 1(b). The periodicity, $p$, of the grating is constrained to the zeroth-order mode propagation only which is given by the

![Figure 1](image-url)
condition $p < \lambda/(1+\sin\theta\cos\Phi)$ which yields $p < 0.586\lambda$ [10]. For the gratings used in this study at the operating frequency of 170 GHz, $p = 0.79$ mm.

The ellipticity introduced in a reflected microwave beam by a polarizer grating primarily depends on the phase shift $\tau$ which in turn depends on the groove profile, the frequency of the incident microwaves and polarization of the incident field. The reflected field components $E_{\theta r}$ and $E_{\phi r}$ can be calculated from the incident field components $E_{\theta i}$ and $E_{\phi i}$ by a series of appropriate vector transformations if the phase shift $\tau$ is known [27-30]. This reflection transformation can be written as

$$\begin{bmatrix} E_{\theta r} \\ E_{\phi r} \end{bmatrix} = \begin{bmatrix} \cos \xi & -\sin \xi \\ \sin \xi & \cos \xi \end{bmatrix} \begin{bmatrix} e^{i\tau/2} \\ 0 \end{bmatrix} \begin{bmatrix} \cos \xi & -\sin \xi \\ \sin \xi & \cos \xi \end{bmatrix} \begin{bmatrix} E_{\theta i} \\ E_{\phi i} \end{bmatrix}$$

(1)

Here, $\xi$ is the rotation angle between the field components in the spherical coordinate system $(\theta, \phi)$ and the field components parallel and perpendicular to the grooves. It is related to the polarizer rotation angle $\Phi$ by the equation $\tan \xi = \cos \Phi \tan \theta$.

The first and third matrices acting on $E_i$ in equation (1) represent coordinate transformations to and from a set of axes aligned with the polarizer grooves. The factor $\tau$ is determined by the groove geometry of the polarizer in relation to the wavelength $\lambda$ of the incident field. Once the reflected field components are known, $\alpha$ and $\beta$ can be calculated from the electric field intensity and phase using equations (2) and (3), following the methods described in [27-31],

$$\tan 2\alpha = \tan 2\gamma \cos \delta$$

(2)

$$\sin 2\beta = \sin 2\gamma \sin \delta$$

(3)

Here, $\gamma = \tan^{-1}(|E_{\phi i}|/|E_{\theta i}|)$ and $\delta = \delta_{\phi} - \delta_{\theta}$ is the phase difference between the reflected field components $E_{\theta r}$ and $E_{\phi r}$. The phase of each field component can be extracted as

$$\delta_{\theta} = \tan^{-1}\left(\frac{\cos(2\xi + \psi)\sin(\tau/2)}{\cos \psi \cos(\tau/2)}\right)$$

(4)

$$\delta_{\phi} = \tan^{-1}\left(\frac{-\sin(2\xi + \psi)\sin(\tau/2)}{\sin \psi \cos(\tau/2)}\right)$$

(5)

From equations (2) and (3) and Figure 1(b), one can see that $-90^\circ \leq \alpha \leq +90^\circ$ and $-45^\circ \leq \beta \leq +45^\circ$.

Several papers [10-14,17] have shown how the phase shift $\tau$ for different groove profiles and various incident angles can be calculated rigorously. Some used generalized space harmonic formulations [10-14] while other used Finite Difference Time Domain (FDTD) analyses [15,16] or rigorous vector theory of diffraction gratings [17]. In our simulations we used the phase shift calculated using the commercially available software HFSS. Because the polarizer gratings used in millimeter-wave transmission lines are planar 1D-periodic structures, it is possible to take advantage of the Floquet spatial harmonic expansion in HFSS and calculate the expected field behavior reflecting off of an entire polarizer using only a model of a single groove segment and the appropriate free space above it. With the appropriate groove model and meshing the reflected field components $E_{\theta r}$ and $E_{\phi r}$ can be calculated with respect to the grating rotation angle $\Phi$ using HFSS for both E-plane and H-plane configurations. We then take advantage of the vector formulation developed in [30] where the polarization of the reflected wave is explicitly calculated using vector transformations in terms of the phase shift between the $E_{\text{fast}}$ or TE (no magnetic field parallel to the grooves) and $E_{\text{slow}}$ or TM (no electric field parallel to the grooves) components of the field at the grating surface. Using the reflected field components from our HFSS simulations and this vector transformation technique, we can perform vector operations in equation (1) to solve for the phases of TE ($\Gamma_{TE} = e^{i\tau/2}$) and TM ($\Gamma_{TM} = e^{i\tau/2}$) components which will provide us with the phase shift as a function of the grating rotation angle $\tau(\Phi) = -\arg(\Gamma_{TE}/\Gamma_{TM})$.

Numerical simulations were performed for both the polarization rotator and the circular polarizer, used in the experiments, using the single groove unit cell model in HFSS at 170 GHz. An example of an HFSS model of a single groove unit cell is shown in Figure 2. The groove shapes are published in [11]. The results are shown in the next section where they are compared with the experimental data.

Simulating a single groove unit cell in HFSS has the advantage of allowing the rapid analysis of arbitrary groove shape in order to study the effect of manufacturing imperfections or any small tilt in the miter-bend assembly.

III. EXPERIMENTAL SETUP
The polarization rotator and circular polarizer were studied individually and in combination to measure their polarization properties. Figure 3(a) is a photograph of a single-reflection setup in our laboratory and 3(b) shows a schematic of the double-reflection combination setup incorporating both polarizers along with a picture of the motorized polarization rotator assembly. In all of our double-reflection experiments, the polarization rotator was positioned in the first miter bend. A vector network analyzer (VNA) is used with millimeter wave extenders (WR5 band) to transmit and receive the microwave radiation at 170 GHz. An HE$_{11}$ mode generator with a linear taper is used to match the 63.5 mm corrugated waveguide. The receiving module is mounted on a rotating stage to measure $E_{\phi}$ and $E_{\theta}$. (b) A schematic is shown for measuring the full polarization map from the combined setup. A photograph of the motorized polarizer miter bend is also shown in the center.

Fig 4: Measured and simulated values of ellipticity ($\beta$) and rotation ($\alpha$) are shown for the polarization rotator (a) and circular polarizer (b) as a function of the polarizer rotation angle $\Phi$.

Fig 5: Calculated and experimental values of the phase shift $\tau$ for the polarization rotator and circular polarizer.

assembly is placed in a 63.5 mm diameter corrugated waveguide, an HE$_{11}$ mode generator, built by GA, is used to create a high purity, $\sim 97.8\%$, linearly polarized HE$_{11}$ mode in a 63.5 mm waveguide. The millimeter wave receiver module of the VNA is mounted on a rotatable stage aligned parallel to the final waveguide aperture. A WR5 rectangular waveguide is used as a receiving antenna, mounted on the VNA receiver,
to measure the radiated field, both intensity and phase, along the axis of the waveguide. We measure the parallel ($E_\phi$) and perpendicular field ($E_\theta$) components of the radiated field after the corrugated waveguide aperture with respect to the rotation angle $\Phi$ of the polarizers. For individual measurements $\Phi$ is rotated by increments of 2°.

IV. EXPERIMENTAL RESULTS ON POLARIZATION

Figure 4 shows the experimental results of the polarization parameters ($\alpha$ and $\beta$) generated by the polarization rotator (a) and circular polarizer (b) as a function of the rotation angle $\Phi$. $\alpha$ and $\beta$ are calculated from the measured reflected field’s ($E_\phi$, $E_\theta$) amplitude ($\gamma$) and phase ($\delta$) information using equations (2) and (3). The results of numerical simulations from HFSS for each groove profile are also shown for comparison. Ideally, the polarization rotator should only rotate the polarization and not introduce any ellipticity. In practice, for a 45° incidence angle, some ellipticity will always be introduced. The tested polarization rotator achieved a good maximum value of the ellipticity of only ~13°. For the circular polarizer we obtained ~ 43° ellipticity, approaching the ideal value of 45° near $\Phi = 56°$. Experimental results show overall very good agreement with the HFSS simulations. For both gratings the phase shift $\tau$, between the field components reflected from the top and bottom of the grooves, was calculated using the incident ($E_\phi$, $E_\theta$) and reflected ($E_\phi$, $E_\theta$) field information following the vector transformation technique described in Section II. The values of $\tau$ calculated as

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**Fig 6:** Calculated (a and c) and experimental (b and d) polarization map of the combined setup. The polarization rotator is placed before the circular polarizer. The ellipticity $\beta$ is compared in (a) and (b) while the rotation $\alpha$ of the ellipse is shown in (c) and (d). Data were taken at every 10° rotation of the two gratings.
Radiated measured phase data and the numerical data from HFSS. Discrepancy between the phase shifts calculated from 0° case is near zero. The measured phase also has large values found in good agreement with the simulation results. Some disagreement is observed between theory and measurements which validates our theoretical approach using HFSS. For completeness, the rotation sense of the elliptically polarized beam is also analyzed and shown in Figure 7(a) showing left and right handed polarization in a right-handed coordinate system. A similar polarization map of α, β and rotation sense measured in a quasi-optical setup was also reported by [32] at 110 GHz for ERCH application on the TEXTOR-tokamak.

In order to evaluate the correlation of the measured and simulated polarization maps, we calculate the efficiency with which our simulation results, (α', β'), reproduce the experimental values (α, β) for all rotation angle combinations of polarization rotator and circular polarizer. This efficiency η is defined as [28]

$$\eta = \cos^2(\alpha - \alpha')\cos^2(\beta - \beta') + \sin^2(\alpha - \alpha')\sin^2(\beta + \beta')$$

(5)

Where η = 1, the two polarizations are the same and where η = 0 they are orthogonal. Figure 7 shows the correlation efficiency of the measured and simulated polarization maps. An efficiency of more than 96% is seen for almost every combination of the rotation angles of the two gratings. The points which correspond to α values close to -90° and 90°, and β values close to -45° and 45° (as shown in Figure 6) have large measurement error bars and are therefore omitted. A higher experimental resolution can lead to better efficiency validating both design and measurements of these gratings.

V. OHMIC LOSS: NUMERICAL SIMULATIONS

When microwaves reflect from the polarizers, some small fraction of power is expected to be absorbed into the metal as a result of surface currents. If the polarizers are not cooled at a commensurate pace, the gratings may experience significant thermal expansion and warping resulting in overall low transmission efficiency due to absorption and mode conversion loss. It is therefore imperative that the expected levels of ohmic loss be (a) predictable and (b) minimized.

The ohmic loss for reflection from a metallic surface at an angle θ is given for the H-plane by $P_L$cosθ, and $P_L$/cosθ for the E-plane case, where $P_L = 4(R_s/Z_0) = 4\sqrt{\pi\mu f / \sigma} / \sqrt{\mu / \varepsilon}$, $R_s$ is the surface resistance, $Z_0$ is the characteristic impedance, $\mu$ is the permeability, $f$ is the frequency, $\sigma$ is the conductivity and $\varepsilon$ is the permittivity. This value of loss increases significantly at millimeter wavelengths due to surface roughness. When the rms value of the surface roughness, $S_R$, is comparable to or larger than the skin depth $\delta$ ($\delta = 0.16 \mu m$ for copper at 170 GHz), this loss must be considered. A number of empirical formulas have been developed to estimate the increase of ohmic loss as a function of surface roughness [33-35].

![Circular Polarizer](image)
We then simulated both polarizers for different rotation angles. A flat mirror was first simulated using HFSS to benchmark the results. We obtained values for normal incidence, $\theta=0^\circ$, of ohmic loss $=0.11\%$; for $\theta=45^\circ$ and the E-plane case, loss $=0.16\%$; and for $\theta=45^\circ$ and the H-plane case, loss $=0.08\%$. These HFSS results are in excellent agreement with the analytical values for $P_L$, described above for a smooth surface. We then simulated both polarizers for different rotation angles. We used the ideal copper conductivity in our calculations. The results can be multiplied by $1/\sqrt{0.92}$ and $1/\sqrt{0.85}$ for Glidcop and C18150 copper chromium zirconium respectively as their bulk conductivities are typically 92% and 85% respectively that of ideal copper. For the ohmic loss correction due to surface roughness we have used the empirical formula defined by Groiss et. al. [33]. A similar model has been developed by [34,35]. These models are employed in HFSS and can be applied to analyze the effect of surface roughness.

Figure 8 shows the simulated ohmic loss, at room temperature, for the polarization rotator and the circular polarizer, with respect to the mirror rotation angle for both the E-plane and the H-plane cases. Figure 8 shows ohmic loss for a smooth surface ($S_{R}=0$) and when the surface roughness is equal to the skin depth ($S_{R}=\delta$) which is $\sim0.16\mu$m at 170 GHz. For the rotation angle $\Phi=0^\circ$, HFSS simulation results are in very good agreement with the high power calorimetric measurements done at JAEA in 2010 (reported in Table-I in [11] for a grating period of 0.79 mm). The JAEA experimental data points are also plotted in Figure 8 for $\Phi=0^\circ$. The JAEA experiments were done with a similar set (identical design) of polarizers built by General Atomics in 240 s pulses of 0.6 MW at 170 GHz. Our simulation results for a polished surface grating are in excellent agreement with the numerical results reported in [11] using space harmonic calculations and the FDTD method. The agreement is excellent considering that the surface roughness of the grating mirrors is of the order of the skin depth and experimental values may be higher due to the temperature rise during the 240s pulses leading to a decrease in the conductivity. To further validate the HFSS simulations, as there were no experimental results to compare with for different rotation angles, we simulated the same grooves in CST-Microwave Studio. This is also plotted in Figure 8 as square dotted points for the smooth surface case. An excellent agreement can be seen between the two simulations.

The grating polarizers manufactured with wire electric discharge machining (WEDM) have surface roughness of a few times the skin depth at millimeter wave frequencies and therefore higher ohmic loss is observed in such cases [11, 36]. However, grating polarizers at 110 GHz and 138 GHz manufacture by direct machining followed by a fine polishing procedure have demonstrated improved RMS surface roughness of $S_{R} \sim \delta/3$ or better yielding an $\sim 60\%$ reduction in the ohmic loss compared with WEDM grating polarizers [36]. This reduction in ohmic loss can be explained by the surface resistivity correction factor developed in [33-35].

A 2D map of the ohmic loss for each rotation combination of the two polarizers was also calculated by combining the losses expected from individual gratings. We assumed ideal copper conductivity in the calculations. For the first polarizer in series (the polarization rotator), the losses were taken directly from simulation results. However the ellipticity of microwaves incident upon the circular polarizer depends on the rotation of the polarization rotator, as described earlier when simulating the polarization map of the combined setup. Vector transformations between the field components incident upon the circular polarizer and the polarizer groove orientation were therefore used to find the loss on the second polarizer. The total ohmic loss for both polarizers was then calculated with respect to the rotation angles. A careful examination of
Figure 6 shows that a required \((\alpha, \beta)\) pair can be obtained by more than one combination of the rotation angles of the two polarizers. For example, \(\alpha = 47^\circ\) and \(\beta = -10^\circ\) can be obtained by eight different rotation angle combinations as shown by the dots on the contour of \(\beta = -10^\circ\) on the map of \(\alpha\) values in Figure 9(a, b). Similar observations were made and experimentally measured at 140 GHz for polarizers used in the ASDEX Upgrade ECRH experiment [37]. Since the polarizer gratings are rotated at different angles for the same \((\alpha, \beta)\) values, the field components seen by the grooves are different and therefore generate different ohmic losses for the eight rotation combinations. By choosing the minimum ohmic loss from these eight values one can generate a minimum ohmic loss map and the corresponding rotation angle map. Figure 9(c) shows the minimum ohmic loss map with respect to the \(\alpha, \beta\) values. One can see that the combined ohmic losses primarily vary between \(-0.23\%\) and \(0.6\%\) for perfectly smooth grating polarizers.

VI. MODE CONVERSION IN GRATING MITER BENDS

We have experimentally studied the mode conversion in the rotator miter-bend for the H-plane case as the grating mirror is rotated. The HE\(_{11}\) mode radiated from the waveguide end in a single miter-bend configuration (Figure 3) was measured in multiple planes parallel to the waveguide aperture. The electric field intensity and phase were measured, at a sampling interval of 1.3 mm on an 18 cm x 18 cm plane using a 3-axis scanner at several distances from the waveguide aperture. The linearly polarized [22] mode contents of the microwave beam were calculated from the measured data using field propagation technique mentioned in [23,24], and, alignment and measurement techniques described in [25,26]. The mode contents were calibrated using the baseline HE\(_{11}\) and HOMs at the end of the HE\(_{11}\) mode generator. A small amount of mode conversion was observed in the rotator miter-bend assembly. Figure 10 shows the measured intensity at the waveguide aperture at the location shown in Fig. 3(a) for grating rotation angles of 90° and 270°. Inspection of the two intensity profiles indicates a small shift along the x-axis in the intensity contours implying \(~1.0\%\) of mode conversion from the HE\(_{11}\) to higher order modes as the grating is rotated by 180°. This conversion corresponds to a very small tilt, \(~0.05^\circ\), in the grating plane as it is rotated in the miter-bend assembly.

VII. SUMMARY

Using HFSS and CST-Microwave Studio we have established a technique to design and simulate an arbitrary grooved shaped grating polarizer in the millimeter wave region. This technique was applied to numerically verify the design of a pair of miter-bend polarizer gratings designed and manufactured by General Atomics for use in the ITER ECRH transmission lines at 170 GHz. The design was further verified by detailed experimental measurements of polarization properties in low power tests using a vector network analyzer. Both the polarization rotator and circular polarizer were tested for rotation \(\alpha\) and ellipticity \(\beta\) of the reflected microwave beam. The measured polarization parameters with respect to the grating rotation angles were in excellent agreement with the simulations. The arbitrary elliptical polarization was induced in the linearly polarized microwave beam when reflected from the combined assembly. The detailed map of ellipticity and rotation measured directly and also by measuring the orthogonal field components of the reflected beam, showed excellent agreement with the numerical simulations. This indicates that the technique used here to evaluate the characteristic phase shift \(\tau\) between the TE and
TM modes of the grating together with HFSS can be used for optimizing better groove profiles with higher accuracy. Although, the work presented here is only for a sinusoidal groove shape, it is not mandatory to use a sinusoidal shape. Other shapes such as a rectangular profile with or without rounded edges have also been used [28, 29]. We have numerically benchmarked our technique for different groove shapes. We have calculated the polarizations maps of ideal rectangular and sinusoidal grooves and compared the results with those in ref. [15, 37], finding excellent agreement. We have also found excellent agreement for rectangular grooves with rounded edges comparing with ref. [28]. These benchmarking results are omitted here for brevity.

We also calculated the ohmic loss for the polarizer rotator and circular polarizer. For rotation angle $\Phi = 0^\circ$ in both the E-plane and H-plane cases, simulated results are in agreement with the high power tests done at JAEO on a similar set of miter-bend polarizers with polished surfaces. The ohmic loss variations as a function of grating rotation angle calculated by CST and HFSS are in agreement with each other validating the numerical simulations. Using the loss on individual gratings and using the vector transformations of field components along and orthogonal to the grooves we were able to predict the combined ohmic loss from both gratings. It was also observed that the same $\alpha$, $\beta$ pair can be obtained by up to 8 combinations of the rotation angles of the two gratings used in this study. The ohmic losses for all these combinations were different which allowed us to select the minimum loss and create a map of the minimum loss as a function of $\alpha$ and $\beta$. This map indicates that combined losses below ~0.6% can be achieved by choosing the appropriate combinations of grating rotation angles. The present analysis should be followed by a thermo-mechanical analysis to complete the design for use at megawatt power level operation.

We have also experimentally observed a small mode conversion of ~1% from HE$_{11}$ to higher order LP modes in the rotator miter-bend assembly by measuring the radiated electric field. The mode conversion is believed to originate from a slight tilt ~0.05° as the grating is rotated. In more recent miter-bend assemblies the mode conversion to HOMs will be reduced to lower values as the polarizer miter bend assemblies are now manufactured with improved tolerances.

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