Numerical Investigation of Higher-Order Mode Characteristics in Polarizer Miter Bend

Y. Fujita[1], S. Ikuno[2], *Member, IEEE*, T. Tsujimura[3], S. Kubo[3,4], and H. Nakamura[3,4]
[1]National Institute of Technology, Hakodate College, Hakodate, Hokkaido 042-8501, Japan, fujita@hakodate.kosen-ac.jp
[2]School of Computer Technology, Tokyo University of Technology, Hachioji, Tokyo 192-0982, Japan
[3]National Institute of Fusion Science, National Institute of Natural Sciences, Toki, Gifu 509-5292, Japan
[4]Department of Energy Engineering and Science, Nagoya University, Toki, Gifu 509-5292, Japan

The electromagnetic wave propagation phenomena in the polarizer miter bend are numerically investigated. In addition, the higher-order mode proportions in the propagation mode are identified from electromagnetic field distribution using the mode expansion technique. The mode expansion results show that the polarization angle is transformed by passing in the polarizer miter bend. Moreover, the fundamental mode proportions that is summation of $\mathrm{HE}^{\mathrm{v}}_{1,1}$ and $\mathrm{HE}^{\mathrm{h}}_{1,1}$ in the propagation mode is about 90 %. The remaining about 10 % mode is converted to the higher-order modes. The error of the mode expansion technique is evaluated by comparing the simulation result and the mode expansion result. From the above results, the mode expansion results are in good agreement around the waveguide center.

Index Terms—**FDTD, millimeter wave, miter bend, mode expansion, polarization.**

I. Introduction

THE MILLIMETER WAVE is used for selectively heating by the electrical characteristics. The high power millimeter wave can be generated using the gyrotron. The above heating technique is widely used in a variety of fields, and the electron cyclotron resonance heating (ECRH) is one of them. ECRH is used for the plasma heating in the nuclear fusion device. The transmission line of ECRH is composed of the corrugated waveguide and the miter bend. The propagation mode of the corrugated waveguide is the hybrid mode that the electric and magnetic field components in the direction of the propagation are non-zero. In this study, $\mathrm{HE}_{m,n}$ mode is adopted for the hybrid mode. $\mathrm{HE}_{1,1}$ that is the fundamental mode has minimum transmission loss. On the other hand, the generation of the higher-order modes that the numbers m, n are large should be minimized. The higher-order modes are generated by misalignment in the straight corrugated waveguide. The oversized waveguide is used as the transmission line for the high power millimeter wave. In addition, the transmission line is not only composed of the straight waveguide because of using the multiple gyrotrons. Therefore, the propagation wave is bent using the miter bend. It is known that the higher-order modes are generated at the oversized miter bend for the diffraction [1]-[2]. For this reason, the transmission loss is 1 % with each pass in the miter bend. The miter bend can be used as the polarizer for replacing the mirror with corrugated mirror. The polarization characteristics at the waveguide center are investigated theoretically using the plane wave. However, it is not considered that the influence of the higher-order mode on the polarization state. The theoretical investigation of the polarization characteristics in detail is difficult for the axisymmetry is broken in the polarizer miter bend.

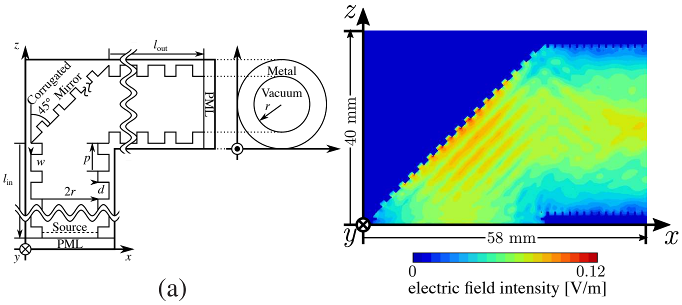
The authors developed the finite difference time domain (FDTD) code for the investigation of the electromagnetic wave propagation phenomena in the polarizer miter bend [3]. The electrical characteristics of a metal are evaluated by the Drude model. The Drude model is incorporated using recursive convolution method into FDTD code. As the results of simulation using the above code, the polarization state at around the waveguide center is in good agreement with theoretical result of the plane wave.

The purpose of the present study is to investigate the higher-order mode proportions in the propagation mode in the polarizer miter bend using mode expansion technique [4]. In addition, the error of the mode expansion technique is evaluated by comparison with the mode expansion results to the simulation results.

II. Numerical Model and Results

The simulation model of the polarizer miter bend is shown in Fig. 1a. We have to utilize a limited waveguide region because of the simulation cost. The perfectly matched layers (PMLs) as the absorbing boundary condition are placed on the edge of the waveguide for resolving the above problem. In this study, we assume that the waveguide consists of the aluminum, and inside of the waveguide is vacuum. The geometrical and physical parameters are fixed as follows: $l_{\mathrm{in}} = 1.4$mm, $l_{\mathrm{out}} = 18$mm, $r = 15.9$mm, $d = 0.8$mm, $w = 1$mm, $p = 1.4$mm, $\omega_{\mathrm{pe}} = 2.8$PHz and $\gamma = 12$THz. Here, ω_{pe} and γ denote the plasma and collision frequencies of aluminum, respectively. In addition, the parameters of the corrugated mirror are fixed as follows: groove depth is 0.8 mm, groove width is 1 mm and groove pitch is 1.8 mm. Moreover, the parameters of the input wave are fixed as follows: mode is $\mathrm{HE}^{\mathrm{v}}_{11}$, amplitude is 1 V/m, velocity is 3×10^8 m/s, and frequency is 84 GHz (wavelength is 3.6 mm). Here, v and h denote the vertical and horizontal polarization, respectively.

First, the electromagnetic wave propagation phenomena in the polarizer miter bend are numerically simulated under the above conditions. The distribution of the electric field intensity



(a) (b)

Fig. 1. Simulation model of the polarizer miter bend (a) and distribution of the electric field intensity (b).

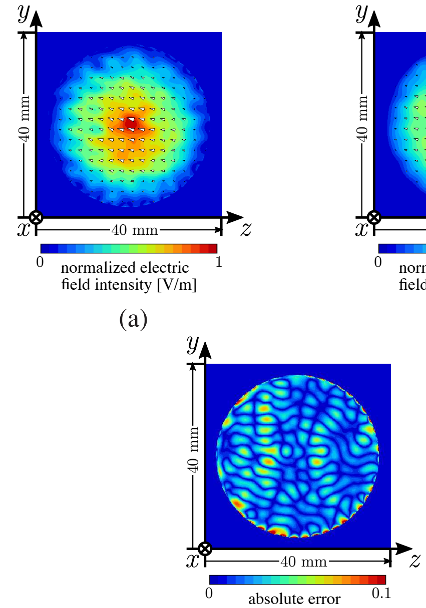
TABLE I
PROPORTIONS OF HIGHER-ORDER MODE.

mode	$\mathrm{HE}^{\mathrm{h}}_{1,1}$	$\mathrm{HE}^{\mathrm{v}}_{1,1}$	$\mathrm{TE}^{\mathrm{v}}_{0,1}$	$\mathrm{HE}^{\mathrm{h}}_{2,1}$	$\mathrm{HE}^{\mathrm{h}}_{1,3}$	$\mathrm{TM}^{\mathrm{h}}_{0,3}$	$\mathrm{HE}^{\mathrm{h}}_{1,2}$
proportion (%)	85.3	4.92	0.96	0.27	0.21	0.16	0.13

is shown in Fig. 1b. Here, the electric field intensity is defined by $\langle|\boldsymbol{E}|\rangle_t$. Note that the bracket $\langle\rangle_t$ denotes the time-average operator. From this figure, the standing wave is confirmed at the connection part in the polarizer miter bend. Furthermore, the distribution is distorted after the bent. The distortion of the distribution is caused by the generation of the higher-order modes, because the frequency of the higher-order mode is difference with the fundamental mode frequency. Therefore, the electric field intensity in the output plane is normalized using the value at the waveguide center as shown in Fig. 2a. From the above figure too, we can say that the higher-order modes are generated because of the conspicuous distortion.

Next, the higher-order mode proportions in the propagation mode are evaluated from the electromagnetic field distribution using the mode expansion technique. In the mode expansion technique, the each higher-order mode proportions are calculated by the orthogonal relationship with the eigenmodes. The top seven of the transmission mode proportion assuming mode number $m < 25$, $n < 25$ are shown in Tab. I. The mode expansion results show that the input mode $\mathrm{HE}^{\mathrm{v}}_{1,1}$ is 4.92 % with each pass in the polarizer miter bend. On the other hand, $\mathrm{HE}^{\mathrm{h}}_{1,1}$ is 85.3 %. The reason of the above results is that the angle of the polarization is changed by passing in the polarizer miter bend. The summation of the fundamental modes that are $\mathrm{HE}^{\mathrm{v}}_{1,1}$ and $\mathrm{HE}^{\mathrm{h}}_{1,1}$ are the about 90 %. The remaining about 10 % is converted to the higher-order modes.

Finally, the mode expansion results are verified by reproducing the distribution of the electric field intensity. The reproduced distribution is calculated by the summation of the theoretical distributions of the higher-order mode in response to the higher-order mode proportions in the propagation mode. The distribution that is reproduced by the best fit mode expansion results is shown in Fig. 2b. The direction of the electric field is the same in Fig. 2a and Fig. 2b. The error distribution is evaluated by the difference between the simulation distribution and the reproduced distribution as shown in Fig. 2c. From this figure, the mode expansion results are in good agreement around the waveguide center. However, the distortion can be seen from the error distribution. Moreover, the error of the mode expansion results near the waveguide wall is large. Thus, we should use more fine meshes to simulate in detail for the surface representation.



(a) (b) (c)

Fig. 2. Distributions of the normalized electric field intensity (a, b) and error distribution (c). Note that the vectors denotes the electric field.

III. CONCLUSION

The electromagnetic wave propagation phenomena in the polarizer miter bend are simulated using FDTD with Drude model. In addition, the higher-order mode proportions in the propagation mode are identified using mode expansion technique. Furthermore, the mode expansion error is evaluated by comparing the simulation result with the mode expansion result. The results in this study are summarized as follows:

- The transformation of the polarization angle can be confirmed in the mode expansion results.
- The fundamental mode proportion in the propagation mode is 90 % with each pass in the polarizer miter bend.
- The remaining 10 % is converted to the higher-order modes.
- The mode expansion results are in good agreement around the waveguide center.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number 15K06650 and 26390135.

REFERENCES

[1] J. L. Doane, *Infrared and millimeter waves*, vol. 13, Orlando: Academic Press, 1985, p. 123.

[2] E. J. Kowalski, D. S. Tax, M. A. Shapiro, J. R. Sirigiri, R. J. Temkin, T. S. Bigelow, and D. A. Rasmussen, *IEEE Trans. Microwave Theory Tech.*, vol. 58, 2010, p. 2772.

[3] Y. Fujita, S. Ikuno, S. Kubo, and H. Nakamura, *Jpn. J. Appl. Phys.*, vol. 55, 2016, 01AH06.

[4] K. Ohkubo, S. Kubo, T. Shimozuma, Y. Yoshimura, H. Igami, and S. Kobayashi, *Fusion Sci. Technol.*, vol. 62, 2012, p. 389.