Optimization of a corrugated millimeter-wave waveguide and a miter bend by FDTD simulation

H. Nakamura1,2, N. Kashima2 A. Takayama1, K. Sawada3, Y. Tamura4, S. Fujiwara5, and S. Kubo1,2
1 Department of Helical Plasma Research, National Institute for Fusion Science, Orosi-cho
322-6, Toki-city, GIFU, Japan
2 Department of Energy Engineering and Science, Graduated School of Engineering, Nagoya
University, Orosi-cho 322-6, Toki-city, GIFU, Japan
3 Faculty of Engineering, Shinshu University, Wakasato 4-17-1, Nagano-city, NAGANO,
380-8553, Japan
4 Department of Intelligence and Informatics, Konan University, Okamoto 8-9-1,
Higashinada-ku, Kobe-city, HYOGO, Japan
5 Department of Helical Plasma Research, National Institute for Fusion Science, Matsugasaki,
Sakyo-ku, Kyoto-city 606-8585, KYOTO, Japan
E-mail: hnakamura@nifs.ac.jp

Abstract. We estimate the transmission efficiency of the electromagnetic wave through the
system composed of waveguide and miter bend by Finite-Difference Time-Domain (FDTD)
simulation. As the first approach of this estimation, we choose the case that the input wave is
TE11 mode. In this case, the efficiency is estimated as 99.65 % for the system without grooves
and 76.48 % for the system with grooves (which is called as “corrugate”). Comparing the
distributions of the input electric field with that of the output electric field, the effect of the
grooves is found as follows: Because the TE11 mode has an anisotropy, its shape is changed
by the miter bend. This property appears in the corrugated system more strongly than the
non-corrugated system.

1. Introduction
Electromagnetic waves to heat plasma in the nuclear fusion devices have been studied both in
experiment and in theory. These studies are mainly classified into three fields, that is (i) the
interaction between plasma and electromagnetic wave, (ii) the transmission of electromagnetic
wave in waveguide, and (iii) the generation of electromagnetic wave. In this paper, we analyze
the electromagnetic field in a miter bend (Fig. 1) by Finite-Difference Time-Domain (FDTD)
simulation to improve the transmission efficiency of electromagnetic wave.

The FDTD method was introduced by Yee in 1966 [1] to solve numerically Maxwell’s
equation, that is \( \frac{\partial \mathbf{E}}{\partial t} = -\mathbf{j}/\epsilon + \nabla \times \mathbf{H}/\epsilon, \frac{\partial \mathbf{H}}{\partial t} = -\nabla \times \mathbf{E}/\mu \), where \( \mathbf{E} = (E_x, E_y, E_z) \), \( \mathbf{H} = (H_x, H_y, H_z) \) and \( \mathbf{j} = (j_x, j_y, j_z) \) denotes an electric field, a magnetic field and an electric
current respectively. The parameters \( \epsilon \) and \( \mu \) are electric permittivity and magnetic permeability.
In our previous works [2, 3, 4], we have developed the FDTD simulation with the Drude-Lorentz
model to investigate optical phenomena related to the electromagnetic response of metals using
near-field scanning optical microscope (NSOM) [5]. We adopted our FDTD-simulation method,
which we have developed in the research of NSOM, into the research of the transmission through the waveguide for the nuclear fusion.

The transmission system of the electromagnetic wave is composed mainly of two components, that is cylindrical corrugated-waveguide and miter bend. Grooves are engaged in both of them, which prevent eddy currents from being generated on the surface of them. The depth, the pitch, and the width of the grooves are designed by the phenomenological theory [6] (see Table 1). Our aim to use the FDTD simulation is to improve the propagation loss of the components.

In the present paper, we pick up the miter bend as the target of analyzation. (As for the corrugated waveguide, we report in another paper[7].) The miter-bend bends the direction of the electromagnetic wave as Fig.2. We estimate the propagation loss of the millimeter-wave through the miter bend.

2. Simulation Model
Figure 2 illustrates the cross-sectional view in the $xz$ plane at $y = 0$ of the three-dimensional FDTD geometry of the miter bend. The cross-sectional view in the $xy$ plane of the cylindrical waveguide is Fig.3.

The input electromagnetic wave with TE$_{11}$ mode enters from the top-left size of the waveguide and it is bended by the miter bend. After all, the electromagnetic wave goes out from the lower-right side (Fig.2). The waveguide and the miter bend (which are made of aluminum) are approximated as the perfect electric conductor (PEC). The whole system is surrounded by the simulation box (67mm $\times$ 34mm $\times$ 67mm) with Mur’s first-order absorbing boundary condition[8] as Fig.2. The parameters for the FDTD simulation are summarized in Table 1.

![Figure 1. Photoshop of miter bend. Grooves are engraved in the inside of miter bend. The width, the depth and the pitch of grooves are 1.0 mm, 0.76 mm, and 1.3 mm, respectively.](image1)

![Figure 2. Schematic picture of wave guide system. The direction of electromagnetic traveling-wave is bended by miter bend. The guiding axis $k$ is defined in the center of the wave guide along the traveling-wave. The input wave enters at $k = 0$ and go out of the wave guide at $k = 100$mm.](image2)

3. Results
To consider the effect of the groove engraved on the surface of the miter bend, we simulated two types of the miter bends as shown in Fig.4. In Fig.4, distributions in the $xz$ plane at
Table 1. Parameters in FDTD simulation of the corrugated waveguide and the miter bend

| Parameter                     | Value          |
|-------------------------------|----------------|
| Input source frequency        | 84 GHz         |
| Wave length                   | 3.57 mm        |
| Inside radius                 | 15.9 mm        |
| Depth of groove               | 0.76 mm        |
| Pitch error                   | 1.3 mm         |
| Width of groove               | 1.0 mm         |
| Grid size ∆x = ∆y = ∆z        | 0.357 mm       |
| Number of meshes              | 188 × 96 × 188 |

Figure 3. Simulated distributions in the xy plane of the averaged electric-field intensity |E(x, y)|_{k=k_0} for two types of miter bends. We plotted the distributions |E(x, y)|_{k=k_0} at the input position (k_0/Δz = 14) and the output position (k_0/Δz = 258) for each miter bend without grooves (a) and with grooves (b), respectively.

Figure 4. Simulated distribution in the xz plane at y = 0 of the averaged electric-field intensity |E(x, z)|_{y=0} for two types of miter bends. (a) miter bend without grooves, (b) miter bends with grooves.

y = 0 of the averaged electric-field intensity |E(x, z)|_{y=0} in the steady state are plotted. Here |E(x, z)|_{y=0} := (1/T_0) \int_{t_0}^{t_0+T_0} |E(x, y = 0, z; t_1)|dt_1, where T_0 = 5 × 1/(88 GHz) \sim 5.68 × 10^{-11} sec.

Moreover, we plotted the |E(x, y)|_{k=k_0} distributions for the steady state in Fig. 3, where |E(x, y)|_{k=k_0} := (1/T_0) \int_{t_1}^{t_1+T_0} |E(x, y, z; t_1)|dt_1 for each position (x, y) in the k = k_0 plane. Here k axis is defined in Fig.2.
Figure 5. The $k$ dependence of the averaged electromagnetic energy $\bar{\varepsilon}(k)$ for the waveguides without grooves (a) and with grooves (b).

In Fig.5, the $k$ dependence of the averaged electromagnetic energy $\bar{\varepsilon}(k)$ is plotted to estimate the transmission efficiency. $\bar{\varepsilon}(k)$ is given by the time average for 5 periods of $\varepsilon(k) = \frac{1}{2} \sum_{(x,y,z) \in S(k)} [E(x,y,z)]^2 + \mu [H(x,y,z)]^2$, where $S(k)$ is the cross-section area of the waveguide at $k$. We define the transmission efficiency as the ratio $\bar{\varepsilon}(258\Delta z)/\bar{\varepsilon}(14\Delta z)$, which becomes 99.65% for the waveguide without grooves and 76.48% for the waveguide with grooves.

4. Discussion and Conclusion

The transmission efficiency for the system composed of waveguide and miter bend is obtained by the FDTD simulation. Comparing the two cases (without grooves and with grooves), it is found that the grooves does not increase the efficiency for the input wave with TE$_{11}$ mode. The reason of this fact is as follows: Because the TE$_{11}$ mode is not the eigenmode of the corrugated waveguide and miter bend (i.e., with grooves), the input wave changes its shape through the system with grooves more strongly than without grooves. In the present simulation, we chose the TE$_{11}$ mode as the first step of the analysis with the miter bend. To improve the estimation of the efficiency, it is necessary to choose the eigenmode of the corrugated waveguide and miter bend as the input wave (e.g. HE$_{11}$ mode).

Acknowledgment

This work is supported by KAKENHI (24656560).

References

[1] Yee K S 1966 IEEE Trans. Antennas Propagat. 14 302
[2] Nakamura H, Sawada K, Kambe H, Saiki T and Sato T 2000 Prog. Theor. Phys. Suppl. 138 173
[3] Nakamura H, Saiki T, Kambe H, Sawada 2001 Comp. Phys. Com. 142 464
[4] Sawada K, Nakamura H, Maruoka T, Tamura Y, Imura K, Saiki T, Okamoto H 2010 Plasma and Fusion Research 5 S2110
[5] Furukawa H and Kawata S 1996 Opt. Commun. 132 170
[6] Doane J L 1985 Infrared and Millimeter Waves 13 123
[7] Tamura Y, Nakamura H, Okamura T, Kashima N, Fujiiwa S and Kubo S 2012 International Conference on Mathematical Modeling in Physical Sciences (IC-MSQUARE 2012) September 3-7, 2012 Budapest, Hungary
[8] Mur G 1981 IEEE Trans. Electromagn. Compat. 23 377