Interactive visualization system to analyze corrugated millimeter-waveguide component of ECH in nuclear fusion with FDTD simulation

N. Kashima¹, H. Nakamura¹,², Y. Tamura³, A. M. Ito² and S. Kubo¹,²

¹ Department of Energy Engineering and Science, Graduated School of Engineering, Nagoya University, Oroshi-cho 322-6, Toki-city, GIFU, Japan
² Department of Helical Plasma Research, National Institute for Fusion Science, Oroshi-cho 322-6, Toki-city, GIFU, Japan
³ Department of Intelligence and Informatics, Konan University, Okamoto 8-9-1, Higashinada-ku, Kobe-city, HYOGO, Japan

E-mail: teamMD@nifs.ac.jp

Abstract. We have simulated distribution of electromagnetic waves through the system composed of miter bends by Finite-Difference Time-Domain (FDTD) simulation. We develop the interactive visualization system using a new interactive GUI system which is composed of the virtual reality system and android tablet to analyze the FDTD simulation. The effect of the waveguide system with grooves have been investigated to quantitatively by visualization system. Comparing waveguide system with grooves and without grooves, grooves have been confirmed to suppress the surface current at the metal surface. The surface current at complex shape such as the miter bend have been investigated.

1. Introduction

Recently, there has been an interest in electron cyclotron heating (ECH) of high temperature plasmas by high-power electromagnetic (EM) waves [1]. ECH is used for heat plasmas and maintain a stable plasma in the Large Helical Device (LHD). To transmit EM waves from a gyrotron efficiently, low loss and high power millimeter wave components have been researched both in theoretically and experimentally [2]. In this paper, we investigated the transmission of EM waves in transmission system that is composed the circular corrugated (CC) waveguide and the miter bend. We adopted FDTD simulation method in the research of the transmission through the CC-waveguide and the miter bend. The FDTD method was introduced by Yee in 1966 [3] to solve Maxwell’s equation numerically. In our group, we have been developing FDTD simulation code and the visualization system to analyze the EM wave transmission [4–7].

EM waves are transmitted through the transmission line. The transmission line is composed of the straight CC-waveguide and the miter bend (Fig. 1). The transmission line is not composed at only a straight component between the gyrotron from LHD in order to insulate the neutrons from the LHD. Thus, the miter bend is used to change the direction of EM waves [8]. Grooves called corrugated are machined on the inside of these components. The eddy currents on the surface of them are prevent by grooves. The pitch ($p = 1.3$ [mm]), the width ($w = 1.0$ [mm]) and the depth ($d = 0.76$ [mm]) of grooves are designed by the phenomenological theory [9].

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CC-waveguide and the miter bend is connected as shown in Fig. 1. The majority of loss in the transmission line originates from the miter bend [10]. The mode-conversion is caused through the miter bend [11]. The mode-conversion is a cause of the losses. The losses on the transmission lines have been roughly estimated [12]. In the present paper, we have analyzed EM waves propagating in the waveguide system by developing original visualization systems.

2. Simulation Method
Fig. 1 illustrates the cross-sectional view in the xz plane at y = 0 of the three-dimensional FDTD geometry of the CC-waveguide and the miter bend. Input EM waves with HE_{11} mode are injected from z_{in} = 0.2 [mm]. The CC-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 with Mur’s first-order absorbing boundary condition [13] as shown by black lines in Fig. 1. EM waves with HE_{11} mode are injected from the CC-waveguide as a red thick arrow in Fig. 1. The HE_{11} mode in the CC-waveguide has advantages of low transmission loss [9], the HE_{11} mode has been adopted as highly reliable transmission mode of EM waves. The parameters for the FDTD simulation are summarized in Table 1.

3. Visualization system
A new interactive GUI system which is composed of the virtual reality (VR) system and android tablet have been developed. The user can analyze EM waves intuitively by moving android tablet. EM waves which propagate the waveguide system are visualized. The user can examine the cross-sectional view of EM waves at any angle by moving the tablet, as shown in Fig. 2. The perspective in the VR space is operated by touching and swiping the tablet display. The tablet tilt is obtained by their gyro sensor. The tablet tilt is sent to the visualization system using

**Table 1.** The common parameters in FDTD simulation of the CC-waveguide and the miter bend.
TCP in Wi-Fi. The tablet position is obtained by Kinect. The Kinect is a motion sensing input device by Microsoft for the Xbox 360 video game console. The Kinect can obtain the depth and position of the human skeleton using the RGB camera and depth sensor. The user can operate the tablet as a plate that cut out a cross-sectional view of EM waves without using a keyboard or mouse user. The schematic diagram of the visualization system is shown in Fig. 3. The visualization system can visualize the three-dimensional EM waves by volume rendering and the surface current of the metal. The intensity and direction of current density \( J = n \times H \) on the metal surface is expressed by colors and the arrowhead shape, respectively. The parameters \( H = (H_x, H_y, H_z) \) and \( n \) denote a magnetic field and the normal vector of the metal surface, respectively. Thereby, the eddy current is confirmed.

![Interactive visualization system](image1)

**Figure 2.** Interactive visualization system using tablet.

![The schematic diagram of the visualization system](image2)

**Figure 3.** The schematic diagram of the visualization system.

4. Results and Discussion
The distribution of EM waves has been simulated in the waveguide and miterbend. Surface current on the metal with grooves and without grooves have been compared using visualization system. Fig. 4 shows surface current in the waveguide system without grooves (a) and with grooves (b). The direction of current density is eddying in the cylindrical waveguide. The intensity of current density in the CC-waveguide is smaller than the cylindrical waveguide. The direction of current density in the CC-waveguide is perpendicular to the groove. Therefore, grooves have been confirmed to suppress surface currents by suppress eddy current. The direction of current density is eddying in the miterbend without grooves, too. The intensity of current density in the miterbend with grooves is smaller than the miterbend without grooves. The direction of current density on the surface that grooves intersect is eddying. Therefore, grooves have been confirmed to suppress surface currents by suppress eddy current, although eddy
current is generated slightly on the surface that grooves intersect. It is necessary to consider the processing of the groove in order to suppress eddy current on the surface that grooves intersect.

![Image of current density](image)

**Figure 4.** Current density of the metal surface in the waveguide system.

5. Future Works

EM waves may have been reflected by Mur’s first-order absorbing boundary condition. It is necessary to use the perfectly matched layer (PML) absorbing boundary condition [16]. The miterbend that are processed various groove are simulated. The purity of the HE_{11} mode is evaluated quantitatively by the processing of the groove.

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