Propagating Mode Analysis and Field Reconstruction in the Corrugated Waveguides of a High Power Electron Cyclotron Heating System

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***Abstract*—A new method is proposed to analyze mode contents of high power electromagnetic waves that are propagating through corrugated waveguides in the electron cyclotron resonance heating (ECH) system for nuclear fusion devices. The method was applied to a 168GHz transmission line of the ECH system in Large Helical Device (LHD) to evaluate the waveguide misalignment. Mode contents of the propagating wave could be well obtained, and the wave field in the waveguide was reconstructed by using the information of each mode.**

I. Introduction And Background

ELECTRON Cyclotron resonance Heating (ECH) is one of the most powerful heating methods for plasma heating and current drive in fusion-oriented plasma devices. The high power millimeter-waves for ECH are usually transmitted by over-sized circular corrugated waveguides. The length of such transmission lines becomes longer and longer due to the huge size of plasma confinement devices. In the over-sized corrugated waveguides, tilt and offset of the waveguide axis easily cause conversion of the transmitted mode of HE_{11} to unwanted modes. Improvement of transmission efficiency is essential in view not only of increase of usable power but reduction of heat load to the millimeter-wave components. We already proposed an alignment method of transmission lines based on infrared (IR) images on a target irradiated by high power millimeter-waves [1]. As a next step, it is important to identify propagating mode contents in the corrugated waveguides for clarifying what kind of misalignment induces such mode conversion. One method of the mode content analysis has been already proposed by using the irradiant waveguide modes [2]. We will report another method of mode contents analysis and reconstruction of the wave field in the corrugated waveguide.

II. Analysis of Mode Contents

In the process of designing phase correcting mirrors and performing waveguide alignment, the phase retrieval method was successfully used to reconstruct the phase information of the radiated waves by using only measured intensity profiles at several positions [3]. By using the phase retrieval method, we can find the complex amplitude at radiating edge of the corrugated waveguide. It can be decomposed by the eigen modes in the corrugated waveguide. The expansion coefficients by the eigen modes give the mode contents of the corresponding eigen modes.

At the waveguide outlet (z=0), the phase can be retrieved by the phase retrieval method. Such amplitude $A(x,y,0)$ and phase $\varphi(x,y,0)$ can be expanded by the orthogonal functions in the waveguide as,

$$A(x,y,0)e^{j\varphi(x,y,0)} = \sum_{n=1}^{N} C_n e^{j\varphi_n}\phi_n(x,y) \qquad (1)$$

, where C_n is the amplitude and φ_n is the phase of a mode n. On the contrary, the expansion coefficients are represented by

$$C_n e^{j\varphi_n} = \frac{\int_S A(x,y,0)e^{j\varphi(x,y,0)} \cdot \phi_n^*(x,y)ds}{\int_S |\phi_n(x,y)|^2 ds}. \qquad (2)$$

So, a fraction of the mode n, p_n, is calculated as,

$$p_n = \frac{|C_n|^2 \cdot \int_s |\phi_n|^2 ds}{\int_S |A|^2 ds} = \frac{|\int_S A(x,y,0)e^{j\varphi(x,y,0)} \cdot \phi_n^* ds|^2}{\int_S |\phi_n|^2 ds \cdot \int_S |A|^2 ds}. \qquad (3)$$

The eigen functions in a over-sized corrugated waveguide with the radius of a are approximately give by [4]

$$\begin{aligned} \phi_{n,m}^{even} &= J_{n-1}(X_{n-1,m}\frac{r}{a}) \cdot \cos(n-1)\phi \\ &\text{for } n,m = 1,2,\cdots \\ \phi_{n,m}^{odd} &= J_{n-1}(X_{n-1,m}\frac{r}{a}) \cdot \sin(n-1)\phi \\ &\text{for } n = 2,3,\cdots, m = 1,2,\cdots \end{aligned} \qquad (4)$$

Here, $X_{n-1,m}$ are m-th roots of Bessel function $J_{n-1}(X_{n-1,m}) = 0$ and $r = \sqrt{x^2+y^2}, \phi = \tan^{-1}(y/x)$.

This method was applied to the 168GHz transmission line in the ECH system of LHD. Figure 1 shows measured amplitude and retrieved phase at the radiating edge of the circular corrugated waveguide 88.9mm in inner diameter. This information was used for mode-contents analysis. Figure 2 shows the analyzed mode contents for the orthogonal even- and odd-modes in the corrugated waveguide. HE_{11} main propagating mode

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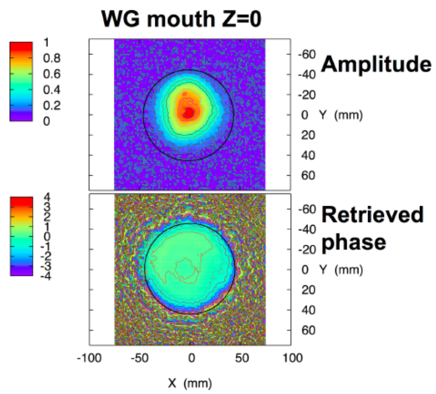

Fig. 1. Measured amplitude and retrieved phase at the radiating edge of the corrugated waveguide.

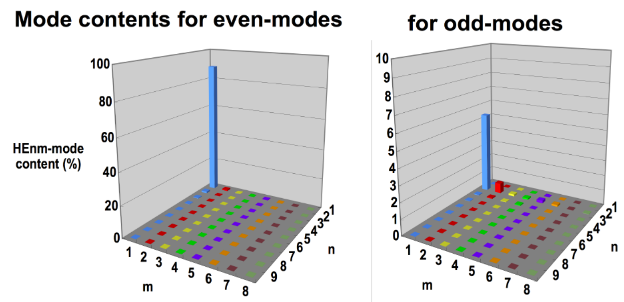

Fig. 2. Results of mode contents analysis for even and odd modes in the corrugated waveguide.

dominates 89% and the other spurious modes are HE_{21}/1.1%, HE_{12}/0.9% (even-mode) and HE_{21}/5.4% (odd-mode).

III. Mode Reconstruction

On the contrary, the electromagnetic field at the arbitrary position, z, in the waveguide can be reconstructed by using the expansion coefficients of each eigen mode, $C_n e^{j\varphi_n}$ and propagation phase factor, $e^{(-j\beta_n z)}$, where β_n is a propagation constant of the mode n in the z-direction.

Figure 3 a) shows the intensity profiles of reconstructed field at several positions (z=0, -1.6m and -3.2m) as indicated in the illustration. The positions of z =-3.2m and z=0 correspond to the entrance and exit of a corrugated waveguide under test, respectively. In general, the n-th moment in the x-direction weighted by the intensity $A(x, y, z)^2$ can be defined as,

$$< x^n > (z) = \int x^n A^2(x, y, z) \mathrm{d}x\mathrm{d}y / \int A^2(x, y, z) \mathrm{d}x\mathrm{d}y \tag{5}$$

As a representative of the power density center, the first moment was calculated. The results are shown in Fig. 3 b). Since the beat wavelength between HE_{11} and HE_{21} (odd-mode), which is the most dominant mode among the unwanted modes, is about 9.8m, this results in a periodic change of the moment $< y >$ of which period corresponds to about a half of the beat wavelength. In x-direction, the non-axisymmetric unwanted even-mode of HE_{21} affects the value of $< x >$ and shows the same periodic change. Although the center of the

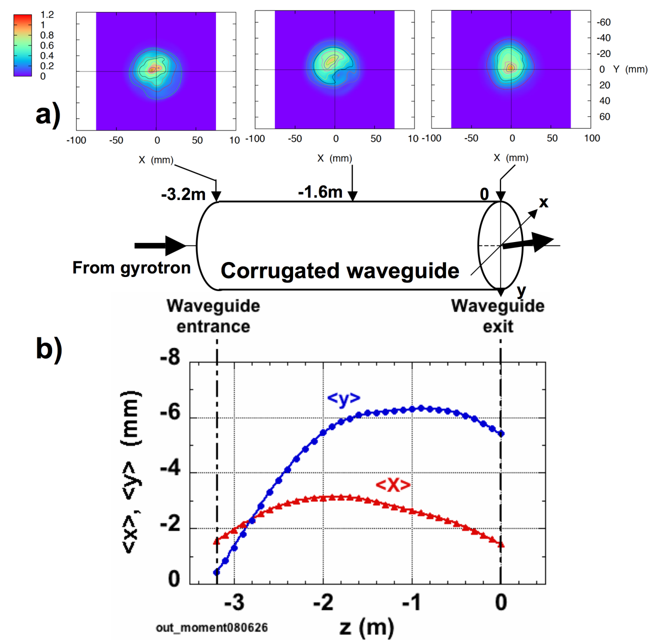

Fig. 3. a) Contour plot of power density of reconstructed electromagnetic field at each position in the corrugated waveguide. b) The first moment calculation for x- and y- direction.

intensity locates around the waveguide axis at the entrance, the calculated phase indicates an inclined phase profile in the y-direction, which is about 0.3 degree. This caused a generation of the dominant unwanted mode of HE_{21} (odd-mode).

IV. Conclusion

Mode contents of high power electromagnetic waves that are propagating through corrugated waveguide in ECH system were well analyzed by using retrieved phase information, and the wave field in the waveguide was reconstructed by using the complex amplitude of each mode. The results probably give the cause of misalignment between the incident beam axis and the waveguide axis. In special, the phase information at the waveguide entrance gives a good guidance for alignment. It was found that a burn-pattern measurement at two positions was insufficient for the beam alignment, because the center of measurable intensity distribution changes with a period of quarter beat wavelength between the related modes.

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