Quasi-Optical High Purity HE_{11}-Mode Exciter for Oversized Corrugated Waveguide Transmission*)

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Oversized corrugated waveguide transmissions are used to transmit high power millimeter wave for electron cyclotron heating in ITER. The HE_{11} mode purity of the waveguide components is a critical issue not only in the high power operation but also in the low power operation to evaluate the components. Conventional single Gaussian beam system causes edge diffraction and excites higher order modes at the waveguide aperture. A proposed HE_{11}-mode exciter uses beam interference between two Gaussian beams interference and serves the high purity HE_{11} mode without the edge diffraction. The HE_{11}-mode exciter consists of a scalar feed horn antenna, quasi-optical mirrors and a beam splitter (combiner). Phase matched mirrors correct the Gaussian-like beam excited from the horn antenna to pure Gaussian beam. Authors report the experimental study of the exciter.

Keywords: electron cyclotron heating, transmission line, Gaussian beam, quasi-optical mirror, high power millimeter wave, mode purity

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1. Introduction

Oversized circular corrugated waveguide (CCWG) will be used for electron cyclotron heating to deliver up to 20 MW of radio-frequency power in the ITER burning fusion-plasma experiments [1, 2]. Each waveguide will be operated in 2 MW of CW power condition. An output beam from gyrotron oscillator is directed to a waveguide transmission line which is mainly propagated in the HE_{11} mode. The CCWG with a diameter of 63.5 mm has been specified for the transmission in mm-wave range at the frequency of 170 GHz. The higher order modes (HOMs) are excited due to misalignment of the coupled beam and due to manufacturing error of the waveguide components in the oversized condition. These cause undesirable events such as overheating or arcing in the lines. The HOMs excitation is concerned with the transmission of a high power mm-wave range to avoid the events. Therefore, experimentally evaluation of the unwanted HOMs excitation is a concern to reduce transmission line loss and to avoid the events. A mode exciter with the high purity HE_{11} mode is required to measure the waveguide mode of the CCWG components, such as miter-bends and bellows. In this study we would like to experimentally examine a high purity HE_{11}-mode exciter. The exciter was designed for low power evaluation.

2. Gaussian Beam System

The HE_{11} mode in the waveguide is matched to the TEM_{00} mode (Gaussian beam) in free space with an optimum mode conversion efficiency of 98% [3]. The radial amplitude distributions are expressed below.

$$HE_{11}\text{ mode: } A_0 = J_0(2.405r/a), \quad (1)$$

$$\text{Gaussin beam: } A_G = \exp(-r^2/[0.645a]^2), \quad (2)$$

where a is the waveguide radius. The conversion loss with 2% from Gaussian beam into the HE_{11} mode comes from two features: the differences of the amplitudes and kurtosis (fat profile) and truncation by the waveguide edge (edge effect) (see Fig. 1).

The coupled mode theory (CMT) is well known and widely used for an electromagnetic field analysis of a waveguide. The CMT is also useful to analyze the fat profile [4]. On the other hand, little is known about the edge effect of the CCWG. The present paper describes the edge effect by using numerical analysis based on the

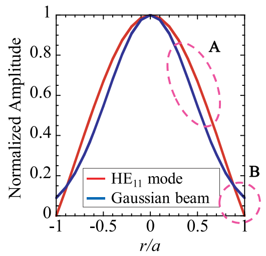

Fig. 1 Radial amplitude distribution with the HE_{11} mode and Gaussian beam following Eq. (2).

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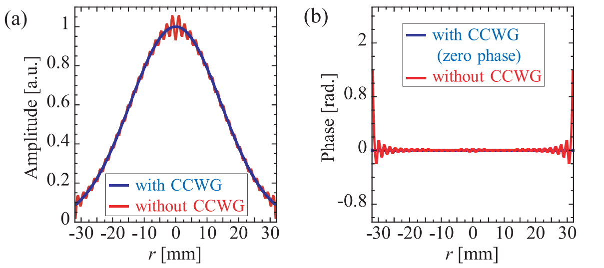


Fig. 2 (a) Intensity and (b) Phase distributions of Gaussian beam with and without CCWG. These are calculated with the MoM simulator.

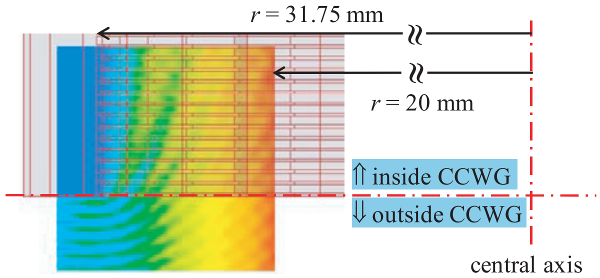


Fig. 3 Contour plot of amplitude distribution as the optimum Gaussian beam was injected into the CCWG.

method of moment (MoM) [5]. The residue of electric field around the waveguide edge sharply decays to zero due to the metallic wall in Fig. 2 (a). A ripple around the center in Fig. 2 (a) and a fluctuation of the phase distribution in Fig. 2 (b) show the excitation of HOMs. Figure 3 shows that diffraction caused at the edge of the metallic wall and interfered with the propagation in the CCWG. These results suggest the coupling loss may be larger than 2% in practice due to the edge effect. Therefore, an amplitude control is required to revise the fat profile and to eliminate the edge effect.

A phase-correcting mirror system with Gaussian Quasi-optics is a certain way of amplitude control [6]. The radiated HE_{11} mode excited from the phase correcting mirrors can reconstruct the HE_{11} mode by the CCWG aperture in the coupling. From the standpoint of experimentation, it was essential to consider the dynamic range of the HE_{11} mode field distribution in a limited mirror size. The higher dynamic range, over 20 dB, was required to attain the higher HE_{11} mode purity with the efficiency of over 0.99 [4].

Recently, beam interference between multiple beams was proposed as another way of amplitude control [4]. In this study, the interference between two Gaussian beams was applied to exciting the HE_{11}-mode.

3. Two Gaussian Beam System

Two Gaussian beam system for the HE_{11}-mode exciter consisted of a scalar feed horn antenna and quasi-optical mirrors. Operation frequency is 170 GHz in this experiment. Figure 4 shows the schematic top view diagram of the HE_{11}-mode exciter. A set of the antenna and the first

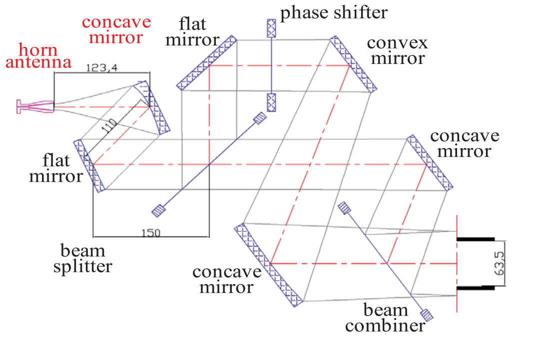
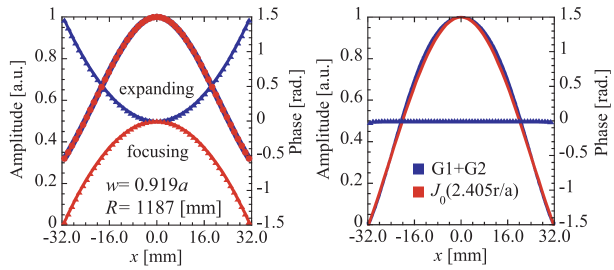


Fig. 4 Schematic top view diagram of the HE_{11} mode exciter.



(a) Two Gaussian beam distribution (b) Interfered Beam distribution

Fig. 5 Beam interference between two Gaussian beam.

concave mirror excited a Gaussian beam. The initial incident beam was a 45 degrees linearly polarized beam in Fig. 4. Wires of a beam splitter (wire grid polarizer) were directed parallel to the vertical direction in Fig. 4. The linearly polarized incident beam was split into the vertical components and the horizontal components in a plane perpendicular to the propagation direction through the wire grid polarizer, respectively. Curvatures of the two Gaussian beams were formed into opposite curvature by the other mirrors. Wires of a beam combiner (wire grid polarizer) were directed parallel to the horizontal direction. Each incident beam with the vertical components and the horizontal components were combined into the same polarization as the initial polarization. Finally, the wave of the interference obtained the HE_{11} mode at the aperture of the CCWG with diameter of 63.5 mm.

The beam interference between two Gaussian beams was calculated by using the MoM simulator. Both of an expanding Gaussian beam (G1) and a focusing Gaussian beam (G2) were prepared at the aperture of the waveguide in Fig. 5 (a). Figure 5 (b) shows interfered beam distribution of G1 + G2 and the ideal HE_{11} mode distribution expressed in Eq. (1). The amplitude distribution in Fig. 5 (b) was well agreed with the HE_{11} mode and the phase distribution was flat. The fact suggests that the interfered beam between two Gaussian beams with optimized beam size is reasonable to excite the HE_{11} mode. What is significant in the exciter is how to excite a pure Gaussian beam.

In this paper, we would like to focus on the excitation of Gaussian beam with the scalar feed horn antenna, the wire grid polarizer and the quasi-optical mirrors.

The phase matched technique based on the Kirchhoff integral was proposed to design the quasi-optical mirrors to excite pure Gaussian beam. The precise phase evolution in the field radiated from the scalar horn antenna was required to design the quasi-optical mirrors. The phase profiles were directly measured along the propagation and were compared with the MoM simulation. The wire grid polarizer is known as a polarizing power divider (combiner). However it is not clear whether it works without phase disruption.

4. Exciting Gaussian Beam

4.1 The scalar feed horn antenna

The scalar feed horn antenna was designed by using the MoM simulator. The designed center frequency was 140 GHz, but the antenna was designed to work in a broadband frequency range of 110-170 GHz. The TE_{10} mode in the WR-6 rectangular waveguide was first converted into the TE_{11} mode in the circular fundamental waveguide, and then the wave was led into the horn aperture with a diameter of 10.01 mm through corrugated taper section.

The intensity and phase distributions radiated from the horn antenna were measured at $z = 50$ to 200 mm in an increment of 50 mm. Figure 6 shows contour plots of measured intensity and phase patterns at the propagating length of $z = 50$ mm. Both profiles had symmetric property without a beam center offset. Figure 7 shows the measured and the MoM profiles at $z = 150$ mm. The profiles were well fit with between the measured and simulated one.

The profiles were analyzed in terms of Gaussian optics. The intensity profile showed Gaussian-like beam in Fig. 7 (a). The waist sizes and the positions were deduced from Fig. 8 (a) as $w_{0x} = 2.84$ mm, $w_{0y} = 2.64$ mm, $z_{0x} = -15.3$ mm, $z_{0y} = -0.94$ mm in the x and y direction, respectively. The Gaussian beam parameters (w_0, z_0) differ between the amplitude and phase evolution in Fig. 8 (b). This means that Gaussian optics cannot express the beam propagation of the horn antenna and is not adequate for the phase correction of the quasi-optical mirrors. Therefore the phase matched mirror was considered to revise the Gaussian-like beam. In addition, phase profile in Fig. 9 was made clear that the existence of the HOMs in the horn antenna other than the HE_{11} mode. The HOMs affect Gaussian optics in an adverse way.

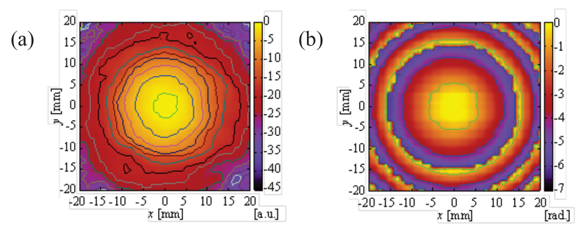


Fig. 6 (a) Intensity and (b) Phase patterns of the horn antenna at $z = 50$ mm.

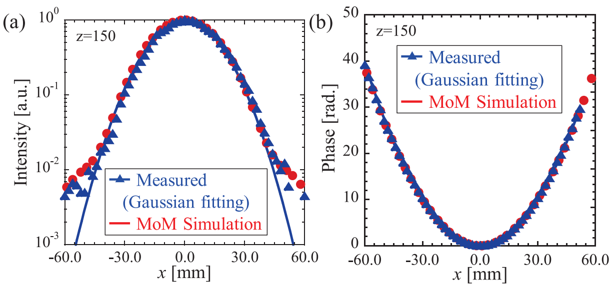


Fig. 7 (a) Intensity and (b) Phase distributions of the horn antenna at $z = 150$ mm in the x-direction.

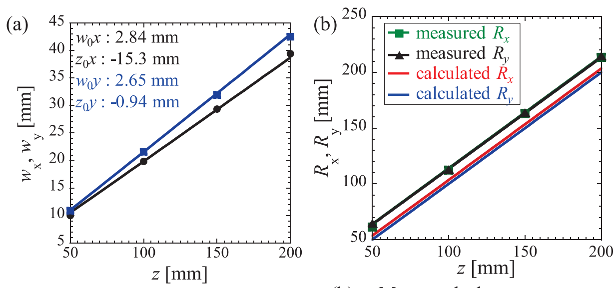
4.2 The phase matched mirror

The phase matched mirror based on Kirchhoff diffraction theory was designed for the first concave mirror. The electric field diffraction pattern U_p from the aperture point (ξ, η) to the point $P(x, y, z)$ is given by:

$$U_\mathrm{p} = \frac{1}{4\pi} \int_A F(\xi, \eta) \frac{\mathrm{e}^{-jkr}}{r} \times \left[\left(jk + \frac{1}{r} \right) \boldsymbol{i}_z \cdot \boldsymbol{r}_1 + jk\boldsymbol{i}_z \cdot \boldsymbol{s} \right] \mathrm{d}\xi \mathrm{d}\eta, \quad (3)$$

where $F(\xi, \eta)$ is the field over a plane aperture [7]. The phase diffracted from the horn antenna was numerically calculated with the integral of Eq. (3) and the geometry of the concave mirror surface was set to match up the phase of the horn antenna with the desired Gaussian beam phase curvature.

The field distribution was analyzed on the basis of



(a) Measured beam size evolution along the propagating z-axis.

(b) Measured phase curvature along the propagating z-axis. Analyzed curvatures were calculated from the waist size w_0 and position z_0 in Fig.8(a)

Fig. 8 Analyzed profiles of the horn antenna in terms of Gaussian optics.

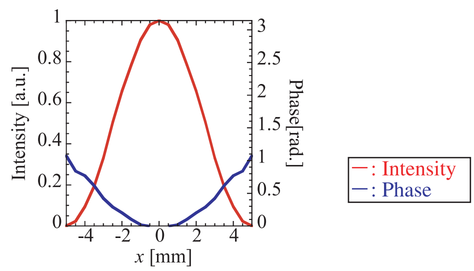


Fig. 9 The field distributions at the antenna aperture by using the MoM simulator.

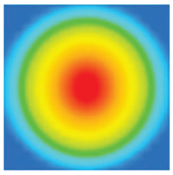


Fig. 10 Intensity patterns of the horn antenna at the aperture using MoM.

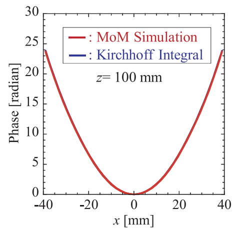


Fig. 11 Phase distribution using Kirchhoff Integral and MoM at z = 100 mm.

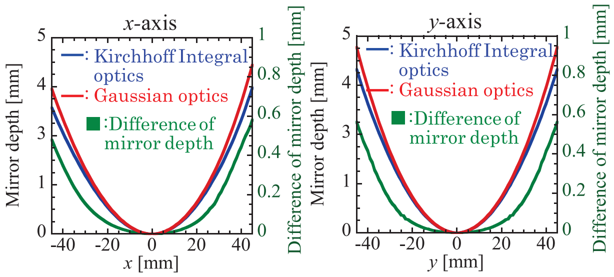


Fig. 12 A comparison of the mirror surface between Kirchhoff Integral optics and Gaussian optics in a incident plane of x-y plane.

the MoM simulation and the Kirchhoff Integral. Figure 10 shows an intensity pattern of the horn antenna at an aperture plane simulated by using the MoM simulator. Its distribution was used as the aperture field distribution in the Kirchhoff Integral calculation. The phase profile in the Kirchhoff Integral was in excellent agreement with the MoM simulation in Fig. 11 as well as the measurement. The Kirchhoff Integral should be useful to design the phase matched mirror surface. Designed concave mirror geometries are drawn in Fig. 12 on the basis of Kirchhoff Integral optics and conventional Gaussian optics. The radial mirror size was 35 mm and compatible with the desired Gaussian beam size of 1.5w. The difference of the mirror depth between the optics was a maximum of 0.31 mm at the radial beam distance of 1.5w. The horn antenna was placed by 123.4 mm distance from the first concave mirror and the desired Gaussian beam which has the waist size of w_0 = 23.47 mm was also placed by 260 mm distance from the first concave mirror.

4.3 The beam splitter (combiner)

Figure 13 shows the geometry of wire grid polarizer. The wire grid polarizer which is tilted by angle $\varphi = 45°$ reflects the field of E_y and transmits the field of E_x. Both amplitudes are equal and cross-polarized as a 45° (x-y plane) linear polarized beam is injected. Figure 14 shows the analyzed field distribution of reflected and transmitted beam, respectively, as the Gaussian beam of 45° linear polarized beam was injected into the wire grid polarizer. The amplitude and the phase properties were almost same within the beam center. The wire grid polarizer works well as a splitter and a combiner without phase disruption.

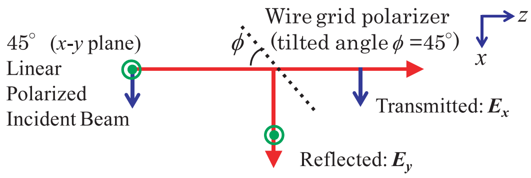


Fig. 13 The geometry of wire grid polarizer.

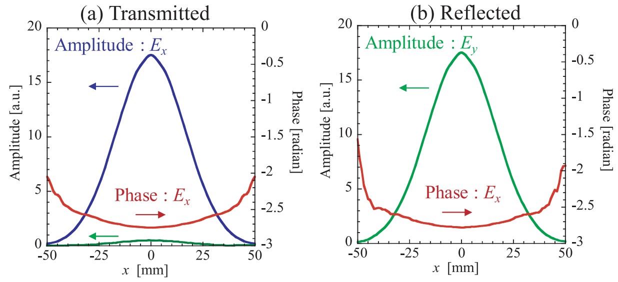


Fig. 14 (a) Transmitted, (b) Reflected amplitude and phase distribution propagated at a distance of 100mm through the wire grid polarizer. (Wire width: 50 µm, Slit width: 75 µm, Pitch period: 125 µm).

5. Summary

It was found that the truncation of the Gaussian beam by the CCWG edge caused diffraction and excited HOMs in the coupling of conventional single Gaussian beam system. Two Gaussian beam system using the beam interference excited high purity HE_{11} mode. The scalar feed horn antenna was designed and measured. The amplitude distribution was Gaussian-like, and the phase distribution was parabolic. But these evolutions were not able to be explained with Gaussian optics. The radiation field evaluation with the Kirchhoff integral was in good agreement with the MoM simulation as well as the experiment. The phase-matched mirror was designed with Kirchhoff integral optics. The property of the wire grid polarizer was confirmed by using the MoM simulator. The wire grid polarizer worked as a power splitter or combiner without phase disruption.

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