Controllability Study of Propagating Mode Content by an Angle-Adjustable Mirror of a Miter-Bend in EC H&CD Transmission Line

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***Abstract*— A miter-bend-type mode converter, which has an angle-adjustable mirror, is proposed to control the transmission mode content in the electron cyclotron heating and current drive transmission line. This component excites the higher order mode by injecting a tilted radio frequency beam into a waveguide using the angle-adjustable mirror. A mock-up model of the converter was developed to evaluate the principle of the mode conversion. The experimental result of the mock-up representing the ratio of LP_{01} mode and LP_{11} mode was successfully controlled by 10% as the theoretical prediction.**

***Index Terms*— Electron cyclotron heating and current drive (EC H&CD), gyrotron, millimeter waves, miter-bend, mode conversion, transmission line (TL).**

I. Introduction

THE electron cyclotron heating and current drive (EC H&CD) system is one of the major heating systems in a fusion device. The EC H&CD system is provided by gyrotrons that generate high power radio frequency (RF) beams, transmission lines (TLs), and launchers, which inject RF power into the plasma. In the EC H&CD system of the International Thermonuclear Experimental Reactor (ITER), the 100–150-m-length TLs consisting of 63.5 mm in diameter corrugated waveguide transmit RF from the 170-GHz/1-MW gyrotrons [1], [2]. In the National Institute of Quantum and Radiological Science and Technology, TL components designed for ITER were examined in the test stand, which has the similar configuration of ITER TL and a 170-GHz high-power gyrotron. A 40-m corrugated waveguide system, including seven miter-bends achieved a 96% RF power transmission efficiency at 0.5 MW/240 s operation [2]. There are two types of launchers in ITER, namely, the equatorial port launcher and the upper port launcher. Both ITER launchers include a dogleg quasi-optical (QO) beam transmission section for neutron shielding. Its transmission efficiency is required to be high enough to prevent severe thermal damage of the components in the launcher. Mode purity is the key issue for the launcher QO design, since the radiation beam of the fundamental transmission mode of corrugated waveguide [LP_{01} (HE_{11}) mode] is applied for the QO mirrors and the beam duct design in the launcher [3]–[5]. Since the higher order modes (HOMs) affect radiation characteristics, HOMs are problematic in launchers, because the wrong radiation beam characteristics increase transmission loss in QO transmission in the launcher and also degrade beam pointing performance.

To improve the mode purity in TL, many studies are underway to examine various sources of HOMs. Oda *et al*. [6] pointed out that the beam coupling into the TL is the major source of HOMs, and the dominant HOMs in high-power TL were found at the LP_{11} mode. This is because geometrical misalignment easily occurs at coupling of the gyrotron beam into the waveguide. Such geometrical misalignment, the center offset and tilt angle of the coupling beam, generates significant LP_{11} mode [6]. Even if the LP_{11} modes at the TL input are minimized by the good alignment of beam coupling, TL components induce mode conversion loss by themselves. Shapiro *et al*. [7] calculated the mode conversion by misalignment in mirror assembly of the miter-bends, which excites the LP_{11} mode in the TL. In general, a single miter-bend induces negligibly small mode conversion. Indeed, the radiation beam from the outlet of the TL contains a nonnegligible amount of LP_{11} mode because of multiple mode conversion effects by many miter-bends in the TL system [7], [8]. Plaum *et al*. [9] reported another important HOMs source, which is caused by the deformed waveguide system. RF transmission loss heats waveguides and other components

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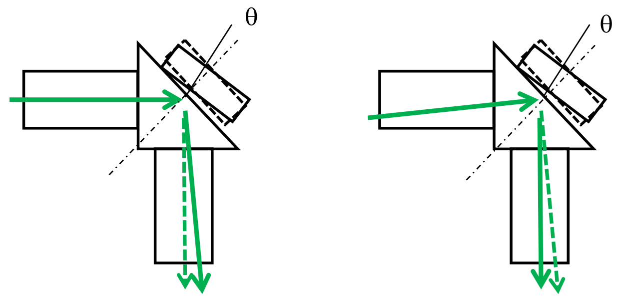

Fig. 1. Concept of miter-bend-type mode converter. RF beam direction is controlled in the miter-bend with a tilted mirror.

causing their thermal expansion during high-power long-pulse operation of TL. An expanded waveguide deforms the structure of the TL system. In particular, a short waveguide section connecting by miter-bends with long straight sections is largely deformed by thermal expansion of the TL. Such a section forms an S-shaped bend, which induces large mode conversion exciting LP_{11} mode [9], [10]. Such HOMs excited in various locations of the TL can propagate through long distance TL, since low mode number HOMs such as LP_{11} mode have the low attenuation rate. Thus, when any low mode number HOMs are excited, the radiation profile at the outlet of the TL is affected, resulting in problems in the launchers.

We propose the idea to improve mode purity at the end of the TL. Since RF power includes only low order number HOMs, transmission loss in the TL does not increase as much as the QO transmission loss in the launchers. Thus, low order number HOMs does not affect total performance of the EC system if they are adjusted to produce the proper radiation beam in the launcher. The TL component which improves mode purity is expected to be useful.

We propose a miter-bend-type mode converter. This proposed system has a tilted and curved mirror in its miter-bend. The theoretical analysis of the converter eliminating the low order number HOMs (LP_{11} and LP_{02} modes) is available with this concept [11]. This system uses a simple method to correct transmission mode purity in the TL. To evaluate the principle of mode conversion, a mock-up model of the miter-bend-type mode converter with an angle-adjustable flat mirror was developed for a milliwatt-class low power test. This paper reports the evaluation of the mode content control using this mock-up model.

II. Miter-Bend-Type Mode Converter

A. Mode Conversion With Tilted Mirror

The concept of a miter-bend-type mode converter is explained in Fig. 1. In Fig. 1 (left), a tilted mirror in the miter-bend reflects the incident LP_{01} mode RF beam with a small tilt angle with respect to the axis of the output waveguide. The tilted RF beam excites the LP_{11} mode in the output waveguide. As a reverse operation, in Fig. 1 (right), incident RF power, which is a mixture of the LP_{01} and LP_{11} modes, is controlled by a mirror in the miter-bend with a tilt angle, and the LP_{11} mode is converted back to the LP_{01} mode. This is applicable for mode purity improvement in the TL. Kowalski *et al.* [11] studied the theoretical analysis of this concept and concluded that a couple of miter-bends with a tilted mirror can compensate for the amplitude and phase combination of LP_{01} and LP_{11} modes assuming that the LP_{11} mode power is small.

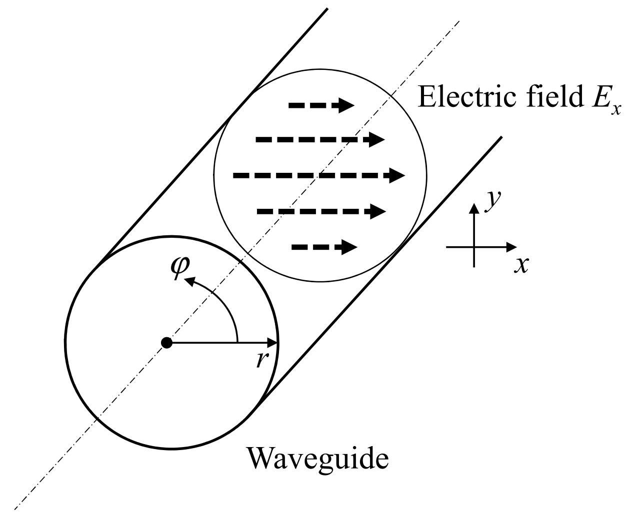

Fig. 2. Coordinate system used in the waveguide field analysis.

B. Formulas of Mode Conversion Theory

To analyze the performance of a miter-bend-type mode converter, the formulas for the mode contents as a function of the tilt angle of the miter-bend mirror were represented according to the methods utilized in the theoretical analysis of LP_{01} beams [11], [12]. Fig. 2 shows the coordinate system used in this analysis.

The electric field was derived as a superposition of field distribution of the LP_{01}, $LP_{02,}$ and LP_{11} modes. The formula of normalized electric field is

$$\begin{aligned} &E_x(r,\varphi)\\ &= \sqrt{P_{01}}u_{01}\exp(j\psi_{01}) + \sqrt{P_{02}}u_{02}\exp(j\psi_{02})\\ &\quad + \sqrt{P_{11}^{\text{odd}}}u_{11}^{\text{odd}}\exp\left(j\psi_{11}^{\text{odd}}\right) + \sqrt{P_{11}^{\text{even}}}u_{11}^{\text{even}}\exp\left(j\psi_{11}^{\text{even}}\right) \quad (1) \end{aligned}$$

where $P_{m,n}$, $u_{m,n}$, and $\psi_{m,n}$ are power ratio, electric field distribution, and phase of each mode. The distribution formulas of the LP_{0n} modes ($n = 1, 2$) and LP_{11} odd/even modes are as follows:

$$\mathrm{LP_{0n}\ mode}: u_{0n}(r) = \frac{1}{\sqrt{\pi}a}\frac{J_0\left(\frac{\nu_{0n}}{a}r\right)}{|J_1(\nu_{0n})|}$$

where r and φ are the coordinates in the circular waveguide, a is the radius of waveguide, and $\nu_{01}(= 2.405)$ and $\nu_{02}(= 5.52)$ are the zeros of the Bessel function J_0

$$\mathrm{LP}_{11}^{\text{odd}}\ \text{mode}: u_{11}^{\text{odd}}(r,\varphi) = \frac{\sqrt{2}}{\sqrt{\pi}a}\frac{J_1\left(\frac{\nu_{11}}{a}r\right)}{|J_0(\nu_{11})|}\sin\varphi$$

$$\mathrm{LP}_{11}^{\text{even}}\ \text{mode}: u_{11}^{\text{even}}(r,\varphi) = \frac{\sqrt{2}}{\sqrt{\pi}a}\frac{J_1\left(\frac{\nu_{11}}{a}r\right)}{|J_0(\nu_{11})|}\cos\varphi$$

where $\nu_{11}(= 3.832)$ is the first zero of the derivative of the Bessel function J_1. In (1), we use the measured powers in the LP_{01} and LP_{02} modes at the zero tilt angle: $P_{01} = 0.9457$

and $P_{02} = 0.02178$ (the measurement is described further in Section II-D). The LP_{11} mode power is zero at the zero tilt angle.

The tilted mirror in the miter-bend is a phase corrector. Therefore, the complex amplitude at the output of this phase corrector is the following:

$$E_x^{\text{out}}(r,\varphi) = E_x(r,\varphi)\exp\left(j\frac{4\pi}{\lambda}\theta r\cos\varphi\right) \quad (2)$$

where θ is the mirror tilt angle and λ is the wavelength. We represent the exponential term in (2) as a Taylor series and project the complex amplitude on to the modes LP_{01}, LP_{02}, and LP_{11}. Since one tilt axis of mirror independently affects one of even or odd modes, the formula with a single term for LP_{11} mode is common for both modes. Even/odd modes are selected according to the angle axis. The amplitudes of the LP_{01} and LP_{11} modes are, respectively

$$C_{01}^{\text{out}} = \sqrt{P_{01}} - \frac{\pi}{2}\left(\frac{4\pi}{\lambda}\theta\right)^2\int_0^a r^3 \times(\sqrt{P_{01}}u_{01} - \sqrt{P_{02}}u_{02})u_{01}dr \quad (3)$$

and

$$C_{11}^{\text{out}} = j\frac{4\pi}{\lambda}\theta\int_0^{2\pi}d\varphi\int_0^a drr^2\cos\varphi \times(\sqrt{P_{01}}u_{01} - \sqrt{P_{02}}u_{02})u_{11}(r,\varphi). \quad (4)$$

The integrals in (3) and (4) can be taken analytically [11]. The modal powers $P_{01}^{\text{out}} = |C_{01}^{\text{out}}|^2$ and $P_{11}^{\text{out}} = |C_{11}^{\text{out}}|^2$ thus can be calculated for our case ($P_{01} = 0.9457$ and $P_{02} = 0.02178$)

$$P_{01}^{\text{out}} = \left[\sqrt{P_{01}} - \left(\frac{2\theta a}{\lambda}\right)^2\left(\frac{\pi^2(\nu_{01}^2-2)}{3\nu_{01}^2}\sqrt{P_{01}} - \frac{8\pi^2\nu_{01}\nu_{02}}{(\nu_{02}^2-\nu_{01}^2)^2}\sqrt{P_{02}}\right)\right]^2 = 0.9457 - 3.6\left(\frac{2\theta a}{\lambda}\right)^2 + 3.4\left(\frac{2\theta a}{\lambda}\right)^4 \quad (5)$$

$$P_{11}^{\text{out}} = \left(\frac{2\theta a}{\lambda}\right)^2\left[\frac{4\pi\sqrt{2}\nu_{01}\nu_{11}}{(\nu_{11}^2-\nu_{01}^2)^2}\sqrt{P_{01}} - \frac{4\pi\sqrt{2}\nu_{02}\nu_{11}}{(\nu_{11}^2-\nu_{02}^2)^2}\sqrt{P_{02}}\right]^2 = 3.2\left(\frac{2\theta a}{\lambda}\right)^2. \quad (6)$$

The results from (5) and (6) are compared with the experimental data in Section II-D.

C. Experimental Model and Measurement System

A mock-up model of a miter-bend-type mode converter with a flat mirror was fabricated using the 63.5 mm in diameter corrugated waveguides (Fig. 3). The aluminum mirror is settled on the two-axis tilt angle control stage, which can control both the vertical (ω) and horizontal (θ) tilt angles of the beam in the miter-bend. The mirror and stages are fixed on the base plate with a support structure. This mock-up model was designed for a low power test, and the movable mirror could not set a vacuum sealing as normal miter-bends for high power operation. For high power operation, an outer housing or a bellows shall be installed for vacuum operation.

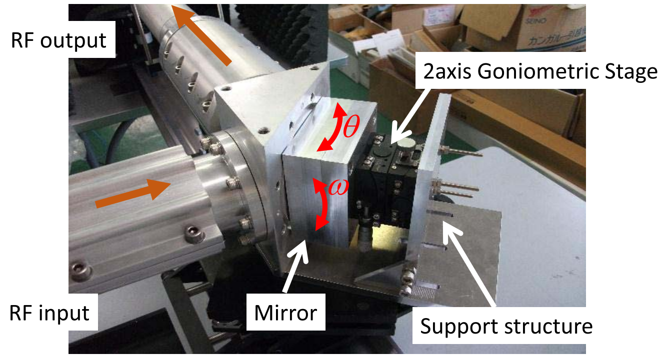

Fig. 3. Mock-up model of the miter-bend-type mode converter developed at QST with the 63.5-mm corrugated waveguide.

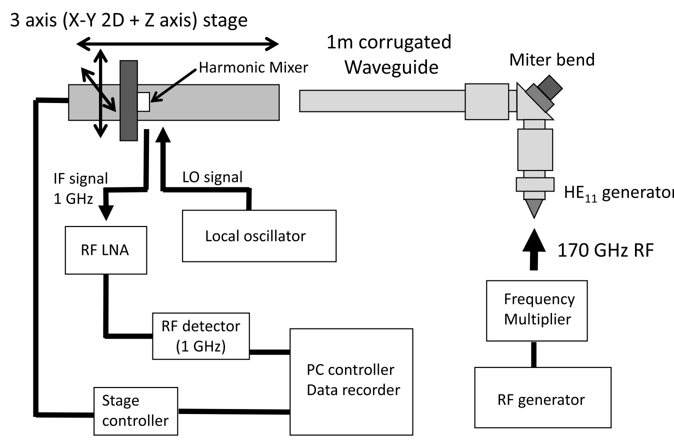

Fig. 4. Experimental setup of the mock-up model of the miter-bend-type mode converter and the measurement system.

Fig. 4 shows the experimental setup of the miter-bend-type mode converter. The milliwatt-class low-power 170-GHz RF source, which utilizes a frequency multiplier and an LP_{01} mode generator, is used for examination. The LP_{01} mode generator is designed for the 63.5 mm in diameter corrugated waveguide. Its mode contents of the output beam were LP_{01}—94 %, LP_{02}—2 %, and less than 1% for each of the other modes. The LP_{01} mode generator was connected to the inlet port of the miter-bend-type mode converter.

The 1-m-length corrugated waveguide is connected to the output port of the miter-bend-type mode converter, and the RF beam is radiated from the end of the waveguide. The radiated beam profile was measured at the distance of 100–500 mm from the waveguide outlet.

For the measurement, a heterodyne detection system, which utilizes a harmonic mixer, was used. The mixer converts a 170-GHz RF signal to a 1-GHz IF signal, and a low noise amplifier amplifies the IF signal to improve the signal/noise (S/N) ratio. The data acquisition system records the IF signal amplitude using an RF detector. The S/N ratio of the measured RF beam profile was 20–30 dB (depending on the measurement position).

The RF detector device was fixed on the 2-D scanning stage and on the 1-D z-axis stage. The automated beam profile

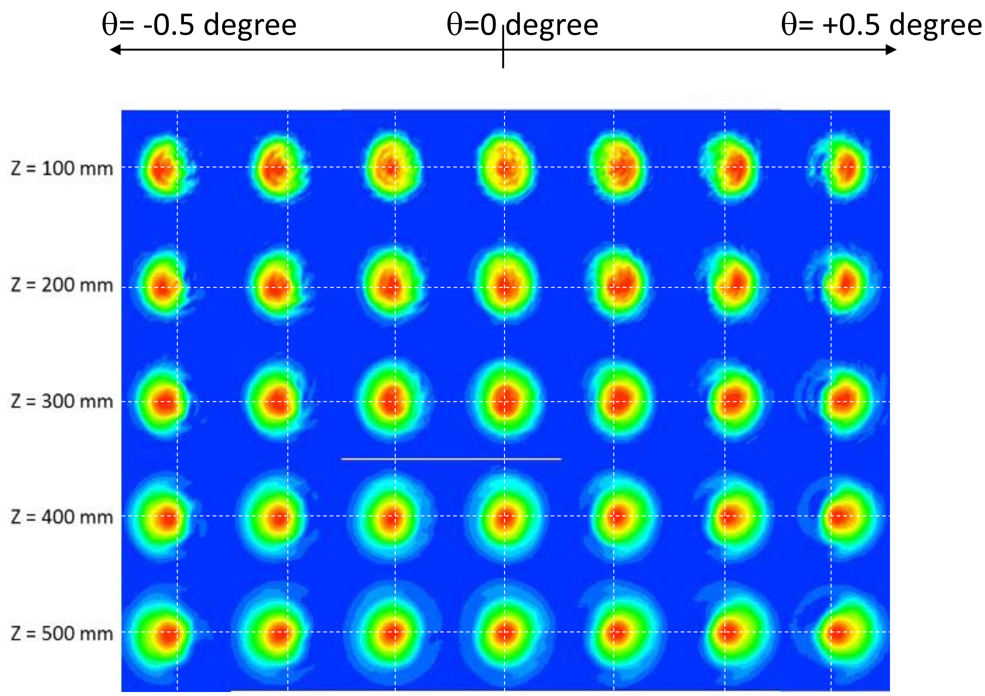

Fig. 5. Measured beam profiles from the output of the miter-bend-type mode converter.

scanner synchronized the 2-D stage and the data acquisition of the RF detector signal, and the profile was recorded. By the 1-D z-axis stage, the beam profiles on different z location planes were acquired. Five planes with a 100-mm distance between them were acquired to measure the beam profile for analysis. Since the beam profile includes only an intensity profile, the phase retrieval analysis was applied to acquire the amplitude/phase profiles at the waveguide outlet plane for mode content analysis [13], [14]. The beam profile was measured for various mirror angle conditions. For each case, the mode contents were deduced.

D. Measurement Result

Fig. 5 shows the measured RF beam profiles. Due to the mode content change by the tilted mirror in the miter-bend, the measured RF beam profile was varied on the tilt angle. The major difference among measured profiles appeared as the offset of beam center. Since there is a 1-m-long waveguide, which is nearly a quarter of the beat wavelength between the LP_{01} and LP_{11} modes, connected after the miter-bend-type mode converter, the effect of mode mixture appears as an offset of the beam center from the waveguide axis. Although the injection angle was changed by the mirror, the output beam profile kept a single peak profile. This indicates that the tilted mirror excites only lower order number HOMs, such as LP_{11} modes, and it does not excite higher order number HOMs, such as $LP_{m,n}$ modes with $m > 3$ or $n > 3$, which increase transmission loss in the waveguide.

These profiles were analyzed by the phase retrieval method, and the mode content was deduced for each condition. The mode content for the LP_{01}, LP_{11}^{even}, and LP_{11}^{odd} modes is plotted in Figs. 6 and 7. Fig. 6 shows the dependence on the horizontal beam angle θ, and Fig. 7 shows the dependence on the vertical beam angle ω. This result demonstrates that the mixture of the LP_{01} and LP_{11} modes varied with the mirror angle. By increasing the tilt angle which increases the beam injection angle, the content of LP_{11} modes is increased. The difference of mirror angle direction appears as odd or even LP_{11} modes. Both plots include the theoretical dependence of

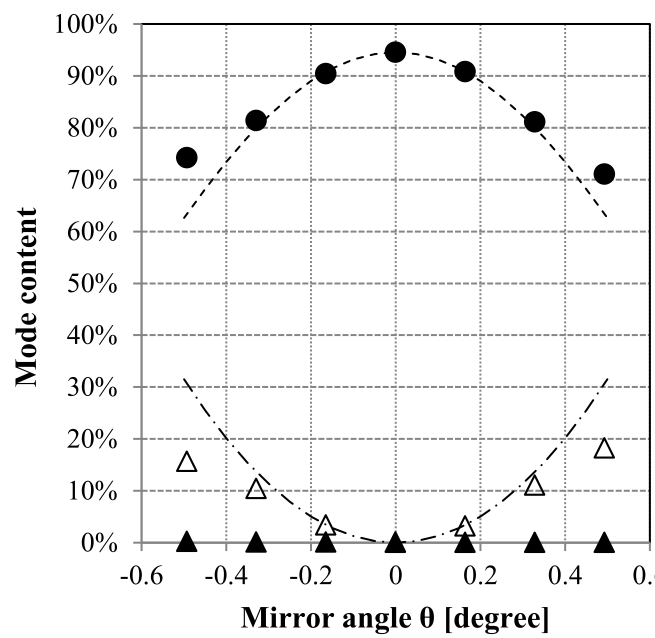

Fig. 6. Dependence of mode content on the horizontal tilt angle of the mirror in the miter-bend. ●: LP_{01} mode. △: LP_{11}^{odd} mode. ▲: LP_{11}^{even} mode. Dashed line: LP_{01} mode theoretical prediction. Dashed-dotted line: LP_{11} mode theoretical prediction.

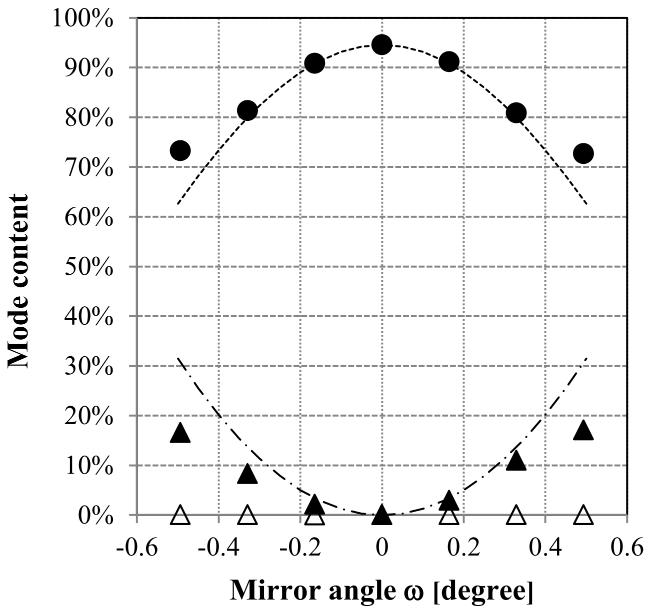

Fig. 7. Dependence of mode content on the vertical tilt angle of mirror in the miter-bend. ●: LP_{01} mode. △: LP_{11}^{odd} mode. ▲: LP_{11}^{even} mode. Dashed line: LP_{01} mode theoretical prediction. Dashed-dotted line: LP_{11} mode theoretical prediction.

the LP_{01} and LP_{11} mode contents on the angle [see (5) and (6)]. The measured mode contents showed good agreement with the theoretical prediction when the mirror tilt angle was smaller than 0.3°.

When the tilt angle is large, measured mode contents show some difference from the theory. The LP_{01} mode content was larger than predicted for both the horizontal and vertical mirror tilts, and the LP_{11} mode content was smaller. At such a large mirror angle, the content of the LP_{11} mode becomes higher than 10%. The formulation used for theoretical analysis is based on a limited number of modes, and a larger number of high order modes may be necessary for accurate prediction at larger angles. Indeed, as far as for compensation of the LP_{11} mode generated in the TL, $>$ 10% mode conversion is not required. Hence, the miter-bend-type mode converter can be used under the condition where the theoretical prediction is accurate. Therefore, the mock-up test validates the concept of the miter-bend-type mode converter.

III. Conclusion

We developed the mock-up of the miter-bend-type mode converter and examined its principle of mode conversion between the LP_{11} and LP_{01} (HE_{11}) modes. The angle-adjustable mirror was installed into the miter-bend of the 63.5 mm in diameter corrugated waveguide for the frequency of 170 GHz, which is the ITER-relevant system. The mode converter was examined using the milliwatt-class low power 170-GHz RF source with the LP_{01} mode generator. The beam profile from the miter-bend-type mode converter was measured for several angle settings to deduce the mode content. As a result, the ratio of the LP_{01} and LP_{11} modes varied for settled mirror angle, and its dependence had good agreement with theoretical analysis. The angle range of the movable mirror was +/−0.3° for both directions, and this produced 10% of mode conversion. Thus, the concept of the miter-bend-type mode converter was successfully validated.

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References

[1] F. Gandini *et al.*, "The EC H&CD transmission line for ITER," *Fusion Sci. Technol.*, vol. 59, no. 4, pp. 709–717, 2010.
[2] K. Takahashi *et al.*, "High power millimeter wave experiment of ITER relevant electron cyclotron heating and current drive system," *Rev. Sci. Instrum.*, vol. 82, no. 6, p. 063506, Jun. 2011.
[3] A. Collazos *et al.*, "Progress on the ITER upper launcher millimeter-wave design and testing," *Fusion Sci. Technol.*, vol. 55, no. 1, pp. 84–93, 2009.
[4] K. Kajiwara, K. Takahashi, N. Kobayashi, A. Kasugai, and K. Sakamoto, "Design of a high power millimeter wave launcher for EC H&CD system on ITER," *Fusion Eng. Design*, vol. 84, no. 1, pp. 72–77, 2009.
[5] K. Takahashi, N. Kobayashi, J. Ohmori, S. Suzuki, A. Kasugai, and K. Sakamoto, "Progress on design and development of ITER equatorial launcher: Analytical investigation and R&D of the launcher components for the design improvement," *Fusion Sci. Technol.*, vol. 52, no. 2, pp. 266–280, Aug. 2007.
[6] Y. Oda *et al.*, "Measurement of RF transmission mode in ITER relevant EC H&CD transmission line," *J. Infr. Millim. Terahz Waves*, vol. 31, no. 8, pp. 949–957, 2010.
[7] M. A. Shapiro *et al.*, "Loss estimate for ITER ECH transmission line including multimode propagation," *Fusion Sci. Technol.*, vol. 57, no. 3, pp. 196–207, Apr. 2010.
[8] R. A. Olstad, J. L. Doane, and C. P. Moeller, "ECH MW-level CW transmission line components suitable for ITER," *Fusion Eng. Design*, vol. 74, pp. 331–335, Nov. 2005.
[9] B. Plaum, G. Gantenbein, W. Kasparek, M. Thumm, and D. Wagner, "Far field calculations and measurements of an S-bend deformed over-sized HE_{11}-waveguide antenna," *Int. J. Infr. Millim. Waves*, vol. 20, no. 6, pp. 1009–1017, 1999.
[10] J. L. Doane, "Design of circular corrugated waveguides to transmit millimeter waves at ITER," *Fusion Sci. Technol.*, vol. 53, no. 1, pp. 153–173, Jan. 2008.
[11] E. J. Kowalski, M. A. Shapiro, and R. J. Temkin, "Simple correctors for elimination of high-order modes in corrugated waveguide transmission lines," *IEEE Trans. Plasma Sci.*, vol. 42, no. 1, pp. 29–37, Jan. 2014.
[12] E. J. Kowalski *et al.*, "Linearly polarized modes of a corrugated metallic waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 11, pp. 2772–2780, Nov. 2010.
[13] A. V. Chirkov, G. G. Denisov, and N. L. Aleksandrov, "3D wavebeam field reconstruction from intensity measurements in a few cross sections," *Opt. Commun.*, vol. 115, no. 5, pp. 449–452, Apr. 1995.
[14] H. Idei, T. Shimozuma, M. A. Shapiro, T. Notake, S. Kubo, and R. J. Temkin, "Experimental verification of phase retrieval of quasi-optical millimeter-wave beams," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 11, pp. 3899–3905, Nov. 2006.

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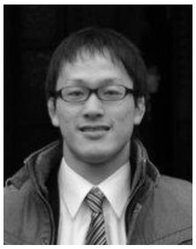

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