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Development of 2-D Antenna Array for Microwave Imaging Reflectometry in LHD

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A 2-D antenna array for the Microwave Imaging Reflectometry (MIR) has been developed for the Large Helical Device (LHD). The MIR is a method of electron density diagnostics by the use of microwave radar techniques to obtain 2-D/3-D images of electron density fluctuations for the investigation of micro-turbulence and magneto-hydrodynamic instabilities in magnetically confined plasmas. The antenna array consists of five antennas in the toroidal direction and eight ones in the poloidal direction, respectively. As a test of an antenna element, a pyramidal horn antenna in the frequency range of 10-15 GHz was compared with the Yagi-Uda antenna. Based on the test results of the lower frequency antenna element, we manufactured a 2-D horn antenna array in the frequency rang of 50-75 GHz.

Keywords: Microwave Reflectometry, Electron density profile, Density fluctuation, 2-D Antenna array

1. Introduction

Turbulence is an important subject of the science of complex system, and imaging is the first step to study turbulence experimentally. In the National Institute of Natural Sciences (NINS), which the National Institute for Fusion Science (NIFS) belongs to, the science of complex system is commonly studied and imaging science has been intensively studied as the NINS Imaging Science Project. Turbulence is also considered to be key phenomena to understand transport in magnetically confined plasmas. Microwave reflectometry is a radar technique for the measurement of electron density profiles and density fluctuations by probing the electron density-dependent cutoff layer in a plasma [1, 2]. This measurement has a good spatial resolution and sensitivity by using a phase detection method. Microwave Imaging Reflectometry (MIR), a multi-channel reflectometry system equipped with the imaging optics, is one of the most powerful tools to study turbulence and instabilities. Recently MIR has been intensively developed [3].

MIR has been developed at NIFS. The first generation MIR system was developed for the Large Helical Device (LHD), a world largest superconducting heliotron-type fusion device [4, 5]. The former system uses probe waves at frequencies of 53, 66 and 69 GHz in X-mode by using three IMPATT oscillators. Three probe waves are mixed with waveguide directional couplers and are illuminated with a horn antenna, and are focused on the plasma by the use of the imaging optics. Probe waves are reflected at three different cutoff layers, which are determined by the electron density and the magnetic field. Thus reflected waves are modulated by the cutoff layer's motion, which corresponds to density fluctuations. Reflected waves are, through the imaging optics again, focused on a receiving horn antenna. Signal receiver uses a super heterodyne method as reflected waves are mixed with the local wave generated with a Gunn oscillator at a frequency of 63 GHz. Reflected waves enter a mixer (down converter) by passing a waveguide, then the reflected waves are down converted to three intermediate frequency (IF) signals, at 3, 6, 10 GHz. The IF signals are separated with band pass filters, then the signals are detected its power by using of diode detectors, respectively. The DC offset of each power signal is cut and amplified with a video amplifier. Through these processes, the power signals becomes fluctuation signals on a cutoff layer. By using the former MIR system, we obtained signals which were similar to magnetic probe signals in LHD.

In this system, three commercially available v-band horn antennas are used as receiving antennas. They have a response with a wide-band and high gain, but they are too large to compose a 2-D antenna array. The required features of an antenna element of the 2-D antenna array are as follows: compactness, high gain, and wide-band response. In an end-fire type antenna, microwave is received on one side and signal is amplified on another side, thus antenna, mixer, filter, and amplifier are aligned in line. By setting this

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antenna-to-amplifier line unit in parallel on a single printed circuit board (PCB), a 1-D array can be easily formed. A high gain 2-D antenna array can be formed by stacking 1-D array PCBs. Thus the end-fire type antenna is attractive for MIR.

A second generation MIR system was also developed for the TPE-RX [6], one of a world largest reversed field pinch device built at AIST. This system uses the probe wave frequency at 20 GHz, local wave frequency at 20.11 GHz, and IF signal frequency at 110 MHz. This system uses a 4×4 2-D antenna array. The antenna element of this antenna array is a planer Yagi-Uda antenna, which is a typical end-fire type antenna.

One of the most important devices in MIR is a 2-D antenna array. This paper describes the recent development of 2-D antenna array at NIFS. We started the development from 20-GHz Yagi-Uda antenna array and have reached to 60-GHz horn antenna array. The detectable frequency becomes 3 times higher and the sensitivity becomes 10 dB higher.

2. Antenna Element

At first, we developed a planer Yagi-Uda antenna array for 8 - 12 GHz. Figure 1(a) shows an element of the planer Yagi-Uda antenna. The antenna consists of three directors, a dipole element, and a reflector. The dipole elements are connected to micro-strip-lines with tapered baluns [7]. The planer Yagi-Uda antenna is composed on a printed circuit board (PCB), which is a comprised of the Teflon plate and the copper foil (double side coated) for high frequency circuit up to over 100 GHz. The thickness of the copper foil is 9 μm. The thickness of the Teflon board is 0.254 mm, as shown in Fig. 1(a). The relative permissibility of the Teflon board is about 2.2 and dielectric loss is very low (~ 0.0009). This PCB is used for all antennas we developed.

The reflector enhances the directivity and sensitivity. We added a cylindrical mirror made of aluminum alloy as a reflector, as shown in Fig. 1(a). The focal point of this mirror is at the dipole element, and the height of the reflector is 12 mm. The mirror improves the sensitivity about 3 dB to 10 dB. It has a hole in order to pass the tapered balun. Figure 2 shows frequency response measured with a vector network analyzer (VNA). The frequency response of the Yagi-Uda antenna has a deep dip at 12 - 14 GHz, as shown in Fig. 2. This dip is not observed in the case of a single planar Yagi-Uda antenna. It is an interference of neighboring Yagi-Uda antennas. In the case of TPE-RX experiments [6], the 4×4 Yagi-Uda antenna array for MIR, that was employed in the experiment had a flat response near 20 GHz,. This test shows that the Yagi-Uda antenna array is not adequate for the variable frequency detection due to the bad frequency response.

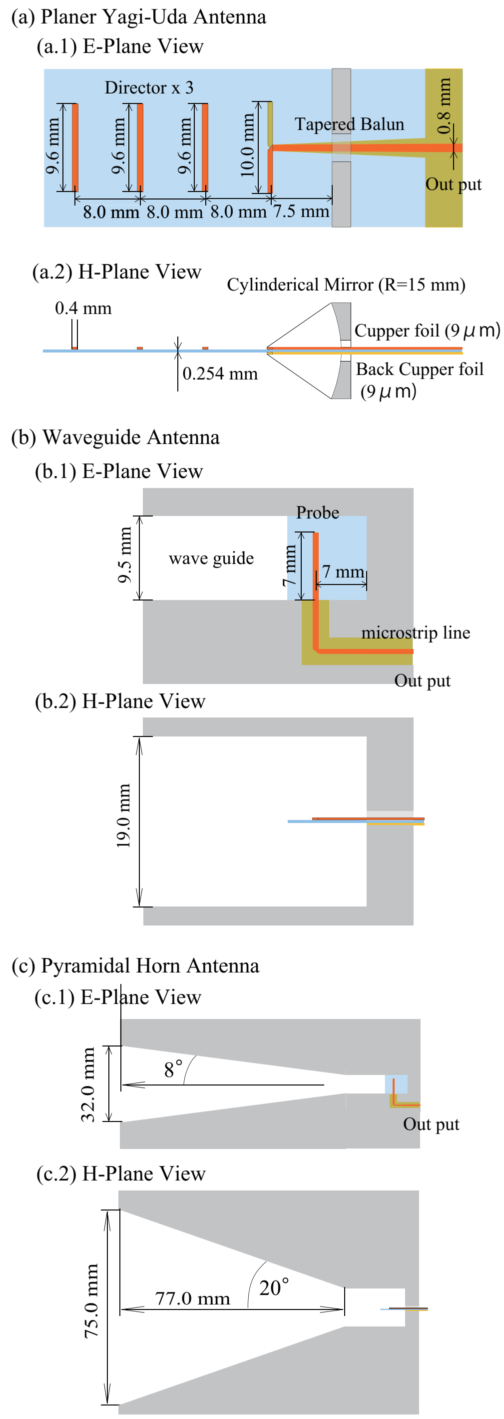


Fig. 1 Schematics of the Yagi-Uda antenna, the waveguide antenna and pyramidal horn antenna.

Secondly, we made a waveguide antenna and tested it. This antenna consists of a waveguide 9.5 mm in width and 19 mm in height, and a 7-mm-long narrow conductor on a PCB, as shown in Fig. 1(b). The size of this waveguide is similar to commercially available waveguides for X-mode, and its theoretical cutoff frequency is 8 GHz. The PCB is inserted in

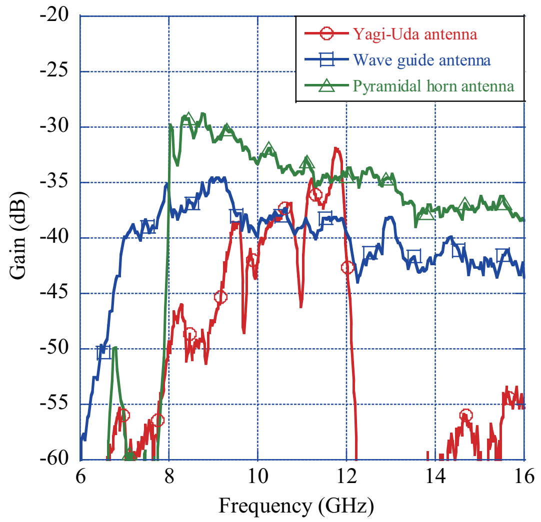


Fig. 2 The frequency responses of the Yagi-Uda antenna, the wave guide antenna and the pyramidal horn antenna, we tested.

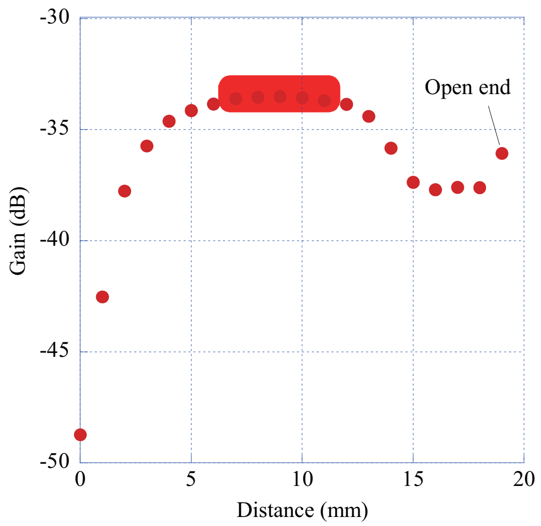


Fig. 3 The optimization of the distance between the mono-pole and the end wall of the waveguide shown in Fig. 1(b) using the microwave at 10 GHz.

the middle of the waveguide, as shown in Fig. 1(b). The narrow conductor on the PCB is connected to a micro-strip-line on the same PCB. This conductor is a monopole working a waveguide-to-micro-strip-line converter. In the optimization of the length of the monopole, we found that an optimum length is between 50% and 80% of the width of the waveguide. Thus we chose 7 mm, which is 73 % of the width. We also optimized the distance between the monopole and the waveguide end. Figure 3 shows the optimization of the distance between the probe and the end wall of the waveguide shown in Fig. 1(b). The microwave frequency is 10 GHz in this optimization. The frequency response is flat between 5 mm and 12 mm at 10 GHz, whose wavelength is 30 mm in vacuum. Thus, the distance between the monopole and the waveguide end should be between 17% and 40% of the microwave wavelength in vacuum. Accordingly, we use 7 mm, which is 24% of the microwave wavelength in vacuum.

Thirdly, we tested a pyramidal horn antenna. Figure 1(c) shows a schematic view of the pyramidal horn antenna tested. The waveguide and the monopole are the same as those shown in Fig. 1(c). Figure 2 shows the frequency responses of the Yagi-Uda antenna, the waveguide antenna, and the horn antenna. The frequency response of waveguide antenna is from 7 to 16 GHz, that of the Yagi-Uda antenna with a cylindrical reflector is from 9 to 12 GHz, and that of the horn antenna is from 8 to 16 GHz. Although the sensitivity of Yagi-Uda antenna with a cylindrical reflector is similar to the waveguide antenna, the bandwidth is narrow. The sensitivity of the horn antenna is about 6 dB higher than that of the waveguide antenna. The antenna with a large open mouth has a high sensitivity.

3. V-band Horn Antenna Array

The frequency response is measured with a vector network analyzer. Considering frequency response of coaxial cable, lower frequency is easier to measure. Consequently, we used the microwave at 10 GHz. In the case of the MIR system for LHD experiments, the frequency of probe wave is between 50 and 75 GHz. They are six times higher than the test frequency. Inversely, the antenna size is six times smaller for LHD experiments. The width of the dipole element of Yagi-Uda antenna for LHD experiments is 0.8 mm. Thus the manufacture of Yagi-Uda antenna becomes harder as the frequency becomes higher. The waveguide size is 1.9 mm×3.8 mm for LHD experiments. The assembly of this waveguide is not very hard. The focal area of the MIR optics for LHD is about 70 mm in the toroidal direction and 80 mm in the poloidal direction. More than four data points are preferable to determine mode numbers. Since plasmas may be more deformed in the poloidal direction than in the toroidal direction, the number of data points in the poloidal direction should be increased. So, we determine the number of antennas as eight in the poloidal direction and five in the toroidal direction, or an antenna separation of 10 mm in the poloidal and 16 mm in the toroidal directions, respectively.

Figure 4 illustrates a cross-sectional view of the V-band (50 to 70 GHz) horn antenna element. The mouth of horn antenna is 9.5 mm×15 mm. The size of waveguide is 1.9 mm×3.8 mm, which is the same as the size of commercially available V-band waveguides. Each antenna element has a mixer diode chip in the waveguide as shown in Fig. 4(a). The mixer is

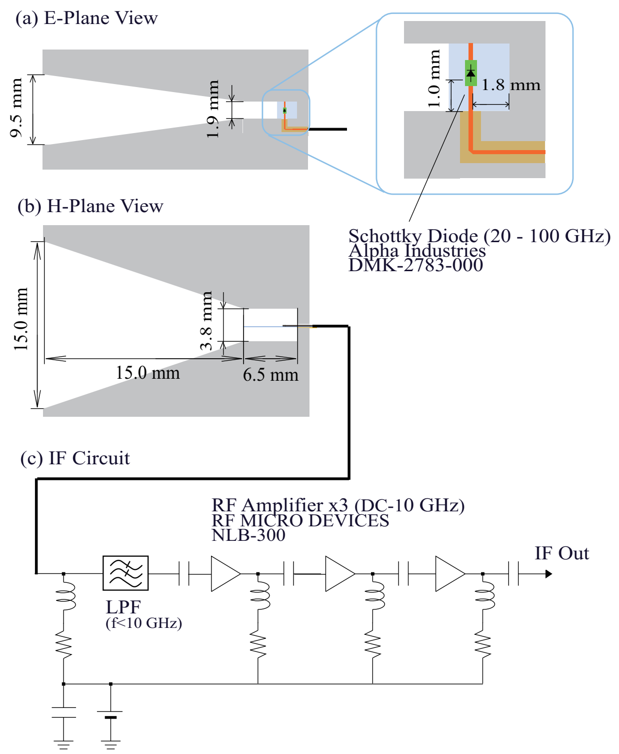


Fig. 4 (a) E-plane view and (b) H-plane view of horn antenna element of the V-band (50 to 70 GHz) 2-D antenna array. (c) Schematic diagram of intermediate frequency (IF) circuit on the antenna PCB.

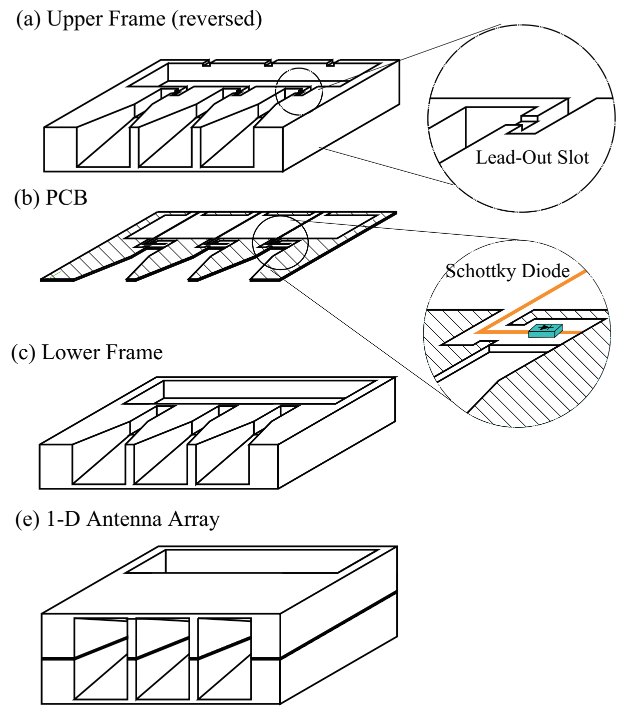


Fig. 5 Schematic view of the 1-D horn antenna array assembly. (a) reversed view of upper structure, (b) PCB, (c) lower structure, (d) completed form.

a surface-mounted type Schottky diode (Alpha Industries, Model DMK-2783-000) working in the frequency range between 20 and 100 GHz. A mixer diode tip is mounted in the middle of the waveguide, and is connected to the ground pattern and the micro-strip-line. The diode is separated by 1.8 mm from the waveguide end.

Figure 5 sketches a schematic view of the V-band 1-D horn antenna array assembly. It has three parts of upper structure, PCB, and lower structure. Figure 5(a) shows a reversed view of the upper structure, and Fig. 5(b) shows the lower structure. The upper and lower structures are made of aluminum alloy, and horn shape and waveguide slots are made by electrical discharge machining. By attaching these slots, a horn antenna is formed. In the upper structure, another slot is formed for passing the micro-strip-line. Figure 5(b) shows PCB, where the mixer diode is mounted. Low-pass filter (LPF) and RF amplifiers are also installed on the PCB. By stacking 1-D horn antenna arrays, a 2-D antenna array is formed.

The horn antenna receives both RF and LO waves and the mixer generates a intermediate frequency (IF) signal. The mixer bias is supplied from a DC power supply through an inductor, and the bias current is optimized. Figure 4(c) shows a schematic diagram of the IF circuit on the antenna printed circuit board. The MIR antenna receives not only reflected waves from plasmas but also the leakage of electron cyclotron heating (ECH) waves. In LHD, the ECH frequencies are 77 GHz, 82.4 GHz, and 84 GHz. The ECH frequencies also down-converted to lower frequencies by the mixer. Since the ECH signal is much higher than reflection signals, it causes bad effects on IF amplifiers. In order to eliminate the down-converted ECH signals, a LPF, whose cutoff frequency is 10 GHz, is placed between the mixer and the first IF amplifier. The LPF is produced by the micro-strip-line technology and it can attenuate the signals by -40 dB or less. The IF amplifiers is low-cost GaAs microwave monolithic ICs with the frequency range of DC to 10 GHz and the 13 dB. Its power is supplied from RF output through the choke inductor and the current limit resistor. The DC-blocking capacitors are needed after the output of the amplifier.

Figure 6 shows a photograph of the 2-D V-band antenna array. Eight antenna elements arranged at intervals of 10 mm comprise the 1-D V-band antenna array. Five 1-D V-band antenna arrays are stacked and tightened with four 8-mm long bolts to produce the 2-D V-band antenna array.

The frequency response and the directivity of an antenna element of the V-band 2-D antenna array were measured. The probe wave frequency was swept between 48 and 76 GHz. The LO wave was generated by up-conversion of the probe wave and the IF

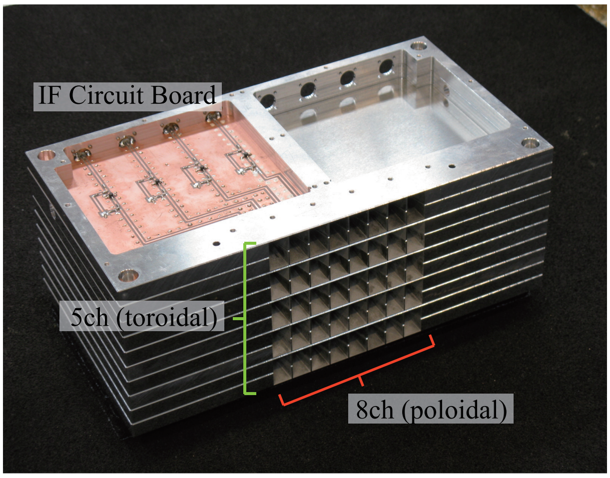


Fig. 6 Photograph of a V-band 2-D antenna array.

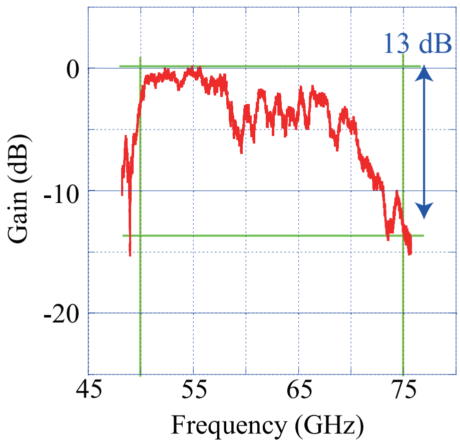


Fig. 7 The frequency response of the V-band antenna array. The gain is normalized to that at 54 GHz.

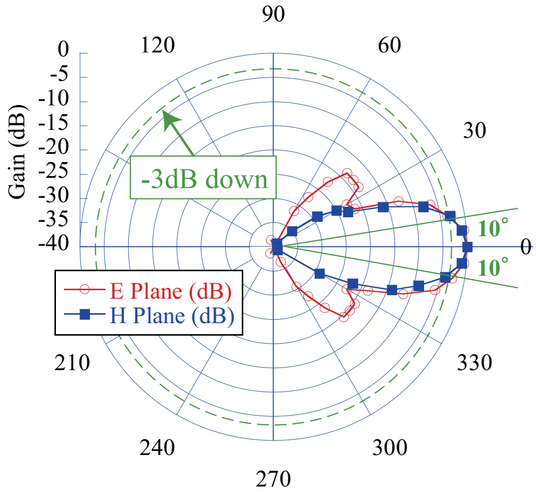


Fig. 8 Radiation pattern of the V-band antenna array.

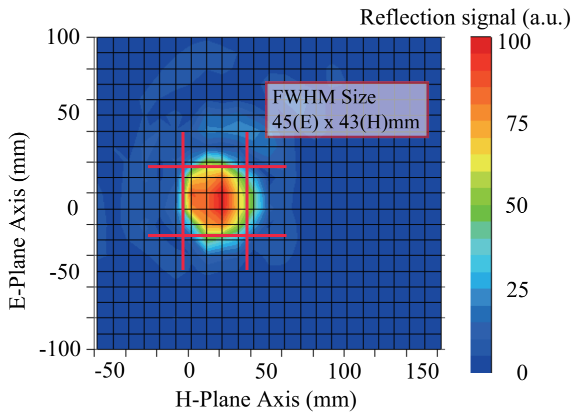


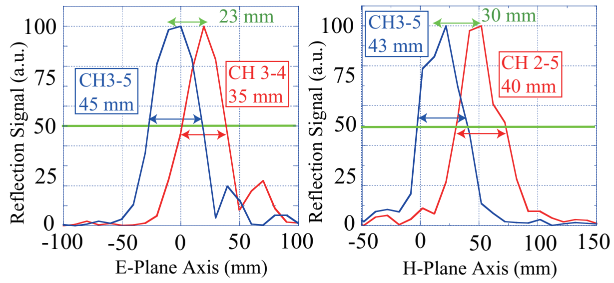
Fig. 9 Resolution pattern.

frequency (110 MHz). Figure 7 shows the frequency response of the antenna element of the V-band 2-D antenna array. The vertical axis indicates gain, and the horizontal axis indicates the probe wave frequency. The antenna array can work in the frequency between 50 and 75 GHz while the gain varies by 13 dB.

Figure 8 shows the angular response of the V-band antenna array at a the frequency of 66 GHz. 0 degree indicates the front of the antenna. At 20 degrees, the response is decreased by -3 dB on both E-plane and H-plane. On the E-plane, there are side robes at angles of about 45 degree, but its gain is as low as -18 dB or less.

The V-band horn antenna array is mounted to a MIR on a test bench. This MIR consists of a main concave mirror with a diameter of 43 cm and a focal length is 62 cm, a detection focusing mirror with a diameter of 43 cm and a focal length of 210 cm, beam splitters, small mirrors, and horn antennas for the probe beam and LO beam. The designed distance between the object and the main concave mirror is 200 cm, and that between the 2-D horn antenna array and the detection focusing mirror is 40 cm. The antenna array is set as the E-plane is horizontal.

Figure 9 shows a received signal pattern at the object with an antenna element of the 2-D V-band antenna array. The vertical axis indicates the position in the E-plane direction, and the horizontal axis indicates the position in the H-plane. The color indicates the intensity of the reflection wave. The resolution pattern at the object position was measured by moving a aluminum speaker dome with a spherical surface. The diameter of the speaker dome is 80 mm. The electromagnetic absorber is in front of the speaker dome, and the opening of 20mm×20mm is installed. The reasons why spherical surface was employed as follows: the spherical surface reflects the wave to wide directions. It may facilitate the adjustment of the optical axis than by using a plane reflector. The oscillating frequency of the surface is 100 Hz, and by oscillating the reflection surface, the background noise can be effectively eliminated. In this measurement, the vertical and horizontal directions of the layer on the



(a) E-plane profile (b) H-plane profile

Fig. 10(a) The E-plane profile of the reflection signal of CH3-4 and CH3-5 in the 2-D V-band antenna array. (b) The H-plane profile of the reflection signal of CH2-5 and CH3-5 in the 2-D V-band antenna array.

focus were scanned with the reflector at intervals of 10 mm. If the reflector is arranged at the focus of the antenna element, the reflected wave from the reflection surface is focused on the antenna element. The pattern indicates the view field of an antenna element on the surface of reflector side. The color indicates the intensity of the reflection signal. The size of the radiation pattern is 45 mm×43 mm, and the shape is circular.

Figure 10(a) and (b) show reflection wave profile. The vertical axis indicates the intensity of the reflection wave, and the horizontal axis indicates the position in the E-plane axis or H-plane axis. CH3-5 is the same channel from Fig.9, and CH3-4 is the next to CH3-5 in the E-Plane axis. And CH2-5 is the next to CH3-5 in the H-Plane axis. The distance between CH3-4 and CH3-5 is 10 mm in the horizontal axis, and the distance between CH2-5 and CH3-5 is 16mm in the vertical axis. The distance between the peaks of signal intensity received two antenna elements are 23 mm and 30 mm in E-plane nad H-plane, respectively. The full-width half-maximum (FWHM) of the signal intensity is about 40 mm.

We also set a rotating wheel with a wave-shaped surface, and tested the reflection from it. The width of the wheel is 20 mm and the wave-shape has an $m = 12$ poloidal symmetry. The amplitude of the detected signal is high enough and the modulation is detected. From these results, it was confirmed that the 2-D antenna array has enough potential to observe the plasma-cutoff layer motion.

4. Conclusions

We developed a 2-D antenna array used for 3-D MIR system. Three antennas were tested, planar Yagi-Uda antenna, waveguide antenna and pyramidal horn antenna. The Horn antenna and planar Yagi-Uda antenna with a cylindrical reflector were compared at 10 GHz frequency range. The peak gain was similar but the gain band width of the planar Yagi-Uda antenna was narrow, probably due to the interference between adjacent elements. The waveguide antenna has a wider frequency band-width than the Yagi-Uda antenna. The output of the waveguide antenna was improved by using the pyramidal horn.

The 8 × 5 2-D V-band (50-to-75 GHz) horn antenna array has been developed for the 3-D MIR system in LHD. In the V-band, the manufacture of a horn antenna array is much easier than a planar Yagi-Uda antenna array. The developed horn antenna array consists of three parts, an upper structure, PCB, and a lower structure. The upper and lower structures are made of aluminum alloy, and horn shape and waveguide slot were made by electrical discharge machining. On the PCB, a receiving circuit pattern was formed. By sandwiching the PCB was upper and lower structures, 1-D horn antenna array was formed. By stacking 1-D horn antenna array with bolts, 2-D horn antenna array was assembled. The 2-D antenna array has four key devices. The horn antennas receive the reflected wave and the local wave in a wide band. A surface mounted Schottky mixer diode is located in horn antennas, and it downcoverts reflectied waves to 1st IF signals. The LPF rejected the ECH power leakage. The IF amplifiers amplify the IF signals with low noises.

The following performances of the 2-D antenna array were measured: the frequency response, the directivity, the radial resolution and separation between channels. As a result, it was confirmed that the 2-D antenna array has fundamental function which the MIR system for 2-D/3-D observation in the plasma diagnostics required.

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