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Upgrade of 2-D Antenna Array for Microwave Imaging Reflectometry and ECE Imaging

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Two types of 2-D Microwave Imaging, Microwave Imaging Reflectometry (MIR) and Electron Cyclotron Emission Imaging (ECEI) have been developed for the Large Helical Device (LHD). These are methods of 2-D / 3-D imaging diagnostics on electron density fluctuations and electron temperature for the investigation of micro-turbulence and magneto-hydrodynamic instabilities in magnetically confined plasmas. 1-D horn antenna array was developed for a 2-D receiver antenna array of the MIR (freq. range: 50 - 75 GHz). This antenna is also able to be used for a receiver of the ECEI (freq. range: 95 - 110 GHz). To apply the ECEI receiver, and to extend the measurement range of these diagnostics, the 1-D horn antenna array was upgraded.

Keywords: Microwave Reflectometry, Electron Cyclotron Emission, 2-D Antenna array

1. Introduction

Imaging is one of the most powerful tools for understanding of complex systems. In magnetically confined plasmas, there are much complex phenomena to study, such as transport and turbulence. In order to understand above-mentioned phenomena, lots of diagnostic methods have been developed. As one of them, microwave diagnostics have been studied and applied.

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. This measurement has a good spatial resolution and sensitivity by using a phase detection method [1, 2]. 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, since it enables us to observe locally.

Electron Cyclotron Emission Imaging is an advanced ECE diagnostic method. By the use of ECEI, we can obtain 2-D/3-D structure of temperature fluctuations. Thereby, the observing of temperature-relating phenomena, such as anormalous transport, instabilities and turbulence becomes possible. When the plasma density and temperature are sufficiently high, the plasma becomes optically thick to some harmonics of the ECE. In LHD, since the electron temperature and the density are sufficiently high, ECE is in the Rayleigh-jeans regime and ECE can be regarded as the black body radiation. Therefore, the plasma electron temperature and its fluctuations can be determined by measuring the intensity of ECE. ECEI is developed for tokamaks, mirror and helical devices [3].

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2. MIR system

Recently MIR has been intensively developed at National Institute for Fusion Science (NIFS) [4, 5]. The first generation MIR system was developed in LHD, which is a world largest superconducting heliotron-type fusion device. Probe beam of the first system has frequencies of 53, 66 and 69 GHz in X-mode generated by three IMPATT oscillators. Three waves are mixed with waveguide directional couplers and are launched with a horn antenna, the probe beam is focused on the plasma by the use of the imaging optics. Reflected waves from three different cutoff layers are received with three v-band pyramidal horn antennas. One antenna is arranged at center, the others are arranged in toroidal and poloidal directions, respectively. This arrangement is to observe both toroidal and poloidal wave numbers. Signal is received with a super heterodyne method by mixing reflected waves and the local wave that is generated from a Gunn oscillator with a frequency of 63 GHz. Reflected waves enter a mixer through a waveguide, then the reflected waves are down converted to three intermediate frequency (IF) signals (3, 6, 10 GHz). The IF signal is separated with band pass filters, then the power of each frequency is detected with diode detectors. In

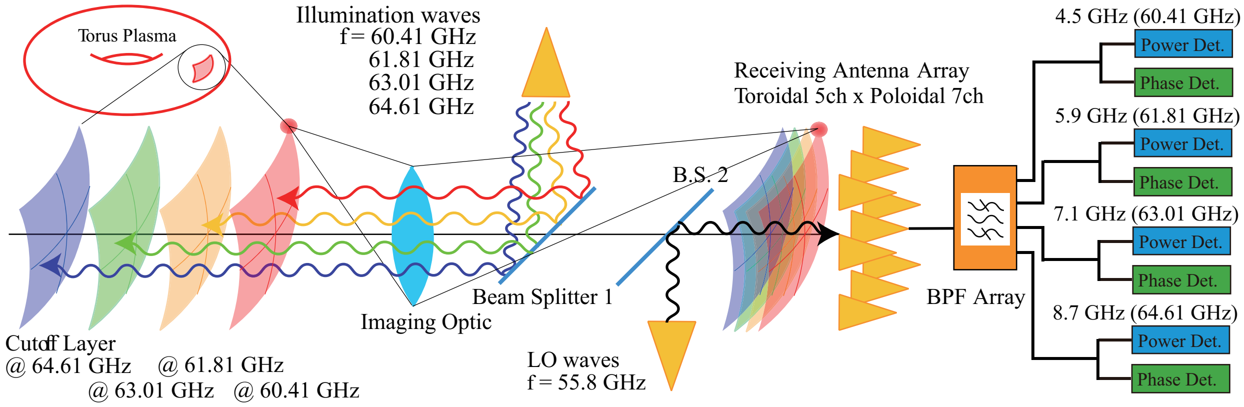

Fig. 1 Schematic view of the MIR system.

this system, we observed the edge harmonic oscillation (EHO). The EHO is also observed with magnetic probes and heavy ion beam probe diagnostics. However, wave numbers could not be estimated due to lack of receiver channels. In this system, phase detection was not available.

The second generation MIR system was planned for improving the above-mentioned problems. We developed a 2-D antenna array [6]. and a frequency-stabilized microwave source. To observe the phase signals, we developed a v-band (50 - 75 GHz) super heterodyne detection system by the use of two Voltage controlled oscillators (VCO) and frequency multiplier. One VCO is at the frequency range of 8 to 13.5 GHz. It makes base frequency of the illumination waves. The other VCO is at frequency of 110 MHz. it is used as IF and is carrier of reflected signals. Two signals from two VCOs are mixed with a single side-band upconverter. The frequency of this upconverted signals is multiplied by six with the frequency multiplier. Through these processes, v-band illumination wave is made. And the LO wave uses base frequency. The illumination and reflected wave section of the imaging optics were the same as the former imaging optics, but LO wave injection system was added. In this system, waveguide coupling method could not be used because the number of antenna channels is too large. Waveguide components, such as waveguides and waveguide mixers are large and expensive. Consequently, the LO signal is injected to antenna elements by the use of optics. Each antenna element must have a compact and low-cost mixer. The channel numbers of toroidal and poloidal directions were 5 × 8, because it is expected that plasmas are more perturbed in the poloidal direction than toroidal direction.

At present, the third generation of the MIR system has been developed. Figure 1 shows schematic view of the MIR system. In order to probe the plural cutoff layers, this system employed a double super heterodyne detection method. The first IF signal at the frequency of 18.33 MHz is divided into four with a four way power divider. The first IF signals are upconverted with four signals, the second IF signals at frequencies of 750, 983, 1183, 1450 MHz. Four upconverted signals are upconverted further with the base signal at the frequency of 9.3 GHz, and the frequency of four signals are increased six fold. Finally, four illumination waves at frequencies of 60.41, 61.81, 63.01, 64.61 GHz are generated. Reflected waves are modulated with fluctuations signals of each cutoff layers. Reflected waves are downconverted with LO waves at the mixer of the antenna element. The signals from each antenna output are 4.5, 5.9, 7.1, 8.7 GHz + 110 MHz + ϕ_1 to ϕ_4. The frequencies of 4.5, 5.9, 7.1, 8.7 GHz and 110 MHz are corresponds 6 times the 2nd IF signals and the 1st IF signal, respectively. These four signals are separated into 4 ways at a frequency separator, and are downconverted with the 2nd IF signals increased frequencies by six. By the above-mentioned processing, four fluctuation signals, 110 MHz + ϕ_1 to ϕ_4 are obtained. The frequency range of these signals can be easily observed for the phase and amplitude information by the use of commercial ICs for telecommunication.

3. MIR antenna array

Requirements of the MIR antenna array are as follows:

- Channels : 5 (toroidal), 7 (poloidal)
- frequency range : 55 - 65 GHz (V-band)
- mixer circuit (each channel)
- IF frequency range : 4 - 9 GHz

We have developed a fabricating method of 2-D antenna array [6]. It based on microstrip-line technique by the use of a high frequency printed circuit board (PCB). Thereby the microwave antenna can be easily made. The type of the antenna element is end-fire planer antenna. In the case of end-fire type antenna, microwave is received on one side and IF signal is outputted on the other side, thus antenna, mixer, and IF circuits are aligned in line. By setting this unit in parallel on a printed circuit board, a 1-D antenna array can be assembled. And a 2-D antenna array can be formed by stacking 1-D antenna array.

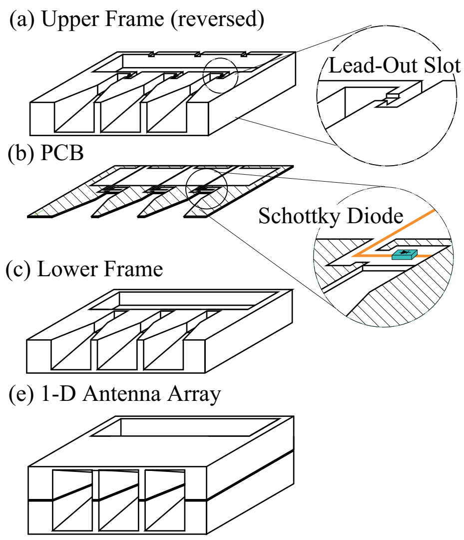

Fig. 2 Schematic view of the 1-D horn antenna array assembly. (a) underside view of upper structure, (b) PCB, (c) lower structure, (d) completed form

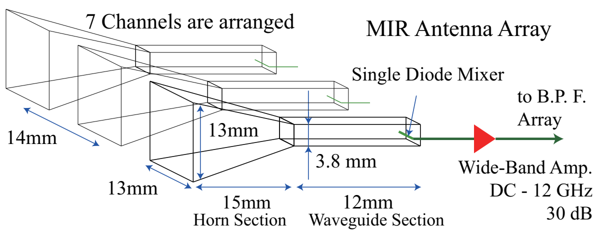

Fig. 3 Schematic view of the 1-D horn antenna array.

Figure 2 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 2(a) shows a underside view of the upper structure, and Fig 2(c) 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 2(b) shows PCB, where the mixer diode is mounted. RF amplifiers is installed on the PCB. By stacking 1-D horn antenna arrays, a 2-D antenna array is fabricated. The mixer is a surface-mounted type Schottky diode working in the frequency range between 20 GHz 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 3 shows schematic view of the MIR 1-D antenna array. Modified points from the second generation MIR antenna are as follows: 1) channel number, 2) shape of the mouth of antenna element, 3) employment of more wide-band IF amplifier, 4) gold plating of PCB. The toroidal and poloidal channel numbers are five and seven, respectively. From former analysis, it was confirmed that if the channel numbers are more than four channels, the wave numbers will be evaluated with sufficient accuracy [7]. Since it becomes easy to adjust an optic system by the existence of a center channel, the poloidal channel number was changed to an odd number, seven. Due to the change in the channel number, the shape of an antenna element is necessary to be modified to fit to a focus plane of the optics. The mouth of the horn antenna is 13 mm × 13 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. The horn antenna receives both RF and LO waves and the mixer generates an intermediate frequency (IF) signal. The mixer bias is supplied from a DC power supply through an inductor, and the bias current is optimized. The IF amplifier was modified more wide-band since the third generation antenna array is planned to be used for ECEI. The IF amplifiers are low-cost GaAs microwave monolithic ICs with the frequency range of DC to 12 GHz and about 30 dB. To prevent rusting, the PCB was plated with gold. Rusting of PCB was seen in the antenna of the second generation. It was confirmed that the characteristics of the strip-line does not deteriorate by plating.

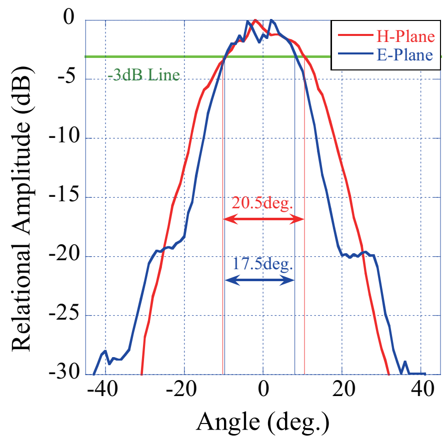

Fig. 4 Radiation Pattern of the MIR antenna element.

Figure 4 indicates the radiation pattern of the antenna element of the MIR antenna array at a frequency of 63 GHz. The vertical axis is the gain, and the horizontal axis indicates angle. 0 degree corre-

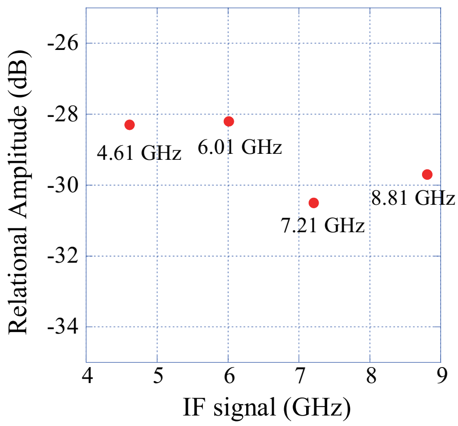

Fig. 5 Frequency Responses of the MIR antenna element.

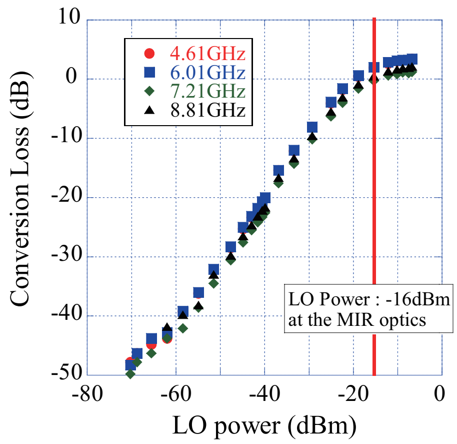

Fig. 6 Conversion losses of the MIR antenna element.

sponds to the normal direction from the front of the antenna. At 20.5 degrees and 17.5 degrees, the responses are decreased by 3 dB on H-Plane and E-Plane, respectively.

Figure 5 shows frequency response of the antenna element of the MIR antenna array. This data are obtained by injecting of four probing frequencies (60.41, 61.81, 63.01, 64.61 GHz) and LO wave at a frequency of 55.8 GHz. The vertical axis indicates the IF output gain, the horizontal axis indicates the frequency of the IF output. Four IF signals have the similar level (between 2.3 dB)

Figure 6 shows the characteristics of the conversion losses of the antenna element. The conversion loss is plotted as a function of supplied LO power level. In this figure, it was confirmed that the four IF signals has the same tendency. The conversion loss curve seems to be saturated at LO powers around -10 dB. In MIR optics, supplying LO power is - 16 dB. Accordingly, the mixer can work under the highly effective.

4. ECEI system

An ECEI system is also developed for LHD. This system uses the same microwave optics. The ECE signals from plasma are focused on the 1-D antenna array through optics. The optics of ECEI system are made by two, receiving optics and LO optics. The receiving optics is the same as MIR receiving optics, since the difference in the frequency range is not affected, and the same diagnostic position is selected.

Figure 7 shows the ECEI receiving system. In our ECEI system, the 1-D antenna array is adopted for obtaining the 2-D ECE profile. 2-D ECEI diagnostics (observing radial and poloidal directions) are being developed on several fusion devices and they gave much results. These systems use surface emission type 1-D antenna arrays. But our antenna array, end-fire 1-D antenna array can easily compose a 2-D antenna array. It is a simple fact that 3-D diagnostics can obtain more information than 2-D diagnostics. The frequency range of the ECEI antenna array is 97 - 108 GHz, and the LO wave is at a frequency of 95 GHz. Therefore, the frequency range of IF signals (downconverted ECE signal) is 2 - 13 GHz. IF signals (spectrum) are separated into 11 signals at frequencies of 2, 3, 4, · · ·, 12 GHz. These frequencies correspond to the radial location where ECE is emitted in plasma.

5. ECEI antenna array

Different points of the ECEI antenna array from the MIR antenna array are the frequency range and addition of a high-pass filter in front of the mixer element. The IF output characteristic of the MIR antenna array in the frequency range of ECEI is indicated in figure 8. This characteristic was obtained by illuminating 95GHz LO wave and w-band sweepable oscillator. Because of the flat IF output in the ECEI range, the mixer and IF circuits of the MIR antenna can be applied to ECEI. The ECEI system employed super heterodyne detection with LO wave at a frequency of 95 GHz. ECE signals from plasma are not only existing in the observing range but also under the LO frequency. The downconverted signals are mixed with higher side band and lower side band. Therefore, to reject the unnecessary lower side band, a high-pass filter is required. The cutoff frequency of the high-pass filter is selected to be 93 GHz. There are two methods to make the high pass filter.

One is to use the waveguide section as high-pass filter. The waveguide works as the high-pass filter. The cutoff frequency of a rectangular waveguide is determined from the size of the waveguide. The cutoff frequency of 93 GHz is correspond to a diameter of 1.588 mm. In a test, the cutoff frequency response was measured by changing the waveguide diameter. In this test, the antenna with changed diameter of

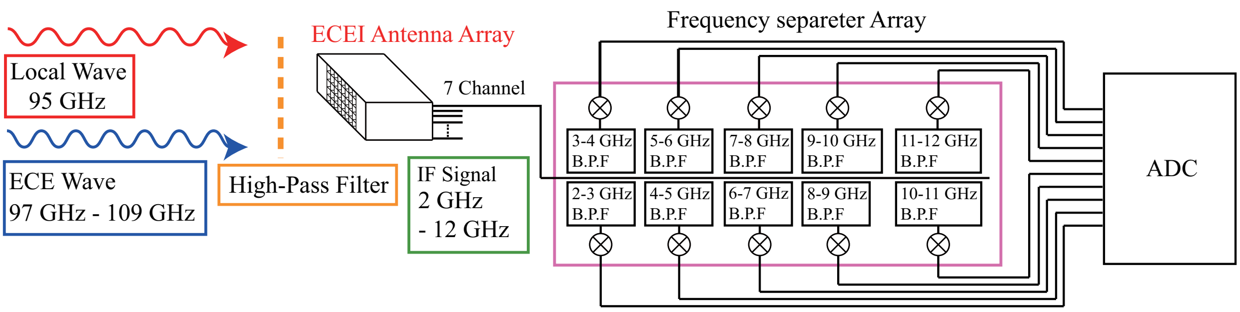

Fig. 7 Receiving Circuit of the ECEI system.

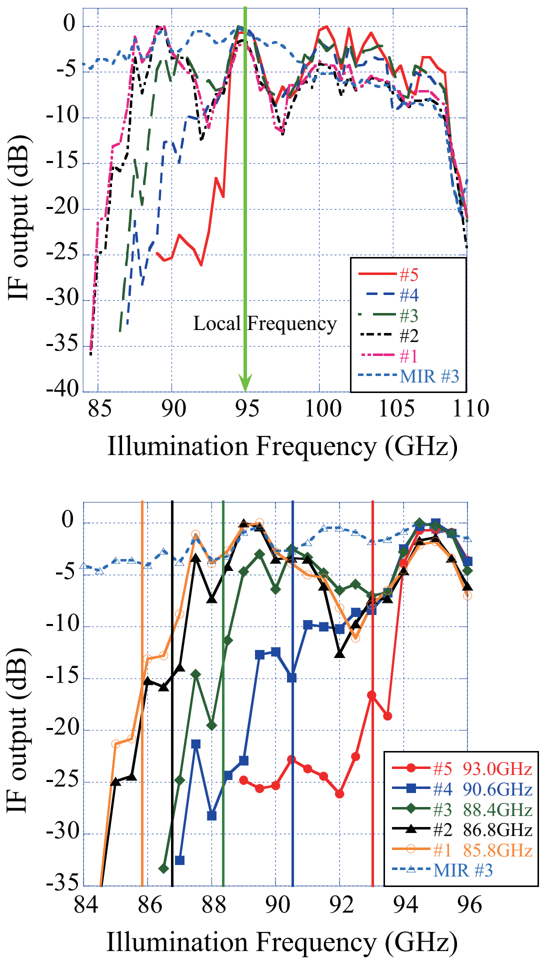

Fig. 8 Cutoff response of the test antenna.

waveguide section from the MIR antenna was used. Figure 8 shows the cutoff response of tested antennas. The vertical axis indicates the gain, the horizontal axis shows illumination frequency. The upper figure is plotted in the whole frequency and the lower figure is a blow-up in a cutoff range. In the figures, ♯5 - ♯1 curves obtained from antennas with waveguide diameters of 1.613, 1.656, 1.697, 1.729, 1.748 mm correspond to 93.0, 90.6, 88.4, 86.8, 85.8 GHz. ♯5, the diameter of 1.613 mm gave a good response. 95 GHz

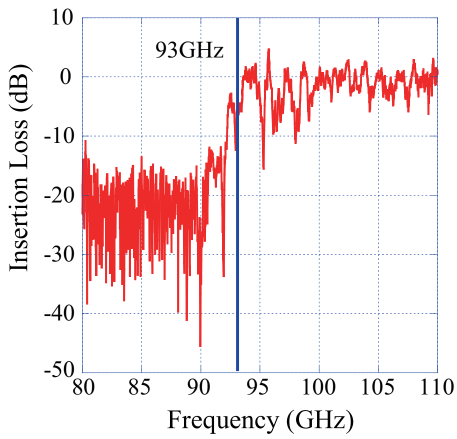

Fig. 9 Cutoff response of dichroic filter.

(LO) wave can propagate by high transmission. At a frequency of 92 GHz, the transmission is under -25 dB. The required performance was achieved. But at a frequency of 97.5 GHz, the gains of ♯5 - ♯1 antennas decreased by about 10 dB.

The other method is the application of a dichroic filter. In the frequency range of microwave, the dichroic filter is a metal plate that a lot of holes. Holes work as circular waveguides, and it can use as planer high-pass filter. Figure 9 shows a cutoff response of a 93 GHz dichroic filter. The diameter of the hole (circular waveguide) is 1.9 mm. This filter rejects signals at lower than 93 GHz signal by about 20 dB. Although there are many sharp undulations in a range higher than 93 GHz (pass-band), the performance is better than that of a waveguide-section-high-pass-filter. Finally we decided that the dichroic filter and the MIR antenna array would be employed as ECEI detector.

6. Summary

A 1-D antenna array for the MIR and the ECEI was upgraded as follows: 1) channel number, 2) shape of the mouth of antenna element, 3) employment of more wide-band IF amplifier, 4) gold plating of PCB. For MIR, antenna array has flat IF signal response.

And the characteristics of the conversion losses were measured. It turned out that our MIR system has enough LO power. For ECEI, development of the high-pass filter was described. Two methods for applying the high-pass filter were presented. One is using the waveguide section of the antenna element as waveguide-high-pass filter. The cutoff response was measured and it determined the best waveguide diameter. The other method, the application of the dichroic filter was also introduced. And a dicrhoic filter and the third generation MIR antenna array are employed as ECEI detector.

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