Development of Microwave Imaging Reflectometer at NIFS

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The Microwave Imaging Reflectometer (MIR) is under development at NIFS. The first MIR system is installed in Large Helical Device (LHD). The optics of this system is made of Aluminum mirrors and Plexiglas plates. In this system, the primary mirror is remotely controlled to optimize the reflection power. The illumination wave is generated by 3 IMPATT oscillators, and the local oscillator (LO) is a Gunn oscillator. This system uses wide band-pass filters. The second MIR system is installed in TPE-RX, which is a large RFP. The optics of this system is made of Aluminum mirrors, Teflon lenses and Plexiglas plates in order to reduce size. In this system the frequencies are so stabilized that noise can be reduced by using narrow band filters. The 4x4 2-D mixer array and phase detection system have been also developed.

Keywords: microwave, imaging, reflectometry, MIR, LHD, turbulence, fluctuation, diagnostics

1. Introduction

It is considered that plasma confinement in a fusion devise is governed by turbulence and instabilities, which often appear in the electron density fluctuations. The microwave reflectometry is a sensitive measurement of turbulent density fluctuations because it uses reflection of the microwave by the plasma with cut-off density [1]. The density fluctuation causes the amplitude modulation and the phase modulation in the reflected beam. Recently the Microwave Imaging Reflectometer (MIR) has been intensively developed because MIR may provide the 2D/3D image of density fluctuation to reveal the physics of turbulence [2]. The short wave fluctuation diverge the reflected wave. MIR takes advantage of large aperture optics to form an image of the reflecting layer onto an array of detectors located at the image plane, enabling localized sampling of small plasma areas.

Issues in the development of MIR are as follows: (1) improvement of sensitivity or the signal to noise ratio; (2) improvement of number of channels in the 2D detector array; (3) reducing the cost. The MIR is under development at National Institute for Fusion Science (NIFS) by collaborating with Kyushu University [3]. The first MIR system has been installed in the Large Helical Device (LHD) [3,4]. The second MIR system has been installed in TPE-RX, which is a large RFP device at National Institute of Advanced Industrial Science and Technology (AIST) [5]. This paper will present how to solve the above issues at NIFS.

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2. MIR System in LHD

Figure 1 shows a schematic diagram of the MIR system in LHD. The illumination wave (RF) is generated by 3 high power (0.5 W) IMPATT oscillators, whose frequencies are 53, 66 and 69 GHz, respectively. These oscillators used to be installed 5 m far from LHD. However, the operation of the IMPATT oscillators was interfered by the leakage of the magnetic field. Actually, the output power of the IMPATT oscillators reduces as the magnetic field increases, and finally no output power are observed. After enclosing in 5 mm thick soft-iron shield case, the power was dropped by 30 %. Therefore the microwave sources are installed 15 m far from LHD and the microwave is transferred using oversized rectangular waveguides (X-band, WR-90) and 90 degree H bends. By using optical system, the illumination wave radiated from a horn antenna (WR-15) is formed to a parallel beam with a diameter of 20 cm at the reflection layer in the plasma. The illumination wave is reflected by the three cutoff layers, which are determined by the local density and the magnetic field in the case of X-mode reflection.

The primary imaging mirror (M_1) is installed in the LHD vacuum vessel. This is an elliptic concave mirror with the size of 43x50 cm and the focal length of 106.5 cm. The distance between the mirror M_1 and plasma is 210 cm. The mirror M_1 is remotely manipulated by the use of ultrasonic motors (USMs). Since the LHD plasma is

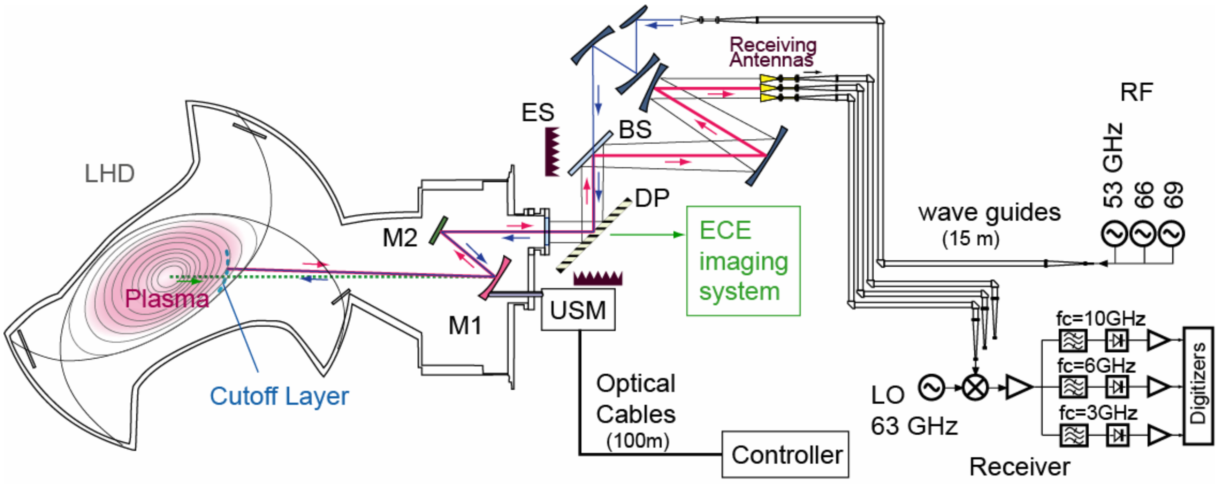

Fig. 1 Schematic view of MIR system in LHD. M1: Adjustable concave mirror, M2: Plane mirror, DP: Dichroic plate (70GHz), BS: Plexiglass beam splitter, US: Ultrasonic motor, ES: ECCOSORB CV3.

twisted, toroidal and poloidal angles of the main mirror should be controlled within 1 degree in order to obtain reflection from plasma [4].

The reflected wave is accumulated by the primary imaging mirror. ECE and the reflected wave are separated by a dichroic plate (DP), which is a high pass filter with a sharp cut-off frequency of 70 GHz. This dichroic plate is an 8 mm thick aluminum alloy plate with many circular holes. The diameter of each hole is 2.5 mm and they are separated by 2.8 mm. The hole has the angle of 45 degree to the plate so that ECE wave more than 70 GHz efficiently passes through the dichroic plate.

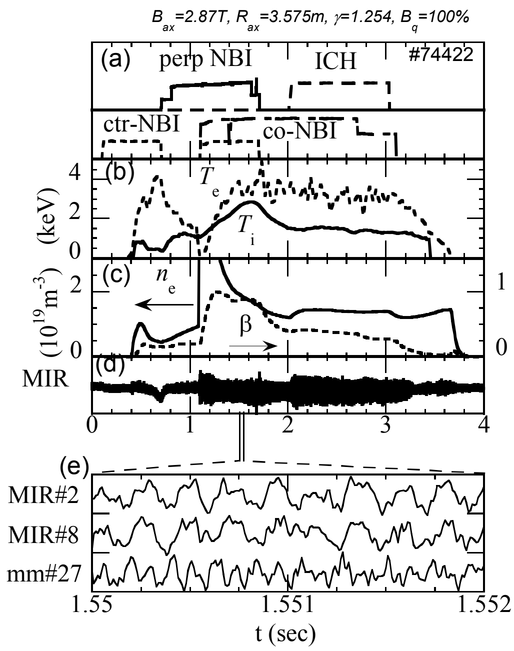

Fig. 2 (a) Heating, (b) temperatures, (c) electron density and beta, (d) MIR signal in slow scale, (e) MIR and magnetic probe signals in fast time scale in LHD.

The reflected beam and the illumination beam are separated by the beam splitter (BS), which is a 3 mm thick Plexiglas plate. The reflected illumination beam by BS and the transmitting illumination beam through DP are absorbed by microwave absorbing forms (ECCOSORB CV-3) in order to reduce background noise. Because of microwave absorbers and beam separation, the leakage of the illumination wave to the receiver is significantly reduced, so that the background level in the signal is drastically reduced.

The plasma image is formed on the front end of receiving horn antenna (WR-15) array by the mirror optics. The pair of antennas is separated by 8.4 cm in the poloidal direction, and another pair by 10.7 cm in the toroidal direction on the cutoff layer. Received reflection wave is transmitted to the heterodyne receiver with oversized waveguides (X-band). In the heterodyne receiver, reflected wave is mixed with the wave from local oscillator (LO) with the frequency of 63 GHz to make intermediate frequency (IF) signals. IF signals selected by band-pass-filters with the bandwidth of 10% of the central frequency are amplified by modular RF amplifiers. Finally they are rectified by Schottky barrier diodes, amplified by DC amplifiers and digitized by PXI digitizer modules.

Figure 2 shows an example of MIR signals in LHD. Clear MIR signals are obtained after adjusting the main mirror. Using this system, novel MHD modes are observed in the case of low density, as shown in Fig.2(e).

3. MIR System in TPE-RX

The second generation of MIR system has been developed for TPE-RX. Main features of the second generation are as follows: (1) narrow IF bandwidth; (2) 2D receiver array; (3) phase detection. Figure 3 shows the schematic view of the MIR system in TPE-RX. In this MIR system a Gunn oscillator generates the RF wave with frequencies of 20 GHz (ω). IMPATT oscillator is not used because its output has many modes with slightly different frequencies.

The primary mirror (M_1), which is an elliptic concave mirror with the size of 40x43 cm, makes the RF beam. The illumination beam designed as its diameter is 9 cm at the window and 10 cm in plasma. As the diameter of the quartz window of the TPE-RX viewing port is 10 cm, the illumination wave can pass through the window. This window size is similar to the open mouse (10.5x8.7 cm) of the 20 dB standard gain horn antenna for 20 GHz (WR-42). Since the magnetic field is very low in TPE-RX, the

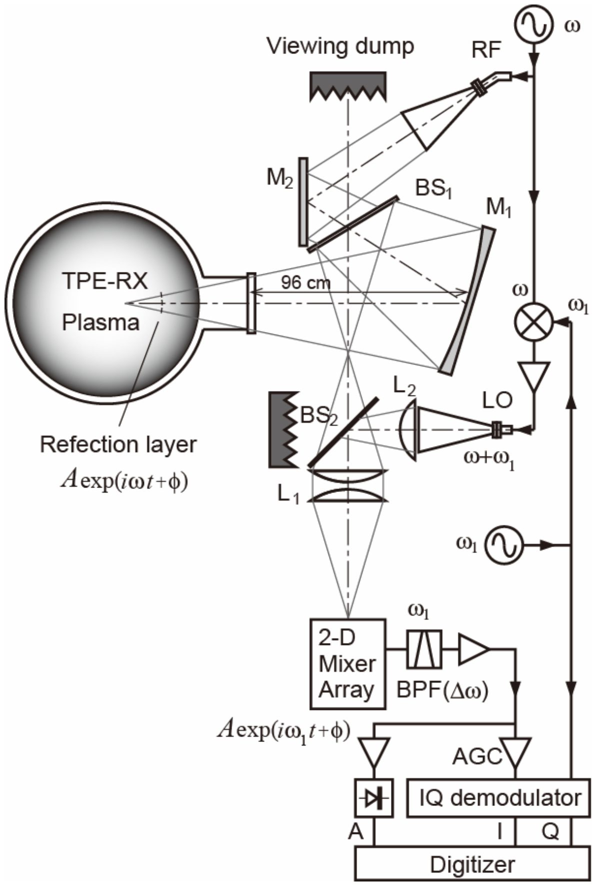

Fig. 3 Schematic view of MIR system in TPE-RX.

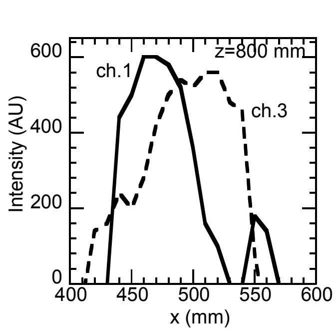

Fig. 4 Test beam profile at the plasma.

illumination wave is in the O-mode, of which cutoff frequency is the plasma frequency. The reflected wave is collected by M_1 and is separated from the illumination beam by the first beam splitter (BS_1). The LO wave and the reflected wave is mixed with the second beam splitter (BS_2). These beam splitters are made of 3 mm thick Plexiglas plate. RF wave reflected by BS_1 and LO wave passing through BS_2 are absorbed by foam absorber (ECCOSORB CV-3) in order to reduce background noise. An image of reflection layer is made onto the 2-D mixer array by the Teflon lens (L_1). As a test, the emission from the position of detector is measured at the position that is 80 cm far from the frame. This position is 133 cm far from the primary mirror M_1, and is 38 cm far from the window of the viewing port. This position corresponds to the position with the minor radius of 30 cm inside the plasma. Fig. 3 shows the resolution at the plasma is 8 cm. The channels 1 and 3 are separated by 4.5 cm at the detector position, and they are separated by 5 cm at the plasma position.

In the 2-D mixer array, four mixer elements are set on a circuit board with a distance of 12 mm, and 4 circuit boards are stacked with a distance of 15 mm. Each element consists of a planer Yagi-Uda antenna, a balun, a beam lead type Schottky barrier diode (SBD) and an IF amplifier. In this system, the balun is improved from the original planer Yagi-Uda antenna system [6]. On the design of antenna system, a computer code for electro-magnetic field (Microwave Office) is employed. Our Yagi-Uda antenna has 3 guiding elements, a pair of dipole and a reflector element. The IF amplifier consists of SAW filters (Murata SAFCC110MCA1T00) and RF amplifiers (RF Micro Devices RF3396). Also the mixer element has two voltage regulators (On Semiconductor MC78LC40NTR) for the power supply of amplifier and the DC bias of SBD. The signal output is a MMCX straight PCB jack connector (HUBER-SUHNER 82_MMCX-S50-0-2/111_KE). The circuit board is a thin Teflon circuit board (Nippon Pillar Packing NPC-F220A(18/18)) with a thickness of 0.18 mm. The circuit is made by the micro strip line technology. The shield box that contains 2-D mixer array has 16 signal output with SMA connector. The MMCX and SMA are connected with a coaxial cable inside the shield box.

The LO wave ($\omega+\omega_1$) is made by mixing the RF wave and the 110 MHz (ω_1) at an up-converter (Hittite HMC523). The lens L_1 and lens L_2 makes a spot of LO wave with the diameter of 10 cm on the 2-D mixer array. By mixing the reflected wave with the frequency of ω and the LO wave, the 2D mixer makes IF signal the frequency of ω_1. Since the IF frequency ω_1 is well stabilized, the noise can be significantly reduced by amplifying with band pass filter (BPF) with a narrow bandwidth (4 MHz).

The reflective wave contains the amplitude A and the phase ϕ, as, $A\exp(i\omega t+\phi)$, where the amplitude A and the phase ϕ is generated by a density fluctuation in the plasma. The phase ϕ is important because it indicates the vibration motion of the reflection layer. The IF signal also contains the amplitude and the phase, as, $A\exp(i\omega_1 t+\phi)$. The amplitude is obtained by rectifying the IF signal with MMIC (Analog Devices AD8362). The phase is obtained by comparing the differential wave (ω_1) and the signal wave with the IQ demodulator (Analog Devices AD8348). I and Q signals correspond to cosϕ and sinϕ, respectively.

Figure 5(a) shows plasma parameters of high Θ RFP plasma in TPE-RX. Here, I_p is the toroidal plasma current, and n_e is the line averaged electron density. F and Θ are the toroidal and poloidal fields normalized by the average toroidal field at the plasma boundary, defined as $F=B_t(a)/\langle B_t\rangle$, and $\Theta=B_p(a)/\langle B_t\rangle$, respectively. Example of MIR signals from this plasma is shown in Fig. 5(a,b). Fig. 5(c) shows MIR channel numbers at the detector position schematically. Here p and t denote the poloidal and the toroidal directions, respectively. Since the imaging optics makes up-side down image, the p direction corresponds to the positive sign in the plasma and the t direction corresponds to the clockwise direction in the top view. As waveforms are similar to other channels, the 2D receiver works well.

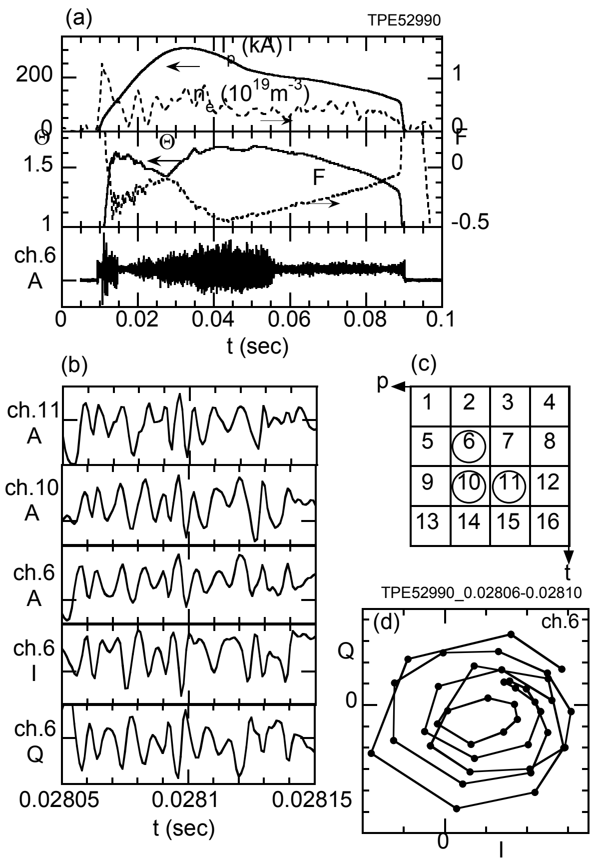

Fig. 5 (a) Plasma parameters and MIR signal in high Θ operation in TPE-RX. (b) Signals of the 2D mixer array of MIR in fast time scale. (c) Schematic view of the 2D mixer array. (d) Lissajous' curve of I-Q signals

Fig. 5(c) also shows I-Q signals of channel 6 of the 2D receiver. Fig. 5(d) shows Lissajous' curve of I-Q signals of channel 6 between t=28.06 and 28.10 msec. If I and Q signals are proportional to cosϕ and sinϕ, respectively, the Lissajous' curve should be circle. In this case, we can find amplitude of I and Q signals are about two times different. May be I and Q signals represent phase because the trajectory is rotating. So this trajectory indicates that the reflection layer moves back and forth. Closed circle indicates a data point, which is taken every 1 μs. At the point (I, Q)=(0.3, 0.2), which corresponds to t=0.028078 sec, the direction of trajectory is turned over. This indicates that the reflection layer motion is turned over at this time.

4. Conclusion

In conclusion, MIR is under development at NIFS. MIR is expected as a new imaging diagnostics of turbulences and instabilities in plasmas. The first generation of MIR has been installed in LHD. This system uses imaging optics and waveguide antenna array as a detector. The second generation of MIR has been installed in TPE-RX. In this system, the differential frequency between the reflected wave and the LO wave is so stabilized that sensitive measurement becomes possible. So, the 2D imaging detector array with planar Yagi-Uda antenna works well. Also preliminary operation of phase detection system has been successful. This result is very encouraging in the development of MIR.

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