Laboratory test of the Microwave Imaging Reflectometry Concept

Y. Nam, I. Hong, M. Kim, W. Lee, G. S. Yun, H. K. Park

POSTECH, Pohang, Gyeongbuk, Korea

Introduction

Microwave Imaging Reflectometry (MIR) is an innovative diagnostic concept for 2-D electron density (n_e) fluctuation measurement to study the anomalous transport physics in fusion plasma. Despite the simple implementation and high sensitivity of the conventional 1-D microwave reflectometry, the phase information of the reflected wave is in general completely obscure due to the complicated 3-D nature of n_e fluctuation. The MIR system, utilizing large optics for sending and receiving the probe beam, overcomes this limitation by forming an image of the cutoff surface on the detector array [1]. In this paper, the physical concept of the prototype TEXTOR MIR system [2] and a lens-based KSTAR MIR system are studied through laboratory investigation. Specifically, the imaging properties of the optics and the curvature matching condition between the probe beam and the plasma cutoff layer have been evaluated. The phase and amplitude of the 2-D diffraction patterns of the reflected beams from a corrugated target are directly measured and compared with simulations.

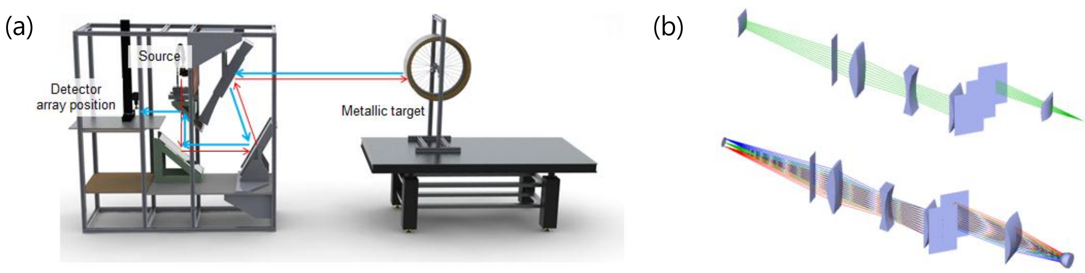

Figure 1. (a) The prototype TEXTOR MIR system with a metallic target (k = 1.25 cm^{-1}, corrugation depth = 1.2π). Red arrows represent the probe beam and blue arrows represent the reflected beam. (b) The launching (top) and receiving (bottom) optics of KSTAR MIR system.

MIR Optics

The prototype TEXTOR MIR optics mainly consists of two large concave mirrors for precise focusing of the probe beam onto the target cutoff surface (Fig. 1a). A purely symmetrical Gaussian probe beam is transformed into a toroidally collimated beam upon hitting the H-plane (toroidal) mirror. The E-plane (poloidal) mirror then adjusts the poloidal beam phase front to match with the target surface. A collimating lens placed in front of the beam source can be slightly moved or replaced for precise curvature matching. On the other hand, the KSTAR MIR system, which is still under development, will adopt lens-based optics (Fig. 1b) to eliminate the spherical aberrations, which are unavoidable in the tilted reflective optics. The KSTAR MIR system is planned to be installed with the 2nd electron cyclotron emission imaging (ECEI) system at the same port and share the zoom optics.

Basically both optical systems are designed to work as both launching and receiving optics at the same time. The large optics transforms the incident beam into a beam suitable for wide illumination on the cutoff surface and collects the reflected beam with minimal loss.

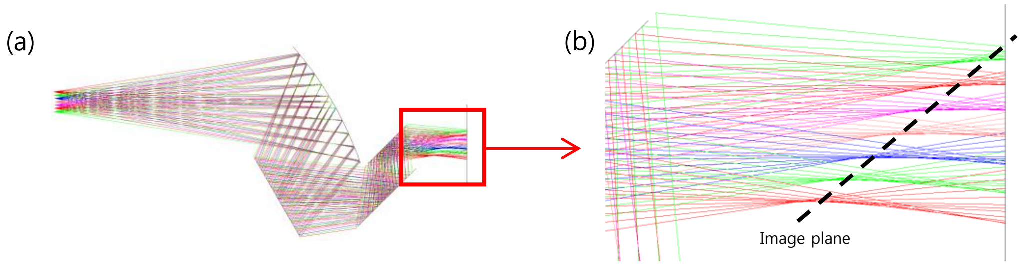

Figure 2. (a) Receiving optics of the prototype TEXTOR MIR system and the reflected beams from target surface. (b) Enlarged view of the slanted image plane formed at the detecting position.

The reflective optics as used in the prototype TEXTOR MIR system causes the axis of beam propagation to be bent, resulting in a severe aberration at the image plane as shown in Fig.2. The probe beam reaching the E-plane mirror has vertically elongated shape. The portions reaching the upper and lower tips of the mirror have apparently different beam path length and eventually results in inclined image plane, while the detector array are vertically aligned: the mismatch between the image plane and detecting plane can cause critical error on the phase reconstruction. This aberration can be overcome by adopting lens based optics instead of mirrors. Lens based optics can send the probe beam to the target without bending of the beam path, and this ultimately prevents the problem of slanted image plane. However, the lens based system can cause standing waves due to multiple reflections between the lenses. The influence of the standing wave on the beam intensity is not large (up to ~5%) whereas the distortion on the phase signal due to the standing wave can cause severe loss of detailed phase information. Slight tilting of the lenses in the horizontal plane reduces the standing wave, but can cause a beam shape distortion as shown in figure 3.

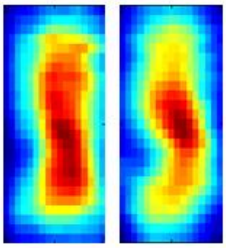

Figure 3. Probe beam passing through the lens based MIR optics. The right figure shows the distortion caused by the lens tilt.

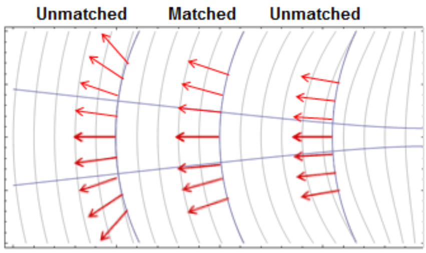

Figure 4. Schematic drawing of curvature matching condition. Only when the beam phase front curvature is matched to the cutoff surface curvature, the beam comes back to the incident path.

The beam sources used in the experiments are Gaussian beams of 88 and 92 GHz. The shape of the probe beam on the target can be modified using a proper optics, and the phase front of the beam incident on the target can be exactly matched to the cut-off layer. The matching is of critical importance, because a slight mismatch can cause severe distortion on the reflected signal from the target. In the case of wrong curvature matching, the beams incident on the edge of the target takes longer/shorter propagation path than it should have, and the image on the detector array becomes elongated/over-focused (Fig. 4). Furthermore, the mismatched reflected beam can spread wide, even to the outside of the collecting optics, reducing the recollection efficiency [3].

The diffraction patterns from the target are measured in both intensity and phase measurements. A corrugated metallic target, shown in Fig. 1a, is used as a replica of the cutoff layer of the tokamak plasma [1]. The target is made of an aluminum plate of width ~ 20 cm wrapped along a wheel of radius R = 30 cm. It can be rotated, which can be regarded as a simple realization of poloidal fluctuation. The corrugation on the target plate, wavenumber k = 1.25 cm^{-1} and depth d = 1.2π, simulates the expected density fluctuation at the plasma cutoff layer. The intensity profile, i.e., the diffraction pattern of the reflected beam has been directly measured by a detector with a horn antenna. Simulation results utilizing the methods of finite difference time domain (FDTD) and analytic Bessel function calculation show that the diffraction patterns can be predicted analytically (Fig. 5a). The investigation on the effect of the curvature mismatch on the intensity profile deformation revealed that the error in target position is tolerable up to ~ 5 cm, which is relatively easily achievable.

The phase measurements have been conducted for the lens based optics on the rotating target. The reconstructed phase signals near the central channels match well to the actual corrugations as shown in Fig. 5b, but those at the sides do not. The combination of deep corrugation depth and the reflector rotation is presumed to result in non-symmetrical and rotation direction-dependent phase profile.

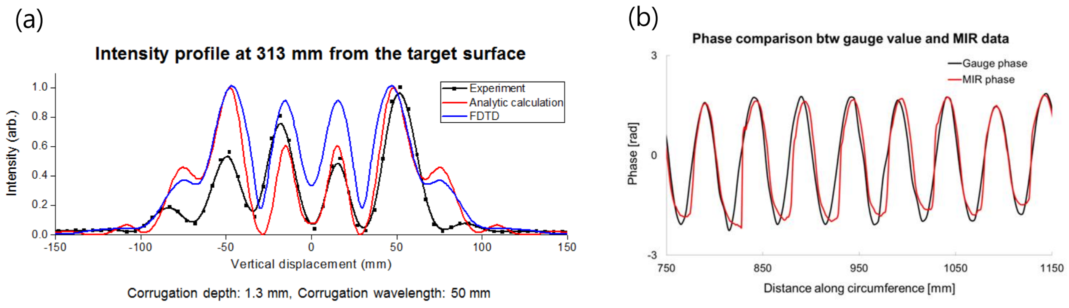

Figure 1. (a) Measured and simulated intensity profiles of diffracted beam. (b) The surface corrugation of the target reconstructed from the phase measurement of the KSTAR MIR system and directly measured by gauge.

In summary, the laboratory investigation of the mirror-based and lens-based MIR systems revealed the important factors for the successful reconstruction of the density fluctuation information.

*Work supported by NRF of Korea under contract No. 20110018724.

[1] T. Munsat, et al. Plasma Phys. Control. Fusion **45**, 469 (2003).

[2] H. Park et al, Rev. Sci. Instrum. **75**, 3787 (2004).

[3] H. Park, et al, Rev. Sci. Instrum. **81**, 10D933 (2010).