Broadband Multichannel Radiometer for ECE Measurements on KSTAR*)

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A broadband heterodyne radiometer system has been developed and installed on KSTAR to measure second harmonic electron cyclotron emission (ECE) at the magnetic field of 3 T. The system consisting of two radiometers (110-162 GHz and 164-196 GHz) can cover a frequency range of 110-196 GHz. The unique and key components to construct this ECE diagnostic instrument are specially-designed detector modules and a diplexer for splitting ECE radiation with high efficiency. The minimum detectable electron temperature with a time response of 1 µs is about 0.23 eV. The observed signal intensity is roughly consistent with the value estimated by using characteristics of various components (waveguide components, sub-harmonic mixers, amplifiers, and intermediate frequency detectors). In this article, design considerations and preliminary ECE measurements will be described.

Keywords: electron cyclotron emission, heterodyne radiometer, electron temperature, tokamak plasma, KSTAR

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1. Introduction

Electron cyclotron emission (ECE) measurement is a powerful diagnostic [1–3] for electron temperature profile measurement of high temperature plasmas confined in a magnetic field. Since the confining magnetic field of a tokamak plasma is inversely proportional to the major radius of the plasma, the ECE frequency simply depends on the radial position of the plasma. When the plasma emits and absorbs radiation as a black body, it is possible to determine the electron temperature profile simply from the measured spectrum.

We have developed a broadband multichannel radiometer system for measuring the second harmonic ECE from the Korea Superconducting Tokamak Advanced Research (KSTAR) [4] plasma (R = 1.8 m, a_p = 0.5 m, k = 2.0, $B_t < 3.5$ T, $I_p < 2$ MA). The unique and important components to construct this ECE diagnostic instrument are a specially-designed detector module [5] and a diplexer for splitting ECE radiation with high efficiency. The KSTAR ECE diagnostic instrument has been developed under the Korea-Japan KSTAR collaboration which started in 2004. In the second experimental campaign (2009.10-2009.12) of KSTAR we have successfully achieved electron temperature profiles [6] from the measured ECE spectrum after absolute calibration. In this article, The ECE diagnostic instrument and preliminary experimental results from the KSTAR tokamak are described.

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2. Heterodyne Radiometer System for KSTAR

Figure 1 shows a block diagram of a broadband heterodyne radiometer system for the KSTAR ECE diagnostic. Two radiometer systems (D-band: 110-162 GHz, G-band: 164-196 GHz) are combined with a diplexer, and can cover the wide frequency range of 110-196 GHz. The detail of the D-band radiometer system is also shown in the figure, since the G-band system is almost similar to the D-band. The electron cyclotron emission radiated from the plasma is observed along the major radius with a concave ellipsoidal mirror located inside the tokamak [7]. The ellipsoidal mirror can be rotated 180 degrees to collect radiation from a hot (873 K) blackbody radiation source [8] in the case of calibration. The ECE radiation collected by the antenna is imaged onto the end of a 63.5-mm-diam corrugated waveguide of 25 m in length via a fused quartz window. The corrugated waveguide is designed to transfer microwaves from 50 to 220 GHz with small loss (~1.0 dB/km at 100 GHz). The beam spot size on the ECR layer is about

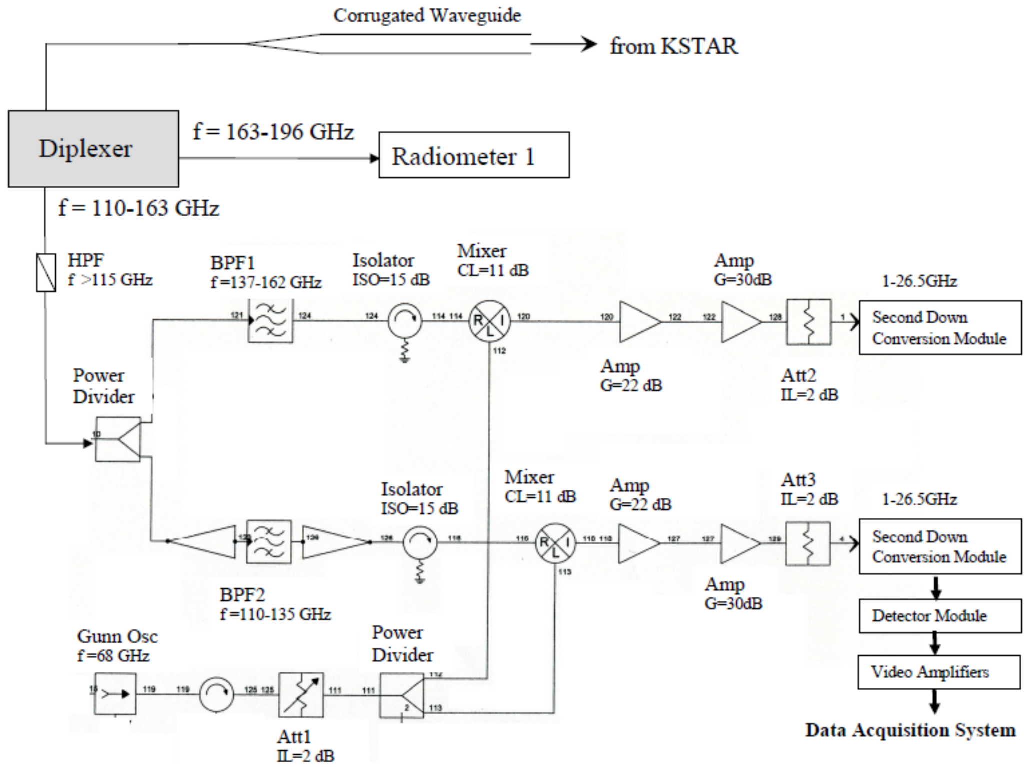

Fig. 1 Block diagram of a broadband heterodyne radiometer system of the KSTAR ECE diagnostic. Two radiometer systems are combined with a diplexer, and can cover the wide frequency range of 110-196 GHz. HPF, high pass filter; BPF, band pass filter; ISO, isolator; CL, conversion loss; IL, insertion loss; G, gain; Att, attenuator.

5 cm over the frequency range of 110 GHz to 156 GHz. Figure 2 shows the radial distributions of the first three harmonics of ECE frequencies in KSTAR at the magnetic field of 3 T. As is shown in Fig. 2, the 2nd harmonic frequency region of 131-196 GHz is useful for electron temperature profile measurements, since there is no overlapping on the 3rd harmonic ECE. Therefore, it is possible to obtain electron temperature profiles in the region of $r = a_p \sim -3/5a_p$ from the measurement of the 2nd harmonic X-mode of ECE. The radiation transmitted through the waveguide is introduced to a specially-designed multiplexer to split high frequency band (f > 163 GHz) and low frequency band (f < 163 GHz) with high efficiency.

A high-pass filter with two tapered transition waveguides (WR12 to WR5) is installed behind the diplexer to eliminate gyrotron radiation at the frequencies of 84 GHz and 110 GHz. The high pass-filtered (f > ~115 GHz) radiation is introduced to the D-band radiometer, and split into two bands (upper sideband and lower sideband) by a 3 dB power divider. The rf power of each band is fed to a sub-harmonic mixer (RPG SHM137) via a waveguide band-pass filter (BPF1, BPF2) to ensure single sideband operation of the mixer. A sub-harmonic mixer provides a simple way of down-converting millimeter waves with a low-frequency local oscillator operating at one half of the signal frequency. The sub-harmonic mixer has the advantage of suppressing the fundamental and other harmonic mixing products in addition to using a low LO frequency (68 GHz). The conversion loss of the mixer is about 11 dB for the rf frequencies of 110-162 GHz with an intermediate frequency (IF) range of 0.1-26 GHz. The IF output of the mixer is connected to two-stage low noise amplifiers (pre-amplifier; MITEQ AFS4-000102650-42-BP-4, Gain: 22 dB, Noise: 4.2 dB), and introduced to a second down conversion module, where the IF signals with frequencies of 8-14, 14-19.5, and 18-26.5 GHz are converted into 1-

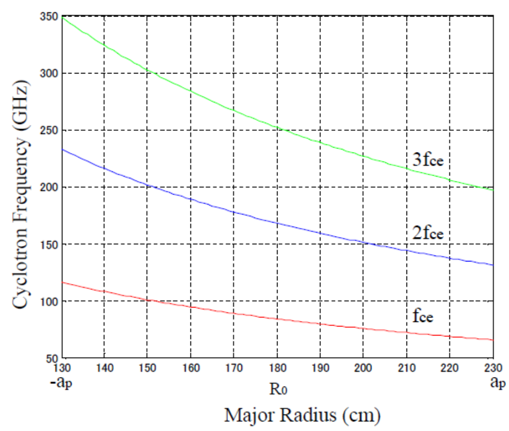

Fig. 2 Frequencies of ECE from the fundamental and harmonics of the KSTAR tokamak at the magnetic field of 3 T.

9.5 GHz by using local oscillators (7, 13, 17 GHz) and mixers, and finally to the detector modules [5]. The detector module is fabricated on a planar Teflon substrate by using the microwave integrated circuit (MIC) technology [9], which consists of 8 channel band-pass filters whose center frequency is from 2 to 9 GHz with a 1 GHz increment. The output of the detector is amplified by a video amplifier with a 1 μs response, and finally recorded. The total losses of the instrument, which are mainly caused by the insertion loss of each waveguide component and conversion loss of the mixers, are roughly estimated to be ~49 dB, and the total gain of the amplifiers is ~120 dB. The estimated sensitivity is 0.48 V/eV, by considering a video detector sensitivity of 6 V/mW. The system sensitivity measured by using a calibration source is ~0.15 V/eV, which is roughly consistent with the estimated value, and the system noise temperature is 0.24 eV. In actual plasma experiments, 23 dB attenuators are added in front of the 2nd down conversion modules to avoid signal saturation.

3. Characteristics of the Diplexer

The 2nd harmonic ECE radiation from the KSTAR plasma is in the range of 110 GHz to 196 GHz when the KSTAR tokamak is operated at the magnetic field of 3-2.5 T. It is difficult to cover this wide frequency band by using one heterodyne radiometer, therefore a combination of two radiometer systems was designed. The key point is how to split ECE radiation efficiently for two radiometer systems. The most conventional way is to apply a 3 dB waveguide directional coupler, which is widely used in microwave diagnostics. In this case, however, we could not avoid the internal loss of the coupler, and the applicable frequency regime is limited due to the waveguide size. Hence we applied a quasi-optical technique to cover a wide frequency band. Figure 3 shows the schematic drawing of the Quasi-Optical Diplexer, which is used to separate signals present in the 25 mm in diameter smooth-walled guide from the plasma into two frequency bands using a frequency selective surface (FSS). The low pass surface aims to allow 110-163 GHz to pass and reflect 163-196 GHz. The filter B351 (from QMC Instruments Ltd, www.terahertz.co.uk) has a 50% transmission at 5.44 cm^{-1}/163 GHz and is built with a multi-layered structure of capacitive and inductive meshes. The multi-layered FSS was originally developed for astronomical applications, which has both high transmission efficiency and good cut-off rejection to select the extremely low astronomical signal levels between intense atmospheric emission lines. The optics of the diplexer are specifically designed to operate over the required wide band, using off-axis ellipsoidal mirrors placed at sums-of-focal length. In addition, the focal length is chosen to be long enough that higher order and X-polar mode distortion are kept below acceptable limits [10]. The dimensions of each optical component of the diplexer are designed to accept 3W (W: the diameter at the 1/e point of a Gaussian beam intensity). The 3 times beam diameters of 110 GHz and 164 GHz are also plotted in the figure.

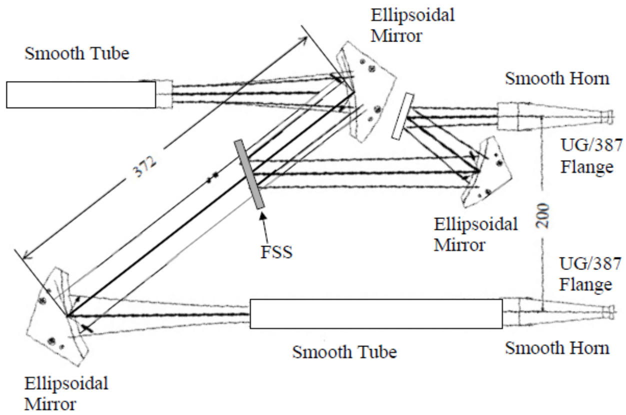

Fig. 3 Schematic drawing of the Quasi-Optical arrangement of a diplexer, which can separate a low frequency band (f < 162 GHz) and a high frequency band (f > 163 GHz) by using a frequency selective surface (FSS).

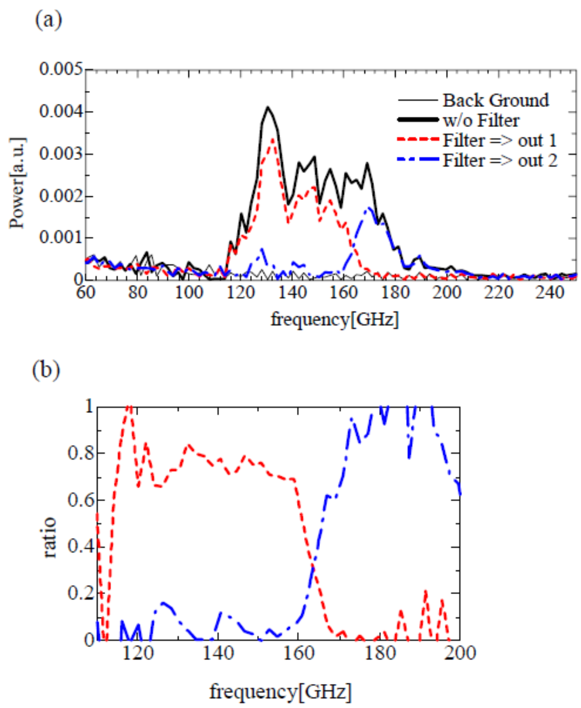

Fig. 4 (a) Raw spectra of Fourier transform spectrometer for a solid-state noise source (ELVA-1, Model number, ISSN-05), which delivers a uniform level of noise spectral density over the whole frequency range. The transmission and reflection spectra of the multi-mesh filter are also plotted. (b) The ratio of the raw spectra without and with the FSS.

The transmission and reflection properties of the FSS were measured by the use of a Fourier transform spectrometer [3] and a solid-state noise source (ELVA-1, Model number, ISSN-05) which is designed to deliver a uniform level of noise spectral density within the main waveguide

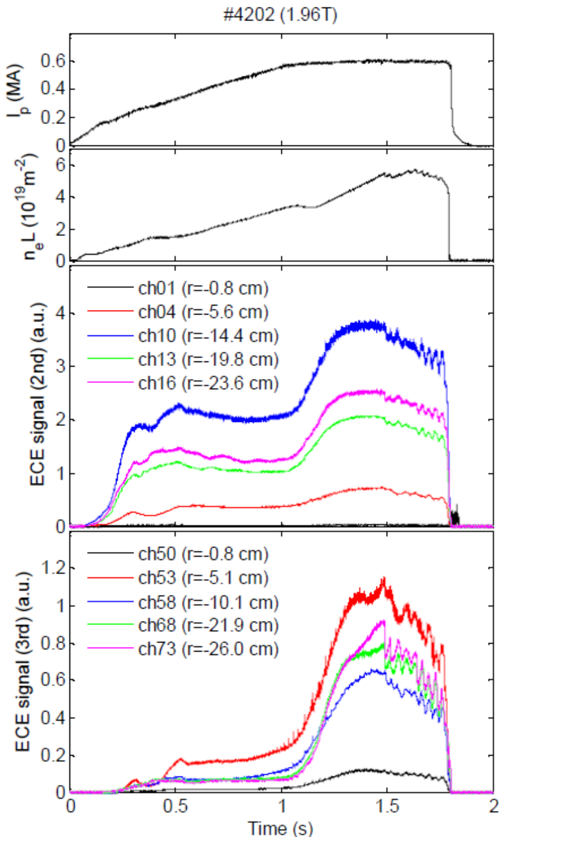

Fig. 5 Time traces of plasma current, line density and ECE signals from different radial positions of the plasma.

frequency range (f = 120-180 GHz). Since the radiation power is very low compared with ECE radiation from the plasma, an accumulation of about 2000 data points is needed to achieve enough signal-to-noise ratio. Figure 4 (a) shows the measured spectrum of the noise source and transmission and reflection spectra of the FSS. Figure 4 (b) shows the ratio of the raw spectra without and with the FSS. It is found that an intersection frequency is 163 GHz and the transmission efficiency is around 80%.

4. Preliminary ECE Measurements

Figure 5 shows typical ECE signals emitted from the different radial positions of the plasma at the magnetic field of 1.96 T. Waveforms of the plasma current and line integrated density are also shown. In the figure, selected chord signals, corresponding to the 2nd and the 3rd harmonic ECE, are plotted. At the present, the instrument has not been calibrated yet, and will be calibrated to achieve electron temperature profiles after the 3rd experimental campaign in 2010. The details of the calibration procedure are described in ref. 11.

5. Summary

The broadband radiometer system for KSTAR has been developed, and successfully operated. The developed multiplexer was found to be useful for splitting radiation efficiently. 2nd down conversion modules are also useful for construction of a broadband multichannel heterodyne radiometer system.

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