3rd Asia-Pacific Conference on Plasma Physics, 4-8,11.2019, Hefei, China

2-D Imaging Diagnostics for Fusion Plasma Employing Millimeter-wave System-on-Chip Advancement

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Millimeter-wave plasma imaging diagnostics have been widely applied on various magnetic fusion facilities around the world and provide crucial contributions on the physics of sawtooth, Alfven eigenmodes, ELMs, and microturbulence. To this end, we have been developing millimeter wave diagnostics to visualize electron density and temperature fluctuations in magnetic fusion plasmas.

In recent years, there have been dramatic advances in monolithic millimeter wave integrated circuit (MMIC) technology making possible system-on-chip (SoC) solutions employing both silicon and GaAs/InP/GaN manufacturing processes for customized instruments and systems. Moreover, driven by applications including 5G wireless networks and point-to-point communications for wireless back-haul, single-chip mm-wave electronics are providing dramatic improvements in gain, noise suppression, and bandwidth. The consequent rapid growth of mm-wave integrated circuits offers the possibility of making ultra-wide band observations in scientific applications. More specifically, millimeter-wave fusion plasma diagnostics require broadband operation, which is approximately nine times wider bandwidth than the recent commercial impetus for communication systems, to acquire as well as track phenomena inside the plasma to understand the physics behavior.

As a first demonstration, a state-of-the-art E-band (70-80 GHz) receiver array was developed using commercially available integrated circuits (ICs) to realize MMIC modularization [1, 2]. In a proof-of-principle demonstration on the DIII-D tokamak, the resultant liquid crystal polymer (LCP) [3, 4] substrate-based horn-waveguide array was shown to overcome major limitations such as space inefficiency, inflexible installation, poor noise shielding, and prohibitively high cost of conventional discrete components. Being more reliable to stand for long-term operation under the harsh environment, each receiver channel is completely modularized and individually shielded which makes the assembly become much easier than waveguide connections.

Recently, our team has successfully designed, fabricated, and measured V-band (55-75 GHz) [5,6] and W-band (75-110 GHz) [7] receiver/transmitter modules for electron cyclotron emission imaging (ECEI) and microwave imaging reflectometry (MIR) diagnostics. The latest W-band receiver array with in-house designed ICs has been installed on the DIII-D tokamak as a new ECEI system upgrade and is capable of observing from the core region (rho ~ [-0.2, 0.4]) to the pedestal region (rho ~ [0.85,0.99]). Current efforts are underway for the development of CMOS monolithic microwave integrated circuit receiver chips at F-Band (90- 140 GHz) permitting measurements at higher toroidal magnetic fields. All of the E-, V-, and W-band receivers with the SoC solution prove that the noise capability of the module is reduced to below 6,000 K noise temperature with >30 dB amplification covering entire 20-35 GHz bandwidth.

This work is supported by US DoE grant DE-FC02-04ER54698.

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