Princeton Plasma Physics Laboratory

PPPL-5274

Low-noise heterodyne receiver for Electron Cyclotron Emission Imaging and Microwave Imaging Reflectometry

B. Tobias, C.W. Domier, N.C. Luhmann, Jr., C. Luo, M. Mamidanna,
T. Phan, A.-V. Pham, and Y. Wang

July 2016

PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S.Department of Energy under Contract DE-AC02-09CH11466.

Princeton Plasma Physics Laboratory
Report Disclaimers

Low-noise heterodyne receiver for Electron Cyclotron Emission Imaging and Microwave Imaging Reflectometry[a)]

B. Tobias,[1,b)] C.W. Domier[2], N.C. Luhmann, Jr. [2], C. Luo[2], M. Mamidanna[2], T. Phan[2], A.-V. Pham[2], and Y. Wang[2]

[1]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA*
[2]*University of California at Davis, Davis, California 95616, USA*

(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)

The critical component enabling electron cyclotron emission imaging (ECEI) and microwave imaging reflectometry (MIR) to resolve 2D and 3D electron temperature and density perturbations is the heterodyne imaging array that collects and downconverts radiated emission and/or reflected signals (50 to 150 GHz) to an intermediate frequency (IF) band (e.g. 0.1 to 18 GHz) that can be transmitted by shielded coaxial cable for further filtering and detection. New circuitry has been developed for this task, integrating gallium arsenide (GaAs) monolithic microwave integrated circuits (MMICs) mounted on a liquid crystal polymer (LCP) substrate. The improved topology significantly increases electromagnetic shielding from out-of-band interference, 10x improvement in signal-to-noise ratio, and dramatic cost savings through integration. The current design, optimized for reflectometry and edge radiometry on mid-sized tokamaks, has demonstrated >20 dB conversion gain in upper V-band (60-75 GHz). Implementation of the circuit in a multi-channel electron cyclotron emission imaging (ECEI) array will improve the diagnosis of edge-localized modes and fluctuations of the high-confinement, or H-mode, pedestal.

I. INTRODUCTION

Microwave and millimeter-wave imaging diagnostics have become important to a wide range of physical investigations on many large and mid-sized tokamaks around the world. ECE-Imaging, for example, provides localized measurements of the fluctuating electron temperature on a poloidal cross-section for a 2D picture of the internal mode structure[1-5]. This results in unique data, including poloidal wavenumbers and turbulence correlation lengths that are not available from other diagnostics that rely on the tomographic inversion of line integrated measurements or detect field perturbations only outside the confined plasma. Techniques of quasi-optical beam forming with large aperture optics that have made electron cyclotron emission imaging (ECEI) instruments so valuable to fusion science are also applied in microwave imaging reflectometry (MIR)[6-8]. Comparison of MIR data to conventional reflectometers demonstrates not only the importance of making multiple poloidally separated measurements, but it also underscores the importance of imaging for controlling scattered radiation that can cause interference and all but eliminate any correlation between the local density perturbation and phase modulation in the diagnostic signal. They key element of both ECEI and MIR is the heterodyne imaging array[9]. Each antenna in the array views a different region of the plasma with a resolution that is determined by the antenna field pattern and operating frequency. Microwave radiation collected by the array must then be downconverted by heterodyne mixing to a lower frequency band so that it can be transmitted several meters away to the sensitive filtering and detection electronics housed outside the high-radiation environment of the tokamak machine hall.

Aside from the frequency range of interest, ECEI and MIR heterodyne imaging arrays have a very similar design. As an example, an imaging array from the DIII-D MIR[8] system is shown in Figure 1. The egg-shaped, high-density polyethylene (HDPE) miniature substrate lenses visible in part a) help to collimate the radiation pattern for miniature dual-dipole antennas shown in part b). The mixing element, a Schottky diode, is mounted directly on the antenna and illuminated simultaneously by the radio-frequency (RF) signal and a local oscillator (LO) source that is coupled by a second set of HDPE lenses. The intermediate frequency (IF) signal obtained by mixing RF and LO power is amplified and transmitted over coaxial cable to further filtering, mixing, amplification, and detection stages. This circuit design utilizes primarily off-the-shelf discrete components (packaged individually by the manufacturer and assembled as a circuit by mating fundamental-mode waveguide) for rapid prototyping and deployment, but has several unfortunate drawbacks. Without taking great care in component selection and assembly, the arrangement of mixer before amplifier in the signal path can lead to a system noise temperature greater than 100,000 K, which is comparable to the thermal photon noise of the plasma itself[10]. Secondly, the antenna and mixing element are difficult to shield from stray heating power and other sources of radiation outside the frequency band of interest. This produces additional noise, intermittent interference, and even raises the risk of damage from RF plasma heating and current drive systems. Electron cyclotron heating power (ECRH) is shielded by quasi-optical notch filters on the DIII-D tokamak[2], but interference from lower-hybrid current drive (LHCD) systems such as those on EAST is more difficult to suppress[11]. Even spontaneous mm-wave bursting, though thought to be outside the imaging frequency band, can saturate the diagnostic and obscure the structure of edge-localized modes in low-collisionality regimes that are of great interest[12].

[a)]Contributed paper published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2016) in Madison, Wisconsin, USA.

[b)]Author to whom correspondence should be addressed: bjtobias@pppl.gov.

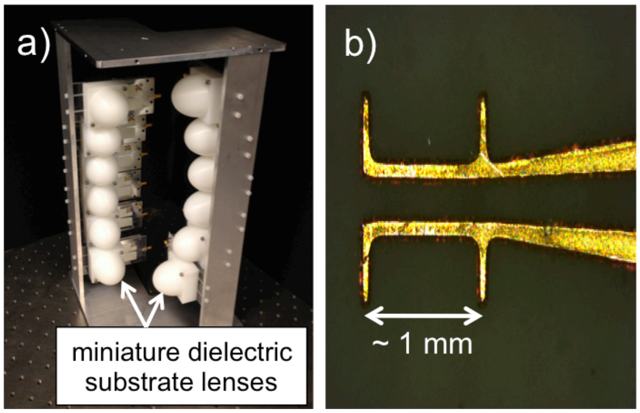

FIG. 1. a) A 12-channel heterodyne imaging array for MIR. Antennas arranged in two planes are combined by a beamsplitter (not shown) and individually offset to match the radius of curvature of the plasma cutoff surface. b) A dual-dipole antenna similar to that placed behind each substrate lens. The mixing element (a Schottky diode) is placed across the two parallel traces and illuminated by both RF signal and LO power.

A new approach to the problem of filtering, mixing, and detecting microwave signals in the tokamak environment has been enabled by recent advances in Gallium-Arsenide (GaAs) monolithic microwave integrated circuit (MMIC) design and substrate materials for integration and packaging. Broad access to semiconductor foundry processes with the feature resolution necessary for high frequency circuits has resulted in a limited but growing range of commercially available low-noise amplifiers (LNAs) and mixers in the V and W frequency bands used by plasma diagnostics. Furthermore, advances in liquid crystal polymer (LCP) technology have led to new materials that have excellent electrical and mechanical properties, are flexible, nearly hermetic, and are available as multi-layer substrates for compact circuit design[13,14]. These technologies make for a cost-effective method of prototyping new circuit configurations with much better signal-to-noise ratios and significantly improved reliability with dramatically reduced cost thanks to greater circuit integration.

In this paper we present the design and initial test results for a V-band heterodyne receiver circuit that will be implemented in future ECEI upgrades for detailed characterization of edge-localized instabilities on medium-sized tokamaks and under conditions of low electron collisionality. These measurements have been corrupted in previous physics studies due to strong bursts of out-of-band emission that will be rejected by the new receiver design. Furthermore, this circuit will reduce the system noise temperature well below the level of thermal photon noise, allowing for greater confidence in low-level fluctuation data and providing an opportunity to reduce IF bandwidth for finer radial resolution[15]. While Section II presents details of a circuit designed for ECEI radiometry, it is noted that a nearly identical circuit can be implemented in MIR as a reflectometer receiver array. Section III provides details of the antenna and packaging design.

II. GaAs-LCP HETERODYNE RECEIVER CIRCUIT DESIGN AND TEST RESULTS

Commercially available GaAs MMIC components have been selected for this prototype circuit due to their favorable gain and noise characteristics. Perhaps the most important components are the LNA and RF mixer, as they determine the operating bandwidth and make the dominant contributions to overall system noise temperature. We have chosen an Analog Devices high electron mobility transistor (HEMT) LNA, part number HMC-ALH382, with a manufacturer's advertised minimum small-signal gain of 19 dB from 57 to 65 GHz with a typical noise figure of 4.8 dB and 20 dB typical wideband gain above 75 GHz. This is paired with an Analog Devices HMC-1081 mixer capable of better than -8 dB conversion gain from 50 to 75 GHz. These are mounted on a multi-layer LCP substrate as shown in Figure 2 a). The LO is multiplied 8x over three stages, as is shown in the schematic diagram provided in Figure 2 b). This allows the mm-wave LO power to be generated on-board from a highly stable and economical synthesizer input below 15 GHz, eliminating the need for sensitive mm-wave sources that would otherwise be mounted outside the tokamak hall and optically coupled through costly runs of low-loss corrugated waveguide.

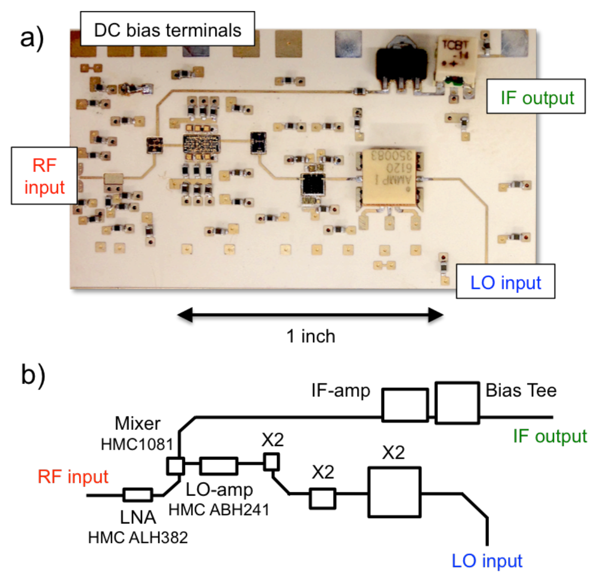

FIG. 2. a) A single-channel heterodyne GaAs-LCP circuit. Multiple channels may be laid out on a single printed circuit to produce a multi-channel imaging array. Only the top layer is shown, obscuring DC bias circuits and a portion of the IF output path. b) Primary components of the circuit are shown with the high-frequency GaAs MMICs labeled by part number.

Microstrip transmission line losses as low as 1.39 dB/cm at 110 GHz have been reported for LCP substrates[14], but care must be taken in the design and implementation of mm-wave interconnects. Therefore, transmission line interconnects are designed with impedance compensating structures that are then wirebonded to the various MMICs. This additional design effort improves the insertion loss at each wirebond by approximately 3 dB and is essential for achieving the required 20 dB overall conversion gain. Circuit test results are shown in Figure 3 and demonstrate excellent performance over a wide bandwidth when a 60 GHz LO is supplied to the mixer input. The LNA and mixer alone deliver very flat 10 dB conversion gain, and the circuit appears to be limited only by the IF power amplifier (and a known issue coupling the output bias tee). Although the bandwidth and frequency response may be improved by the implementation of custom MMICs, this off-the-shelf selection appears well suited to imaging the plasma edge at a tokamak such as DIII-D when operating with a toroidal field on axis in an approximate range of 1.5 to 1.8 T.

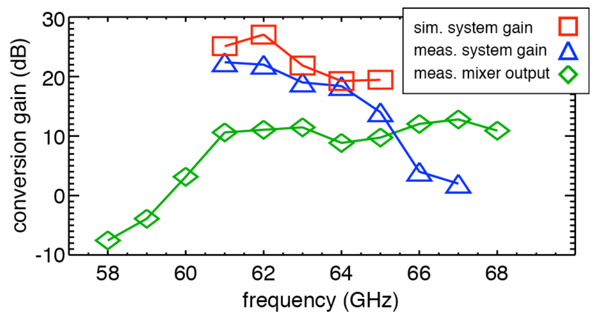

FIG. 3. The measured conversion gain at the output of the high-frequency mixer (green diamonds) is compared to that measured at the IF output terminal (blue triangles) and the expected overall system gain (red squares) with a 10 GHz LO signal supplied.

III. ANTENNA AND PACKAGING DESIGN

Coupling the new GaAs-LCP heterodyne receiver to plasma radiation or reflected power for 2D imaging of fluctuating electron temperature or density requires integrating an appropriate antenna element and packaging multiple circuits as an imaging array. A horn antenna with Vivaldi aperture feed, inspired by the finline waveguide-microstrip transition reported in Ref. 16, has been designed to match the performance of existing dual-dipole antennas while providing additional rejection to out-of-band emission. Figure 4 a) and b) show the antenna feed that is to be integrated with the LCP substrate and the pyramidal horn. A 5 mm length of waveguide extends from the throat of the horn to provide 80 dB total rejection of radiation near 5 GHz, such as ion cyclotron heating (ICRH) and lower-hybrid current drive (LHCD) power. Figure 4 c) shows the simulated radiation pattern for this horn antenna, demonstrating side-lobes below -15 dB. This will allow the array to be used with the existing quasi-optical lenses and tokamak port windows.

IV. SUMMARY

A new heterodyne receiver has been designed for mm-wave imaging systems, including ECEI and MIR, that takes advantage of recent developments in GaAs MMIC and LCP technology for improved performance, reliability, and cost savings through greater component integration. The prototype circuit exhibits better than 20 dB overall conversion gain for V-band frequencies of interest. Additionally, an integrated end-fire Vivaldi antenna and compact package design have simulated acceptable antenna gain with low side-lobes necessary for high-resolution 2D plasma imaging. The resulting improvements in system noise temperature and electromagnetic shielding of stray radiation will be implemented in diagnostic upgrades during the coming year in order to provide new data pertaining to the physics of edge-localized modes.

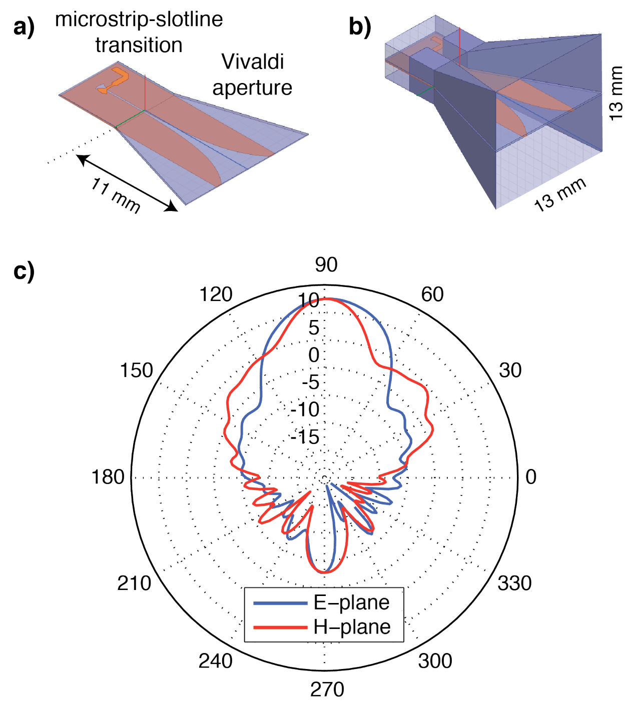

FIG. 4. a) Model of the Vivaldi aperture antenna feed. b) The pyramidal horn and short waveguide section enclosing the slotline feed. c) Simulated antenna gain patterns in the E- and H-planes at 65 GHz (dB scale). The half-power beam angles are 34° and 23°, respectively.

IV. ACKNOWLEDGMENTS

This work was supported by the US Department of Energy under DE-AC02-09CH11466 and DE-FG02-99ER54531.

V. REFERENCES AND FOOTNOTES

[1]B.H. Deng, C.W. Domier, N.C. Luhmann, Jr., D.L. Brower, G. Cima, A.J.H. Donné, T. Oyevaar, and M.J. van de Pol, Rev. Sci. Instrum. **72**, 301 (2001).
[2]B. Tobias *et al.*, Rev. Sci. Instrum. **81**, 10D928 (2010).
[3]I.G.J. Classen *et al.*, Rev. Sci. Instrum **81**, 10D929 (2010).
[4]G.S. Yun *et al.*, Rev. Sci. Instrum. **81**, 10D930 (2010).
[5]B. Wan *et al.*, Fusion Sci. and Tech. **59**, 631 (2011).
[6]E. Mazzucato, Nuclear Fusion **41**, 203 (2001).
[7]T. Munsat *et al.*, Rev. Sci. Instrum. **74**, 1426 (2003).
[8]C.M. Muscatello *et al.*, Rev. Sci. Instrum. **85**, 11D702 (2014).
[9]H.J. Hartfuss, T. Geist, and M. Hirsh, Plasma Phys. Control. Fusion **39**, 1693 (1997).
[10]G. Cima, Rev. Sci. Instrum. **63**, 4630 (1992).
[11]J. Li and B. Wan, Nuclear Fusion **51**, 094007 (2011).
[12]B. Tobias, M.E. Austin, J.E. Boom, I.G.J. Classen, C.W. Domier, N.C. Luhmann, Jr., R. Nazikian, and L. Yu, Proceedings of the 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2012 P4.019
[13]K. Aihara, M.J. Chen, and A.-V. Pham, IEEE Trans. on Microwave Theory and Techniques **56**, 2111 (2008).
[14]A.-V. Pham, M.J. Chen, and K. Aihara, *LCP for Microwave Packages and Modules* (Cambridge University Press, 2012)
[15]J. Lai, C.W. Domier, and N.C. Luhmann, Jr., Rev. Sci. Instrum. **85**, 033501 (2014)
[16]D. Kuwahara, *et al.*, Rev. Sci. Instrum. **85**, 11D805 (2014).

Princeton Plasma Physics Laboratory
Office of Reports and Publications

Managed by
Princeton University

under contract with the
U.S. Department of Energy
(DE-AC02-09CH11466)

P.O. Box 451, Princeton, NJ 08543
Phone: 609-243-2245
Fax: 609-243-2751

E-mail: publications@pppl.gov

Website: http://www.pppl.gov