Title
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Journal
Review of Scientific Instruments, 89(10)

ISSN
0034-6748

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Publication Date
2018-10-01

DOI
10.1063/1.5035559

Peer reviewed

Millimeter-wave System-on-chip Advancement for Fusion Plasma Diagnostics

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

Recent advances in RF system-on-chip technology have provided mm-wave fusion plasma diagnostics with the capability to overcome major challenges: space inefficiency, inflexible installation, sensitivity, susceptibility to EMI, and prohibitively high cost of conventional discrete component assemblies as higher imaging resolution and data accuracy are achieved by increasing the number of channels. Nowadays, shrinking transistor gate lengths on fabrication techniques have enabled hundreds of GHz operation, which is suitable for millimeter-wave diagnostics on current and future tokamaks. The Davis Millimeter Research Center (DMRC) team has state-of-the-art high-frequency development equipment and experience on designing fully customized ICs for fusion science applications. The DMRC has successfully developed V-band (55-75 GHz) transmitter and receiver chips for Microwave Imaging Reflectometer (MIR) instruments. The transmitter can illuminate 8 different frequencies simultaneously within 55-75 GHz. Moreover, the receiver has the capability to amplify the reflected signal (> 30 dB) while offering 10-30x reduction in noise temperature compared to current MIR instruments. Plasma diagnostics requires ultra-wideband (more than 20 GHz) operation which is approximately nine times wider bandwidth than the recent commercial impetus for communication systems. Current efforts are underway for GaAs MMIC receiver chips at W-Band (75-110 GHz) and F-Band (90- 140 GHz) permitting measurements at higher toroidal magnetic fields.

I. INTRODUCTION

Advances in device fabrication and the scaling of feature size have recently extended the maximum operating frequency of CMOS technologies considerably in excess of a hundred gigahertz. Single-chip CMOS electronics in the mm-wave spectrum start being promising to implement the integration in the high frequency regime while considerably reducing the system space and solving serious issues on shielding. The mm-scale wavelength of V-band (about 5 mm in free space) offers the integration of analog and microwave components such as monolithic microwave integrated circuits (MMICs) onto a single chip with a high-frequency package.

Existing MIR systems have been implemented and installed in several major magnetic confinement devices such as the DIII-D tokamak in San Diego and the EAST tokamak in Hefei. All of them have already demonstrated encouraging results of visualizing density fluctuations thus offering more potential on instability observations. The DIII-D MIR instrument currently uses a 12-vertical-channel Schottky diode heterodyne receiver array with 4 simultaneously tunable transmitter signals, thus providing a 12x4 pixels image[2].Both of the MIR systems share the same port and window on the tokamak including large aperture optics with the ECEI diagnostic systems, and therefore the combination is capable of probing the density and temperature fluctuations over a specific area inside the plasma.

[a)]Published as part of the Proceedings of the 22nd Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2018) in San Diego, California, USA.
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[c)]Reference for a "Team" authorship.

II. V-BAND CMOS-BASED TRANSMITTER

To allow detection of the radial distribution of plasma density fluctuations, the transmitter needs to illuminate multiple frequency tones simultaneously while receiving each tone reflecting from the corresponding density-dependent cutoff layer inside the plasma[1]. FIG. 1 illustrates the current MIR transmitter architecture built up with commercially available waveguide components. Low frequency microwave sources are upconverted to V-band (55-75 GHz) using an upconverting mixer. The RF output of the mixer is then amplified and radiated from a standard horn antenna. However, the main challenge here is the limited number of tones due to the maximum available output power of the V-band power amplifier. Ideally, while increasing the number of IF inputs, more frequencies would be transmitted on the output. However, the power amplifier in the current system provides only 20 mW maximum saturated output power, thus yielding 1.25 mW per frequency as N=2, where N = number of IF input sources and 2N = number of output frequencies. Due to the requirement that the transmitted power into the plasma be sufficiently high to receive sufficient power at the receiver side, the existing transmitter is limited to generating 4 frequencies simultaneously. To improve the spacing resolution by increasing the number of frequencies transmitted, this limitation can be solved by the UCD designed CMOS transmitter chip shown below.

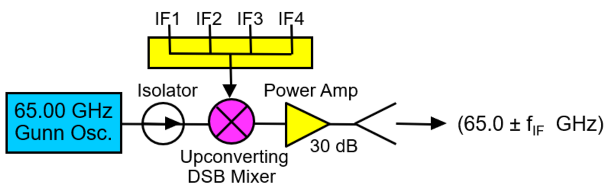

FIG. 1. Current MIR transmitter architecture with commercial available waveguide components.

To this end, the proposed V-band transmitter for the MIR system upgrade has been designed, fabricated, and tested[3]. Aimed at increasing the spacing resolution and bandwidth of the current system, the CMOS-based transmitter expands the capabilities to illuminate 8 various frequencies simultaneously located within V band (55-75 GHz). In other words, the output frequencies are tunable over the entire 20 GHz bandwidth covering the wide dynamic range for the DIII-D tokamak. FIG. 2 shows the chip photo presenting four low frequency IF inputs, V-band LO input, and RF output port. The output spectrum of the transmitter with 64 GHz LO input illustrates eight tones with around 0 dBm power level. From the presented output spectrum result, the LO leakage as well as other interferences are 20 dB below the desired RF outputs which avoids inter-modulation issues. To eliminate the interferences coming from noisy environment with various diagnostics system, there is a dichroic plate in the front to filter out out-of-band radiations and the following processes all include a band-pass filter in each stage.

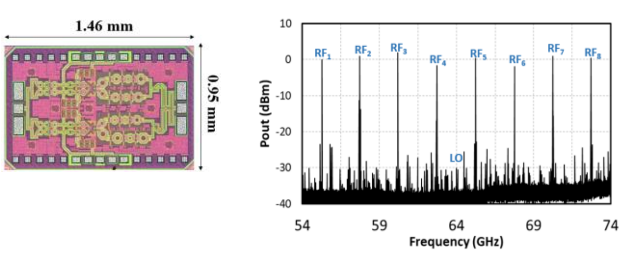

FIG. 2. Photo and measured output spectrum of V-band transmitter.

The transmitter chip is only 1.7 mm x 1.3 mm as shown above. Currently, costing less than $70 per chip to fabricate, the CMOS-based transmitter chip will replace as much as $40,000 worth of discrete waveguide components with higher spacing resolution capability. In the middle of 2018, the chip will be packaged and shielded in a single module and attached with existing horn antenna and LO input sources[4].

III. V-BAND CMOS-BASED RECEIVER

On the receiver side, the existing system includes 12 vertically-aligned elements with a mini lens attached to each element to receive RF and LO signals following which then the down-converting process occurs in the first stage. Here, there exists a critical problem preventing all of the elements from performing identical behavior such as conversion gain. The LO drive power for each antenna is slightly different because the quasi-optical coupling can result in alignment issues and non-uniform beam pattern causing a variation in conversion gain over the array which requires further attenuated calibration. In addition, the Schottky diode heterodyne receiver possesses high noise and large conversion loss in the front-end with resulting system noise temperature of $\sim$55,000 K.

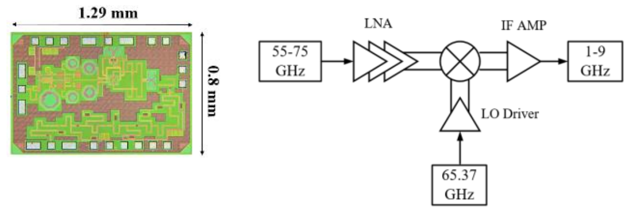

FIG. 3. V-band receiver chip photo and architecture.

FIG. 3 presents the architecture of the V-band receiver chip. A compact, low-noise, and easy-assembling in-house design receiver chip includes a three-stage broadband low-noise amplifier, a double-balanced mixer, and an IF amplifier offering more accurate sensing capability. The V-band receiver for the MIR system upgrade has been designed, fabricated, and tested. Aimed at improving the noise temperature and overall conversion gain through the entire 20 GHz bandwidth, the CMOS-based receiver is measured to offer about 30 dB conversion gain with noise figure lower than 10 dB (noise temperature below 2,600 K). In addition, the LO drive is fed directly from waveguide thus preventing misalignment. The compact 1 mm^2 receiver chip costs only $70 per chip to fabricate and will significantly bring down the system cost. Replacing the current receiver array with the upgrade module array is simple and makes the system easier to dissembling while debugging in the future.

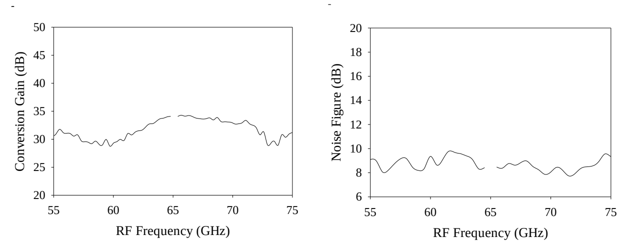

FIG. 4. Measured conversion gain and noise figure results. The receiver is able to down-covert 55-75 GHz signal with double sideband modulation.

IV. SINGLE MMIC MODULE FOR TRX ARRAY

After the V-band receiver chip has been designed, fabricated, and shown to satisfy the application requirements, there remains the need for integration and packaging which introduce many challenges and losses at mm-wave frequencies. SoC integration of the heterodyne architecture will deliver the advantages of higher isolation from electromagnetic interference. Although the system-on-chip (SoC) topology has already reduced the interface issues compared to the system-on-substrate method, the packaging solution is still a critical part of the implementation of the receiver module. The latest LCP receiver project, which has included a commercially-available GaAs receiver chip produced by Gotmic AB, has demonstrated the successful upgrade on the DIII-D ECEI system. By using the typical wire-bonding topology as a packaging solution, a unique pattern is required and needs to be carefully designed to compensate for the considerable inductance from the wire bond.

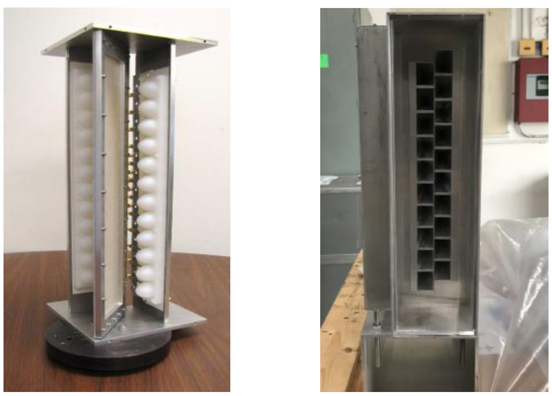

FIG. 5. Comparison between ECEI receiver system with mini-lens array and single MMIC with horn antenna modules. The SoC solution offers availability of shielding each channel individually.

For a single channel, a horn antenna with fundamental transition offers enormous attenuation for out-of-band interference. In addition, using active bias controllers to design the DC power board provides the capability of automatically turning on and off the device sequentially which is crucial to a long-term operation system. It is capable of ensuring that each of the channels will not have considerable difference between them under a process variation. The DC board will connect with the RF board through the headers to provide different bias voltages for the receiver chip. These receiver modules will then directly be installed to individual IF modules which are now using in the current MIR system through the SMA connectors.

Fig. 6 shows the comparison of current ECEI system and the one upgraded with SoC solution. The new version of enclose box on the right includes 20 receiver modules and the LO input chain. On the other hand, the existing system shown on the left consists of Schottky diodes mounted on printed antenna with mini lens. The SoC solution not only shrink the front-end system but also isolates every single module. Each channel is completely modularized and individually shielded. Besides, the LO chain has been designed to fit into the box therefore avoid any misalignment issues from original optical-coupled method.

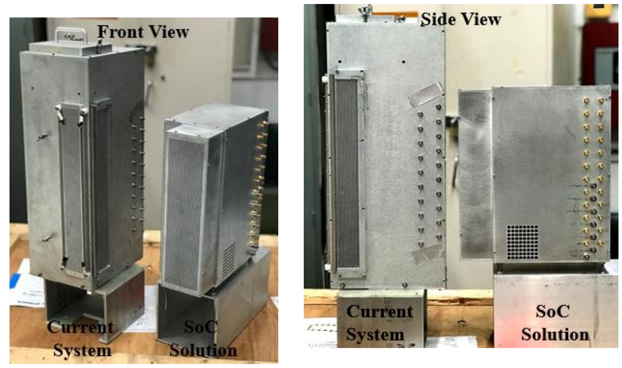

FIG. 6. The front and side view of ECEI receiver array.

V. SUMMARY

In summary, our system-on-chip approach allows the entire receiver to be packaged in a hermetically sealed structure that not only performs better, but is more compact, more reliable, and far simpler to service in the worst-case scenario of microchip failure. This broadband portfolio covering the entire 55-75 GHz high-frequency spectrum delivers significant data simultaneously in a stable and highly accurate method.

ACKNOWLEDGMENTS

This work was supported by the U.S. DOE under Grant Nos. DE-FG02-99ER54531. The assistance of CiC and NDL from Taiwan for measurements are appreciated.

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