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Spectrum Efficient D-band Communication Link for Real-time Multi-gigabit Wireless Transmission

Vessen Vassilev*, Zhongxia Simon He*, Sona Carpenter*, Herbert Zirath*, Yu Yan*, Ahmed Hassona*, Mingquan Bao†, Thomas Emanuelsson†, Jingjing Chen*, Mikael Hörberg†, Yinggang Li†, and Jonas Hansryd†
*Chalmers University of Technology, Gothenburg, Sweden
†Ericsson AB, Gothenburg, Sweden

***Abstract*—This manuscript presents results of wireless real-time data transmission at 143 GHz. The transmitter/receiver (Tx/Rx) front-end circuitry is integrated on a single monolithic microwave integrated circuits (MMICs), realized in a 250-nm indium phosphide (InP) double heterojunction bipolar transistor (DHBT) technology. The Tx module shows gain of 12 dB at 143 GHz with output power of -2.3 dBm at 1 dB gain compression. The Rx module has a gain of 15 dB with noise figure (NF) of 13 dB at 143 GHz. The minimum NF of 10 dB is measured at 132 GHz.**

The Tx/Rx front-end modules were integrated in two radio units to demonstrate a real time wireless data transmission. At a distance of 10 m and using 40 dBi gain antennas, the highest data rate achieved was 5.3 Gbit/s using 64 QAM modulation over a 1 GHz channel with spectrum efficiency of 5bit/s/Hz.

***Index Terms*—Millimeter-wave (mmW) integrated circuits, monolithic microwave integrated circuits (MMICs), Millimeter wave communication, quadrature amplitude modulation (QAM).**

I. Introduction

The need for higher data-rate drives the development of transceivers to increasingly higher frequencies. D-band (110-170 GHz) is an attractive alternative for backhauling next generation radio networks as an alternative to optical fiber. Real-time wireless communication-links beyond 100 GHz have been demonstrated at [1], [2] and [3] with bit rate and spectrum efficiency summarized in Fig. 1. The highest order of modulation among them is 16 QAM realised with a front end based on a combination of InP HEMT and Schottky diode technologies [2]. In this paper we present a real-time data transmission at 143 GHz using up to 64 QAM modulation and fully integrated transmitter/receiver (Tx/Rx) MMIC chipset packaged in modules.

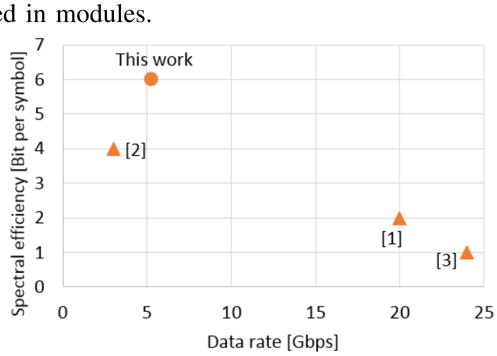

Fig. 1. Real-time transmission and detection experiments beyond 100 GHz.

The transceiver modules consist of a X3 frequency multiplier for the LO signal, a double balanced Gilbert cell IQ up-converter/down-converter, and a 3 stage power amplifier for the Tx and LNA for the Rx. The MMICs are designed using an InP double-heterojunction bipolar transistor (DHBT) technology with 250-nm emitter width from Teledyne Scientific Company. The layer structure of the process includes four metal layers on top of the wafer separated by thin (2 um) BCB films. The ground layer for the transmission lines is the first (bottom) layer and is therefore positioned on the upper surface of the wafer. As result, the ground of the MMIC is not connected to the waveguide block when the circuit is attached to a waveguide block. Packaging such a circuit therefore requires additional bond-wire to provide connection between the MMIC ground and the waveguide block. This ground bond wire represents additional inductance in series to the inductance of the wire connecting the MMIC and the waveguide transition. This increases the inductance of the interconnect and, given the high frequency, it has a major effect on the performance of the circuits after packaging.

The MMICs used in this work are modified versions of a chipset previously presented by the authors [4]-[6]. To facilitate packaging, the original chipset was upgraded with thru-substrate vias connecting an additional metal layer on the bottom of the MMIC to the top ground layer providing natural connection between the grounds when the MMIC is attached to the waveguide block. In addition, larger bond pads were used to improve the yield after bonding the circuits. These larger area pads have higher parasitics for on-wafer measurements, but are more rigid mechanically and provide sufficient area to place a pair of bond wires, reducing the inductance of the bond wire interface.

II. Module design

The mechanical design of the transceiver modules is based on the split-block technique, where the RF waveguide is split in the middle of the broad wall. The module has dimensions of 56/38/20 mm and is shown in Fig. 2. To attach the MMIC and provide interface to IF (0-18 GHz), LO (36-53 GHz) and RF (110-170 GHz) ports, we use a carrier board. The board consists of 1 mm copper plate covered with 50 um Rogers Ultralam 3908 bonding film and 50 um Rogers Ultralam 3850HT dielectric. Measured and published dielectric constant for the 3850 film is 3.25 with a loss factor of 0.007 at 98 GHz

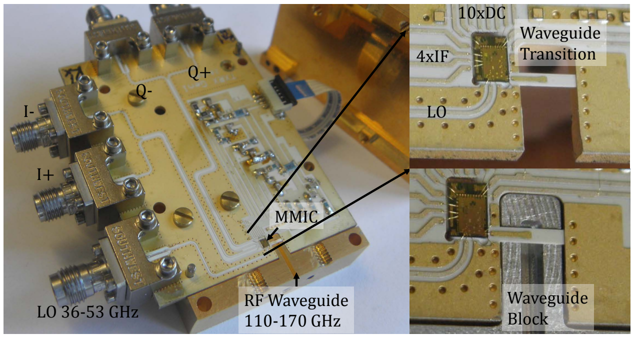

Fig. 2. Tx or Rx module with the carrier board and LO, IF and RF ports.

TABLE I
MEASURED LOSS/MM OF THE DIELECTRIC STACK
(50 μm OF ULTRALAM 3908 AND 50 μm OF ULTRALAM 3850HT).

Frequency, GHz	1	3	18	46	53	140
Loss, dB/mm	0.004	0.01	0.042	0.081	0.091	0.2

[7]. The measured loss/mm at few frequencies is presented in Table I. The lines connecting the IF ports to the MMIC have length of 66 mm while for the LO-path, the corresponding line length is of 30.7 mm. The loss between the connectors and the MMIC at IF is therefore 0.7 and 2.8 dB at 3 and 18 GHz respectively. The corresponding line loss for the LO line is 2.5 and 2.8 dB at 46 and 53 GHz.

The carrier board features an integrated waveguide to microstrip transition realized by removing a section of the metal plate, as shown in Fig. 2, so that the dielectric forms a bridge, which is then placed in a channel in the waveguide block.

Measurements of back to back waveguide transitions indicate a loss of 0.9 dB and 1.7 dB per transition for frequencies of 120 GHz and 140 GHz. This loss does not include effects related to the bond wire between the transition and the MMIC.

III. MODULES PERFORMANCE

Measured gain and noise of the Tx/Rx modules are summarized in Table V, Tx output power (Pout) and Rx input power (Pin) are also given at 1 dB gain compression point.

A. Transmitter Module

The gain of the Tx module was measured as function of the LO frequency for a fixed IF frequency of 3 GHz using a network analyzer together with a frequency extension module to reach the desired RF frequency. Calibrated IF power is applied to the input of the Tx. The measured upper sideband (USB) gain and RF return loss are shown in Fig. 3.

TABLE II
SUMMARY OF TX/RX PERFORMANCE AT 143 GHZ.

Tx Gain	Tx Pout	Tx Pn	Tx IF BW
12 dB	-2.3 dBm	-135 dBm/Hz	4 GHz
Rx Gain	Rx Pin	Rx NF	Rx IF BW
15 dB	-38 dBm	13 dB	4 GHz

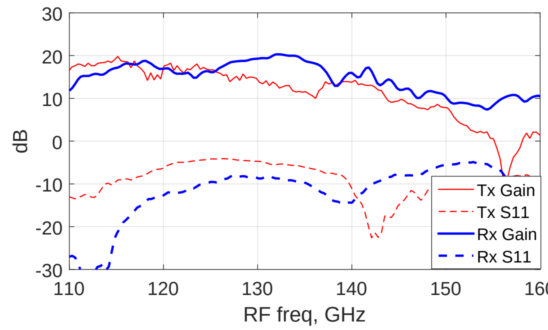

Fig. 3. Tx, Rx module USB gain vs. RF frequency for IF=3 GHz.

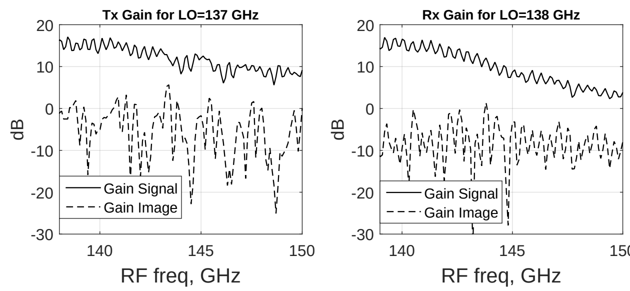

Fig. 4. Gain for the signal band and the image band (lower sideband) vs. RF for both Tx and Rx modules.

The minimum IF frequency of the modules is limited to 1 GHz by the IF hybrids, and the 3 dB IF bandwidth (highest frequency where the gain drops by 3 dB) is typically 3-5 GHz depending on the LO frequency. Measured sideband gains vs. RF frequency is shown in Fig. 4. Image band suppression varies with the IF frequency and is typically 10-15 dB within the 6 GHz IF bandwidth.

The 1 dB compression point for the Tx module occurs at Pin of -15 dBm with corresponding output power of -2.3 dBm. Measurements of the power spectrum at the transmitter output in presence of LO shows noise power (Pn) of the transmitter to be -135dBm/Hz.

B. Receiver Module

The gain of the Rx module was measured as a function of the LO frequency for a fixed IF frequency of 3 GHz in a similar manner as for the Tx. Calibrated RF power of -45 dBm provided by the extender module is applied to the input waveguide port of the receiver. After combining the 4 IF ports in hybrids, the second port of the analyzer is connected to one of the IF port of the hybrids and measures the power of the downconverted RF from the upper sideband. The ratio of the RF to the IF power represents the conversion gain of the Module. The input return loss is measured for the RF port of the receiver. The measured gain and RF return loss is shown in Fig. 3 for fixed IF at 3 GHz. Gain for the signal band and the image band vs. RF for the Rx module at LO 138 GHz is shown in Fig 4.

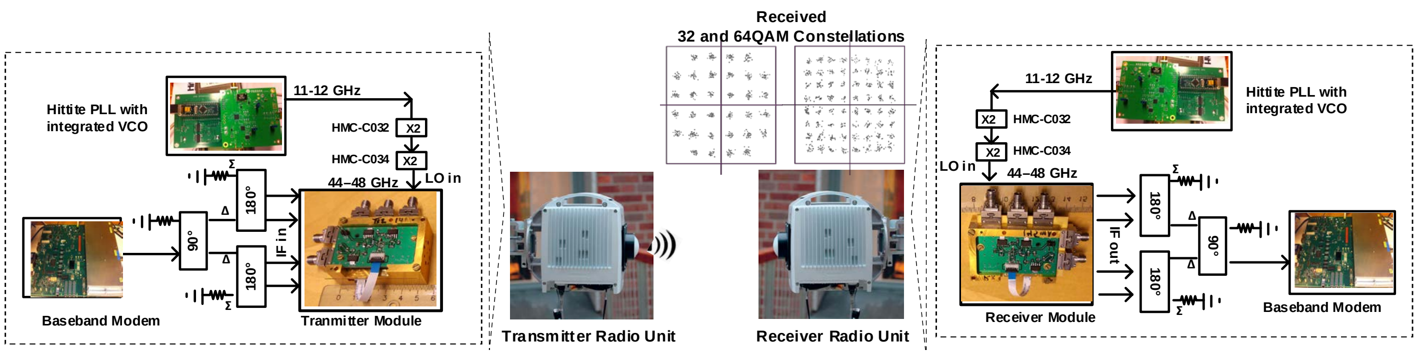

Fig. 5. Tx/Rx Radio units containing the front-end modules, LO generation circuitry, IF hybrids, Modem boards and IF boards. Screen shots of 32 and 64 QAM signal constellations are also shown.

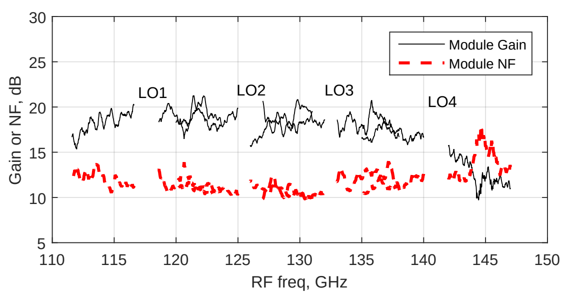

Fig. 6. Receiver NF and LSB/USB Gain for LO frequencies: 117.6, 126, 132 and 141 GHz where each sideband is given for IF=1 GHz to 6 GHz.

Noise of the Rx module was characterized through a traditional Y-factor measurement where hot (room temperature) and cold (78 K) absorbers are used as a termination at the RF port. The noise level at the USB/LSB IF ports are measured for several LO frequencies and the IF noise spectrum is recorded from 1 GHz to 6 GHz. The measured noise figure (NF) and gain are shown in Fig. 6.

Output power as a function of input power was measured for the receiver module at several LO frequencies. The RF input power corresponding to 1 dB gain compression varies between -38 and -45 dBm depending on the LO frequency.

IV. Wireless Link Demonstration

The Tx/Rx modules were integrated into radio-units together with 40 dBi antennas, a real-time modem with bandwidth limited to 1 GHz, and an IF board to convert baseband to IF and vice versa as shown in Fig. 5. The symbol rate of the modem was limited to 888 Mbaud. PLL synthesizer provides LO of 11.625 MHz for the Tx module, which is multiplied to 46.5 GHz and applied to the LO port of the Tx module where it is additionally multiplied by 3 in the Tx MMIC. The IF ports of the modules are combined in a pair of 180^0 hybrids to achieve single ended ports for the I and the Q channels. The I/Q channels are then connected to 90^0 hybrid to separate upper/lower sidebands (USB/LSB). With IF centered at 3.5 GHz and USB the transmitted RF is centered at 143 GHz. The LO for the Rx is synthesized at 11.75 GHz, it is

TABLE III
Link performance.

Modulation	Modem BW MHz	BER After correction	SNR dB	Data Rate Gbit/s
32 QAM	1000	0	23.7	4.44
64 QAM	1000	3.3e-8	24.1	5.33

multiplied to 47 GHz in a series of two commercial doublers and then applied to the Rx module. It is additionally multiplied to 141 GHz in the Rx module where the IF is centered at 2 GHz. In the experiment one transmitter and one receiver radio-units were separated by 10 m in a lab environment. Several modulation formats and symbol rates were tested. Summary of the achieved data rate and bit error rates (BER) is given in Table IV. After excluding the error correction bits, the actual data rate is 85% of the one quoted in Table IV.

The highest data rate achieved is 5.3 Gbit/s using 64 QAM, with BER of 3.3e-8 and SNR of 24 dB over a 1 GHz channel.

V. Conclusion

We present first results of a real-time transmission of data at 143 GHz at a distance of 10 m using a fully integrated chipset incorporated in split-block waveguide modules. The performance of the transceiver modules is summarized in Table V. Currently the highest order modulation achieved was 64 QAM over a 1 GHz channel resulting in data rate of 5.3 Gbit/s. Given the Tx/Rx module performance summarized in Table V we expect a possible hop-length of about 100m.

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TABLE IV
LINK PERFORMANCE MEASURED INDOOR AT A DISTANCE OF 10 M.

Modulation	Symbol Rate Mbaud/s	Modem BW MHz	BER After correction	SNR dB	Data Rate Gbit/s
32 QAM	444	500	0	28	2.22
32 QAM	888	1000	0	25.5	4.44
64 QAM	444	500	0	27.5	2.66
64 QAM	888	1000	0	25	5.33
128 QAM	444	500	0	28	3.1
256 QAM	222	250	1e-6	29.5	1.776

TABLE V
SUMMARY OF TX/RX MODULES AT 143 GHZ.

Tx Gain	Tx Pout	Tx Pn	Tx IF BW
12 dB	-2.3 dBm	-135 dBm/Hz	4 GHz
Rx Gain	Rx Pin	Rx NF	Rx IF BW
15 dB	-38 dBm	13 dB	4 GHz

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