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Abdelaziz Hamani, Francesco Foglia Manzillo, Alexandre Siligaris, Nicolas Cassiau, Frédéric Hameau, et al.. A 56.32 Gb/s 16-QAM D-band wireless link using TX-RX systems-in-package with integrated multi-LO frequency synthesis in CMOS 45nm. RFIC 2022 - IEEE Radio Frequency Integrated Circuits symposium, Jun 2022, Denver, United States. pp.75-78, <10.1109/RFIC54546.2022.9863127>. <cea-04684949>

**HAL Id: cea-04684949**

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Submitted on 3 Sep 2024

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# A 56.32 Gb/s 16-QAM D-band Wireless Link using RX-TX Systems-in-Package with Integrated Multi-LO Generators in 45nm RFSOI

**Abstract**—This paper presents an energy-efficient wideband D-band wireless link using receiver (RX) and transmitter (TX) modules based on a channel-bonding scheme. The modules include RX and TX integrated circuits (ICs) fabricated in 45nm CMOS RFSOI technology. They are mounted on low-cost multi-layer printed circuit boards (PCBs) and connected to patch antennas. The RX and TX ICs are composed of two down-conversion and up-conversion chains, respectively, operating over contiguous sub-bands around 147.96 GHz. The required multiple millimeter-wave local oscillator signals (LOs) are generated on-chip. The presented wireless system achieves a data rate of 56.32 Gb/s by using 16 QAM modulation over 8 radiofrequency (RF) channels, with a competitive energy consumption (RX+TX) of 18 pJ/bit, including the LOs generation circuitry.

**Keywords**—D-band, wireless link, receiver, transceiver, IC chip, module, PCB, high data rate, 16-QAM, low noise amplifier, LO generation, mixer, CMOS 45nm.

## I. INTRODUCTION

High-capacity short-range wireless links providing data rates up to 100 Gb/s require to use a bandwidth in the range of a few tens of GHz with moderately complex modulations schemes. Such a wide bandwidth is only available beyond 100 GHz. For this reason, the D-band frequency range, spanning from 110 to 170 GHz, has been recently proposed for several applications including short-range high-speed communications [1]-[6]. Furthermore, a high signal-to-noise ratio (SNR) is needed at the receiver (RX) when spectrally efficient high-order modulations are used. Most of the previously reported high-performance D-band front-ends have been realized using III-V processes [1]-[3]. These technologies allow the realization of lower noise RXs and higher output power transmitters (TXs), compared to CMOS technologies [4]-[6]. Nevertheless, they are not optimal for high-volume and/or low-power applications. Regarding the radiating elements, on-chip antennas [7], [8], achieving very low efficiency, or bulky external antennas, e.g. standard horns, [9], [10] have been proposed in the literature. These options tend to increase the cost and loss of the wireless module. Then, novel efficient architectures suitable for high-yield, low-cost semiconductor process and packaging technologies are essential for the development of future D-band front-ends.

This paper presents a wireless link at D-band based on RX and TX systems-in-package, using 45nm RFSOI for the RX/TX ICs and low-cost laminate technology for the antennas. As opposed to previous works with similar total bandwidth [4]-[5], the proposed system relies on a multi-channel architecture to achieve simultaneously wideband operation with low-noise RX,

high output power TX and very small area. In addition, compared to most of the previous works, the required millimeter-wave (mmW) local-oscillator (LO) signals are generated on-chip. The realized RX and TX ICs are co-integrated with patch antennas on low-cost multilayer printed circuit boards (PCBs). The in-package antennas implement over-the-air power combining in the TX and over-the air demultiplexing in the RX, in order to avoid lossy combiners and splitters. The proposed wireless link demonstrates a data-rate of 56.32 Gb/s with multi-channel single-carrier 16-QAM signal, over a range of a few centimeters. Please, note that the link range can be easily extended by using the proposed modules as primary sources of three-dimensional (3-D) electromagnetic (EM) lenses, as in [8], or planar transmitarray lenses.

## II. RX AND TX MODULES ARCHITECTURE

Both the RX and TX systems-in-package comprise a two-channel CMOS integrated circuit (IC) in 45-nm RFSOI technology. Each of the two IC outputs is connected to a 2×1 patch antenna array, as shown in Fig. 1.

### A. Multi-channel architecture

The RX module receives a signal spanning from 139.32 GHz to 156.6 GHz from the TX module that implements channel bonding in two steps. First, at intermediate frequency (IF), 4 base-band (BB) adjacent channels, each with a 2.16 GHz bandwidth (BW), are grouped. The IF band ranges from 57.24 GHz to 65.88 GHz. A second channel bonding is realized at RF by combining two sets of 4 IF channels into two adjacent sub-bands in the D-band, namely, the lower band (LB) and the upper band (UB). Thus, 8 RF channels are transmitted. For measurement purposes, the two IF signals are taken from a common input pad in the TX IC, using a passive splitter. The two D-band output signals (LB and UB) are obtained by using two mixers and on-chip generated LOs of 82.08 GHz and 90.72 GHz, respectively. They are next amplified separately by two power amplifiers (PAs), and sent to a two-port patch antenna

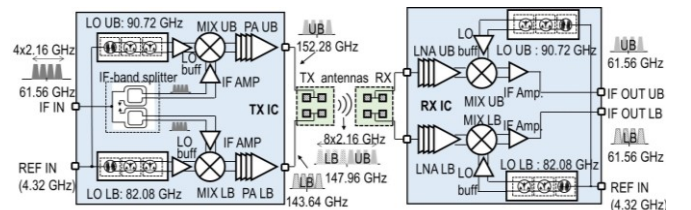


Fig. 1. Block diagram of the TX and RX IC modules.

array. The two sub-bands are combined over-the-air resulting in a signal ranging from 139.32 GHz to 156.6 GHz. At the RX side, the signal is received by an identical two-port antenna connected to the two RF inputs of the RX IC. The inputs of the two low noise amplifiers (LNAs) are matched at the center frequency of the LB and UB, respectively. A down-conversion mixer and an amplifier are implemented in each RX sub-band chain, as shown in Fig. 1. Each RX chain comprises an on-chip LO generator tuned on the same frequency of the corresponding TX LO. The TX and RX LO generators use an integer frequency multiplication technique [6] and only require a common lower frequency reference signal (REF IN) of 0 dBm, with a 4.32 GHz BW. The RX module provides two outputs centered at the same IFs used in the TX, corresponding to the down-converted LB and UB of the received D-band signal, respectively.

### B. RX and TX IC circuitry

Figure 2 shows the LNA, mixers, IF section circuitry and the simulated gain and noise figure (NF) of the LB and UB chains of the RX IC. Both RX chains are similar, only some passive circuits are sized differently. The LNA consists of four stages with capacitively neutralized pseudo-differential common source cells. The differential mode and the matching among the LNA stages are achieved with transformers. The mixer is a balanced Gilbert cell followed by a single-stage differential amplifier (IFA) centered at the IF band.

Each channel in the TX IC consists of a two-stage differential amplifier at IF, a Gilbert mixer and a four-stage power amplifier. This circuit is similar to that reported in [6].

Figure 3 shows the photograph of the fabricated ICs. The power consumptions of the RX and TX ICs are 420 mW and 600 mW, respectively.

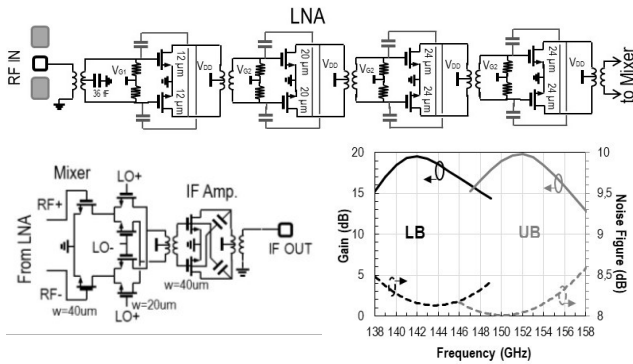


Fig. 2. RX IC schematics (one chain) and RX IC simulated performance.

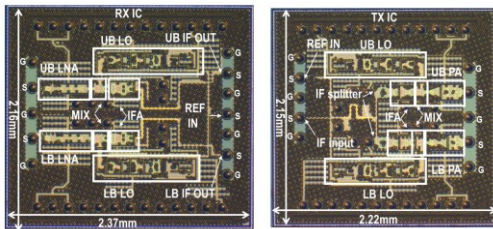


Fig. 3. 45nm CMOS RFSOI RX and TX [6] IC microphotographs.

### C. Systems-in-package and antenna integration

The RX and TX system-in-package are shown in Fig. 4. The stack-up comprises two Astra MT77 layers (thicknesses of 127  $\mu\text{m}$  and 256  $\mu\text{m}$ ), with double-side Cu-metallization (18  $\mu\text{m}$ -thick), and a 128 $\mu\text{m}$ -thick bonding layer. The ICs have C4  $\mu\text{bumps}$  and are flip-chipped on the top side of the modules. Each of the RX and TX antenna comprises two individually fed arrays based on two aperture-coupled patches, fabricated on the backside of the module. Both arrays are parallel-fed and enclosed in the same via-fence cavity. Figure 5 shows the simulated antenna gain and radiation patterns in both E- and H-planes, when a single port (i.e. LB or UB) is excited. The patch arrays are offset, along the H-plane, with respect to the symmetry axis of the overall two-port antenna. Thus, the gain in the broadside direction (7.7 dBi at 147.96 GHz), i.e. along the link direction, is about 1 dB less than the peak value.

## III. EXPERIMENTAL RESULTS

The RX and TX modules are characterized individually over-the-air using continuous wave (CW) signals, commercial RX/TX D-band equipment and horn antennas. Figure 6 reports measured RX and TX gain versus frequency, the RX NF performance (on the left) and the gain and equivalent isotropic radiated power (EIRP) of the TX module as a function of input power (on the right). The RX with the antenna achieves peak gain values of about 15 dB and 14 dB for the LB and UB chains, respectively. The RX module NF has been extracted from the EVM of modulated test signals and varies from 10 dB to 14 dB in the signal band. The TX peak gain including the antenna is 29 dB and 26 dB for the LB and UB, respectively. The TX EIRP saturates at 16 dBm and 10 dBm at the center of the LB and UB, respectively, and has an input 1dB compression point (ICP1dB) of -16 dBm. The on-chip LO signals phase noise (PN) is

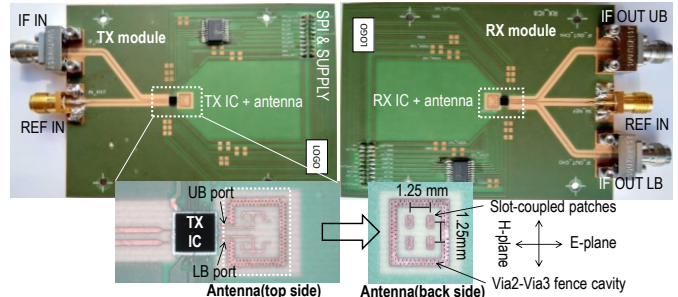


Fig. 4 Realized RX (left) and TX (right) modules.

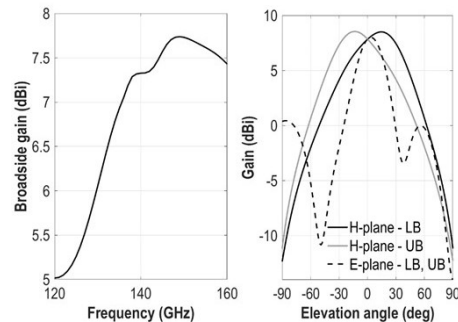


Fig. 5. Antenna simulated performance.

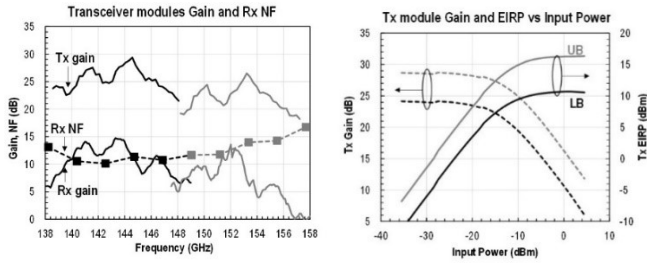


Fig. 6. RX and TX module measured performance.

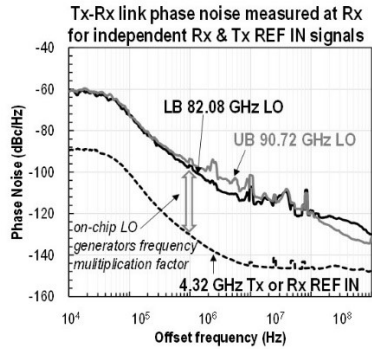


Fig. 7. On-chip LO generation performances.

characterized at the RX. To measure it, a single tone at 61.56 GHz is injected at the TX module IF input, resulting in two tones radiated at the center frequencies of the LB and UB. For this signal, each of the RX outputs provides a single tone at the center of the IF band that includes the impact of the cumulated on-chip RX and TX LO PN, since the two modules are fed by independent (i.e. uncorrelated) REF IN signals from commercial PLLs. Figure 7 compares the RX PN with the phase noise of one of the REF IN PLLs. The PN for the two LO frequencies is close to -100 dBc/Hz at 1 MHz offset and corresponds to the REF IN PN up-scaled by the integer frequency multiplication factor ( $\times 19$  for the LB LO and  $\times 21$  for the UB LO) plus 3 dB due to the cumulated, uncorrelated TX and RX PN. The REF IN signals are generated using a couple of commercial PLL demo boards, as shown in Fig. 8.

Figure 8 presents a scheme and pictures of the setup used to characterize the full wireless link. The multi-channel IF input signal for the TX is generated using an arbitrary waveform generator (AWG) and an external up-conversion mixer. The signal power is adjusted to be -25 dBm at the TX input, i.e. 9 dB below the ICP1dB. The down-converted modulated output signals from the RX are acquired using a 200 GS/s sampling scope. A commercial LNA with 20 dB of gain and 5 dB of NF is used to boost the signal between the RX module output and the scope and compensate connectors and cable losses. A full multi-channel digital-baseband (DBB) TX and RX is implemented in Matlab. It controls the AWG to provide the input waveform and the sampling scope to recover the received waveforms. The modulated multi-channel TX IF waveform is shown in Fig. 8. It includes preambles for frame synchronization, I/Q mismatch, and carrier frequency offset (CFO) estimation and correction at the DBB RX. In the payload section, scattered BPSK modulated pilots are inserted for phase tracking and correction. The DBB RX provides demodulated

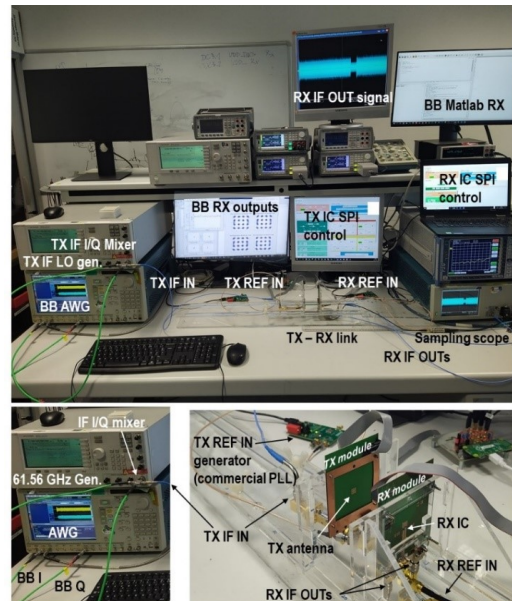
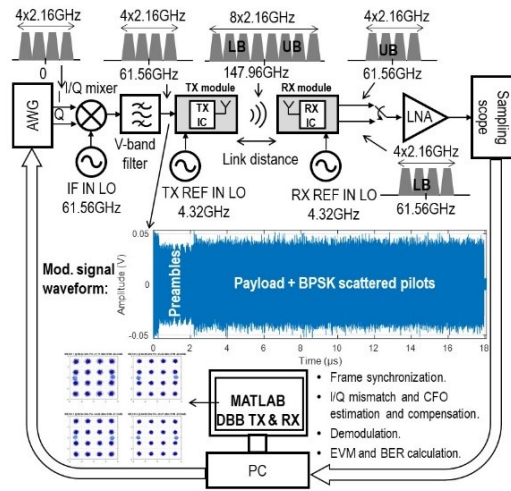


Fig. 8. RX-TX link characterization setup and DBB details.

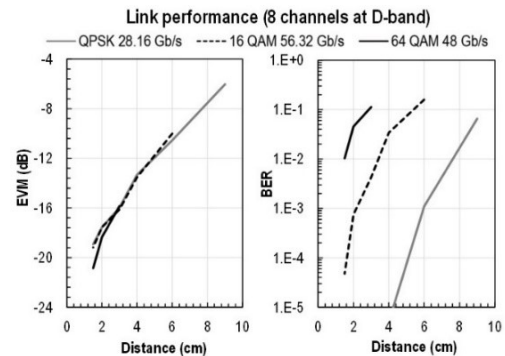
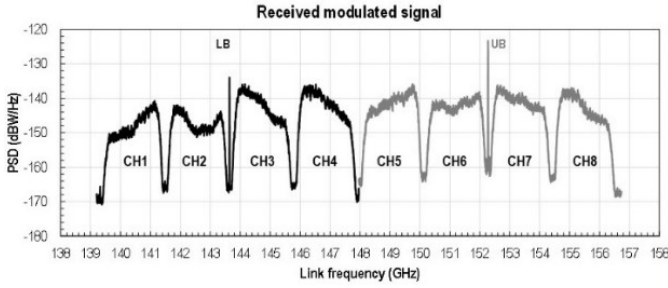


Fig. 9. EVM and BER performances.

BER metrics as well as EVM and constellations for each channel in the received signal. Figure 9 shows EVM and BER for an 8-channel signal using QPSK and 16 QAM with 1.76 Gbaud per channel, and 64 QAM with 1 Gbaud, as a function of link distance. An overall data rate of 56.32 Gb/s can be achieved for uncoded BER of  $10^{-2}$  at 3 cm using 16 QAM



CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
141.975GHz	144.135GHz	146.295GHz	148.455GHz	150.705GHz	152.865GHz	155.025GHz	157.185GHz
EVM=12.4%	EVM=10.7%	EVM=10.6%	EVM=10.9%	EVM=12.5%	EVM=12.3%	EVM=13.3%	EVM=12.4%
7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s
EVM=9.6%	EVM=8.9%	EVM=8.5%	EVM=8.6%	EVM=9.5%	EVM=9.0%	EVM=9.7%	EVM=9.0%
6Gb/s	6Gb/s	6Gb/s	6Gb/s	6Gb/s	6Gb/s	6Gb/s	6Gb/s

Fig. 10. Transmitted spectrum including 8 bonded channels and demodulated constellations.

modulation with  $EVM \leq 10\%$  ( $-16\text{dBm}$ ), and 48 Gb/s at 1.5 cm for 64 QAM modulation ( $EVM \leq 20\%$ ). Figure 10 shows the received spectrum at the two outputs of the RX module and the constellations for 16 and 64 QAM multi-channel modulation at 1.5 cm link distance. Table 1 presents a summary of the performance of the proposed RX/TX wireless system and compare it with other similar works.

#### IV. CONCLUSION

In this work, a D-band RX-TX link is demonstrated with a maximum data rate of 56.32 Gb/s for multi-channel 16 QAM modulation at 3 cm. The in-package antennas can be easily combined with EM lenses to enhance the antenna gain (e.g. 25 dBi at TX and RX) and increase the link range up a few meter. The link operates in the 139.32-156.6-GHz band and consumes

420 mW for the RX and 600 mW for the TX, from a 1 V supply. To the best of the authors' knowledge, this is the first demonstration of a D-band RX-TX wireless link with on-chip mmW low-PN, multi-LO generation. The system enables up to 64-QAM transmission over the air using multiple simultaneous channels. Moreover, low-cost fully-packaged RX and TX modules including antennas are demonstrated. The full transceiver exhibits a high energy efficiency of 18 pJ/b, including RX and TX LO generation, compared to previous works.

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Table 1. Performance comparison of D-band RX-TX links.

	This work	[1]	[2]	[3]	[4]	[5]
Module Technology	PCB with on-board antenna	No module	Silica carrier with WR6.5 interface	Glass carrier with WR6.5 interface	No module	PCB with on-board antenna
IC Technology	45nm RFSOI	250nm InP	70nm GaAs	130nm SiGe-BiCMOS	22nm FDSOI	45nm RFSOI
Frequency (GHz)	140-158	110-170	142/157	135-170	125-145	144
Tx Psat (dBm)	11-16**	9	8	13	2.8	7*
Tx/Rx Gain (dB)	25/15**	24/26	12/12	18/65	27/18	18/18
RX NF (dB)	10-14**	9.5	6	8-11	8.5*	5.5*
Tx+Rx P <sub>DC</sub> (mW)	600+420	165+92***	150+60***	2100+1300***	198+196***	3816***
Energy eff.	18 pJ/b	5.35 pJ/b***	21 pJ/b***	94.5 pJ/b***	-	1192 pJ/b***
N. CHs x BW (GHz)	8 x 2.16	1x22 for QPSK 1x3 for 64 QAM	1 x 2	1 x 6	-	16 x 2.36
Modulation DR (Gb/s)@ EVM	16 QAM 56.32@20% 64 QAM 48@10%	QPSK 48@32% 64 QAM 18@6.8%	128 QAM 10@6.8%	64 QAM 36@7%	-	QPSK 3.2@32%
Link Type	Tx/Rx with 7.7 dBi antennas @ 3cm	Probes + 40dBi antennas @1.8m	Waveguides + attenuator	Waveguides + attenuator	-	21 dBi beamformers @1m

\*Simulated value. \*\*Includes IC to antenna module insertion loss and antenna gain. \*\*\*Does not include LO generation