A 60 GHz 64-element Phased-Array Beam-Pointing Communication System for 5G 100 Meter Links up to 2 Gbps

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Abstract**—This paper presents a 60 GHz communication link system and measurements using a 64-element phased array transmitter. The transmit array includes high-efficiency on-wafer antennas, 3-bits amplitude and 5-bits phase control on each element, a measured saturated EIRP of 38 dBm at 60 GHz and scans to +/- 55^o in the E- and H-planes with near-ideal patterns and low sidelobes. The phased-array transmitter is used in a 60 GHz communication link with an external up-conversion mixers and a Keysight 802.11ad waveform generator. A standard gain horn with a gain of 20 dB is used as the receiver, coupled to a Keysight high-speed digital demodulation scope. The communication link achieves a 16-QAM modulation with 3.85 Gbps at 4 m (full 802.11ad channel) and a QPSK modulation with 1.54 GBps over 100 m while scanning to +/-45° in both planes.**

I. INTRODUCTION

The unlicensed 60 GHz spectrum has generated a lot of interest from a variety of companies and research laboratories for Gbps communications [1], [2]. Also, the adoption of the Wireless Gigabit Alliance (WiGig) IEEE 802.11ad standard [3] had a large effect on the industry's interest in this frequency band. Furthermore, a beam-forming protocol is defined in this standard which permits the use of phased-array transmitters and receivers to improve the channel efficiency and system performance. The realization of highly-complex phased array transmitters and receivers in CMOS as well as SiGe BiCMOS technologies has also increased the interest in this area and made it possible to build communication systems operation at relatively short distances (0.5-5 meters).

Wafer-scale arrays are an efficient technique for building large-scale millimeter-wave arrays with phase and amplitude control capabilities. These have been demonstrated at 94 GHz and 112 GHz using 9-16 element arrays [4], [5], and at 60 GHz using 64-element (22x22 mm^2) [6] and 256-element arrays (41.2x42 mm^2) [7]. Integrated phased arrays with larger number of elements provide better directive scanning control for high-data rate communication links. In this work, we demonstrate the first 60 GHz communication link at 100 meters with up to 2 GBps data-rate while the phased-array is scanning +/-45° in all planes.

II. WAFER-SCALE PHASED-ARRAY CHIP

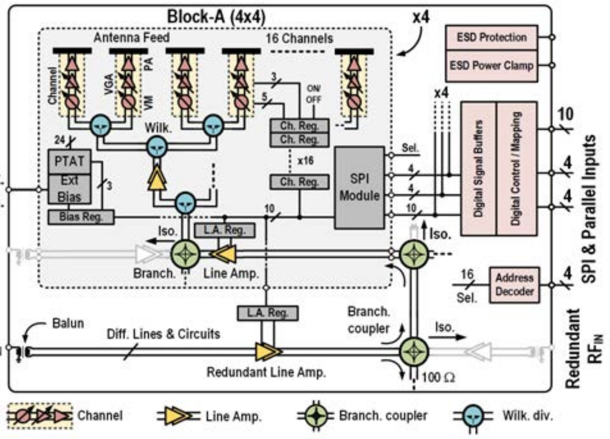


Fig. 1. Block diagram of the 64-element transmit phased array chip with high efficiency on-wafer antennas.

Fig. 1 presents the block diagram of the 64-element wafer-scale phased-array transmitter array built in the Jazz SBC18H3 process technology with f$_T$=240 GHz. The array consists of 4 sub-arrays each with 16 elements and driven by differential line amplifiers, transmission-lines, splitters and transformers. Each phased-array element consists of a VGA (3-bits and 10 dB gain control), phase shifter (5-bits) and two-stage differential amplifier with a P$_{sat}$ of 3-4 dBm at 60 GHz. The measured gain of the single-channel phased-element is 22 dB with an RMS gain and phase error of 1.5 dB and 7^o at 60 GHz and the details of the circuits are presented in [6], [7]. A 100 μm thick quartz wafer is attached to the top of the silicon chip and has a simulated efficiency of 45% at 60 GHz. The measured saturated EIRP in the far-field range is 38 dBm with an half-power beamwidth of 12.5^o (array directivity of 23 dB, array gain of 19.5-20 dB) and the array scans to +/-55^o in both E and H-planes with near ideal patterns and low sidelobe levels.

The wafer-scale phased array transmitter is placed on a Rogers RO4350B board (t=6.6 mils, ϵ_r=3.48) and bonded to

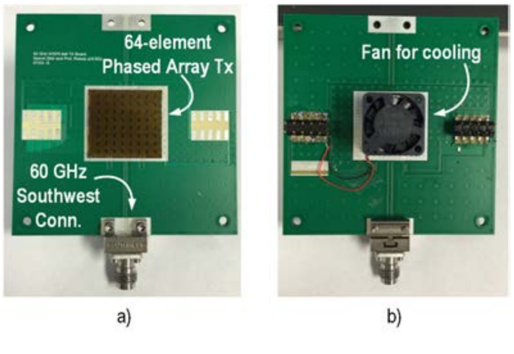


Fig. 2. The 64-element Tx phased array board; a) front and b) back view.

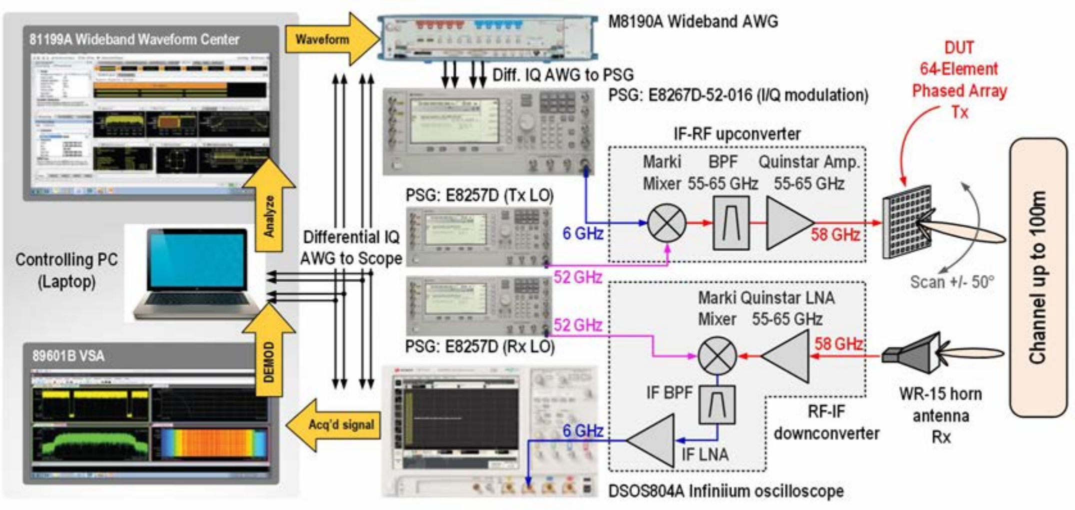


Fig. 3. Measurement setup for the 60 GHz communication link.

RF, SPI, VDD and Ground pads as shown in Fig. 2. The Rogers board is fabricated on top of a 32 mil FR-4 board for mechanical backing and strength. Thermal vias through the RO4350B and the FR-4 board conduct the heat from the silicon chip to the backside. The RF input signal at 60 GHz is fed to the phased array using a 1.85mm Southwest Microwave connector. The 64-element phased array is biased at 2.5 V and consumes 3.4 A, for a total power consumption of 8.5 W. Due to the relatively high power consumption, an aluminium heat sink and a miniature air-fan are attached on the PCB backside to stabilize the working temperature at $\sim 55°$.

III. SYSTEM DESIGN AND MEASUREMENTS

To demonstrate the performance of the 64-element transmit phased array, a 60 GHz link with 4 m and ∼100 m link are built using the setup shown in Fig. 3. First, differential I/Q baseband signals with up to 3.85 Gbps modulation and following the 802.11ad standard are generated using the Keysight M8190A Arbitrary Waveform Generator (AWG). The baseband signals are fed to a Keysight E8267D Vector Signal Generator and up-converted to a center frequency of 6 GHz. The modulated 6 GHz IF signal is in turn up-converted to 58-62 GHz using a wideband Marki Microwave Mixer (7-65 GHz) and another Keysight signal genetor (E8257D) is used as an local oscillator (LO) at 52-56 GHz. For an LO of 52 GHz, the up-converted image is centered at 46 GHz and is rejected using a 55-65 GHz band-pass filter (BPF) before the 60 GHz amplifier. A 55-65 GHz Quinstar amplifier is then used to amplify the modulated RF signal. The amplified signal is then fed to the input of the 64-element Tx array. The RF power at the input of the phased array (1.85mm connector) is 0 dBm to result in an EIRP of 32-33 dBm at 58-62 GHz.

In the receiver chain, the received signal is captured using a WR-15 waveguide horn antenna with a 20 dB gain at 60 GHz, and then amplified using a 55-65 GHz Quinstar Low Noise Amplifier (LNA) with a gain of 33 dB and a NF of 3.5-4.5 dB. Next, the amplified RF signal is down-converted using a Marki Microwave Mixer to 6 GHz using another 52 GHz LO signal generated from a Keysight E8257D Signal Generator. The down-converted signal is passed by a bandpass filter with a center frequency of 6 GHz and a 3-dB bandwidth of 2 GHz, and is then amplified with an IF amplifier before being fed to a Keysight DSO804A 10-bit Real-time Oscilloscope with 8 GHz bandwidth.

For the link measurements, an EIRP of 32 dBm is radiated from the 64-element array due to 3-4 dB back-off operation for better EVM and low ACPR. The calculated SNR values for the 4-m and 100-m links are 47 and 20 dB, respectively. Note that the receive horn antenna has a relatively low gain of 20 dB (instead of the usual 23-25 dB) so as to have a

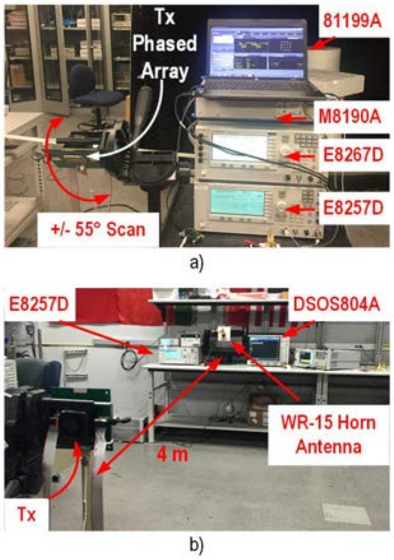
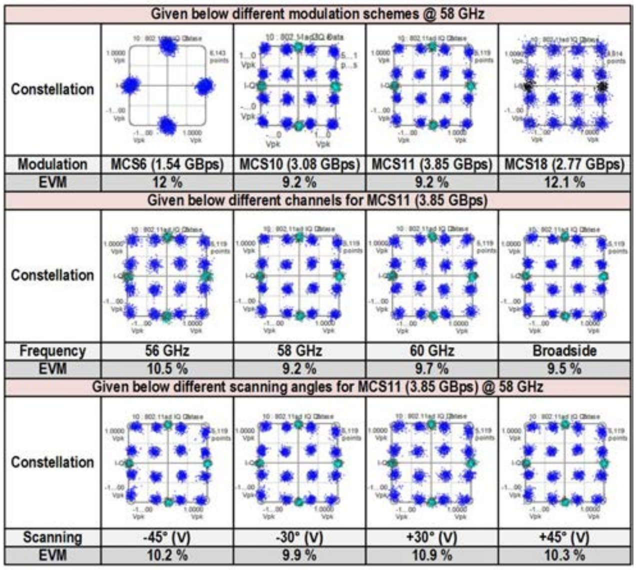
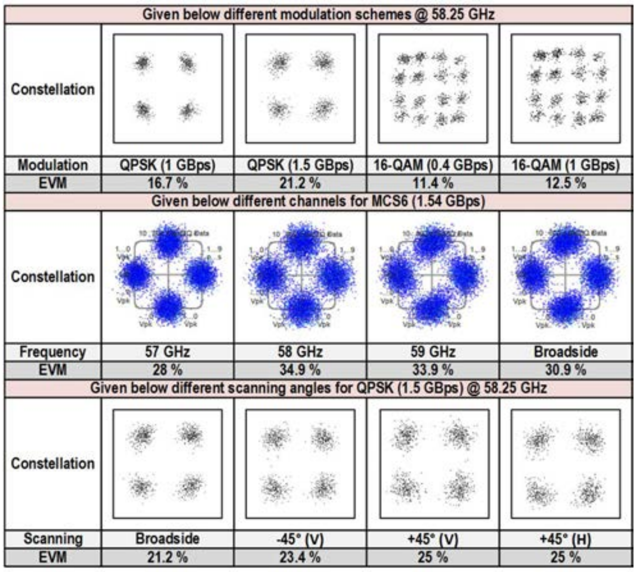


Fig. 4. Measurement setup at 4 m: a) Tx bench and b) Rx bench.



Given below different modulation schemes @ 58 GHz				
Constellation				
Modulation	MCS6 (1.54 GBps)	MCS10 (3.08 GBps)	MCS11 (3.85 GBps)	MCS18 (2.77 GBps)
EVM	12 %	9.2 %	9.2 %	12.1 %
Given below different channels for MCS11 (3.85 GBps)				
Constellation				
Frequency	56 GHz	58 GHz	60 GHz	Broadside
EVM	10.5 %	9.2 %	9.7 %	9.5 %
Given below different scanning angles for MCS11 (3.85 GBps) @ 58 GHz				
Constellation				
Scanning	-45° (V)	-30° (V)	+30° (V)	+45° (V)
EVM	10.2 %	9.9 %	10.9 %	10.3 %

Fig. 5. Measured constellations for different modulation schemes, frequencies and scanning angles for a 4 m link distance.



Given below different modulation schemes @ 58.25 GHz				
Constellation				
Modulation	QPSK (1 GBps)	QPSK (1.5 GBps)	16-QAM (0.4 GBps)	16-QAM (1 GBps)
EVM	16.7 %	21.2 %	11.4 %	12.5 %
Given below different channels for MCS6 (1.54 GBps)				
Constellation				
Frequency	57 GHz	58 GHz	59 GHz	Broadside
EVM	28 %	34.9 %	33.9 %	30.9 %
Given below different scanning angles for QPSK (1.5 GBps) @ 58.25 GHz				
Constellation				
Scanning	Broadside	-45° (V)	+45° (V)	+45° (H)
EVM	21.2 %	23.4 %	25 %	25 %

Fig. 7. Measurement constellations for different modulation schemes, frequencies and scanning angles at 100-m distance.

symmetrical link between the transmitter and receiver.

The measurement setup for the 60 GHz 4 m communication link is shown in Fig. 4. On the Tx bench, the 64-element phased array is placed on a tripod to measure the scanning performance of the array with a communication waveform. The Rx bench is placed 4-m away and a stationary horn antenna is used. The measured constellations at different modulation schemes (IEEE 802.11ad), center frequencies and scanning angles are shown in Fig. 5. The measured transmit EVMs for MCS6 (QPSK data with a 1.54 Gbps effective PHY data-rate), MCS10, MCS11 and MCS18 (16-QAM data with a 3.08, 3.85, 2.77 Gbps, respectively) are between 9 and 12% at 58 GHz center frequency. The transmit EVM performance of the 64-element array is between 9 and 10% at 56, 58 and 60 GHz with +/-45^o scanning angles in all planes. This shows that the 64-element phased-array transmitter can maintain a complex communication link at all scan angles and with virtually no added distortion.

The measurement setup for the 100 m communication link is shown in Fig. 6. The Tx bench is placed on the 6th floor and the Rx bench is set at the far-side of the parking lot. Despite cars and trees around the setup, the communication links works well and the measured constellations are shown in Fig. 7. The measured transmit EVMs for 1 GBps and 1.5 GBps QPSK are 16.7% and 21.2%, respectively. For 1 Gbps and 16QAM, the measured EVM is 12.5%. The IEEE 802.11ad link performance on MCS6 (QPSK data with a 1.54 Gbps) at 57, 58, and 59 GHz center frequencies are provided in Fig. 7. Finally, the performance of the 64-element phased array is also measured for 1.5 GBps QPSK with +/-45^o scanning in both E- and H-planes with an EVM of 20-25% at 58 GHz.

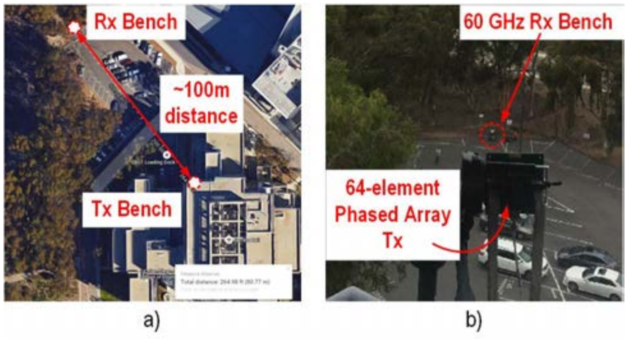


Fig. 6. 100-m measurement setup; a) Google map and b) photo.

REFERENCES

[1] A. Tomkins et al., ”A 60 GHz, 802.11ad/WiGig-Compliant Transceiver for Infrastructure and Mobile Applications in 130 nm SiGe BiCMOS,” *Solid-State Circuits,IEEE Journal of*, vol.50, no.10, pp.2239-2255, Oct 2015.

[2] M. Boers et al., ”A 16TX/16RX 60GHz 802.11ad Chipset with Single Coaxial Interface and Polarization Diversity,” *IEEE Solid-State Circuits Conference Digest of Technical Papers (ISSCC)*, Feb. 2014

[3] Part 11: *Wireless LAN MEdium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band*, IEEE Std. 802.11ad-2012, 2012.

[4] Y. Atesal et al.,”Millimeter-Wave Wafer-Scale Silicon BiCMOS Power Amplifiers Using Free-Space Power Combining,” *IEEE Transactions on Microwave Theory and Techniques*, vol.59, no.4, pp.645-655, Apr 2011.

[5] W. Shin et al., ”A 108-116 GHz 4x4 Wafer-Scale Phased Array Transmitter with High-Efficiency On-Chip Antennas,” *IEEE Journal Solid-State Circuits*, vol. 48, no. 9, pp. 2041-2055, September 2013.

[6] S. Zihir, O.D. Gurbuz, A. Karroy, S. Raman, G.M. Rebeiz, ”A 60 GHz 64-element wafer-scale phased-array with full-reticle design,” in *Microwave Symposium (IMS), 2015 IEEE MTT-S International*, May 2015, pp.1-3.

[7] S. Zihir et al., ”A 60 GHz single-chip 256-element wafer-scale phased array with EIRP of 45 dBm using sub-reticle stitching,” in *Radio Frequency Integrated Circuits Symposium (RFIC), 2015 IEEE*, May 2015, pp.23-26.