A 37-42 GHz 8x8 Phased-Array for 5G Communication Systems with 48-50 dBm EIRP

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***Abstract*— This paper presents a 5G 39 GHz 8x8 phased array. The array is based on 2x2 TRX beamformer chips in SiGe technology with 6 bits of phase control and 8 bits of gain control. Sixteen of the beamformer chips are flipped on a low-cost printed circuit board (PCB) with a 1:16 wilkinson network. The antenna is designed with a stacked-patch structure and has an impedance bandwidth of 7 GHz (35.5-42.5 GHz). The 8x8 phased-array has a measured EIRP of 48-50 dBm at P1dB and Psat with a 3-dB bandwidth of 36.5-42 GHz. The phased-array can scan to +/-50° in the azimuth plane and +/-45° in the elevation plane with very low sidelobes, and achieves $<$ -30 dB cross polarization levels at all scan angles. An error vector magnitude (EVM) measurement was done with the 8x8 array using a 16-QAM 100 MHz waveform with α=0.35 (PAPR=6.6 dB) and a very low EVM is achieved (1.2-4.75%) over a wide range of EIRP, and up to 46 dBm of average power.**

***Keywords*— 5G communication, stack-patch antenna, PCB, flip-chip, EVM.**

I. Introduction

Millimeter-wave phased-arrays for the fifth-generation (5G) communication standard provides an optimal solution for high data-rate communication systems. The beam steering capabilities of phased-arrays greatly compensate for the increasing path loss found at mm-waves and allow for long distance gigabit-per-second communication systems. In the past two years, several phased-array-based 5G systems have been demonstrated at 28 GHz [1]-[5], and 12 Gbps at 300 meters was shown to be possible using a 64-element phased-array [1]. However, to-date, there has been no demonstration of a 39 GHz phased array with high EIRP, acceptable efficiency and good patterns.

In this paper, a millimeter-wave 5G 39 GHz 8x8 phased array is presented. The phased-array is based on sixteen 2x2 SiGe TRX beamformer chips. The SiGe chip has a high degree of integration and is low-cost in commercial volumes, making 5G 39 GHz phased-arrays affordable.

The 8x8 phased-array employs the architecture shown in the Fig. 1a. The beamformer chips are flipped on one side of a low-cost multilayer printed-circuit board (PCB) and 64 antenna elements are placed on the other side of the board. The antennas are fed by beamformer chips using a coaxial probe feed located very close to the chip output ports, and this ensures minimum transmission-line loss between the chip and the antenna. A transceiver chip is used at the sum port, and an optional bandpass filter (printed on the PCB) can be used to greatly reduce any LO or image leakage.

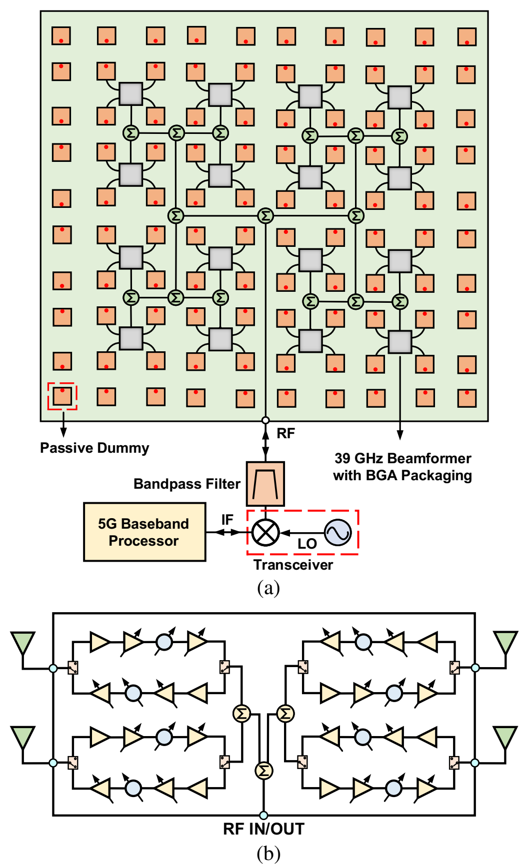


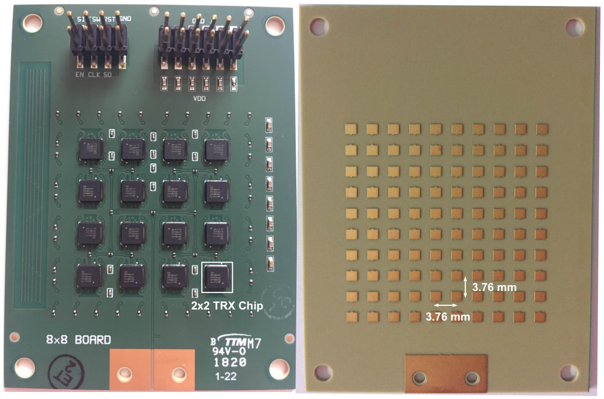
Fig. 1. (a) Block diagram of the 39 GHz 8x8 phased-array, and (b) 2x2 39 GHz 5G TRX quad beamformer chip.

Table 1. Summary of the 2x2 TRX beamformer chip

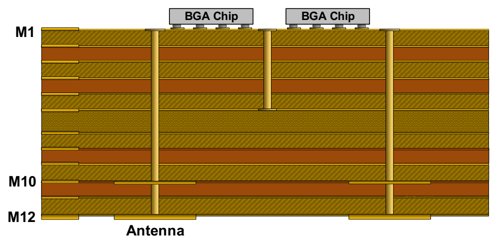
Receive mode		**Transmit mode**	
Gain (dB)	27	Gain (dB)	25
NF (dB)	5.5	Pout (dBm) @ P1dB / @Psat	8.5 / 10
Gain control (dB)	25	Gain control (dB)	25
Phase shifter	6-bit	Phase shifter	6-bit
DC power (W)	0.6	DC power (W)	1
VDD (V)	2.5	VDD (V)	2.5

II. 2x2 TRX Quad Beamformer Chip

Fig. 1b presents 2x2 TRX beamformer chip architecture. The chip is fabricated in SiGe technology with 0.5 mm ball-grid array (BGA) packaging. Each chip has four RF TRX



(a)



(b)

Fig. 2. (a) Front and back view of 39 GHz 8x8 phased-array, (b) stackup of low-cost PCB board.

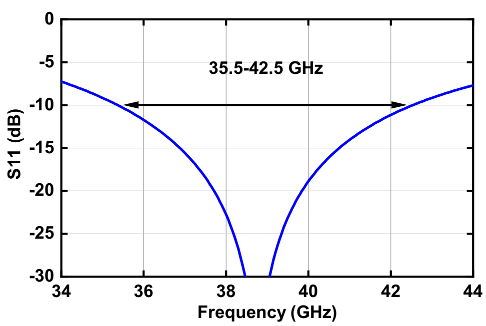
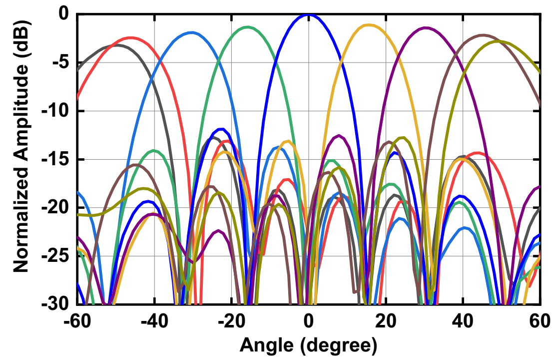


Fig. 3. Simulated S11 of the 39 GHz stacked-patch antenna.

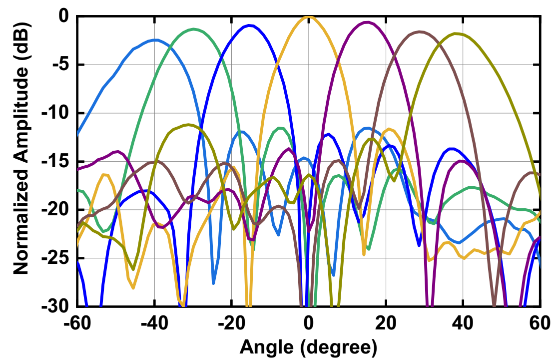
channels and a common RF port, and each channel contains a 6 bits phase shifter, 25 dB variable gain amplifier, and a PA and LNA. The power amplifier has a measured OP1dB of 8-9.5 dBm at 37-41 GHz. The digital control of the chip is implemented through a serial-peripheral interface (SPI). Table 1 presents a summary of the 2x2 TRX beamformer chip.

III. 39 GHz 8x8 Phased-Array Design

The 8x8 phased-array is built on a low-cost PCB board (Fig. 2b). Sixteen of the 2x2 TRX beamformer chips are placed on the M1 layers, and are connected to a 1:16 wilkinson network on M1. The Wilkinson network employs commercially available 0201 resistors for reduced cost. The SPI lines and VDD are routed on M3-M5, and M2 is the ground plane for Wilkinson network and transmission-lines between the chips and antennas. Also, passive antenna



(a)



(b)

Fig. 4. Measured:(a) H-Plane pattern (azimuth) and (b) E-Plane pattern (elevation) in the RX mode at 39 GHz.

dummies are placed surrounding the 8x8 active elements to improve the performance of the edge elements. The dummies are terminated with 50 Ω resistors placed on the M1 layer.

The antenna is based on a stacked-patch structure to improve its bandwidth, and M10/M12 are used, together with M6 for the antenna ground. The simulated antenna impedance is shown in the Fig. 3 with a -10 dB bandwidth of 35.5-42.5 GHz. The antenna feeds between two adjacent rows of elements are rotated so as to obtain a low cross-polarization level. The 8x8 phased-array results in a cross-polarization level below -30 dB for all scan angles in the azimuth and elevation planes. The antennas have a grid size of 3.76 mm (0.52λ @41 GHz) on both the x and y-axis, resulting in a total active array size of 30.1x30.1 mm^2. This allows for scanning of up to +/-60° in the H-plane (azimuth) and up to +/-50° in the E-plane (elevation).

IV. Pattern and EIRP Measurements

The phased-array is first calibrated at 39 GHz using far-field method by measuring the amplitude and phase response of each channel. The offset between the reference channel and all other channels is compensated using phase shifter and VGA on each channel. A residual +/-1.5 dB amplitude variation and +/-10 degree phase variation are obtained after calibration, and the calibration setting obtained at 39 GHz is used at all frequencies from 36.5-42 GHz.

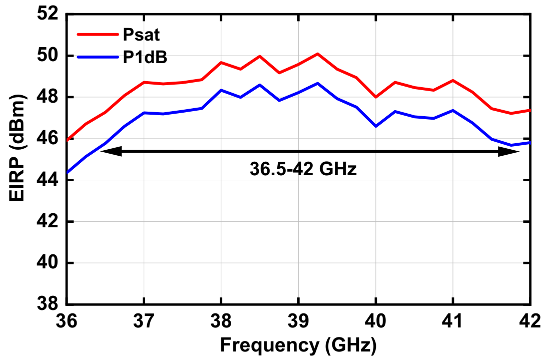


Fig. 5. Measured EIRP versus frequency of the 39 GHz 8x8 array.

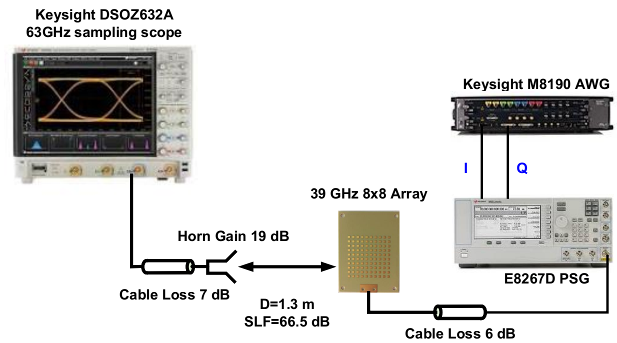
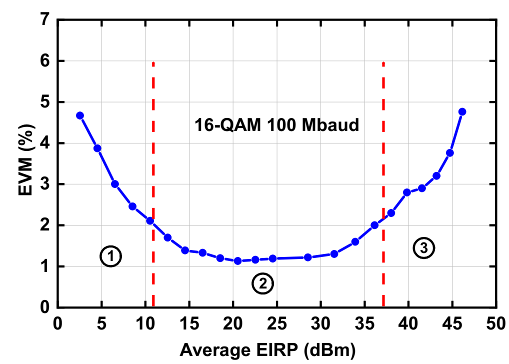
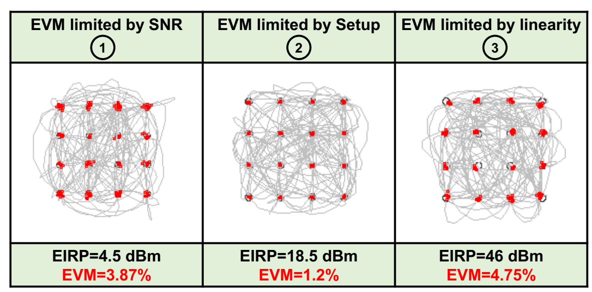


Fig. 6. EVM measurement setup for the 39 GHz array.



(a)



(b)

Fig. 7. Measured: (a) EVM versus different average EIRP with 100 Mbaud 16-QAM modulation, (b) constellations for different EIRP levels.

Fig. 4 presents the measured RX patterns for the 8x8 array at 39 GHz in the azimuth and elevation planes (similar patterns were obtained in the Tx mode and are not shown). In the azimuth plane, the array scans +/-50° without grating lobes. In the elevation plane, the array scans +/-45° without observing any scan-blindness. Also, the array has sidelobe levels of -12 dB with uniform illumination, and -18 dB sidelobes with 6 dB taper is achieved (not shown). As expected, the measured cross-polarization level is $<$ -30 dB in the E and H-plane and is not shown. The phased-array consumes 10 W in the RX mode and 16.25 W in the transmit mode, which is quite competitive knowing that the EIRP is 48-50 dBm.

Fig. 5 presents the measured effective isotropic radiated power (EIRP) of the 8x8 array at broadside. A peak EIRP of 48-48.5 dBm at P1dB and 49.5-50 dBm at Psat is achieved. The EIRP shows a 3-dB bandwidth of 36.5-42 GHz which covers the entire 39 GHz 5G band, and can be calculated as:

$$EIRP_{sat} = 20logN + 4 + 10 = 36 + 4 + 10 = 50\ dBm$$

and agrees well with simulations. An antenna gain of 4 dB is used and includes both the antenna loss and the transmission-loss to the 2x2 beamformer chip (1 dB).

V. EVM Measurements

A complex modulation measurement was performed on the 39 GHz phased-array with the setup shown in Fig. 6. The distance between the array and horn is 1.3 m resulting in a space-loss-factor of 66 dB. A Keysight M8190 arbitrary waveform generator (AWG) is used to generate a 16-QAM 100 Mbaud baseband signal with a pulse shaping factor α=0.35, resulting in a peak-to-average-power-ratio (PAPR) of 6.6 dB. The baseband signal is upconverted to 39 GHz using a Keysight E8267D signal generator and fed into the 8x8 array. A Keysight DSOZ632A 63 GHz real-time scope is used to demodulate the signal and is connected to the receiving horn. The scope has excellent sensitivity even at -40 dBm and does not require an external amplifier. The 16-QAM waveforms are demodulated using the Keysight Vector Signal Analysis software (VSA, 89600).

The Fig. 7a presents the measured error vector magnitude (EVM) for different EIRP levels, referenced to the constellation peak. In region 1, the EVM is limited by the SNR due to the low EIRP. In region 2, the EVM is limited by AWG SNR together with the phase noise from the source and real-time scope. And in region 3, the EVM is limited by the nonlinearity of both the TX array and the signal generator. The 39 GHz array is capable of producing 46 dBm of average power for a 16-QAM signal with $<$ 5% EVM and for backoff only 3.5 dB from $EIRP_{sat}$. Fig. 7b presents the measured constellations in the different EIRP regions, all with low EVM values.

VI. Conclusion

This paper presents a millimeter-wave 37-42 GHz 8x8 phased-array for 5G systems. The phased-array achieves an EIRP of 48-50 dBm at P1dB and Psat with a 3-dB bandwidth of 36.5-42 GHz. The array can scan up to +/-50° in the azimuth plane and +/-45° in the elevation plane. EVM measurements using a 16-QAM 100 MHz waveform indicate $>$ 44 dB of dynamic range with $<$ 5% EVM (EIRP of 2-46 dBm). The phased-array is an excellent candidate for 5G 39 GHz mm-wave systems.

ACKNOWLEDGMENTS

The authors thank Integrated Device Technology, IDT, for sponsoring the beamformer chips used in this work. The array was assembled by Kyocera International, San Diego, using their advanced phased-array assembly line. 5G beamformer chips (different versions) are available from IDT.

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