Over-The-Air Tests of Phased Array Antenna Module for 5G 28 GHz band

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In response to the emerging 5G New Radio (NR) millimeter-wave technology, we have developed our state-of-the-art Phased Array Antenna Module (PAAM) named "FutureAccess™", with robust performance at 28 GHz band. The PAAM integrates an Array Antenna, Beam Former ICs (BFICs), Frequency Conversion IC (FCIC), Band-Pass Filters (BPFs) and Power Combiners/Splitters (COMB-SPLITs). The performance of millimeter-wave band devices must be evaluated at Radiation Interface Boundary (RIB) as per 3GPP specifications. We have confirmed the PAAM's performance characteristics in the Over-The-Air (OTA) tests conducted at our facility in Fujikura.

Fig.1. Application image of RF module for FWA and MWA base station.

1. Introduction

5G is derived from "The fifth generation" of mobile communication technology. So far mobile communications have undergone generational technological change almost every decade, and the technological advancements and system developments built up by previous generations have been passed on to the next generation for further development. Download traffic on mobile networks continues to increase year after year since early 2000s, when the provision of the third-generation mobile communication systems (3G) began, and as of 2019, monthly traffic was 1000 Terabytes in total and 4 Gigabytes per subscription. In order to meet these growing traffic demands, the solution is to introduce and expand 5G systems, which can provide dramatically higher communication capacity[1)].

Sub6-GHz band (FR1) (frequencies below 6 GHz) and the millimeter-wave band (FR2) (24.25 to 71 GHz) are mainly adapted for 5G systems. Figure 1 shows the application image of Fixed Wireless Access (FWA) and Mobile Wireless Access (MWA) to the base station (gNB). Communications in millimeter-wave band are essential to establish massive communication between FWA's CPE (Customer Premise Equipment), mobile terminals, etc. and base stations[2)].

To develop the Phased Array Antenna Module (PAAM), Fujikura signed an agreement with International Business Machines Corporation (IBM) in 2019 to use their license of 5G-related millimeter-wave Radio Frequency Integrated Circuit (RFIC) technology. In 2020, we co-developed a next-generation millimeter-wave RFIC for 5G millimeter-wave communications operating in the 3GPP bands n257 (28 GHz band), n258 (26 GHz band) and n261 (27 GHz band). Utilizing this RFIC, we have developed the new PAAM, "FutureAccess™". In this paper, we report the evaluation results and the performances of our PAAM in Over-The-Air (OTA) tests.

Abbreviations, Acronyms, and Terms.

5G—Fifth generation mobile communication systems
Generic term for the fifth generation communication technology.

5G NR—5G New Radio
It is a new radio access technology (RAT) developed by the 3GPP for the 5G mobile network.

PAAM—Phased Array Antenna Module
Antenna modules opreating phase-controlled signals simultaneously from each antenna element and working as a larger antenna that has higher gain and directivity.

RF—Radio Frequency
Frequency after up-convertion or the transmitted signal frequency.

IF—Intermediate Frequency
A frequency to which a carrier wave is shifted as an intermediate step in transmission or reception or frequency after down-conversion.

BFICs—Beam Former ICs
ICs to control amplification and phase-shift of transmitted and received signals.

FCIC—Frequency Conversion IC
IC to perform up/down-conversion of IF signals and RF signals respectively.

COMB-SPLITs—Power Combiners/Splitters
Components for combining and splittting RF power while receiving and transmitting respectively.

BPFs—Band-Pass Filters
Components for suppressing spurious emissions.

OTA tests—Over-The-Air tests
Tests for evaluating transmit / receive performance and reliability of wireless devices and their antennas and other components.

3G—The third generation mobile communication systems
Generic term for the third generation communication systems.

FR1—Frequency Range 1 (Sub 6 GHz)
410-7125 MHz frequency band in which 5G NR can operate.

FR2—Frequency Range 2 (Millimeter wave)
24.25 to 71GHz frequency band in which 5G NR can operate.

FWA—Fixed Wireless Access
A wireless communication standard that enables broadband communication between fixed outdoor devices.

MWA—Mobile Wireless Access
A wireless communication that allows terminals to communicate while moving, and the handover processing is performed between base stations.

gNB—gNodeB
A node in a cellular network that provides connectivity between user equipment (UE) and the evolved packet core (EPC). A gNodeB is the functional equivalent of a base station in a traditional cellular network.

CPE—Customer Premises Equipment
Communication equipment such as communication terminals and wiring on the premises owned by the subscriber.

RFIC—Radio Frequency Integrated Circuit
General term for integrated circuits (ICs) that process radio frequency (RF) signals.

3GPP—Third Generation Partnership Project
A project by national standardization bodies that examines and coordinates specifications for standards for mobile communication systems beyond 3G.

n257, n258, n261 —n257, n258, n261
n257 (26.50-29.50 GHz), n258 (24.25-27.50 GHz), n261 (27.50-28.35 GHz) bands used in 5G NR.

Tx—Transmitter
A circuit that accepts signals or data in and translates them into a form that can be transmitted, usually over a distance.

Rx—Receiver
A circuit that accepts signals from a transmission medium and decodes or translates them into a form that can drive local circuits.

TDD—Time Division Duplex
A two-way communication technique allowing to use the same frequency band by alternating the transmission times of a device.

H pol. , V pol.—Horizontal polarization, Vertical polarization
Radio waves whose plane of orientation of the electric field is horizontal (H pol.) or vertical (V pol.) with respect to the ground.

EIRP—Equivalent Isotropic Radiated Power
Equivalent power radiated from an isotropic directivity device producing the same field intensity at a point of observation as the field intensity radiated in the direction of the same point of observation by the discussed device.

Horn antenna—Horn antenna
A pyramidal horn antenna of known gain.

FSPL —Free Space Path Loss
It is the amount of attenuation a radio wave with a given frequency suffers as it propagates in free space.

CW—Continuous Wave
An electromagnetic wave of constant amplitude and frequency, typically a sine wave, that for mathematical analysis is considered to be of infinite duration.

LO—Local Oscillator
A low phase noise oscillator used with the mixer to translate the frequency of a signal.

SG, VSG—Signal Generator, Vector Signal Generator
For generating high quality test signals.

SA—Spectrum Analyzer
For various frequency-domain analysis of the device under test.

VNA—Vector Network Analyzer
It is used for measuring transmission and reflection parameters of a device under test.

Abbreviations, Acronyms, and Terms.

S-parameters—Scattering parameters
It is used to characterize electronic circuits and components at high frequency.

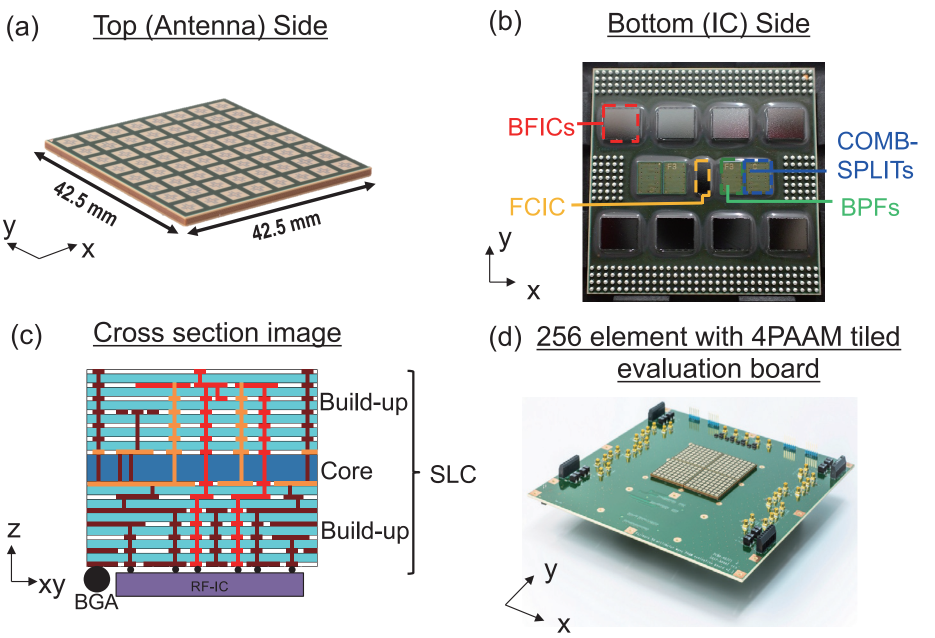
oPsat—Output saturated power
Defined as saturated power, the output power when the amplifier's output is saturated.

oP1dB—Output 1dB compression point
Defined as the output power level at which the gain drops by 1 dB from its constant value.

The true-time-delay circuit—The true-time-delay circuit
A circuit capable of providing variable phase shifting across the signal spectrum to eliminate beam squint phenomenon.

PAE—Power Added Efficiency
It is a measure of the power conversion efficiency of a power amplifier.
PAE = (PowerRF_out - PowerRF_in)/PowerDC

ISSCC—International Solid-State Circuits Conference
It is the foremost global forum for presentation of advances in solid-state circuits and system-on-a-chip.



These figures are reproduced from ref. [3,4,5].

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Fig. 2. (a) Overview of PAAM from antenna side, (b) Overview of PAAM from IC side, (c) Cross section image of PAAM, (d) 256 element with 4PAAM tiled and evaluation board [3)-5)].

2. Overview

Figures 2 (a) - (c) show overviews of our PAAM from the antenna side, the IC mounted side and the cross-sectional image of the PAAM [3), 4)]. The PAAM incorporates a 64-element dual polarized Array Antenna, 8 Beam Former ICs (BFICs), Power combiners/splitters (COMB-SPLITs), Band-Pass Filters (BPFs) and Frequency Conversion IC (FCIC). The function of the BFICs is to amplify transmitting and receiving signals and controlling their phases to realize beamforming. The COMB-SPLITs combine and split RF signals while receiving and transmitting respectively. The BPFs suppress unwanted signals outside the desired band. The FCIC up-converts and down-converts baseband signals of intermediate frequency (IF) and RF signals during transmitting and receiving respectively. The PAAM can switch between transmitting (Tx) and receiving (Rx) modes in each BFIC and in the FCIC, and can work as a transmitter/receiver supporting time-division duplex (TDD) operation.

The PAAM can transmit and receive dual polarizations of horizontal polarization (H-polarization, H pol.) and vertical polarization (V-polarization, V pol.). With these functions, we can realize polarization-multiplexing communication (carrying out two different communications simultaneously). Because the array antennas are arranged in two dimensions for horizontal and vertical directions, the PAAM can transmit and receive directional beams in both horizontal and vertical directions and enable beamforming in the range of ±60 deg. in both horizontal and vertical directions. In addition, it is possible to expand the number of antenna elements by tiling PAAMs as shown in Fig. 2 (d) [5]. In this paper, we report the evaluation results of PAAM with 64 elements array antenna (64 element PAAM) and 256 elements array antennas (256 elements array antenna).

2.1 Operating bands of the PAAM

In order to cover multiple 3GPP frequency bands, the PAAM mounts a wideband FCIC and BFICs. However, there is a problem of transmitting and receiving spurious emission and image bands because of the wideband covered. Then, the BPFs suitable for the desired frequency band are selected with using the same FCIC and BFICs. We have fabricated individual PAAMs with 4 types of BPFs: F1 (BPF type F1), F2 (BPF type F2), F3 (BPF type F3) and F4 (BPF type F4). When we appropriately use the PAAM according to the unique frequency bands, the PAAM can cover all 3GPP bands n257 (28 GHz band), n258 (26 GHz band), and n261 (27 GHz band) in the 24-30 GHz range.

Table 1. Frequency band and covered frequency range of PAAM.

Frequency band	BPF type	Frequency range (GHz)	
		Min.	Max.
n258	F1	24.25	26.10
	F2	25.65	27.50
n257	F3	26.50	28.35
	F4	27.65	29.50

2.2 OTA test system

Figure 3 shows an OTA measurement block diagram and Figure 4 shows its overview [4]. In OTA tests of the PAAM, we set the evaluation board of the PAAM inside an anechoic chamber. Anechoic chamber is characterized by its metallic walls with foam RF absorbers in order to reduce reflections [6] and thereby decreasing interference to measurements.

2.2.1 Definition and measurement methods of Equivalent Isotropic Radiated Power

Equivalent Isotropic Radiated Power (EIRP) is defined as the equivalent power radiated from an isotropic directivity device producing the same field intensity at a point of observation as the field intensity radiated in the direction of the same point of observation by the device under test (DUT). An isotropic antenna radiates power equally in all directions. EIRP is an important indicator for describing the transmitting performances of RF devices and it is also used as a legal or regulatory standard value for setting limits on the radiated power of RF devices [6].

Originally, EIRP is calculated by Equation (1) using the

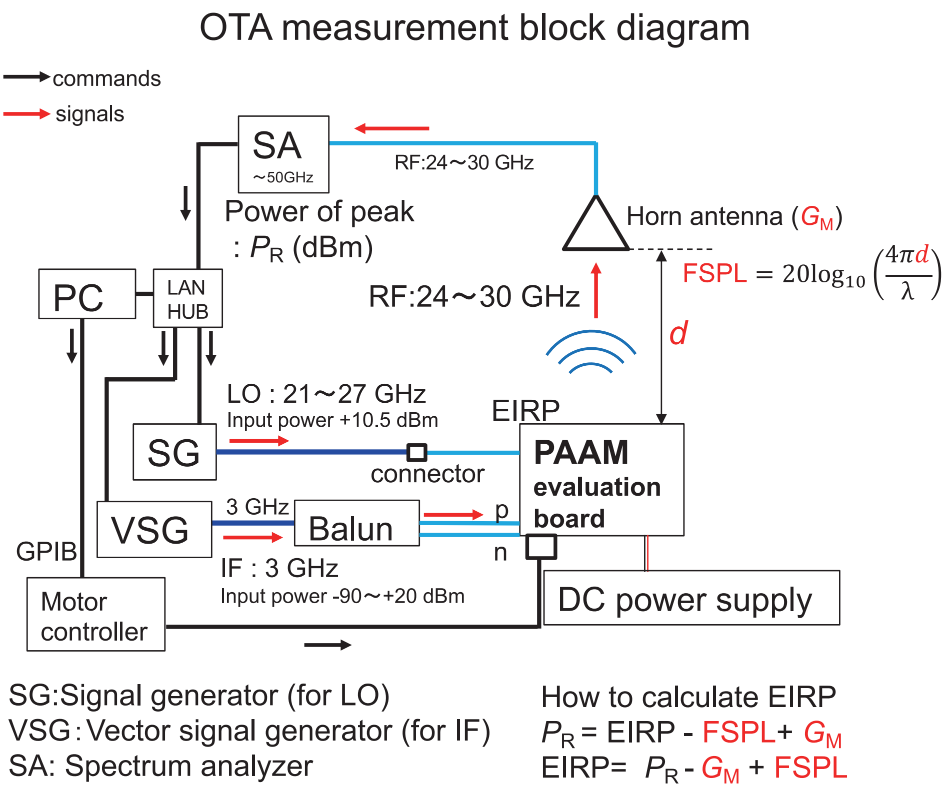

Fig.3. OTA measurement block diagram for Tx mode and how to calculate EIRP.

output power of the signal generator as P_T, the antenna gain as G_A and the cable loss as L_C.

$$\text{EIRP (dBm)} = P_T \text{ (dBm)} + G_A \text{ (dBi)} - L_C \text{ (dB)} \quad (1)$$

However, in the case of PAAM, it is difficult to directly check P_T because we cannot separate antenna and BFICs. So we calculated EIRP from the received power P_R including the Free Space Path Loss (FSPL) and the horn antenna gain (G_M) as follows:

$$\text{EIRP (dBm)} = P_R \text{ (dBm)} - G_M \text{ (dBi)} + \text{FSPL (dB)} \quad (2)$$

From Friis's transmission formula [7], with distance d between the PAAM and the horn antenna and wavelength λ, FSPL is calculated as,

$$\text{FSPL (dB)} = 20 \log_{10} (4\pi d / \lambda) \quad (3)$$

2.2.2 Overview of basic performances of the PAAM using continuous wave

Figure 3 shows an OTA measurement block diagram where we have evaluated the basic performances of the PAAM with continuous waves (CW). The LO signal from the signal generator (SG) and the IF signal from the vector signal generator (VSG) are input to the PAAM evaluation board. The FCIC up-converts the IF signal to RF signal. The RF signal is transmitted to the horn antenna by the array antenna of the PAAM. The power and qualities of the received RF signal are analyzed at the spectrum analyzer (SA).

The OTA tests are performed with the PAAM and horn antenna facing each other with polarization matched at a distance d. We have to set the distance d above the far field for more accurate measurements. Therefore, we set the distance d = 0.575 m for 64 element PAAM as shown in Fig. 4. And d = 3.0 m for 256 element PAAM. EIRP was calculated according to Equations (2) and (3), respectively.

3. Test Results

3.1 BPFs frequency dependence

Figure 5 shows the S-parameters (reflection coefficients: S11, S22; transmission coefficients: S21, S12) of the BPFs measured with a vector network analyzer (VNA)[8]. From Fig. 5, the center frequencies of each BPF are 25.2 GHz, 26.6 GHz, 27.4 GHz, 28.6 GHz . From the transmission performances, each BPF in pass band of 24.25-29.50 GHz show powers within 3 dB from the maximum powers, and the stop band powers of each BPF are suppressed more than 30 dB compared to the pass band powers. From these results, the frequency response of each BPF of the PAAM sufficiently satisfies the demands of 3GPP frequency band.

3.2 Output power performances of the PAAM

The saturated output powers (oP_{sat}) converted to EIRP of the 64 element PAAM are 55.3 and 57.6 dBm for H pol. and V pol. respectively in the beam peak direction. The combined power gain[9] of 256 element antenna array is calculated as $20\log_{10}(256)$ = 48.2 dB, and that of the 64 element array antenna is calculated as $20\log_{10}(64)$ = 36.1 dB, which are obtained by the superposition of powers from each element in the array. The gain of 256 element PAAM over 64 element PAAM is 12.0 dB ideally. Here, the oP_{sat} (66.4 and 68.6 dBm) of the 256-element PAAM is close to 12.0 dB higher than the oP_{sat} (55.3 and 57.6 dBm) of the 64 element PAAM. In other words, our PAAM can successfully combine beam powers and shows higher EIRP with tiling multiple PAAMs.

3.3 Beam forming

3.3.1 Beam forming of 64 element PAAM

Figure 6 shows the beamforming patterns in the Tx mode and the beam sensitivity patterns in the Rx mode of the 64 element PAAM [5]. In Tx mode, the PAAM generates RF signal at 28 GHz by up-converting IF signal at 3 GHz with 25 GHz LO signal, and the RF signal is transmitted. In Rx mode, the polarization matched horn antenna connected to the SG transmits RF signal at 28 GHz towards the PAAM. Then, the same LO signal of 25 GHz is used to down-convert the received RF signal to IF signal at 3 GHz, and the IF signal is received with SA.

θ indicates the directional angle of the transmitting and receiving beam patterns. The directional beam patterns in Tx and Rx mode are confirmed in the range of $\theta = \pm 60$ deg. In these measurements, no phase calibration is performed on individual antenna elements of the PAAM. So our PAAM can realize very good beamforming without phase calibration in the range of $\theta = \pm 60$ deg. at both polarizations of H pol. and V pol.

A vector-type phase shifter requires adjustment of the amplitudes of in-phase and quadrature signals[10], and those adjustment errors sometimes result in output power

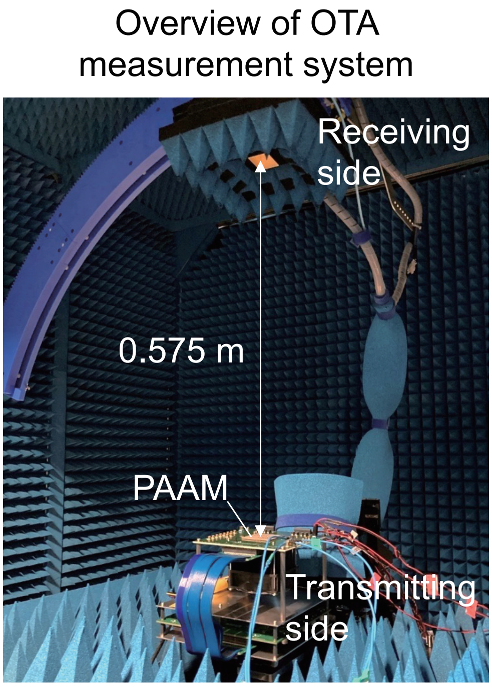

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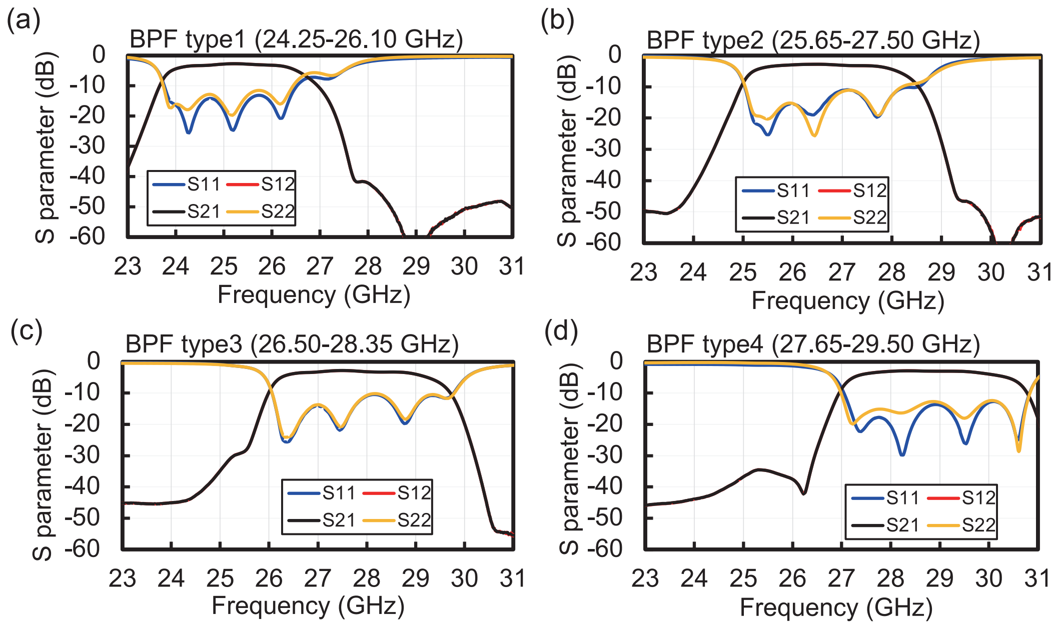
Fig.4. OTA test measurement system setup[4] .



These figures are reproduced from ref.[8].
[8] X. Gu et al., "Antenna-in-package integration for a wideband scalable 5G millimeter-wave phased-array module", IEEE MWCL, vol. 31, no. 6, pp. 682-684, 2021

Fig.5. BPFs S-parameter measurement results (a) 24.25-26.10 GHz, (b) 25.65-27.50 GHz, (c) 26.50-28.35 GHz, (d) 27.65-29.50 GHz.[8]

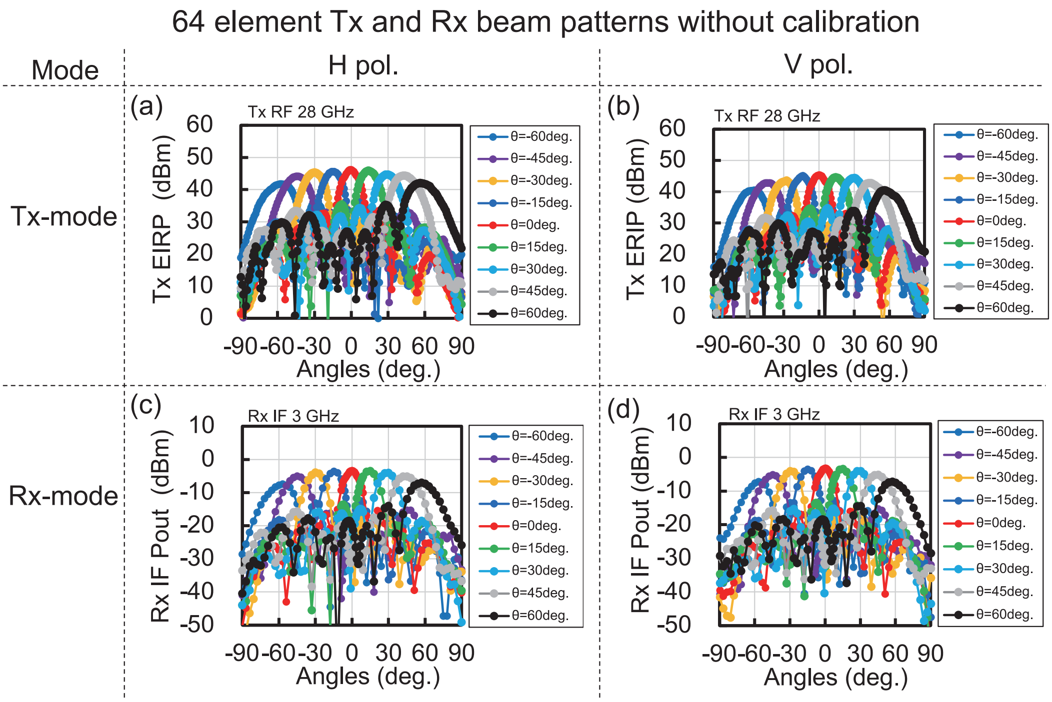


Fig. 6. Measured beam patterns of 64 element PAAM in Tx mode and Rx mode ((a) Tx mode H pol., (b) Tx mode V pol., (c) Rx mode H pol., (d) Rx mode V pol.) [5].

These figures are reproduced from ref.[5].
[5] B. Sadhu et al., "A 24-to-30GHz 256-element dual-polarized 5G phased array with fast beam- switching support for >30,000 beams", IEEE ISSCC, pp. 436-438, February, 2022.

variations of the desired signal. On the other hand, our developed RFIC incorporates the true-time-delay phase shifter, and the amplitude variations with respect to the phase is extremely small, furthermore, the beamforming is independent of the wavelength, which is an advantage in broadband beamforming[11].

3.3.2 Beam patterns of 256 element PAAM

Figure 7 shows the beamforming patterns of the 256 element PAAM in Tx mode[5]. In this measurement, no phase calibration is performed on individual antenna of the 256 element PAAM as in the case of the 64 element PAAM. So by tiling 4 PAAMs, we can generate good beamforming in the range of $\theta = \pm 60$ deg. at both polarizations of H pol. and V pol. without the phase calibration.

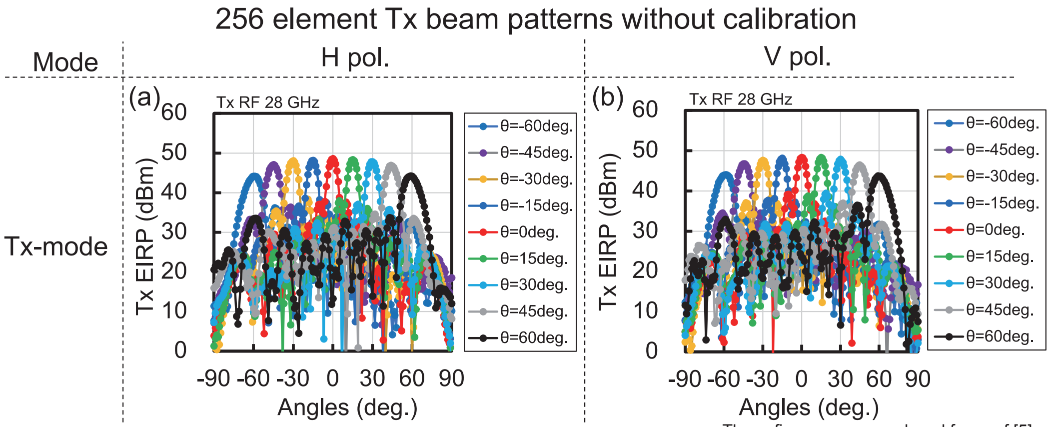


Fig. 7. Measured beam patterns of 256 element PAAM in Tx mode ((a) H pol., (b) V pol.) [5].

These figures are reproduced from ref.[5].
[5] B. Sadhu et al., "A 24-to-30GHz 256-element dual-polarized 5G phased array with fast beam- switching support for >30,000 beams", IEEE ISSCC, pp. 436-438, February, 2022.

Table 2. Comparison of overviews of IBM / Fujikura PAAM specification [5] and reported values of other institution [12,13] (AZ : Azimuth direction, EL : Elevation direction)

Reported society and groups	This work ISSCC2022 IBM / Fujikura[5]	ISSCC2017 JSSC2017, IBM / Ericsson[12,13]
IC Technology	130 nm SiGe BiCMOS	130 nm SiGe BiCMOS
Unit IC number of elements	2×8 TRx	2x16 TRx
Unit tile module array size	64, Dual Pol.	64, Dual Pol.
Scaled tiles module array size	256, Dual Pol.	—
RF frequency (GHz)	24-30	27-28.5
IF frequency (GHz)	2-5	3
5G NR band support	Yes (n257, n258, n261)	Yes (n261)
BFICs die area (mm²), die area / TRx element (mm²)	37, 1.2	166, 5.2
Module Tx EIRP at boresight (dBm)	56 at P_{sat} (64Tx)	54 at P_{sat} (64Tx)
	68.5 at P_{sat} (256Tx)	
Module Rx oP_{1dB}[14] (dBm)	11	—
Tx and Rx beam scan range (deg.)	AZ ±60 EL ±60	AZ ±50 EL ±50
Module Tx PAE (%)	20.5 at P_{sat}	13.8 at P_{sat}
Num. of beams supported for fast beam-switching	>30,000 (beamcalc mode)	128 (†)
	256 (beam table mode)	
Fast beam-switching speed (ns)	8	4
Beam-switching latency (ns)	200 (beamcalc mode)	—
	120 (beam table mode)	—

4. Comparison with other publications

Table 2 shows a summary of the measured performance of our developed PAAM (This work) [5] and a comparison with other publications [12, 13]. The important features of our developed PAAM are summarized below.

- Our developed PAAM can transmit and receive beams without phase calibration in the range of $\theta = \pm60$ deg. at both polarizations of H pol. and V pol.

- Our developed PAAM sufficiently covers the demanded 3GPP frequency band, and it can be used for wider band than other reported frequency band.
- Larger number of antenna elements can be realized by tiled PAAMs.
- Fast switching mode supports maximum beam numbers over 30,000.
- P_{sat} of 256 element PAAM is 68.5 dBm converted to EIRP, which is larger transmitting power than other reported values.
- Power Added Efficiency (PAE) [15] is 20% in our developed PAAM, which is relatively larger class on Si-based Phased Arrays.

The performances of our developed PAAMs was jointly reported with IBM at the International Solid-State Circuits Conference (ISSCC) in February 2022 [5].

5. Conclusion

We have developed a PAAM for 5G millimeter-wave communications. Radiated transmitter / receiver characteristics of 64 element PAAM as well as 256 elements array antenna were confirmed in the OTA tests. We have demonstrated that our PAAM can be utilized in the 5G millimeter-wave communications, and that it has many advantages compared to other works [12), 13)].

In the future, we plan to demonstrate mutual transmitting/receiving tests with PAAMs facing each other and reliability tests to evaluate them under actual use environments.

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