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A Compact RF Frontend Module of Active Phased Array Antenna for High SHF Wideband Massive MIMO in 5G

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SUMMARY In order to meet various requirements for the 5th generation mobile communication, a high SHF wideband massive-MIMO system has been widely studied which offers wide system bandwidth and high spectral efficiency. A hybrid beamforming configuration which combines analog beamforming by APAA (Active Phased Array Antenna) and digital MIMO signal processing is one of the promising approaches for reducing the complexity and power consumption of the high SHF wideband massive-MIMO system. In order to realize the hybrid beamforming configuration in high SHF band, small size, low power consumption and precise beam forming over the wide-band frequency range are strongly required for RF frontend which constitutes analog beam former. In this paper, a compact RF frontend module for high SHF wideband 5G small cell base station is proposed. This RF frontend module is prototyped. Various key components of the RF frontend module are fabricated in 15 GHz band, and measured results show that high RF performances are able to meet the requirements of RF frontend.

key words: *massive MIMO, active phased array antenna, high SHF, RF frontend, 5G*

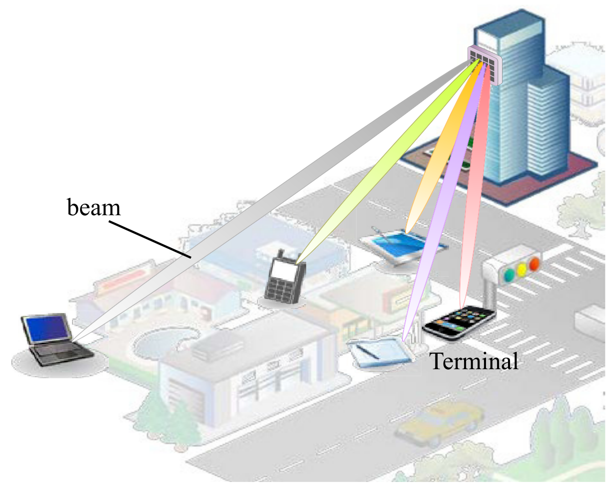

Fig. 1 Envisioned use case of massive MIMO in 5G small cell.

1. Introduction

In recent years, the mobile data demand has been growing explosively due to the widespread use of smart phones and various new applications. With the mobile traffic in the early 2020's being predicted to be 1000 times greater than that of 2010, the 5th generation mobile communication system (5G) has to accommodate the huge traffic demands [1]. In 5G, heterogeneous network configurations with macro cells using lower frequency and small cells using higher frequency have been proposed [2]. Thus, 5G small cells are expected to provide high speed transmission scheme for limited users in LOS environment. Other users will be covered by macro cells.

5G small cell base stations inevitably use higher frequency band such as high SHF band (6–30 GHz) than UHF band used by conventional mobile macro cell system to benefit from wide system bandwidth. However, the large propagation losses at high frequency band make it challenging to realize practical mobile communication that involves links of more than a few tens of meters. Massive multiple-input multiple-output (MIMO) [3] in higher frequency band is one of the promising technologies for 5G mobile communication system. The use of more than 100 antenna elements enable high antenna beam gain and compensation of large propagation loss. It can also obtain benefits of spatial multiplexing capability by multi-beam multiplexing transmission. Figure 1 shows an envisioned use case of massive MIMO in 5G small cell. The antenna system at the base station is composed of massive antenna elements, from which multiple sharp beams are radiated to each of corresponding terminals.

The massive MIMO configuration has been widely studied [4]. The hybrid beamforming configuration, which is realized by combining analog beamforming by APAA (Active Phased Array Antenna) and digital MIMO signal processing, has been widely proposed [5]–[9]. Compared with the full digital massive MIMO configuration which is widely used in low frequency band, this configuration dramatically reduces the complexity of digital circuits and the number of data converters such as ADC (Analog to Digital Converter) and DAC (Digital to Analog Converter). We have already proposed a sub-array APAA-MIMO configuration with hybrid beamforming for 5G [10], [11]. Figure 2 shows a configuration of sub-array APAA-MIMO. Each sub-array can form and radiate a beam and control the beam direction. In this configuration, the number of converters can be reduced from the number of antennas to that of sub-arrays.

Each sub-array is constituted by a RF frontend which includes various RF circuits. In order to realize the massive

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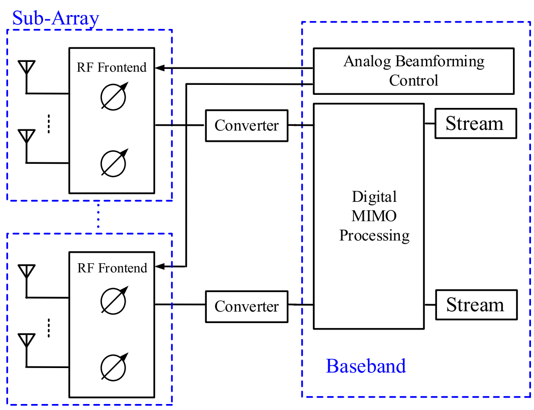


Fig. 2 Sub-array APAA-MIMO block diagram.

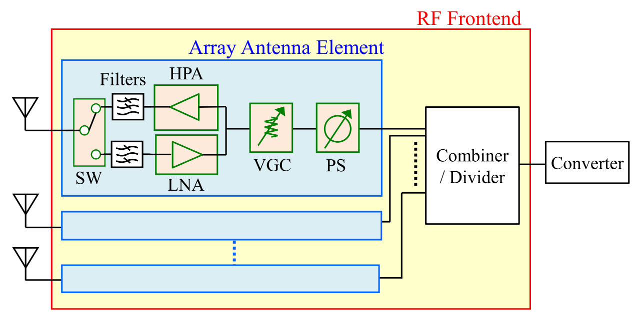


Fig. 3 Simplified block diagram of RF frontend.

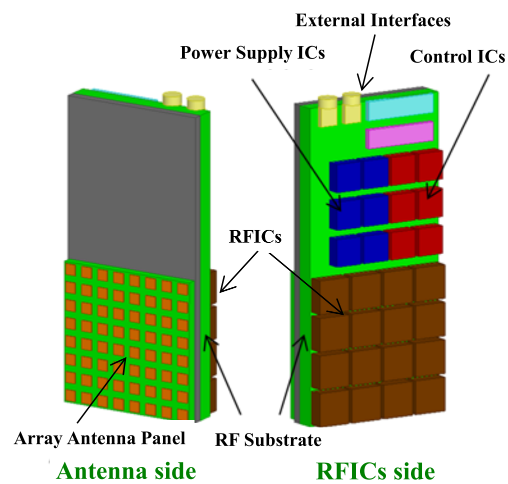


Fig. 4 The structure of proposed RF frontend module.

MIMO concept by utilizing hybrid beamforming configuration, small size, low power consumption and precise beam forming over the wide-band frequency range are strongly required in the RF frontend.

In this paper, we present a compact RF frontend module for the high SHF wideband 5G small cell base station. This RF frontend module is prototyped. Various key components of the RF frontend module are fabricated in 15 GHz band, and measured results show high RF performances to meet the requirements of the RF frontend. The structure of this paper is as follows. Section 2 describes a block diagram and structure of the proposed RF frontend module. Section 3 shows the development results of key components and the prototype RF frontend module. Finally, Sect. 4 draws a conclusion.

2. Configuration of RF Frontend Module

Figure 3 shows the simplified block diagram of RF frontend which includes multiple array antenna elements. Each array antenna element has a high power amplifier (HPA), a low noise amplifier (LNA), a switch (SW), a gain control circuit (VGC), a phase shifter (PS) and filters. Each element has a function of phase and amplitude control for analog beamforming. All elements are connected to a combiner and a divider.

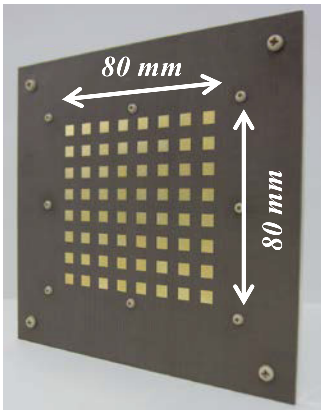
Since dense deployment of 5G small base station is envisioned as shown in Fig. 1, small size and thin structure are important features for easy installation such as building walls and ceilings. However, in conventional sub-array for high SHF band, RF frontends are located behind an array antenna panel in a three-dimensional configuration that makes the sub-array antenna equipment larger and thicker [12]. In order to satisfy the demands of small size and thin structure, we have proposed a compact RF frontend module where all the components are unified including RF active circuits (HPA, PS, etc.), RF passive circuits (antenna, filters, etc.), power supply IC and control IC. Figure 4 shows the structure of the proposed RF frontend module. RF substrate is composed of a multilayer board and contains RF passive circuits in its internal layer. RF active circuits are integrated into RFICs. Moreover, each ICs and external interfaces are mounted on the opposite side of an array antenna panel formed by patch antenna elements. Thus all functions for analog beam forming are highly integrated on planar module.

3. Fabricated Key Components and Module

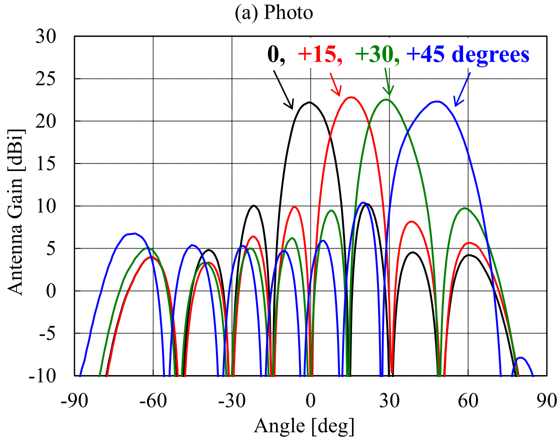
Due to the spatial frequency dependencies among array antenna elements for APAA, available area for circuit components are extremely limited in high SHF band. Generally, the element pitch is on the order of half the wavelength. It means available area for circuit components of each element is only 10 mm × 10 mm at 15 GHz. This size limitation requires both the miniaturization and the low power dissipation of RF frontend components.

In addition, inter-beam interference among analog beams becomes an issue in a sub-array APAA-MIMO configuration. In order to prevent this issue, precise beam forming is required in this RF frontend module. In 5G, these requirements must be satisfied besides conventional requirements for a transceiver of mobile communication.

In order to meet these requirements, we fabricated key components (Antenna panel, HPA, PS and filters) of RF frontend module in 15 GHz.



(a) Photo



(b) Measured results

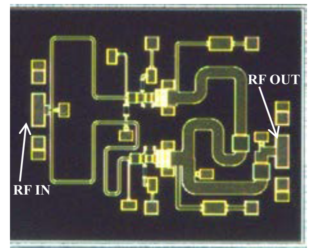
Fig. 5 Photo and RF performance of the fabricated array antenna panel [11].

3.1 Array Antenna Panel

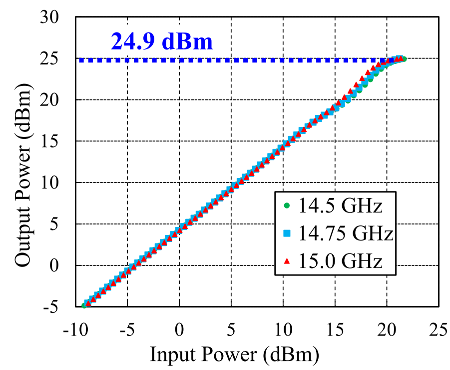
Figure 5 (a) shows the fabricated array antenna panel formed by 64 (8 × 8) patch antenna elements [11]. It can radiate a sharp beam toward unit terminals. In order to direct a beam for wide angle, for example ±45 degrees, the element pitch is set to 0.5 wavelength. The size of array antenna for 15 GHz is 80 mm × 80 mm. Because of the narrow element pitch, the effect of mutual coupling between antennas cannot be negligible, and therefore we have designed array antenna while taking it into account. Figure 5 (b) shows the measured array antenna patterns of fabricated antenna at the beam angle of 0, +15, +30, and +45 degrees. It is confirmed that the antenna gain achieved over 21 dBi and is almost constant in every beam scan angle.

3.2 High Power Amplifier

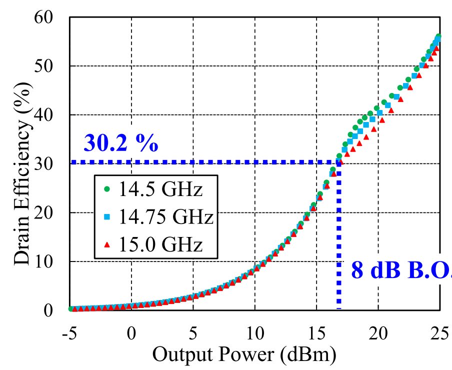
From an energy efficiency and equipment size points of view, power dissipation is one of the key technical issues of the RF frontend module. A HPA is a crucial component of the RF block since it strongly determines power consumption. In order to improve the power efficiency at average power level as well as peak power level, a dynamic load



(a) Chip photo



(b) Measured results of the output power



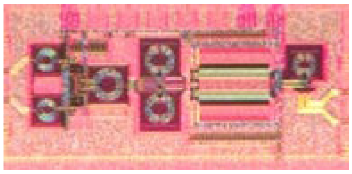
(c) Measured results of the drain efficiency

Fig. 6 Chip photo and RF performance of the fabricated HPA.

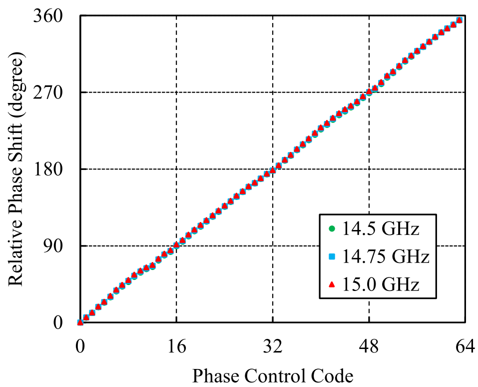
modulation scheme is employed to the HPA. Figure 6 (a) shows the chip photo of the fabricated HPA with GaAs process and the size is 1950 μm × 1350 μm. This HPA has Doherty configuration, and high efficiency over wide frequency band is realized by designing it with taking parasitic components of transistors into consideration [13]. Figure 6 (b) and 6 (c) show the measured output power and drain efficiency of the fabricated HPA at 14.5, 14.75 and 15.0 GHz, respectively. It achieved the saturated output power of 24.9 dBm and drain efficiency of 30.2% at the 8 dB back off point, exhibiting state-of-the-art performances at these frequency bands.

3.3 Phase Shifter

A sub-array APAA-MIMO system requires precise analog beamforming. In order to realize accurate phase control in each element of the RF frontend module, we developed an accurate 6-bit vector-sum PS with the phase calibration technique [14]. Generally, a vector-sum PS is superior to

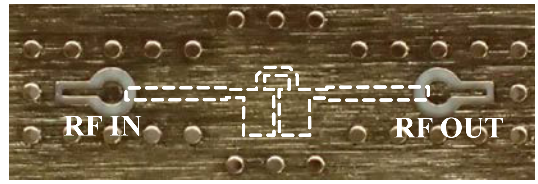


(a) Chip photo [14]

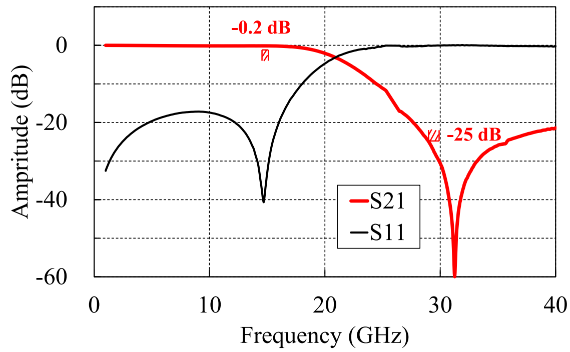


(b) Measured results

Fig. 7 Chip photo and RF performance of the fabricated PS.

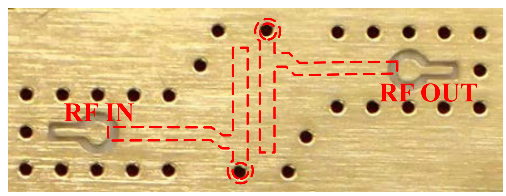


(a) Photo

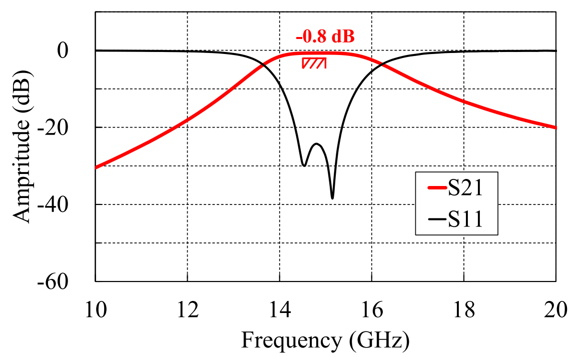


(b) Measured results

Fig. 8 Photo and RF performance of the fabricated low pass filter.



(a) Photo



(b) Measured results

Fig. 9 Photo and RF performance of the fabricated band pass filter.

a passive PS in its small area and low loss [15], [16]. The prototype PS is fabricated in a 65 nm CMOS technology. Figure 7 (a) shows the chip photo of the PS, which only occupies an active area of 1000 μm × 350 μm. Figure 7 (b) shows the measured 6-bit phase shift referred to 0 degree state after the calibration. The phase error is 1.4 deg.-rms at 14.75 GHz. The experimental results indicate that the developed vector-sum PS with the calibration is an effective approach to achieve accurate phase control performance.

3.4 Filters

In order to satisfy the requirements of spurious emission in a transmitter and spurious response in a receiver of a base station transceiver, filters with high attenuation and low insertion loss performance are required between each antenna element and active circuits such as HPA and LNA in the RF frontend module. In order to meet the size requirement of the RF frontend module and achieve high performance, we developed filters which were formed on a multilayer board [17]. Figure 8 shows the photo and measured RF performance of the fabricated low pass filter utilizing non-adjacent coupling. The effective size of this low pass filter is 3 mm × 1.5 mm. It achieved 0.2 dB insertion loss of pass band (14.5–15.0 GHz) and 25 dB attenuation of the second harmonics band (29.0–30.0 GHz). Figure 9 shows the photo and measured RF performance of the fabricated band pass filter. The effective size of this band pass filter is 4.2 mm × 5.7 mm. It achieved 0.8 dB insertion loss of pass band (14.5–15.0 GHz) and high attenuation at out of pass band.

3.5 RF Frontend Module

The RF frontend module was prototyped to prove the feasibility of small size and thin structure. Figure 10 shows the photo of the prototype RF frontend module and corresponding RF circuit configuration [17]. The thickness of the prototype is only several millimeters. Antenna side shows the antenna panel explained in the Sect. 3.1. RFICs side consists of 16 silicon ICs [18] and 64 GaAs ICs [13]. The GaAs IC consists of 3 MMICs. Each of MMICs: a three-stage HPA, a two-stage LNA and a SW. The final stage of three-stage

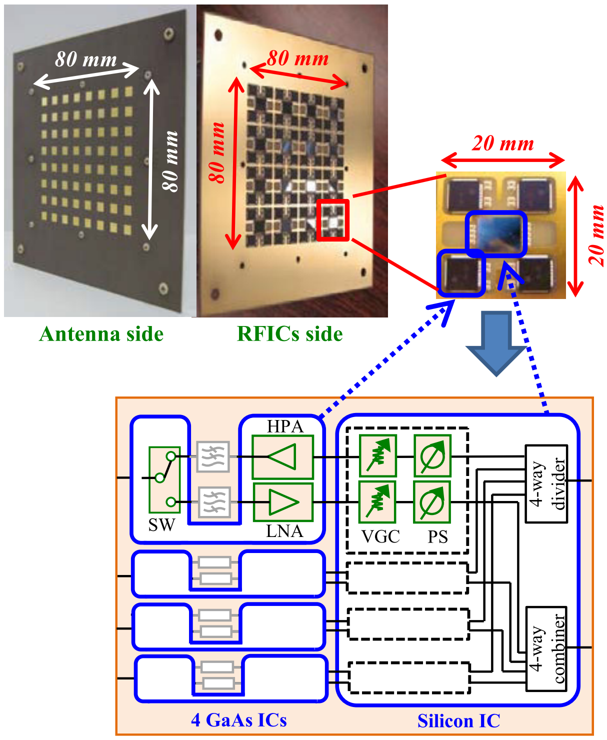


Fig. 10 Photo of the prototyped RF frontend module and corresponding RF circuit configuration.

HPA is the Doherty-HPA explained in the Sect. 3.2. These 3 MMICs are integrated into a 32-lead QFN. Silicon IC integrates 4-channel RF paths, a 4-way on-chip Wilkinson divider and a combiner. Each RF path includes a phase shifter explained in the Sect. 3.3 and a variable gain controller of which gain control range is 20 dB. Wafer level chip scale package is applied to miniaturize chip size. All components are highly integrated on the module. Mounting area of the 4 GaAs ICs and 1 Silicon IC is 20 mm × 20 mm which is equal to the area of 4 patch antenna elements. The effective area size of antenna elements and that of RFICs are exactly the same. It shows possibility to realize scalable arrangement of this RF frontend module, and this feature enables scalable antenna aperture size of 5G small cell. In addition, expected EIRP (Equivalent Isotropically Radiated Power) of the 64 elements prototype RF frontend module is over 50 dBm which is enough for prospective 5G mobile communication in urban area.

4. Conclusion

The compact RF frontend module for high SHF wide-band massive MIMO in 5G was proposed. Key RF components were fabricated, and measured results meet the requirements of low power consumption, filtering and precise beam forming. The prototype compact RF frontend module shows prospects for future 5G small cell deployment. We believe that our proposed compact RF frontend module is one of the attractive solutions for the 5G base station in high SHF band.

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References

[1] ITU-R WP5D Workshop, “Research Views on IMT Beyond 2020,” Feb. 2014. http://www.itu.int/oth/R0A06000063/en
[2] S. Suyama, J. Shen, A. Benjebbour, Y. Kishiyama, and Y. Okumura, “Super High Bit Rate Radio Access Technologies for Small Cells Using Higher Frequency Bands,” Proc. IEEE IMS 2014, pp.1–4, June 2014.
[3] F. Rusek, D. Persson, K.L. Buon, E.G. Larsson, T.L. Marzetta, O. Edfors, and F. Tufvesson, “Scaling Up MIMO: Opportunities and Challenges with Very Large Arrays,” IEEE Signal Processing Mag., vol.30, no.1, pp.40–60, Jan. 2013.
[4] J. Hoydis, S. ten Brink, and M. Debbah, “Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?,” IEEE J. Sel. Areas in Commun., vol.31, no.2, pp.160–171, Feb. 2013.
[5] J. Brady, N. Behdad, and A.M. Sayeed, “Beamspace MIMO for Millimeter-Wave Communications: System Architecture, Modeling Analysis, and Measurements,” IEEE Trans. Antennas Propag., vol.61, no.7, pp.3814–3827, July 2013.
[6] W. Roh, J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, “Millimeter-Wave Beamforming as an Enabling Technology for 5G Cellular Communications: Theoretical Feasibility and Prototype Results,” IEEE Commun. Mag., vol.52, no.2, pp.106–113, Feb. 2014.
[7] T. Obara, S. Suyama, J. Shen, and Y. Okumura, “Joint fixed beamforming and eigenmode precoding for super high bit rate massive MIMO systems using higher frequency bands,” IEEE PIMRC 2014, pp.607–611, Sept. 2014.
[8] A. Okazaki, H. Iura, N. Fukui, K. Take, and A. Okamura, “A study on next-generation wireless access with higher frequency bands,” IEICE Tech. Report, RCS2014-81, pp.287–292, June 2014. (in Japanese)
[9] A. Taira, H. Iura, K. Nakagawa, S. Uchida, K. Ishioka, A. Okazaki, S. Suyama, T. Obara, Y. Okumura, and A. Okamura, “Performance evaluation of 44 GHz band massive MIMO based on channel measurement,” Proc. GLOBECOM2015 Workshop, pp.1–6, Dec. 2015.
[10] H. Iura, A. Okazaki, K. Kihira, N. Fukui, K. Take, and A. Okamura, “A study on Antenna Configurations for MIMO system using Analog Beamforming,” IEICE Tech. Report, RCS2014-227, Dec. 2014. (in Japanese)
[11] A. Taira, S. Yamaguchi, K. Tsutsumi, S. Shinjo, A. Okazaki, and A. Okamura, “A Hybrid Beamforming Architecture for High SHF Wideband Massive MIMO in 5G,” Proc. 13th IEEE VTS Asia Pacific Wireless Communications Symposium, Aug. 2016.
[12] A.M. Kinghorn and A. Nejman, “PicoSAR - An Advanced Lightweight SAR System,” Proc. IEEE EuRAD 2009, Sept. 2009.
[13] K. Nakatani, Y. Komatsuzaki, S. Shinjo, J. Kamioka, R. Komaru, H. Nakamizo, K. Miyawaki, and K. Yamanaka, “A Highly Integrated RF Frontend Module including Doherty PA, LNA and Switch for High SHF Wide-band Massive MIMO in 5G,” Proc. IEEE PAWR 2017, pp.37–39, Jan. 2017.
[14] T. Maruyama, K. Tsutsumi, E. Taniguchi, and M. Shimozawa, “1.4 deg.-rms 6-bit Vector-Sum Phase Shifter Calibrating I-Q Generator Error by VGA for High SHF Wide-Band Massive MIMO in 5G,” in Proc. 2016 Asia Pacific Microwave Conference, New Delhi,

India, pp.1–4, Dec. 2016.
[15] K. Koh and G.M. Rebeiz, "A 6–18 GHz 5-Bit Active Phase Shifter," in Microwave Symposium Digest, pp.792–795, 2010.
[16] K.-J. Koh and G.M. Rebeiz, "0.13-μm CMOS phase shifters for X-, Ku-, and K-band phased arrays," IEEE J. Solid-State Circuits, vol.42, no.11, pp.2535–2546, 2007.
[17] H. Nakamizo, "RF front end of active phased array Antenna for high SHF wideband massive MIMO in 5G," The International Wireless Industry Consortium workshop on Antenna Innovation and Evolution, May 2016.
[18] K. Tsutsumi, W. Yamamoto, T. Maruyama, T. Fujiwara, I. Somada, T. Hagiwara, E. Taniguchi, and M. Shimozawa, "A 15 GHz 4-Channel Transmit/Receive RF Core-Chip for High SHF Wide-band Massive MIMO in 5G," Proc. IEEE SiRF 2017, pp.115–117, Jan. 2017.

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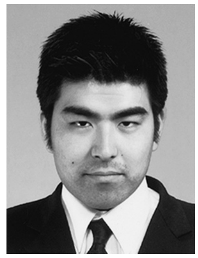

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