Recent trends and future prospective on millimeter-wave CMOS circuits

Minoru Fujishima^{a)}

School of Engineering, The University of Tokyo

7–3–1 Hongo, Bunkyo-ku, Tokyo 113–8656, Japan

a) fuji@ee.t.u-tokyo.ac.jp

Abstract: Millimeter-wave communication uses a frequency of at least 30 GHz, which is higher than that commonly used for wireless local-area networks (LANs) and cellular phones. Millimeter waves have been used for business communications and radar in luxury cars; however, their use has not yet spread to the general public. In recent years, an increasing amount of research results on millimeter-wave complementary metal-oxide semiconductor (CMOS) integrated circuits has been reported in line with the increasing attention focused on millimeter waves used for high-speed wireless communication, which can realize a communication speed higher than 1 Gbps. We discuss the social background behind this recent change in communication technologies and examine the challenges and future prospects of millimeter-wave CMOS integrated circuits.

Keywords: millimeter wave, CMOS circuit, high-speed wireless communication, digital home appliance

Classification: Integrated circuits

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1 Introduction

Millimeter waves are extremely high-frequency (short-wavelength) waves that have been known to scientists for many years. They have recently attracted much attention regarding their application to digital home appliances. This is because millimeter waves are not only capable of realizing ultrahigh-speed wireless communication, which cannot be achieved with the 2–3 GHz-band frequencies used for wireless LAN, but can also be applied to radar and image sensors. Thus far, millimeter waves have been used for radar in cars, as well as in business wireless communications. In recent years, the development of technology for realizing low-cost and low-power wireless communication using millimeter waves has been rapidly promoted all over the world. We examine the background behind the trend that has currently placed millimeter waves in the spotlight, despite the fact that they have not necessarily been in the mainstream of semiconductor applications during their long research history. We also consider the future direction in the development of millimeter-wave devices.

Fig. 1. Millimeter waves and wireless LAN. The wavelength of millimeter waves is one-tenth or less than that of radio waves used for wireless LANs but 10,000-fold that of visible light.

2 Attention-grabbing millimeter waves in 60 GHz band

2.1 History of millimeter waves and air their propagation characteristics in 60 GHz band

Millimeter waves are radio waves with a frequency band of 30–300 GHz and a wavelength of 1–10 mm. This wavelength is approximately 10,000-fold that of visible light. The wavelength of millimeter waves is approximately one-tenth that of 2–3 GHz radio waves used for wireless LANs; however, millimeter waves travel in extremely straight lines and are negligibly diffracted by objects. Therefore, they are electromagnetic waves with characteristics similar to those of light, the waves of which essentially are not transmitted other than in unobstructed spaces (Fig. 1).

Studies on millimeter waves date back to the late 19th century when Maxwell established basic equations in electromagnetics. In the 1890s, Bose conducted the first experiment using millimeter waves by applying them to produce an interelectrode spark. Microwave communication has been launched by these early experiments on millimeter waves.

Fig. 2. Attenuation of radio waves in air. In the 60 GHz band, in which high-speed communication can be realized, millimeter waves attenuate owing to absorption by O_2 in air.

Such millimeter waves have come into the spotlight again because of the discovery of the 60 GHz absorption band in 1946, about 60 years ago. Figure 2 shows the attenuation constants of radio waves in air owing to the presence of oxygen and water vapor. Millimeter waves exhibit significant attenuation of as large as ~ 15 dB/km at 60 GHz because of the resonance of oxygen molecules in air. This is the largest attenuation in the millimeter-wave frequency band of 30–300 GHz.

The frequency band that does not have good transmission characteristics in air is considered to be a serious disadvantage to wireless communication because of its unsatisfactory transmission distance. From a different viewpoint, however, this characteristic suggests high tolerance to interference between

terminals that are separated at more than a certain distance. The effective use of this characteristic enables us to allocate a broad bandwidth centering around 60 GHz to communications. Because the communication capacity is proportional to the bandwidth according to Shannon's theorem, a high communication speed can be achieved by allocating a broad bandwidth. With this background, the 60 GHz band is currently attracting the most attention among the millimeter-wave bands.

In some frequency bands around the 60 GHz band, such as at approximately 35 GHz and 80 GHz, no absorption due to oxygen and water occurs and the attenuation in air is small. These frequency bands are generally called radio wave windows, where the amount of attenuation is approximately 0.1–0.3 dB per 1 km in air, which is far less than that at 60 GHz. The 77 GHz band is currently being applied to automobile long-range radar (LRR) because of this characteristic.

The 7-GHz-range band was allocated with a specified low power (10 mW) (in 2000)

- Almost the same range as that of UWB (3.1–10.6 GHz)
- No interference with currently used frequencies

Fig. 3. Current allocation of 60 GHz frequency band in various countries. In Japan, in 2000, a 7-GHz-range frequency band of 59–66 GHz was allocated for wireless communication with a specified low power of 10 mW.

2.2 Allocation of 60 GHz frequency band

Figure 3 shows the current allocation of the 60 GHz frequency band in various countries. Frequency bands of 59.4–62.9 GHz, 57–64 GHz, and 57–66 GHz are allocated in Australia, North America, and European countries, respectively. In Japan, since 2000, the 7-GHz bandwidth of 59–66 GHz has been allocated with a specified low power output of 10 mW. This frequency band uses almost the same range as the 3.1–10.6 GHz band, which, in the US, is allocated to microwave ultrawide-band (UWB) communications (a short-distance high-speed wireless communication that uses a microwave UWB).

In the microwave UWB, some existing radio stations use 5-GHz-range frequency bands; therefore, we must avoid the use of these frequency bands; hence, full-band use is not possible. Moreover, the output power is also

limited to the field intensity equivalent to that of weak radio signals from stations using frequencies of 322 MHz or lower.

A communication speed of 480 Mbps has been achieved with the UWB. Furthermore, higher speeds of up to 1 Gbps may be possible using higher standards. We can easily achieve a transmission speed exceeding 1 Gbps in the 60 GHz millimeter-wave band, in which the 7-GHz bandwidth can be fully used.

3 Background behind increased use of 60-GHz-band CMOS circuits

The 60 GHz band has the above distinct transmission characteristics, and a standard based on them has been established. However, today's millimeter-wave CMOS circuit boom involving both industry and academia would never have occurred merely by finding the advantages and establishing associated standards. In addition to its physical characteristics, we have recently begun to clearly see the social background that has enabled us to apply the 60 GHz band to CMOS circuits, which incur a high developmental cost.

Three factors behind the accelerated research and development of CMOS circuits are considered, aiming at the application of millimeter waves. First, new applications, such as those resulting from the shift to digital appliances, for example, Hi-Vision, have been developed. Second, the demand for frequency resources has increased, namely, unused frequency bands have been sought. Third, technologies for realizing new devices have evolved [1].

Fig. 4. Change in application fields of wireless communication in electronic home appliances. Hi-Vision images will be transmitted using wireless communication owing to the application of millimeter waves to electronic home appliances.

3.1 Background (1): Shift to Hi-Vision

The high-definition multimedia interface (HDMI) is the standard for transmitting Hi-Vision moving images. HDMI1.2 requires a transmission speed of

1.65 Gbps for each of the three RGB pins ($1.65 \text{ Gbps} \times 3 \text{ colors} = 4.95 \text{ Gbps}$). This speed can be easily achieved in wireless communication using the 60 GHz band. This is because no radio stations transmit in the 60 GHz band, in contrast to the UWB, and therefore, full-band use is possible. Moreover, radio waves with an output power of 10 mW, which is approximately 2 orders higher than that of waves in the UWB, can be used for communication; thus ultrahigh-speed wireless communication of over 1 Gbps can be realized. Furthermore, the comprehensive digitization of terrestrial broadcasting, which is planned to be completed in 2011, will promote the rapid spread of Hi-Vision-based electronic home appliances, such as TVs and videos (Fig. 4).

The 60-GHz-band communication is the strongest candidate for realizing wireless communication of at least 1 Gbps, where Hi-Vision signals can be transmitted without a time delay. If digital circuits and millimeter-wave front ends (circuits for converting digital signals into millimeter-wave-band radio signals or vice versa) are constructed on a chip, ultrahigh-speed wireless communication can be realized at a low cost by a CMOS fabrication process that is suitable for mass production, resulting in the development of new applications. Moreover, not only moving images but also 2–3 Gbyte movies and other digital content can be sent in a few seconds using the 60 GHz band, increasing the value of ultrahigh-speed communication.

3.2 Background (2): Expansion of frequency resource

Ubiquitous sensor networks that use wireless communication will greatly contribute to the safety and peace of our lives in the increasingly complicated society of the future, through the introduction of sensors into objects such as cars, electronic home appliances, and even humans. A huge number of sensors are used in applications based on sensor networks, and each of them performs wireless communication, which requires a number of communication

Fig. 5. Chronological change in device performance. The high-frequency performance of CMOSs is being rapidly improved owing to miniaturization technology. Their performance is expected to exceed the high-frequency performance of SiGe semiconductors by 2014 at the current rate of the progress of the technology.

channels proportional to the number of terminals. Because frequencies are considered to be limited resources, we must explore new frequencies to create new applications, such as sensor networks. The exploration of new frequencies also constitutes part of the background of the research and development of the millimeter-wave frequency band.

3.3 Background (3): Advance of device technology

To incorporate millimeter-wave communication devices into digital home appliances, it is necessary to fabricate millimeter-wave circuits by the process used for fabricating logic CMOSs. The high-frequency performance of metal-oxide semiconductor field-effect transistors (MOSFETs) was markedly improved by the use of CMOS miniaturization technology. According to the 2007 version of the International Technology Roadmap for Semiconductors (ITRS 2007), the cutoff frequency of MOSFETs (f_T) is expected to become greater than that of SiGe HBTs by 2014 (Fig. 5). If semiconductor devices consisting of different materials are manufactured with identical accuracy, their high-frequency characteristics will be determined by the mobility of carriers in semiconductor materials. The high-frequency performance of Si semiconductors, in which the mobility of electrons is lower than that in InP and SiGe semiconductors, will be lower than that of such compound semiconductors manufactured with the same fabrication accuracy as that of the Si semiconductors. The high-frequency performance of conventional Si semiconductors was initially lower than that of compound semiconductors. However, there has been much greater investment in the development of miniaturization technology than in the research of compound semiconductors in order to

Fig. 6. Change in the number of reports on millimeter waves. The number of reports on GaAs markedly decreased whereas the number of reports on CMOSs markedly increased over 2006–2007. (This result was obtained by searching for keywords in reports registered in the IEEE eXplorer database.)

improve the performance of digital circuits, resulting in the rapid advancement of micromachining technology for Si semiconductors rather than for compound semiconductors. This miniaturization technology has enabled to reduce the carrier traveling time, which governs the high-frequency performance of devices, and to overcome the handicap of the low mobility. It is expected that n-channel MOSFETs (nMOSFETs), the fabrication of which is based on the CMOS process, will exhibit higher speed and superior higher-frequency performance than other devices within the next ten years. As a result, applications based on submillimeter-wave and millimeter-wave bands above 10 GHz, which have not been used thus far, are expected to be created using CMOS technology, which is suitable for mass production.

4 Trends in research and development of millimeter-wave circuits

With the above technological and social background, the research and development of millimeter-wave-band ICs that use Si-group-based devices, such as SiGe and CMOSs, have intensified in recent years. In 2006, IBM reported a 60-GHz-band transceiver chip made using SiGe technology [2]. Figure 6 shows the trend in the number of reports on millimeter waves. Note the change in the number of reports on GaAs and CMOSs between 2006 and 2007. Until 2006, compound semiconductors, including GaAs semiconductors, with high device performance had been mainly developed and promoted for application to millimeter waves. In 2007, however, the number of reports on millimeter waves using GaAs decreased, and instead, the number of reports on CMOSs markedly increased. Nearly 150 reports were published in FY 2007, suggesting a strong focus on millimeter-wave CMOS circuits. It is probable that a considerable number of researchers have shifted their research target from GaAs to CMOS in recent years. IEEE802.15.3c, established in 2008, is a standard for 60-GHz-band wireless communication and will promote further research and development in the future. (The preparation of a new standard by IEEE802.15.3 Task Group 3c (TG3c) is ongoing as of September 2008. Details of the progress are available at <http://www.ieee802.org/15/pub/TG3c.html>).

Millimeter-wave CMOS circuits are being researched and developed with the main aim of realizing a 60-GHz-band transceiver, and the challenges facing researchers are not limited to those related to circuits. We introduce some specific challenges in the research of millimeter-wave CMOS circuits different from the design challenges for other GHz bands.

4.1 Evaluating technology for millimeter-wave devices

A model for devices using the millimeter-wave band is needed for the development of millimeter-wave CMOS circuits. To construct a device model, it is necessary to establish a high-accuracy evaluation method for the millimeter-wave band. When a device fabricated on a Si wafer is evaluated, the electric characteristics of the device are measured by placing a high-frequency mea-

suring probe (RF probe) in contact with the electrode (pad) on the wafer. The obtained result includes the characteristics of the pad because the pad used for measurement purposes is attached to the device. De-embedding is necessary to remove the electric characteristics of the pad and obtain those of the device only. In de-embedding, we must consider the electromagnetic coupling between the pad wiring layer and the Si wafer, wiring loss from the pad to the device, and the characteristics of the interlayer connection via hole from the topmost pad through to the bottom layer connected to the device. However, it is difficult to maintain high accuracy for de-embedding because the frequency characteristics of pads in the millimeter-wave band exhibit complicated behavior, such as that of a distributed circuit, that cannot be described by a simple resistance/capacitance model. Thus, the quality of circuit design is dependent on the accuracy of the evaluation of the pad characteristics in the millimeter-wave band.

4.2 Simulation accuracy and device modeling

Not only should models of conventional devices, such as MOSFETs, inductors, and capacitances, be constructed, but also, device models specific to millimeter waves, such as transmission lines and baluns (balanced-to-unbalanced transformers, which are circuits for converting between balanced and unbalanced signals), are needed. However, for devices developed since the generation of the 90 nm or later CMOS process, which is used for the fabrication of millimeter-wave CMOS circuits, the number of wiring layers is large and parasitic elements are added because dummy metals are inserted owing to the limitations of the fabrication process. Moreover, the Si wafer used for CMOS circuits is conductive, and thus the interaction between circuits and wafers cannot be ignored. Therefore, it is difficult to adapt the equivalent circuit models of millimeter-wave-band passive devices, which have been developed in the compound semiconductor industry, to the design of millimeter-wave CMOS circuits without any modification. The adaptation of such models to deal with unexpected factors in design will lead to an improvement in design accuracy.

The Berkeley short-channel IGFET model (BSIM) has been continuously developed as a CMOS device model for over ten years at the University of California, Berkeley, US. In line with the advance of miniaturization technology, models that are appropriate to the technology are being provided. It is an important task to improve the design environment by considering the use of millimeter waves in order to continue the application of state-of-the-art device technology. At present, the construction of an original device model is the only way to promote the research and development of millimeter-wave CMOS circuits under the condition that no device model that satisfactorily accommodates the millimeter-wave band is provided by industry. Namely, it is necessary to have knowledge of not only circuit design but also device modeling and the underlying layout to carry out the research and development of millimeter-wave CMOS circuits. Conversely, it is possible to markedly improve circuit performance if the layout of the device, as well as the circuit

design, is optimized for millimeter-wave CMOSs by precise modeling of the circuit.

4.3 Efficiency of power amplifier circuit

There are also many tasks that must be completed in the technology of circuits and architecture in order to realize the millimeter-wave band in CMOS circuits, in addition to the evaluation and modeling of devices. One challenge is related to the decrease in the voltage tolerance.

The high-frequency performance of MOSFETs has been improved owing to miniaturization technology, which has caused a decrease in the voltage tolerance. This relationship is expressed by the Johnson limit, which describes the trade-off between the voltage tolerance and the cutoff frequency obtained from the band gap of semiconductors. The Johnson limit originally referred to the relationship between the high-frequency characteristics and the voltage tolerance for bipolar transistors [3]. The relationship between the cutoff frequency for Si bipolar transistors f_T and the voltage tolerance between the collector and emitter, BV_{CEO} , is given as

$$f_T \cdot BV_{CEO} = 200 \text{ GHz} \cdot \text{V}. \quad (1)$$

When f_T and BV_{CEO} in eq. (1), which is not always applied to MOSFETs, are replaced with the cutoff frequency and the voltage tolerance at the drain for MOSFETs, respectively, f_T becomes $\sim 100 \text{ GHz}$ at a supply voltage of 1 V for a 90 nm nMOS. The voltage tolerance is at approximately twice the supply voltage, indicating that the relationship of the Johnson limit roughly holds. A value of $400 \text{ GHz} \cdot \text{V}$ has been achieved recently [4]. With the further progress of miniaturization technology in the future, much remains to be studied regarding to what degree f_T will be increased while the voltage tolerance is maintained. Nonetheless, the improvement of voltage tolerance will remain a major issue.

We also have the task of realizing a high-output power amplifier using CMOSs because of the decrease in the voltage tolerance owing to the Johnson limit. A maximum output of 10 dBm is currently allowed in the 60 GHz band; however, the voltage amplitude reaches 2 V_{pp} under a load of 50Ω , exceeding the voltage tolerance. It is necessary to decrease the load impedance measured from the side of the power amplifier to below 50Ω in order to realize a high output without exceeding the voltage tolerance. In this case, the voltage amplitude will decrease, whereas the current amplitude will increase. The loss due to parasitic resistance will increase with increasing current amplitude, which reduces the efficiency of the power amplifier circuit.

As a result, the power added efficiency (PAE: expressed by the ratio of the power obtained by subtracting the input ac power from the output ac power to the dc power supplied to the power amplifier) obtained for the 60-GHz -band CMOS power amplifier has so far been less than 10% . A power of at least 100 mW is required to obtain an output of 10 mW at a power efficiency of 10% . Recently, the achievement of a power efficiency close to 20% has been reported [5]. For mobile terminals with low power consumption, it will be

important to increase their power efficiency while maintaining high reliability by using miniaturized MOSFETs.

5 Perspective of millimeter-wave CMOS circuit

The 60-GHz-band millimeter-wave CMOS circuits are mainly being studied and developed in accordance with the IEEE802.15.3c standard. We examine the approach of applying the broad 60 GHz band to realize wireless communication with low power consumption. We also consider the prospects of wireless communication at frequencies higher than 100 GHz.

Fig. 7. Block diagram schematically showing millimeter-wave-band pulse communication. The use of pulse communication enables us to remove the local oscillator circuits, which have high power consumption, and the A/D and D/A converter circuits from the transmitter and receiver circuits.

5.1 CMOS millimeter-wave pulse transmitter and receiver circuit

In Japan, the 7-GHz bandwidth has been allocated for wireless communication in the 60 GHz band with a specified low power output. It is possible to remove millimeter-wave oscillator circuits with high power consumption from transmitters and receivers in pulse communication with a broad frequency band to realize low-power-consumption millimeter-wave communication. Figure 7 shows a block diagram schematically showing pulse communication.

Chip micrograph
CMOS 90nm 9M1P

Technology	90nm CMOS
Frequency	59-66GHz
Modulation	PPK
Supply Voltage	1.15V
Max Data Rate	1.5Gbps
Power Consumption	11mW@ 1.5Gbps
Core Size	90 × 20μm ²

Fig. 8. Image and specifications of a 60 GHz CMOS pulse generator circuit chip. Millimeter-wave pulse signals can be generated using the CMOS delay circuit without local oscillator circuits.

Fig. 9. Image and specifications of 60 GHz CMOS pulse receiver chip. Millimeter-wave pulse signals can be received by detecting envelopes using a non-linear amplifier circuit without local oscillator circuits.

Fig. 10. I/O waveform of 60 GHz CMOS pulse communication circuit. Digital signals can be decoded at the output by inputting the amplitude modulation signals in the 60 GHz band to the receiver.

The 60-GHz-band millimeter-wave pulse signals are generated in transmitter circuits when each of multiple pulse generator circuits with a pulse width of 16 ps is operated with a time delay of 16 ps [6]. Figure 8 shows an image and the specifications of a chip on a CMOS pulse transmitter. The pulse generator circuits that make use of this method, in which no passive elements are used, can be realized with a size of $90\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$. The pulse spectra generated are maintained within the specified spectrum mask in the limited frequency bands by arranging the envelopes of pulse signals in the circuit. The power consumption at a data transfer rate of 1.5 Gbps is 11 mW.

In the receiver circuit, the millimeter-wave pulse signals received are used as base band signals because of square wave detection using a nonlinear amplifier circuit [7]. These signals are encoded to digital signals using a limiting amplifier (LA). Figure 9 shows an image of the receiver chip. The core area of the pulse receiver is $565\text{ }\mu\text{m} \times 727\text{ }\mu\text{m}$. Figure 10 shows the result of observing the output waveform using a sampling oscilloscope when the input

Fig. 11. Allowable electric field intensity at a position 3 m from a weak radio station. High electric field intensity is allowed at frequencies of 322 MHz or lower and 0.15 THz or higher in weak radio stations. The values in parentheses represent the converted values of the transmission power spectrum in the case of using an omnidirectional antenna.

consists of 2 Gbps millimeter-wave pulse signals. The power consumption at 2 Gbps is 19.2 mW.

5.2 From millimeter-wave to terahertz communication

The frequency band of millimeter waves ranges from 30 GHz to 300 GHz (= 0.3 THz). However, general applications will be limited to the 76 GHz band used for car radar and the 60 GHz band used for high-speed data communication in the near future. Both the 60 GHz and 76 GHz bands are part of the standard frequency band with the specified low power, in which it is permitted to output a power of 10 mW without a license. However, communication using the specified low power must satisfy the designated applications and communication methods.

For some weak radio waves, the applications and communication methods are not limited. In Japan, when radio waves exhibit the electric field intensity shown in Fig. 11 at a point 3 m from the transmitter, the waves at this point can be applied to wireless communication as a weak radio station without limitations on the applications and communication methods. As is clear from the figure, the allowable electric field intensities have a difference of a factor of 10 or more between the bands below and above 322 MHz; therefore, weak radio waves with a frequency of 322 MHz or lower are generally selected for use as simple radio waves. This is because the high electric field intensity at a point 3 m from the transmitter means that the radio waves can travel a long distance.

Similar to the frequency of 322 MHz or lower, an electric field intensity of 500 $\mu\text{V/m}$ is permitted for a frequency of 0.15 THz (= 150 GHz) or higher. In the standard for weak radio stations, it is stated that a hollow horn wire

must be used and that the resolution bandwidth (RBW, which is the bandwidth of band-pass filters with respect to the signals input into a spectrum analyzer) of the spectrum analyzer used to indicate peak values must be set to 1 MHz. This indicates that the electric field intensity is determined by the power per 1 MHz in weak radio stations. The electric field with an intensity of $500\text{ }\mu\text{V/m}$ at a point 3 m from a weak radio station is converted into a transmission spectrum of 75 nW/MHz under the assumption of an omnidirectional antenna. The power per 1 MHz is markedly different between frequencies below 322 MHz and those above 0.15 THz. For example, when the relative band (=bandwidth/carrier wave frequency) is 1/10, the bandwidths of 200 MHz and 0.2 THz carrier waves are 20 MHz and 20 GHz, respectively. When these values are multiplied by 75 nW/MHz , the outputs of weak radio stations with bandwidths of 20 MHz and 20 GHz become $1.5\text{ }\mu\text{W}$ and 1.5 mW , respectively. The output of 1.5 mW , which is far below the maximum value of 10 mW allowed for the specified low power, may enable radio signals to be transmitted with a relatively high output of at least 1 mW from weak radio stations.

Moreover, the loss of radio waves in air at 0.15 THz is less than that at 60 GHz, as shown in Fig. 2. The O_2 absorption band is at 60 GHz and 118 GHz, and the H_2O absorption band is at 183 GHz and 325 GHz. The 0.15 THz band with little attenuation of radio waves by air is used in radio astronomy. The 0.12–0.17 THz and 0.2–0.3 THz bands suggest the possibility that short-distance communication with a transmission output smaller than that in the 60 GHz band can be realized at a communication speed of over 10 Gbps at weak radio stations.

It is difficult to obtain high transmission output in millimeter-wave CMOS circuits; therefore, we should consider the possibility of ensuring the necessary transmission distance by making use of frequency bands that are little attenuated by air.

6 Conclusion

Millimeter-wave technology using CMOS circuits has been experiencing a boom in recent years, and between one-third and one-half of the reports in the session on high-frequency waves at a recent international conference on integrated circuits concerned millimeter waves. Millimeter-wave communication enables us to combine wireless communication and a high communication speed of 1–10 Gbps, which is equivalent to that in the previous-generation optical communication, and thus has attracted much attention. The difficulty of communicating in blind spaces, which is an obstacle to the practical application of millimeter-wave communication, has been overcome owing to the realization of the array antenna and digital processing technology. Millimeter-wave communication is expected to rapidly spread in the future as a result of changes in the social environment and advances in technology.

Minoru Fujishima

received the B.E., M.E. and Ph.D degrees in Electronics Engineering from the University of Tokyo, Japan in 1988, 1990 and 1993, respectively. He joined the faculty of the University of Tokyo in 1988 as a Research Associate, and is currently an Associate Professor of the School of Frontier Sciences, University of Tokyo. He was a visiting Professor at the ESAT-MICAS Laboratory, Katholieke Universiteit Leuven, Belgium, from 1998 to 2000. His interests are in designs of low power and high-speed CMOS circuits.