Overview of sub-terahertz communication and 300GHz CMOS transceivers

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Abstract  A 44 GHz frequency band from 252 GHz to 296 GHz has been identified for communications. This frequency band is part of the 300 GHz band, which is expected to be utilized for ultra-high speed wireless communication toward 6G. In this letter, we will discuss the requirements for ultra-wideband wireless communications in the sub-terahertz range, including the 300 GHz band, and clarify the necessity of a communication system based on phased arrays. Finally, a 300 GHz CMOS wireless transceiver capable of transmitting data rates of up to 80 Gb/s that can be utilized as an element of this phased array is presented.

Keywords: sub-terahertz, millimeter wave, wireless communication, CMOS, high-speed, 300 GHz, beam forming

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Data rates for both wired and wireless communications are increasing every year [1]. In particular, the data rate of wireless communication continues to increase at a rate of 10 times in almost four years, which is much faster than the rate of increase of the data rate of wired communication. As a result, by the year 2020, the data rate of wireless communications will already reach 100 gigabits per second at the research level [2]. If the data rate of wireless communication continues to grow at this rate, the maximum data rate per carrier is expected to be the same for wired and wireless communication by 2030.

On the other hand, the 5th generation communication, so-called 5G, started globally around 2020. Recently, discussions on its next generation, Beyond 5G or 6G, have started. According to a published white paper [3], Beyond 5G not only aims to improve data rates compared to 5G, but also to expand the coverage of high-speed communications to the sky, sea, and even space. Higher carrier frequencies are expected to contribute to higher data rates. Figure 1 shows the allocation of frequencies from 252 GHz to 296 GHz, which are the main frequencies for 300 GHz band communications; 252 GHz to 275 GHz have been previously identified for mobile and land-fixed communications. In addition, at the 2019 World Radiocommunication Conference (WRC 2019), 275 GHz to 296 GHz were also identified for telecommunication toward 6G. In this letter, we will discuss the requirements for communications for the first time in WRC 2019. As a result, a total of 44 GHz of continuous frequency bands can be used for communications in the 300 GHz band.

2. Relationship between frequency bandwidth and communication capacity [5]

According to the Shannon-Hartley theorem, the communication capacity $C$ is

$$C = B \log_2 \left(1 + \frac{S}{N}\right),$$

where $B$ is the frequency band, $S$ is the signal power, and $N$ is the noise power. If we consider (1) in the receiver of wireless communication

$$C = B \log_2 \left(1 + \frac{P_r}{kT \cdot NF}\right),$$

where $P_r$ is the received power, $k$ is Boltzmann’s constant, $T$ is the absolute temperature, and NF is the noise figure of the receiver. Here, the frequency band $B$ appears twice in the equation. When $B$ is small and $P_r \gg kT \cdot NF$, (2) can be approximated as

$$C \approx B \left(\log_2 \frac{P_r}{B} - \log_2 (kT \cdot NF)\right).$$

Since the change in $B$ contained in the logarithm in parentheses has less effect on $C$ than the change in $B$ outside the
Fig. 2  Relationship between RF frequency band and communication capacity. Calculations were made for the cases of received power of 0.1 µW, 1 µW, and 10 µW. In all cases, the communication capacity is saturated when the bandwidth becomes very wide.

parentheses, $C$ increases almost proportionally to $B$ in this region. This is the motivation for increasing the carrier frequency to widen the frequency band. Conversely, when $B$ is large and $P_r \ll kT B/NF$, (2) becomes

$$C \simeq \frac{P_r}{kT \cdot NF \cdot \ln 2},$$

and the communication capacity is determined by the received power regardless of the frequency band. In other words, to expand the frequency band and increase the communication capacity, sufficient received power is necessary.

Figure 2 shows a graph of the communication capacity against the frequency band when the received powers are 0.1 µW, 1 µW, and 10 µW. The reason why the received powers are much larger than that of microwave communication is that the frequency band is assumed to be ultrawide band of over 1 GHz. From Fig. 2, it can be seen that when the received power is 0.1 µW, the increase in communication capacity approaches saturation in the range where the frequency band exceeds 10 GHz. In WRC 2019, not only the 300 GHz band, but also the 400 GHz band, from 356 GHz to 450 GHz, has been identified for communication [4]. In the 400 GHz band, up to 94 GHz of bandwidth is available. Therefore, a frequency band of up to 100 GHz will be the technology target for the next decade. The 44 GHz frequency band available in the 300 GHz band and the 94 GHz frequency band in the 400 GHz band require a received power of about 1 µW to provide sufficient communication capacity. This is a notable difference from microwave communication.

Figure 3 shows the relationship between the frequency band and the signal-to-noise ratio when the received powers are 0.1 µW, 1 µW, and 10 µW. Figure 3 also shows the signal-to-noise ratio required for QPSK, 16QAM, and 64QAM communications. For a frequency band of 100 GHz, even QPSK requires 1 µW of received power. Furthermore, to achieve 16QAM or 64QAM communication, 10 µW of receiving power is required. Therefore, in order to realize ultra-wideband communication beyond 10 GHz, which is expected in sub-terahertz communication, it is necessary to increase the received power.

3. Relationship between frequency and communication distance

In general, the higher the carrier frequency is, the more difficult it becomes to extend the communication distance. The main reason is the frequency band that can be expanded by increasing the carrier frequency, as discussed in Section 2. Increasing the received power to widen the frequency band is necessary regardless of the carrier frequency. On the other hand, even when the frequency band is equal, increasing the carrier frequency is thought to shorten the communication distance. There are two main reasons for this. One is atmospheric attenuation, and the other is propagation loss. In this section, the transmittable distance from the viewpoint of carrier frequency is considered.

Figure 4 shows a graph of atmospheric attenuation from the millimeter wave band to the terahertz band [6, 7]. It can be seen that the atmospheric attenuation increases as the frequency increases, and when the atmospheric attenuation exceeds 10 dB at 1 km, long distance communication becomes difficult. This level is exceeded at 60 GHz, 183 GHz, 325 GHz, and over 360 GHz. Therefore, it is difficult to transmit over long distances on the ground with an atmosphere using a frequency band beyond 300 GHz, which exceeds the millimeter wave band. On the other hand, even in the millimeter wave band, atmospheric attenuation can be reduced by avoiding the above frequencies. In particular, the atmospheric attenuation from 252 GHz to 296 GHz used in the 300 GHz band is as small as 0.3 dB/km. Figure 5 shows the transmittable distances for the frequencies from 200 GHz to 500 GHz. Here, the transmittable distance is defined as the distance where the atmospheric attenuation is 10 dB. The gray area in Fig. 5 is a frequency band that is not specified for communication. Figure 5 shows that in the 300 GHz band, the transmittable distance is about 3 km.
under good weather conditions. Therefore, even in the 300 GHz band, the atmospheric attenuation is much lower than the 17 dB/km atmospheric attenuation in the 60 GHz band, and the atmospheric attenuation does not interfere with long-distance communication. On the other hand, in the 400 GHz band, the transmittable distance is limited to about 50 meters due to the inclusion of frequencies where the atmospheric attenuation peaks.

On the other hand, the propagation loss, which is the ratio of received power to transmitted power, is given by

\[
\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4 \pi d}\right)^2
\]

(5)

according to Friis’ propagation formula. Here, \(P_r\) is the received power, \(P_t\) is the transmitted power, \(G_t\) and \(G_r\) are the transmit and receive antenna gains, respectively, \(\lambda\) is the wavelength, and \(d\) is the communication distance. From this equation, we can see that under the condition of constant antenna gain, \(P_t\) becomes smaller in proportion to \(\lambda^2\). In other words, if the antenna gain does not change, \(P_t\) will rapidly decrease as the frequency increases. On the other hand, the antenna gain \(G_t\) is given by

\[
G_t = \frac{4 \pi}{\lambda^2} A_t,
\]

(6)

where \(A_t\) is the effective antenna area. If the effective antenna area does not change, the antenna gain increases inversely proportional to \(\lambda^2\). Substituting equation (6) into equation (5), we get

\[
\frac{P_r}{P_t} = \frac{A_t A_r}{(\lambda d)^2}.
\]

(7)

where \(A_t\) and \(A_r\) are the effective transmit and receive antenna areas, respectively. This is the equation shown in Friis’ original paper [8]. This equation means that under the condition that the effective antenna area is constant, \(P_t\) increases inversely proportional to \(\lambda^2\) [9].

If we substitute the equivalent isotropic radiated power EIRP(= \(P_t \cdot G_t\)) into (5), we get

\[
P_t = \text{EIRP} \cdot G_t \left(\frac{\lambda}{4 \pi d}\right)^2.
\]

(8)

Furthermore, by applying (6) to \(G_t\), we obtain

\[
P_t = \text{EIRP} \frac{A_t}{4 \pi} = \text{EIRP} \frac{\Omega}{4 \pi},
\]

(9)

where \(\Omega\) is the solid angle from the transmitter to the receiving antenna. From (9), it can be seen that \(P_t\) is determined by the EIRP, \(A_t\), and \(d\), and is independent of \(\lambda\). In other words, the carrier frequency and propagation loss are essentially unrelated. Wideband communication that requires large received power affects the transmittable distance, but if the bandwidth is the same and atmospheric attenuation is ignored, the transmittable distance does not change even if the carrier frequency is increased.

Since the most important reason to increase the carrier frequency is to increase the bandwidth, let us assume that the relative bandwidth is constant. We also assume that \(P_t\) is inversely proportional to the carrier frequency, i.e., proportional to \(\lambda\), because it is difficult to obtain a large \(P_t\) when both the carrier frequency and bandwidth increase. If \(A_t\) and \(A_r\) are constant, \(G_t\) is inversely proportional to \(\lambda^2\), and thus EIRP is inversely proportional to \(\lambda\). Since \(A_t\) is constant, \(\Omega\) does not change, so \(P_t\) is inversely proportional to \(\lambda\). This means that the signal-to-noise ratio can be maintained with a constant relative bandwidth. In other words, in order to increase the bandwidth by increasing the carrier frequency, it is necessary to keep the effective area of the antenna unchanged. In this case, the antenna gain increases in proportion to the square of the frequency.

4. Terahertz communication and phased array

If the antenna size is constant, the received power increases in proportion to the frequency even if the transmit output power decreases in proportion to the wavelength (and in-
Table I  Output power and antenna gain versus the number of parallel phased array transmitters, with 0 dBm (1 mW) transmit power and 7 dBi antenna gain per element.

| Number of Elements | Combined output power | Antenna gain |
|--------------------|-----------------------|--------------|
| 4 parallel (2 x 2) | 6 dBm (6mW)           | 13 dBi       |
| 64 parallel (2 x 2) | 18 dBm (64mW)         | 25 dBi       |
| 1k parallel (2 x 2) | 30 dBm (1W)           | 38 dBi       |
| 16k parallel (2 x 2)| 42 dBm (16W)          | 50 dBi       |

Fig. 6  The relationship between (a) the transmittable distance and (b) the half-power beamwidth when n is varied in an n x n phased array system. It is assumed that the carrier frequency is 300 GHz, the data rate is 100 Gb/s (16 QAM and 25 Gbaud), the receiver NF is 10 dB, and the BER is 10^-3.

versely proportional to the frequency). In this case, the antenna gain increases inversely proportional to the square of the wavelength according to equation (6). This means that the transmit beam of the transmitter becomes sharper and the receive range of the receiver becomes narrower. Beam steering technology is important for realizing communications with high antenna gain. For electronic beam steering, phased array antennas are used, which control the beam direction by changing the phase of feeding and receiving antennas arranged on a plane. When a phased array is used for the transmitter and a transmitter element is connected in parallel to each antenna element, the antenna gain is not only improved, but the transmit power is also increased due to spatial combination of power. In general, it becomes difficult to generate high transmit power as the frequency increases, but parallel combination can compensate for the transmit power. Table I shows the output power and antenna gain of a 0 dBm transmitter and a patch antenna with an antenna gain of 7 dBi. 4 (2 x 2) parallel elements would limit the application to short-range communication, but 16k (128 x 128) parallel elements would result in a total output power of 16 W and an antenna gain of 50 dBi [5]. Even with such a large number of elements in parallel, the size of the antenna is only about 10 cm because the wavelength in the 300 GHz band is about 1 mm.

Figure 6(a) shows the transmittable distance of the phased array antenna calculated in this table. In the case of the smallest 2 x 2 element, the transmittable distance is limited to about 50 cm, but with the 64 x 64 element, the transmittable distance is 10 km, and with the 128 x 128 element, the transmittable distance is 100 km. 64 x 64 elements can be used for communication from the ground to an aircraft, and 128 x 128 elements can be used for a link between the ground and a low earth orbit (LEO) satellite. On the other hand, how much precision is required for beam control? Figure 6(b) shows the relationship between the number of phased array elements and the half-power beamwidth, which is relatively wide at 25 degrees for 2 x 2 elements, 0.8 degrees for 64 x 64 elements, and 0.4 degrees for 128 x 128 elements. If a phased array system with such precise beam control could be realized, it would be possible to achieve long-distance sub-terahertz communications.

5. 300 GHz CMOS transceivers

Transceivers with precise beam control are the key to the practical application of 300 GHz band communications. On the other hand, digital processing is essential to control the beam and to compensate the performance variations in the background. Digital processing can only be realized in CMOS integrated circuits. If a 300 GHz transceiver is to be realized in a CMOS integrated circuit, the fmax (unity gain frequency) of silicon MOSFETs will be an issue. In general, the high frequency characteristics of silicon MOSFETs are inferior to those of compound semiconductors and SiGe [10, 11, 12, 13, 14, 15]. Therefore, it is difficult to realize a high-power transmitter. However, if the transmitter is to be incorporated into a phased array, even if the output power of each transmitter is 0 dBm, it is still possible to achieve long-distance communication as shown in Fig. 6. Therefore, it is important to realize transmitters with a medium output power of about 0 dBm even with CMOS integrated circuits with inferior characteristics. Therefore, we have developed a single-chip CMOS transceiver with a transmit power of −1.6 dBm output.

Figure 7 shows a part of the 300 GHz channel allocation proposed in IEEE Standard 802.15.3d [16]. Here, 252.72 GHz to 321.84 GHz are allocated in several frequency bands. For example, 32 channels are allocated in the 2.16 GHz band, which is similar to the basic channel allocation in the 60 GHz band. However, some of the grayed-out frequency bands in this band are not specified for communications and cannot be used in practice. We have developed a prototype transceiver using channel 66, which has a frequency band 12 times larger than 2.16 GHz.

The problem in realizing a 300GHz transceiver using CMOS is that it is difficult to realize a 300GHz amplifier. Therefore, as shown in Fig. 8, it is not possible to use the power amplifiers and low-noise amplifiers used in ordinary transceivers [17, 18, 19, 20]. Also, it is not possible to use...
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Fig. 8 Schematic architecture of a wireless transceiver, where the use of CMOS precludes power amplifiers, low-noise amplifiers, and local oscillator signal generation using the fundamental wave.

Fig. 9 Architecture of a 300GHz CMOS transceiver using Ch 66 of IEEE 802.15.3d. A rat-race circuit is used to integrate the transmitter and receiver.

Fig. 10 Chip micrograph of an 80 Gb/s 300 GHz CMOS transceiver using Ch 66 proposed in IEEE 802.15.3d, fabricated using a 40 nm bulk CMOS process.

As a result, only the desired signal can be extracted if the signal is taken out from the differential port of the rat-race circuit.

On the other hand, in the receive mode, the common-mode port of the rat-race circuit is used in Fig. 9. In the receive mode, the baseband signal is not input, and the signal of half the frequency of the local oscillation signal (indicated as LO in Fig. 9) is input to the doubler (mixer) in common-mode. This doubler is the same circuit that operated as a mixer in the transmit mode. This generates a common-mode 300 GHz band local oscillation signal (denoted as LO\textsuperscript{2} in Fig. 9) in the common mode. As a result, the 300 GHz band local oscillation signal with enhanced power can be extracted from the common-mode port of the rat-race circuit. In the receive mode, this signal is input to the 90-degree hybrid to generate a quadrature signal, which is then input to the fundamental mixer.

Figure 11 shows a wireless communication experiment using an 80Gb/s 300GHz CMOS transceiver with IEEE 802.15.3d Ch 66. 80 Gb/s is achieved using 16 QAM, 20 Gbaud.

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sent to a real-time oscilloscope for signal analysis. The results are shown in the table on the lower right. The maximum symbol rate of 20 Gbaud was obtained at a communication distance of 3 cm in 16QAM using channel 66. The data rate at this time was 80 Gb/s, and the transmit output power was −1.6 dBm. Although it did not reach the target output power of 0 dBm, we were able to take a step toward a phased array system using CMOS integrated circuits.

6. Conclusions

The invention of the magnetron made it possible to generate high-power microwaves [31], and as a result, research on wireless communication using microwaves has made great progress since 1920. In addition, the invention of low-loss optical fiber [32] has greatly advanced the research of wired communication using optical fiber since 1970. The data rate of wired communication is much higher than that of wireless communication, making it possible to send large amounts of digital data. However, wireless communication, which allows communication without the use of connecting lines, did not end with the advent of optical communication. On the other hand, we believe that the sub-terahertz communication discussed here will blossom from 2020, 50 years after the start of the progress of optical communication in 1970. Even if sub-terahertz communication can achieve the same speed as wired communication and can communicate without connecting lines as wireless communication, microwave communication and optical communication will continue to remain in our lives. Sub-terahertz communications will not only have high data rates, but will also extend coverage to the sky, sea and space, where high-speed links have not been possible.

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