Invited Paper

Emerging applications with terahertz communication

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Abstract: Terahertz communication using an unallocated frequency band called 300-*GHz* band exceeding 275 *GHz* attracts attention. In this 300-*GHz* band, research on wireless communication circuits not only using compound-semiconductor transistors with superior high-frequency performance but also using BiCMOS integrated circuits using silicon germanium transistors and advanced miniaturized CMOS integrated circuits have increased. In this paper, application and future of terahertz communication technology with the 300-*GHz* band attracting attention is discussed.

Keywords: Terahertz, 300 *GHz* band, Communication, Integrated circuits

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1. Introduction

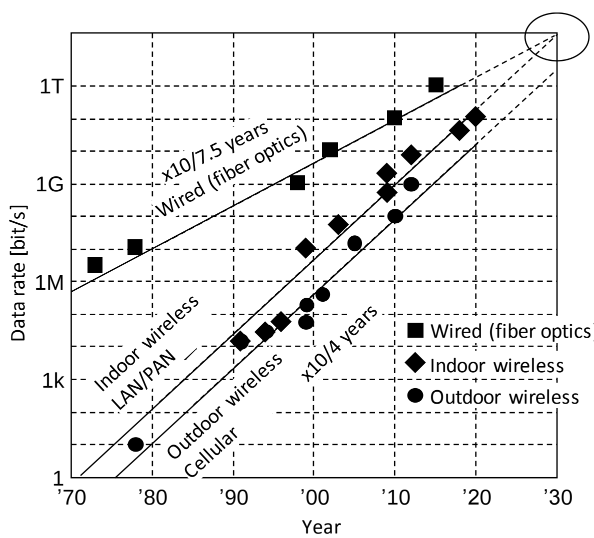

Fig. 1 Evolution of data rate of wired communication and wireless communication. The evolution of data rate of wireless communication is faster than wired communication, and it is expected to reach 100 gigabits per second in 2020. Furthermore, if evolution continues at this rate, the data rate of wireless communication will be equivalent to wired communication in 2030.

The data rate of communication has increased exponentially year by year [1] (Fig. 1). Especially, the improvement of the data rate of wireless communication is remarkably rapid as compared with wired communication. If the data rate improves with this advancement, in 2020, the data rate of 100 gigabits per second which could not be realized except for optical communication can be realized by wireless communication. In the field of ultrahigh-speed wireless communication, wireless circuits with data rates exceeding 100 gigabits per second have recently been released as if to support this [2]. Extrapolating the graph as this data rate growth will continue in the future will result in the possibility that the wireless data rate will catch up with the wired data rate in 2030. Of course, there are still many technical challenges left to keep the wireless data rate catching up with the wired data rate, and it cannot simply be realized. However, soon, the common sense that the data rate of wireless communication is low will pass away.

On the other hand, the frequency band exceeding 275 *GHz* is not currently used. Discussions on utilizing this wide frequency band for communication are being advanced in the International Telecommunications Union Radiocommunication Sector (ITU-R). Since the band of 252 *GHz* to 275 *GHz* has already been allocated to communication, it is expected that a continuous wide band exceeding 252 *GHz* that centers 275 *GHz* will be available soon for wireless communication. Since this frequency is included in the band of 220 *GHz* to 330 *GHz* of the waveguide WR-3, research on communication in this frequency band has become active in recent years. The communication using this band of WR-3 is called 300 *GHz* band communication. In this paper, newly developed applications of terahertz communication including the 300 *GHz* band will be discussed.

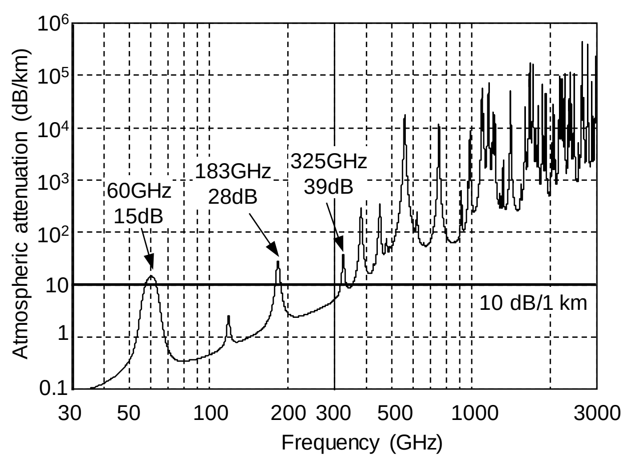

Fig. 2 Atmospheric attenuation of radio waves from 30 *GHz* to 3 *THz*. For 60 *GHz*, 183 *GHz*, 325 *GHz*, the atmospheric attenuation of 1 *km* exceeds 10 *dB*. Atmospheric attenuation exceeds 10 *dB/km* at all frequencies above 351 *GHz*. On the other hand, at other frequencies, the atmospheric attenuation of 1 *km* is not significant.

2. Features and applications of 300 GHz band communication

Applications of terahertz communication depend on the characteristics including communication distance. Therefore, firstly its characteristics are considered, and appropriate applications are discussed. Next, the channel allocation in the recently standardized 300-*GHz* band is introduced, and finally the possibility of future space application is discussed.

2.1 Features of terahertz communication

In the terahertz band, atmospheric attenuation is large, and people probably imagine that the application seems to be limited to short distance communication. In fact, how much is the atmospheric attenuation? Figure 2 shows atmospheric attenuation from 30 *GHz* to 3 *THz* [2, 3]. If the atmospheric attenuation is less than 10 *dB*, the effect is relatively small. On the other hand, for example, if the atmospheric attenuation at 1 *km* exceeds 10 *dB*, kilometer-class communication becomes difficult. Such frequencies are 60 *GHz*, 183 *GHz*, 325 *GHz* and over 351 *GHz*. Except for these frequencies, the influence of atmospheric attenuation is relatively small for medium-range communications of at least about 1 *km*. Figure 3 shows the distance at which the atmospheric attenuation reaches 10 *dB* to estimate the communicable distance. From 192 *GHz* to 298 *GHz*, there are frequency bands with a communication distance of 2 *km*. This is one reason why the 300 *GHz* band is attracting attention as a communication application.

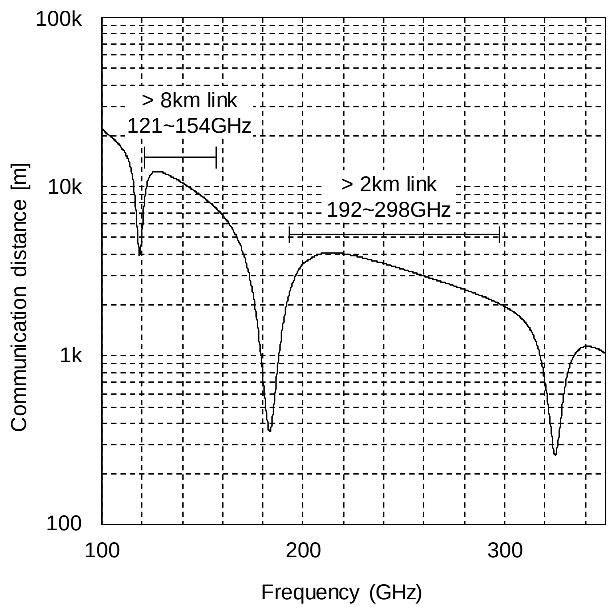

Fig. 3 Communication distance from 100 *GHz* to 350 *GHz*. The communicable distance is calculated from the distance at which the atmospheric attenuation reaches 10 *dB*. In the frequency band from 192 *GHz* to 298 *GHz*, the communication distance is over 2 *km*, and in the frequency band from 121 *GHz* to 154 *GHz* the communicable distance is over 8 *km*.

On the other hand, it is necessary to consider free space propagation loss besides atmospheric attenuation. Propagation loss is given in

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \qquad (1)$$

using the receiving power P_r, transmitting power P_t, transmitting antenna gain G_t, receiving antenna gain G_t, wavelength λ, and communication distance d. This formula is known as Friis' transmission equation. According to this formula, as the wavelength becomes shorter, the receiving power becomes smaller and the propagation loss increases. On the other hand, if the effective areas of the transmitting and receiving antennas are, respectively, the antenna gain is given by

$$G_t = \frac{4\pi}{\lambda^2} A_t \qquad (2)$$

$$G_r = \frac{4\pi}{\lambda^2} A_r. \qquad (3)$$

The antenna gain is proportional to the effective area and increases in inverse proportion to the square of the wavelength. Substituting (2) and (3) into (1) yields

$$\frac{P_r}{P_t} = \frac{A_t A_r}{(\lambda d)^2}. \qquad (4)$$

This is the formula that is given in Friis' original paper [4]. (4) shows that if the effective area of the antenna is constant, the receiving power increases in inverse proportion to the square of the wavelength, and the propagation loss decreases. In terahertz communication, it is important not to make the antenna small to realize medium to long distance transmission. In this case, since the antenna gain becomes high, terahertz communication is more suitable for one-to-one communication than broadcasting.

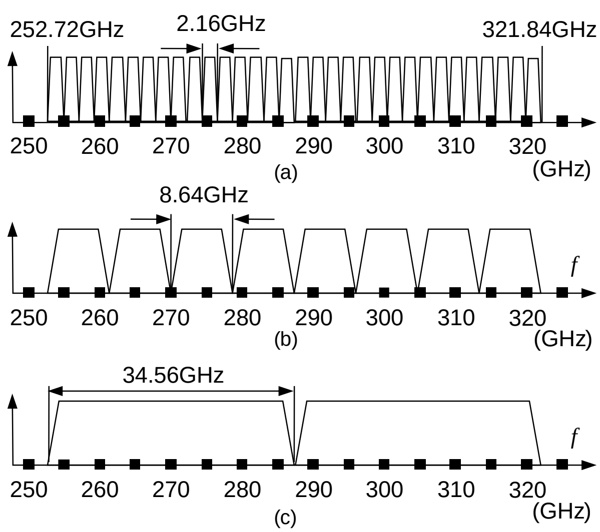

Fig. 4 In IEEE 802.15.3d, channels in multiple bands are allocated in the frequency band from 252.72 *GHz* to 321.84 *GHz*. (a) and (b) are examples of channels allocated in IEEE 802.15.3d. (c) When the channel of the 34.56 *GHz* band is allocated, the wired communication interface CEI-28G can be connected.

2.2 Possible applications of 300*GHz*-band communication

As the 300 *GHz* band realizes the same data rate as optical communication, application examples such as wireless back- and fronthaul, intra-device wireless communication, point-to-point switching connection for data center, proximity wireless for kiosk downloading are shown in PAR (Project Application Request) of IEEE 802.15.3d [5].

On the other hand, small latency is one of the advantages of wireless communication for optical communication. The propagation velocity of the electromagnetic wave is inversely proportional to the square root of the dielectric constant of the medium. For this reason, the propagation speed of atmospheric electromagnetic waves is about 50% faster than that of optical fibers, and wireless communication is excellent in real time applications. Utilizing this property, a microwave line dedicated to high-speed transactions costing 250 million dollars was laid between New York and Chicago [6]. With terahertz communication, the same communication capacity as optical communication can be transmitted with low latency. In Japan, 8*k* broadcasting has been launched in 2018. When transmitting this uncompressed 8*k* video, a communication capacity of up to 144 gigabits per second is required. Setting the roll-off factor of digital modulation to 0.25 enables radio communication of 144 gigabits per second with 16 QAM of 45 *GHz* band. This frequency band can be allocated in the 300-*GHz* band. For example, using a drone equipped with an 8*K* camera enables rapid real-time observation of the situation of disaster sites and distress places. This is a new application that cannot be realized by conventional wireless communication and optical communication.

2.3 Channel allocation for 300-*GHz*-band

In IEEE 802.15.3d, channel allocation in the 300-*GHz* band has been standardized [7]. In this standard, channels are allocated to a band close to 70 *GHz* from 252 *GHz* to 321 *GHz* shown in Fig. 4, which is composed of frequencies already allocated for communication and frequencies expected to be allocated communication in the future. To maintain compatibility with the conventional 60 *GHz* band standard, a plurality of channel bands which are multiples of 2.16 *GHz* as shown in Figs. 4 (a) and (b) are assigned to this frequency band. On the other hand, considering that the data rate of wireless communication is close to optical communication, it is preferable to consider compatibility with wired communication standards. For example, the electrical interface of FPGA (Field Programmable Gate Array) and optical fiber has a 28 gigabit per second NRZ (Non-Return to Zero) standard called CEI-28G (Common Electrical Interface 28 Giga-bit-per-second). If these two NRZ signals are allocated to I and Q signals used for QPSK (quadrature phase shift keying), 56 gigabit-per-second wireless communication is achieved. Since the symbol rate is 28 gigabaud, if it is modulated with the roll-off factor 0.2, the frequency band becomes 33.4 *GHz*. According to the IEEE 802.15.3 d standard, a channel suitable for this band is not currently defined. However, if 34.56 *GHz* which is 16 times 2.16 *GHz* is allocated, this frequency band is suitable for connecting this 28 gigabits-per-second NRZ wired signal to 56 gigabits-per-second QPSK radio signal. As shown in Fig. 4 (c), two channels are allocated to the 34.56 *GHz* bandwidth in all frequency bands defined by IEEE 802.15.3d. In this channel allocation, when using a channel on the low frequency side from 252 *GHz* to 287 *GHz*, the distance at which the atmospheric attenuation becomes 10 *dB* is about 2 *km*, which is suitable for medium to long distance communication.

2.4 Space application with terahertz communication

In terahertz communication, if the antenna effective area is constant, the higher the frequency, the higher the receiving power. In the future, if a high-power terahertz transmitter and a high-gain antenna are available, the space without atmospheric attenuation becomes a promising application target. In the 300 *GHz* band, an antenna gain of 70 *dBi* can be obtained with an antenna diameter of 1.2 *m*. The beam diameter φ at which the antenna with the gain G is located at the distance d is independent of the frequency

$$\phi \simeq \frac{4d}{\sqrt{G}}. \quad (5)$$

If a 70 *dBi* antenna is used, the beam diameter of 1000 *km* ahead will be 1.3 *km*. The spreading of the terahertz beam diameter over the laser beam helps to ease the beam control requirements of the antenna. Furthermore, in the terahertz communication in the space without atmospheric attenuation, a frequency band exceeding 300 *GHz* can be utilized for long distance communication. Although not in the 300 *GHz* band, the frequency band from 121 *GHz* to 154 *GHz*, as shown in Fig. 3, the distance at which the atmospheric attenuation becomes 10 *dB* exceeds 8 *km*. If this currently unallocated broadband can be used for communication, since the atmospheric density is about half of the sea level at about 5000 *m* altitude, high-speed communication between the ground and the space can be achieved at high altitude desert without rain attenuation. Supercomputers whose power consumption increases exponentially with performance growth may not be able to be built on the ground. Also, since the data center handles exponentially increasing amounts of data, its footprint will also increase. If ultrahigh-speed terahertz communication can connect the ground and the space, these large facilities may be able to be constructed in space [9].

3. Conclusion

Since the first magnetron idea was proposed in 1921, high-output UHF signals were obtained, and microwave research such as radar became active. After 50 years from the invention of magnetron, a single mode fiber was invented in 1970 and optical communication has been actively studied since then. As a result, long distance and large capacity transmission have become possible, and the social environment has been greatly changed. Fifty years later, after 2020, there is a sign that terahertz communication will establish a new world. Terahertz communication which connects with a communication capacity far beyond microwave communication to a place not connected by wired communication may greatly change the future society.

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