



**Asia-Pacific Telecommunity**

**APT Report on  
Technology trends of Telecommunications above 100 GHz**

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## 2. Scope

This Report provides recent technology trends of wireless communications using carrier frequencies of over 100 GHz. The Report also gives guidance for each administration to design wireless communication systems in the frequency range of 100 GHz - 600 GHz.

## 3. List of Acronyms

HDTV	High-Definition Television
SHV	Super High Definition
UHD	Ultra-high Definition
MIMO	Multiple Input Multiple Output
WDM	Wavelength Division Multiplexing
ASK	Amplitude Shift Keying
PSK	Phase Shift Keying
HEMT	High Mobility Electron Transistor
HBT	Hetero-bipolar Transistor
ITRS	International Technology Roadmap for Semiconductors
IrDA	Infrared Data Communication Association
DVD	Digital Video Disc
MMIC	Microwave Monolithic Integrated Circuit
FEC	Forward Error Correction
DVB-C	Digital Video Broadcast via. Cable
RTD	Resonant Tunneling Diode

## 4. Introduction

Demand has been increasing for higher data rate in wireless access systems in order to keep up with the remarkable speed-up of fiber-optic networks. 10-Gbit/s data rate is an urgent need for the wireless transmission of 10-Gigabit Ethernet (10GbE) signals, and multiplexed uncompressed high-definition television (HDTV) signals. In the future, 20, 40, and 100 Gbit/s will be required for the wireless technologies, which can transmit Super Hi-Vision (SHV)/Ultra High Definition (UHD) TV data, having 16 times the resolution of HDTV (at least 24 Gbit/s), OC-768/STM-256 data (43 Gbit/s), and 100GbE (100 Gbit/s). In addition to these access network applications, there has also been a need in close proximity wireless transfer of large amount of data, for example, between mobile terminals and storage devices. Such a near-field data transfer technology will possibly evolve to wireless interconnections in devices and equipments.

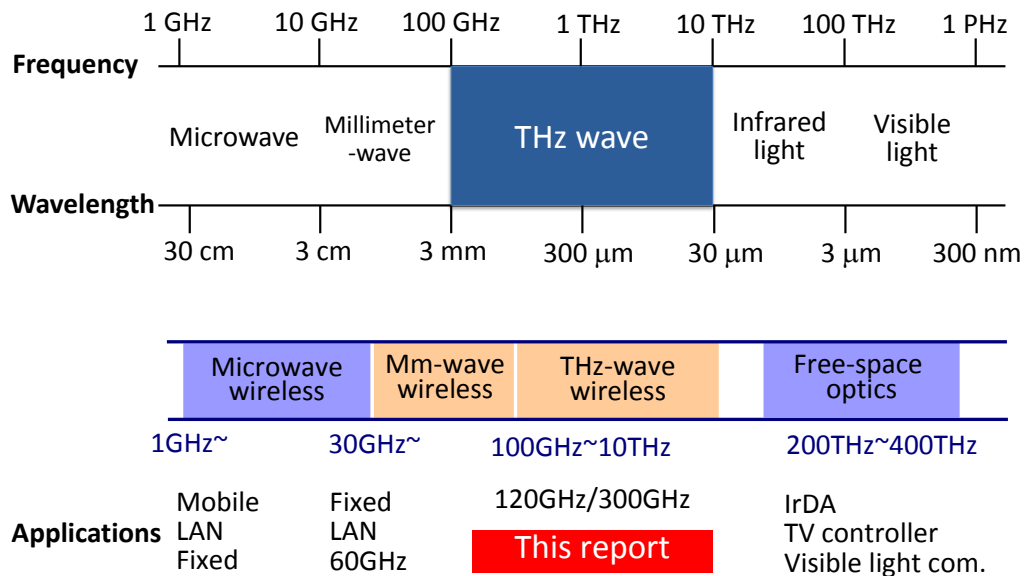


Figure 1 Definition of electromagnetic waves and their typical wireless applications.

To achieve such high data rates in wireless communications, there has been an increasing interest in the use of electromagnetic waves at frequencies above 100 GHz by making use of extremely large bandwidth, in contrast to improving spectral efficiency at lower frequencies [1, 2]. The electromagnetic wave at frequencies from 100 GHz to 10 THz is referred to as terahertz (THz) wave, which is located between microwave and infrared light waves as shown in Fig 1. The terahertz wave has not yet been utilized and/or developed over ten decades.

## 5. Background and motivation

In this section, we discuss and clarify the motivation of using high frequencies above 100 GHz in the future wireless communications. Generally, towards 10~100 Gbit/s wireless communications, three approaches can be considered as follows;

- 1) Improvement of the spectral efficiency with use of multi-value modulation or MIMO (multiple input multiple output) at microwave and millimeter-wave frequencies such as 60 GHz
- 2) Free-space optical link possibly with WDM technologies, which have already been established in the fiber-optic communications technologies
- 3) Use of terahertz carrier frequency with simple modulation format like ASK (amplitude shift keying) and PSK (phase shift keying)

This report is concerned with the third approach by using 100~500 GHz frequencies. There are several reasons why these frequencies are of importance.

First, Fig. 2 shows the relationship between carrier frequency and data rate in various wireless communications technologies. As can be seen in the figure, the data rate increases with the carrier frequency. In general, the typical value of the data rate (bit/s) is 10~20 % of the carrier frequency (Hz), assuming the simplest ASK modulation. In order to achieve the data rate of 10~100 Gbit/s, it is efficient to use the carrier frequencies of 100 to 500 GHz.

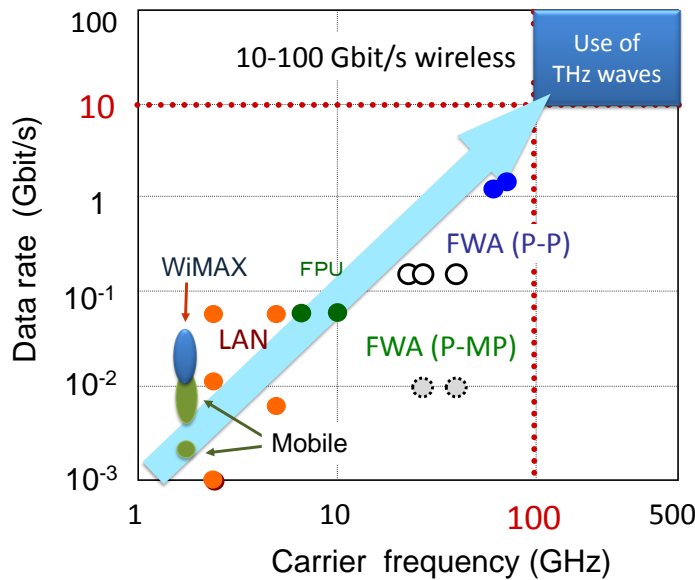


Figure 2 Relationship between data rate and carrier frequency.

Second, the use of terahertz waves at frequencies above 275 GHz has attracted a great deal of interest for wireless communications, mainly because these frequencies have not yet been allocated to specific applications and thus will possibly be used for extreme bandwidth high-speed communications.

Third, developments in the 100 to 500 GHz region are most realistic in terms of enabling technologies such as semiconductor electronic devices and integrated circuits. Currently, oscillators and amplifiers with the operation frequency of 200 to 400 GHz have been developed by compound semiconductor technologies such as InP HEMTs and HBTs. According to the ITRS (International Technology Roadmap for Semiconductors) roadmap, the cut-off frequency of Si-CMOS will reach 1 THz within 10 years.

Fourth, from the viewpoint of atmospheric attenuation of electro-magnetic waves, 500 GHz is nearly an upper limit even for short range (~100 m) applications. The attenuation is 1 dB per 10 m below 500 GHz as shown in Fig. 3.

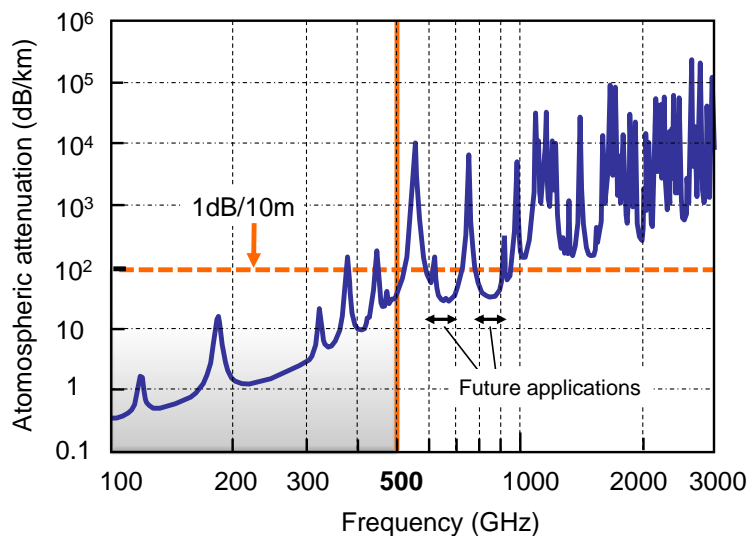


Figure 3 Atmospheric attenuation of radio waves above 100 GHz.

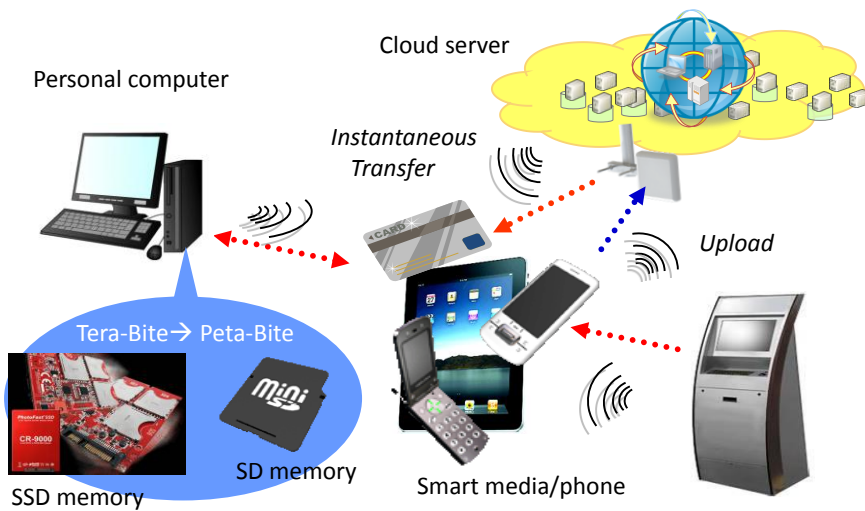


Figure 4 Application scene of terahertz wireless communications.

In addition to the device speed, there is an important merit in choosing higher carrier frequencies. At frequencies of over 300 GHz, the antenna size becomes an order of sub-millimeter, which is smaller than that of lens used in the common IrDA module. For example, size of the array antenna unit in the commercially available 60-GHz wireless home link, which is used between the DVD player and HDTV display, is about 25 mm x 25 mm. At 300 GHz, the array antenna will be 5 mm x 5 mm. This leads not only to the dramatic decrease in the cost of transceiver modules, but also to the wide spread of wireless terminals used in the last access to the network, and in the short range data transfer as illustrated in Fig. 4 [3].

Table 1 Summary of wireless communications technologies above 100-GHz frequency.

Frequency	Technology		Bit rate	Application	Affiliation
	Tx	Rx			
120 GHz	Photonics-based	MMIC (direct det.)	10 Gbit/s	6ch HDTV	NTT
120 GHz	MMIC	MMIC (direct det.)	20 Gbit/s (with pol.MUX)	5 km with FEC	NTT
200 GHz	Photonics-based	Disc. comp. (heterodyne det.)	1 Gbit/s	NA	IEMN (France)
220 GHz	MMIC	MMIC	~15 Gbit/s	Digital TV	Fraunhofer IAF
250 GHz	Photonics-based	Disc. comp. (direct det.)	8 Gbit/s	NA	NTT Osaka-U
300-400 GHz	Photonics-based	Disc. comp. (direct det.)	>20 Gbit/s	NA	Osaka-U NTT
300 GHz	Frequency multiplexer	Disc. comp. (heterodyne det.)	~100 Mbit/s	Analog / Digital TV	TU Braunschweig
300 GHz	Resonant-tunneling diode	Resonant-Tunneling Diode	1.5 Gbit/s	HDTV	Rohm Osaka-U
625 GHz	Frequency multiplexer	Disc. comp. (direct det.)	2.5 Gbit/s	NA	NJ IT Bell Lab

## 6. Recent development of wireless communications technology above 100 GHz

Table 1 summarizes recent development of wireless links using radio waves at frequencies of over 100 GHz.

The first demonstration of wireless link with over-100-GHz carrier frequency is the 120-GHz-band system developed at Nippon Telegraph and Telephone Corporation (NTT). The 120-GHz-band systems initially adopted a photonics-based transmitter in the wireless link, where generation and modulation of 120-GHz radio waves were made with use of broadband photonics technologies [4]. The same approach has been employed in the 300-GHz-band systems (details will be described later). Early in 2000s, they reached a bit rate of 10 Gbit/s and this system was successfully applied to multi-channel transmission of uncompressed high-definition (HD) TV signals, and has passed a field experiment at a transmission distance of over 100 m. With progress in the semiconductor IC technologies, they introduced all electronics-based transmitters, which contribute to a reduction in size, weight and cost together with ease of operation [5]. A trial use of this system was conducted within the live broadcast of the 2008 Olympic Games in Beijing by NTT and Fuji Television Network Inc. In addition, the transmission distance has been extended to 5 km by developing a power amplifier for the transmitter. The long-term stability has been improved with a forward-error correction (FEC) technique developed by Japan Broadcasting Corporation (NHK). Further details are attached to Annex of this report.

At 200-GHz-band frequencies, there are three reports with different approaches. Ducournau of IEMN et al. demonstrated 1-Gbit/s wireless transmission at 200 GHz. They used a photonics-based transmitter and a heterodyne receiver with a sub-harmonic mixer [6]. Song et al. of NTT succeeded in 8-Gbit/s wireless transmission using a photonics based transmitter [7]. They developed a direct-detection receiver with a Schottky-barrier diode integrated with a planar antenna as shown in Fig. 5. The bit rate is determined by the bandwidth of the receiver, in particular, those of the antenna, the IF circuitry and the connectorized package. Kallfass of Fraunhofer Institute reported the first MMIC-based transmitters and receivers, and successfully demonstrated a digital video (DVB-C) transmission at 220 GHz, and 15-Gb it/s error-free transmission [8].

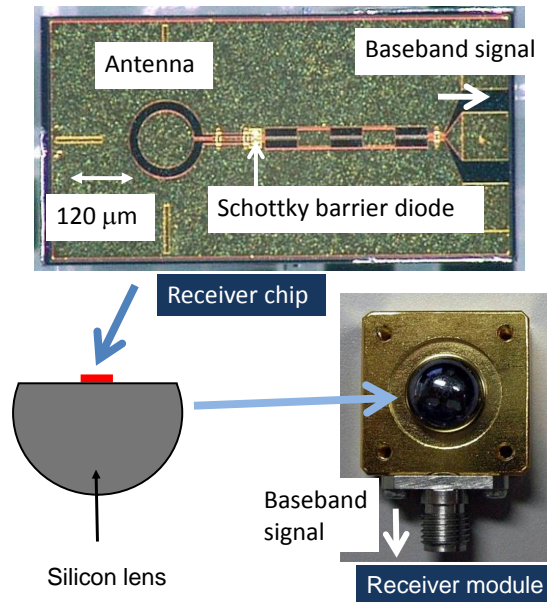


Figure 5 Example of receiver chip and module for 200-GHz and 300-GHz band systems.

At 300-400GHz, researchers at Terahertz Communications Lab in Germany developed a 300-GHz wireless link based on commercially available electronic components such as sub-harmonic mixers and multipliers [9, 10]. With the system, they investigated propagation conditions and channel modeling beyond 300 GHz, and also demonstrated a transmission of the analog and digital TV signals. Osaka University and NTT developed 300-GHz band wireless link using a photonics-based transmitter as shown in Fig. 6 [11-13]. They demonstrated the utilization of extremely broad bandwidth of over 30 GHz.

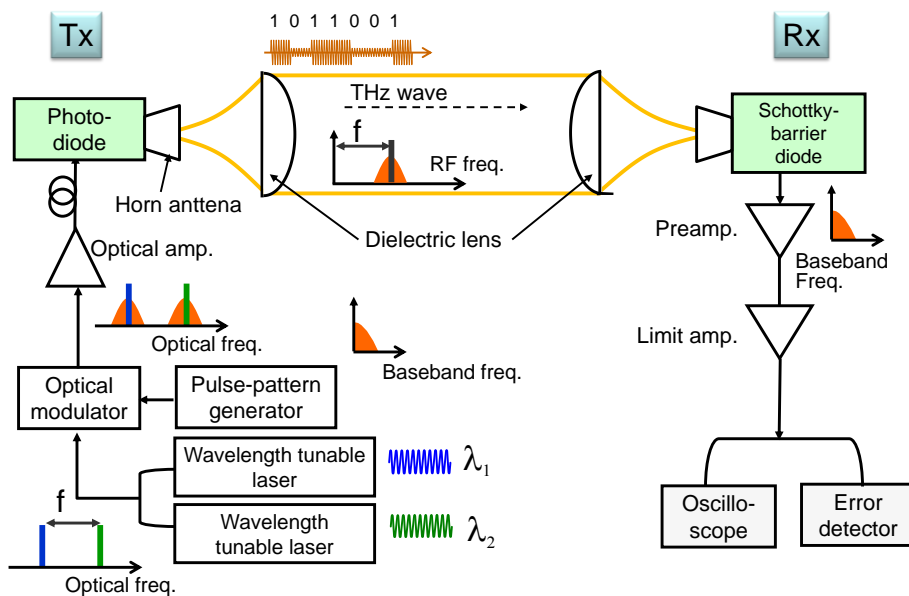


Figure 6 Block diagram of the wireless link using photonics-based terahertz-wave transmitter.

In Fig. 6, first, an optical THz-wave signal is generated by heterodyning the two wavelengths of light from the wavelength-tunable light sources. The optical signal is digitally modulated by the optical intensity modulator driven by the pulse pattern generator. Finally, optical signal is converted to an

electrical signal by the photodiode, and it is emitted to the free space via a horn antenna with a gain of 25 dBi. The emitted terahertz wave is well collimated by a 2-inch-diameter Teflon lens. In this system, the bandwidth of the photodiode is 140 GHz, which corresponds to the maximum bit rate of 90 Gbit/s in the case of ASK modulation.

Figure 7 shows the eye diagram experimentally obtained at 20 Gbit/s. The eye is clean and open, which indicates an error-free transmission at 300 GHz.

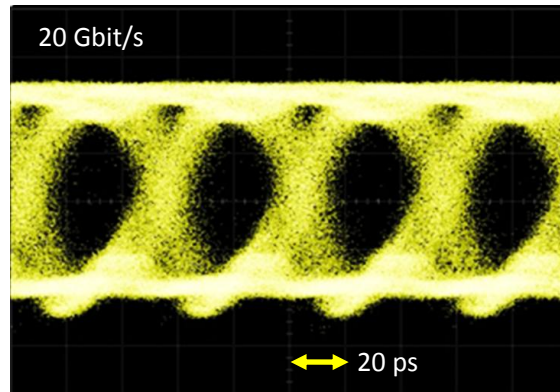


Figure 7 Eye diagram at 20 Gbit/s at 300 GHz.

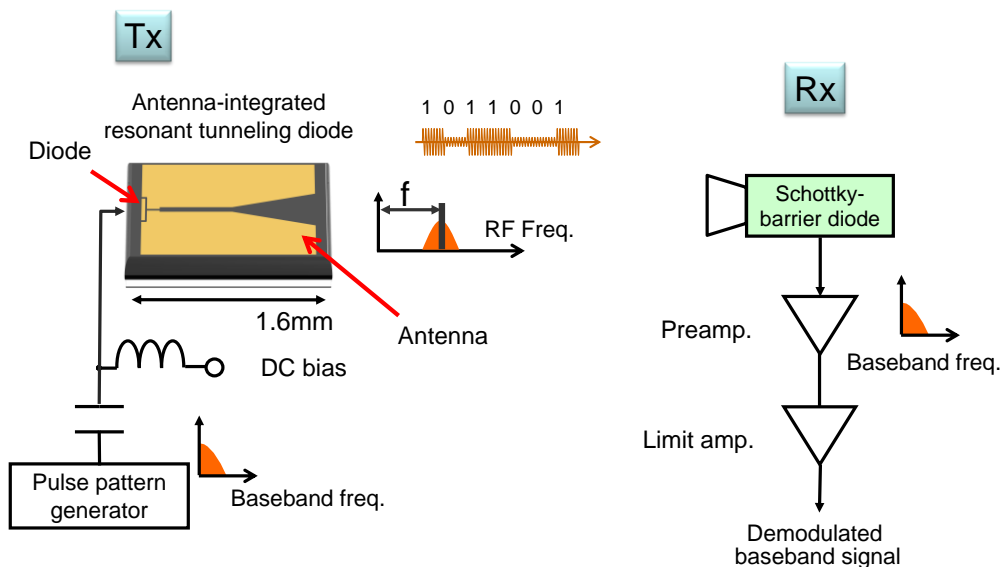


Figure 8 Block diagram of the wireless link using self-oscillator-based transmitter.

Mukai of Rohm and a group of Osaka University examined the use of electronic oscillator in the 300-GHz band wireless link [14]. The oscillator is the so-called resonant tunneling diode (RTD), which oscillates at an appropriate DC bias voltage. By changing the bias voltage, 300-GHz carrier signal is modulated as ON and OFF depending on the amplitude of the bias voltage. As for the receiver, the direct-detection receiver is used. The maximum bit rate was 1.5 Gbit/s and they succeeded in the transmission of uncompressed HDTV signals with only “diode” technologies. They further demonstrated that the RTD can be also operated as a detector with high sensitivity [15]. Moeller and Federici et al. of Bell Labs and New Jersey Institute of Technology reported an error-free 2.5 Gbit/s transmission at 625 GHz, where an atmospheric window lies as shown in Fig. 3, using frequency multiplier for the transmitter [16].

## 7. Future technical issues

Utilization of frequency region over 100 GHz for wireless communications has attracted a world-wide attention. The first technology demonstrators at 100 GHz, 200 GHz and 300 GHz have employed photonics-based transmitter, but a steady progress in semiconductor IC technology have also realized all electronics-based system, although the bite rate obtained with the photonics-based system is still higher than that of MMIC-based one at over 200 GHz.

Future work addresses higher bit-rate transmission by increasing of the video bandwidth of the receiver circuit. Photonics-based approach should continue to be a carrying vehicle for the exploration of undeveloped frequency regions. In the near future, semiconductor electronics technology, in particular, silicon LSI technology could be introduced in 300~500 GHz bands for compact and cost-effective wireless communication systems. The integrated antenna technology to steer beams is also crucial for many applications in LAN/PAN, where MEMS and/or meta-material technologies will play a key role [17, 18].

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## Annex

### Technologies and characteristics of 120-GHz-band wireless link for 10-Gbit/s data transmission

#### Background of development

Demand for over gigabit-class wireless communications is increasing year by year. Gigabit Ethernet are now widely used, and 10-Gigabit Ethernet (10 GbE) market now grows rapidly. In the field of broadcasting, the number of programs running on the high-definition television (HDTV) standard is increasing. The data rate of uncompressed high-definition television (HDTV) signals, 3-dimensional television (3DTV) and 4K digital cinema is 1.5, 3.0, and 6.0 Gbit/s, respectively.

Recently, gigabit-class wireless links using 60-, 70-, and 80-GHz-band millimeter-waves (MMWs) have been developed to meet these broadband communication demands. In particular, the 60-GHz band is stipulated as a license-free spectrum in many countries, and this band has been widely used for mainly indoor applications, such as uncompressed video streaming over the wireless home networks. A fixed wireless access (FWA) has already achieved a 1.25-Gbit/s and 2.5 Gbit/s data rate using the 60-, 70-, and 80-GHz band.

The use of undeveloped frequencies above 100 GHz is one of the promising methods for achieving wireless links with a data rate of 10 Gbit/s or more, because the data rate depends on the carrier frequency of wireless communications. However, over-100-GHz-band has not been commercially used because it has been difficult to generate and detect over-100-GHz-band signals. Recent progress in electronic devices, especially compound semiconductor devices, has opened the way for researchers to focus on MMICs that operate at frequencies over 100 GHz.

In Japan, the experiments of 10-Gbit/s wireless links were conducted in the 120 GHz band. The wireless link employs 0.1- $\mu\text{m}$ -gate InP high-electron-mobility transistor (HEMT) monolithic microwave integrated circuits (MMICs) to generate and detect 120-GHz-band signals [19]. The wireless link achieved the transmission of 10-Gbit/s data and that of six-channel of uncompressed HDTV signals over a distance of 5.8 km [20]. These experimental results show the usefulness of over-100-GHz-band for 10-Gbit/s wireless data transmission.

#### Outline of the system configuration

Figure 1 shows the configuration of the 120-GHz-band wireless link. The wireless link employs the direct ASK modulation and demodulation architecture. The transmitter consists of three components: the head, which generates the radio signal; the controller, which supplies power, the data signal, and control signals to the head; and the antenna [20]. Table 1 shows the specifications of the transmitter. The wireless transmitter uses four kinds of Cassegrain antennas (CAs) with diameters from 100 mm (37 dBi) to 600 mm (52 dBi). A standard horn antenna with a gain of 23 dBi can also be attached to the transmitter. The center frequency is 125 GHz, and output power is 16 dBm. Figure 2 is a photograph of the transmitter.

There are three MMW modules in the transmitter: a transmitter (Tx) module and two power amplifier (PA) modules [21]. The wireless link system uses an amplitude shift keying (ASK) modulation scheme. The Tx module multiplies 15.625-GHz CW signal from a phase-locked oscillator (PLO) up to 125 GHz. The ASK modulator modulates the 125-GHz MMW signal with 10-Gbit/s data signal, and the modulated 125-GHz MMW signals are amplified up to 0 dBm. The output of the Tx module is input to the first PA module. The first PA module amplifies the MMW signals up to 10 dBm, and the second one amplifies them up to 16 dBm.

The receiver also consists of the head, the controller, and the antenna. The received 120-GHz-band MMW signal was input into the receiver (Rx) module. In the Rx module, the received MMW signals

are amplified by a low-noise amplifier (LNA) and demodulated by an ASK demodulator. The Rx module outputs the demodulated data signal [20]. The demodulated data signals are amplified by an amplifier and E/O-converted. Therefore, the receiver outputs 10-Gbit/s optical data signal.

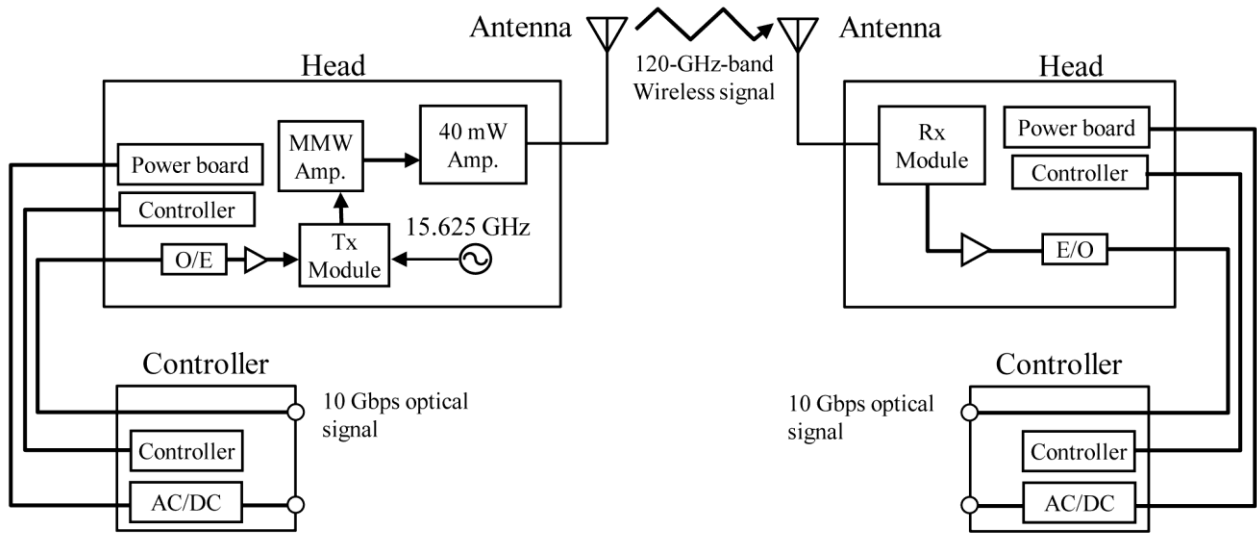


Figure 1 Schematic diagram of 120-GHz-band wireless link.



Figure 2 Photograph of 120-GHz-band wireless transmitter.

Table 1 Specifications of 120-GHz-band wireless link

Output power	16 dBm
Center frequency	125 GHz
Modulation	ASK
Occupied bandwidth	116.5-133.5 GHz
Transmission rate	1 Mbit/s - 11.1 Gbit/s
Antenna	CA, Horn Antenna
Antenna gain	CA: 37, 49,50,52 dBi Horn antenna: 23.3 dBi
Cassegrain Antenna diameter	100 mm (37 dBi) 450 mm (49, 50 dBi) 600 mm (52 dBi)

## Key components

120-GHz-band wireless signals are generated by a 0.1- $\mu\text{m}$ -gate InP HEMT MMICs [19]. InP HEMT features high-frequency, low-noise, and high-power operation, and it is regarded as key devices for next generation broadband wired/wireless communications. The InP HEMT devices typically have a unity current gain frequency  $f_t$  of 170 GHz and a maximum oscillation frequency  $f_{max}$  of 350 GHz. The photograph of the transmitter (Tx) MMIC chip is shown in Fig. 3(a). It includes a frequency doubler, an ASK modulator, a narrow band-pass filter, and power amplifiers in one chip. The chip size is 1 X 3 X 0.15 mm. The typical output power of the Tx chip is 0 dBm. The receiver (Rx) MMIC chip includes low-noise amplifiers, a band-pass filter, an ASK de-modulator, and a receive signal strength indication (RSSI) circuit for external gain control. These Tx chip and Rx chip are integrated in a metal package. The photograph of the Tx module is shown in Fig. 3(b).

The first PA module in Fig. 1 uses a PA InP HEMT MMIC. This amplifier has a common-source five-stage configuration. The chip size is 1 X 2 X 0.15 mm. The small signal gain of first PA module is 11.5 dB. The output 1-dB gain compression point is 13 dBm, and maximum output power is around 15 dBm.

The second PA module in Fig. 3 uses the 0.08- $\mu\text{m}$ -gate-length InGaAs/InP HEMT MMICs, which improve the breakdown voltage [22]. The devices typically have a unity current gain frequency  $f_t$  of 180 GHz and a maximum oscillation frequency  $f_{max}$  of 650 GHz. The improvement in the breakdown voltage of HEMT contributes to increase the maximum output power of PA circuit. The maximum output power of the second PA was 21 dBm and output  $P_{1dB}$  reached 16 dBm at 125 GHz.

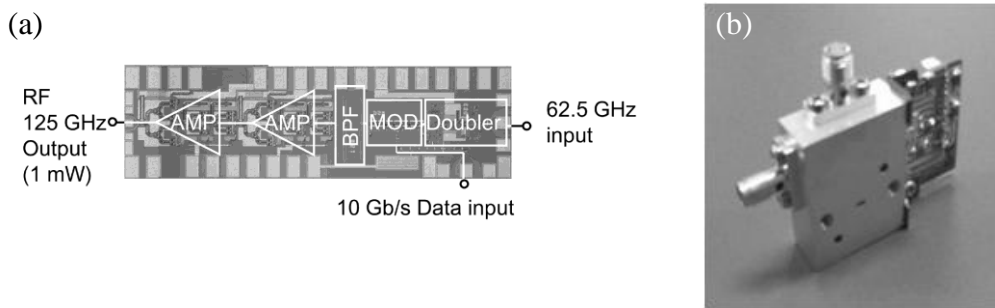


Figure 3 Photograph of (a) Tx MMIC chip and (b) Tx module.

## Transmission experiments

10-Gbit/s wireless transmission experiment over a distance of 5.8 km was achieved by using the 120-GHz-band wireless link [20]. Figure 4 shows the experimental setup of 5.8-km-long transmission experiment. The transmitter and the receiver was set at Tokyo Heliport (Koto-ku) and the Fuji Television coastal studio (Minato-ku) in Tokyo, Japan, respectively. The weather was fine during the experiment. The antenna gains of the transmitter and the receiver are 52 and 49 dBi, respectively. The transmitted data was 10.3-Gbit/s random data and forward error correction (FEC) using Reed-Solomon (RS) coding was used. Experimental conditions and calculated received power for the experiment is shown in Table 2. Received power was about -42 dBm. A BER of below  $10^{-12}$  was obtained during the experiment. Moreover, multiplexed uncompressed HD videos could be transmitted without errors over the 120-GHz-band wireless link.

To clarify the dependence of transmission characteristics on weather conditions, long-term transmission experiments were conducted. The measurement was done from March to December in 2008 in the Atsugi area, Japan [23]. The distance between the transmitter and receiver is 400 m. Figure 5 shows the rain intensity dependence of the measured attenuation factor. The theoretical value for a specific attenuation factor  $\gamma$  (dB/km) with respect to rain rate  $R$  (mm/hr) is calculated by:

$\gamma = kR^\alpha$  where:  $k = 1.4911$ ,  $\alpha = 0.6609$   
 (k and  $\alpha$  are referred from Recommendation ITU-R P.838.)

The theoretical value agrees well with the measurement result in the range from 10 to 80 mm/hr. The rain attenuation factor obtained by the measurement is about 9, 17 and 23 dB/km when the rain rate is 20, 40 and 60 mm/hr, respectively.

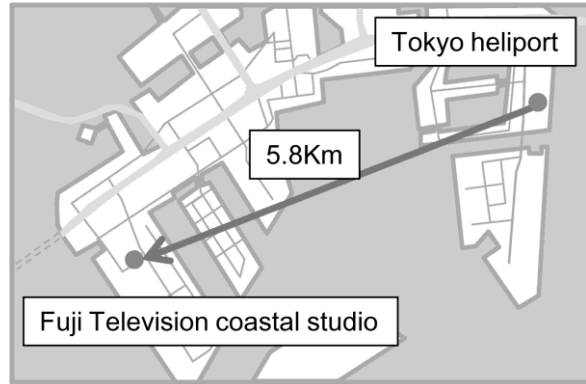


Figure 4 Experimental setup of 5.8-km-long transmission experiment.

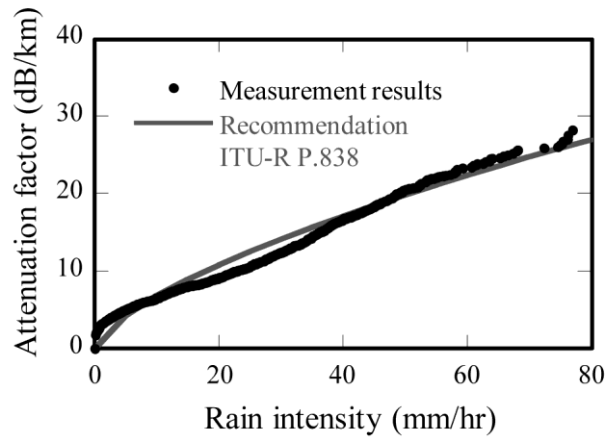


Figure 5 Experimental setup of 5.8-km-long transmission experiment.

Table 2 Experimental conditions and calculated received power for 5.8-km transmission experiment.

Output power	16 dBm
Antenna gain (Tx)	52.0 dBi
Antenna gain (Rx)	48.7 dBi
Absorption Coefficient by air	1.5 dB/km
Transmission distance	5.8 km
Free space transmission loss	149.2 dB
Absorption loss by air	8.7 dB
Calculated received power	-41.2 dBm
Received power (Experiment)	-42.0 dBm

## Possible applications

Figure 6 shows possible applications of 120-GHz-band wireless links. One application is fixed wireless access for a 10-Gigabit Ethernet. A 10-Gbit/s wireless link can be used for temporary gigabit access because it can be set up quickly and inexpensively. Therefore, it is a key component of a disaster-recovery wireless link. Furthermore, it can transmit various high-definition movies, such as 4K cinema and 3DTV, therefore, it can be used for remote medical treatment, and public viewing of the digital cinema at various events. Another application is hot spot links. Because of the spread of portable media players, many people download music and movie files from the Internet. The movie data on a DVD takes just 3.9 seconds to transmit over 120-GHz-band wireless link.

One of the possible applications is a multiplexed wireless transmission of uncompressed HDTV signals. The 120-GHz-band wireless link can transmit multi-channel HDTV signals without deterioration and with quite a small latency, which makes the TV program production easy. A combination of the 10-Gbit/s wireless link and fiber networks would enable large-scale live relay broadcasting of HDTV programs.

Figure 7 shows the photograph of the 120-GHz-band wireless link when it was used for live 4K video relay. On July 2009, the 4K video of the solar eclipse shot at Amami Island, Kagoshima Japan, was transmitted to Osaka Japan through fiber IP networks, and it was transmitted to a planetarium in a science museum across the river over the 120-GHz-band wireless link. The planetarium showed a live solar eclipse video with a 4K resolution standard. On February 2011, a remote academic symposium using 4K video transmission was held. A schematic of the remote symposium is shown in Fig.8. A conference hall in Kyoto Japan was connected to the other hall in Tokyo Japan with a 10 Gigabit Ethernet networks, and a part of the network employed the 120-GHz-band wireless link. The presentations held at both halls were shot by 4K cameras and were transmitted to the other hall. Two pairs of 120-GHz-band wireless link were used to meet the bi-directional communication of 10 Gigabit Ethernet. In the conference, a mock remote medical treatment demonstration using 3DTV videos was presented in addition to academic presentations.

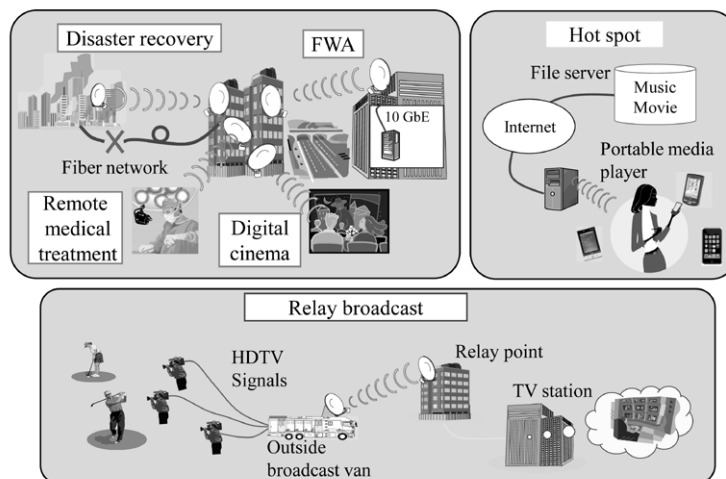


Figure 6 Possible applications of 120-GHz-band wireless link.

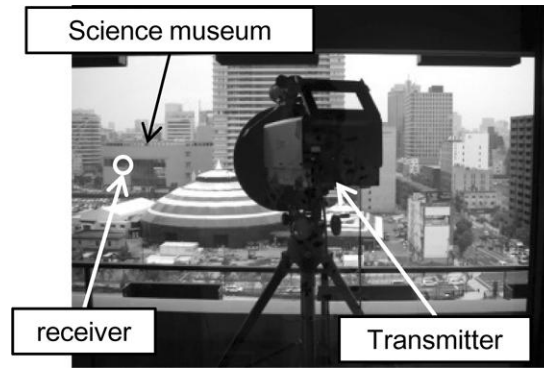


Figure 7 Photograph of 120-GHz-band wireless link used for live 4K video relay.

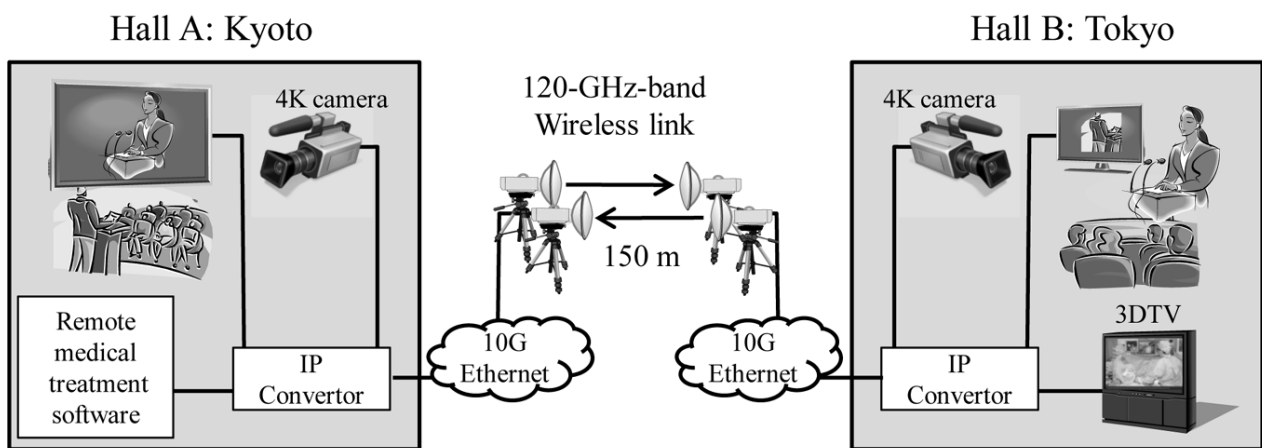


Figure 8 Schematic of remote symposium using 120-GHz-band wireless link.

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