Challenges for Ultrahigh-Speed Wireless Communications Using Terahertz Waves

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Abstract: Demand is increasing for higher data rate in wireless communications in order to keep up with the remarkable speed-up of fiber-optic networks such as Ethernet LANs. One of the most direct and easiest ways to achieve a higher data rate of 10-100 *Gbit/s* is to increase carrier frequencies to terahertz regions of from 100 *GHz* to 500 *GHz*. This paper will review our recent challenges for high-speed wireless communications technologies using terahertz electro-magnetic waves.

Keywords: wireless communications, Terahertz, photodiode, giga-bit

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1. Introduction

Recently, there has been an increasing interest in the use of electromagnetic waves at frequencies above 275 *GHz* for wireless communications [1]. This is mainly because that these frequency spectra have not yet been allocated to specific applications and thus we can possibly make use of ultra-large bandwidth for high-speed communications [1-3]. As the first step for the exploration of these electromagnetic waves, 300~500-*GHz*-range is considered to be realistic since enabling semiconductor electronic and photonic devices operating at this frequency range have recently started to be in our hands. Theoretical study of transmission characteristics in indoor short-range communications at 350 *GHz* [2], and experimental demonstration of analogue video-signal transmission over distances of up to 22 *m* at 300 *GHz* [3] have been reported.

In 2000, we started the use of >100 *GHz* electro-magnetic waves to increase the bit rate in wireless communications. First, we proposed the use of 120-*GHz*-band to achieve the 10 *Gbit/s* data rate, and our initial technology demonstrator was based on the transmitter which employs photonic techniques for the generation and modulation of 120-*GHz*-band signals [4-7]. Then, we developed MMIC chipsets and their integrated modules for all-electronic transmitters as well as receivers using InP-HEMTs [8]. The all-electronics-based 120-*GHz*-band system was successfully deployed for the broadcasting of HDTV in the 2008 Olympic Game held in Beijing, and for the error-free transmission at 10 *Gbit/s* with a link distance of 3 *km* together with FEC (forward error correction) technology [9].

Fig. 1 shows the relationship between carrier frequency and data rate in various giga-bit wireless technologies. Our next target with terahertz communications is the data rate of 40~100 *Gbit/s* using 250~500-*GHz*-band carrier frequencies. In this paper, we first describe the background of our research, discussing possible needs in high-speed wireless links and approaches to realizing them. Second, we show our recent preliminary experiments on giga-bit wireless link using 250 to 400 *GHz* carrier frequencies [10, 11].

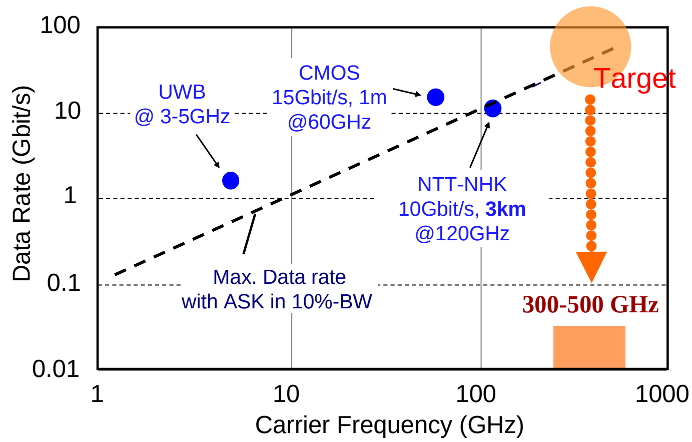


Fig. 1 Relationship between carrier frequency and data rate in wireless communications.

2. Trends and needs

Fig. 2 shows a trend in wired (fiber-optic) communications such as Ethernet and passive optical network (PON). They are now reaching 100 *Gbit/s* and 10 *Gbit/s*, respectively. In Fig. 3, a trend in wireless communications is superposed on that of wired. For the application to fixed wireless access (FWA), field pick-up unit (FPU), wireless back haul, which are located between Ethernet and PON, we have a very high speed wireless up to 10 *Gbit/s* capability using 60 to 120 *GHz* frequencies. Within a few years from now on, the bit rate will reach several tens of *Gbit/s* even for wireless LAN and PAN.

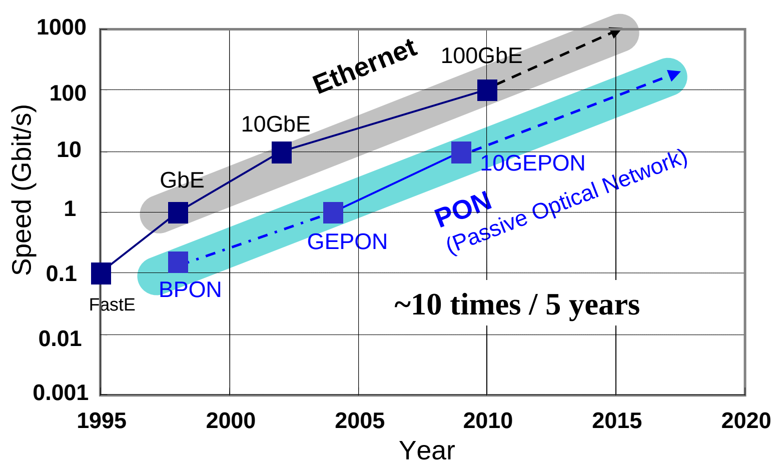


Fig. 2 Trend in wired communications technologies.

In addition to these trends, giga-bit wireless has recently been spreading in home networks. Here, uncompressed high-definition TV data with a bit rate of over 1.5 *Gbit/s* is transmitted from DVD or camera to TV set. Several Japanese consumer-electronics makers have already introduced such a giga-bit wireless interface into their leading products.

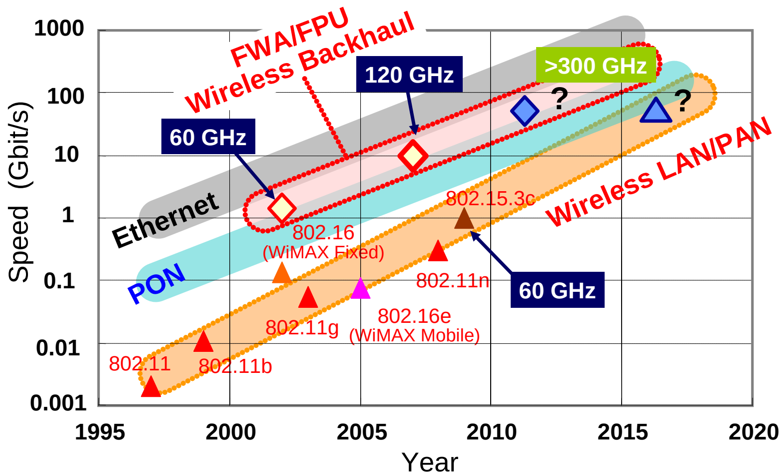


Fig. 3 Trend in wireless communications technologies.

Now, the next generation HDTV has come on stage. It is so-called ultrahigh definition TV, or UHD, and has 16 times resolution, which requires at least 24 *Gbit/s* data rate (Fig. 4).

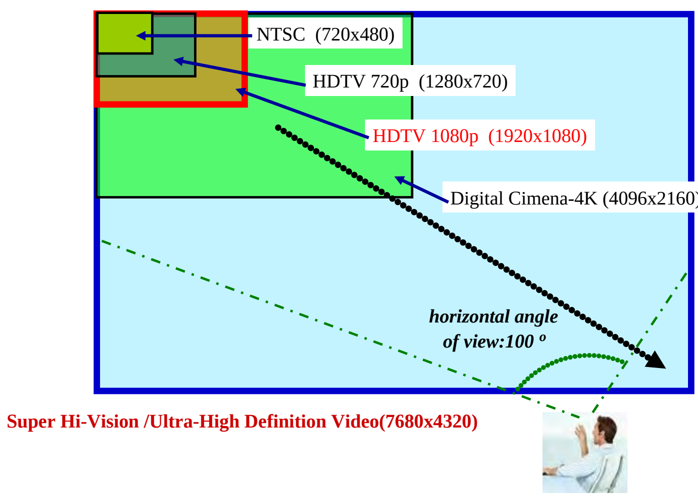
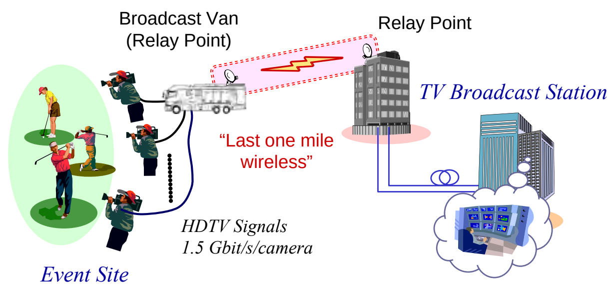


Fig. 4 Evolution of high-definition TV technologies.

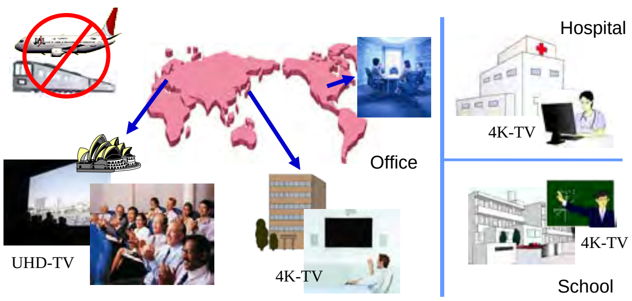
Fig. 5 Close proximity wireless transfer technologies [12, 13].

There has also been an increasing need in close proximity wireless transfer of large amount of data between mobile terminals and storage devices as shown in Fig. 5. There are consortiums named as “Transfer Jet” [12] and “Giga-IR” [13] using microwaves (560 *Mbit/s*), and infrared lights (1 *Gbit/s*), respectively.

From the above trends, high-speed wireless communications technology will eliminate bottlenecks in the speed of access networks. Currently, multi-channel transmission of uncompressed HDTV data has been realized by our 120-*GHz*-band wireless (Fig. 6(a)) [6, 7, 9], and in the future, wireless transmission of UHD data will allow us to enjoy highly-realistic sensation teleconferences, for example, without traveling all over the world (Fig. 6(b)).



(a)



(b)

Fig. 6 Application scenes of ultrahigh-speed wireless in access networks.

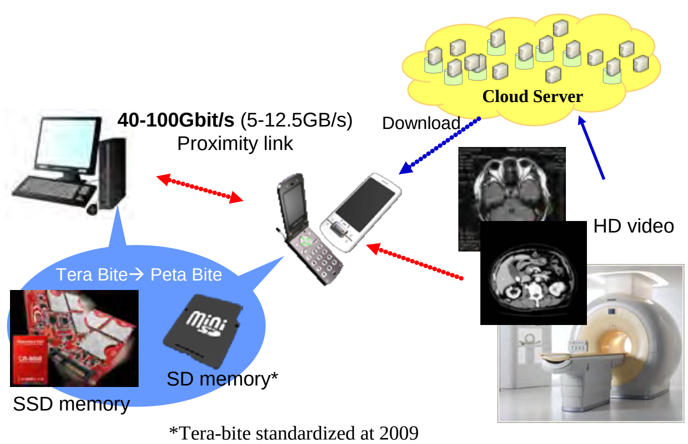


Fig. 7 Application scene of ultrahigh-speed wireless in large-volume data transfer and/or exchange.

Fig. 7 shows another application scene, where we will handle a tera-bite data such as medical video data together with solid-state memory, and we will perform instantaneous transfer of such a large-volume data with 40~100 *Gbit/s* wireless link.

3. Approaches to high-speed wireless

Towards 40~100 *Gbit/s* wireless, there are several approaches; 1)multi-value modulation with existing millimeter waves such as 60 *GHz*, 2) free-space optical link possibly with WDM technologies, and 3) use of terahertz carrier frequency with simple modulation format like ASK and PSK.

Frequencies at above 275 *GHz* have not yet been allocated for any specific use. In particular, use of 300~500 *GHz* region has attracted increasing interest. This comes from the recent progress in the operation frequency of semiconductor devices and circuits. According to the ITRS roadmap, the cutoff frequency of Si-CMOS will exceed 500 *GHz* within a few years. 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. This also allows us to bring wireless interconnections into modules and packages similar to optical interconnections. From the viewpoint of atmospheric attenuation of electro-magnetic waves, 500 *GHz* is nearly an upper limit in “last-one-mile” applications as shown in Fig. 8.

Thus, our approach is to make use of ultra-large bandwidth at 300~500 *GHz*. Utilization of full 300~500 *GHz* bands could be classified into two ways as shown in Fig. 9. One is to use extremely large bandwidth of over 40 *GHz* in a single channel. For example, the bit rate of Super Hi-Vision (SHV)/Ultra High Definition (UHD) TV data (24 *Gbit/s*), which requires over 40 *GHz* DSB bandwidth for ASK modulation format. Wireless transmission of OC-768/STM-256 data (43 *Gbit/s*) requires over 70 *GHz* bandwidth with the same format. The other use is to allocate multiple channels of giga-bit signals such as Gigabit Ethernet (1 *Gbit/s*) and HDTV (1.5 **Gbit/s**). 80 channels of HDTV signals can be allocated in 300~500 *GHz* bands.

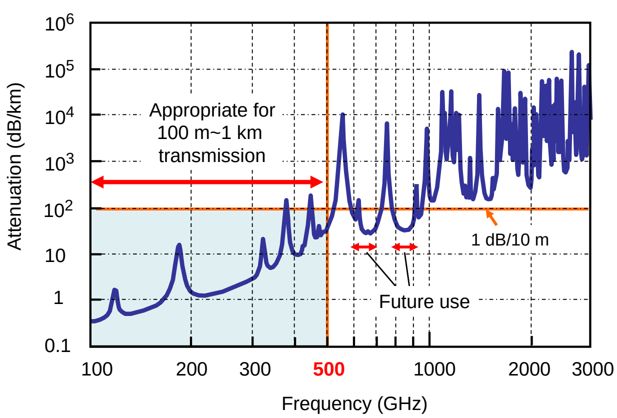


Fig. 8 Atmospheric attenuation of radio waves.

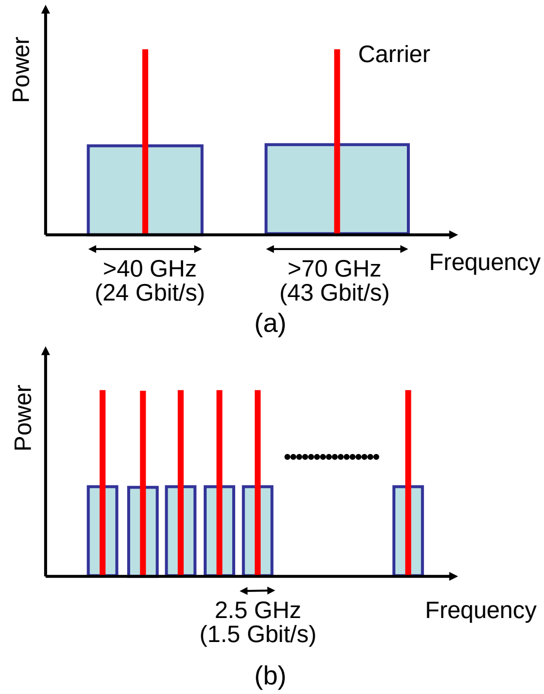


Fig. 9 Possible utilization of 300-500 GHz bands. (a) Ultra-broadband channel. (b) Multiple giga-bit channels.

3. Giga-bit wireless experiment at 300~400 *GHz*

As enabling technologies, photonic generation and modulation of terahertz waves is the most efficient and easiest way for the transmitter, while the receiver can be realized with the state-of-the-art electronic devices such as Schottky-barrier diodes. This approach has been successfully adopted as the initial version of our 120-*GHz*-band wireless link systems [4-7].

To generate 300~400 *GHz* signals with photonic techniques, high-frequency photodiode is a key device. Fig. 10(a) shows the band diagram of the photodiode optimized for the operation at 300~400 *GHz* [14]. This structure is a modification of the uni-traveling-carrier photodiode (UTC-PD). The UTC-PD has a feature of both high-speed and high-output power operation owing to its unique carrier transport mechanism [15].

The photodiode chip was packaged into the module with a rectangular waveguide (WR-3) output port [14]. The frequency dependence of the output power was evaluated by heterodyning the two wavelengths of light from the wavelength-tunable light sources at around 1.55 μm. The terahertz output power was measured by thermo-coupled power meter. Fig. 10(b) shows the frequency dependence of the output power generated from the module. The 3 *dB* bandwidth is 140 *GHz* (from 270 to 410 *GHz*). The peak output power was 110 μW at 380 *GHz* for a photocurrent of 10 *mA* with a bias voltage of 1.1 *V*. The output power could be further increased to over 400 μW with increasing the photocurrent up to 20 *mA*.

Fig. 11 shows the block diagram of the wireless link using photonics-based terahertz-wave transmitter [10]. 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, the

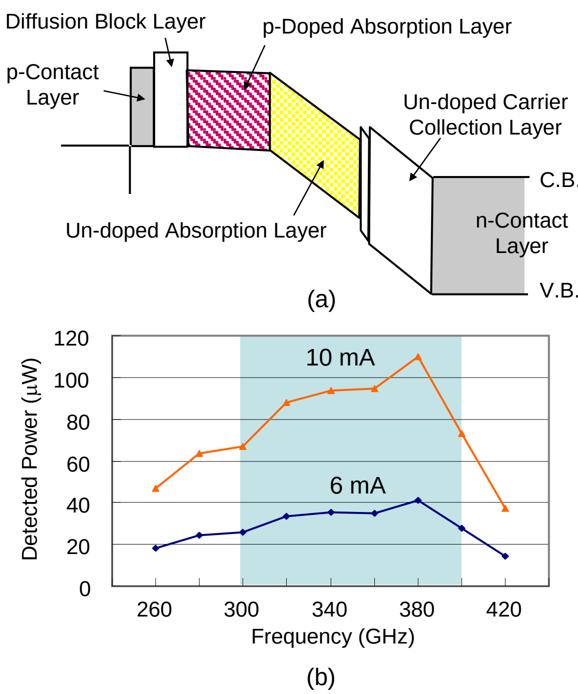


Fig. 10 Band diagram of the photodiode (a), and frequency dependence of output power from the module for photocurrent of 6 *mA* and 10 *mA* (b).

optical signal is converted to an electrical signal by the UTC-PD module, 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. Fig. 12 shows a close-up view of the transmitter. Main features of this photonic approach are that carrier frequency is widely tunable, and that the modulation frequency can be increased to at least 40 *Gbit/s*.

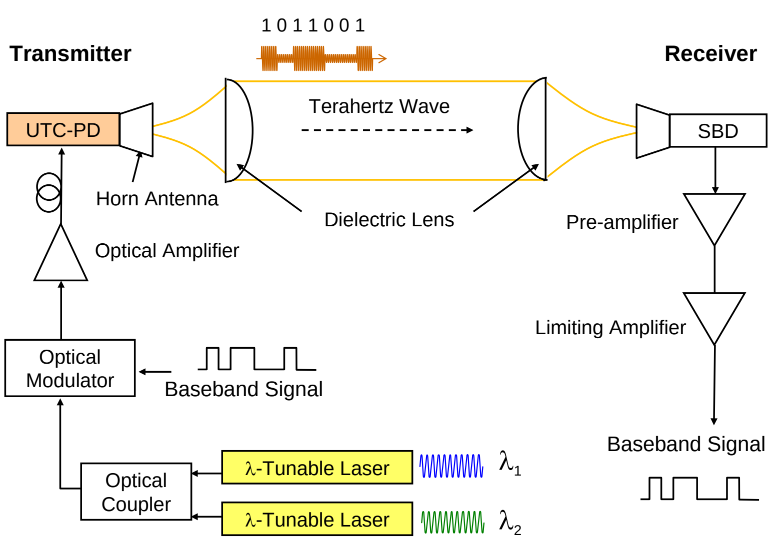


Fig. 11 Block diagram of the wireless link using photonics-based terahertz-wave transmitter.

The receiver consists of the Schottky barrier diode (SBD) followed by a low-noise pre-amplifier and a limiting amplifier. The SBD module is a commercially available one (WR2.8ZBD) from Virginia Diode Inc [16]. The specification of the operation frequency is

265~400 *GHz*. The video bandwidth of this SBD module is currently limited to about 300 *MHz* with the 50-ohm load.

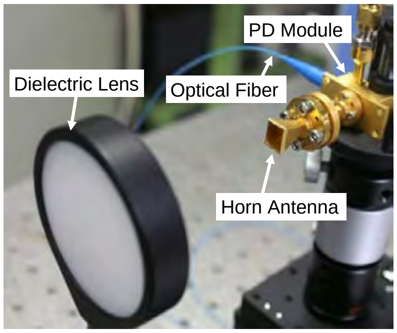


Fig. 12 Photograph of the transmitter with the dielectric lens

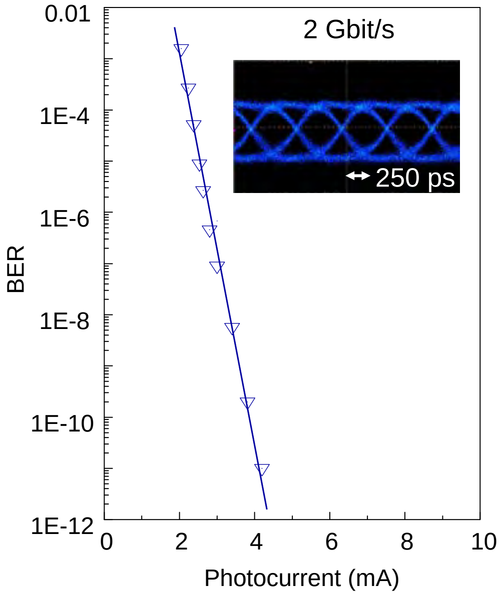


Fig. 13 BER characteristics at 2 Gbit/s with a carrier frequency of 300 GHz. Horizontal axis is a photocurrent of the transmitter

Fig. 13 shows transmission characteristics at a carrier frequency of 300 *GHz*. The transmission distance was 50 *cm*, but can be extended to a few meters, since the emitted terahertz wave is well collimated.

Although the receiver bandwidth is limited to several hundreds of *MHz*, the maximum bit rate was 2 *Gbit/s*. Error-free transmission was obtained for the transmitter photocurrent of as low as 4 *mA*, or for the output power of about 10 μW. It should be noted that the output power of the transmitter is proportional to square of the photocurrent.

Fig. 14 shows a series of eye diagrams for different carrier frequencies at a bit rate of 1 *Gbit/s*, measured before the limiting amplifier in order to see waveform deterioration more clearly. Eye patterns were clean, which ensures an error-free transmission from 280 *GHz* to 400 *GHz*. Very small change in the eye opening is mainly due to the carrier frequency dependence of the responsivity of the Schottky barrier diode (SBD). The SBD responsivity is highest at around 300 *GHz* and decreases when the carrier frequency increases up to 400 *GHz*.

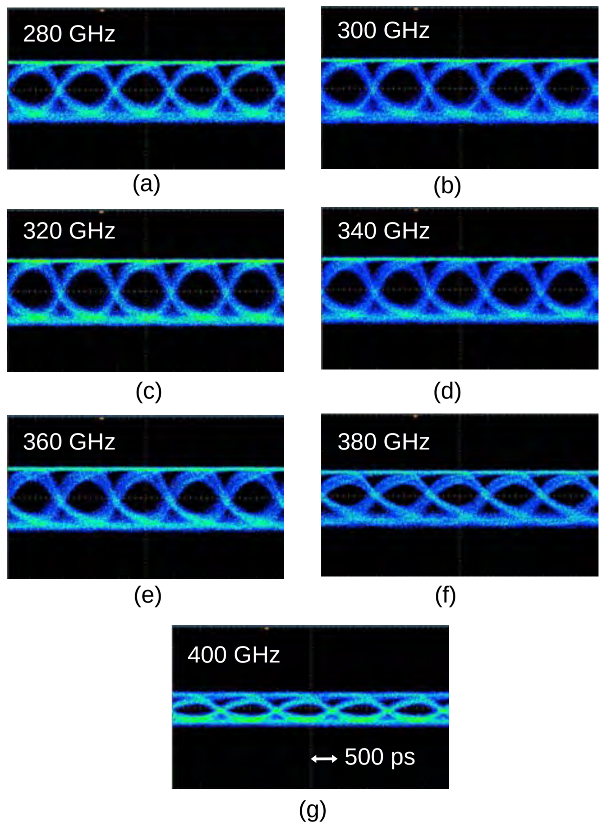


Fig. 14 Eye diagrams at a bit rate of 1 *Gbit/s* with carrier frequencies from 280 *GHz* to 400 *GHz*.

From the above results, the concept on the possible utilization of 300~400 *GHz* bands for multi-channel giga-bit link has been confirmed. In particular, an error-free transmission with a transmitter power of 10 μW/channel at 2 *Gbit/s* is encouraging for practical short-distance applications. 40-channel giga-bit transmission requires 400 μW in total, which is available by increasing the photodiode current as described.

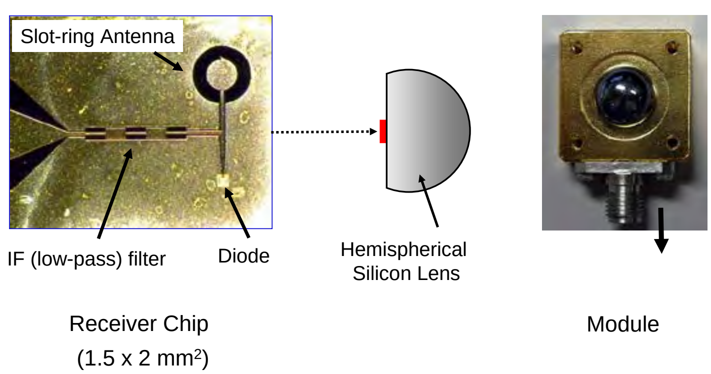


Fig. 15 Photograph of the integrated receiver designed at 250 *GHz* [11].

For higher bit-rate transmission such as 43 *Gbit/s*, the video (baseband) bandwidth of the receiver should be increased by incorporating appropriate intermediate frequency (IF) circuit as already demonstrated in our 120-*GHz*-band systems [6, 17]. We have fabricated and tested integrated receiver at 250 *GHz*, which has a video bandwidth of 4.5 *GHz* [11]. Photographs of the receiver chip and module are shown in Fig. 15. Maximum bit rate of 8 *Gbit/s* has been confirmed and further increase in the bit rate of over 10 *Gbit/s* is rather optimistic.

5. Conclusions

Utilization of frequency region over 275 *GHz* for wireless communications has attracted a worldwide attention. In order to demonstrate possible applications, we have developed a wireless link using photonics-based transmitter with high-power broadband photodiodes operating at 300~400 *GHz* bands. With commercially available Schottky barrier diode detector, an error-free transmission up to 2 *Gbit/s* has been obtained at 300 *GHz* with a transmitter power of 10 μW. In addition, 1 *Gbit/s* transmission has been demonstrated over an ultra-wide carrier frequency range from 280 *GHz* to 400 *GHz*.

Future work addresses higher bit-rate transmission by increasing of the video bandwidth of the receiver circuit. Photonics-based approach should 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 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.

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