Compact Terahertz Receiver for Short-range Wireless Communications of Tens of Gbps

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In the near future, trillions of things such as mobile smart devices, machine-to-machine (M2M) platforms, and sensors will be connected to networks and a huge amount of data will be flooded to cloud networks. A "hyper connected world" is dawning. Wireless communication systems that support this trend are required to be able to send a huge amount of data instantaneously. The transmission speed of the wireless communication systems has been increasing year by year and is anticipated to reach tens of Gbps and beyond. Radio signals with a frequency greater than 100 GHz are called terahertz (THz) waves, and they offer a usable frequency band that is more than 100 times wider than that used by current mobile systems. Such systems that use the THz-wave band will be able to increase the speed of communications up to 100 Gbps or more. Therefore, THz-wave communication systems are expected to be used in such applications as front haul systems in cellular networks, rack-to-rack or inter-rack communications in data centers, instant data downloading systems for 4K or 8K HD video, and so on. This paper describes our indium phosphide (InP)-based high electron mobility transistor (HEMT) technology, THz circuit design techniques, and packaging techniques for constructing compact apparatus, which are being developed by Fujitsu and Fujitsu Laboratories to realize THz-wave communication systems. This paper also reports on a compact 300 GHz receiver capable of receiving a 20 Gbps data stream and its application demo.

1. Introduction

High-volume data communications such as video and music downloads are widely used on mobile devices such as smartphones and tablets. With an anticipated shift to high-volume data communications, such as 4K and 8K HD video and high-resolution audio sources, there will be an increasing need for near-instantaneous downloads. This makes a speed increase in wireless communication devices necessary. **Figure 1** shows a data-rate trend of various wireless communication systems. The data rate has been increasing year by year, reaching 1 Gbps today and it will go up to 10 Gbps and above in the near future. Recently, radio signals with higher frequencies have been used for enhancing data rates. Wireless communication systems that use millimeter-wave bands such as 60 GHz bands and E-band (80 GHz bands) have been commercialized, offering a data rate of more than 1 Gbps.

Radio signals with a frequency greater than 100 GHz, which are called terahertz (THz) waves, are greatly attracting attention in various fields such as spectroscopy, imaging, and wireless communication.[1)] In particular, THz waves with a frequency greater than 275 GHz are not allocated for any commercial use and are a frontier band.[2)] From the viewpoint of wireless communications, such devices that use the THz-wave band are able to increase the speed of communications up to 100 Gbps or more since the THz-wave band allows for more than 100 times the usable frequency band width compared with the 0.8–2.0 GHz band used by the current mobile devices. However, since THz-wave signals attenuate seriously due to the atmosphere and rain, promising applications of THz-wave communication systems are discussed while focusing on those for short-range applications, for example, front haul systems in cellular networks, rack-to-rack or inter-rack communications in data centers, instant data downloading systems, and so on.[3)]

Since 2002, THz-wave communication systems have been studied and developed with a

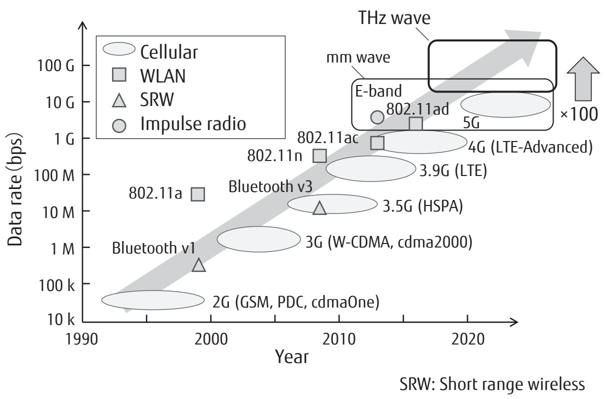

Figure 1
Data-rate trend of wireless communication systems.

photonics-based approach.[4] Following that, steady-step advances in III-V devices and silicon (Si) devices have started to show fruitful results these days in the THz-wave communication systems developed with an electronics-based approach.[5]

Fujitsu and Fujitsu Laboratories have been developing fundamental technologies such as devices, circuits, and packaging for realizing THz-wave applications, based on high electron mobility transistors (HEMTs).[6] We have been producing great results both in the digital and analog fields since their invention (1979).

In this paper, we report on an advance in THz devices, circuit design, and compact packaging techniques, focusing on THz reception technologies. Finally, we introduce the world's first compact 300 GHz receiver that was developed by assuming its use in 300 GHz instant data downloading systems.

2. InP HEMT Technology for THz Applications

HEMTs are superior in terms of their high speed and low noise and are used to support current sensing and communications technologies. Familiar examples of their application are in 76 GHz vehicle-mounted radar systems[7] for preventing collisions and receivers for satellite broadcasting.

Indium phosphide (InP)-based HEMTs usually have an indium gallium arsenide (InGaAs) channel layer and an indium aluminum arsenide (InAlAs) supply layer on an InP substrate. Since the InGaAs channel layer transports electrons at double the speed that is obtained on gallium arsenide (GaAs) channel layers, InP HEMTs are greatly superior in terms of high-speed and low-noise performances comparted with conventional GaAs HEMTs, gallium nitride (GaN) HEMTs gathering much attention today, and cutting-edge Si devices. We have developed a 94 GHz passive image sensor[8] and a 70–100 GHz impulse radio transceiver[9] with InP HEMTs and demonstrated their excellent performance below a frequency of 100 GHz. However, much higher performance is needed for realizing THz transceivers.

A useful barometer of wireless communication devices is the maximum oscillation frequency, f_{max}. In general, devices with f_{max} two to three times greater than the carrier frequency of radio systems are necessary. Since the f_{max} of our InP HEMTs was about 300 GHz, we had to improve device performance by a factor of more than two.

To enhance the f_{max}, we carried out the following three measures.[10]

1) Shortening the gate length and the gate-source distance

To achieve high speeds and frequencies in HEMTs, it is effective to miniaturize the device size. Employing high-performance electron beam lithography apparatus, we shrunk the gate length to 75 nm from the conventional 130 nm. Moreover, we shortened the distance between the gate and source electrodes by 20%, reducing parasitic resistances.

2) Introducing "cavity" structure around the gate

In our HEMT IC fabrication process, benzocyclobutene (BCB) is used as an insulating film to achieve a low permittivity (ε=2.8) which is advantageous in terms of high-frequency operation. With conventional structures, the gate electrode periphery was also filled with BCB which increased parasitic capacitance and impaired high-frequency characteristics. In order to solve this problem, we eliminated the BCB from the gate electrode periphery and created a "cavity" structure, reducing the parasitic capacitance by 30%.

3) Optimizing the composition ratio, x, of the $In_xGa_{1-x}As$ channel layer

For the $In_xGa_{1-x}As$ channel layer, the composition ratio, x, is usually set to 0.53. Under this condition, the channel layer is lattice-matched to the InP substrate, achieving the best crystal stability. Conversely, to enhance the electron transport property (ETP), it is preferable to increase the composition ratio to more than 0.53, which gives rise to crystal instability due to an increase in lattice distortion, and which causes an increase in drain conductance. Considering that trade-off, we set the composition ratio to 0.63, resulting in an increase in ETP by 15% in comparison with that of the conventional device structure.

Figure 2 shows a cross section and a radio frequency (RF) response of our InP HEMT developed with the three measures. The f_{max} of this device improves up to 660 GHz, which is large enough for IC operation in the 300 GHz band.

3. THz Circuit Design Techniques

Employing the InP HEMT technology reported in section 2, we developed a 300 GHz receiver IC (RX IC). It is essential to establish THz circuit design techniques for effectively using the superior device performance. The RX IC consists of a low-noise amplifier (LNA), a detector (DET), and a differential post amplifier (POSTAMP). The LNA amplifies a received OOK (on-off keying) signal, and then the DET detects its envelope. The POSTAMP amplifies the envelope signal and sends it to a signal processing unit. The OOK signal with a data rate of several tens of Gbps has a broad-band spectrum power in a band of several tens of GHz. Thus, the key for designing the LNA and the DET is to broaden their bandwidth. In addition, from the viewpoint of receiver sensitivity, high gain and low noise are needed for the LNA.

In designing LNA, we employed common-gate (CG) architecture where gate terminals are connected to the ground. In terms of high gain and wide bandwidth at higher frequencies, the CG architecture is superior to the common-source (CS) architecture where source terminals are connected to the ground.

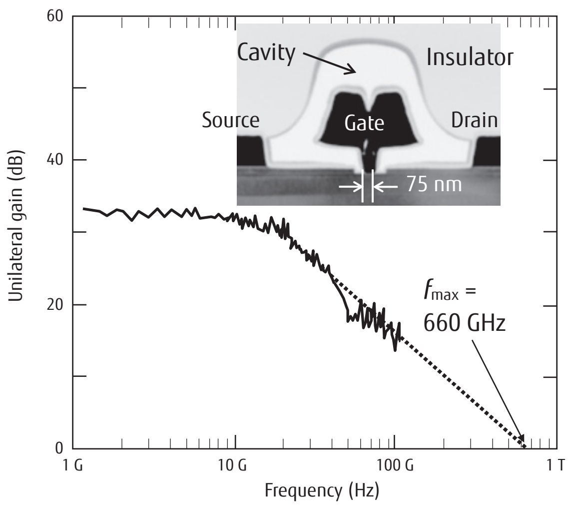

Figure 2
Cross section and RF response of 75 nm InP HEMT technology.

An input impedance of the CG transistor is mostly represented as the inverse of the transconductance, g_m, which is proportional to the size of the transistor (gate width). Therefore, choosing a proper transistor size gives an excellent input impedance matching in a wide bandwidth of frequencies. On the other hand, since an output impedance of the CG transistor is approximately given by an output capacitance (gate-drain capacitance, C_{gd}), connecting a series inductor to the output compensates for the output capacitance, establishing an output impedance matching. The simple input/output matching circuits give less loss, allowing for higher-gain and wider-bandwidth performances.

Furthermore, in designing the 300 GHz LNA, we introduced a control of the negative/positive feedbacks in the CG transistor. We balanced the positive feedback through the C_{gd} and C_{gs} (gate-source capacitance) and the negative feedback through the output inductor and the gate inductor, so as to maximize the gain and bandwidth performances while avoiding oscillations.

One more challenge in developing THz amplifiers is to keep circuit stability. The wavelength of the THz radio at 300 GHz is as short as 1 mm in the air and only about 0.3 mm in the InP substrate. Therefore, in the case of amplifier chips with a length more than a few millimeters, part of the amplified signal may propagate in the substrate as a wave and reach the input port. If the phase of the returned signal coincides with that of the input signal, oscillations occur due to the positive feedback, disrupting the normal amplification. To avoid any unexpected feedback, we employed microstrip lines (MSLs) for signal interconnection. The ground plain of the MSL shields the substrate from circuits formed on the surface. At the input terminal, short-stubs in parallel were deployed for cancelling capacitances between the input terminal and the ground plain.

Figure 3 shows a chip photograph and circuit characteristics of the LNA we developed. The LNA contains 6-stage CG amplifier units. We obtained a gain of more than 20 dB in a wide frequency range from 240 GHz to 320 GHz. The flatness of the gain is good enough for amplification of OOK signals with a data rate of several tens of Gbps without distortion.[11] The noise figure (NF) of this LNA was as low as 9.8 dB at 300 GHz.

Next, we developed an RX IC that integrates LNA, DET, and POSTAMP, as shown in **Figure 4**. InP HEMT Schottky diodes were employed for the DET. The POSTAMP we developed is a 3-stage differential amplifier with a gain of 20 dB and a bandwidth of more than 20 GHz. As for the circuit performance, we achieved a maximum sensitivity of 100 kV/W at 295 GHz and sensitivities of more than 50 kV/W in a wide frequency range of more than 30 GHz, which are enough for demodulating a 20 Gbps OOK signal in the 300 GHz band.

4. Packaging Techniques for Compact THz Receivers

In this section, we will describe compact packaging techniques for the RX IC reported in section 3. Assuming an instant downloader as a use case of THz-wave communication systems, we tried to miniaturize a receiver module so that it could be installed in smartphones.

Existing high-sensitivity THz-wave receivers consist of a module containing the receiver IC and an exterior antenna, with a specialized component called a waveguide to connect them. Thus, the receivers produced were large and difficult to integrate into mobile devices.

The most effective way to miniaturize the receiver module is to build the antenna directly into the receiver IC module and eliminate the waveguide. Then, modules with built-in antennas were built by connecting the antenna and the receiver chip through an internal printed-circuit substrate, making a waveguide unnecessary. The problem in doing so was that the most common materials for printed-circuit substrates such as ceramic, quartz, and Teflon, cause significant signal attenuation and loss of receiving sensitivity in the THz-wave band.

Below are the features of the newly developed technology.

1) Employment of a low-loss polyimide in the THz-wave band

We used a polyimide that can be micro-fabricated for the printed-circuit substrate. Signals received by the antenna are delivered to the receiver chip through a connecting circuit. In order to ensure that the THz signal is delivered through the connecting circuit dependably, with low loss, the top and bottom layers of the printed-circuit substrate are grounded, and these layers are connected with through-hole vias. These vias need to be spaced apart by less than one-tenth of the signal's wavelength—in this case, less than a few tens of microns—in order for the radio waves to be delivered properly. While polyimide as a material has a 10% higher loss than quartz, because its processing accuracy is more than four times higher, the through-hole vias can be placed within several tens of microns of each other, halving the loss as compared to a connecting circuit on a quartz printed circuit.

2) Establishment of flip-chip mounting technology in the THz-wave band for the first time

In order to deliver the received signal from the

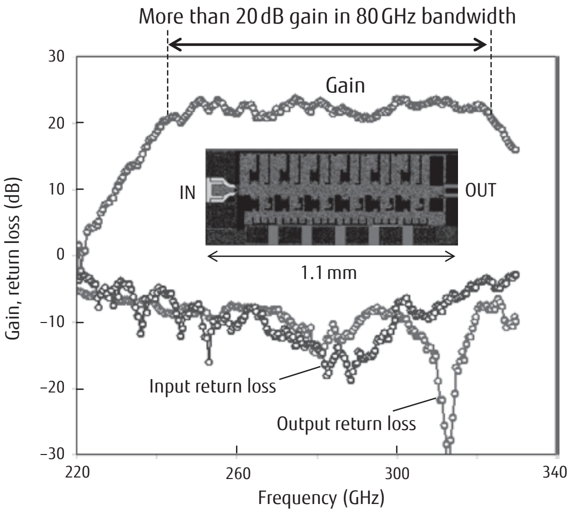

Figure 3
LNA developed and its characteristics.

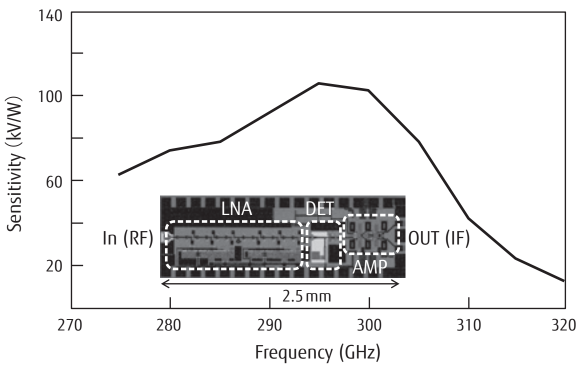

Figure 4
300 GHz receiver IC and its sensitivity.

connecting circuit on the printed-circuit substrate to the receiver chip with low loss, we developed flip-chip mounting technology that faces the circuit-forming surface of the receiver chip toward the printed-circuit substrate. This mounting technology is used for mounting millimeter-wave band collision-avoidance radar chips, but by using it with the polyimide circuit substrate-based low-loss delivery technology mentioned above, we have successfully expanded the applicable frequencies into the THz-wave band for the first time.

By using these two technologies, we developed the world's first 300 GHz band receiver module with an internal antenna. With a cubic volume of 0.75 cm^3 (not including output terminals) it can be installed in mobile devices. In evaluation, we confirmed that the receiver module successfully demodulated 20 Gbps OOK signals in the 300 GHz band.[12)]

5. Compact Receiver for 300 GHz Instant Data Downloader

The developed receiver module was installed in a smartphone-sized terminal, which was powered by an external power source and had a coaxial cable for sending the demodulated signal in the intermediate frequency (IF) to a signal processing unit. **Figure 5** shows the receiver terminal and an illustration of an instant data downloading system. With the receiver terminal and the server which was developed by Nippon Telegraph and Telephone Corporation (NTT), a research collaborator, a data downloading experiment was performed in a shielded room. In the experiment, high-definition (HD) videos were downloaded by touching the receiver terminal on the front panel of the server and tapping a start button. The results confirmed a high-speed downloading performance with a data rate of 2 Gbyte/s (16 Gbps), which is equivalent to that of one DVD's volume of data in about three seconds.[13)]

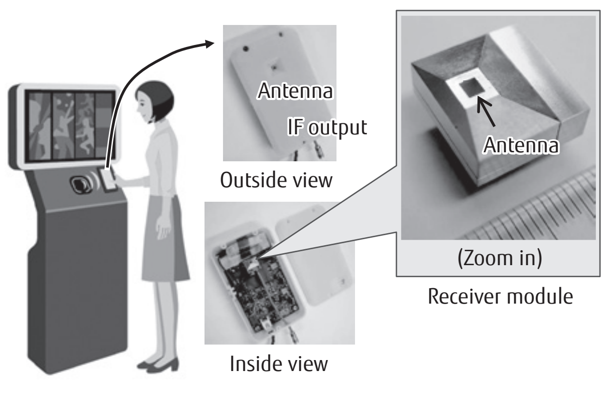

Figure 5
Compact receiver for 300 GHz instant downloader.

6. Conclusion

We have discussed fundamental technologies for realizing THz-wave communication systems. InP HEMT technology, THz circuit design techniques, and compact low-loss packaging techniques were described, focusing on THz reception technology. We demonstrated the instant usability of short-range THz-wave communication systems for high-speed data transmission through an experiment of data downloading at 300 GHz. For the next step, we will improve the fundamental technologies further and discuss various use cases, hoping to become an important player for realizing THz-wave communication systems.

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