Terahertz Wave Sensing Technology Supporting Safety and Security

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Abstract

Terahertz waves have a frequency between light waves and radio waves. They can realize high-resolution sensing while maintaining transmittance performance, and thus are expected to be used in various applications necessary for achieving safety and security. On the other hand, there are various technical issues for terahertz wave sensing, such as calculation of near field reflection coefficients, and ensuring yield. This paper describes the digital signal processing technology and device technology that serve as core technologies for the 300Ghz-band terahertz wave sensing systems that Mitsubishi Electric is developing. It also presents the results of demonstration experiments that clarify the effectiveness of the terahertz wave sensing system, and shows that it is possible to achieve mm-class imaging and μm-class displacement estimation.

1. Introduction

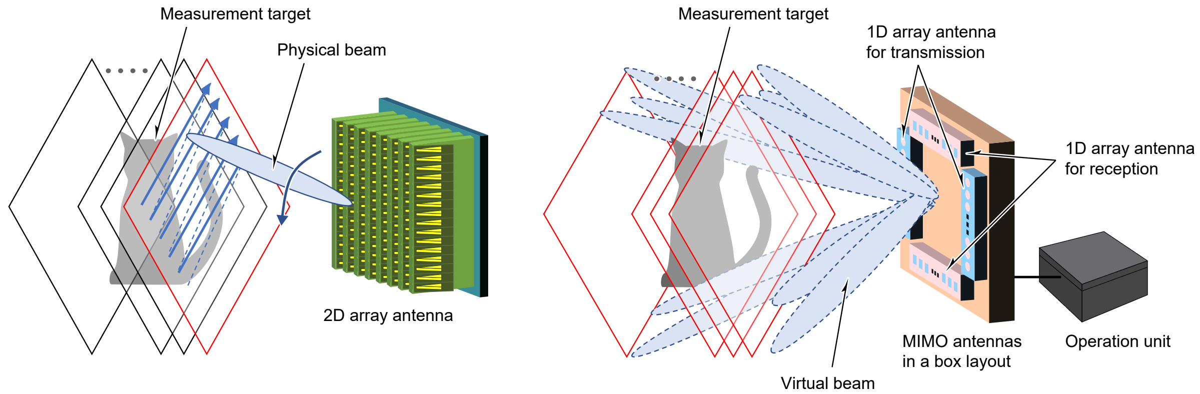
Light and radio waves have previously been used as media for sensing the shape or movement of target objects present in neighborhood space. For light waves, there are sensors capable of high-resolution sensing, such as cameras and Time of Flight (ToF) sensors. However, it is difficult to sense hidden objects because light waves are highly susceptible to shielding, and are greatly affected by obstacles. Radio waves, on the other hand, have outstanding transmittance properties compared to light waves. However, they have longer wavelengths and thus it is hard to achieve high resolution.

Thus, terahertz waves have attracted attention in recent years as a sensing medium with the characteristics of both light and radio waves. Terahertz waves are electromagnetic waves with a frequency between light waves and radio waves (100Ghz to 10Thz), and they allow sensing even objects behind obstacles with high precision and definition. Therefore, these waves are expected to see application in fields related to safety and security such as imaging applications like body scans and infrastructure inspection, and movement detection applications like infrastructure inspection. While touching on applications where terahertz wave sensing is expected to be used, this paper discusses development and demonstration testing results of our company's sensing technology using 300Ghz-band terahertz waves which will help realize these applications.

2. Sensing System Using Terahertz Band

With this terahertz wave sensing system, sensing is performed through beam-scanning of the target space for measurement, based on the principles of Multiple-Input Multiple-Output (MIMO) radar. With MIMO radar, a signal is sent from a transmission array antenna, and the signal reflected by the measurement target is received by a reception array antenna. Sensing is performed by calculating the reflection coefficient of each part of the measured space from the received signal.

Terahertz waves have high distance attenuation, and a terahertz wave sensing system is assumed to take the neighborhood region (Fresnel zone) as the observation environment, and thus the reflected waves cannot be regarded as far field (plane waves) as in the case of conventional MIMO radar. Therefore, in previous directivity control via beamforming, measurement takes time because focus control is performed according to distance with the antenna element, after identifying coordinates (i.e., the point of interest) in the space to be measured. Manufacturing of array antennas for transmitting and receiving terahertz waves requires microfabrication to arrange antennas at high density, and it is hard to ensure yield during manufacturing. These problems are solved with virtual focus sensing technology and MIMO antennas in a box layout, as shown in Fig. 1.



Physical beam is controlled according to the points of interest in the spaces existing at each focal distance.

(a) Physical beam sensing + 2D array antenna (conventional technology)

Focus control is performed virtually for data measured in physical space, and measurement data for the point of interest to be measured is generated simultaneously.

(b) Virtual focus sensing + MIMO antennas in a box layout (developed technology)

Fig. 1 Sensing System Using Terahertz Band

With widely-used 2D array antenna radar, a physical beam with directivity is formed by adjusting signal phases from antenna elements, and the measurement target is sensed while varying the beam direction. Therefore, sensing can only be done for one point of interest at a time. With virtual focus sensing technology, on the other hand, reflected waves are measured without performing directivity control, and multiple points of interest to be measured can be simultaneously sensed by forming a virtual beam focused on those points in a virtual space.

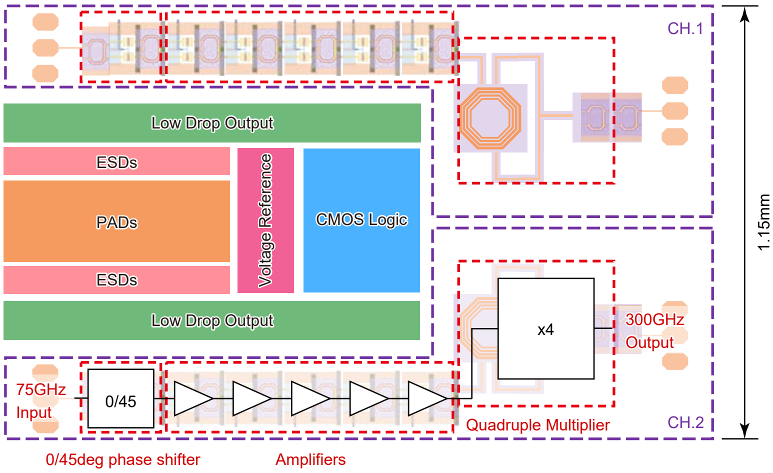
For our terahertz wave sensing system, we have developed a box MIMO antenna arrangement as a MIMO configuration capable of ensuring yield during manufacturing. In this arrangement, 1D array antennas for transmission, with antenna elements placed in a straight line, are arranged in the vertical direction, and 1D array antennas for reception, with the same linear structure, are arranged in the horizontal direction. An equivalent to a 2D array antenna is realized by calculating distance to the point of interest through combination of all of the transmission antenna elements and reception antenna elements, and then estimating the reflection coefficient. Furthermore, by placing the two 1D array antennas for transmission and two 1D array antennas for reception in a box layout, an aperture area is obtained which is equivalent to a high-density layout of antennas in two-dimensions, and this enables high-resolution sensing.

3. Terahertz Wave Device Technology

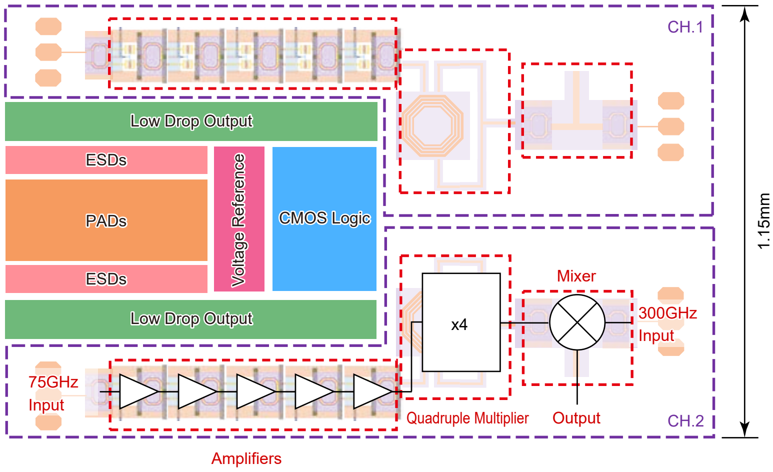
In order to realize the aforementioned MIMO antenna in a box layout, Mitsubishi Electric has developed 1D array antennas that operate in the 300GHz band. Element technologies needed to realize array antennas can be broadly divided into two categories: (1) radio-frequency integrated circuits (RFIC), and (2) antenna packages. This section presents these technologies owned by Mitsubishi Electric.

Figure 2 shows the composition of the 300GHz-band transmission and reception RFICs we have developed. A 45nm Silicon on Insulator–CMOS (SOI-CMOS) process, promising both good integration performance and higher output, is used for this development.

The transmission and reception RFICs must be lined up at an interval of half wavelength, and high-density layout is required with two systems laid out in 1.15mm or less, as shown in Fig. 2. Due to the unprecedented high- density layout, it is necessary to reduce the number of circuits as much as possible. Therefore, the transmitter RFIC is not configured with two conventional double multiplier stacked on top of each other, but rather with a 0/45deg phase shifter, 75GHz band amplifiers, and a quadruple multiplier as shown in Fig. 2(a), while the receiver RFIC is configured with 75GHz band amplifiers, a quadruple multiplier, and a fundamental wave mixer as shown in Fig. 2(b), forming a 300GHz band transmitter/receiver RFIC with a different circuit configuration than conventional ones.



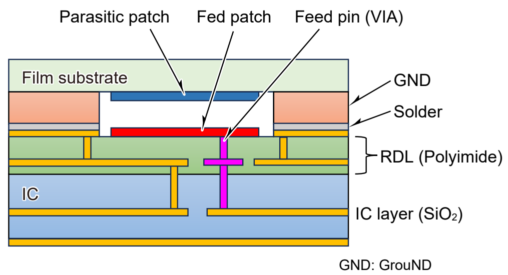
(a) Transmitter RFIC



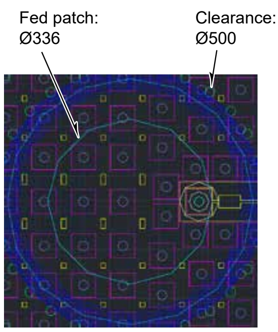
(b) Receiver RFIC

Fig. 2 Configuration of 300GHz band RFIC

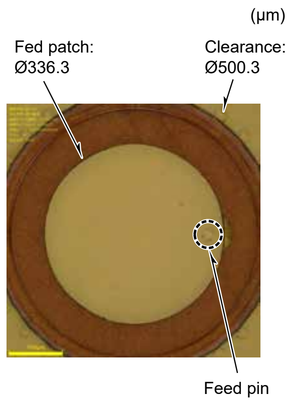
The basic configuration of the 300GHz-band antenna package, a prototype drawing, and a prototype sample are shown in Fig. 3. This structure is a dual patch antenna using the redistribution layer process. This process is an IC post-processing technology. The constituent elements are: the IC layer (base material: SiO_2), redistribution layer (RDL), and single-sided film substrate. The antenna fed patch, consisting of a circular patch, is formed on the top layer of the RDL. Power is supplied to the antenna through the backside. This is done via a matching circuit formed on the IC layer by using a feed pin (stack VIA) which connects the IC layer from the RDL.



(a) Conceptual illustration of side view



(b) Prototype drawing



(c) Prototype sample

Fig. 3 Basic configuration of 300GHz band antenna package

The parasitic patch, on the other hand, is formed on the single-sided film substrate, and mounted using conductive tape so that the parasitic patch faces downward. As shown in Fig. 3(b) and (c), a pattern manufacturing error of 1μm or less was achieved for the antenna fed patch as a result of this mounting, and it was confirmed that manufacturing can be done with high precision using this process. The above shows that this method enables high-precision manufacturing and mounting, as well as broader bandwidth due to the use of a dual patch antenna, making it easy to achieve the desired antenna characteristics.

4. Results of Terahertz Wave Sensing Demonstration Experiments

Demonstration experiments on tomographic imaging(1) and vital sensing(2) were carried out to confirm the effectiveness of the 300GHz-band terahertz wave sensing system. Figure 4 shows the measurement system that was used and the results of the measurement. The aforementioned 1D array antennas are currently under development, so a 2D array antenna is simulated by moving a single transmission horn antenna and reception horn antenna placed on an XY stepper, and sensing a stationary body. The inside of a suitcase was filled with expanded polystyrene panels. Then, a toy gun and knife were embedded in separate panels, and tomographic imaging was carried out. The results confirmed that contours and surfaces of the target objects can be imaged with mm precision at the layers where the model gun and knife were respectively placed.

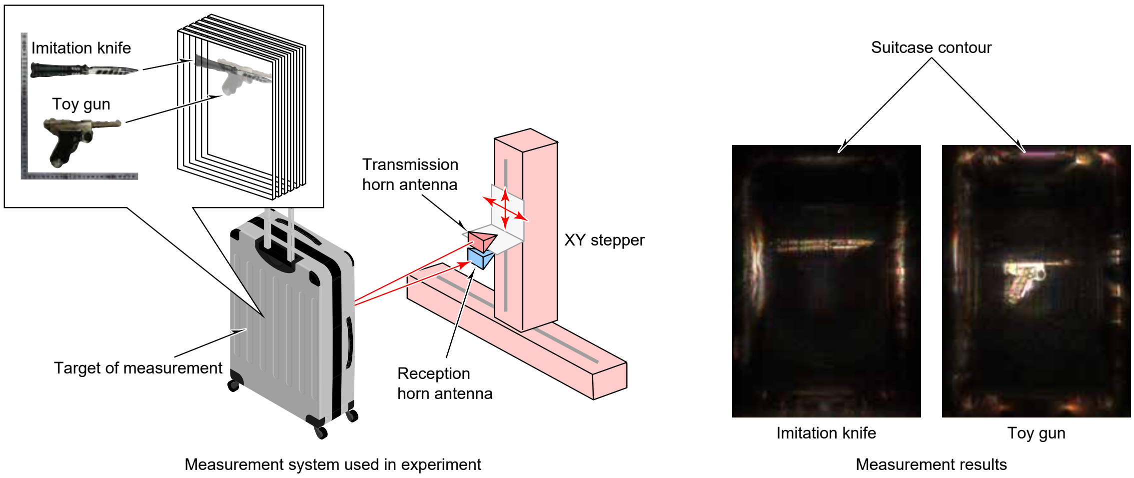


Fig. 4 Results of Tomographic Imaging

Next, vital sensing was carried out as an example of a movement detection application. This involved capturing the pulse information from a human body. Figure 5 shows the measurement image and results. Unlike tomographic imaging, this validation involves sensing a moving body, and thus the experiment was carried out by simulating directivity with a lens. The experiment results confirmed that chest displacement on the order of μm which occurs due to the heartbeat can be estimated, and estimation can be done with an error of 0.5% relative to the electrocardiograms (ECG) used to estimate heartbeat intervals in the medical field.

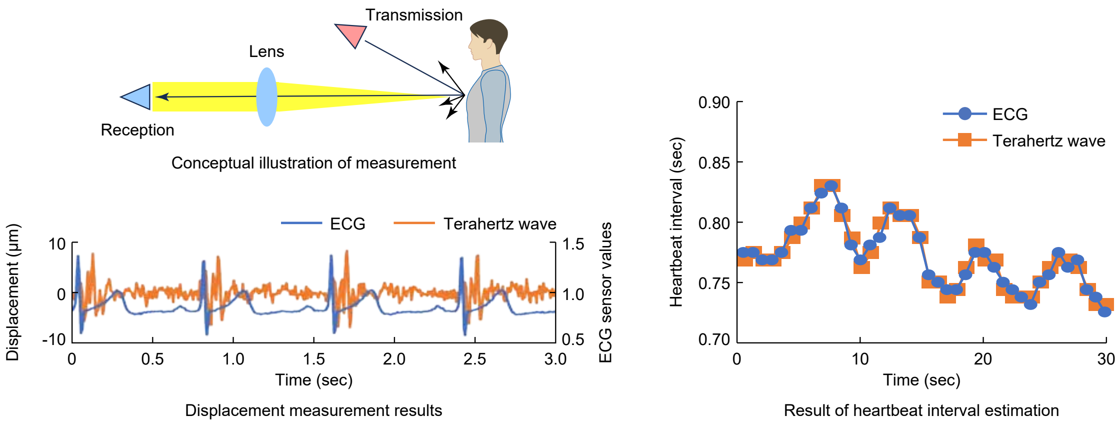


Fig. 5 Result of Vital Sensing Measurement

Based on the above validation, the technology is expected to be used in areas such as nondestructive inspection and infrastructure monitoring, which make use of the characteristics of 300GHz-band terahertz waves.

5. Conclusion

This paper has discussed Mitsubishi Electric's technology and demonstration experiment results for a 300GHz terahertz wave sensing system for realizing high-resolution sensing of hidden objects. It was shown that high resolution and transmittance performance can be achieved with core technologies for 300GHz-band terahertz waves—i.e., virtual focus sensing technology, 300GHz-band RFIC, and packaging technology—and that applications can be expected across a variety of fields, including security gates and vital sensors.

References

(1) Taira, A., et al.: 300GHz band Sub-Terahertz Sensing Technologies for High Resolution Imaging, IEICE Technical Report, 123, no. 76, RCS2023-77, 288–293 (2023)
(2) Umeda, S., et al.: Experimental study of vital sensing using 300GHz band sub-terahertz wave, IEICE Technical Report, 123, no. 108, RCS2023-100, 109–114 (2023)