

Fundamental research on non-destructive testing of reinforced concrete structures using sub-terahertz reflected waves

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Abstract. Terahertz and sub-terahertz waves are unexplored waves range between infrared waves and microwaves. This range features with unique characteristics of both light straightness and electromagnetic wave transmission. Terahertz and sub-terahertz waves are attractively new diagnose method of inner objects because they are safer compared to normal non-destructive inspection methods involving high energy, such as X-rays. Hereby, a novel non-destructive inspection method for concrete and reinforced concrete structures is proposed using sub-terahertz reflection imaging. In Japan, where earthquakes and other natural disasters frequently occur, this technique is expected to be used to remotely inspect the deterioration of damaged RC structures that are difficult to access to. The results of this study confirm that various types of condition changes in concrete can be found by using this sub-terahertz imaging method. The presence of cracks/voids in concrete and under the finishing layers was successfully detected based on differences in reflectance. Moreover, the presence of metals inside/behind the concrete specimens was able to be identified. It was also confirmed that the decline rate of the mechanical properties of concrete could be evaluated according to the decrease in reflectance due to the existence of fine cracks.

1 Introduction

In recent years, the deterioration of social infrastructure in Japan, such as reinforced concrete structures built during the period of rapid economic growth (1970s), has pointed out the importance of appropriate investigation, diagnosis, and maintenance management. In addition, from the perspective of decarbonized society, it is desirable to avoid demolishing buildings and to extend the service life of RC structures through necessary and affordable repairs. Against this background, there is a growing need for non-contact, nondestructive inspection methods to diagnose the deteriorations of infrastructures without compromising their performances.

There are several non-destructive and micro-destructive testing methods proposed for reinforced concrete structures [1-3]. Besides, there are also established investigation methods using optical systems, such as peeling estimation of finishing materials by infrared thermography and rebar exploration by electromagnetic radar [4-7].

On the other hand, non-contact and remote inspection methods which can be used in situations where people cannot easily approach and work, are imperatively needed while have not fully developed yet. In particular, it is difficult to collect information on inner cracks of materials and the condition of embedded reinforcing bars by visual inspection or digital cameras. It should be pointed out that no testing method has been established

to obtain such information in a non-contact way until now.

In this study, we propose a non-contact, non-destructive inspection method for reinforced concrete structures using Sub-Terahertz (THz) waves that can penetrate concrete and finishing materials. This enables remote diagnosis of invisible internal damage from the surface and provides information necessary for proper maintenance. In view of the future practical application, we adopted an areal measurement method using a Sub-THz camera, which has the potential to measure a wide area, and report the results of a basic study on specimens simulating cracks and reinforcing bars.

2 Measurement using Sub-THz Waves

2.1 Terahertz / Sub-Terahertz wave

Fig. 1. shows the bandwidths of THz and Sub-THz waves. THz waves are electromagnetic waves with

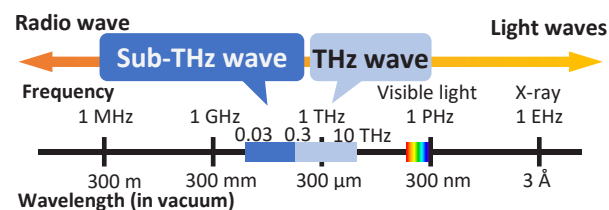


Fig. 1. Frequency bands of THz and Sub-THz waves

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frequencies ranging from 0.3 to 10 THz and wavelengths from 30 μm to 1 mm (in vacuum). They have high permeability to nonpolar materials, including concrete, but high absorptivity to polar materials, such as water. Sub-THz waves, with frequencies ranging from 0.03 to 0.3 THz and wavelengths from 1 to 10 mm (in a vacuum), have similar properties to THz waves, but have higher transmission performance.

Their wavelength is intermediate between that of radio waves and light waves, and thus have both transparency and directivity. They also has the characteristics of low energy which is safety to the human body compared to X-rays [8].

Therefore, (Sub-)THz waves have potential for use in non-destructive testing.

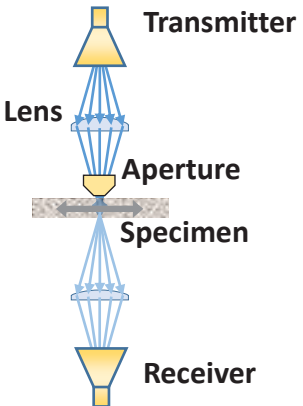
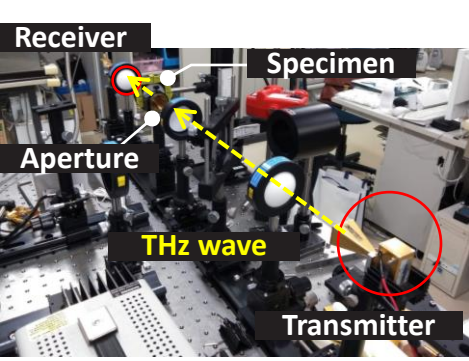
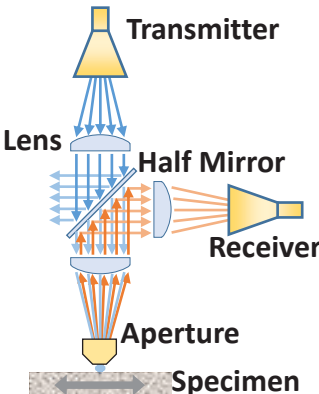
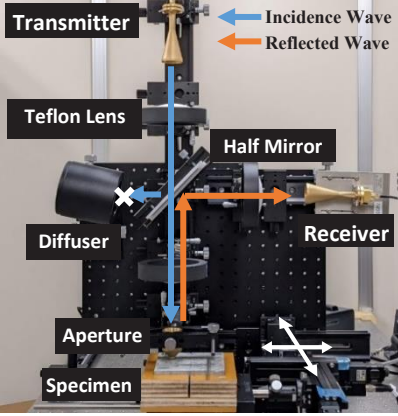
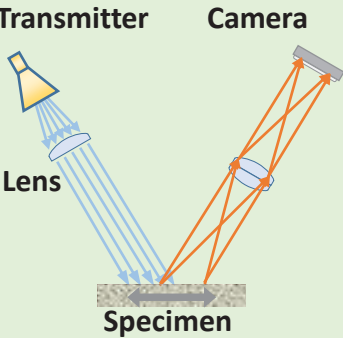
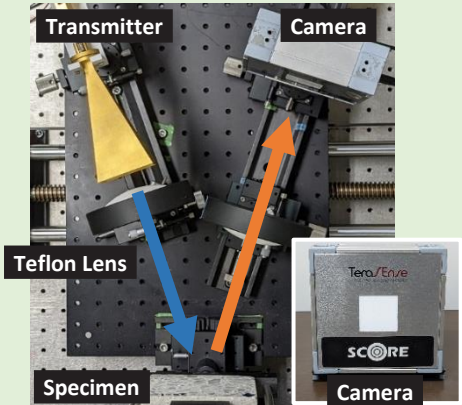
2.2 Previous studies on cement materials

Due to their high permeability to concrete and other construction materials, THz waves are being considered for application in the construction field.

Measurement methods using THz waves can be broadly classified into those using transmitted waves and those using reflected waves.

First, an example of measurement using transmission waves is described, as shown in the item (a) of **Table 1**. Some studies have successfully detected voids and embedded metal pices in concrete from the decrease in transmittance, showing the possibility of detecting internal defects in concrete using THz waves [9, 10]. In addition, the property of THz waves to be

Table 1. Comparison of measurement systems using Sub-Terahertz waves

	Conceptual Diagram	Photograph of measurement system	Characteristics
(a) Transmission			• Aperture improves resolution. • Requires equipment on both sides of the specimen. • Time-consuming measurement
(b) Reflection and Half Mirror			• Resolution improvement by aperture • Unsuitable for remote measurement • Measurement takes time
(c) Reflection and Camera			• Camera-based areal measurement • Real-time monitoring • Improved transportability due to smaller size and lighter weight

easily absorbed by water has been used to detect minute cracks in concrete using water as a sensitizer, and to estimate the concentration of chloride ions [8, 11]. Other studies have been conducted to evaluate the self-healing effect inside the self-healing concrete, which cannot be visually confirmed [12].

Another measurement example using reflected waves, as shown in the item (b) of **Table 1**, is also discussed. There exist studies that have shown the detection of crack expansion by the increasing area of the decrease in reflectance, as well as studies that detect invisible cracks in concrete poles [13, 14]. There are also studies that have shown that moisture content can be estimated from the reflectance using a measurement system with a half-mirror [15].

Although such measurements using transmitted and reflected THz waves have been performed on cement materials, they have only been studied on a laboratory scale. There are still issues to be solved for wide-area measurements on actual structures.

In transmission wave measurement, it is necessary to install the oscillation and detection devices on both sides of the object, making it difficult to move the device, which is particularly disadvantageous when the object is thick, e.g. concrete structures.

Measurement using a half-mirror systems has a huge intensity attenuation when passing through the half-mirror, resulting in a lower signal-to-noise ratio. In addition, measurement systems using an aperture to improve resolution can not be measured from a distance because the aperture must be installed just in front of the test object.

Furthermore, in previous studies, since there is only one detector element, images are generated by determining the reflectance in a small area at a time and arranged in a mesh-like pattern. Although this method has the advantage of high resolution, it is time-consuming to generate images and does not allow for wide-area scanning or real-time monitoring.

Thus, for the application to practical structures, the measurement system must be small, lightweight, and portable, as well as be capable of areal measurement and real-time monitoring.

2.3 Measurement using a Sub-THz camera

Existing measurement methods using (sub-)THz waves, as described above, have problems in non-contact, wide-view monitoring of real structures.

As a solution to this problem, we constructed a measurement system using a sub-THz camera. The sub-THz camera has a 2.4 cm square sensor with 256 elements suitable for the sub-THz band, benefitting its ability to measure and monitor an area in real time.

An overview of the measurement system is shown in the item (c) of **Table 1**. A GUNN diode capable of oscillating from 18 to 52 GHz was used as the source of the sub-THz wave.

3 Outline of Experiment

3.1 Measurement Overview

In this study, in order to confirm the accuracy of measurement, experiments were conducted on specimens with aluminum tape attached to the back of the specimens to simulate buried steel bars and on specimens with slits introduced to simulate cracks.

3.2 Materials and Mix proportions

Ordinary Portland cement (OPC, density 3.16 g/cm³, specific surface area 3140 cm²/g) was used, crushed sand (surface dry density 2.66 g/cm³) and land sand (surface dry density 2.62 g/cm³) as fine aggregate, crushed stone (surface dry density 2.68 g/cm³, maximum size 20 mm) as coarse aggregate, AE water reducer (density 1.05 g/cm³) was used as admixture.

The concrete/mortar Mix proportions are shown in **Table 2**. All water cement ratios were 55 %. The slump of the concrete was 14 cm, and the air content was 4.9 %. The slump flow of the mortar was 240 mm at 15 pours and the air content was 7.4%.

An outline of the test specimen is shown in **Fig. 2**. Concrete plates of 100 mm width and height were prepared as the specimens for foundation tests. The specimens were demolded one day after casting, cured in water for 28 days, cut to the specified thickness using a wet concrete cutter, dried at 60 °C for 3 days, and measured.

Table 2. Concrete and Mortar Mix proportion

	Unit weight (kg/m ³)				
	W	OPC	S	G	AE
Concrete	168	306	790	1053	1.38
Mortar	301	547	1368		

Table 3. Experimental Parameters

Category	Parameters	variable
Backside metal	Thickness [mm]	10, 20, 30
	Aluminum tape width [mm]	10
	Frequency [GHz]	20~50, every 5 GHz
Slit	Thickness [mm]	10
	Slit width [mm]	0, 1, 2.5, 5, 10
	Covering material	None, mortar 5 mm
	Frequency [GHz]	20~50, every 5 GHz

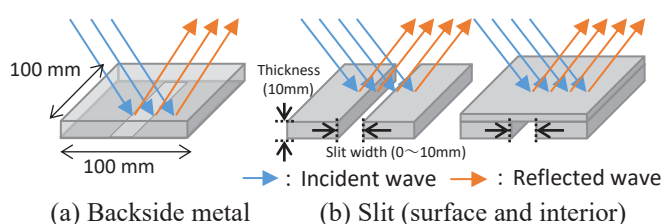


Fig. 2. Overview of test specimen

3.3 Measurement parameters

The measurement items are listed in Table 3. Because this is a fundamental experiment on the application of Sub-THz waves to concrete, measurements were made with schematic parameters of slit and aluminum tape instead of crack and rebar, respectively.

First, measurements were made on specimens with aluminum tape applied to the back of the specimens to simulate buried rebar. Here, the backside metal was measured to make it easy to compare the presence/absence of metal on the same concrete. The thickness and frequency at which metal could be detected were investigated using specimens of different thicknesses.

Measurements were also made on pre-cut specimens with slits width from 0 to 10 mm, and when the slit was covered by a 5 mm thick mortar.

4 Results and discussion

4.1 Backside Metals measurement

Fig. 3. shows the measurement results for a concrete specimen with aluminum tape stuck to the back surface. For the specimen with a thickness of 10 mm, the reflection effect of the aluminum tape can be seen as a vertical line at the position indicated by the dotted line, except at 45 GHz. At 45 GHz, the incident and reflected waves interfere with each other, possibly canceling out the metal reflections. In the 20 mm thick test specimen, the presence of aluminum tape can be confirmed at 30 GHz and 40 GHz. However, with a specimen thickness of 30 mm, the green color representing the reflective intensity of concrete emerged under all frequencies, and the response of the aluminum tape cannot be confirmed.

The results show that the system is strongly affected by interference, and the degree of interference varies

finely with frequency. Therefore, it is necessary to study the most suitable best frequency while changing the frequency more finely.

In terms of clarity, the edges of the tape were blurred at frequencies between 20 GHz and 30 GHz, while at higher frequencies, the boundaries of the tape could be detected relatively clearly. Thus, when aluminum tape was applied, the tape could be detected according to a difference in the reflection intensity up to a thickness of 20 mm, and the higher the frequency is, the more clearly the tape boundary could be.

4.2 Surface slit measurement

Fig. 4. shows the measurement results when the slit width was varied. The larger the slit width is, the wider the range of low reflectance in the center became, confirming at all frequencies. For a slit width of 1 mm, a decrease in reflectance was observed only at 50 GHz. For the slit width of 2.5 mm, the decrease in reflectance was detected at 20 GHz, 30 GHz, 45 GHz, and 50 GHz. The slit width of 5 mm showed a reduced reflectance at all frequencies. Thus, we confirmed that the surface slit can be detected by the decrease in reflectance, and even when a slit with a narrow width of 1 mm, it can be detected at 50 GHz.

Although relatively large size slits were measured in this study, further studies will be needed to measure the fine cracks in actual buildings in the future.

4.3 Internal slit measurement

Fig. 5. shows the results when the slit width was varied while the slit was covered by a 5 mm thick mortar simulating the finishing material. Compared to the exposed slit, the response was generally weaker, and the detection limit of the slit width was 2.5 mm.

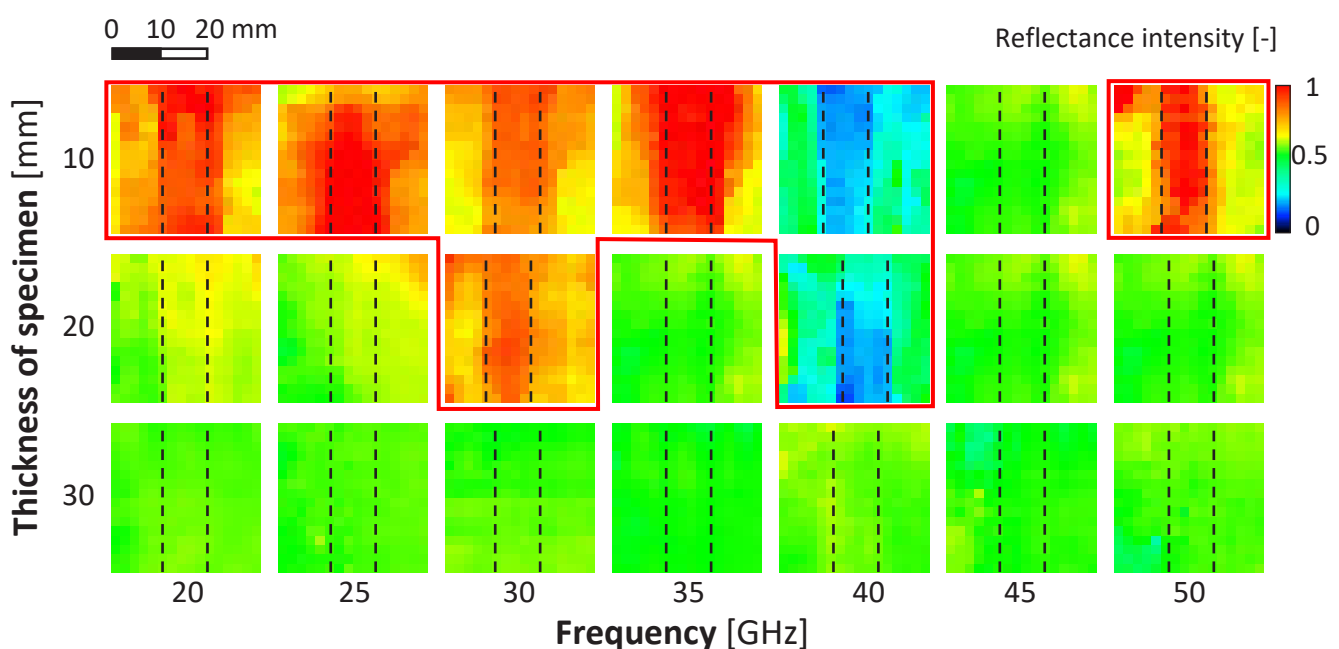


Fig. 3. Detection of aluminum tape on the back surface of concrete

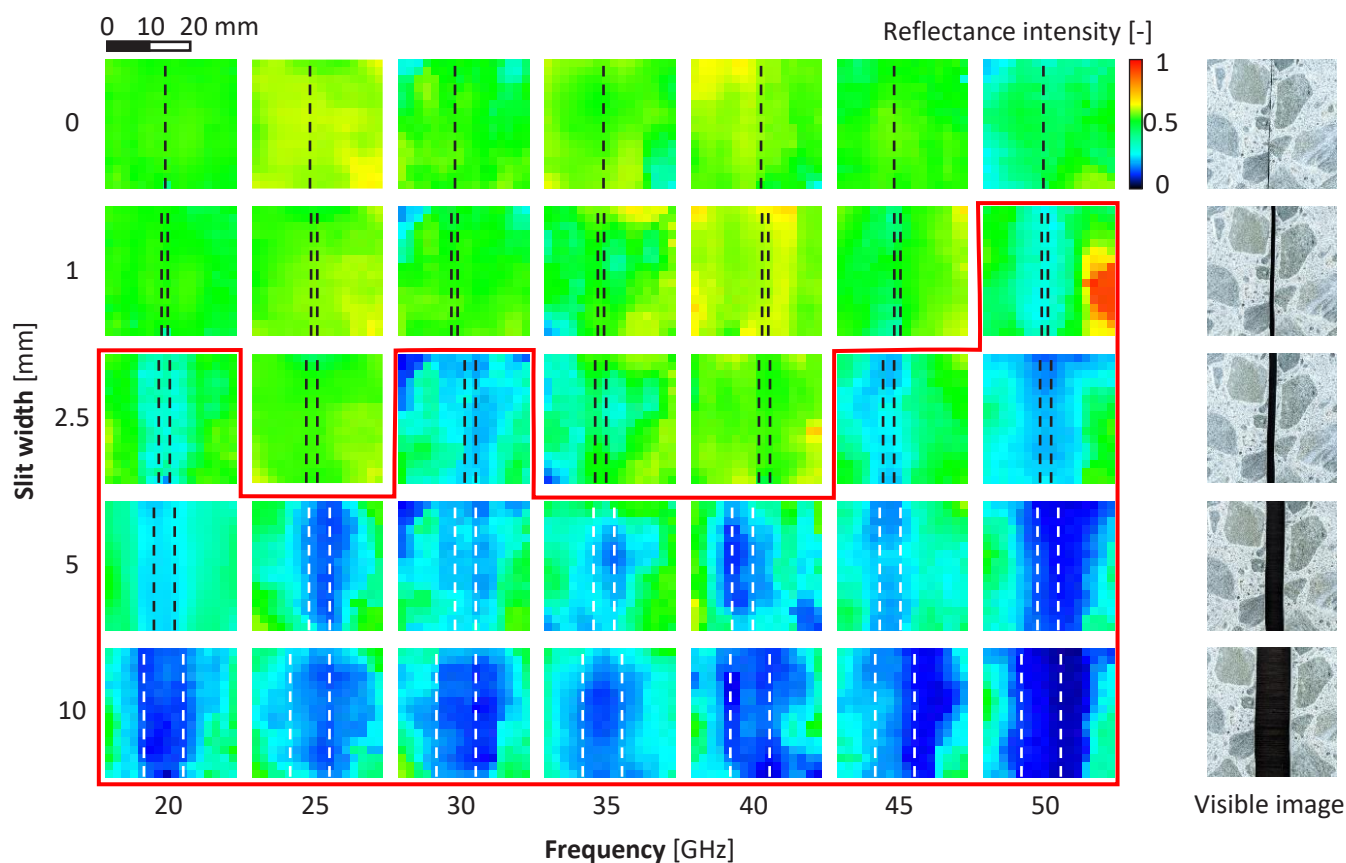


Fig. 4. Detection of surface slits

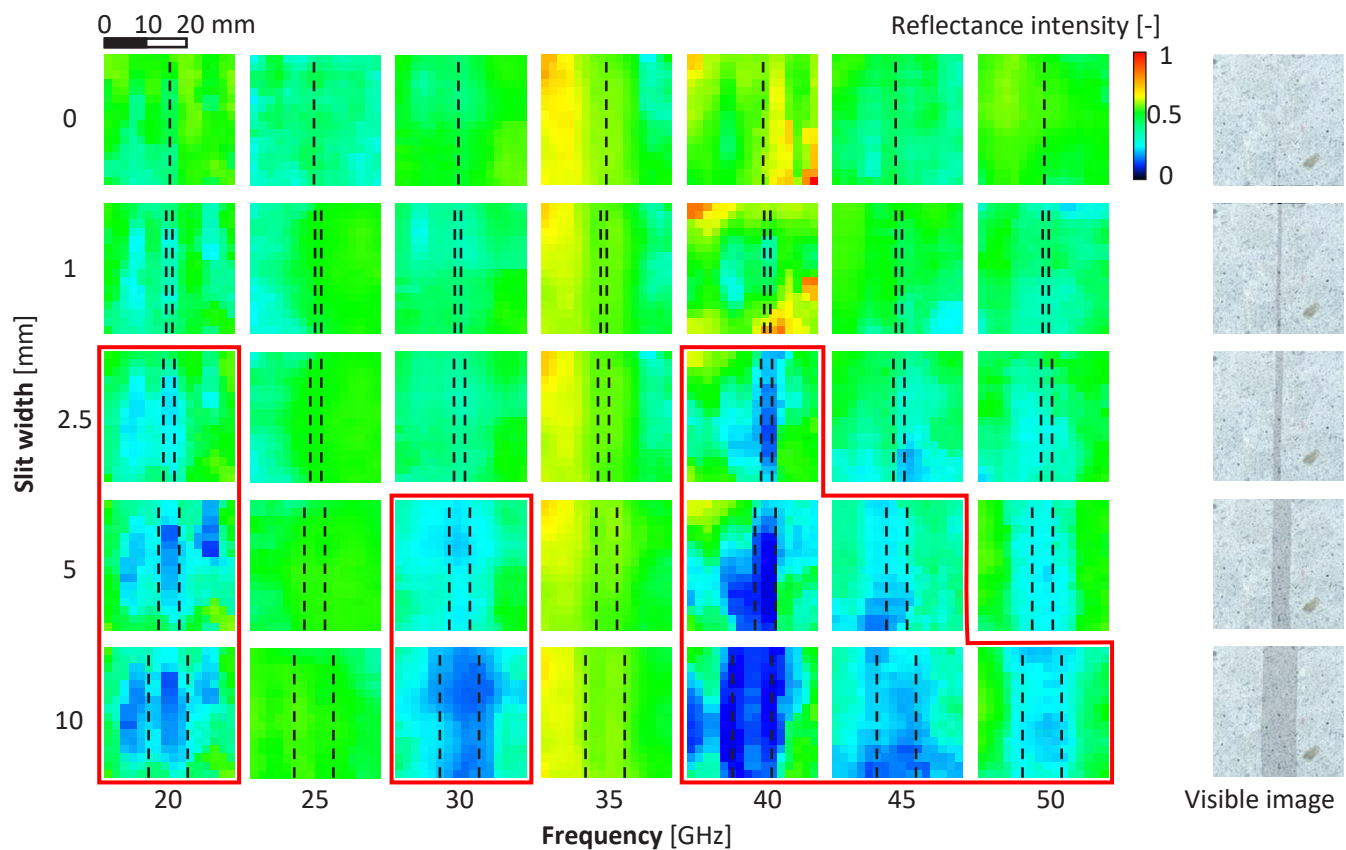


Fig. 5. Detection of internal slit

5 Conclusion

In this study, we conducted measurements using a sub-THz camera to simulate buried rebar and defects on the surface or inside of concrete, assuming that the nondestructive inspection method using sub-THz waves will be applied to reinforced concrete structures. The following are the findings obtained.

- 1) Aluminum tape placed on the back of the specimen to simulate embedded rebar could be detected up to 20 mm thickness of the specimen.
- 2) In the measurement of specimens with slits simulating cracks, detection was possible for slit widths greater than 1 mm.
- 3) Even when the slit was hidden by placing a 5 mm thick mortar, it was possible to detect a slit of up to 2.5 mm.
- 4) It was confirmed that reflectance and transmittance varied sensitively with frequency, and further studies are needed to establish their relationship in the future.
- 5) Camera-based measurement enables areal measurement and real-time monitoring.
- 6) The downsizing and weight reduction of the measurement system has improved its transportability, confirming the possibility of measurement on real structures.

Further applications are expected by using a camera with even higher sensitivity and multiple built-in elements and by increasing the intensity of the oscillation. In addition, the THz wave is expected to be utilized as a nondestructive inspection technology for structures by combining it with the THz wave corrosion detection and Ground Penetrating Radar (GPR) described earlier.

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