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Observation of damage in insulated copper cables by THz imaging ☆

Seiya Takahashi [a,*], Tomoyuki Hamano [a], Kaori Nakajima [a], Tadao Tanabe [b], Yutaka Oyama [a]

[a] Department of MS&E, Graduate School of Engineering, Tohoku University, Aramaki Aza Aoba 6-6-11-1020, Sendai 980-8579, Japan
[b] Institute of Multidisciplinary Research for Advanced Materials Coordinator, Center for Fusion Research of Nano-Interface Devices, Low-carbon Research Network Tohoku University 2-1-1, Katahira, Aoba-ku, Sendai 980-8577, Japan

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ABSTRACT

A novel non-destructive inspection method using terahertz waves for the detection of broken wires in copper cables shielded by insulating polymer opaque in the visible and near infrared light region is presented. Terahertz reflection imaging, using a 0.14 THz IMPATT oscillator and a Schottky barrier detector, was applied to insulated copper cables that had been artificially damaged. The internal insulated wires embedded in the opaque polyethylene can be clearly visualized using THz radiation. It was shown that a gap in a wire can be detected by a decrease in the intensity of the reflected signal where the size of the gap is greater than the wavelength of the oscillator.

1. Introduction

Stable electrical power networks are essential not only for industry but also for domestic use. Electrical conductors are classified depending on the type of conducting and insulating materials, and the structure of these materials. With the spread of electrical power delivery networks, deterioration of conducting cables is becoming more of an issue, and inspection to locate broken wires in the cables is becoming ever more important. However, copper wires shielded by insulator opaque in the visible and near infrared light region cannot be inspected by eye, so traditional methods for inspecting covered copper cables involve removing the insulator. This destructive method is inefficient, because after inspection, the insulator needs to be repaired, and the repair is usually imperfect. The removal and repair of the insulator also takes time and effort, and, in addition, deterioration can be accelerated by water penetrating the cable at the site of the repair. To overcome these problems, a nondestructive inspection methodology is required. Of the nondestructive inspection methods, consideration should be given to X-ray inspection methods; however, this presents a health hazard, as there is a risk of exposure of personnel to radiation. Thus a safe, nondestructive inspection method needs to be established. In this paper, we evaluate a terahertz wave inspection method and show it to be a promising and safe, non-destructive inspection technology.

Terahertz waves are electromagnetic waves in the frequency range between approximately 0.1 THz and 10 THz. Pioneering work on the generation of THz waves based on the excitation of phonon-polaritons in GaP was done by Nishizawa and Suto [1], and various kinds of THz light sources have been developed for practical applications. For a frequency tunable THz light source, we have developed a high Q factor source based on the differential frequency generation principle (DFG) using GaP [2] and GaSe [3]. However, the size of the equipment for these THz lasers is not small, thus they are impractical for inspection work in the field. For practical use, semiconductor device light sources are appropriate. Therefore, we applied a TUNNETT (tunnel injection transit time effect diode) [4] oscillator for the inspection of defects in building blocks by THz imaging. Various kinds of semiconductor device light sources have also been developed by many research groups. Traditional GUNN [5] and IMPATT [6] oscillators can be adapted, and a recently developed quantum cascade laser [7] operating at THz frequencies can also be applied for this kind of work.

The quantum energy of THz photons is approximately equal to the thermal energy at room temperature (0.1 THz to 10 THz correspond to the quantum energy of 4.1×10^{-4} eV to 4.1×10^{-2} eV and temperature of 4.8 K to 480 K). It is very small in comparison with those of X-ray and there is no risk of ionizing the human tissues; thus THz radiation will not show a health hazard. Because THz frequencies are located between the frequencies of radio waves and infrared light, terahertz radiation has characteristic features of both radio waves and infrared or visible light.

* Corresponding author. Tel.: +81 90 4883 8881.
E-mail addresses: b3tm5327@s.tohoku.ac.jp (S. Takahashi), thamano@material.tohoku.ac.jp (T. Hamano), nkjmkori@material.tohoku.ac.jp (K. Nakajima), tanabet@tagen.tohoku.ac.jp (T. Tanabe), oyama@material.tohoku.ac.jp (Y. Oyama).

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The feature of radio waves means easily passing through nonpolar materials such as a paper, wood, and polymers. The feature of infrared or visible light means that it is possible to control the optical path by using mirrors or lenses and to obtain the high reflection from the metal surface. In addition, it is also characteristic feature of terahertz radiation that its vibrational frequency band corresponds to the resonance frequency band of intermolecular while the vibrational frequency band of infrared light corresponds to that of intramolecular. In view of these characteristics, THz waves have been applied to the non-destructive inspection of the adhesion of ceramic tiles on the space shuttle [8]. We ourselves have published experimental results on the use of THz imaging for inspecting defects in building blocks [9]. Moreover, THz waves can pass through the materials used as insulation for electrical conducting cables, because these insulators are usually made from polymers such as polyethylene, vinyl chloride or Teflon. Thus, THz imaging of metal cables encased in polymers is possible. If there is damage to one of the wires in the cable, a different response can be obtained in comparison with an undamaged wire. Therefore, terahertz waves can be safely used for nondestructive inspection.

For this study, reflected image measurements of copper cables covered with polyethylene were conducted using a wave source at 0.14 THz. According to our own transmittance measurement of the polyethylene insulator at 0.14 THz and more than 1 THz, it was shown that the polyethylene insulator is more transparent at lower frequency and the transmittance at 0.14 THz, that is about 60%, is higher than that over 1 THz. The possibility of detecting breakages in a wire in the cable was investigated by imaging cables with artificially damaged wires.

2. Experimental

2.1. Preparation of damaged copper cables

Fig. 1 shows photographs of a typical covered copper cable. The cover is made from insulating black polymerized polyethylene in which the carbon is added with the below 1% concentration for the reduction of deterioration by ultraviolet radiation from the sun [10] and the conductor inside comprise stranded wires, with the 12 outermost wires corresponding to the reflection surface for THz imaging. In order to examine the capability of the system for imaging various levels of damage, one disconnection sample with a copper wire with a different size gap cut into it were made. After removing the cover from the cable, one of the outermost wires was cut to simulate a broken wire. The cable was covered again with the removed opaque polyethylene. The sample with a gap of almost 0 mm (about 0.2 mm) and 3 mm before being re-covered are shown in Fig. 2. The reflection imaging measurements were carried out on the same sample by changing the gap 3, 2.5, 2, 1.5, 1, and almost 0 mm, in turn.

2.2. Reflection imaging apparatus and measurement sequences

A schematic diagram of the reflection imaging system is shown in Fig. 3. A 0.14THzIMPATT oscillator is used for the THz light source. The generated THz waves are collimated by a Teflon lens, and then focused on the surface of the outermost wires by mirrors. The reflected and scattered THz waves from the surfaces of the wires are collected by mirrors surrounding the cable, and the reflected waves are detected by a Schottky barrier diode. The oscillator and detector are operated at room temperature. Rotational and longitudinal scanning of the cable was done at fixed angular and distance intervals, every 3.6 degree and 0.1 mm, respectively, and all the measurement sequences were automatically controlled by a computer. The precision of alignment of the cable in the equipment was less than 12μm. The measurement average number is 4, then the standard deviation of measured data is 1.6×10^{-3}, and SN rate is 63 dB.

3. Results and discussion

Fig. 4(a) shows a typical example of the angular dependence of the reflected THz intensity at one fixed longitudinal position obtained from a copper wire cable surrounded by insulating black polyethylene. As shown in the figure, 12 reflection intensity peaks can be observed corresponding to the number of outermost copper wires in the cable. Our measured transmittance of the insulating black PE is 60%. Therefore reflected wave intensity from

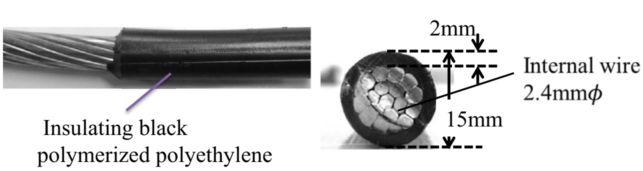
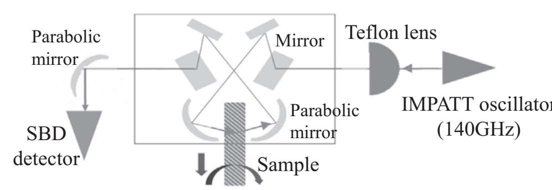


Fig. 1. The photographs of typical covered copper cable sample.



[PCT/JP patent pending (2012), PCT/JP2012/072139]

Fig. 3. The schematic drawing reflection imaging system.

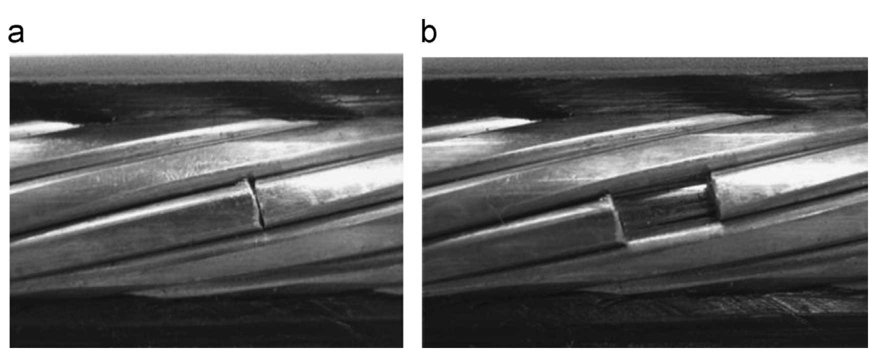


Fig. 2. The photographs of artificially made disconnected copper wire portion with the snapped space of (a) almost 0 mm, (b) 3 mm. THz imaging was carried out after the opaque polyethylene insulator was attached again.