Passive imaging using a 4K-cryocooled THz photoconductive detector system with background-limited performance

Makoto Aoki, Saroj R. Tripathi, Masanori Takeda, and Norihisa Hiromoto
Graduate School of Science and Technology, Shizuoka University, Shizuoka 432-8011, Japan

***Abstract*—We have demonstrated THz passive imaging of a razor blade, a coin and a paper written by a pencil concealed in a plastic package and an envelope using a high-sensitive THz photoconductive detector system. In our imaging system, we achieved a background limited NEP of 1.0×10-14 W/√Hz in the frequency range of 1.5 - 3 THz.**

I. Introduction And Background

In recent years, terahertz (THz) imaging have gained attention in security applications and non-destructive inspection owing to its excellent characteristics such as penetration of many non-conducting materials without ionization and identification of various materials using specific absorption spectra[1]. Hu and Nuss demonstrated THz imaging applications to package inspection and chemical content mapping in biological objects using the THz-time domain spectroscopy (TDS)[2]. Kawase et al. reported the detection and identification of drugs concealed in envelopes using continuous-wave THz wave parametric oscillator[3]. Moreover, Lee et al. demonstrated the use of the terahertz quantum cascade laser (QCL) and the uncooled microbolometer camera for real-time imaging at a standoff distance of 25 meters[4]. However, using the current technologies such as THz-TDS, high power THz sources, liquid He cooled high-sensitive THz detectors, the practical implementation of the THz imaging system is far from the reality. For the practical application of passive imaging, we have developed a THz detector system which employs high-sensitive and broadband THz photoconductive detectors. We used a mechanical 4K GM cryocooler instead of liquid helium making our system practical and convenient[5].

In this work, we made a passive image of a razor blade, a coin and a paper written by a pencil concealed in a plastic package and an envelope to demonstrate an efficacy of THz passive imaging system developed in our laboratory.

II. 4K-cryocooled THz Photoconductive Detector System

The THz detector system comprises of a compact 4K cryocooler with a low-vibration cold work surface, four detector mounts with cold THz filters and light-collecting optics, and low-noise preamplifiers. The 4K-cryocooler is a two-stage GM mechanical cooler and its cold head is structurally isolated from but thermally connected to the cold work surface on which detectors are installed. Measured vibration amplitude of the cold work surface was less than 2.6 μm which was much smaller than the ordinary level of 10μm of the GM cryocooler. Temperature of the work surface decreases to below 4 K within 5.5 hours after switching on.

Figure 1 shows the configuration of detector mounts on the cold work surface. Two detector mounts look one direction through cold filters and a z-cut crystal window, whereas the other two look the opposite direction. Four detector mounts are occupied by four different THz photoconductive detectors with different impurity ionization energies. The high frequency channel use a p-Ge:Ga photoconductive detector and a lightly stressed p-Ge:Ga (LS-Ge:Ga) photoconductive detector having an acceptor level of 10.8 meV corresponding to response in the frequency range of 2.5-4.0 THz[6]. The LS-Ge:Ga detector is strained by only small stress of about 150 kg/cm^2, having much higher responsivity than non-stressed p-Ge:Ga detector. The middle frequency channel adopts a stressed Ge:Ga (St-Ga:Ga) detector, strained by a maximum stress of ~6000 kg/cm^2, having an acceptor level of about 5.4 meV and detection frequencies in the range of 1.5-3.0 THz[7]. The low frequency channel is an n-GaAs detector with a donor level of 5.7 meV and having response to photons with energy above 4.3 meV through photo-thermal effect, corresponding response to 0.8-1.6 THz frequency radiation[8].

The performance of photoconductive detectors is listed in Table 1. The responsivity for 20 Hz optical chopping is a little

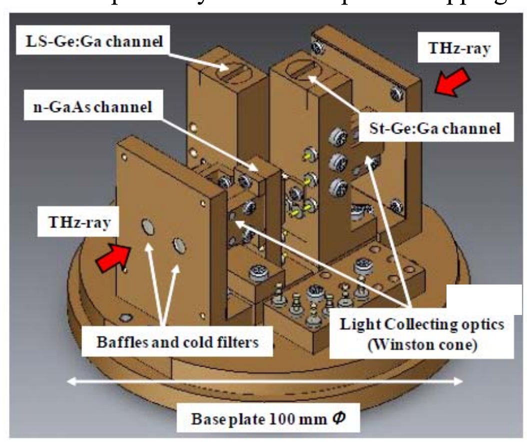

Fig. 1. Configuration of detector mounts on the cold work surface for 4K-cryocooled THz photoconductive detector system.

Table 1. Optical and electrical performances of photoconductive detectors operating at the temperature of 4 K.

photoconductive detector	Ge:Ga	LS-Ge:Ga	LS-Ge:Ga	S-Ge:Ga	n-GaAs #3
Applied strerss [kg/cm^2]	0	150	600	6000	-
Breakdown field [V/cm]	2.2	0.6	0.48	0.32	3.0
Bias field [V/cm]	1.4	0.28	0.24	0.18	2.4
Ionization energy [meV]	10.4	10.3	9.4	5.3	4.9
Cutoff frequency [THz]	2.51	2.49	2.27	1.27	1.2
Background photon influx [photons/s]	4.0E+13	4.0E+13	4.0E+13	3.9E+13	8.0E+12
Noise voltage density (Background-limit) [V/√Hz]	2.8E-07	5.7E-07	-	1.8E-06	2.1E-07
Responsivity※ [A/W]	1.6	8.9	12	54	0.29
ηG※	0.021	0.10	0.14	0.29	0.0013
Responsivity※※ [A/W]	1.38	6.5	8.9	48.2	0.21
ηG※※	0.018	0.076	0.104	0.25	0.00091
NEP※ [W/√Hz]	1.7E-13	6.4E-14	-	3.2E-14	7.3E-13
NEP※※ [W/√Hz]	2.0E-13	8.8E-14	-	3.7E-14	1.0E-12

※DC, ※※AC Chopping frequency : 20Hz

978-1-4577-0509-0/11/$26.00 ©2011 IEEE

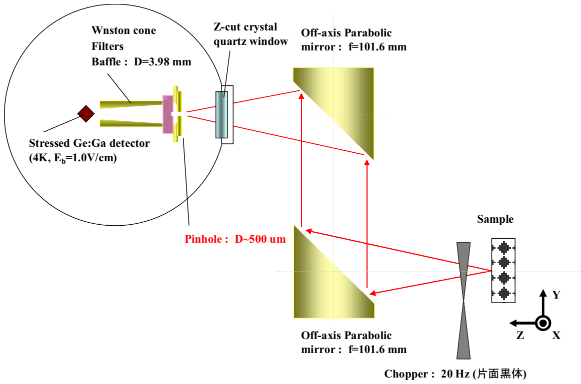

Fig. 2. Optical system for THz passive imaging.

smaller than that of DC measurement because an optical efficiency of chopping is less than one. The responsivity of LS-Ge:Ga is more than five times of that of Ge:Ga though the cutoff frequencies are not so different, which is mainly originated from longer lifetime of free holes in the stressed p-type impurity semiconductors. The responsivity of n-GaAs detector was not very high, but it increased at temperatures higher than 4K because the photo-thermal effect helped the ionization of carriers to the conduction band more efficiently. This effect was however small at a large bias voltages near the breakdown.

III. Experiments And Results

The emitted thermal radiation from the imaging object is very weak. Besides this, there exist similar thermal radiations from the surrounding objects. Therefore, it is desirable to use the background limited (BLIP) detectors for the passive imaging. In our passive imaging system, we used the stressed Ge:Ga detector having BLIP performance, covering 1.5 to 3 THz frequency region. Our system consists of two off-axis parabolic mirrors, a Winston cone and a 400 μm pin hole placed in front of the cone as shown in Fig. 2. This configuration avoids unwanted scattering light and enabled us to achieve the high spatial resolution and high detectivity. The noise voltage density of our system shows good consistency to the theoretical values (photon noise limited) and attains the BLIP performance. NEP of our system is 1.0×10^{-14} W/√Hz and the minimum detectable temperature defined by noise equivalent temperature difference (NEΔT) is 3.8 mK. Similarly, the minimum detectable emissivity defined by noise equivalent emissivity difference (NEΔε) is 1.5×10^{-5}.

To demonstrate the applicability of our system, we imaged the safety razor blade and 100 yen coin and the paper written by the pencil concealed in the plastic package and the envelope. The spatial resolution of full width at half maximum (FWHM) determined using knife-edge method is 430 μm. The passive THz image of safety razor blade in the plastic package is shown in Fig. 3(a), which is obtained by scanning 25×50 mm^2 with the measurement resolution of 0.5 mm, revealing the razor blade. Figure 3(b) and 3(c) show the passive image of the safety razor blade and 100 yen coin and the paper written by the pencil concealed in the envelope with the scanning step of 250 μm, respectively. We distinguished two metallic objects successfully and clearly identified the characters using our non-contact and non-invasive passive imaging system.

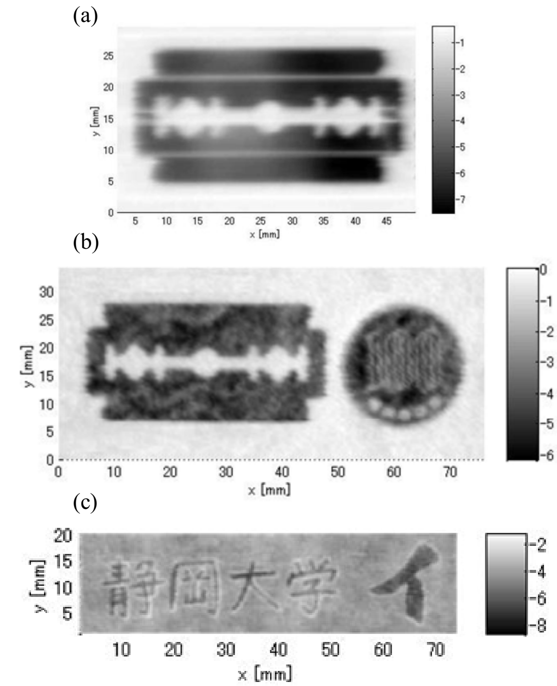

Fig. 3. THz passive images at 1.5 to 3.0 THz. (a) safety razor blade in the plastic package. (b) safety razor blade and 100 yen coin in the envelope. (c) paper written by the pencil in the envelope.

IV. Conclusions

We have demonstrated the sensing potential of our 4K-cryocooled THz photoconductive detector system with background-limited performance by taking THz passive images. We show that this system can be applied to the applications in security, industry and medical uses.

References

[1] D. Mittleman, et al., "Recent advances in terahertz imaging," Appl. Phys. B: Laser Opt. **68**, 1085 (1999).

[2] B. B. Hu and M. C. Nuss, "Imaging with terahertz wave," Opt. Lett. **20**, 1919 (1995).

[3] K. Kawase, et al., "Non-destructive THz imaging of illicit drugs using spectral fingerprints," Opt. Express **11**, 2549 (2003).

[4] A. W. M. Lee et al., "Real-time terahertz imaging over a standoff distance (>25 meters)," Appl. Phys. Lett. **89**, 141125 (2006).

[5] M. Aoki, et al., "Background-limited operation of 4K-cryocooled THz photoconductive detector system with a wide frequency range of 0.8 to 4 THz," Proc. IRMMW-THz2009, W4A01.0387 (2009).

[6] N. Hiromoto, M. Saito, and H. Okuda, "Ge:Ga far-infrared photoconductor with low compensation," Jpn. J. Appl. Phys. **29**, 1739 (1990).

[7] N. Hiromoto, T. Itabe, H. Shibai, H. Matsuhara, T. Nakagawa, and H. Okuda, "Three-element stressed Ge:Ga photoconductor array for the infrared telescope in space," Appl. Opt. **31**, 460-465 (1992).

[8] K. Watanabe, M. Ueno, M. Wakaki, O. Abe, and H. Murakami, "GaAs:Se and GaAs:Te Photoconductive Detectors in 300μm region for Astronomical Observations," Jpn. J. Appl. Phys. **47**, 8261 (2008).