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Terahertz homodyne spectroscopic imaging of concealed low-absorbing objects

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Abstract. Terahertz (THz) homodyne and direct spectroscopic images of low-absorbing materials packaged between up to six layers of a cotton fabric are recorded at 0.3 and 0.6 THz at room temperature. More than two orders of magnitude higher dynamic range is revealed due to the detection in a homodyne scheme, which is realized using paper sheets as a phase-shifting mechanism. It is demonstrated that the homodyne approach can serve as a convenient imaging tool to identify and resolve objects manifesting low absorbance of THz radiation, such as paper tissue, nitrile, and low-density polyethylene concealed in a textile environment. [DOI: 10.1117/1.OE.58.2.023104]

Keywords: terahertz imaging; homodyne detection; terahertz spectroscopy; low-absorbing objects.

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1 Introduction

Terahertz frequency radiation (THz) has low-absorption in nonconducting materials, such as clothing fabrics or packaging supplies, which allows to serve as a versatile tool to display contents of packaged and concealed objects in various environments.[1,2] However, when the concealed objects themselves exhibit low absorption in THz frequencies, a direct THz imaging approach becomes unsuitable due to a small signal-to-noise ratio. To tackle this problem, a coherent heterodyne THz imaging[3,4] approach can be employed to reduce the noise floor up to four orders of magnitude, thus allowing to resolve low-absorbing materials. Nevertheless, the heterodyne approach requires at least two signal sources synchronized via a phase-locking loop, which currently makes this technique complicated and not very practical in screening applications. A solution is hence needed that would make THz imaging systems competitive in practical implementations.

In this article, a THz homodyne and direct imaging of low-absorbing materials packaged between up to six layers of cotton fabric at 0.3 and 0.6 THz are demonstrated and compared. The homodyne phase-shifting scheme was realized here in a simple way by varying the number of office paper sheets in the optical path. It is shown that homodyne THz imaging can serve as a convenient imaging tool to screen low-contrast suspicious inclusions in textiles.

2 Samples and Their Characterization

Two types of samples were selected for the experiments. The first group included reference objects—a steel blade, serving as a reflecting reference, and a 0.6-mm diameter hypodermic needle for the spatial resolution reference. The second group consisted of low-absorbing materials—a sealable low-density polyethylene (LDPE) (two layers of LDPE film) bag, a tissue paper, and a nitrile glove (two layers of nitrile film), which were enveloped in two or six layers of cotton fabric. All the low-absorbing samples and cotton layers were characterized individually beforehand in the THz range via absorption measurements using frequency domain THz spectrometer Toptica TeraScan 780 (Toptica Photonics Ltd.). Moreover, a refraction index dispersion analysis of a standard office paper sheet (areal density 80 g/m^2, thickness of 0.1 mm) was performed, which was used here to vary the phase of the THz radiation in one of the arms of the optical set up. These results are plotted in Fig. 1. One can see that a two-layer cotton fabric exhibits the highest absorption of all the tested materials, except for the frequency range below 0.2 THz where the absorption of a nitrile glove is the highest. We also note that cotton and nitrile glove spectral dependences are very similar. Terahertz frequencies of 0.3 and 0.6 THz (highlighted as vertical lines) were employed enabling the use of our electronic sources for THz imaging. Spectra around 0.6 THz (dotted line) display a significant difference (>35%) in absorbance between the cotton, LDPE bag and paper tissue, and a smaller difference (around 15%) between the cotton and the nitrile. The same trend is observed at 0.3 THz (dashed line), which suggests that a simple direct THz imaging setup can be used without resorting to more advanced techniques. However, in order to reliably distinguish the absorption between a cotton fabric and nitrile glove (<10% difference), different means are needed. A THz homodyne scheme is implemented and described in the following that allows for an unambiguous distinction between the materials.

3 Experimental Setup and Measurement Technique

Figure 2 presents the THz homodyne imaging implementation scheme.[5] Terahertz radiation was generated by an electronic source based on a frequency-synthesizer whose 12.5-GHz frequency signal was multiplied via a multiplier chain (Virginia Diodes Inc.) by a factor of 24 or 48 to operate at frequencies 0.3 and 0.6 THz, respectively. The THz beam delivered from the source is collimated with an off-axis

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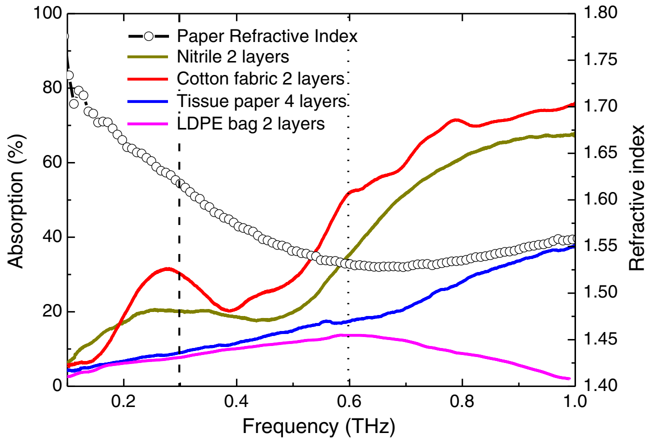

Fig. 1 Absorption spectra of the studied objects: nitrile glove, cotton fabric, tissue paper, and LDPE bag (left scale). Right scale displays refractive index of the office paper used to shift the phase of the THz radiation in a homodyne scheme. Spectra were measured using frequency domain terahertz spectrometer.

parabolic mirror PM1, then split with a high-resistivity silicon beam splitter (thickness 370 μm) S1 into two arms: the upper and the lower one with a ratio of 60:40. The phase of the more intensive (upper) beam was varied by a paper stack, P, and delivered using a flat mirror, M1, to another off-axis parabolic mirror, PM2, with a focal length 10 cm to focus the radiation onto the sample. The transmitted radiation is focused with a high-density polyethylene (HDPE) lens, L1 (focal length 5 cm), and through a beam splitter, S2, diverted to the detector for the image formation. The remaining (lower arm) less intense radiation part is directed via a splitter S1, flat mirror M2, an off-axis parabolic mirror PM3, and a beam splitter S2 (splitting ratio 60:40), which was employed to generate a homodyne signal. In the direct-detection mode, only the upper arm was used for imaging, while the lower one was blocked. Intensity of the THz beam was detected at room temperature using a broadband InGaAs bow-tie diode[6] that is well-suited for the THz direct[7] as well as the multispectral THz imaging aims.[8,9]

The THz source was electronically modulated at 1-kHz frequency. Detected signals were amplified and registered using a lock-in amplifier. Samples were placed on an electronically controlled $X-Y$ stage to implement the raster scanning. Data are recorded and processed via custom-made computer software.[8,9]

The imaging setup was calibrated to determine dynamical range of the homodyne system. The experiment was carried out in both direct and homodyne modes at 0.3 THz frequency by stacking office paper sheets in the upper arm, as shown in Fig. 2 (left panel). The results are depicted in Fig. 2 (right panel). The homodyne detected signal reveals more than two orders of magnitude higher dynamic range in comparison to the direct one at 0.3-THz range, and a factor of 25 improvements at 0.6 THz. Better contrast can thus be expected in the homodyne mode for recording THz images of low-absorbing materials.

4 Homodyne Terahertz Imaging Results

Photos of the packaged objects and their THz images recorded in the direct and homodyne modes are presented in Fig. 3. Direct imaging at 0.6 THz (left panel) clearly reveals packaged highly reflective objects—a steel blade and a needle. The nitrile glove is also resolved here due to its relatively higher absorption (Fig. 1). It is worth noting that the number of packaging cotton fabric layers exhibits no pronounced influence on the quality of the image.

The contrast noticeably changes at 0.3-THz frequency, in particular, the low-absorbing objects—the LDPE bag and the tissue paper, are invisible in the direct detection mode [Fig. 3(d)]. The piece of a nitrile glove still can be identified because of its relatively higher absorption, while only contours of the hypodermic needle can be resolved due to the longer illuminating wavelength. Therefore, a direct THz

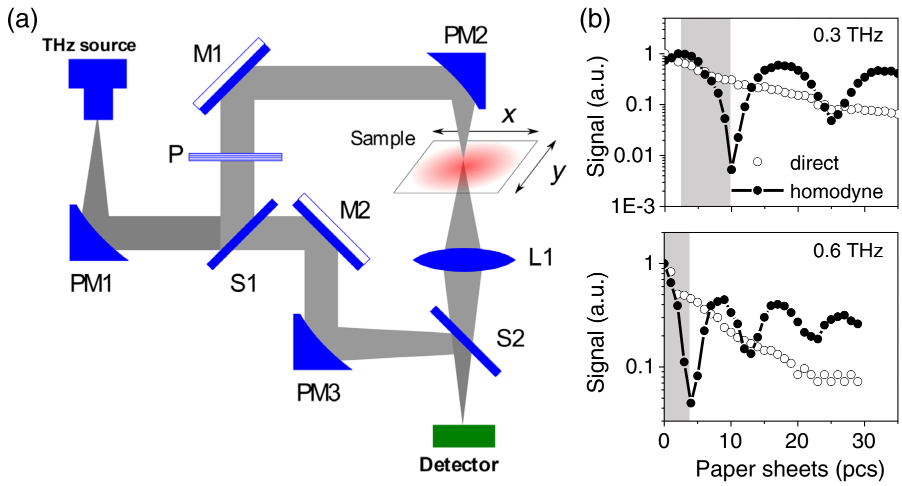

Fig. 2 (a) Setup for THz imaging in transmission geometry using direct and homodyne modes. Letters S denotes beam splitters, L, lenses; P, paper sheet placement; PM, off-axis parabolic mirrors; and M, flat mirrors. (b) Estimates of the system dynamic range at 0.3- and 0.6-THz frequencies. Normalized detected signal recorded in both, direct and homodyne, schemes is shown as a function of paper sheets pieces, which was used to vary the phase of the radiation. Shadowed area indicates the regime of optimal homodyne operation. Note the increase of dynamic range in the homodyne mode.

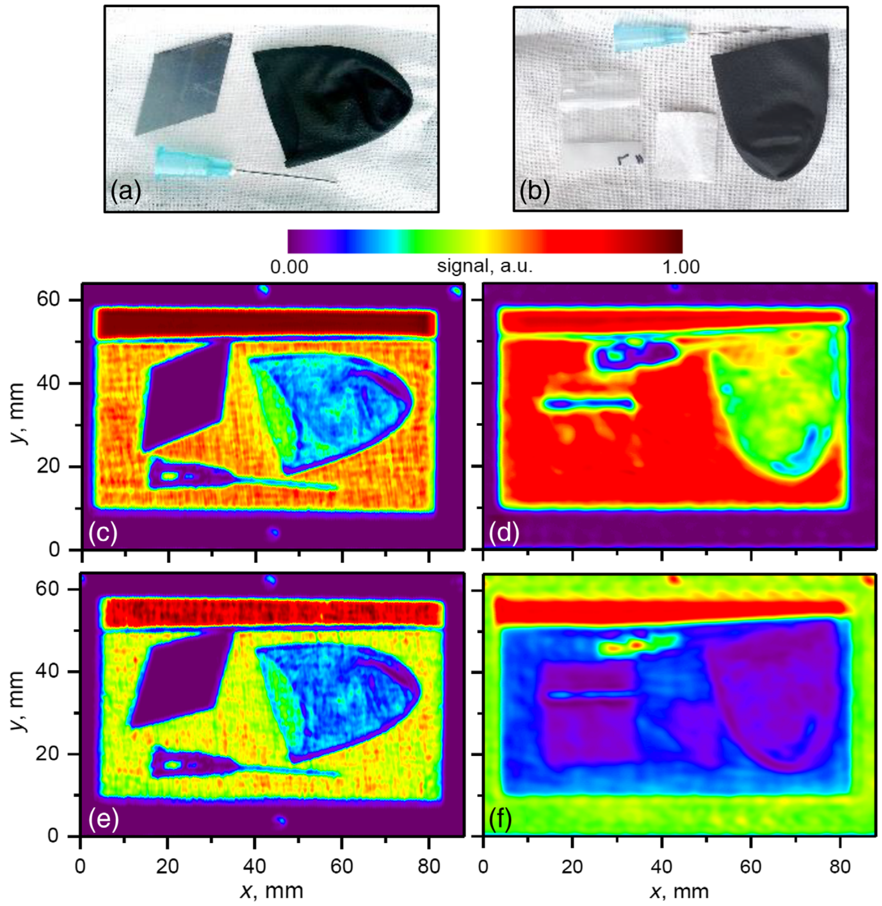

Fig. 3 Left panel: Photo (a) and direct images at 0.6 THz of steel blade, hypodermic needle, and a piece of nitrile glove enveloped in two and six layers cotton fabric (c) and (e), respectively. Note good contrast despite different cotton fabric layers. Signal-to-noise-ratio (SNR) is 1900 and 700, respectively. Right panel: Photo of the sample (b) and its direct (d) and homodyne (f) image at 0.3 THz. The sample consisted of a sealable LDPE bag, tissue paper, nitrile glove, and hypodermic needle enveloped in two layers of cotton fabric. SNR is 100 and 200, respectively. THz imaging parameters: XY pixel size—0.3×0.3 mm^2, image size—299×212 pixels, integration time—10 ms. About 10 paper sheets were used to manage phase in the homodyne imaging.

imaging is not the optimal technique in this case, and so our homodyne detection scheme was applied. Phase-imaging can offer a higher image contrast for weak-absorption or transparent materials if one compared it with intensity-related imaging; however, the recording setup requires interferometer arrangement to measure the phase-distribution in the sample.[10] As described earlier, office paper sheets are used to vary the needed phase-shift. Taking into account the thickness of one paper sheet and the refractive index of paper (∼1.62 at 0.3 THz, Fig. 1), one can estimate that 2π phase-shift can be accumulated using 16 pieces of paper.

As can be seen in Fig. 3(f) (right panel), THz homodyne imaging allows to clearly resolve low-absorbing thin materials, such as the LDPE bag and a tissue paper hidden in two layers of cotton fabric. To extend the measurement scale for thicker samples exceeding the illuminating wavelength (1 mm in our case), one needs to overcome the restrictions induced by 2π phase-ambiguity. Phase-unwrapping method with a noise-suppression algorithm[11] can be an effective way for data processing allowing for the extension of the operation range to other THz frequencies.

To illustrate the suitability of the homodyne THz imaging for identifying thin, low-absorbing objects, a sample containing different amounts of paper sheets, a piece of sticky tape, LDPE bag, and letters “THz” written using conventional pencil (graphite) on the sheet of a paper were constructed. The metal washer served as a reference for highly reflecting materials.

Imaging results at 0.6 THz are displayed in Fig. 4. It is seen that homodyne detection, by varying the phase, enables a high contrast and better resolution of low-absorbing materials, and even allows to distinguish pencil-written letters. While images recorded at 0.3 THz (Fig. 5) do not allow for the determination of the letters, the increased contrast, nevertheless, permits clear detection of the low-absorbing objects.

5 Conclusion

Homodyne and direct imaging of materials with low-absorption features in the THz range were investigated and compared. The homodyne scheme using paper sheets as the phase-tuning component allowed us to increase the detection dynamic range by more than two orders of

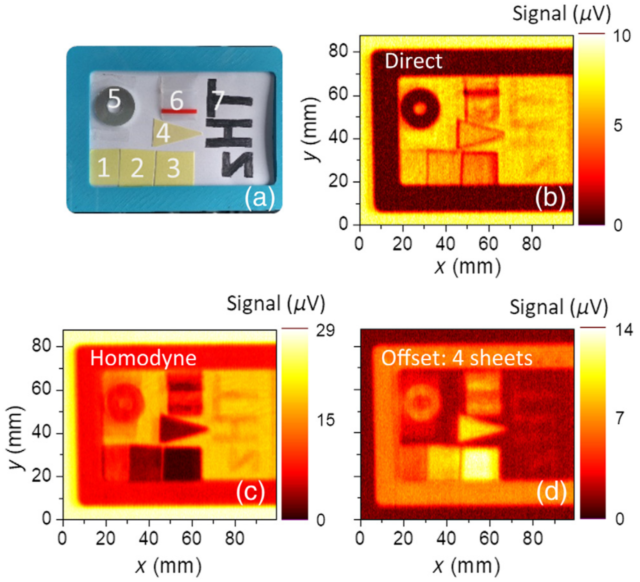

Fig. 4 (a) Panel—photo of the sample composed of different constituents: numbers 1 to 3 indicate the amount of the paper sheets; 4 is sticky tape; 5 stands for metal washer as the reference; 6 denotes LDPE bag; 7 shows letters "THz" written using conventional pencil (graphite). Images (b–d) were recorded at 0.6 THz in transmission geometry. Panel (b) presents direct imaging; panels (c, d)—images recorded in homodyne schemes using 0 and 4 sheets of paper for the phase-shifting. Pixel size—0.3×0.3 mm^2, image size—330×293 pixels, integration time—10 ms.

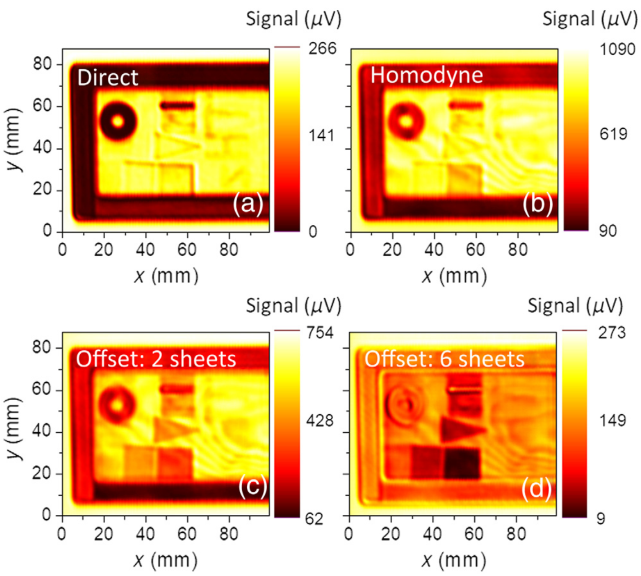

Fig. 5 Sample as in Fig. 4(a). Images (a–d) were recorded at 0.3 THz in transmission geometry. Panel (a) presents direct imaging; panels (b–d)—images recorded in homodyne schemes using 0, 2, and 6 sheets of paper for the phase-shifting.

magnitude. It was demonstrated that the homodyne THz imaging system at 0.3 and 0.6 THz in transmission geometry enables to detect low-absorbing objects enveloped in up to six layers of cotton fabric. It is illustrated that the homodyne spectroscopic THz imaging can serve as a convenient tool to resolve the concealed objects fabricated from materials manifesting low-THz absorption coefficient.

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References

1. P. U. Jepsen, D. G. Cooke, and M. Koch, "Terahertz spectroscopy and imaging—modern techniques and applications," *Laser Photonics Rev.* **5**(1), 124–166 (2011).
2. U. Puc et al., "Terahertz spectroscopic identification of explosive and drug simulants concealed by various hiding techniques," *Appl. Opt.* **54**(14), 4495–4502 (2015).
3. D. Glaab et al., "Terahertz heterodyne detection with silicon field-effect transistors," *Appl. Phys. Lett.* **96**(4), 042106 (2010).
4. L. Minkevičius et al., "Terahertz heterodyne imaging with InGaAs-based bow-tie diodes," *Appl. Phys. Lett.* **99**(13), 131101 (2011).
5. I. Kašalynas et al., "Method and device for the spectroscopic imaging of the object," The State Patent Bureau of the Republic of Lithuania 6297 (2016).
6. D. Seliuta et al., "Silicon lens-coupled bow-tie InGaAs-based broadband terahertz sensor operating at room temperature," *Electron. Lett.* **42**(14), 825–827 (2006).
7. I. Kašalynas et al., "Terahertz imaging with bow-tie InGaAs-based diode with broken symmetry," *Electron. Lett.* **45**(16), 833–835 (2009).
8. I. Kašalynas et al., "InGaAs-based bow-tie diode for spectroscopic terahertz imaging," *J. Appl. Phys.* **110**(11), 114505 (2011).
9. I. Kašalynas et al., "Continuous wave spectroscopic terahertz imaging with InGaAs bow-tie diodes at room temperature," *IEEE Sens. J.* **13**(1), 50–54 (2013).
10. Y. Wang et al., "Continuous-wave terahertz phase imaging using a far-infrared laser interferometer," *Appl. Opt.* **50**(35), 6452–6460 (2011).
11. X. Wang, L. Hou, and Y. Zhang, "Continuous-wave terahertz interferometry with multiwavelength phase unwrapping," *Appl. Opt.* **49**(27), 5095–5102 (2010).

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