The active-passive continuous-wave terahertz imaging system

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Abstract. Active and passive terahertz (THz) imaging have recently become essential instruments of various THz applications. In this paper the active- and passive-mode THz imaging systems are studied and the hybrid active-passive THz imaging system is suggested. The concept of image contrast was used to compare the active and passive THz imaging results. In order to achieve better image quality the hybrid system is considered to be effective. The main advantage of the proposed system is the combination of the self-emitted radiation of the object with the back scattered source radiation. The experimental results demonstrate that the active-passive modality of THz imaging system allows retrieving maximum information about the object. An approach to synthesise the active-passive THz images was proposed using the false-color representation.

1. Introduction and Background
Terahertz (THz) imaging is widely used in such branches of fundamental and applied science as biomedical science and chemical physics [1–3], non-destructive evaluation of composite materials and constructions [4–5], quality-control in pharmaceutical industry [6], detection of concealed objects, drugs and explosives in security applications [7–9], and astrophysical science [10].

THz imaging systems can be classified as pulsed and continuous and the latter of these two types can be employed in either active or passive mode. While pulsed systems are efficient for two- and three-dimensional imaging [11–12], continuous systems using more powerful sources are applied for highly sensitive and remote imaging [13–16].

Active and passive imaging are different in technical realization and have different basic principles. Active imaging system [9,13–14,17–18] detects THz radiation reflected from the object, while passive imaging system [14,19–20] receive only thermal THz radiation of the object. Two modalities also have different imaging characteristics, such as contrast, resolution, dynamic range, and signal-to-noise ratio.

This paper compares two THz imaging modalities and describes a possible way of making hybrid active-passive system in order to increase imaging efficiency. To receive quantitative characteristic of THz imaging we used test-samples of different spatial frequencies and calculate Modulation Transfer Function (MTF). The obtained results show the potential advantages of hybrid THz imaging since it gives more information about the object.
2. Experimental Setup and Samples
To compare active and passive THz imaging modalities and to receive hybrid images we used the following experimental setup (figure 1(a)).

![Diagram of experimental setup]

**Figure 1.** (a) Schematic representation of experimental setup used to study THz imaging in the hybrid mode. BWO stands for the backward-wave oscillator, and PC stands for the personal computer; (b) Examples of passive and active THz images of the test object, placed on the human body beneath the T-shirt.

Active and passive modes have the same detection system based on the heterodyne principle. Schottky and Gunn diodes are used as the photo-mixer and local oscillator, respectively. The THz image is provided via the raster scanning of the object plane by mechanical mirror-based scanning. To make active images we used the backward-wave oscillator (BWO) as a source of quasi-monochromatic continuous-wave THz radiation. The operational frequency of the BWO is tunable in the range of 0.2 to 0.3 THz and is set near 0.25 THz to lock it to the local oscillator. The output power of the BWO THz beam for these conditions is ~ 50 mW. The detecting system includes lens with focal length 50.0 mm. The beam shape of BWO is rather nonhomogeneous, thus, the studied object is illuminated non-uniformly. To correct it and to use maximal output beam we applied the reshaper (or THz homogenizer). It consists of hollow metal-coated prism with small plastic particles inside. These particles cause scattering which leads to source beam homogeneity.

The object was remote from the system at a distance of 4 meters. It constituted of test-samples on a human body behind different clothes materials: T-shirt, jacket, and coat. Test-samples consisted of cardboard base with metal stripes of several width. Thus the spatial frequency of the test-samples was different: $f = 0.035, 0.052, 0.714,$ and 0.105 cm$^{-1}$. To enable the active and passive THz imaging techniques to be compared, images of the test objects were detected in the same position within a short time period.

3. Active and Passive Image Quality. Hybrid Imaging Synthesis
In the figure 1(b) active and passive images are shown. We calculated the images intensity cross-sections, which were used to understand image quality of two imaging modalities. The example of intensity cross-sections are presented in figure 2(a).

We received such cross-sections for all test-samples and all clothes materials in order to study image contrast of different objects and scattering conditions. For the obtained curves we applied the harmonic approximation of the intensity curves by the use of the Gaussian least squares method:

$$I = A + B \sin(2\pi fx + C),$$

(1)
where $x$ is the horizontal coordinate, the frequency-dependent coefficients $A, B, C$ are the mean intensity, the amplitude of intensity oscillation, and the harmonic phase shift, respectively.

By finding values of coefficients $A$ and $B$ for each case, we can calculate the image contrast for exact spatial frequency as $K = B/A$ and receive MTF in each imaging condition as the function $K(f)$ of spatial frequency. Four test-samples are enough to estimate the MTF character in active and passive modes. The obtained results are shown in the figure 2(b–d). The same character and tendency are obvious for these curves. There are intersection points which divide the whole frequency range into two parts. In the left one the active MTF curve lies above the passive curve and active THz imaging provides higher contrast for visualizing the low-spatial frequencies of

![Image](image.png)

**Figure 2.** (a) Image intensity cross section (solid curves) and the appropriate harmonic approximation (dashed curves) for images from the figure 1(b), respectively. (b–d) Active and passive MTFs, $K(f)$, for the test samples placed under T-shirt (b), jacket (c), and coat (d). Red and blue regions indicate the spatial frequencies for which the active or passive mode is more effective, respectively. (e) Result of image synthesis (hybrid THz image) of the test sample covered with T-shirt.
the object, in the the right one the passive MTF is higher than the active values and it allows us to detect small details of the object more effectively. Physically, the differences between the active- and passive-mode MTFs appear mainly due to the variation in THz-wave scattering for different cover materials. Matter, such as clothing fabric with its partially-ordered structure, causes THz radiation to scatter in a complex manner [21–25], which leads to decreased resolution of the THz images.

Thus there are no definitely preferred imaging modality in the whole spatial frequency range. But the combination of them in a hybrid system can cause increasing of the imaging quality. In this case it is possible to obtain the highest envelope of MTF.

To make it clear, we propose one of the possible imaging synthesis algorithm based on the threshold filtration procedure. The hybrid image is resented in the false-color (figure 2(e)), but other methods can be used in order to extract more information about the object. In our case of metal-striped test-samples, the hybrid image helps us to detect metal objects under clothes by the used of the high contrast of the active imaging and to resolve the object details by the used of the passive imaging.

4. Conclusions
In the present paper we have compared active and passive THz imaging modalities, and experimentally demonstrated the advantage of their combination on a hybrid imaging system. The obtained MTF curves for different imaging condition illustrate the spatial frequency regions of effectively using of active or passive modes. The demonstrated synthesised false-color THz image justify the potential of hybrid imaging in various THz applications, such as biomedical systems, security applications, the medical and pharmaceutical sciences, chemical physics, astrophysics, and materials sciences.

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