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Speckle patterns formed by broadband terahertz radiation and their applications for ghost imaging

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ABSTRACT

Speckle patterns can be very promising for some applications due to their unique properties. This paper presents the possibility of numerically and experimentally formation of speckle patterns using broadband THz radiation. Strong dependence of the statistical parameters of speckles, such as size and sharpness on the parameters of the diffuser are demonstrated: the correlation length and the mean square deviation of the phase surface inhomogeneity. As the surface correlation length increasing, the speckle size increases and its sharpness decreases. Alternatively, increasing of the surface height standard deviation leads to a speckle size decreasing and sharpness increasing. The dimensions of the individual experimentally formed speckles correspond to obtained results of numerical simulation. The possibility of the formed speckle patterns application for the implementation of the ghost imaging technique has been demonstrated by methods of numerical modeling.

Introduction

Speckle pattern formation is a phenomenon that occurs in situations where a coherent light reflects or transmits through a rough surface or a turbid medium^{1,2}. Despite the fact that the occurrence of speckle-noise can affect negatively for some imaging techniques (e. g. optical coherence tomography and LIDAR technologies), there are fields in which usage of speckle patterns can be very promising: it applied for image retrieving in speckle metrology³, single pixel imaging⁴, for ghost imaging⁵⁻⁸, cryptography technique⁹ etc. In turn, terahertz (THz) radiation, due to the optical properties of various materials in this frequency range, as well as the features of individual properties of the radiation itself, is becoming more popular in quality control systems¹⁰⁻¹², safety¹³⁻¹⁶ and biomedicine application¹⁷⁻¹⁹, communication²⁰⁻²³.

The formation of speckle patterns for THz radiation begins to be studied in detail only at the present time. The first speckle structures in the THz region were first obtained using monochromatic continuous THz radiation and discussed in papers^{24,25}. All these results were experimentally tested using a free electron laser (FEL). In²⁵⁻²⁷ formation of speckle patterns by reflection FEL THz radiation from a random rough surface was also considered. The use of other sources of monochromatic radiation is presented in²⁸. In this paper, for the formation of speckles, metal disk with a set of various random amplitude images around the disk circumference was used. In works²⁵⁻²⁸, the possibility of application such speckle structures for the ghost imaging technique was demonstrated. High energies, various amplitude and phase objects transmission are the main advantages of monochromatic continuous THz radiation.

Usually, pulsed THz radiation has low energies^{29,30}, but there are already widespread methods of generating high-energy radiation, for example, such as in organic crystals^{31,32} or by filamentation in gases or liquids^{33,34}. The generation of speckle structures by pulsed THz radiation has not been studied yet. However, it should be noted that mask formation methods using nonlinear transformations in the crystal for generating the pulsed THz radiation exist and could be found in³⁵. In this case, spatial light modulator, which modulate pump radiation is used. The modified beam is directed to the crystal for generating the THz field. This allows the ghost-imaging technique in the THz range realization. A variant of amplitude modulation of probe radiation was proposed as a separate method for implementing THz imaging with sub-wavelength accuracy³⁶. Producing of speckle patterns for terahertz spectral range is of great interest to various applications related to terahertz imaging. This aspect motivated us to study speckle-pattern formation by broadband pulsed THz radiation.

In this work we present a numerical model describing the formation of speckle patterns using broadband pulsed radiation of THz spectral range. Some of statistical characteristics of obtained speckle patterns, such as size and sharpness, and their dependencies on parameters of random phase screen are discussed. Some limitations were shown that affect the size of speckle patterns formed by broadband THz radiation. Experimental verification of the formation of speckle patterns was carried out. Furthermore, in the paper the possibility of utilizing THz speckle patterns in pseudothermal light ghost imaging algorithm

was numerically demonstrated. An opportunity of application of numerically formed speckle patterns for reconstructing ghost images even in case of working with broadband THz pulses is also shown.

Mathematical model

In this work we study formation of speckle patterns using broadband pulsed THz radiation. There are a lot of approaches for obtaining of random light fields^{37–39}. One of the most widespread methods propose using random refractive inhomogeneity for light modulation⁴⁰. In our paper we expand this approach for broadband THz radiation and we form speckle patterns by means of transmission of THz pulses through the transparent plate with random rough surface on its back side. This random phase screen provides a phase modulation of THz pulses, which leads to the appearance of speckle patterns at some distance behind the screen, as shown in the Fig. 1 a. In this section, a numerical model of speckle formation is presented and the dependence of the speckle parameters on the characteristics of the transparent plate with random rough surface is investigated.

Speckle pattern formation in the monochromatic and pulsed THz radiation

In the first part of the mathematical modeling, the formation of speckle structures by THz radiation, both monochromatic and pulsed, is considered. To describe speckle pattern formation for the monochromatic THz radiation we use model of Gaussian beam with the field distribution E_{in} which can be described by:

$$E_{in}(x, y, z) = \exp(ikz)E_0 \frac{-ika^2}{z - ika^2} \exp\left(\frac{ik(x^2 + y^2)}{z - ika^2}\right), \quad (1)$$

where x, y, z are the spatial coordinates, a is the spatial parameter of Gaussian beam related to the beam waist, E_0 is the initial amplitude of beam, k is the wave number.

Suppose, that a Gaussian beam that is incident to the random phase screen at $z = 0$. Using the phase shift introduced by random phase screen, the field distribution of beam right after the random phase screen is evaluated in the following way⁴¹:

$$E(x, y, z = 0) = E_{in}(x, y, z = 0) \cdot \exp\left(i \frac{2\pi}{\lambda} (n - 1) h(x, y)\right), \quad (2)$$

where λ is a wavelength, n is the refraction index of material of plate with random rough surface on its back side, $h(x, y)$ is the function of height profile of random rough surface. Gaussian random rough surface model is used for formation of rough structure⁴². This surface has two parameters which describe the height profile. The first parameter is the root mean square deviation of the surface height h_{RMS} , and the second parameter is the horizontal correlation length Cl of the surface, which shows the frequency of spatial inhomogeneities of the surface. Formation of Gaussian random rough surface $h(x, y)$ is described by the following equation:

$$h(x, y) = \frac{2L}{\sqrt{\pi N Cl}} F^{-1} [F(H_1) \cdot F(g)], \quad (3)$$

where L is the length of the surface side, N is a size of the matrix $h(x_i, y_j)$ ($i, j = 1, 2, \dots, N$) obtained due to discretization, H_1 is $N \times N$ matrix of random numbers with Gaussian distribution φ and standard deviation h_{RMS} : $H_1 = h_{RMS} \cdot \varphi$, g denotes a Gaussian filter $g(xy) = \exp(-2(x^2 + y^2)/Cl^2)$ with correlation length Cl ; F and F^{-1} are direct and inverse Fourier transforms, respectively. Figure 1 b, c demonstrates two examples of Gaussian random rough surface $h(xy)$ with different values of h_{RMS} and Cl .

While propagating along the z axis over the distance Δ , the intensity profile of the modulated beam becomes random, which results in a speckle pattern formation at the observation plane $z = \Delta$. Propagation of the modulated beam along z axis was calculated by means of the well-known two methods: Fresnel propagation formula (see Methods) and the angular spectrum approach (plane wave decomposition, see Methods). It is worth remarking that both methods provided the same numerical results for speckle pattern formation.

Consider formation of speckle patterns for pulsed THz radiation. Taking into account all spectral components of THz pulse with spectrum $S(\nu)$, we have:

$$E(x, y, \Delta, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \exp(-i2\pi\nu t) E(x, y, \Delta, 2\pi\nu/c) d\nu. \quad (4)$$

Figure 1. (a) Scheme of acquisition of speckle patterns for monochromatic THz radiation: beam with Gaussian intensity distribution transmits through the random phase screen and propagates over the distance $\Delta = 5$ cm. (b, c) Two samples of Gaussian random rough surface. Surface has large value of h_{RMS} and low value of Cl (b), low value of h_{RMS} and large value of Cl (c). Speckle patterns produced by (d) monochromatic THz radiation with frequency $\nu = 0.7$ THz, produced by pulsed THz radiation with symmetric spectrum (e) and spectrum with shifted central frequency (f). Spectrum (g) with a blue curve has a symmetric Gaussian shape, spectrum with red curve has gaussian shape with shifted central frequency. As a material of plate with random rough surface on its back side with refraction index $n = 1.55$ for THz spectral range was used, parameters of the surface are of $h_{RMS} = 0.3$ mm and $Cl = 0.9$ mm. The distance between random phase screen and speckle pattern observation plane is $\Delta = 5$ cm.

Thus, we obtain time-dependent speckle pattern distribution $E(x, y, \Delta, t)$. The overall speckle pattern intensity $I_r(x, y)$ that is evaluated by integrating $E_r(x, y, \Delta, t)$ over the pulse duration T is given by:

$$I(x, y) = \int_T |E(x, y, z, t)|^2 dt = \int_{-\infty}^{\infty} |S(2\pi\nu)E(x, y, z, 2\pi\nu/c)|^2 d\nu. \quad (5)$$

Depending on the shape of the time-domain spectrum the resulting speckle image can change considerably. Below we present a comparison of speckle images obtained using monochromatic and pulsed THz radiation. We confine our modelling by using two types of pulses. First type has Gaussian spectrum shape with central frequency $\nu_0 = 0.7$ THz and can be described as (the blue curve in Fig. 1 g):

$$S_1(\nu) = 2\tau_p \sqrt{\pi} \exp(-4\pi^2(\nu - \nu_0)^2 \tau_p^2), \quad (6)$$

where $4\tau_p \sqrt{\log 2}$ is the duration of the pulse, ν_0 is the central frequency of the pulse. The second type of pulse has asymmetric spectrum shape (an asymmetric spectrum is usually observed in experiments) with central frequency $\nu_0 = 0.5$ THz (the red curve in Fig. 1 g):

$$S_2(\nu) = 10^{10} [\sin(0.1\nu)]^6 \exp^{-12\nu}. \quad (7)$$

Some typical speckle patterns for monochromatic and pulsed THz radiation are shown in Fig. 1 d,e,f. The frequency of the monochromatic THz radiation was taken as $\nu = 0.7$ THz, the duration of THz Gaussian pulse was 2 ps. For the plate with random rough surface on its back side with refraction index $n = 1.55$ for THz spectral range was used, and parameters of the rough surface were chosen as $h_{RMS} = 0.3$ mm and $Cl = 0.9$ mm. The distance between random phase screen and speckle pattern observation plane was $\Delta = 5$ cm.

As it can be seen from Fig. 1, speckle patterns significantly vary depending on type of radiation (monochromatic (Fig. 1 d) and pulse (Fig. 1 e,f) and shape of pulse spectrum (Fig. 1 g). Comparing speckle images in Fig. 1 d and e,f it is noticeable

that number of speckles in Fig. 1 e,f which is produced by THz pulses with spectrum S_1 , has been increased dramatically. It can be explained by the fact that different spectral components of the pulse produce different speckle patterns which overlap each other. This increases the overall number of speckles in the image which is the advantage of the pulsed radiation over the monochromatic one. However, the shift of the central frequency of the pulse from $\nu_0=0.7$ THz in S_1 to $\nu_0=0.5$ THz in S_2 leads to the decrease of contrast of speckle image, forming a lighter background comparing to speckle images for monochromatic THz radiation and THz pulses with spectrum S_1 . Shift of the central frequency of the pulse from $\nu_0=0.7$ THz in S_1 to $\nu_0=0.5$ THz in S_2 does not make significant changes because of using the same total spectrum range (Fig. 1 g). Broadband radiation forms a lighter background comparing to speckle images for monochromatic THz radiation and THz pulses with spectrum S_1 .

Statistical characteristics of speckle patterns

Due to the extensive use of speckles in the optical range¹⁻⁸, such possibilities of application of speckle patterns in the THz frequency range is needed to be considered. For the qualitative applications of speckle structures in the THz range, it is necessary to analyze their characteristics. In this section, we describe some characteristics of speckles formed by the propagation of broadband THz radiation trough of the random rough surface.

For statistical characteristics of speckle patterns generated by THz pulsed radiation, we considered the two parameters. The first parameter is an equivalent circular diameter (ECD) of a single speckle. This parameter is usually responsible for the spatial resolution of the reconstructed picture by various methods using speckles, for example²⁸. The second parameter is described by the following equation:

$$P = \left\langle \frac{I_{peak}}{ECD} \right\rangle, \quad (8)$$

where I_{peak} is a peak intensity of a speckle, $\langle \cdot \rangle$ denotes an ensemble average over m single speckles. Parameter P can be considered as an average degree of sharpness of the speckle pattern. This parameter is more responsible for the contrast of the speckle patterns. And P should decrease in order to obtain single speckles that are more obvious in intensity (amplitude). The dependence of these parameters on root mean square deviation of the surface height h_{RMS} and correlation length CL is presented in Fig. 2.

Figure 2. A graphical representation of speckle pattern unit cell of transverse intensity distribution and its parameters. All dependences are plotted for the Gaussian field of broadband THz radiation with a central frequency of radiation 0.7 THz (6).a; dependence of equivalent circular diameter of speckle on correlation length of surface (b), dependence of equivalent circular diameter of speckle on RMS of surface height (c); dependence of sharpness of speckles (P (8)) on correlation length of surface (d), dependence of sharpness of speckles (P (8)) on RMS of surface height (e).

As it can be seen from Fig. 2 b, the increase of correlation length leads to the magnification of the speckle size⁴¹, wherein the saturation occurs at the certain value of the correlation length after which the speckle size remains approximately constant. It can be explained by the fact that by considering broadband pulsed radiation, the use of a field with certain wavelengths affects the speckle size. In this case, the speckle size becomes comparable with the maximum wavelength containing in the spectrum of THz pulses. Moreover, according to Fig. 2 c, increasing of the root mean square deviation of the surface height leads to the decrease of the speckle size. An increase in the surface roughness after a certain value leads to a decrease in the

speckle size, when the phase incursion of the field at the minimum and maximum described by equation (3) becomes greater than 2π . This was observed in the work⁴¹. For speckles formed by broadband radiation, adjacent frequencies will contribute. Then the steepness of the front after passing the inhomogeneity element increases so much that a strong difference in the phase difference arises at neighboring points, and the speckle decreases. Those. a strong increase in roughness (phase greater than 2π) is equivalent to a decrease in the correlation length. As one could expect the sharpness of the speckles is decreasing with the growth of the correlation length as it is shown in Fig. 2d. At the same time the value of speckle sharpness grows with magnification of the root mean square deviation of the surface height due to the strong phase shift for the whole spectrum, see Fig. 2e. The study of these parameters makes an important contribution to the usage possibility of formed speckle patterns in various applications. In essence, the speckle diameter is responsible for the spatial resolution of the images, and P is responsible for the image contrast. Thus, it is possible to control changes in the formed speckles by changing various characteristics in the phase object.

Experimental verification

THz imaging setup was used for experimental verification of broadband THz field speckle patterns formation. Schematic diagram of detection system is shown in Fig. 3a (A detailed description of the experimental setup is presented in the work⁴³). The terahertz radiation was generated due to optical rectification of femtosecond pulses in lithium niobate crystal⁴⁴. The femtosecond pulses from a regenerative Ti-sapphire amplifier (pulse duration 35 fs, energy 1.1 mJ, 1 kHz repetition rate, 800 nm central wavelength) were used as pump radiation. The pulse energy was divided into two parts using a beam splitter (1:49 for probe and pump beam respectively). The probe pulse passed through the delay line and was detected by an electro-optical system (EOS). In this case, a 18x18x1 mm ZnTe crystal was used.

Figure 3. (a) Schematic diagram of detection system in THz imaging setup. The Gaussian THz field (I) passes through a transparent phase plate with a random distribution, where it changes its spatial distribution (II). After that, the THz field is detected by the EOS in each pixel of the camera using probe beam (III). In this experiment, the probe beam changes its time delay relative to the THz field and makes it possible to detect the time profile of the THz pulse. (b) Photo of the phase plates made from ABS plastic ($n(\text{THz})=1.55$) (parameters: $h_{\text{RMS}}=0.8$ mm and $Cl=1.5$ mm (top), $h_{\text{RMS}}=0.6$ mm and $Cl=0.9$ mm (bottom)). (c) Initial THz profile (1) and result of THz field speckle patterns from the radiation intensity recorded on an imaging setup in case THz radiation propagates through the phase plates (2 is b (top) and 3 is b (bottom)) located at a distance of 5 cm from the ZnTe crystal, 4 - typical result of numerical calculation of speckle pattern formation for the same conditions b.

The generated THz field with the parameters given below (see Methods) had a Gaussian profile (Fig. 3c(1), a(I)) and passed through the phase diffused plates what were printed from plastic with the following parameters: a refractive index in

the THz range $n_{THz}=1.55$ (photos of phase objects are shown in Fig. 3 b), $h_{RMS} = 0.8$ mm and $Cl = 1.5$ mm (shown at the top of Fig. 3 b)), $h_{RMS} = 0.6$ mm and $Cl = 0.9$ mm (shown at the bottom of Fig. 3 b)). The parameters of the phase object were selected in relation to the studies carried out in the previous section (*Statistical characteristics of speckle patterns*) for later comparison of the size of the speckles with the numerically calculated ones. Then, the modulated THz field (shown on the II Fig. 3 a) was detected by ZnTe crystal, where the real valued spatial distribution of THz pulse in temporal domain⁴⁵ was measured. After that EOS allows to completely detect the entire picture of THz radiation by using a probe femtosecond field (shown on the III Fig. 3 a) and register it on the CMOS camera (CCD). Processing of the experimental results included: averaging in each pixel of the frame by 10 scans to increase the signal to noise ratio. Then Fourier transform was done for each pixel in order to obtain spectra at each point of the frame. Finally the radiation energy in each pixel was calculated by multiplying the amplitude at the corresponding frequency.

As it can be seen from Fig. 3 c(1), a THz field with a slightly shifted Gaussian profile was suppressed at the input. However, after passing through the plates, a changes in the spatial distribution of the THz radiation intensity can be noticed. Local maxima are clearly observed, which can be attributed to individual parts of the speckle structure. Moreover, the radii of these peaks are within the segment of 1-2 mm (Fig. 3 c 2,3) which corresponds to the estimates given in Fig. 2 b,c. For example, typical numerical calculation result for the parameters selected in the experiment is shown in (Fig. 3 c 4). It can be seen from the figure that typical speckle sizes are also in the range of 1–2 mm. Both results (numerical calculation and experimental one) correspond to the 1-2 mm segment of speckle size calculated on the bases of the equations given in works^{46,47}. Thus, the possibility of speckle formation by broadband THz radiation has been experimentally confirmed in the work.

Application in Ghost Imaging algorithm

In ghost imaging technique classical laser beams typically used to reconstruct ghost images. In this work we employ speckle patterns obtained numerically for both monochromatic and broadband pulsed THz radiation (section *Mathematical model*). The scheme of ghost imaging that is utilized in our model is a classical pseudo thermal light ghost imaging setup shown in Fig. 6 (see Methods). In this scheme THz radiation is incident onto the rotating plate with random rough surface on its back side, thus representing a random phase screen, and it forms speckle-picture.

In this paper the ghost image reconstruction is considered for both monochromatic and broadband pulsed THz radiation. For the monochromatic case we use frequency-dependent speckle patterns $I_r(x, y, \nu) = |E_r(x_2, y_2, z = \Delta)|^2$ from the equation (11) and for the case of the pulsed THz radiation we use speckle patterns described by Eq. (5) by taking into account all spectral components of the pulse. For ghost image reconstruction we calculate cross-correlation function⁴⁸ between the speckle pattern I_r and the intensity transmitted through the object B_r and measured by a point detector that is evaluated by means of the following equation:

$$B_r = \int dx dy I_r(x, y, z = \Delta) T(x, y), \quad (9)$$

where $T(x, y)$ is the transmission function of the object. Using a large number of realizations of speckle structures, one can calculate the image estimation function $G(x, y)$ in the following form:

$$G(x, y) = \frac{1}{M} \sum (B_r - \langle B \rangle) I_r(x, y) = \langle B \cdot I_r(x, y) \rangle - \langle B \rangle \langle I_r(x, y) \rangle. \quad (10)$$

Here $\langle \cdot \rangle \equiv 1/M \sum_r$ deotes an ensemble average over M realizations of ghost imaging algorithm.

As an object to be imaged it was used a rectangular ring, shown in Fig. 4 a, defined by the inequalities $a_x < |x| < b_x$, and $a_y < |y| < b_y$, in which the geometric parameters are determined by the following values $a_x = 4$ mm, $b_x = 6$ mm, $a_y = 3$ mm, $b_y = 5$ mm, respectively. Numerical results for the monochromatic THz radiation ghost-image reconstruction are obtained for frequency $\nu = 0.7$ THz and shown in Fig. 4 b, d for different number of realizations of the ghost imaging algorithm, $M = 10000$ and $M = 20000$, respectively. Parameters of the random phase screen were chosen as follows: $h_{RMS} = 1.0$ mm, $Cl = 1.0$ mm, $n = 1.55$. The choice of parameters was carried out on the basis of the estimates made in previous section (*Statistical characteristics of speckle patterns*). It was necessary to obtain such a ratio of parameters at which the speckle diameter (ECD) was close to the minimum and the value was high (P). The distance between the random phase screen and the registration plane is $\Delta = 5$ cm. Signal-to-noise ratio is evaluated in the same manner as it was suggested in⁴⁸. The ghost image reconstruction results for the pulsed THz radiation for the same parameters of the random phase screen were obtained for the Gaussian pulse with duration of 2 ps and spectral profile with central frequency $\nu_0 = 0.7$ THz as shown in blue curve Fig. 1 g. Reconstructed images for different number of realizations of ghost imaging algorithm, $M = 10000$ and $M = 20000$, respectively, are presented in Fig. 4 c, e.

Figure 4 c,e demonstrate, that speckl-patterns formed by broadband THz radiation can be used for ghost-imaging technique. Now we can see clearly that the increase of the number of realizations of ghost imaging algorithm in Fig. 4 as one could

Figure 4. Results of a numerical experiment for ghost imaging. Reference object (a), reconstructed images from data with a narrow (b, d) and wide spectrum (c, e) for 10 (b, c) and 20 (d, e) thousand realizations.

expect leads to a growth of the quality of reconstructed image that is also in accordance with rise of SNR⁸. In case of image reconstruction with pulsed THz radiation the values of SNR of obtained images are about 10 % lower comparing with the corresponding frequency domain results. When comparing monochromatic and pulsed radiation, the same contrast ratio is observed for other central radiation frequencies. It can be explained by the fact that speckle patterns from different spectral components overlap each other. This leads to a decrease of the sharpness of reconstructed images.

Conclusion

In this study, the possibility of experimentally forming speckle patterns using pulsed broadband THz radiation was demonstrated. Numerical modeling was used to describe the conditions for the formation of a speckle structure with the help of a transparent phase object. It was shown that changes in the statistical characteristics of speckles (sizes and sharpness of speckles) are significantly determined by the spectrum of the pulsed THz field and the characteristics of the phase object. The characteristics of the phase object include the length of its correlation and the root-mean-square deviation of the surface height. We guess that the minimum spectrum size is still limited by the maximum frequency in the THz field spectrum. An increase in the correlation length leads to an increase in the speckle size, while saturation occurs at a certain value of the correlation length, after which the speckle size remains approximately constant. Moreover, an increase in the root-mean-square deviation of the surface height leads to a decrease in the speckle size. At the same time, the value of speckle sharpness increases with an increase in the root-mean-square deviation of the surface height due to a strong phase shift for the entire spectrum. Using theoretical estimates, an experimental verification of the formation of speckle patterns for a pulsed THz field was carried out. According to the statistical characteristics, the experimentally obtained speckle structures correspond to the numerically calculated results. Experimental verification demonstrates, in principle, the possibility of forming speckle patterns using broadband THz radiation. Moreover, the work has numerically demonstrated the opportunity of using such speckles in the image restoration system using the ghost imaging method. It must be said that the use of broadband radiation reduced the contrast of the restored images by only 10 %. But at the same time, a broadband radiation will allow in the future to restore not only the image of an object itself, it can also control its spectral properties. This feature is very widely used in various applications of science and technology.

Methods

Methods of THz radiation beam propagation.

The famous Fresnel propagation equation is described by:

$$E(x_2, y_2, z = \Delta) = \frac{\exp(ik\Delta)}{i\lambda\Delta} \iint E(x_1, y_1, z = 0) \exp(i\frac{k}{2\Delta} [(x_2 - x_1)^2 + (y_2 - y_1)^2]) dx_1 dy_1 \quad (11)$$

where x_1, y_1 are the source plane coordinates, x_2, y_2 are the observation plane coordinates, Δ is the distance between source and observation plane (distance of the beam propagation). Here $E_r(x_1, y_1)$ and $E_r(x_2, y_2)$ is the field distribution in the source and observation plane, respectively. The integral (main text equation (3)) was evaluated numerically by means of FFT algorithm.

In the second method we utilized angular spectrum approach (plane wave decomposition¹).

$$E(x_2, y_2, z = \Delta) = F^{-1} [H(v_1, \Delta) \cdot F[E(x_1, y_1, z = 0)]] \quad (12)$$

where $v_1 = (v_{x1}, v_{y1})$ is a spatial frequency of source plane, F and F^{-1} are direct and inverse two dimensional Fourier transforms, respectively, H is the transfer function of free-space propagation $H(v_1, \Delta) = \exp(ik\Delta) \exp(-i\pi\lambda\Delta(v_{x1}^2 + v_{y1}^2))$.

Experimental parameters of THz radiation.

The timeform of THz pulse and its spectrum are shown in Fig. 5. The duration of a THz pulse is 1 ps, and the spectrum range is from 0.05 to 2 THz, pulse energy 300 nJ, the spatial dimension of the Gaussian profile at half-height (FWHM) is 5 mm (Shown Fig.3 c1).

Figure 5. (a) The timeform of experimental THz pulse. (b) Spectrum of experimental THz radiation

Model of ghost imaging for pulsed THz radiation.

Figure 6. Model of ghost imaging for pulsed THz radiation. THz pulses are incident onto the plate with changing random rough surface (PP) on its back side, representing a random phase screen. The random phase screen introduces a phase shift which subsequently leads to the appearance of random speckle patterns. After that beam is divided into two parts by beam splitter (BS), the first beam interacts with the object (O) and propagates to the single pixel detector (SPD). The second beam is recorded by CCD camera without interacting with the object.

The scheme of ghost imaging has a classical pseudo thermal light ghost imaging setup. Here THz pulses are incident onto the plate with changing random rough surface on its back side, representing a random phase screen. The random phase screen introduces a phase shift which subsequently leads to the appearance of random intensity distributions (speckle patterns). After that the beam is divided into two parts by beam splitter. The first beam interacts with the object and propagates to the single pixel detector. The second beam is recorded by multi pixel detector without interacting with the object. Then the cross correlation function between speckle patterns registered by multi pixel detector and overall intensity of speckle patterns transmitted through the object is calculated⁴⁸.

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Author contributions statement

L.L. and V.Z. performed numerical simulations, A.I. and Y.G. conducted the experiment, B.N. prepared review of the existing works in the field of the study, A.T. conceived the experiment and research, L.L., A.I. and N.P. analysed the results. All authors reviewed the manuscript.

Additional information

Competing interests: The authors declare that they have no competing interests.

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