Feasibility of Real-Time Terahertz Speckle Metrology

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***Abstract*—A 100-W terahertz free electron laser and a 160x120 microbolometer focal plane array were used to record speckled images of different objects. First- and second-order statistics of the speckle patterns obey classical dependencies. Using a set of speckle photographies, recorded with a repetition rate of 41 frames/s, amplitude and logarithmic decrement of damped rotational oscillations of a diffuse reflector were determined.**

I. INTRODUCTION AND BACKGROUND

NOVOSIBIRSK free electron laser (NovoFEL) emits, as a continuous 5.6 MHz stream of 100-ps pulses, an intense monochromatic coherent radiation, which can be continuously tuned within a spectral range of 1.2 – 2.4 THz. Because of a high radiation power, real-time imaging with a frequency up to 90 frames/s using a 160x120 microbolometer focal plane array (FPA) and the NovoFEL has been recently demonstrated [1]. Speckled images of objects illuminated with a diffuse terahertz radiation were observed. This first observation of terahertz speckle patterns in the space domain opens the door to speckle photography and speckle interferometry in the terahertz spectral range. Speckle structure of terahertz radiation in the time domain was previously observed in [2].

In this paper we present the results of a detailed investigation of speckle pattern characteristics and demonstrate the application of the real-time speckle photography for detection of object movement.

II. TERAHERTZ SPECKLE PATTERN STATISTICS

Three configurations used in the experiments are shown in Fig. 1. Images of different objects illuminated by directional or scattered from a rough cupper surface laser radiation (Fig. 1,a) were obtained at $f = 2.3$ THz. Because of a high sensitivity of the microbolometer array, equal to 1.6×10^4 V/W, plane-polarized laser radiation was attenuated to an acceptable level with a photolithographic polarizer. An example of speckled image is shown in Fig. 2.

Statistical characteristics of subjective and objective speckle patterns were studied using configurations shown in Fig. 1,b,c. The intensity distribution followed Gaussian probability function (Fig. 3), excluding the region near zero intensity, probably, due to noise and non-uniform background IR radiation. Speckle pattern contrast was equal to unity, which evidenced that a fully developed speckle pattern was created. Characteristic shape of an individual speckle was described with a function of $1+\cos(\alpha x)$. Speckle size of the objective speckles was inversely proportional to the diaphragm aperture diameter, whereas size of the subjective speckles did not depend on the aperture size, both in a good agreement with the theory [3].

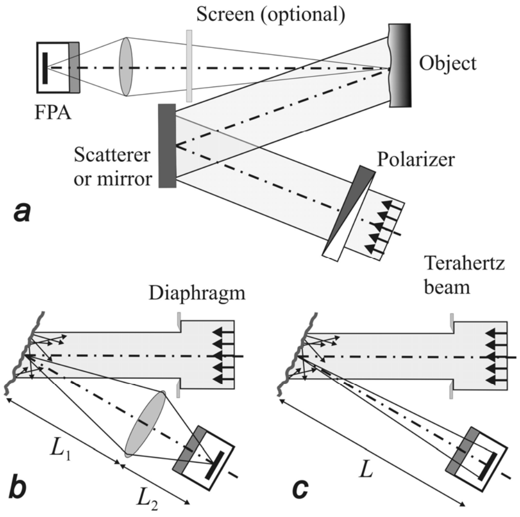

Fig.1. Configuration for speckle photography (a) and the experimental setups for study subjective (b) and objective (c) speckle patterns.

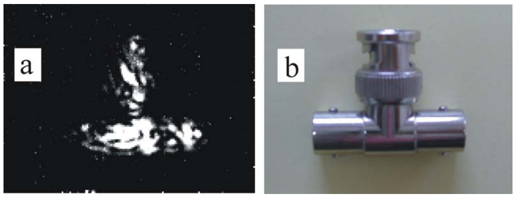

Fig. 2. (a) Image of a BNC connector illuminated with diffuse monochromatic terahertz radiation; (b) photography of the connector in visible light.

Pearson correlation coefficient (PCC) for sequential objective speckle patterns, recorded at growing distances from the scatterer (Fig. 4,a), decreased following the expected inequality: $\delta l \ll 8\lambda z^2 / D^2$. PCC vs. diaphragm aperture for the subjective patterns, which expected to be unity, slightly decreased (Fig. 4,b), probably, due to non-uniformity of the incident beam.

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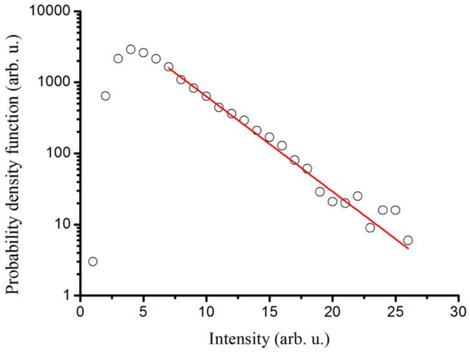

Fig. 3. First order speckle statistics: probability density function vs. intensity of a speckle pattern obtained using 1.5×10^5 pixels

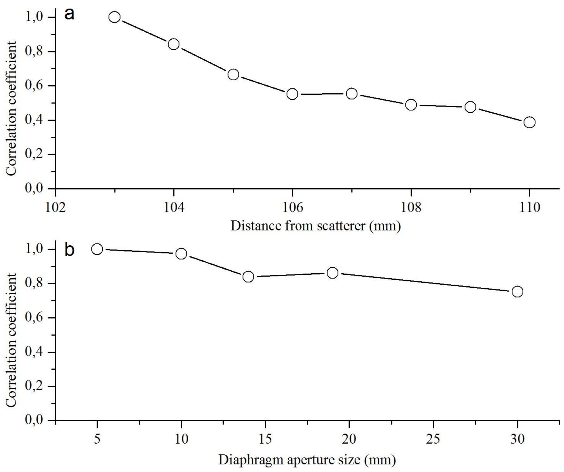

Fig. 4. Second order speckle statistics: cross-correlation functions for objective and subjective speckle patterns

Thus, these experimental results evidence, that statistical characteristics of terahertz speckle patterns obey to the regularities discovered for visible light [3] with reasonable accuracy. This means that terahertz speckle patterns can be employed for the development of terahertz speckle photography and speckle interferometry.

III. DEMONSTRATION OF REAL-TIME TERAHERTZ SPECKLE PHOTOGRAPHY

Speckle photography and speckle interferometry have received considerable attention in experimental mechanics [4]. They are now firmly established as major tools in nondestructive testing and inspection. Using in speckle metrology long-wave radiation of the terahertz region can substantially expand a range of measurable displacements.

To demonstrate the feasibility of terahertz speckle metrology we, using a stationary plane metallic key as an object (see Fig. 1,a), have recorded a terahertz video, while the rotating scatterer was spinning down. Three frames extracted from the video are shown in Fig. 5. Tracing the speckle pattern moving over the object image, one can measure frame-by-frame scatterer displacement. The result of this procedure for 250 sequential frames is presented in Fig. 6. All individual measurements have been done observing the displacement of the speckles passing nearby the point marked in Fig. 5. The solid curve, obtained by fitting the experimental points with a function of $y = y_0 + A\exp(-t/T)\sin[\pi(t-t_c)/w]$, enabled to determine the amplitude and logarithmic decrement of damped rotational oscillations of the reflector with high precision.

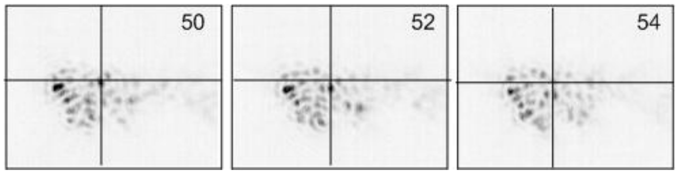

Fig. 5. Three frames extracted from a “terahertz video” (41 frames/s): inverted images of a stationary metal key illuminated with a diffuse radiation reflected from a rotating scatterer

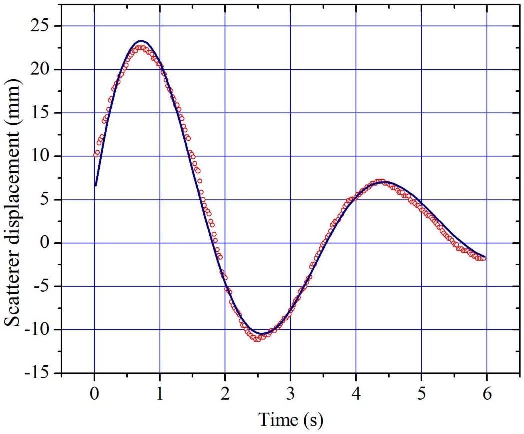

Fig. 6. Amplitude of damped oscillations of the rotating scatterer (points at a radius of 4 cm) retrieved from sequential frames of the speckle pattern

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