Terahertz pulsed time-domain holography and iterative phase retrieval methods

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Abstract—We present latest results obtained in the scope of imaging methods which allows one to recover spatial phase distribution in the terahertz wave-fields. One of these methods is the terahertz pulse time-domain holography. The second one is the iterative phase retrieval approach, transferred from the visible frequency range.

Index Terms—Terahertz digital holography, terahertz phase retrieval, wavefront reconstruction, inverse problem.

I. INTRODUCTION

Terahertz (THz) imaging proposes emerging number of its practical applications due to the ability of THz radiation to penetrate various non-metal materials, that are opaque for visible light [1]. From the numerous papers on THz imaging [2-4], several main methods of obtaining 3-dimensional inner structure of an object are found. The first approach is based on tomographic object reconstruction [5]. The second approach comes from optical interferometry and classical digital holography. Up to now, several 3D imaging methods in THz regime based on interferometric [6-7] and holographic [8-9] techniques have been demonstrated. These methods allow phase retrieval, thus allowing to convert time-domain data into third spatial dimension and hence obtain the object's optical relief information.

In this paper, we review terahertz pulse time-domain holography (THz PTDH) method proposed by authors earlier [10], which is based on direct time domain field profile recording followed by numerical wavefront inversion for object amplitude-phase characteristics reconstruction. This method avoids reference THz beam and employs a recording scheme, which is similar to the THz time-domain spectroscopic (THz TDS) setup.

For the case of single (fixed or tunable) wavelength high-power THz source the other method that we have proposed recently can be used. This method utilizes iterative phase retrieval approach. It currently performed well in optical imaging and also provides simple recording setup, due to the fact that it does not require neither reference beams and nondirect field measurements (as opposed to the THz TDS), putting all complexity into the data processing algorithm. This method allows one to retrieve information about the complex wave field after the measuring of several spatial intensity distributions at the different frequencies and/or at the different planes of registration and then uses iterative procedure for wavefront restoration.

II. THE PRINCIPLES OF TERAHERTZ PULSE TIME-DOMAIN HOLOGRAPHY

Terahertz pulse time-domain holography method got its name because the full electric field can be recorded with electro-optic (EO) sampling. There's no need in reference source used in optical holography to record phase information, full broadband THz registered wavefront can be easily inverted numerically.

In our earlier paper this technique was studied in detail [11]. Namely: its spatial resolution, dynamic diapason, and noise affect on reconstruction. Later [12], it was suggested to use virtual reference source, which radiation is numerically added to the registered diffraction pattern, and reconstruction can be performed both numerically and optically, if hologram mask is properly scaled to the optical wavelength. Methods comparison can also be found in previously mentioned reference [12]. Experimental results on THz pulse wavefront inversion object reconstruction were published later [13].

III. THE CONCEPT OF PHASE RETRIEVAL IN TERAHERTZ IMAGING

In the discussion on transition a phase retrieval method from optical to THz frequency range, one should mention, that as variables the same parameters as in optical methods can be used. Very good results were reported for changing the wavelength of radiation [14-15], and/or distance from the object to the registration plane [16]. Problems in that case arise from the increase of the wavelength by three orders of magnitude, while geometric dimensions of the individual elements traditionally used in setups remain practically invariable. This leads to a necessity to work in the near-field diffraction, which, in turn, requires an adjustment in the used mathematical models of optimization of the parameters of the optical system. In the THz region we examined the configuration of the phase retrieval methods, based on the iterative procedure of solving the wave propagation equation (specifically - the Fresnel transform), using several spatial intensity distributions [17] and free space as the phase analyzer. In the mentioned work, generalized iteration algorithm allows one to use both wavelength and distance as variable parameters is described in detail.

As shown by numerical simulations, the main restriction on the phase reconstruction using this configuration is...
applied by the sampling theorem. In accordance with it, sampling the signal while recording the intensity distributions forbids the iterative procedure using Fresnel transform in the very near zone, where fine parts of the object are reconstructed due to the presence of high spatial frequencies. Also, we have investigated the alternative configuration of the method based on angular spectrum propagator [18]. The longitudinal intensity distributions were analyzed and the selection criterion for the data in case of using plane waves was determined.

IV. A COMPARISON OF METHODS BY MEANS OF NUMERICAL SIMULATION

To show the ability of both techniques to reconstruct 3D objects, we demonstrate, yet numerically, the reconstruction of purely at phase object. As an object we consider Teflon, that is transparent in THz and has the flat refractive index of $n_{eff} = 1.46$ in the whole available THz spectral range, thus allowing to call it purely phase object (fig. 1). For dispersive objects refractive index can be measured by THz TDS at first. The size of the object is 6.4×6.4 mm, its thickness is changed from 1 to 2 mm.

![Fig. 1. 3D model of the sample (a), phase distribution brought by the object to 300 um: reconstructed by THz TDS (b), reconstructed by iterative algorithm using 300 um and 10 different intensity patterns obtained by means of numerical simulations at various distances.](image)

As possible to see from fig. 1., both methods are demonstrate a good quality of reconstruction for numerical simulation. We believe that this imaging techniques have great potential for security, biological and other applications.

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