Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 73 (2015) 49 – 53
Physics Procedia

4th International Conference Photonics and Information Optics, PhIO 2015, 28-30 January 2015

The modeling peculiarities of diffractive propagation of the broadband terahertz two-dimensional field

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Abstract

In this paper, we discuss the features of numerical simulation of propagation of the two-dimensional pulsed broadband terahertz (THz) fields. A set of separate spectral components used to describe diffraction of broadband THz pulses. To eliminate sampling theorem restriction in the numerical simulation of diffraction process for the complete spectral range, we use the representation of two-dimension fields as angular spectrum for the high-frequency spectral components and the convolution of initial fields with the impulse response for the low-frequency components. The peculiarities of diffraction of pulsed broadband terahertz radiation are manifested in the form of the dips in its spectrum, which is obtained at different points of the screen. The application of the given model for THz pulsed time-domain holography is demonstrated by the reconstruction of the image of the letter "K".

Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

Keywords: terahertz holography; wavefront propagation; terahertz radiation; terahertz imaging; diffraction theory.

1. Introduction

The problem of describing of the propagation of two-dimensional broadband THz fields is important for the investigation of their diffraction [Kozlov et al. (2010)]. It also important for the applications of the method of THz Pulsed Time-Domain Holography (PTDH) [Petrov et al. (2013)], which opens ample opportunities for analysis of dielectric properties of various objects, determining there topology, characterization of explosives [Chen et al. (2004), Chen et al. (2007), Oliveira et al. (2004), Melinger et al. (2010), Fan et al. (2007)], nondestructive monitoring of composite materials [Balbekin et al. (2015), Stoik et al. (2008)], analysis of spectral characteristics of biological tissues and biomolecules [Haddad et al. (2013), Walther et al. (2000), Fische (2002), Tsurkan et al.

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Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)
doi:10.1016/j.phpro.2015.09.120

(2013), Strepitov et al. (2014), Smolyanskaya et al. (2014), Sushko et al. (2013)], etc. In this paper, modeling particularities of propagation of spatio-temporal THz wave train during its decomposition on separate spectral components are considered. In according to the scalar diffraction theory, the Rayleigh-Sommerfeld equation can be used to calculate spatial distributions of wave fields for each wavelength. However, this equation have high computational complexity and its use is impractical due to a large number of spectral components. Therefore, in this paper we will consider other method: the representation of the field as the angular spectrum (AS) and by convolution (C) of the initial field in the object plane with the impulse response function.

2. Mathematical model developed for numerical simulation of propagation of the two-dimensional broadband THz fields

Let the real part of the pulsed terahertz field density $E(x, y, t)$ is defined in the registration plane (x, y). Generally, it can be measured by raster scanning in the recording plane with coordinate system x, y by using electro-optical detection. We can pass into the spectral domain by applying the Fourier transformation to $E(x, y, t)$ and thereby obtain the spectral dependence of the complex amplitude of the THz field for each point on the screen:

$$u_{x,y}(\nu) = \hat{F}_{1D}(E_{x,y}(t)) = \int E_{x,y}(t)\exp(-2\pi i\nu)dt \tag{1}$$

where $\hat{F}_{1D}$ is a one-dimensional Fourier transform. Obtained this way three-dimension array $u(x, y, \nu) = |u(x, y, \nu)|\exp[i\varphi(x, y, \nu)]$ contains spatial distribution of the amplitude $|u(x, y, \nu)|$ and phase $\varphi(x, y, \nu)$ at each point x, y for each frequency ν. After transformation of the data from $u_{x,y}(\nu)$ to $u_\nu(x, y)$ we obtain the spatial distribution of the THz field on each spectral component.

In the scalar diffraction theory, when we consider the two most common methods of calculation of wavefront propagation from the object plane (x', y') to the recording plane (x, y) (namely, AS and C), it should be noted that their applicability is limited by the sampling theorem. Thus AS method defined as:

$$U(x,y,l) = \iint_{-\infty}^{+\infty} u(f_x, f_y)\exp\left[2\pi i(f_x x + f_y y)\right]\exp\left[\frac{2i\pi z}{\lambda}\sqrt{1-(\lambda f_x)^2-(\lambda f_y)^2}\right]df_x df_y \tag{2}$$

where $u(f_x, f_y) = \iint_{-\infty}^{+\infty}\exp\left[-i2\pi(f_x x + f_y y)\right]u(x', y')dx'dy'$ is the angular spectrum, is restricted by the inequality [Petrov et al. (2012)]:

$$\nu \ge \nu_0 = cl / D\Delta x. \tag{3}$$

Here c is the speed of light, l is the distance from the initial object plane to the remote recording plane, D is a linear dimension of the calculated field in the initial plane, Δx is a pixel size.

Similarly, the field $u(x, y, l)$ can be calculated using the method C

$$U(x,y,l) = u(x',y',0)\otimes h(x,y,l). \tag{4}$$

Here h is the impulse response function:

$$h(x,y,l) = \frac{\exp\left[2\pi ir/\lambda\right]}{i\lambda r}\frac{l}{r}, \tag{5}$$

and r is the distance between the object and registration planes: