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ScienceDirect

Procedia Engineering 201 (2017) 53–60

Procedia Engineering

www.elsevier.com/locate/procedia

3rd International Conference "Information Technology and Nanotechnology", ITNT-2017, 25-27 April 2017, Samara, Russia

Defined distribution forming in the near diffraction zone based on expansion of finite propagation operator eigenfunctions

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Abstract

This study considers the solution of the inverse diffraction problem for 1D finite (in the spatial and spectral regions) optical signal propagation operator in free space of the near zone (over a distance of several wavelengths). The beam propagation distance and the intervals of input domain and spatial frequency are the parameters of the operator. They change the set of the eigenvalues and eigenfunctions determining the number of degrees of freedom for approximation of a defined distribution. We have solved the inverse problem, namely we have performed the calculation of the input signals ensuring the forming of the defined distributions at various distances.

Peer-review under responsibility of the scientific committee of the 3rd International Conference "Information Technology and Nanotechnology".

Keywords: 1D finite propagation operator; diffraction near zone; eigenfunctions; approximation of a signal; solution of the inverse problem

1. Introduction

Because of the diffraction phenomenon, radiation passing through a hole of subwavelength size is scattered in all directions. The smaller the hole size, the more light is scattered and the larger the spot size of the light beam that has passed even a short distance from the hole. Thus, diffraction imposes fundamental limitation on the achievable optical resolution [1]. Since the realization of this fact, many attempts have been made to overcome the diffraction

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Peer-review under responsibility of the scientific committee of the 3rd International Conference "Information Technology and Nanotechnology".
10.1016/j.proeng.2017.09.659

limit, which could provide visualization of details whose dimensions are less than half the wavelength. The high interest is associated with the fact that the application field of superresolution is not restricted by improving the quality of images, but efficiency in record packing on information optical media, in lithography and nano-structuring, optical operation up to atomic dimensions, and many other fields has already been shown.

One of the directions effectively used to achieve superresolution is near-field optics [2-4]. Near-field optics examines fields in proximity to the source of radiation or the surface of the action, which involves the consideration of evanescent (non-propagating) waves [5]. In this case, there is no restriction to the size of the light spot, the localization of the laser beam can be arbitrary small, although, as the papers [6, 7] show, it depends significantly on the size of the details of the surface relief. With regard to the above mentioned, an important role is played by the longitudinal component of the electric field [8-10], the detection of which represents a certain complexity [11-14].

Another direction oriented to overcoming the diffraction limit outside the zone of evanescent waves (at a distance greater than the wavelength) is associated with the concept of a superoscillating field [15-17]. The study examines the possibility of superresolution in the far zone using hyperlens and metalens [18], as well as optical eigenmodes [19, 20].

In this research, we examine the forming of defined distributions on distances over of the wavelength from the input plane based on the theory of communication modes [21, 22]. For this purpose, we consider the eigenfunctions of the propagation operator in the near field and use them to approximate the defined distributions [23, 24]. The limitation of the propagation operator both in the spatial and spectral regions leads to the need for a numerical calculation [25-28] of the eigenfunctions. In particular, the paper [28] considered a finite one-dimensional transform corresponding to the optical fields propagation operator in free space and based on the expansion in plane waves. It has been shown that such an operator is standard, therefore the set of its eigenfunctions is orthogonal and, consequently, can be used to approximate some defined distributions. In this case, the propagation distance of the beam and the intervals of input domain and spatial frequency are the parameters of the operator. They change the set of eigenvalues and eigenfunctions, determining the number of degrees of freedom for approximating a defined distributions and possibility to solve inverse problem.

2. Theoretical information

Let us consider the propagation of one-dimensional light waves in free space on the basis of the scalar theory of diffraction. In accordance with this theory, the propagation equation based on the expansion in terms of the basis of plane waves, has the following form [29]:

$$F(u,z)=\frac{1}{\lambda}\int_{-x_0}^{x_0} f(x)\left\{\int_{-\alpha_0}^{\alpha_0}\exp\left(i\frac{2\pi}{\lambda}z\sqrt{1-\alpha^2}\right)\exp\left[i\frac{2\pi}{\lambda}\alpha(u-x)\right]\mathrm{d}\alpha\right\}\mathrm{d}x\,, \tag{1}$$

where $f(x)$ is the input field, limited by an interval $[-x_0, x_0]$ in the spatial region, and in the spectral region by an interval $[-\alpha_0, \alpha_0]$, λ is the wavelength of the radiation, z is the propagation distance, $F(u,z)$ is the output field.

Let us rewrite the operator (1) in the form:

$$F(u,z)=\int_{-x_0}^{x_0} f(x)K(u,x,z)\,\mathrm{d}x\,, \tag{2}$$

where $K(u,x,z)=\frac{1}{\lambda}\int_{-\alpha_0}^{\alpha_0}\exp\left(i\frac{2\pi z}{\lambda}\sqrt{1-\alpha^2}\right)\exp\left[i\frac{2\pi\alpha}{\lambda}(u-x)\right]\mathrm{d}\alpha\,.$ (3)

The integral (3) is the inverse Fourier transform in bounded limits. For the case of infinite limits, there exists an analytic form for writing the given integral using the first kind Hankel function [30]. When $|\alpha|>1$, the waves are evanescent (damped) and do not propagate in free space over a distance of more than a third of the wavelength [31]. In the discrete form, the operator (2) can be written as follows: