Journal of Quantitative Spectroscopy & Radiative Transfer 162 (2015) 184–189

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

An improved analysis of the scattering properties of half-space problem with multiple defect particles for an optical surface

L. Gong [a,*], Z.S. Wu [b], Z.J. Li [b], G. Zhang [b]

[a] School of Photoelectric Engineering, Xi'an Technological University, Xi'an, Shaanxi 710021, China
[b] School of Science, Xidian University, Xi'an, Shaanxi 710021, China

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form
11 April 2015
Accepted 15 April 2015
Available online 25 April 2015

Keywords:
Multiple scattering
Finite-difference time-domain
Optical surface
Defect particle

ABSTRACT

Based on the practical situation of nondestructive examination, an improved analysis of the scattering properties of multiple-defect particles for an optical surface is shown. Using finite difference time domain method, the generalized perfectly matched layer can work very well against the half-space problem of optical surface and defect particles. Boundary-connecting condition is reduced by three-wave method. Reciprocity theorem is applied to near-far field extrapolation. Results are compared with those obtained using CST Microwave Studio software, and both are found to match each other very well, thereby proving the reliability of the proposed method. Angle distributions of double particles with different positions are shown. Some selected calculations on the effects of sphere number and sphere separation distance are described. As the most important factor, the position factor is numerically analyzed in detail. Theory and model are valuable in examining inspect optical or wafer surface.

1. Introduction

Effective extraction of optical surface roughness and defect character has important practical value in improving the efficiency of an optical system. Optical system performance is directly influenced by optical surface quality. Detection and control of optical surface roughness and defect particles are some of the most important points of research on the preparation of optical surface and nanometer/subnanometer structural material [1,2]. To meet the increasing requirements of high-quality optical systems, the purity and roughness of optical surfaces have to be improved [3–5].

Light scattering is a powerful tool for optical surface quality control. Investigation of light scattered by an optical surface through computer simulation is a reliable tool for the investigation of the properties and functional abilities of an optical system by defect particles with the optical surface [6]. This tool helps reduce manufacturing and experimental costs. The work done in the manuscript provides theoretical basis and technological support for optical film and nondestructive examination, as well as for the optical performance design of nanometer structure. Scattering source particles above the surface or defects below the surface give rise to polarization and scattering intensity that differ from those predicted by microroughness. It can help derive some information on defect particles such as size, material, shape and so on [7–10]. With this goal in mind, a number of theories have been developed to predict scattering by defects on or inside surfaces, namely BV theory [11,12], null-field method [13], discrete dipole approximation [14–16], discrete sources method [6–8,17], T-matrix theory [18–21] and so on. However, validation of those theories have been carried out only in a few cases, and the composite scattering field among particles and the factor influence

---

[*] Corresponding author.
E-mail address: zzgonglei@126.com (L. Gong).

http://dx.doi.org/10.1016/j.jqsrt.2015.04.007
0022-4073/© 2015 Elsevier Ltd. All rights reserved.

rules are not simulated and analyzed in detail. For these reasons, researchers from our and Sun's groups have studied with finite difference time domain (FDTD) method [22–24]. Given that FDTD is directly applied to Maxwell equations, a strong trend has been observed over the last few decades. FDTD is a straightforward technique, based on relatively easy mathematical operations that can be handled even by simple computers for nanoparticles. In addition, the shape, material, position and location of objects are not limited. Surface-enhanced Raman scattering (SERS), incident beam shape and roughness are considered by Sun's group and they did not talk the half-space problem [22]. Analyses of composite light scattering properties between wafers and different shapes of spheres with different positions have been conducted by our group [23,24]. Different positions include spheres above, below, inlay a wafer. Different shape particles include sphere, ellipsoid, column and some non-spherical particles. In addition, the defect particles medium can be different from the top and bottom spaces. The aim of this manuscript is to determine an effective laser detection area in a nondestructive testing project by computing and analyzing the effects of separation distance, particle position, location and particle number of defect spheres.

This paper is arranged as follows. In Section 2, theoretical treatment is given for the determination of the scattering problem of particles and surface. In Section 3, we present numerical results about spheres and optical surface with different conditions. In the last section, conclusions are drawn.

Notably, the theory and numerical arithmetic described in this paper are applicable to the randomly distributed particles of different materials on an optical surface. The radii of these particles are comparable with the incident wavelength.

2. Scattering model and half-space FDTD method

2.1. Scattering model

In the optical system manufacture industry, many steps are required, such as deposition, polishing and so on. During these procedures, multi-body defect particles at different positions may form. These multi-body defect particles are regarded as spheres in the paper for the length limited (Fig. 1).

2.2. Half-space FDTD method

Some half-space problems in optics and electromagnetics are concerned with the top and bottom spaces when using two different mediums. In the half-space problem of optical system manufacture, the incident wave produces reflectance and transmission waves. The incident and reflectance fields are on the top space, whereas the transmission filed is in the bottom space. This method is called three-wave method.

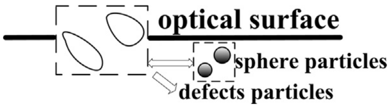

Fig. 1. Schematic of defect particle with different shapes and positions.

Fig. 2 shows the measurement geometry used in this paper. A plane wave polarized light of wavelength λ irradiates the surface and particles at an incident angle of θi and an azimuth angle of ϕ.

Fig. 3 shows the schematic of half-space scattering zone and the field about s- polarization light. The incident field can be written as $\vec{E}_{inc}$ or $\vec{H}_{inc}$, the reflectance field as $\vec{E}_{ref}$ or $\vec{H}_{ref}$, the transmission field as $\vec{E}_t$ or $\vec{H}_t$, and the scattering electric field as $\vec{E}_s$ or $\vec{H}_s$. The upon-surface field can be obtained as $\vec{E}=\vec{E}_{inc}+\vec{E}_{ref}+\vec{E}_s$ and $\vec{H}=\vec{H}_{inc}+\vec{H}_{ref}+\vec{H}_s$. The down-surface field can be obtained as $\vec{E}=\vec{E}_t+\vec{E}_s$ and $\vec{H}=\vec{H}_t+\vec{H}_s$. In the subsequent depiction, time dependence, $\exp(-i\omega t)$ where ω is circular frequency is assumed and suppressed. The incident field can be written as follows:

$$\vec{E}^{inc}\left(\vec{r}\right)=\left[E_{\perp}\left(\vec{r}\right)\hat{s}+E_{\parallel}\left(\vec{r}\right)\hat{p}\right] \tag{1}$$

Next, s-polarization light is analyzed in detail. Electric and electromagnetic fields are decomposed along the *x,y,z* axis. Decomposition variable can be expressed as follows:

$$E_y^{i(p)}\left(\vec{r}\right)=E_{\perp}\exp\left[i(k_{xi}x+k_{zi}z-\omega t)\right] \tag{2}$$

$$E_y^{r(p)}\left(\vec{r}\right)=R^pE_{\perp}\exp\left[i(k_{xr}x+k_{zr}z-\omega t)\right] \tag{3}$$

$$E_y^{t(p)}\left(\vec{r}\right)=T^pE_{\perp}\exp\left[i(k_{xt}x+k_{zt}z-\omega t)\right] \tag{4}$$

Magnetic field can be expressed as follows:

$$H_x^{i(p)}\left(\vec{r}\right)=\frac{E_{\perp}\ \cos\ \theta}{Z_0}\exp\left[i(k_{xi}x+k_{zi}z-\omega t)\right] \tag{5}$$

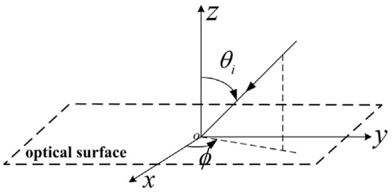

Fig. 2. Schematic of incident angle and zone azimuth angle geometry.

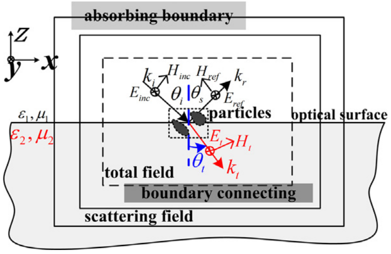

Fig. 3. Schematic of half-space scattering zone and field about s-polarization light.