Journal of Quantitative Spectroscopy & Radiative Transfer 219 (2018) 255–261

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Multiple scattering of a focused laser beam by a cluster consisting of nonconcentric encapsulated particles

Hany L.S. Ibrahim[a,*], Elsayed Esam M. Khaled[b]

[a] Telecom Egypt Company, Qina, Egypt
[b] Electrical Engineering Department, Faculty of Engineering, Assiut University, Assiut, Egypt

ARTICLE INFO

Article history:
Received 24 April 2018
Revised 16 July 2018
Accepted 9 August 2018
Available online 22 August 2018

Keywords:
Multiple scattering
T-matrix
Nonspherical coated particles
Laser beam

ABSTRACT

The optical characteristics of a cluster consisting of zinc sulfide (ZnS) particles doped with a nonconcentric spherical copper (Cu) cores illuminated with an arbitrarily focused Gaussian beam are investigated. The presented aggregations of nonconcentric doped particles (i.e. core with offset origin) form linear chains or densely packed clusters. The laser beam is modeled using angular spectrum of plane waves method and then combined with the cluster *T*-matrix method which is modified to solve such difficult multiple scattering problem. This combination provides a powerful mathematical technique to obtain the phase (scattering) matrix of a cluster illuminated with any incident electromagnetic fields. The scattering matrix provides complete descriptions of the scattering characteristics in the far field zone. The computed results are shown for different beam waists with respect to the cluster. The scattering processes and its results help understanding many cluster characteristics and nonlinear processes. The presented numerical results show that the elements of the scattering matrix are sensitive to the focusing of the incident beam and characteristics of the cluster constituents. The illustrated results are important for researches aim to improve polymer properties and to study several branches of practical sciences and industries such as nanotechnology, pharmaceuticals, chemistry, and biology.

This paper represents the first attempt to study the multiple scattering from a cluster of nonspherical particles with nonconcentric spherical cores illuminated by an arbitrarily focused laser beam.

1. Introduction

The radiative properties of a cluster consisting of micro or nano coated particles are relevant to a wide variety of applications in many areas such as pharmaceuticals, nanotechnology, chemistry, biology, health sciences, and astrophysics [1]. Moreover various particles characteristics, such as shape, refractive index, composition, and surface roughness have important influences to the light scattering by such particles. In some cases, improving the handling properties of a material as in a doped zinc sulfide (ZnS) particle with a copper (Cu) core can enhance the photoluminescence process [2,3]. zinc sulfide (ZnS) is a common pigment of phosphorescent materials that has applications in the optoelectronics industry [4]. Also the photoluminescence results from the nonlinear optical characteristics of the ZnS particles make this material a suitable candidate for applications in the low voltage display technology [5]. A cluster consisting of ZnS axisymmetric particles encapsulated with Cu core can enhance the photoluminescence from such materials. In many cases, cores of the particles in the clusters are nonconcentric with the particles. Therefore in such cases, understanding light interactions processes are important keys to characterize the properties of the constituents of the clusters and to know how the polarization and frequency of the laser beam behave during the scattering processes.

The analysis of scattering of light, especially focused laser beam, with a cluster is not an easy task. Some researchers illustrated a numerical analysis of the scattering problem of a cluster illuminated with a plane wave [6–8]. Ibrahim et al. [9] divided such problem into two parts; the first is the incident beam modeling using the angular spectrum of plane wave method [10], and the second is the interaction of the incident beam with the cluster through the use of a modified *T*-matrix technique [7]. Their method provide certain advantages: (1) the elements of the *T*-Matrix are independent on the incident fields but depend only on the scatterer properties, therefore these elements are computed once for each case of the scatterer and then used for different

* Corresponding author.
E-mail addresses: hany_louka@yahoo.com (H.L.S. Ibrahim), esamk54_2000@aun.edu.eg (E.E.M. Khaled).

https://doi.org/10.1016/j.jqsrt.2018.08.009
0022-4073/

cases of illuminations such as direction, polarization, and shape of the incidence light, (2) the incident field can be decomposed into simpler basis functions (spectrum of plane waves) and then manipulated in a modified *T*- matrix system to compute the scattered fields and different optical characteristics. Moreover using plane wave spectrum technique to model the incident light enables researchers to represent any physically realizable beam which has no mathematical representation such as beams with ripples.

In our previous research [8] a cluster consisting of dielectric nonconcentric encapsulation particles illuminated with a plane wave only is investigated. Also in our previous work [9] the scattering of a focused laser beam by a cluster consisting of homogeneous particles is studied. So the new case in this paper is the investigation of the scattering processes of a focused laser beam by a cluster consists of nonspherical particles encapsulated with shifted cores. To the best of our knowledge this is the first attempt in the literature to tackle such type of problem. So we modified the cluster *T*-matrix method to deal with both a focused laser beam scattered by a cluster of nonspherical coated particles with shifted cores. This illustrated technique is applied to a practical case that is a cluster consisting of nonspherical zinc sulfide (ZnS) particles doped with nonconcentric spherical copper (Cu) cores illuminated with an arbitrarily focused laser beam. To check the validity of our technique the calculated results of a cluster consisting of dielectric nonconcentric encapsulation particles illuminated with a laser beam of very wide waist are contrasted with cases of a cluster illuminated with plane wave [8], and with cases of homogeneous axisymmetric particles illuminated with an arbitrarily focused electromagnetic Gaussian beam [9]. No differences were noticed in all the cases.

2. Method and theoretical analysis

Fig. 1 shows a cluster consisting of N ($N=5$ in this work) identical oblate spheroidal particles of zinc sulfide (ZnS) material with an off-centered spherical copper (Cu) core. The particles are centered at local origins of a right-handed Cartesian coordinate systems (x_i,y_i,z_i), where i indicates the particle's index. In the chain cluster all particles are oriented along the x-axis of a right-handed Cartesian coordinate system. The greater radii of the particles (which is b_s) are along the x-axis and each particle touches the following one. The center of the middle particle is at the origin as shown in Fig. 1(a). In the packed cluster the center of the first particle is located in the origin and its greater radius is along the x-axis. The second particle touches only the first particle and its center is located on the x-axis. Also its greater radius is along the x-axis. The third particle touches only the first particle. Its center is located on the y-axis and its greater radius is along the y-axis. The centers of the fourth and fifth particles are located at the z-axis along each side of the first particle. Their smaller radii are on the z-axis and their greater radii are oriented along the x-axis, each of them touches only the first particle as shown in Fig. 1(b). The global Cartesian coordinate system of the cluster is (x, y, z) as shown in the figure. The radii of the shell are a_s and b_s, and that of the core is a_c. The cores are shifted by an offset distance L along the z-direction. The cluster is arranged as a linear chain as in Fig. 1(a) or as a packed cluster as in Fig. 1(b).

The surface of the core can be described, with respect to the local coordinate axis (x_i,y_i,z_i) as [11],

$$r_c(\theta_i) = a_c\left[p_i\cos(\theta_i) + (1 - p_i{}^2\sin^2(\theta_i))^{\frac{1}{2}}\right] \quad (1)$$

where $p_i = L_i/a_c$, and θ_i is local theta angle of the spherical coordinate system (r_i, θ_i, ϕ_i). By defining the core/particle size ratio $R = a_c/a_s$, it can be seen that the core remains inside the shell as long as the condition $(L_i/a_s + R) <= 1$ is fulfilled. All the detailed analysis for the oblates constructing the cluster is given in [11].

The cluster is illuminated with a focused Gaussian beam of a waist $2w_0$ and wavelength λ propagating along the z-direction. The vector spherical harmonics (VSH) expansion of the plane wave spectrum which is used to model the incident beam [10] is,

$$\mathbf{E}^{inc}(k\mathbf{r}) = H\sum_m\sum_n D_{mn}\left[a^t_{emn}\,\mathbf{M}^1_{emn}(k\mathbf{r}) + a^t_{omn}\,\mathbf{M}^1_{omn}(k\mathbf{r}) + b^t_{emn}\,\mathbf{N}^1_{emn}(k\mathbf{r}) + b^t_{omn}\,\mathbf{N}^1_{omn}(k\mathbf{r})\right] \quad (2)$$

where H, and D_{mn} are normalization factors depend on the incident beam. The $a^t{}_{emn}$, $a^t{}_{omn}$, $b^t{}_{emn}$, and $b^t{}_{omn}$ are the incident Gaussian beam expansion coefficients, and $\mathbf{M}^1{}_{emn}$, $\mathbf{M}^1{}_{omn}$, $\mathbf{N}^1{}_{emn}$, and $\mathbf{N}^1{}_{omn}$ are VSH of the first kind. m (in italic) is the azimuthal mode index and n is the mode number. The symbols e and o stand for even and odd respectively. $\mathbf{r}$ is a position vector, and the wave number is $k = 2^*\pi/\lambda$. In the case of a unit amplitude incident plane wave, H is unity and the azimuthal mode index $m = 1$. The advantages of this modeling method are: (1) it can be used for a beam whether or not it has a mathematical formula and (2) it can be used to model for physically realizable beams with ripples [10]. All the analysis of modeling the beam can be found in [10].

In general calculations of the elements of the fields are infinite. In practical computer calculations they must be limited to a finite size by truncating the expansion series to a maximum number $n = n_{\max}$. If number of the terms in the series is greater than $n_{\max}$ then the computations will lead to the truncation error or a convergence error. For scattering of a single particle $n_{i,\max} = x + 4.05x^{1/3} + 2$ where x is the size parameter of the particle. The method for convergence and plane wave truncation can be found in details in Ref [10].

Because of electromagnetic interactions between the particles, the scattered fields from each particle i are interdependent, therefore the total incident field illuminating the particle j can be represented as a superposition of; (1) external incident field from the incident beam, and (2) sum of all fields scattered from all other particles illuminating the particle j, that is

$$\mathbf{E}^{inc}_j = \mathbf{E}^{inc} + \sum_{\substack{l=1\\ l\neq j}}^{N}\mathbf{E}^{sca}_l \qquad j = 1,\ldots,N. \quad (3)$$

where N is the number of the particles in the cluster. These jth particle illuminating fields can be expanded in VSH as,

$$\mathbf{E}^{inc}_j = \sum_{mn}\left\{\left(a^{j\,t}_{mn} + \sum_{l\neq j}a^{j\,l}_{mn}\right)\mathbf{M}^1{}_{mn}(k\mathbf{r}_j) + \left(b^{j\,t}_{mn} + \sum_{l\neq j}b^{j\,l}_{mn}\right)\mathbf{N}^1{}_{mn}(k\mathbf{r}_j)\right\}, \quad j = 1,\ldots,N. \quad (4)$$

The expansion coefficients $a^{j\,t}_{mn}$ and $b^{j\,t}_{mn}$ describe the expansion coefficients of the external incident laser beam illuminating particle j and $a^{j\,t}_{mn}$, $b^{j\,t}_{mn}$ describe the expansion coefficients of the field scattered from particle l and illuminating particle j. Then the expansion coefficients of the total scattered fields from the particle j can be written in form of T-matrix notation as,

$$\begin{bmatrix} f^j \\ g^j \end{bmatrix} = \mathbf{T}^j\left(\begin{bmatrix}\mathbf{a}^{jt}\\ \mathbf{b}^{jt}\end{bmatrix} + \sum_{l\neq j}\begin{bmatrix}\mathbf{a}^{jl}\\ \mathbf{b}^{jl}\end{bmatrix}\right), \qquad j = 1,\ldots,N. \quad (5)$$

where $f^{\,j}$, $g^{\,j}$ are the scattered field expansion coefficients of the particle j, and $\boldsymbol{T}^{\,j}$ is the T-matrix of the particle j and is given in detail in [7]. Following the analysis given in [8] and [9], we finally