Journal of Quantitative Spectroscopy & Radiative Transfer 195 (2017) 176–188

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Numerical analysis of primary rainbows from a homogeneous cylinder and an optical fiber for incident low-coherent light

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ARTICLE INFO

Article history:
Received 29 August 2016
Received in revised form
5 January 2017
Accepted 6 January 2017
Available online 24 January 2017

Keywords:
Scattering
Mie theory
Surface waves
Fiber optics

ABSTRACT

This work provides a numerical study of the scattering of low-coherent light by an infinite right circular cylinder and various types of optical fiber (with step- and graded-index profiles) in the vicinity of primary rainbows, caused by light that has been subjected to one internal reflection. The scattered intensity is analyzed in terms of the Fourier transform as well as in the time domain (by examining the impulse response of a fiber) with the aim to obtain a detailed information about the scattering process. The analysis reveals a wealth of information about the scattering process that is not obvious when a fiber is illuminated by a temporally coherent light source. The results also provide an idea for the characterization of the core size of step-index optical fibers.

1. Introduction

The phenomenon of a rainbow continues to inspire many researchers. A generic, monochromatic rainbow formed with the use of a linearly-polarized beam of laser light is a useful tool for non-invasive analysis of weakly-absorbing single particles as well as their ensembles. The subject of rainbow metrology was launched by Presby and Marcuse [1], who studied the possibility of using the rainbow as a tool to characterize optical fibers and preforms. A related work by Roth et al. [2], concerns a method for refractive index measurements of burning droplet streams. Their solution has been extended by van Beeck and coworkers to perform additional size and temperature measurements [3–5]. Other researchers applied this technique to characterize initial disturbances of a liquid jet [6]. By integrating the rainbow technique with a phase-Doppler system, it became possible to characterize a particle's size/temperature as well as its velocity simultaneously [7]. Several authors have performed numerical and experimental observations of rainbow scattering by individual layered objects [8–10] and particles with non-circular cross-section [11–14]. Furthermore, a lot of effort has been done to investigate the effects of particle's refractive-index gradient on rainbow patterns [15–19]. Studies on polydisperse systems such as spray droplets [20–24] have been also carried out.

In general, the use of a laser beam is common and allows to characterize micro-domain systems with potentially high sensitivity as well as accuracy. Undoubtedly, a precise qualitative and quantitative understanding of the rainbow mechanisms is necessary to solve an inverse problem, i.e., to relate the optical field back to the properties of interest in the object. As scattering of light by transparent objects involves various scattering processes, such as diffraction, refraction, reflection, transmission, and surface waves (which interact with each other and are not separable in space in the framework of the Lorenz-Mie theory), the inverse problem is decidedly non-trivial [25–27].

A recent approach to characterization of single and transparent particles on the basis of rainbow technique uses a beam of light of low temporal coherence [28,29] instead of a laser beam. The idea behind this method is to arrange measurement conditions in such a way that the scattered optical field becomes easier in terms of causal as well as inverse reasoning. Both studies shown that the scattered far field may be accurately described by approximate models of scattering derived from Airy's theory and Nussenzveig's Complex Angular Momentum approach.

The purpose of this paper is to provide a comprehensive analysis of rainbow scattering by various kinds of transparent fibers: (i) silica 125 μm circular cylinder, (ii) step-index and (iii) graded-index optical fiber (both 125 μm in outside diameter and with variable core diameter) with the aim of obtaining detailed information about the scattering process. In particular, it is explored how the scattering varies as the incident light is changed from monochromatic source to a broader spectrum. By doing this, it becomes possible to observe several phenomena that are not obvious when a fiber is illuminated by a temporally coherent light source.

The scattered far field of an illuminated fiber is initially studied in detail using the Fourier transform, which decomposes the

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http://dx.doi.org/10.1016/j.jqsrt.2017.01.009
0022-4073/

scattered intensity in frequency. This approach provides information about the scattering processes by examining the interference of various scattering contributions that are attributable to geometric optics. The results also provide an idea for the characterization of the core size of step-index optical fibers.

A further analysis involves scattering of a light pulse instead of a continuous wave. By examining the time delays of the scattered light as a function of scattering angle it is possible to reveal some intricate details of scattering. Unlike the Fourier transform, the time-domain analysis removes much of the interference between scattering components which contribute to the scattered far field.

The body of the paper is organized as follows. Section 2 provides a detailed analysis of low-coherent light scattering by various types of fibers by means of the Fourier transform. Section 3 is devoted to numerical predictions of the impulse response. Finally, concluding remarks are presented in Section 4.

2. Analysis of low-coherent light scattering by means of DFT

Consider an infinitely long, circular fiber composed of a series of concentric layers. Each layer is characterized by a size parameter $x_j = 2\pi r_j/\lambda$ and a complex index of refraction $m_j(\lambda) = , n_j(\lambda) + \mathrm{i}\kappa$ where $j = 1, 2, \ldots, J$ with J denoting the total number of layers, r_j is the radius of the j^{th} layer, λ is the wavelength of the radiation incident on the fiber, and $\mathrm{i} = (-1)^{1/2}$. Each of the layers is assumed to be dispersive (chromatic dispersion), while the imaginary part of $m_j(\lambda)$ is wavelength-independent, which is correct for most optical glasses [30]. A right-handed cylindrical coordinate system is attached to the fiber, whose symmetry axis coincides with the z axis, see Fig. 1a.

The fiber is illuminated normally by a collimated beam of polychromatic light, propagating in the negative x direction and polarized along the z axis (TM polarization). The scattering angle θ is measured clockwise from the $-x$ axis. A general discussion on scattering of polychromatic beams is the subject of Ref. [31]. The electromagnetic incident field is a vector superposition of N mutually incoherent monochromatic fields propagating in the same direction and distributed over the range of angular frequencies $\Delta\omega = [\omega_{\min}, \omega_{\max}]$ [31]:

$$\mathbf{E}^{\mathbf{inc}}(x, t) = \sum_{n=1}^{N} \mathbf{E}_n^{\mathbf{inc}}(t) exp\Big(- \mathrm{i}k_n^{inc}x - \mathrm{i}\omega_n t\Big), \tag{1}$$

where $\mathbf{E}_n^{\mathbf{inc}}(t)$ is the complex amplitude of the electric field which fluctuates randomly in time with the period long compared to the complex temporal term $\exp(-i\omega_n t)$, and k_n^{inc} is the (real-valued) wave vector. An expression for the complex magnetic field $\mathbf{H}^{\mathbf{inc}}$ is obtained by replacing $\mathbf{E}$ with $\mathbf{H}$ in Eq. (1). Scattering of each monochromatic wave from the spectrum of the incident light is considered as a separate event. The transformation of the incident field $[\mathbf{E}^{\mathbf{inc}}, \mathbf{H}^{\mathbf{inc}}]$ into the scattered field $[\mathbf{E}^{\mathbf{sca}}, \mathbf{H}^{\mathbf{sca}}]$ upon its interaction with the fiber is treated rigorously with the use of separation-of-variables solution of Maxwell's equations [32] and Debye series expansion [33]. Assuming that the interaction of light with the fiber is linear, the time-averaged Poynting vector of the

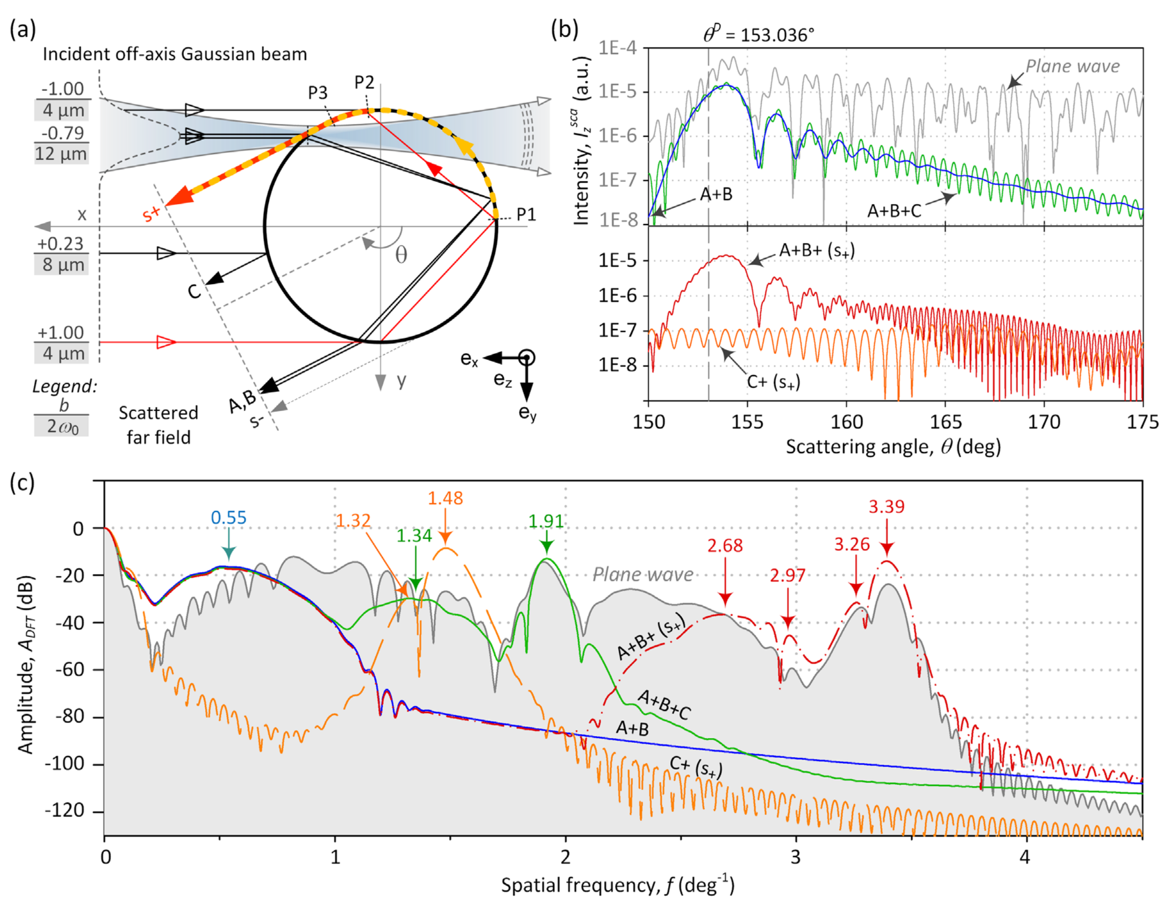

Fig. 1. DFT analysis of scattering near the primary rainbow – case of a circular homogeneous cylinder illuminated by a single-wavelength beam. (a) Quasi-selective generation of light rays A and B (one internal reflection), C (external reflection), and surface waves $s+$, $s-$, with the use of a Gaussian beam of diameter $2\omega_0$ focused on the cylinder at impact parameter $b = [-1, 1]$. (b) Graphs of intensity as a function of scattering angle showing the contribution made by different ray paths and their coherent sum. (c) DFT of the scattered intensities from Fig. 1b. DFT parameters (see text): sampling range 153.036–175°, sampling resolution: 0.002°, 65536 DFT samples [zero-padded], Hann window function.