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Non-diffractive beam in random media

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ABSTRACT

Beam propagation has been given important attention in a variety of applications in medicine, remote sensing and information science. Especially, the beam propagation in highly scattering media, which is called random media, is important. In general, the multiple scattering gets rid of beam characteristics, e.g., intensity distribution, phase front, and polarization. In this study, self-converging effect of annular beam was applied in random media. Diluted milk was used as random media, and the transmitted light was detected with a narrow view angle of 5.5mrad. The collimated annular beam of a few tens millimeters takes a few hundred meters to transform its beam shape into the non-diffractive beam in free space, while this transformation was shorten only to 20 cm in random media, that is, the collimated annular beam caused its transformation at only 20 cm in random media. The transformed beam kept its optical characteristics of “non-diffractive beam”. Such transformation of the annular beam needs the appropriate condition of random media. Media concentration and propagation distance control the generation of the center peak intensity of the transformed beam. This study indicates the generation of the non-diffractive beam in random media and reveals its appropriate condition.

1. Introduction

The advantage of non-diffractive beam, quasi-Bessel beam, is well known [1–5]. It is utilized as the super resolution techniques at the observation of scanning microscope and semiconductor manufacturing process [6–9], where the propagation characteristics of the non-diffractive beam take attention. The unique characteristics of the non-diffractive beam in long path propagation are reported too [10–12]. Many of their application scenes use an annular beam, which is applied as the same technique as a zone-plate on X-ray imaging optics. Non-diffractive beam generated from an annular beam is well analyzed under these former studies [13–17].

On contrary, the propagation control of optical beam in dense scattering media, which is called random media, takes most of the attention [18–25]. Human tissue is one of such random media. Optical sensing technology of human tissue is focused at the viewpoints of safety and high-resolution compared with X-ray and ultra-sound apparatuses. The optical topography is one of the successful applications of such dense material sensing. It treats the scattered light as stochastic method, e.g., its time of flight indicates the information of the target material, while its optical properties such as intensity, phase, and polarization are ignored. In general, plural scattering collapse the wavefront and phase of the propagating beam in highly scattering materials. The wavefront and polarization information are not kept in random media.

The author started the study of the annular beam on the consideration of long-range beam propagation in lidar application [26–29]. Under this study, high-tolerance of the non-diffractive beam against the atmospheric fluctuations was found out. It is the effect of self-converging process on the annular beam propagation. The author thought that this effect of the high tolerance was available in the scattering media too. Although the atmospheric fluctuation is different from optical scattering, the optical effects against the beam are the same, that is, they come down to the changes of amplitude and phase.

The focus of this study is the generation of non-diffractive beam in random media. In choosing the random media, processed milk was utilized. The milk qualities (particles' sizes and ingredients concentration) were well controlled in the various seasons of Japan. The experiment was conducted carefully without the influence of partial change of refractive index (index unevenness). The beam propagation in dense scattering media is equivalent to treat the near range beam propagation characteristics in random media.

This report states the generation of the concrete non-diffractive beam in random media and reveals its optical property. The author made this study progress after the first result shown in Ref [30]. This paper adds new considerations and discussions to link to the future study.

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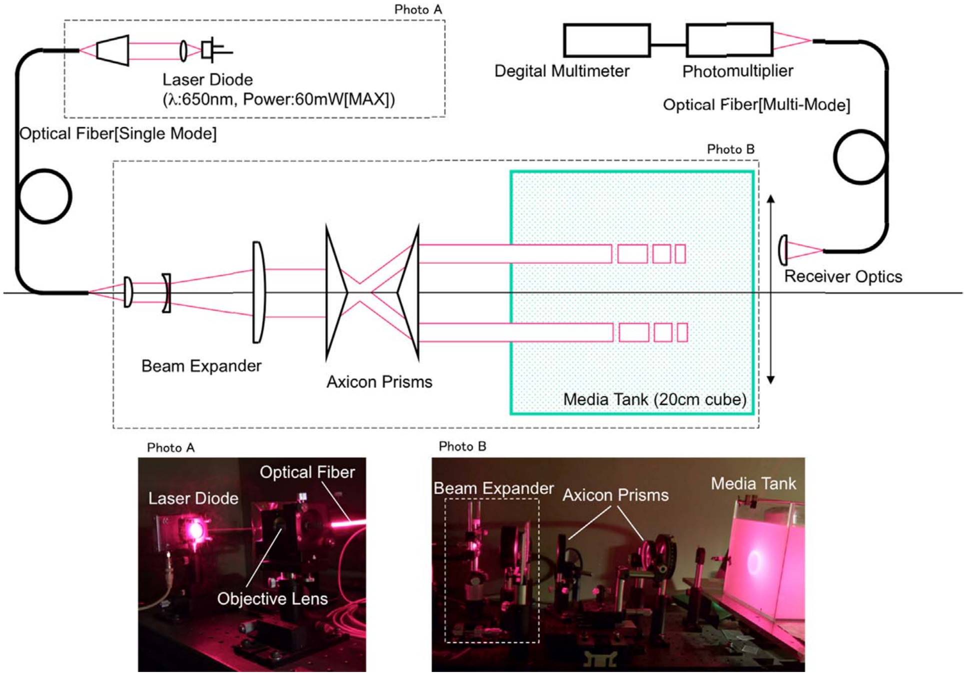

Fig. 1. Experimental setup of annular beam propagation in random media.

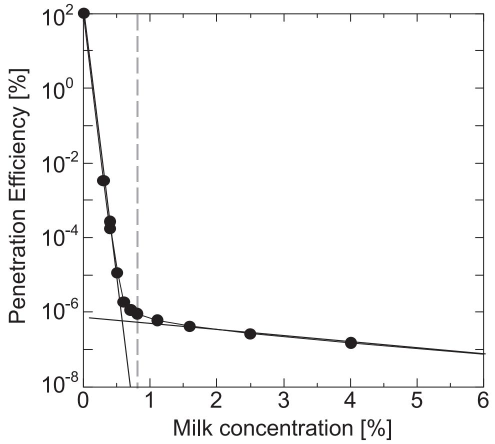

Fig. 2. Penetration efficiency of the annular beam in diluted milk.

2. Fundamental experiment

The experimental setup of the optics is shown in Fig. 1. The light source was a laser diode with a wavelength of 650 nm. Its power was 60 mW(max) as continuous wave (CW). The beam was coupled into a single-mode optical fiber to get the Gaussian distribution. After that, it was expanded and passed through a pair of Axicon prisms to change its distribution to the annular beam. Its transformation is written as Eq. (1) [5,31–33].

$$a(r) = \sqrt{\frac{R-r}{r} g(R-r)} \tag{1}$$

where $a(r)$ and $g(r)$ are an annular and a Gaussian beam distributions, respectively. R is an outer radius. The annular beam feature (outer radius and radial thickness) can be controlled by the size of the incident Gaussian beam and the interval of the Axicon prisms. The collimated annular beam entered and propagated the random media, and was detected at the end of the media by a detector module, which consisted of a fiber-coupling lens, a multi-mode fiber, and a photomultiplier. The optical view angle of the detector module was restricted to 5.5 mrad. Its aperture was 6mmϕ. The quasi-straight directed light was detected. The transmitted light distribution was obtained by scanning the receiver module vertically against the optical axis. The random media was the diluted milk. It was the processed product of low fat milk, which consists of lipid and casein. Their diameters were 1 μm and 0.1 μm, respectively. Their concentrations were rigorously kept to 1.8% and 2.4%, respectively all throughout seasons. As the scattered light intensity of the casein is much smaller than that of lipid because of the difference of cross-sections, the scattering property of the lipid is dominant. The milk was utilized by diluting with pure water. The geometrical form factor was estimated to be 0.916, under the condition that refractive index of the lipid particle and the water were 1.59 and 1.33, respectively. The solution was well mixed, and the measurement started after its flow and convection were settled down. The media tank was 20 cm cube. The experiment was conducted carefully without the influence of partial change of refractive index (index unevenness). The integration time was estimated experimentally to obtain repeatable results. As a result, it was fixed to 2 ms.

At first, the propagation efficiency was examined as the fundamental experiment in random media. The transmitted light efficiency was examined against the milk concentration. The Gaussian beam was used and the detector module was fixed at the center (on the optical axis). The result is shown in Fig. 2. The efficiency curve has two parts, i.e., the steep decay part and the slow decay part. The steep decay part was in the region of 0–0.7%. This decay comes from the decrease of the straightly propagated beam as Lambert-Beer's Law. It is equivalent to the energy decrease of the non-scattered direct light. The root mean free path was about 20 cm at the concentration of 0.5%. It explains that the incident light hits the particles at the propagation distance of 20 cm on average. The attenuation ratio was calculated 80.6 per milk concentration [%]. On contrary, in the concentration of 1.0% and more, the decay rate becomes slow. The scattering light is dominant in this slow decay region. The mean free path at the concentration of 4% was calculated as 5 cm. The attenuation ratio was calculated 11.5 per milk concentration [%]. In the scattering light dominant region, the intensity distribution of the transmitted light became a convex curve. Fig. 3 shows the intensity distributions of the transmitted light through the media of the concentrations of 1% and 6%. It becomes equivalent to the intensity distribution of sphere radiation at the propagation distance of 20 cm at the media concentrations of 1% and 6%,