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Generation control of a non-diffractive beam in random media by adjusting concentration

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ABSTRACT

It takes a long distance of more than 200 m to generate a non-diffractive beam from an annular beam of 40 mm φ (diameter) in space. The authors have worked on the generation, control and optimization of a non-diffractive beam in random media with a short distance (a few tens of centimeters). In this work, the transmittance and the forward scattering waveforms of an annular beam at different propagation distances in random media are presented. Higher intensity of the center peak of a non-diffractive beam can be generated for short-distance propagation and high concentration in random media. The random media under consideration have the same scattering coefficients for all propagation distances. These scattering coefficients depend on the balance between forward scattering and multiple scattering. This balance is defined as the weight parameter α. By using the parameter α, an optimization of a non-diffractive beam in random media is proposed, which is based on adjusting the concentration and the propagation distance in random media.

1. Introduction

Non-invasive and non-contact sensing methods such as optical topography and optical coherence tomography, are widely used in medical examination [1–7]. The aforementioned optical sensing technologies have the merit of low risk, high resolution and low cost in comparison with other sensing methods, such as computer tomography, ultrasound imaging and magnetic resonance imaging. However, in strong scattering media (called random media or colloidal suspension), such as the human tissue, which contains scattering particles, the light cannot propagate a long distance because of scattering and absorption. Thus, it is hard to get any information from the deep area inside the human tissue samples [7–12]. Optical sensing could be applied in a variety of random media if the propagation distance and propagation efficiency are improved. Wavefront modulation of transmission beams was suggested in several previous researches [13–17]. This method can help to suppress the diffraction and improve the propagation efficiency. In fact, a modulated light based on the propagation environment can propagate more efficiently in random media [16].

Ideally, a non-diffractive beam is a beam which can keep its original wavefront intensity distribution during its propagation. Moreover, it can suppress beam broadening and have a high tolerance to air fluctuations effectively as compared with a Gaussian beam [18–23].

In this research, we focus on the self-transformation of an annular beam. This beam can be simply created by a pair of Axicon prisms, and the polarization of the annular beam remains unchanged after its transformation. An annular beam of 40mmφ transforms into a quasi-Bessel function beam after it propagates at the distance of 200–300 m in air [24]. The quasi-Bessel beam maintains its waveform in a certain region. In this study, we call it "non-diffractive beam" [25,26]. The main peak diameter of the transformed non-diffractive beam is very narrow in comparison with the transmitting annular beam. It takes advantage of high resolution for sensing works.

In our previous work, the non-diffractive beam was generated by using an annular beam in random media at a short range of mere 20 cm. Although only the main peak and sub-peaks on the measured waveform were observed, we confirmed it as having the same features as a non-diffractive beam. As the concentration of the random media changed in a certain range, the waveform variation of the non-diffractive beam showed the same tendency with a self-focusing of the annular beam in air. The non-diffractive beam also kept the same polarization with the incident annular beam [24].

The non-diffractive beam is only transformed at a certain concentration and propagation distance in the random media. In this work, we focus on how to control and optimize the non-diffractive beam in random media. First, the transmittance and the forward scattering waveforms of the annular beam in random media at different propagation distances are presented. Then, a new method to optimize the non-diffractive beam by adjusting the concentration or the propagation distance in random media is proposed. Finally, the following two topics

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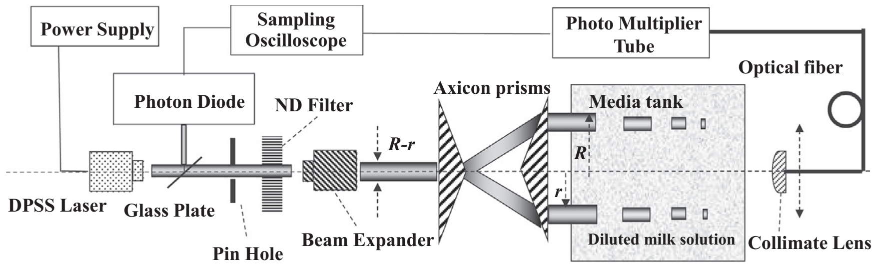

Fig. 1. The experiment system to analyze light propagation characteristics in random media.

Table 1
Specification of the experiment system.

Light source	DPSS laser CryLas, 1Q532-1: Wavelength: 532 nm; Pulse width: 2 ns; Peak power: 4.6 kW; Repetition: 15 kHz.	**Annular beam converter**	Axicon prims: Zenith angle: 150° (± 10′); Diameter: 50.8 mm; Annular beam diameter range: 24–42 mm
Receiver	Optical elements: Optical Fiber: Multiple mode Diameter.: 50 µm; Collimate lens N.A.:0.55 View angle: 5.5mrad; PMT: Hamamatsu R-636; Response time: 0.78 ns Sampling oscilloscope: Agilent, DCA-J 86100 C with 83484 A module Bandwidth: 50 GHz	Random media	Media tank: Material: Tempax glass; Size: W*H*L 20 cm*20 cm*(10–30) cm; Media: Processed milk with 1.8% fat; Fat size: 1.1 µm; Diluted range: 0.1–1.0%;

will be discussed:

The relationship between the non-diffractive beam intensity and propagation distance in random media;

The correlation between non-diffractive beam self-focusing in air and in random media.

2. Experimental system

Fig. 1 and Table 1 show the schematic diagram of the experimental system and the specification of the optical elements in our system, respectively.

A high power diode pumped solid state laser (4.6 kW peak power; 2-ns pulse duration) was utilized. The use of a pulsed beam was to increase the efficiency of the non-diffractive beam in random media. As compared with a continuous wave (CW) beam, pulse light interferes only in the time of the pulse width and it can prevent the interference cancelling by multiple scattering. A neutral density filter was used to adjust the optical intensity. A pair of Axicon prisms was used to create the annular beam, and a beam expander was used to control the thickness (the difference between the external diameter and internal diameter) of the annular beam.

The intensity of the Gaussian beam can be expressed as in Eq. (1), and the transformation function from an incident beam to an annular beam is expressed as in Eq. (2) [25–28].

$$g(r) = \frac{1}{\pi h^2}\cdot \exp[-(\frac{r}{h})^2] \quad (1)$$

$$a(r) = \sqrt{\frac{R-r}{r}}\cdot g(R-r) \quad (r>0) \quad (2)$$

Here, h is the distance from the center to the position where the intensity of the Gaussian beam becomes $1/e^2$ of the center value; R is the external radius of the annular beam which is determined by the interval between Axicon prisms, and r is the internal radius of the annular beam. Three media tanks with different sizes were used to change the propagation distance (10, 20 and 30 cm). The processed milk with 1.8% fat was chosen as the random medium. The diameter of the fat particles is about 1.1 µm, which would cause Mie scattering for visible light. The scattering coefficient of milk diluted with water at the concentration of about 30% is close to that of the human tissue [28]. The optical receiver unit consists of a collimated lens and a multiple mode optical fiber, and this combination helps reduce the detection angle to 5.5mrad. The receiving unit was set on an auto mechanical stage with the smallest step of 0.1 mm on horizontal-axis. A photo multiplier tube (PMT) was used as a detector to obtain the weak optical signal through the random medium, and a sampling oscilloscope was used to monitor the pulsed electric signal from PMT.

3. Results and discussion

3.1. Transmittance in random media

For measuring transmittance accurately, we took off the beam expander and the Axicon prisms from the optical system in Fig. 1, and used the laser beam of a small spot of < 0.3 mm from laser head, which had a Gaussian intensity distribution. The incident beam was emitted into the media tank; then forward scattering intensity was detected by the PMT at the center optical axis of the back side of the media tank.

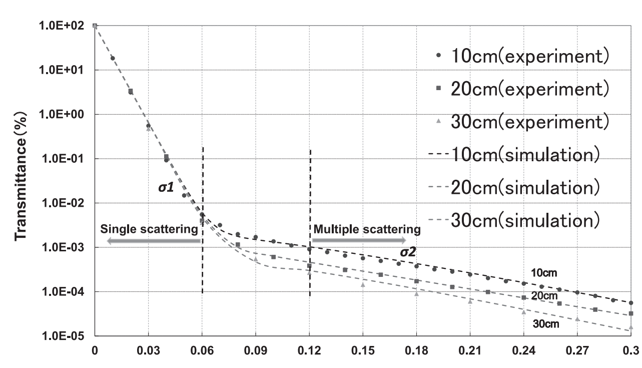

Fig. 2. Transmittance in random media at different propagation distance.