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PROPAGATION OF DIFFRACTION-FREE AND ACCELERATING LASER BEAMS IN TURBID MEDIA

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ABSTRACT. We experimentally investigate propagation of laser beams with Gaussian, Bessel and Airy transverse profiles in turbid media. We evaluate and compare the self-healing properties of these beams.

1. Introduction

Laser beams with specially shaped transverse profiles have interesting physical behaviors and applications; hence they receive a growing attention. One of the most commonly used profiles is the Bessel beams, which are also called diffraction-free beams. The depth of focus of a Bessel beam is much longer than Rayleigh distance of a Gaussian beam (of comparable spot size) and its transverse profile does not change in free space propagation [1]. Another intriguing feature of Bessel beams is 'self-healing'. When the beam encounters an obstruction, it reproduces the original profile after short propagation [2]. The self-healing nature of these beams also yields deeper penetration and slower attenuation in turbid media like biological tissues. Therefore Bessel beams are attractive for imaging deeper into tissues [3]. Airy beams are another example of diffraction-free beams [4]. In addition, however, they exhibit 'acceleration'. The focus of an Airy beam moves along a parabolic path. They also have 'self-healing' properties [5] yet, Airy beam propagation in highly scattering media has not been investigated in detail. In this study, we give experimental results on propagation of laser beams with Gaussian, Bessel and Airy transverse profiles in turbid media. As tissue-simulating phantoms, we used intralipid-water solutions with different mix ratios. We investigated change of intensity and beam profiles at the sample exit for varying scatterer density. As the mix ratio increases, intensities of Bessel and Airy beams decrease slower as compared to Gaussian Beams. On the other hand, we also observe that self-healing does not necessarily yield better reconstruction of beam profiles. Bessel beams, which exhibit slowest attenuation, also suffer highest beam profile deterioration.

2. Experiment

In our experiments we used 10% intralipid emulsion as tissue-simulating phantom [6]. The emulsion was diluted in distilled water and put into a quartz cuvette with 10 mm beam path. For the light source, we used He-Ne laser (632 nm) with expanded beam diameter of about 2 mm. The laser beam has nearly Gaussian intensity profile. For Gaussian beam measurements, the beam was directly focused into the sample cell. Rayleigh range of the focused Gaussian beam is 1.8 mm. The beam waist was at the inner face of the sample cell output window. In Bessel beam experiments, Gaussian laser beam was passed through a conical lens and then Bessel beam was generated. The maximum diffraction-free propagation distance of the Bessel beam is about 30 cm. We produced 1D and 2D Airy beams with the special optical element demonstrated earlier [7]. The propagation distance is about 8 mm for Airy beam. In all cases, we have chosen optical configurations such that the diameter of focal spot was approximately the same ($\sim$50 μm) at the end of sample cell.

Firstly, we investigated the propagation and scattering behaviors of these shaped laser beams in the turbid media. We put distilled water into the sample cell and dropped very small amounts of diluted intralipid-%10. We recorded the beam profile at the cell output for each mix ratio.

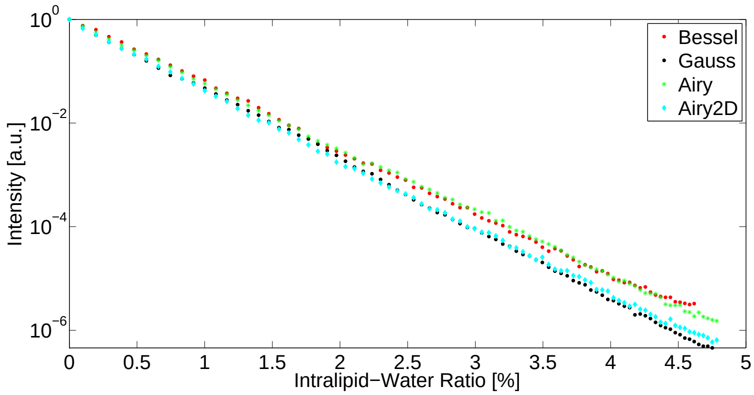

Figure 1. Change of Intensity at output with intralipid water ratio.

In Fig.1, we show the peak intensity as a function of intralipid-water ratio for Gaussian, Bessel, 1D and 2D Airy beams. From these results, we observe that the beam intensity decreases slower for Bessel and one-dimensional Airy beams as compared to Gaussian and two-dimensional Airy beams. For each type of the beams, we calculated extinction coefficient (μ_e) from the graph (Fig. 1). For Bessel and 1D Airy beams, μ_e is 28.2 r mm^{-1}, for Gaussian beam μ_e is 31.0 r mm^{-1} and for 2D Airy beam μ_e is 30.0 r mm^{-1}(where r is the intralipid/water volume ratio).

In order to investigate the self-healing (or self-reconstruction) properties of the shaped beams, we compared the measured beam profiles at different mix ratios. Examples of recorded profiles are shown in Fig. 2. To have a quantitative evaluation of self-reconstruction, we calculate the overlap integral of the diffuse beams with the beam in case of pure water.

The results are normalized so that overlap of 1 indicates perfect reconstruction. We observe that the profiles of 1D Airy and Gaussian beams show better resilience against increasing of scatterer densities (Fig. 3). However the profile of Bessel beam deformed significantly when mix ratio was increased. This is a significant result, as it is commonly believed that Bessel beams reconstruct better than Gaussian beams.

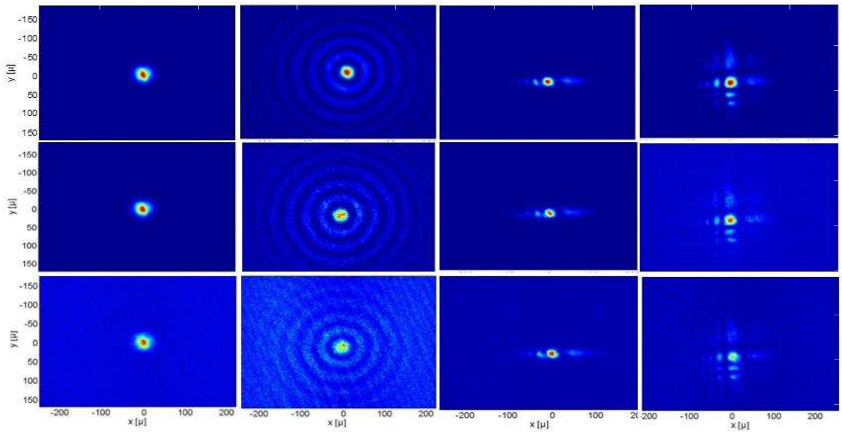

Figure 2. Measured beam profiles at the sample medium. Columns (from left to right) correspond to Gaussian, Bessel, 1D Airy and 2D Airy beams. Rows (from top to bottom) correspond to 0, 3.0 and 4.4% intralipid-water ratios.

We attribute the results of self-reconstruction to the effect of beam area. Bessel beams exhibit several rings around the focal spot, hence they have the largest area in the sample cell. As a result, they encounter more scatterers and their shape deteriorates faster. On the other hand, since the rings provide energy to the beam center during propagation, the maximum intensity drops slower as compared to the other beam profiles. We also compared overlap results of Bessel beams with different beam sizes (generated by 1° and 5° cone angles). We find that the intensity of the beam with smaller size (larger cone angle) drops slower, in consistence with our interpretation.

In our experiments, we also observe that 2D Airy beams attenuate faster as compared to 1D. We attribute this difference to the fact that the foci of 2D Airy beams move on a parabola in two-dimensions, hence they have a longer effective path through the scattering medium.

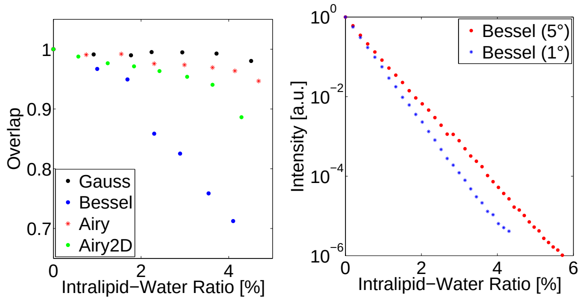

Figure 3. Left: Overlap integral of measured beam profiles. Right: Change of intensity at the sample output with intralipid-water ratio for two Bessel beams with different beam sizes.

Acknowledgments

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