# Optimization of Non-diffractive Beam Propagation in Random Media Formed by Annular Beam

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Abstract: Light is quite difficult to propagate a long distance in random media such as human tissue or atmospheric dense cloud because of its scattering and absorption. For optical sensing, it is important to increase propagation efficiency which means expanding the sensing range. An annular beam can transform its waveform into a non-diffractive beam due to its propagation in a long distance. In our previous work, we found the annular beam also had non-diffractive effect when it propagated in diluted milk solution of a few tens centimetres at the concentration of less than 1%. In this study, to clear up how to control and optimize the non-diffractive effect of the annular beam in random media, numerical calculation of propagation characteristics of annular beam in air was estimated. The narrow annular beam with a small diameter would generate a high intensity non-diffractive beam at a short distance. We also had three sets of experiments of annular beam propagation in random media with the same view point as the calculation, but its propagation characteristics was evaluated by milk concentration. They showed the same variation of a non-diffractive beam with the result of numerical calculation in air. These results provide us a hint of optimization for annular beam propagation in random media.

## 1 INTRODUCTION

Optical sensing is widely used in environmental observation, medical examination, military and other industrial fields as a non-invasive and non-contact sensing technology (Shiina, 2007) (Aruga, 1999). But for visible light and near-infrared light, it is very hard to propagate a long distance in random media (Craig, 1998) such as human tissue and atmospheric dense cloud because of its light absorption and scattering, especially when the size of the scattering particle is close to the wavelength of the light (Profio, 1989) (Ishimaru, 1989) (Diruan, 1991). For optical sensing, it is important to increase propagation efficiency to expand the sensing range.

We focused on the self-transformation of the annular beam through its propagation (Voelz, 2009) (Chen 2008) (Eyyuboglu, 2006). The annular beam can be easily created from a Gaussian beam by a pair of axicon prisms. Comparing with other types of annular beams, this type is high efficiency because none of the light is cut down (Shiina, 2007). The annular beam with the diameter of 40mm can transform its waveform into the non-diffractive beam (quasi-Bessel beam) at the propagation distance of 210m. Comparing to the Gaussian beam, the non-diffractive beam has better resistance to air fluctuation when it propagate in air (Rao, 2008) (Gercekcioglu, 2010) (Baykal, 2005) (Eyyuboglu, 2008) (Shiina, 2005). In our previous work, we found the annular beam also had the non-diffractive effect when it propagated in random media, the milk solution at concentration of less than 1% with the length of tens centimeters (Peng, 2011).

In this study, for the purpose of controlling and optimizing non-diffractive effect of the annular beam in random media, we had numerical calculation and three sets of experiments. In Chap. 2, theory of the annular beam and propagation characteristics were discussed when propagation distance, ring thickness and diameter of annular beam were varied. In Chap. 3, it showed experimental results with the same viewpoint as the calculation shown in Chap. 2. The calculation and the experimental results were compared in criterion of propagation distance and the concentration of random media.



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# 2 THEORY ANALYSIS

Because the non-diffractive beam formed from the annular beam is decided by not only its propagation distance, but also the incident beam characteristics such as the thickness and the diameter of the annular beam. It is also affected by the concentration of the random media.

## 2.1 Annular Beam and Non-Diffractive Beam

The annular beam we used was created from Gaussian beam by a pairs of Axicon prisms (Fedotowsky, 1974) (Scott, 1992) (Aruga, 1997) (Aruga 1999) (Kono, 1997).The conversion function from an incident beam to an annular beam is shown by formula (1) and (2).

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

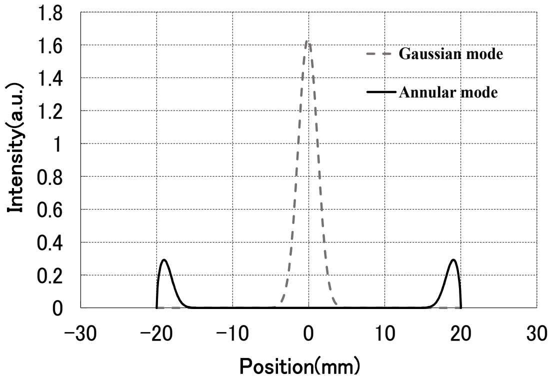
$$a(r)=\sqrt{\frac{R-r}{r}}\cdot g(R-r) \quad (2)$$

*g(r)* is an intensity function of Gaussian distribution, and *a(r)* is an intensity function of an annular beam. *h* is a distance from the center to the point of beam radius, where the intensity becomes $1/e^2$ of the center value. *R* is the external radius of the annular beam decided by the interval between Axicon prisms, and *r* is the internal radius of the annular beam decided by width of *g(r)*. The radius of the incident beam could be expressed as *R-r*.

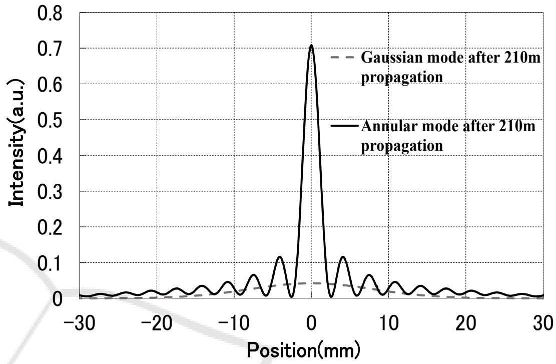
Using Fresnel diffraction equation (3), we calculated propagation characteristics of the Gaussian and the annular beam in air.

$$u(x_0,y_0)=\frac{A}{i\lambda L}\iint f(x,y)\exp(ikl)dxdy \quad (3)$$

$u(x_0, y_0)$ is a diffractive beam function, $f(x, y)$ is an amplitude function of the incident beam, $\lambda$ is a wavelength, $L$ is a propagation distance, $k$ is a wave number, and $l$ is the distance from the incident point $(x_0, y_0)$ to the target point $(x, y)$. Figure 1 (a) shows the intensities of the Gaussian beam and the annular beam calculated by formula (1) and (2). They have the same total light intensity. Figure 1 (b) shows the intensity of the Gaussian beam and the annular beam after they propagated at 210m in air. Although the Gaussian beam diffused because of diffraction, the annular beam changed its wave shape into the non-diffractive beam after its propagation. As the width of the main peak of the non-diffractive beam becomes




(a) Incident Gaussian and annular beam.




(b) Gaussian and transformed non-diffractive beam after the propagation.

Figure 1: Propagation characteristics of Gaussian and annular beam. (*h*=1.8mm, *R*=20mm.).

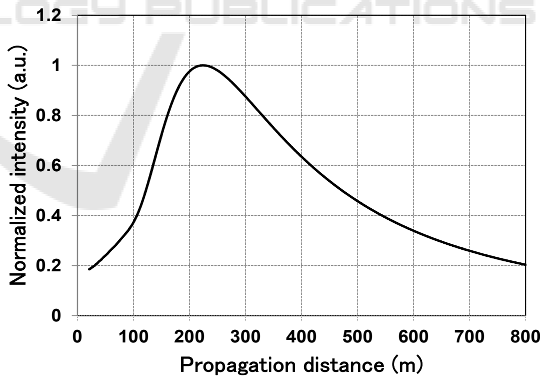



Figure 2: Center intensity of non-diffractive beam against propagation distance in air. (*h*=1.8mm, *R*=20mm.).

narrow, it is an advantage of high resolution for optical sensing. Figure 2 shows variation of the center intensity of the non-diffractive beam against the propagation distance in air. The center intensity hadthe maximum when the annular beam propagated at the distance of 210m, where the non-diffractive beam was transformed completely. This distance would be changed when the annular beam had the other diameter or the thickness of the ring.

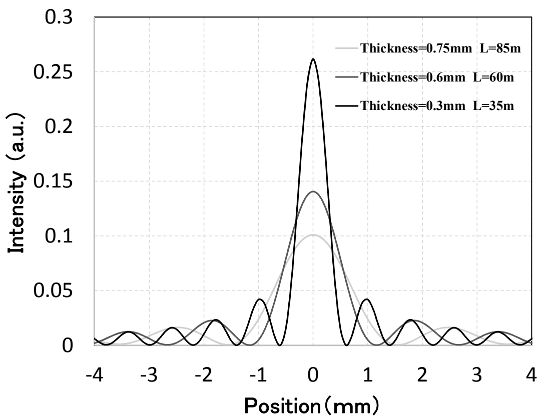



Figure 3: Variation of the non-diffractive beam with different thickness ($R$=12mm).

Figure 3 shows the maximum intensity of the non-diffractive beam while the annular beam had the same diameter and the different ring thickness. The transformed beam had the higher center intensity with a main peak when the thickness of the annular beam was narrower, but the distance where the non-diffractive beam was obtained became short when the thickness of annular beam became narrow. The width of the main peak of the non-diffractive beam was about twice of the ring thickness of the incident annular beam.

Figure 4 shows the variation of the intensity of the non-diffractive beam while the annular beam had the same ring thickness and the different diameters. All the main peaks of the non-diffractive beams had the same width. The high center intensity was obtained when the diameter of the annular beam was small. The distance where the non-diffractive beam was maximum became short due to the decrease of the diameter of the annular beam.

## 2.2 Propagation in Random Media

At the previous study, non-diffractive effect was confirmed in the diluted milk solution at the concentration of less than 1% when the annular beam propagated at 20cm. We considered the annular beam remained its coherency after it scattered several times in the forward direction with a narrow scattering angle, and converted into a non-diffractive beam.

When the multiple scattering occurred in random media, the incident light will change its propagation direction several times when it hits the scatters. The transport mean free path is defined as the average distance light travelled between successive impacts. It can be written as formula (4),

$$L = \frac{1}{n(1-g)C_{sca}} \tag{4}$$

$n$ is the number of scattering particles in unit volume, $g$ is the anisotropy parameter, and $C_{sca}$ is the scattering cross-section. According to Mie theory, the

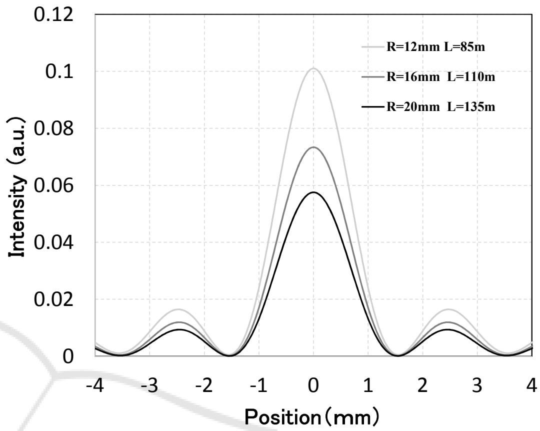



Figure 4: Variation of the non-diffractive beam with different Diameter (Thickness=0.75mm).

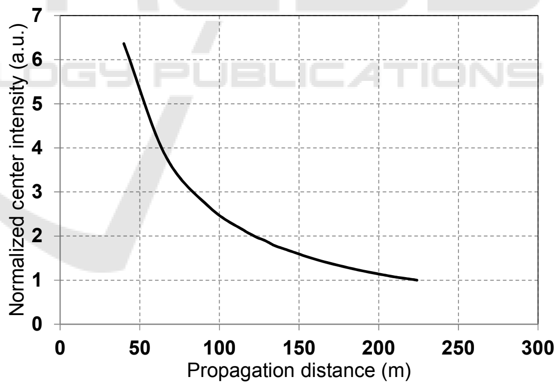



Figure 5: Center intensity of non-diffractive beam against the propagation distance in air (with lens effect, Thickness=3mm, $R$=20mm.).

transport mean free path can be expressed by the concentration of the random media $R_m$, as formula (5).

$$L = \frac{4.292}{R_m} \times 10^{-4} \tag{5}$$

In our experiment, the transport mean free path would be about 5cm when the concentration was 0.8%. When the length of the random media was set as 20cm, 4 or 5 times scattering would be occured according to transport mean free path of 5cm. So the maximum total optical path would become about 1m (20cm*4 or 5) when the scattered light travelled to the forward direction. For the annular beam with diameter of 40mm, the non-diffractive effect is originally emerged after the propagation of a few hundred meters in air. We considered that scattering particles act as a lens in the random media. The light spread its travel direction by keeping its polarization. This lens effect is depended on number of scattering particles in unit volume of the random media.

Figure 5 shows the center intensity variation of non-diffractive beam in air when we set a lens to made annular beam focus at each distance. Center intensity was high when it focus in a short distance.

# 3 EXPERIMENT

## 3.1 Measurement System

Figure 6 and Table 1 shows the structure of measurement system and the specification of the optical elements in our measurement system, respectively.

A high power DPSS laser was introduced, and the pulsed beam was used to increase the efficiency of non-diffractive effect in random media. An ND filter was used to adjust the optical intensity. A beam expander and a pair of axicon prisms helped to control the thickness and the diameter of the annular beam. To change the propagation distance, three sizes of media tanks were used. The processed milk with 1.8% fat was chosen as the random media. The fat particles in the milk have the scattering coefficient similar with human tissue, so that we can model the human tissue by adjusting the concentration of the milk. The absorption in the milk solution is very weak, which can be ignored to compare with the effect of scattering. The combination of a collimate lens and a multiple mode optical fiber made a narrow view angle of 5.5mrad, which helped to catch up the forward scattering light, and this combination was set on a mechanical stage controlled by PC with the resolution of 0.1mm at horizontal-axis. A photo multiplier tube (PMT) was used as a detector to obtain the weak optical signal through the random media, and a sampling oscilloscope was used to monitor the pulsed electric signal from PMT.

Table 1: Specification of the experiment system.

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

## 3.2 Result

In the three sets of experiments, the milk concentration

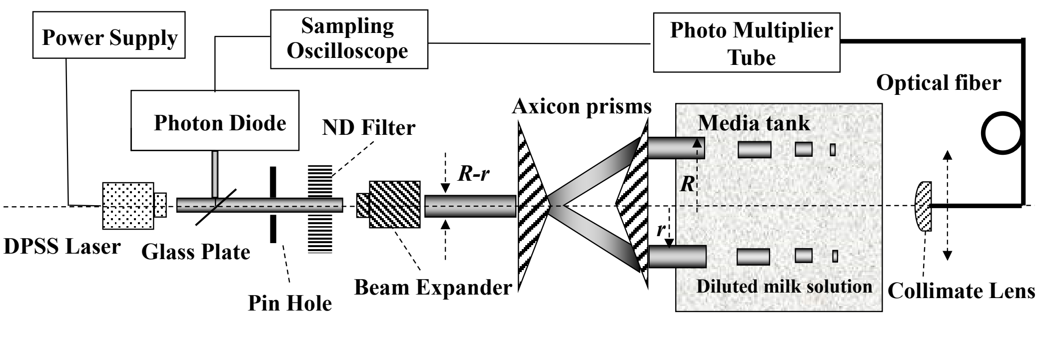



Figure 6: The experiment system to analyze light propagation characteristics in random media.

was set as 0.1%~1.0% in steps of 0.1%. The observed waveforms were combined two parts. The first part was an isotropic intensity distribution caused by multiple scattering. This part covered in all of the scattering angle. Another part was non-diffractive effect as a small peak at the center on the waveform. The width of the center peak is about 6mm. For comparison of the waveform, first, the intensity of non-diffractive beam at 20mm away from center was normalized as 1. The non-diffractive effect was evaluated by the intensity ratio between the center intensity and the intensity at 3mm away from center, where was the foot of the peak of non-diffractive beam.

### 3.2.1 Propagation Distance

In the first experiment, a propagation distance was set as 10, 20 and 30cm by using the different media tanks. Figure 7 shows the different non-diffractive beams converted by the annular beams with the same ring thickness, the diameter, and the different propagation distances. The waveform of 10cm and 20cm propagation were added 0.02 and 0.01 in intensities respectively, to facilitate visualization. These three non-diffractive beams at the different propagation distance obtained maximum in the concentration of 0.4%, 0.6% and 1.0%. Figure 8 shows the intensity ratio of the non-diffractive effect when the isotropic intensity was subtracted. The center intensity ratios were 1.8%, 1.2% and 0.85% at the propagation distance of 10, 20 and 30cm, respectively. As we considered the scattering particles act as lens, this result shows the non-diffractive beam has a high intensity in short distance propagation with high concentration. It has the same tendency with the calculated result shown in Fig. 5, the non-diffractive beam had a high intensity in a short distance when a lens effect with short focal distance was considered.

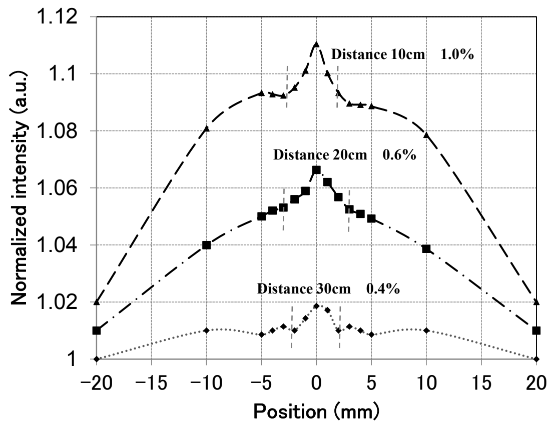



Figure 7: Scattering wave fronts of annular beam with different distance (Diameter: 40mm, Thickness: 3mm).

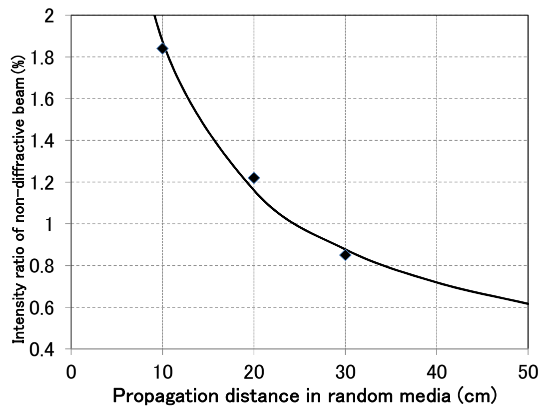



Figure 8: Intensity ratio of non-diffractive beam against propagation distance in random media.

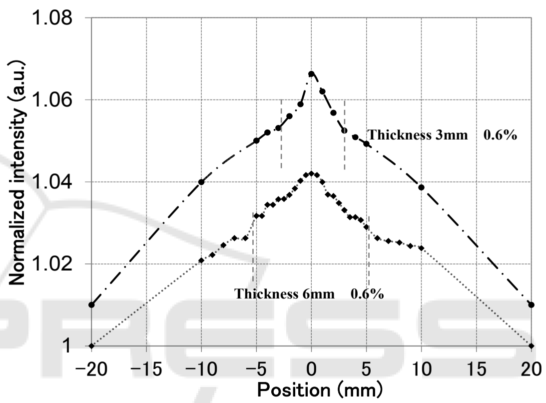



Figure 9: Scattering waveforms of annular beam with different thickness (Diameter: 40mm; Distance: 20cm).

### 3.2.2 Annular Beam Thickness

As the next experiment, the ring thickness of annular beam was set as 3 and 6mm. Figure 9 shows the difference between two non-diffractive beams converted by the annular beams with the same diameter and the same propagation distance but with the different ring thickness. The waveform intensity obtained by the annular beam of ring thickness of 3mm has been added 0.01 for visualization. In the case of the annular thickness of 3mm, the width of the main peak of the obtained waveform is narrower than that of the case of 6mm. Both widths of the main peaks are about twice of the thickness of the incident annular beams. The two non-diffractive beams were transformed in the concentration of 0.6%. The center intensities ratios of the non-diffractive beams are 1.2% and 1.0%. This result shows the annular beam with the narrow thickness would generate a narrow width and a high intensity of the non-diffractive beam in random media. These variation had agreement with the numerical calculation in Fig.3.

### 3.2.3 Annular Beam Diameter

In the third experiment, annular beam diameter was set as 24, 32 and 40mm, respectively. Figure 10 shows the non-diffractive beams converted by the annular beams with the same ring thickness and the same propagation distance but with the different diameter. The waveform converted by annular beams with the diameter of 24mm and 32mm were added 0.02 and 0.01 in intensity for visualization. The center intensities were 3.7%, 2.9% and 1.2% higher than the intensity around away from center, and the widths of the main peaks are 5~6mm. Figure 11 shows the intensity ratio between the non-diffractive beam and the main peaks widths against the diameter of the annular beam. They show that the non-diffractive beam with the high intensity would be transformed at the low concentration of the random media when the annular beam diameter is small, but the width of the main peak was kept in around 5~6mm when the ring thickness of the annular beam was 3mm. Comparing to the numerical calculation, the width of main peak was considered to be twice of the annular beam thickness. These results were coincided with the theory numerical calculation in Fig.4.

# 4 CONCLUSIONS

In this study, we considered that the propagation characteristics of the annular beam in air was associated with its experimental results in the random media. They showed agreement in non-diffractive beam propagation characteristics. For the same incident annular beam, the random media at a short propagation distance with a high concentration could generate a high intensity non-diffractive beam. And

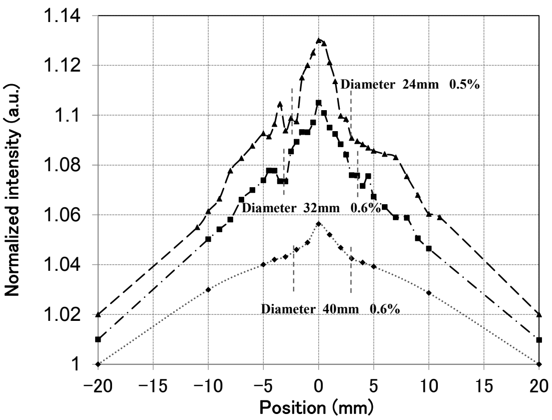



Figure 10: Scattering waveforms of annular beam with different diameters (Thickness: 3mm; Distance: 20cm).

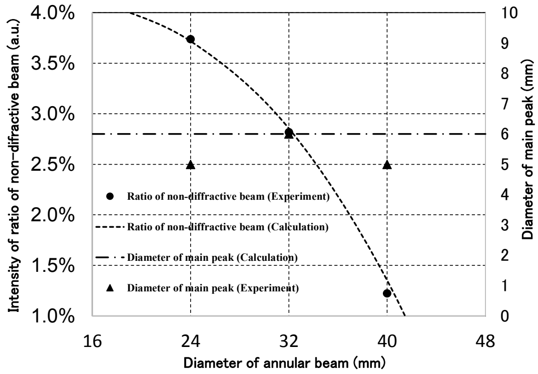



Figure 11: Variation of intensity ratio and main peak width of non-diffractive beam. (Thickness: 3mm; Distance: 20cm).

for the same random media, the annular beam with the narrow thickness or the small diameter could generate a high intensity non-diffractive beam. The width of the non- diffractive beam would be twice of the thickness of the annular beam. And the non-diffractive effect was generated in the random media and had the same tendency with its propagation in air. The results of the calculation and the experiment were coincide with each other.

In future, further analysis of annular beam propagation in random media should be explained by diffusion and scattering theory, and the mathematical relationship between non-diffractive beam waveform and parameters such as the ring thickness or the diameter of the annular beam should be cleared up.

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