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2017

Perinchery, S. M., Shinde, A., & Murukeshan, V. M. (2017). Imaging objects behind small obstacles using axicon lens. Proceedings of SPIE - International Conference on Optical and Photonics Engineering, 10449, 104490G-. doi:10.1117/12.2269563

<https://hdl.handle.net/10356/106842>

<https://doi.org/10.1117/12.2269563>

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Imaging objects behind small obstacles using axicon lens

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ABSTRACT

Axicon lenses are conical prisms, which are known to focus a light source to a line comprising of multiple points along the optical axis. In this study, we analyze the potential of axicon lenses to view, image and record the object behind opaque obstacles in free space. The advantage of an axicon lens over a regular lens is demonstrated experimentally. Parameters such as obstacle size, object and the obstacle position in the context of imaging behind obstacles are tested using Zemax optical simulation. This proposed concept can be easily adapted to most of the optical imaging methods and microscopy modalities.

Keywords: Axicon lens, imaging behind obstacle, Bessel beam, cloaking, optical imaging

1. INTRODUCTION

Biomedical engineering and optics play a very vital role in the areas such as imaging[1-3] and translational medicine[2, 4-10]. Over the years there has been a lot of advancement specifically in biomedical optics, lasers and imaging[11]. However, these techniques are limited in its potential when the sample or test target needs to be imaged behind opaque objects.

Macleod in the mid 1950's introduced an optical element called axicon lens which can produce line focus[12]. Axicon lens is also known as conical lens or rotational symmetric prism. The inherent shape of axicon lens is known to contribute many special optical properties. For instance, axicon lens has been one of the primarily used optical element to demonstrate enhanced depth of field by self-reconstruction property (Bessel beam) of light beams. Based on this self reconstruction phenomenon, specifically in microscopy axicon lens have been principally employed to image deeper into tissue media[13, 14]. Axicon lens are known to efficiently collimate conical wave fronts of light beams[15]. In fact, there are reports of using axicon lens specifically as an optical element for collecting light[16]. A recent article by Zheng *et al* has also reported the potential of axicon lens to enable fluorescence volume imaging[17]. These optical properties of axicon lens made it applicable in wide range of studies such as interferometry, antennas, tweezing[18], surgery[19] wavefront sensor[20].

In this article, we demonstrate image behind small obstacles blocking the field of view (FOV) during imaging in free space using axicon lens. We have performed optical ray tracing using Zemax in order to address the advantages of axicon lens over the normal lens (bi-convex) while imaging behind small opaque obstacle in real time. As a proof of concept, we further demonstrated imaging behind surgical needle blocking FOV of a camera.

2. RESULTS

2.1 Extended depth of field (DOF) of axicon lens

A comparison of ray diagram using Zemax simulation of conventional convex lens and an axicon lens is shown in Figure 1. As shown in Figure 1, it is evident from the simulation that axicon lens has extended depth of field compared to the conventional convex lens which has a fixed focus point. Figure 1b shows that an axicon has the property to transform a point source to a range of points along the imaging optical axis.

Figure 1. Illustration of ray trace of conventional convex lens and axicon lens (a) Convex lens (b) Axicon lens. Note the convex lens focal length is 125 mm.

Figure 2. Image captured behind an opaque object for convex lens at different obstacle thickness and focus depths. (a) Ray diagram and detector view for biconvex lens separated by 2 mm from an obstacle. Note: a1, a2 and a3 are detector view for obstacle thickness 0.01, 0.05 and 0.2 mm respectively (b) Ray diagram and detector view for biconvex lens separated by 150 mm from an obstacle. Note: b1, b2 and b3 are detector view for obstacle thickness 0.01, 0.05 and 0.2 mm respectively. 1 is point source illumination, 2 is a rectangular and 3 is a biconvex lens (25 mm diameter).

2.2 Imaging behind an opaque rectangular obstacle using conventional lens

Figure 2 shows the optical simulation of imaging behind a rectangular opaque obstacle (100 % absorbing medium) using conventional convex lens (LA1986 - N-BK7 Plano-Convex Lens, $f = 125$ mm, Thorlabs), which was placed within the FOV of the detector. In this optical simulation study, we have considered two separate position (distance) of convex lens with respect to the rectangular obstacle and three different thickness for the obstacle. In the initial configuration (Figure 2a), the rectangular obstacle is placed 0.5 mm from the point source and 2 mm from the convex lens. Imaging behind the rectangular obstacle was simulated for three different obstacle thickness 0.01 mm, 0.05 mm and 0.2 mm. The simulation of the image formation by convex lens is projected in the detector screen, as shown in Figure 2 (a1, a2 & a3) respectively. For the second configuration (Figure 2b), the rectangular obstacle is placed 0.5 mm from the point source and 150 mm from the convex lens. Here we considered same three different thickness 0.01 mm, 0.05 mm and 0.2 mm for the obstacle. The image formation in the detector screen is shown in Figure 2 (b1, b2 & b3) respectively. From the both the convex lens configuration results (Figure 2), it is evident that detector view is clearly blocked by the obstacle at all the settings.

Figure 3. Image captured behind an opaque object for axicon lens at different obstacle thickness and focus depths. (a) Ray diagram and detector view for axicon lens separated by 2 mm from an obstacle. Note: a1, a2 and a3 are detector view for obstacle thickness 0.01, 0.05 and 0.2 mm respectively (b) Ray diagram and detector view for axicon lens placed 150 mm from an obstacle. Note: b1, b2 and b3 are detector view for obstacle thickness 0.01, 0.05 and 0.2 mm respectively. 1 is point source illumination, 2 is a rectangular obstacle and 3 is a axicon lens (25 mm diameter).

2.3 Imaging behind an opaque rectangular obstacle using axicon lens

Figure 3 shows the optical simulation of imaging behind a rectangular opaque obstacle (100 % absorbing medium) using axicon lens (Conical lens, Apex angle, 170° , Material: UVFS, Thorlabs), which was placed within the FOV of the detector. Similar to the convex lens configuration, in this optical simulation study we have considered two separate position (distance) of axicon lens with respect to the rectangular obstacle and three different thickness for the obstacle. In the initial configuration (Figure 3a), the rectangular obstacle is placed 0.5 mm from the point source and 2 mm from the axicon lens. Imaging behind the rectangular obstacle was simulated for three different obstacle thickness 0.01 mm, 0.05 mm and 0.2 mm. The simulation of the image formation by axicon lens is projected in the detector screen, as shown in Figure 3 (a1, a2 & a3) respectively.

For the second configuration (Figure 3b), the rectangular obstacle is placed 0.5 mm from the point source and 150 mm from the axicon lens. Here we considered same three different obstacle thickness 0.01 mm, 0.05 mm and 0.2 mm. The image formation in the detector screen is shown in Figure 3 (b1, b2 & b3) respectively. It can be observed from Figure 3a3 and Figure 3b3, the image is not formed behind the detector screen above thickness of 0.2 mm obstacle size. However as compared to convex lens, axicon lens with an extended focal depth can image around opaque obstacle below 0.2 mm thickness at different imaging planes, even when the axicon lens is kept close to the obstacle. These results clearly validate the advantage of using an axicon lens with extended focal depth to image behind small objects.

2.4 Proof of concept

Figure 4. Illustration of optical setup using axicon lens.

For experimentally validating the concept of imaging behind small objects using axicon lens, a simple optical configuration was setup in white light reflection mode (Figure 4). In Figure 4 axicon lens was used as both the illumination and imaging arm. For illumination, white light FA-150EN Fiber Illuminator (Correct Shimadzu, Japan) is used. Plano-Convex Axicon lens (Conical lens, Apex angle, 170° , Material: UVFS, Thorlabs) have been used. ITL200, Thorlabs was the tube lens used before the camera (Andor iXon3 EMCCD). The axicon lens and tube lens was separated by 8 cm (fixed position). The fluorescence emission is filtered by an emission filter and imaged by the camera. All the images were captured by Andor iXon3 EMCCD camera. The camera was positioned at the focus position of the tube lens (14.8 cm). A surgical needle having a thickness of 0.35 mm was used as the obstacle in the field of view.

Figure 5 illustrates the ability of using large depth of focus of axicon to image sample behind surgical needle (obstacle) using white light in real time. It is evident from the Figure 5, that irrespective of the position of sample (object to be imaged) or needle (obstacle), it is still possible to image the sample clearly behind the needle. This method allows the precise positioning of the needle on the sample. In this configuration, slight shadow can be observed when the sample is very close to the object. However, it doesn't affect the imaging significantly Figure 5c.

3 DISCUSSION

Optical cloaking and invisibility research has taken a giant leap in the recent past and there have been many reported articles in this area [21-24]. However, the proposed concepts and imaging is quite different and novel

with significant advantages. The proposed theories for cloaking devices uses transformation optics and conformal mapping[25, 26]. These methods are realized mostly using artificial electric and magnetic materials (metamaterials). Recently, there is also a growing interest for carpet cloak technique, which compresses an object in only one direction into a conducting sheet[27]. Moreover there are also other approaches such as quasi conformal mapping which uses non resonant elements (dielectric material) to enable cloaking[28]. However, fundamentally all these methods bend and stretch the light. This also involves changing environment of object to be cloaked.

In our study, we are not manipulating (bending or stretching) the optical rays or neither changing the environment of the obstacle and thus our technique differ from the optical cloaking methods. In contrast to optical cloaking, we have used extended depth of focus of the axicon (Figure 1), and demonstrated that it is possible to image the sample at a different focal plane, irrespective of the position of obstacle or sample position. Therefore, during imaging the sample, the obstacle will be in a defocused plane making it invisible which allows the sample to be imaged behind the opaque obstacle. This imaging concept is initially tested by optical simulation in this study by using Zemax. A comparison in the ability of conventional lens and axicon lens as an imaging arm to image behind objects is shown in Figure 2 and Figure 3. It is evident from the optical simulation results that axicon lens as compared to convex lens is able to perform imaging behind small obstacle.

Figure 5. Illustrate the image behind surgical needle (a) axicon – object separated by 7.5 cm, object – needle separated by 1 cm (b) axicon – object separated by 3.5 cm, object – needle separated by 3 mm. (c) axicon – object distance is 1 cm, needle inserted to object. Please note image is shown in inverted mode for better visibility behind needle area.

Self-healing properties is an important property of Bessel beam. Axicon lenses are known to be used for generating Bessel beam. It has been demonstrated by earlier study by Bouchal *et al.*, that an ideal nondiffracting beam can exactly reconstruct its initial intensity profile behind an obstacle of arbitrary form and size[4]. However, it is important to note that in this study we are illuminating and imaging through the same axicon lens (Figure 5). This means either the reflected light from the object is imaged by the camera through the axicon lens around the obstacle. The reflected light from the object does not have self-healing properties. Only the excitation beam through axicon can have the property of nondiffracting beam. This enhanced depth of field of axicon comes at the cost of degraded image quality. But we are still able to visualize the features behind the needle as shown in (Figure 5).

4 CONCLUSION

In this report, we have demonstrated using optical simulation and experimental evaluation, the potential of axicon lens to image behind small opaque obstacle. The large depth of field of axicon lens as compared to conventional lens enable it to image behind small obstacle at different imaging planes. It is envisaged that this simple and cost effective optical configuration can offer a wide range of potential applications in a variety of fields such as diagnostic imaging, theranostics, microsurgery, to name a few.

ACKNOWLEDGMENT

The authors acknowledge the financial support received from Ministry of Education (MOE-AcRF RG162/15) and MOE-AcRF RG98/14.

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