Low cost adjustable axicon

R. DE SAINT-DENIS*, E. CAGNIOT, P. LEPRINCE, M. FROMAGER, K. AIT-AMEUR
Centre de Recherche sur les Ions, les Matériaux et la Photonique, UMR 6252, CNRS-ENSICAEN-CEA-UCBN, CIMAP-ENSICAEN,6 BD Maréchal Juin, F14050 Caen, France

In this paper we propose a very simple device that acts as an adjustable axicon: it simply consists in a 0.25mm thick silicon wafer deformed in its centre by a small ball. Beam shapings comparable to those usually generated by axicon are observed: Bessel beams and dark hollow beams, both very useful in cold atoms manipulation.

(Received August 1, 2008; accepted after revision September 26, 2008)

Keywords: Axicon, Hollow beam, Deformable mirror, Bessel beam, Dark hollow beam

1. Introduction

Axicon is a generic name for optic devices able to produce a longitudinal focus line rather than a focus point. This can be achieved by generating a nondiffracting beam since its radial intensity (including on-axis intensity) remains the same along propagation axis. In the case of circular cylindrical coordinates these beams are called Bessel beams since their radial intensity profiles are given by Bessel functions [1-2]. These works have demonstrated that a thin annular slit illuminated by a laser beam generates in the focal plane of a lens a beam whose intensity profile is well described by Bessel functions. Even if this solution is mathematically exact and can be relatively easily implemented [3], it implies dramatic losses since it deals with amplitude masks. Naturally many other techniques have been developed to circumvent this drawback: see for example Ref. [4] for holographic techniques, axicon can be composed of several successive optics [5], aberrating lenses have also been successfully used [6] or in [7] a gradient index axicon is generated. This list is not exhaustive and each quoted paper refers to other ways to build an axicon but the most common and oldest one is the refractive cone initially introduced by McLeod [8]. In that case, the optical element is a cone of transparent media that induces a linearly dependent phase shift to the incident beam phase front. The properties of this device have been intensively studied and used over years: see for instance Ref.[9] where high-order Bessel beams are generated sending high-order Laguerre-Gaussian beams on the conical lens or Ref.[10] that presents beam shapings of interest of Gaussian beams by axicon. Beam shaping capability is the reason why axicon has recently regained interest since it is also able to produce a dark hollow beam very useful in optical trapping and guiding of ultra cold atoms [11-12]. This kind of axicon is quite difficult to produce, since a linear retardation has to be etched or machined in a transparent media, it follows that conical axicon is quite expensive. Moreover, a perfect vertex is difficult to achieve leading to defects in the desired intensity profiles [13].

Our very simple system proposes to reproduce the linear phase shift just by pushing in its centre a circular reflecting deformable surface. From this point of view, our axicon can be regarded as a deformable mirror with a single centred actuator. This kind of simple deformable mirrors has already been studied but, to the best of our knowledge, never in the field of laser beam tailoring. Many weak number actuators mirrors have been designed to correct thermal lens effects induced in laser materials [14-17], and some others have already been developed in order to correct even higher order aberrations [18]. In imaging field these elementary deformable surfaces can correct spherical aberrations encountered when a beam is deeply focused on biological tissues [19], or in deepest layer of data storage disk [20-21].

Our aim is quite different as we intend to show that our deformable mirror behaves just like a conical axicon. That is why after having presented the global geometry of our system, we have monitored the shape of the deformed surface using a Shack-Hartman wave-front sensor. Then we present the beam shapings that our device is able to produce and we demonstrate that they are comparable to ones previously observed in literature. The main advantage in addition of a low cost is that the proposed device is completely adjustable: one can for instance rapidly switch from a Bessel beam to a dark hollow beam.

2. Experimental set up

Before to proceed, let us recall again the basic idea that is quite simple: considering a circular reflecting surface, one can easily imagine that a punctual actuator pushing in the middle will generate a conical shape. Due to this geometry, one can expect this optical device to behave like an axicon. Figure 1 shows the scheme of the deformable axicon: the deformable surface is a 2 inches diameter, 0.25mm thick silicon wafer. This polished surface acts as a mirror which reflectivity can be drastically improved if a metallic coating is deposed. The flat mirror is fixed at the outer edge by a mount and a retaining ring. The thickness of the interface between the mirror and its mount is important since it partially determines the shape of the induced distortion. Moreover, this quantity dramatically changes wafer rigidity and can early lead to failure even for small deformations. Before breaking of the wafer for strong deformations, a defect is definitely written in the whole crystalline structure involving thus a poor quality beam shaping.

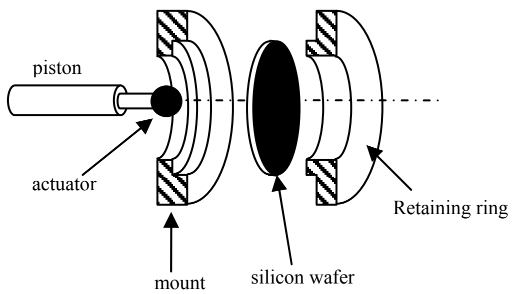

Fig. 1. Adjustable axicon geometry.

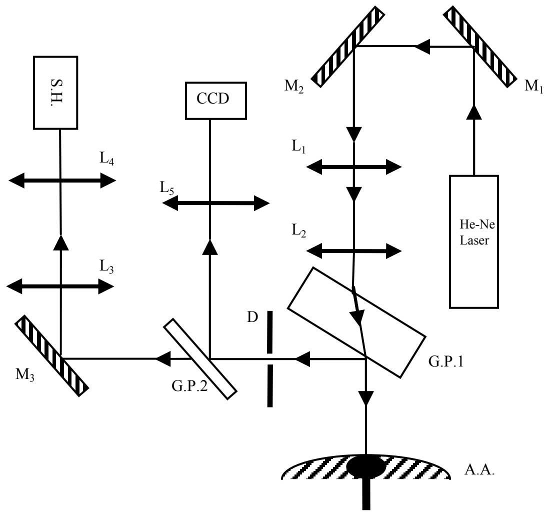

Fig. 2. Experimental set up: A.A is the adjustable axicon, D is diaphragm, M_i are mirrors, L_i lenses, G.P. glass plates, S.H. a Sack-Hartmann wave-front sensor.

In order to ensure a punctual contact between the single actuator and the surface, we have chosen a small metallic ball as actuator. Its position is adjusted with a standard translation stage that can of course be replaced by any electro-mechanical device like piezo-electric actuator in order to allow quick shift between different induced deformations. The experiments have first been carried out with a standard 2 inches mount provided by THORLABS and an independent actuator fixed on an X-Y-Z translation but we suggest building a one piece device to definitely set the centring of the actuator and for sake of global rigidity of the device. Actually centring and alignment is quite sensitive and rapidly leads to distorted beam shapings comparable to those observed in the case of axicon under oblique illumination [22].

Knowing mechanical properties of silicon, the shape of the mount and the position of the metallic ball, one could derive formulas giving the shape of the deformed surface [14,15,17]. In our case, we have chosen to monitor it experimentally using a Shack-Hartmann wave-front sensor. Figure 2 sketches the experimental scheme used both for recording wave-fronts and beam shaping. The source is a He-Ne laser with M² factor close to 1, and a beam waist radius of 325 μm. The size of the incident beam on the axicon is adjusted with a telescope composed of lenses L_1 and L_2. A large plate of glass is used to separate incident and reflected beams; a diaphragm is then set in order to stop one of the two reflections of the glass sheet. Then the beam can be sent on a CCD camera in order to monitor its intensity profile: lens L_5 is necessary since the induced axicon is divergent. A telescope (L_3, L_4) can also image the surface of the mirror on a Shack-Hartman Wave front sensor (HASO 32 provided by IMAGINE OPTIC).

3. Results

Fig. 3 shows the shape of the induced axicon for increasing deformations. We can note that the recorded profiles do not present any vertex and that axicon shape is mainly due to off-centre part of the device for the strongest deformations. In fact, for smallest deformations wave-front sensor records aberrations that correspond mainly to beam defocusing. This point is in a good agreement with results presented for thermal lens compensation by deformable mirrors [14-17]. Thus, for small deformations, our mirror acts as a divergent lens, but the more we deform the more high-order aberrations appear leading to a surface that is no longer quadratic except in the middle. Actually, if the incident beam has a too small radius, even for strong deformations, it only undergoes defocusing. But thanks to telescope (L_1,L_2), the size of the incident beam can be increased and beam shapings typically obtained with standard conical axicon are observed.

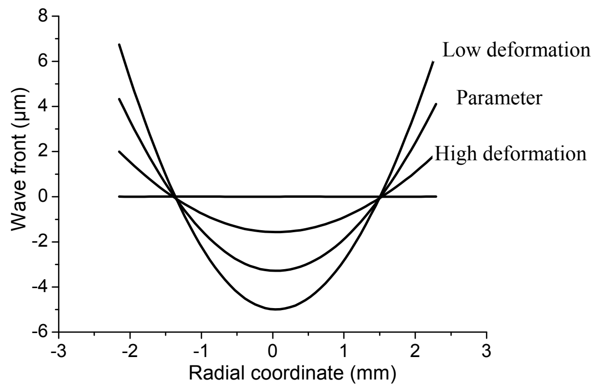

Fig.3. Mirror shape for increasing deformation.

In a general case, a diffractive optical element is able to perform a beam tailoring in a given plane but the induced beam profile evolves along propagation axis: in most experiments, one tries to extend the area of the desired pattern [23]. In the case of axicons, beam shapings of interest spread along optical axis in a given order. This order can be roughly determined using geometrical optic hypothesis [13].

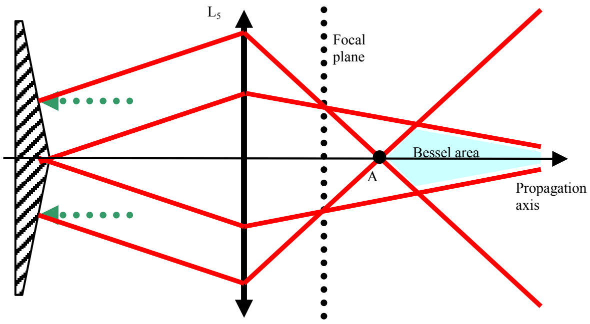

Fig.4. Prediction of beam shaping by geometrical optics. Dashed arrows represent the incident beam.

Fig. 4 presents the expected sequence of patterns after the axicon. The incident light is reflected on the conical mirror and then diverges, the light is then focused by lens L_5 set down at a distance *l* from the mirror. After the lens, a wide annular beam becomes thinner and thinner and produces a dark-hollow beam around the focal plane of the lens. This one expands until point A where the Bessel area begins, i.e. the area where the beam has a Bessel profile. Our device is able to produce this succession of patterns in the expected areas and the diffraction has to be taken into account to predict the real shapes. These calculations have been performed but are presented elsewhere: actually, the monitored wave-front gives us the shape of the deformable mirror which introduced in a model is able to explain any experimental observations of this work.

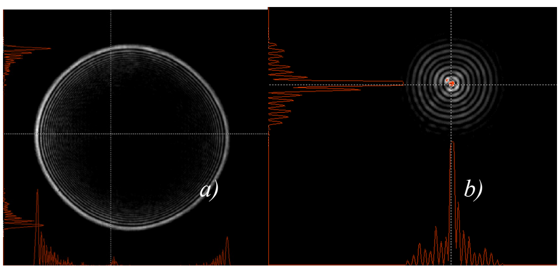

Fig. 5: a) Dark hollow beam and b) Bessel beam.

Fig. 5 shows two generated intensity profiles of interest: a) a dark hollow beam and b) a Bessel beam. Note that figure 5 a) does not exhibit a perfect dark hollow beam but presents a given number of secondary rings that are perfectly predictable taking into account bluntness of the vertex [13]. This drawback is even well known for refractive axicon since it is usual to add a stop in order to limit the formation of this kind of rings. Note that in our case, disappearing of these rings can be obtained by closing a simple diaphragm set between L_5 and the mirror.

Naturally, Fig. 5 b) looks like Bessel beam but in order to judge quality of the transformation, it is usual to plot the curve that gives evolution of on-axis intensity which is shown in figure 6. One can note that on-axis intensity arises from zero (annular beam) and then oscillates around a constant value; in this area, a Bessel beam is observed. Then, on-axis intensity decreases implying a broadening of the central peak and a progressive disappearing of the annulus. The length of the Bessel area can be adjusted from few centimetres to few meters depending on chosen focal length of lens L_5 for a given deformation of the silicon wafer.

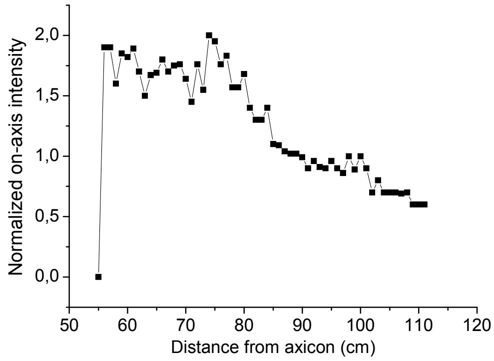

Fig. 6. On-axis intensity evolution.

Nevertheless, one can note that the longer this area, the more the on-axis intensity oscillates. So a compromise has to be found since limitation of the oscillations also depends on how strong the deformation is, i.e. how well the conical shape is achieved. But in this case, the optical device is very divergent, and has to be coupled with a strong convergent lens if one intends to observe beam shapings not so far away from the axicon. Once again on-axis intensity oscillations are well known and are well predicted by the Fresnel integral [24-25]. In the latest references, note that a comparison is given between phase retardation introduced by perfect focusers and computed generalized axicons. As in our case, it is shown that central part of the phase profile only corresponds to focus.

4. Conclusions

We have demonstrated in this paper that we are able to build a low cost optical device able to produce beam shapings usually performed by conical axicons: Bessel beams and dark hollow beams both very useful in cold atoms trapping and guiding. Note that in our case a single optical element can be used since our axicon is adjustable i.e. it can rapidly switch from one intensity profile to another in a given plane. Quality of our beam transformation is comparable to those observed in literature for blunt conical axicons or aberrated lenses. Moreover, this works is only a feasibility study and this device can naturally be easily improved modifying the deformable surface material, choosing another geometry for the mount, one could achieve better quality in beam tailoring.

As a conclusion, our device presents the advantages to be adjustable and low cost. Nevertheless, one have to pay attention to geometrical aspects: i) the incident beam has to be wide enough not to see only central part of axicon that only introduces defocusing, ii) one have to choose an adapted convergent lens after the deformable mirror since it acts as a divergent axicon.

References

[1] J. Durnin, J.Opt.Soc.Am A **4,** 651 (1987).
[2] J. Durnin, J. J. Miceli, J. H. Eberly, Phys.Rev.Lett. **58,** 1499 (1987).
[3] M. Fortin, M. Piché, Ermanno Borra, Optics Express, **12**, 5887 (2004).
[4] C. Lopez-Mariscal J.C.Gutiérrez-Vega, Am. J. Phys. **1**, 36 (2007).
[5] M. Honkanen, J. Turunen, Optics Communications **154**, 368 (1998).
[6] R. M. Herman, T. A.Wiggins, J. Opt. Soc. Am. A **8**, 932 (1991).
[7] D. J. Fischer, C. J. Harkrider, D. T. Moore, Applied Optics, **39**, 2687 (2000).
[8] J. H. McLeod, J. Opt. Soc. Am, **44**, 592 (1954).
[9] J. Arlt, K. Dholakia, Optics Communications **177**, 297 (2000).
[10] K. Ait-Ameur, Journal of modern optics, **46**, 1537 (1999).
[11] D. P. Rhodes, G. P. T .Lancaster, J. Livesey, D. McGloin, J.Artl and K.Dholakia, Optics Communications **214**, 247 (2002).
[12] I. Manek, Yu. B. Ovchinnikov, R. Grimm, Optics Communications **147**, 67 (1998).
[13] B. Dépret, P. Verkerk, D. Hennequin, Optics Communications **211** 31 (2002).
[14] J. Schwarz, M. Ramsey, I. Smith, D. Headley, J. Porter, Optics Communications **264,** 203 (2006).
[15] J. Schwarz, M. Ramsey, D. Headley, P. Rambo, I. Smith, J. Porter, Appl. Phys. B **82**, 275 (2006).
[16] J. Schwarz, M. Geissel, P. Rambo, J. Porter, D. Headley, M. Ramsey, Optics Express **14**, 10957 (2006).
[17] U. J. Greiner, H. H. Klingenberg, Optics Letters **19**, 1207 (1994).
[18] G. Figueira, J. Wemans, H. Pires, N. Lopes, L. Cardoso, Optics Express **15**, 5664 (2007).
[19] M. J. Booth, M. A. A. Neil, T. Wilson, Journal of microscopy, **192**, 90 (1998).
[20] M. J. Booth, M. Schwertner, T. Wilson, M. Nakano, Y. Kawata, M.Nakabayashi S.Miyata, Applied Physics letters, **88**, 0311109, (2006).
[21] M. Schwertner, M. J. Booth, T. Tanaka, T. Wilson S. Kawata, Optics communications, **263,**147 (2006).
[22] A. Thaning Z. Jaroszewicz, A. T. Friberg, Appl. Optics **43**, 9 (2003).
[23] R. de Saint Denis, N. Passilly, M. Laroche, T. Mohamed-Brahim, Kamel Aït-Ameur, Applied Optics **45**, 8136 (2006).
[24] J. Sochacki, A. Kolodziejczyk, Z. Jaroszewicz, S. Bara, Applied optics, **31**, 5326 (1992).
[25] J. Sochacki, A. Kolodziejczyk, Z. Jaroszewicz, S. Bara, Optics Letters, **17**, 7 (1992).

*Corresponding author: renaud.de_saint-denis@ensicaen.fr