# Photographing by means of a diffractive axicon

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## Abstract

*In this paper we demonstrate that the light diffracted by a simple compact disc can be used to generate photographic images of a certain kind. Being the compact disc an axicon that generate a diffraction-free beam, we show that the focalization position of an image depends of the wavelength of the diffracted light, what makes possible its use as a spectral filter.*

## Introduction

Since before the definition of the term "axicon", fifty years ago, the axicon had generated many discussions that were extremely important to our knowledge in optics [1]. According to the definition of H. McLeod, an axicon is an optical element that images a point into a line segment along the optical axis [2-4]. Traditionally, axicons are refractive and made of a glass cone.

The diffraction pattern produced by a compact disc (CD) under monochromatic illumination or by any kind of spiral structure was calculated by Ferrari [5], showing the formation of a diffraction-free beam [6] whose length depends of the wavelength, the period (spiral grooves) and the radial dimensions of the structure. Magalhães [7] made a special treatment, which can turn a problem easier to explain than in that with spiral treatment, it is the circular approach. In many cases this last one can explain images done with spiral structures, usually in dimensions much greater than the structure period.

Sochacki [8] made a comparison of the depth of focus between a computer-generated holographic uniform-intensity axicon and a holographic Fresnel lens also under monochromatic image.

In this paper we discuss the possibilities of application of a CD as an element that forms images under white light illumination.

## Experimental Setup

We employ an ordinary compact disc, but without the reflective layer, fixed to a support as showed in figure 1. We cover the center of the CD to avoid the light that passes through the parts without grooves. As object we use a string of a hundred small colorful light bulbs (of power 0.5W each) placed at the mean distance $\bar{Z}_o$ of the CD. To register the image was used the color negative film *Pro image 100 Kodak Professional* (F), placed inside a *Yashica FX-3 camera* without lens.

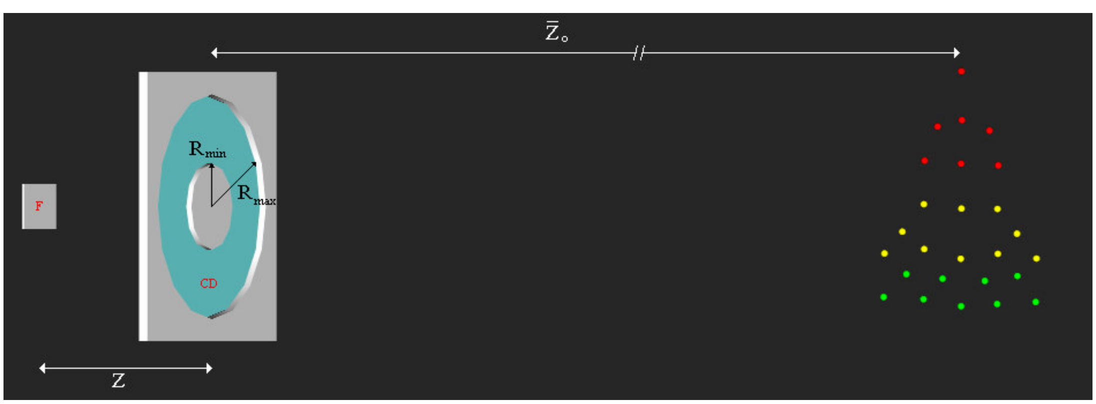



**Figure 1:** Experimental setup to the image caption. Z is the distance between the film and the CD. $\bar{Z}_o$ is the distance between the object and the CD. $R_{min}$ and $R_{max}$ are the minimum and maximum radius of the CD.

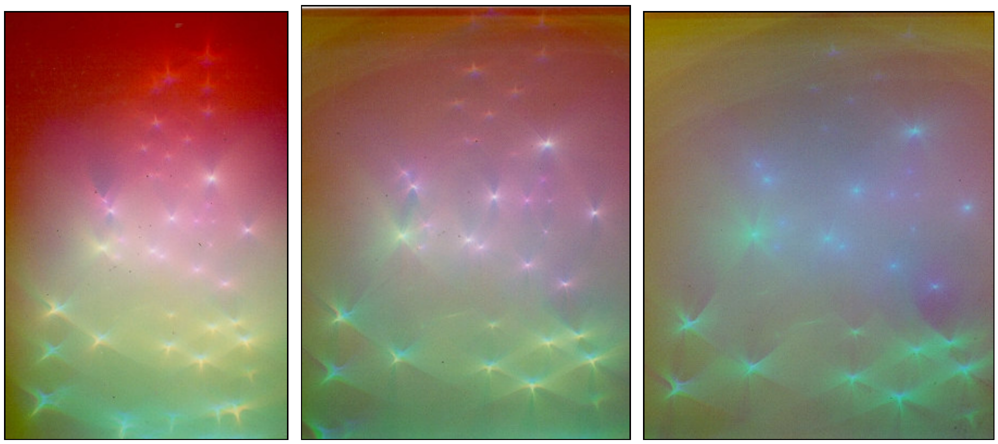
The lamps were at a mean distance $\overline{Z}_o$ of $(4.3 \pm 0.1)$ m and distributed by color along a height of 1m.

Dislocating the film with respect to the CD (changing Z) we could see the image formation of each color lamp set occurring inside a length interval. We registered the image of the set of lamps at different positions with exposure time of $(1.0 \pm 0.1)$ s.

The diffraction efficiency of the used compact disc was $(11.1 \pm 0.8)\%$

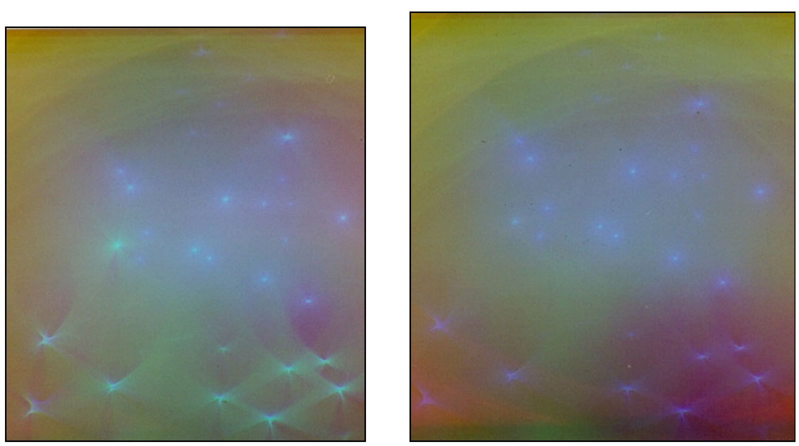
## Results and Discussions

We registered the image of the set of lamps in the film at different positions as shown in figures 2,3. The figures are in the same size ratio, but inverted (top-bottom) to facilitate the comparison with the real object schematized in figure 1.



(a) (b) (c)

**Figure 2:** Image of the lamps at Z distances: (a) $9.0 \pm 0.3$ cm, (b) $12.5 \pm 0.3$ cm and (c) $14.0 \pm 0.3$ cm.



(a) (b)

**Figure 3:** Image of the lamps at Z distances: (a) $16.0 \pm 0.3$ cm and (b) $16.5 \pm 0.3$ cm.

In figure 2(a), we can see the red, yellow and green light bulbs. As the Z distance increases until 12.5 cm 2(b), no great change in the color distribution of each lamp can be seen. In 2(c), we can perceive a change in the image of the red lamps, their color change from red to violet. This kind of change also happens between figures 3(a) and 3(b), but now from yellow to violet.

Using a mean wavelength and its deviation from its mean value [9], we made a study of the depth of focus for the colors we used as objects.

By means of Ferrari [5] and Magalhães [7] results shown in equation 1, we could verify the theoretical results.

$$(r_0 / n\lambda)R_{min} < Z < (r_0 / n\lambda)R_{max} \quad (1)$$

Where,
$R_{min}$ and $R_{max}$ are the minimum and maximum radius of the compact disc;
$r_0$ is the radial distance between adjacent turns in it;
n is the diffraction order, in our case n=1;
λ is the wavelength considered.

Utilizing the data shown in table 1 we got three intervals to the length of the diffraction-free beam, each one corresponding to a color. These lengths are shown in table 2.

| $r_0$ | $R_{min}$ | $R_{max}$ | $\lambda_R$ | $\lambda_Y$ | $\lambda_G$ | $\lambda_P$ |
|---|---|---|---|---|---|---|
| 1.5 ± 0.1µm | 2.2 ± 0.1cm | 5.8 ± 0.1cm | 683 ± 58nm | 578 ± 13nm | 532 ± 33nm | 410 ± 30nm |

**Table 1:** Values used to calculate the length (in Z direction) of the three diffraction-free beams produced. We used the same $r_0$ value used in [5].

| Color | $Z_{min}$ | $Z_{max}$ |
|---|---|---|
| Red ($\lambda_R$) | 4.83 ± 0.57cm | 12.7 ± 1.4cm |
| Yellow ($\lambda_Y$) | 5.71 ± 0.48cm | 15.1 ± 1.1cm |
| Green ($\lambda_G$) | 6.20 ± 0.63cm | 16.4 ± 1.5cm |
| Violet ($\lambda_P$) | 8.04 ± 0.88cm | 21.2 ± 2.1cm |

**Table 2:** Theoretical results to the three diffraction-free beams. The errors in Z's were calculated by Error Propagation [10].

Analyzing the figures 2(b) and 2(c) by means of table 2, we can see that between the interval 12.5 ± 0.3 - 14.0 ± 0.3cm the mean red diffraction-free beam, for the first order (n=1), ends. Theoretically this occurs in 12.7 ± 1.4cm. The same analysis can be done to the figures 3(a) and 3(b), where we find the theoretical result of 15.1 ± 1.1cm to the mean yellow diffraction-free beam.

The depth of focus of the system is directly related with the length of the diffraction-free beams. For white light objects, this depth begins at the red $Z_{min}$ and finishes at the violet $Z_{max}$. By table 2, we have 16 cm of depth of focus. We could determine experimentally that the depth of focus achieved was much greater than that of a photographic objective of the same focal length and aperture (90.0 ± 3.9 $cm^2$).

If the used light bulbs were of pure color (like LEDs) one could see the lamps in the image vanishing at the end of the respective diffraction-free beam, as we observed.

As the angles of diffraction are very oblique to the caption by the camera, it was not possible to catch sharpness images of the object at the beginning of the diffraction-free beams.

Images of extensive white light objects cannot be done by the system. The applications are related with point objects, like astronomical images, because it only can get the central position of the object. Besides, as in any single optical element, aberrations grow very fast as the incidence angle increases and the point images becomes a double parabola spot at an angle 7º.

The efficiency of the system is restricted by the diffraction efficiency of the diffraction element, about 10%. Works like Marciante [11,12], about the construction of diffraction elements with diffraction efficiency next to 100%, bring us expectation of evolution in this area, making practical systems possible.

## Conclusions

We showed that is possible to get images of point elements and to use for advantage the spectral separation inside a longitudinal field with great depth of focus. The efficiency of the system is restricted for the diffraction efficiency of the diffraction element.

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