A diffraction experiment at the near field: the homemade Talbot effect

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Abstract

Diffraction refers to a kind of optical pehenomena which occurs when light approaches an element (object or aperture) whose features are in the range of the illuminating wavelength (small apertures, sharp edges, ...). It can be explained by means of the undulatory nature of light or also geometrically by using simple ray optics. Diffraction phenomena are impressive and not intuitive, so it make them very interesting to bring examples to the classroom. The most popular diffraction experiments show effects in Fraunhofer regime, that is to be said, far from the diffractive object. Common examples are the single or double slit experiments. In this manuscript, we propose and show a less common diffractive effect that occurrs in the Fresnel regime, near to the diffractive object. It is the Talbot effect or self-imaging phenomenon, which appears by illuminating a diffraction grating with a collimated monochromatic beam. It consists of the aparition of replicas of the grating intensity pattern at periodic distances multiples of the so-called Talbot distance. We show how this effect may be shown into the classroom with cheap and easy to find elements. In addition, we take advantage of its dependence on the coherence degree of the source to introduce the concept of optical coherence and show its effect on the contrast of the Talbot self-images. These experiments could be appropriate for undergraduate students or introductory physics courses.

Keywords: Diffraction, optics, Talbot effect.

1. Introduction

The Talbot effect or self-imaging phenomenon is an interferometric effect discovered by H. F. Talbot in 1836 [1], [2]. It appears when a diffraction grating is illuminated with a collimated monochromatic beam. This effect has been found also for other types of waves, besides electromagnetic, such as mechanical waves in water, [3], and it has been analyzed under many configurations, for cylindrical gratings [4], with non-collimated beams, with polychromatic illumination [5], [6], with rough diffraction gratings [7], all of them resulting in very interesting properties and behaviors. Besides, it has applications in many different branches of science and technology such as machine tool, optical encoders, dimensional metrology, and so on, [8].

The governing equation of the effect can be easily obtained by propagating the transmittance of a diffraction grating using the Fresnel approach, [2]. The effect consists of the apparition of exact replicas of the grating intensity pattern at different periodical distances from the grating, called Talbot distances, which are given by

$$z_T = 2mp^2 / \lambda , \qquad (1)$$

where p is the period of the diffraction grating, considered one-dimensional, λ is the illumination wavelength, and m are integers. It appears when the diffraction orders produced by the grating interfere at the near field. In fact, the Talbot distance can be deduced geometrically, as it is clearly derived in ref. [3]. Figure 1 shows how the diffraction orders generate the Talbot-self-images by constructive interference. In this figure, light propagates towards the right and the diffraction orders are represented as translucent red straight lines. To show the effect, only zeroth and $\pm$ first diffraction orders are necessary. As can be observed, red periodic areas just equal to the grating intensity profile appear at several distances, z_T, $2z_T$, $3z_T$, ... , multiples of the Talbot distance. Equation (1) can be obtained geometrically by calculating the distances from the grating where the interference between zeroth and first diffraction orders is constructive just at the same positions as the grating intensity pattern (intense red areas at z_T and $2z_T$ in Figure 1). Thus, Talbot planes corresponds to those distances. In the same fashion, by taking zeroth and third diffraction orders, constructive interference appears at distances $z=(2m-1)z_T/4$ but with a periodicity half of that of the diffraction grating, [3].

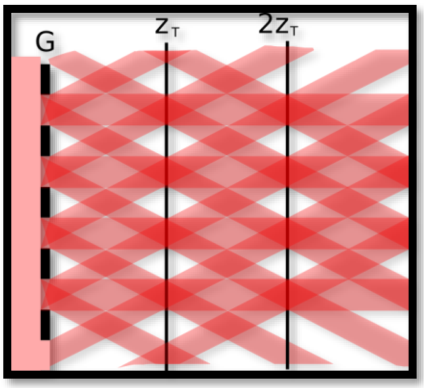

Figure 1.- Geometrical explanation of the Talbot effect. The translucent redish lines represent the diffraction orders (0 and $\pm$ 1), G is the diffraction grating, and the first two Talbot distances are marked with vertical solid lines. Light is considered monochromatic and collimated, and propagates towards the right.

We show in Figure 2 four examples of Talbot effect obtained anallytically from the intensity calculated by propagation of the grating transmittance by using the Fresnel kernel with plane wave illumination, in a similar way as it is made in [4]. The period of the gratings, placed at $z=0$, is $p=20\ \mu m$, and the Talbot distance results $z_T=1.26$ mm and $z_T=1.5$ mm for $\lambda=632$ nm and $\lambda=532$ nm, respectively. As can be observed, the self-images (dashed white lines into Figure 2) appear at different distances from the grating plane for each wavelength, revealing its dependence on the illumination wavelength. In addition, self-images do not strictly appear at exact planes but we may observe them along an interval around each self-image. From Figure 2 we may deduce that the observable range for each one results around $z_T \pm z_T/8$.

On the other side, regarding the type of grating, the 2D intensity carpet is longitudinally displaced (z-axis) for phase-based gratings with respect to amplitude-based gratings by a length of $z_T/4$, despite of that the Talbot distance is the same since the period and the illumination wavelength are the same. The displacement or position of the near field intensity carpet depends on the kind of grating, as it is demonstrated in [9].

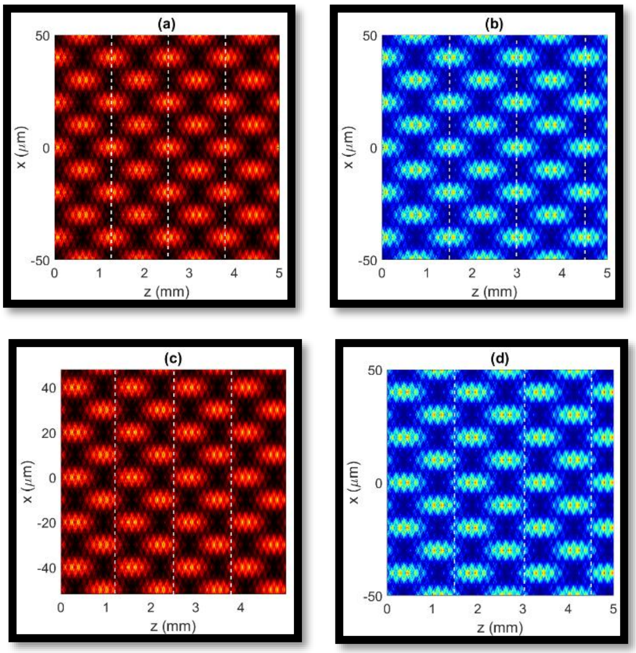

Figure 2.- Talbot effect analitically obtained with plane wave illumination and a diffraction grating of period p=20 µm placed at $z=0$. Diffraction orders up to the ± 5 have been taken into account. (a) Amplitude-based grating, λ=632 nm, (b) amplitude-based grating, λ=532 nm, (c) phase-based grating, λ=632 nm, and (d) phase-based grating, λ=532 nm. Vertical white dashed lines correspond to the first three Talbot planes.

2. Educational approach

From the educational point of view, the Talbot effect can be used to show the wave nature of light through the concept of diffraction. The most common experiments to show diffraction to students are those based on small apertures [10], [11], or the double slit experiment [12] but all of them show diffractive effects in the Fraunhofer regime, which is at the far field. In this work, we pretend to show a diffractive phenomenon in the Fresnel regime, which is at the near field, closer to the diffractive element, by using a diffraction grating.

A diffraction grating is not easy to find but we may use different conventional objects that actually act as a diffraction grating. On the one hand, we may use a Compact Disc (CD), a Digital Versatile Disc (DVD), or a Blue-Ray disc, [13]. After taking out the protective plastic and/or the label, they reveal a phase-based diffraction grating engraved on the plastic. It cannot be seen with the naked eye but looking at a white light source though it, one may see the diffractive effect due to the grating, as a kind of rainbow [14]. The period of the grating is different for CDs and DVDs, being p=1.52 µm and p=0.72 µm, respectively. Assuming an illumination wavelength of λ=632 nm, the first Talbot self-image appears at z_T=7.32 µm for the CD and 1.64 µm for the DVD. The distances between correlative Talbot planes are also these ones. Then, it is obvious that it is not possible to observe the Talbot effect with the naked eye by using these diffraction gratings. To enlarge the period and, therefore, the Talbot distance, we may use other elements which behave as diffraction gratings. In this work, we have used a comb and an amplitude-based grating printed on an acetate film with a conventional printer, Figure 3.

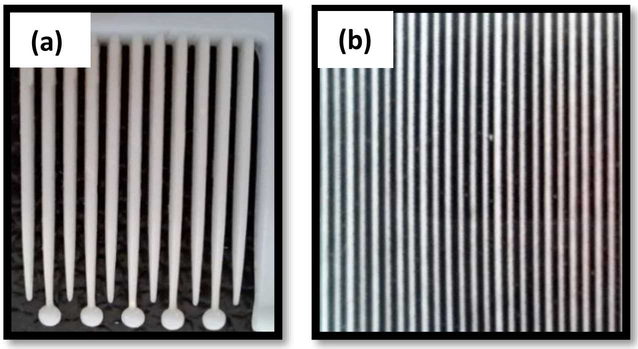

Figure 3.- Images of the (a) comb and (b) acetate grating.

The advantage of the printer is that it allows to obtain diffraction gratings with different periods just in a moment. Thus, the dependence on the period of the grating of the near field intensity pattern can be shown easily. As we may observe in Figure 3(b), some imperfections due to the printing process are produced in the acetate grating but they are not important since the self-imaging phenomenon is a self-healing process and these imperfections disappear while one observes the fringes further, [15].

3. Experiments

The optical set-up is very simple, Figure 4. It consists of the light source (two lasers with different wavelength and some LEDs in our case), optical elements such as lenses to enlarge the beams, the diffraction grating, and a paper screen which facilitates the observation of the self-images.

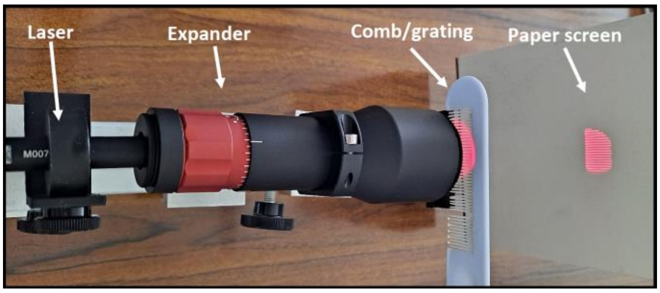

Figure 4.- Experimental set-up.

3.1. Coherent illumination

In the first experiment, we use a laser pointer (λ=632 nm) with an expander (x10). Thus, we observe the near field diffraction pattern of the grating comfortably. The period of the comb is p= 1.53 mm approximately and, therefore, z_T results quite large, z_T=7.36 m. Despite of that, we may observe fringes at z_T /2 (with the same period as the grating but as a negative) and at z_T /4 (with half period of the grating), see Figure 2 and ref. [3]. Assuming that observable fringes with the same period as the diffraction grating are present at $z_T \pm z_T/8$. The first self-image would be observable within the interval (6.44 m – 8.28 m). As a conclusion, it is easy to find the Talbot self-images and show them to the students by using a conventional comb. We show in Figure 5 three images of the fringes for the comb at different distances for each of both used laser pointers. The Talbot self-images appear at different distances for each one as we have mentioned before (z_T=8.8 m and z_T=7.36 m, for λ=532 nm and λ=632 nm, respectively).

In addition, we show in Figure 6(a)-(c) the fringes at different distances for the acetate grating and the green collimated laser. In this case, the period of the grating is p=0.65 mm and, therefore, z_T=1.59 m. The minimum printable period depends on the quality and characteristics of each printer. In our case, the obtained period is nearly the minimum possible. As the Talbot distance is shorter in this case, it could be more appropriate to bring it to the classroom than the comb.

With a collimated beam as the used up to now, Talbot self-images have the same period as the diffraction grating. Small differences in Figure 5 and Figure 6(a)-(c) are due to the size of the pictures, that have been taken with a conventional digital camera.

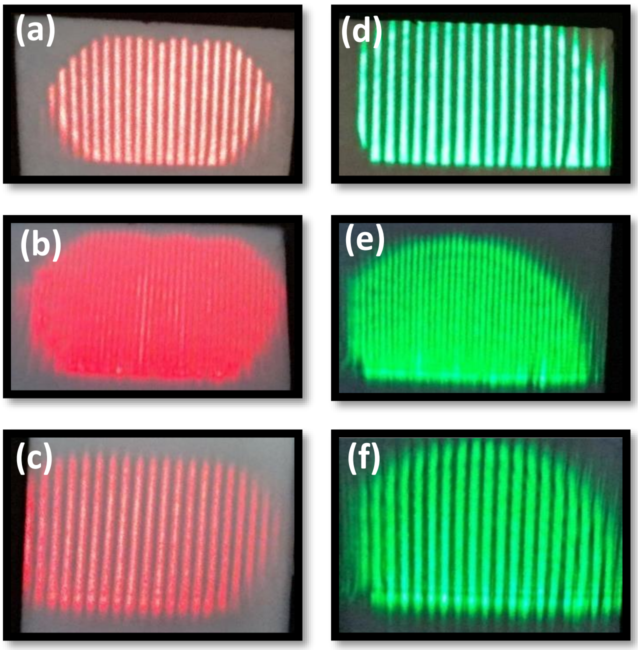

Figure 5.- Diffraction fringes obtained with the comb at different distances and illumination wavelengths. (a) Close to the comb, λ=632 nm, (b) $z=z_T$ /4, λ=632 nm, (c) $z=z_T$ /2, λ=632 nm), (d) close to the comb, λ=532 nm, (e) $z=z_T$ /4, λ=532 nm, and (f) $z=z_T$ /2, λ=532 nm.

3.2. Non-coherent illumination

To be able to observe interferometric effects, the beams that are interfering must be optically coherent, as it happens when a laser is used. In this section, we show how the diffraction grating behaves at the near field with non-coherent sources such as a white light. To do it, it can be used the flash LED of our smartphone, just placing the LED before the expander/lens. Now, the illumination beam is slightly divergent. With diverging or converging light, the period of the self-images increases or decreases, respectively, as we separate from the grating plane, [4]. In addition, the source is no longer monochromatic but it has a wide spectrum. Each wavelength produces self-images at different distances and we observe the incoherent summation of all of them, [5]. LED light, besides having small temporal coherence length (wide emission spectrum), also has small spatial coherence length due to the size of the emitting area. Both facts make almost not possible to observe diffractive effects (interferometric), such as the Talbot effect. We show in Figure 6(d) the intensity close to the grating. In this image, the polychromatic effect is slightly sensed at the edges, which turn more reddish. We may increase the spatial coherence length of the white LED by placing a small hole after it. Figure 6(e) shows the fringes close to the acetate grating by placing a small hole of 1 mm diameter approximately between the LED and the expander/lens. Fringes are now visible although they have low contrast. Due to the low coherence degree, compared to the laser pointer, higher order self-images are not produced anyway. This fact opens the possibility of talking to the students about the different kinds of light sources, the concept of coherence and coherence degree, the concept of polarization and polarization state, etc, [16].

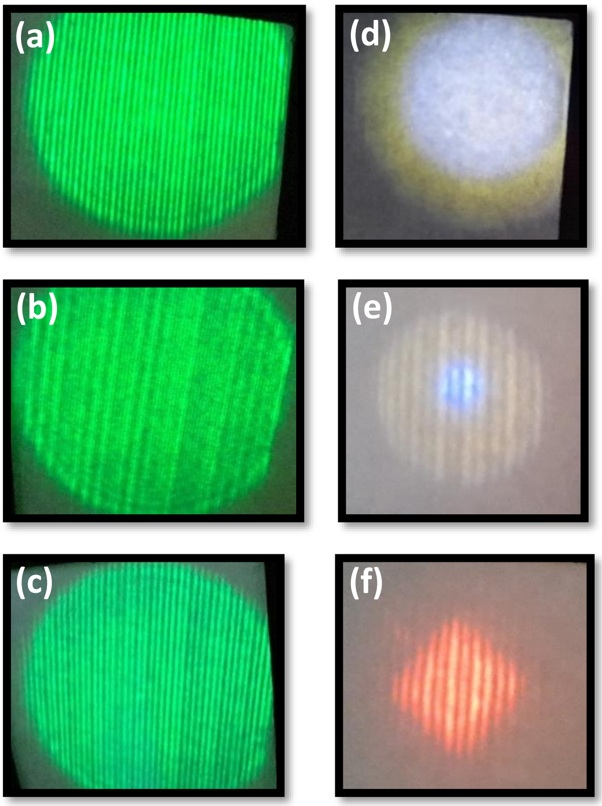

Figure 6.- Diffraction fringes obtained with the acetate grating at different distances. (a) Close to the grating (laser, λ=532 nm), (b) at z_T/4 (laser, λ=532 nm), (c) z_T/2 (laser, λ=532 nm), (d) close to the grating (white LED), (e) close to the grating (white LED and small aperture), and (f) close to the grating (Red LED ans small aperture).

To finalize, we may use a quasi-monochromatic LED as illumination source. In this case, we increase the temporal coherence length since it is related to the width of the emission spectrum. The temporal coherence, and therefore the coherence degree, are higher for narrower emission spectra. Figure 6(f) shows the fringes, at the same distance from the grating as Figure 6(d) and (e), for the quasi-mono chromatic LED and the small hole, revelaing interference fringes with higher contrast, since the source is more coherent than the white LED. Besides, the shape of the LED is square in this case and this is the reason why the fringes have a square frame around them.

Conclusions

Summarizing, in this work we show how a near field diffractive effect such as the Talbot effect can be shown and explained with common cheap elements such as combs, printed diffraction gratings, laser pointers, or even the LED flash of the smartphone. This experiment allows explaining the wave nature of light, the dependence of diffraction on the wavelength of light, the concept of optical coherence, the effect of the pitch size of the diffractive element, and so on. Diffraction and optical coherence effects are usually explained by means of far field effects but, in this work, we use a near field effect such as the Talbot effect to show them, revealing to the students that diffraction is not an only far field effect but it appears close to the diffractive element. In addition, we use the set-up to introduce the concept of optical coherence, showing how it affects to the interference behavior of a source by using a couple of LEDs (white and red). These experiments could be appropriate for undergraduate students or for courses of introductory optics and physics.

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Ethical statement

No conflict of interest.

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