Controlling light diffraction with magnetic nanostructures

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ABSTRACT

We are presenting the main results of our research using smart fluids to control the light scattering using some devices based on nanotechnology. We are presenting the Ferrolens or Ferrocell®, which consists of a Hele-Shaw cell with ferrofluid, and the "Polarifluid", which is a Ferrolens placed between two crossed polarizers illuminated with white light, subjected to a magnetic field. We have obtained the equations which represents these systems and solved them analytically and numerically, in order to compare with the patterns obtained using the experiments. We also explore the experiment with the patterns obtained from the atmospheric optics such as the parhelic circle and sundogs, obtaining experimentally the jumping laserdogs and the parlaseric circle.

Keywords: ferrofluid, ferrolens, diffraction, light polarization, Polarifluid.

1 INTRODUCTION

The simple observation of patterns is one of the ways that allows us to advance in the understanding of the phenomena of the nature and to stimulate the technological progress. For example, Michael Faraday created the concept of the "lines of force" observing the patterns produced by iron fillings in the presence of various magnets, defining that the magnetic field is a pecular region of space in the neighbouhood of magnetized bodies. In this way, from the visualization of iro filings patterns, the concept of field evolved and pervaded many branches of science. The present work explores some results based on the existence of light patterns in a thin film of ferrofluid subjected to an external magnetic field. We present two devices, the Ferrolens [1-3] and the Polarifluid [2, 3].

Although the general interest about this type of device has increased significantly lately due the impressive light patterns obtained, scientific studies on this device are scarce. For example, only one YouTube video on how to make a Ferrolens (Ferrocell) has more than 222,000 views in two years [4], while a search in the Google Scholar query reports only seven scholarly works using the Ferrolens devices [1, 2, 3, 5, 6, 7, 8] discarding studies from detail of the physical properties of ferrofluids in magneto-optics that do not deal with the light pattern formation [9].

In this way, another objective of this work is to contribute to the study of the formation of patterns in these devices.

2 LIGHT PATTERNS WITH LIGHT DIFFRACTION

The Ferrolens and the Polarifluid are essentially the light scattering in a thin film of ferrofluid, due to the formation of a diffraction grating in the ferrofluid subjected to a magnetic field. Basically, the magnetic nanoparticles arrange themselves in complex geometries in ferrofluids, such as labyrinth or needles, due to the long range dipolar interactions.

2.1 Ferrolens

Considering the plane of the Ferrolens of Fig. 1(a), the magnets can create different magnetic field configurations, depending on their orientation, as it is shown in Fig. 1(c), see ref for more details.

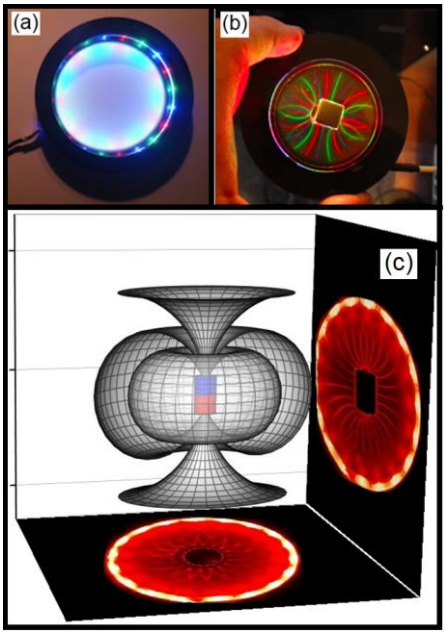

Figure1. The ferrolens with a light source of a circular ring of LEDs in (a) with different colors, and light pattern btained for cube magnet in (b). Image of the magnetic contours obtained for a single cylindrical magnet in two orthogonal planes using the Ferrolens, using with a light source of a circular ring of red LEDs.

Using a different geometry of the light source, we obtained the patterns of Fig. 3, for more details see ref.

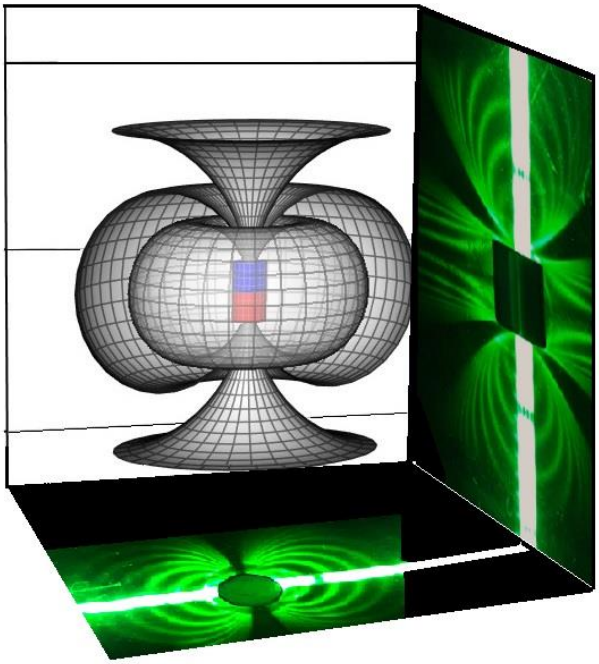

Figure 2. Image of the magnetic contours obtained for a single cylindrical magnet in two orthogonal planes using the Ferrolens, for a geometry of a linear light source, using a trip of green LEDs.

The nature of these light patterns can be related to isopotentials of the magnetic field, see ref. Considering the poles of magnets as magnetic charges, we have obtained in Figures 3, 4 and 5 the simulation of the magnetic isopotentials of different magnet ensembles, and their repspective patterns obtained with Ferrolens.

Besides light patterns, a laser beam passing through the Ferrolens can be diffracted by a magnetic fiels, with effects similar to those obtained in atmospheric optics for the case of parhelic circle, sundogs, and jumping sundogs [1, 10, 11], with jumping laserdogs and parlaseric circle [5, 6].

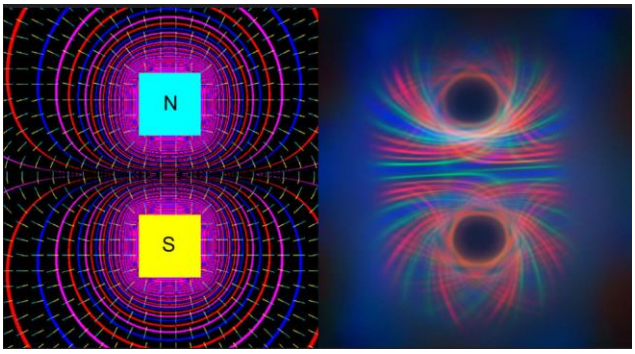

Figure 3. Simulation and light pattern from the Ferrolens for a configuration of magnets north-south.

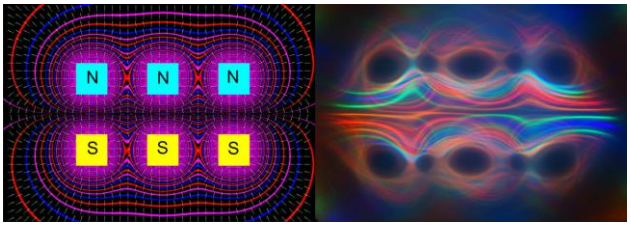

Figure 4. Simulation of isopotential lines and light pattern from the Ferrolens in the presence of three north-south magnets.

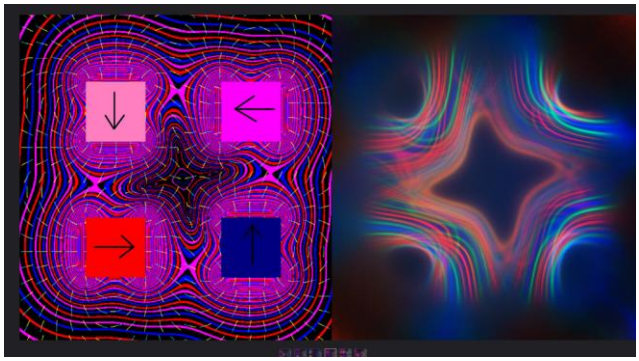

Figure 5. Another light pattern obtained with four magnets, represented in the simulation as colored squares oriented with an arrow from south to north, and light pattern from the Ferrolens.

The nanoparticles create a structure very similar to a diffracting grating from the influence of the orientation of a magnetic field. The light diffracted by the ferrofluids grating seemed to follow isopotential lines of this scalar field, having the light source as the origin of the light line, because each diffraction line is perpendicular to the scatterer

The relationship between the diffracted lines and the magnetic potential V is clear when considering a single dimension. In the one-dimensional case *for* the direction x, so that $V = constant/x$. Hence the vector associated with light lines $\boldsymbol{D}$ and the magnetic scalar potential V is given by

$$\vec{D} = -\frac{dV}{dx}\hat{\imath} \tag{1}$$

2.2 Polarifluid

Polarifluid is a Ferrolens with two crossed polarizers, in which a white light source was generated using a LED panel light (12 W), illuminating over the complete surface of a square Ferrolens (22 mm × 22 mm) homogeneously, with a methacrylate diffuser using backlighting technique. The Ferrolens is placed between two crossed polarizers, as it is shown in the diagram of Fig. 6(a). The image is obtained directly from the system polarizers/Ferrolens and registered using a camera, placing a magnet in front of the analyzer. In Fig. 6(b) we can see the base of the Ferrolens

and polarizers, and thee whole set is placed in a box for spurious light insulation, as it is shown in Fig. 6(c).

We can see some examples of light polarization by light transmission in Fig. 7, with the typical structural colors of polarized light in a regular piece of plastic in Fig. 7(a), the polarized light obtained with the Polarifluid for a magnetic field of a composed magnet arrangement in Fig. 7(b), and in Fig. 7(c) the simulation of the light polarization pattern for this magnetic field. In Fig. 8, we are showing the polarized light pattern obtained for a cubic magnet in polar configuration at different positions in the Polarifluid viewing plane.

In order to simulate these patterns obtained with polarized light, we have observed that the light intensity patterns I can be approximated to the effects of a static magnetic field B as

$$B(x,y,z) = B_0 H_m(x) H_n(y) e^{-(x^2+y^2)/w^2(z)} e^{i\varphi(z)}, \quad (2)$$

$$I(x,y,z) = |B(x,y,z)|^2, \quad (3)$$

in which x, y, and z are spatial coordinates, B_0 is the maximum intensity of the magnetic field, and H_m and H_n are the spatial derivatives of the magnetic field functions. For a more detailed explanation of how to obtain these equations, see the references [1-3].

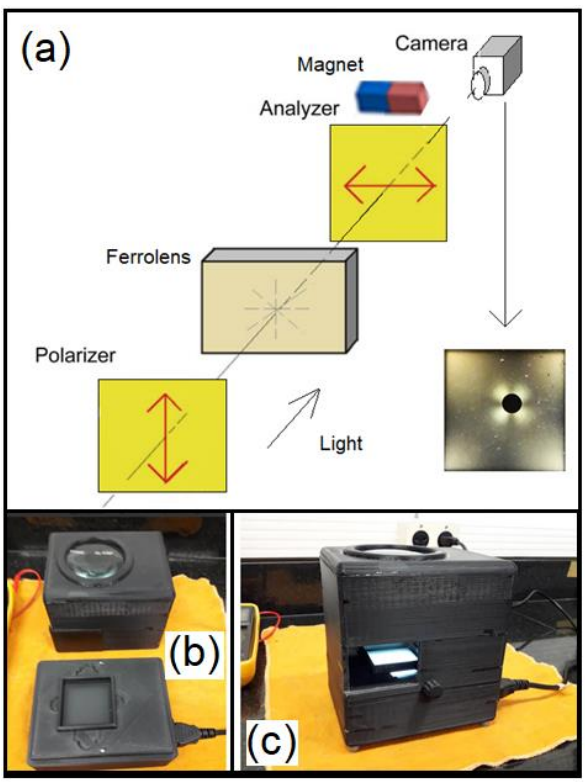

Figure 6. In (a) the diagram of the Polarifluid using polarized light.. The base of this device is shown in (b), with the cover. In (c) is shown the Polarifluid with the access to the analyzer, where the magnet is placed.

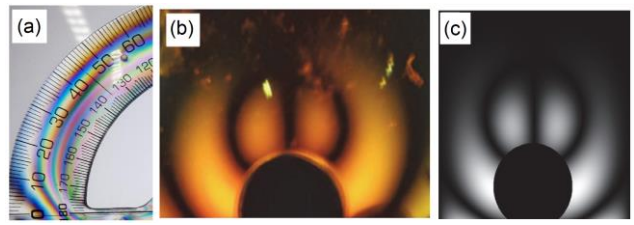

Figure 7. Example of light polarization in Polarifluid. The polarized light in a regular piece of plastic in (a), the polarized light obtained with the Polarifluid for a magnetic field of a composed magnet arrangement in (b), and in (c) the simulation of the light polarization pattern for this magnetic field.

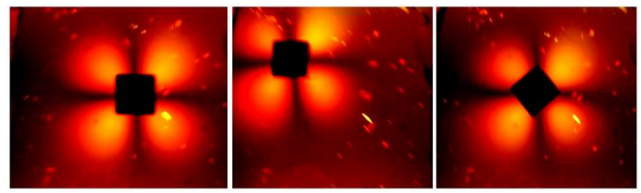

Figure 8. The polarized light pattern for a cubic magnet in the polar configuration (0.6 T) at different positions in the Polarifluid viewing plane.

In Fig. 9(a) we present the diagram of the magnetic field flux of a axially magnetized ring, in Fig. 9(b) the pattern obtained with Ferrolens, the light pattern obtained with Polarifluid in Fig. 9(c), and the simulation of the polarized light intensity using Eqs.(2)-(3) in Fig. 9(d).

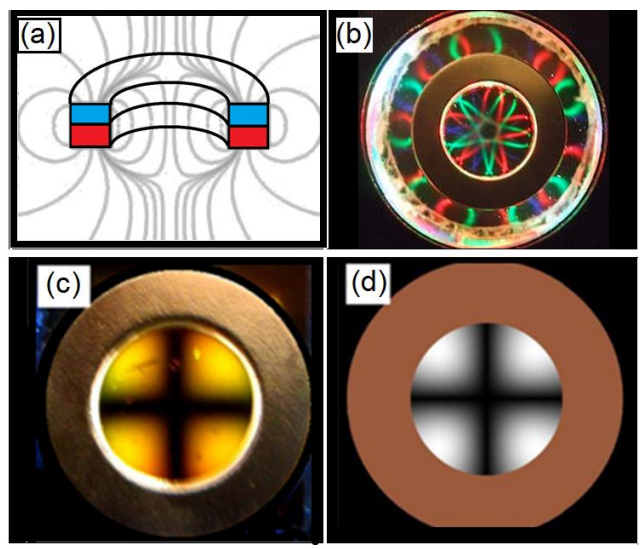

Figure 9. In (a) there is the diagram of the magnetic field flux of an axially magnetized ring (1 T), in (b) the pattern obtained with Ferrolens, the light pattern obtained with Polarifluid in (c), and the simulation of the polarized light intensity in (d).

Using a diametrically magnetized ring we can see two different polarized light patterns, showing the dependence

of the patterns with respect to the magnetic field orientation in Fig. 10.

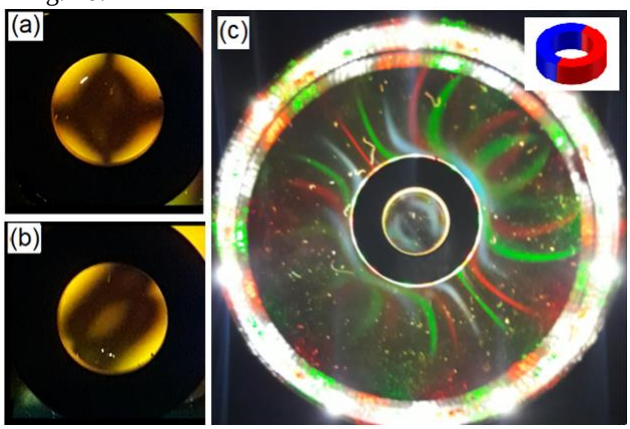

Figure 10. Light polarization patterns of a magnet ring with a diametrically magnetization (1 T). Changing the orientation of the ring,we can see different patterns in (a) and in (b). In (c) the light pattern obtained with Ferrolens with an inset of the magnetic field diagram of this ring.

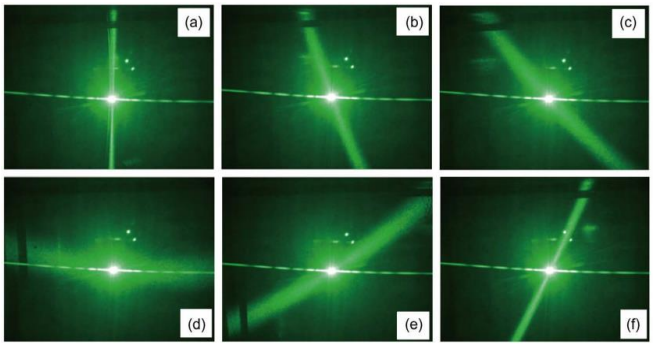

Figure 11. Jumping laser dogs obtained for different orientations of the magnetic field in a Ferrolens [1, 5, 6]. Using the fixed light diffraction the reference, we have measure the following angles between the laser dog and the reference: (a) 90˚, (b) 120˚, (c) 135˚, (d) 180˚, (e) 225˚, and in (f) the laser dog is rotated 245˚.

In Fig. 11 we can observe the jumping laser dogs, obtained by diffracting a laser beam passing through the Ferrolens.

3 CONCLUSIONS

We have explored some light patterns associated with magneto-optical effects in a thin film of ferrofluid, using the Ferrolens and the Polarifluid. These devices provide tools that allow fast observation of magnetic fields generated by magnets or coils. The nanoparticles subjected to the magnetic field create a structure very similar to a diffracting grating. The diffracted light by the ferrofluids grating seemed to follow isopotential lines of this scalar field.The light patterns obtained with Ferrolens depends on the geometry of the light source. The polarized light patterns resemble the patterns of hyperbolic polynomials.

The relationship between the wavelength of light and the size of the light scatterer causes the existence of diffraction effects. In the case of ferrofluids we have the formation of needles with the application of the magnetic field, whereas in the case of atmospheric optics we have ice crystals acting as scatterers, giving the pseudo impression that the light can be curved.

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