FERROCELL AND MAGNETIC PATTERNS

Illustration of Concepts, Experiments and Demonstrations.

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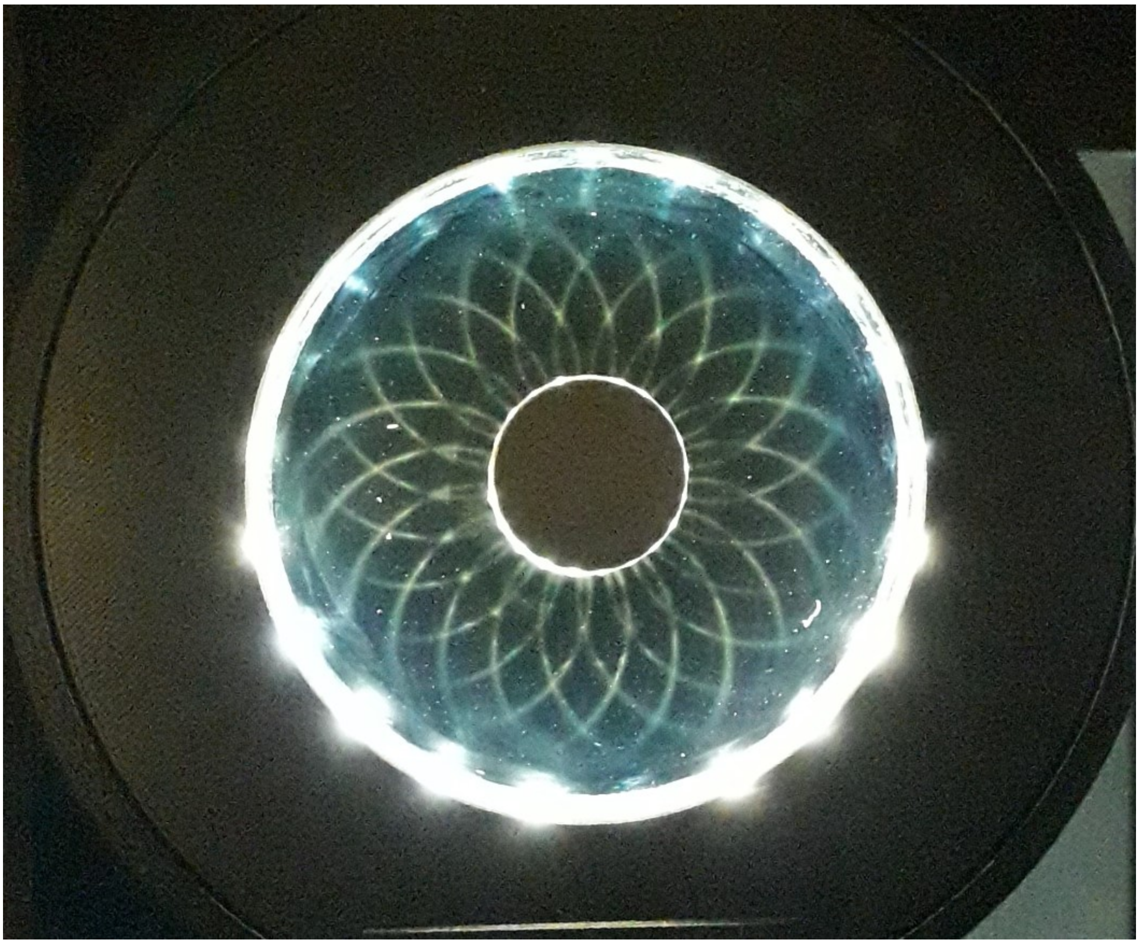

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Alberto Tufaile & Adriana Pedrosa Biscaia Tufaile

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Prologue

This book was born out of a direct request by Timm A. Vanderelli to us, when he found out that we had written a physics book for science teachers.

Our goal is to write a book, or an essay, that shows our personal experience with the use of Ferrocell. You will notice that at the beginning of most chapters there are questions that guide your reading. At the ending of each chapter, there is a list of references related to the chapter. Some of our articles that are references in these chapters are open access and we strongly encourage you to also consider the references in these articles as an important part of understanding this book. Some topics in this book presented in a chapter and can be taken up in a different perspective in the following chapters.

As interest in Ferrocell goes far beyond the community of physicists, material scientists and engineers, we try to illustrate the main concepts through images, avoiding formulas whenever possible, but at some points in this book they will appear.

Much of our research presented in this book is mainly supported financially by Brazilian agencies FAPESP (Fundação de Amparo à Pesquisa do Esatdo de São Paulo) e CNPq (Conselho Nacional de Densenvolvimento Científico e Tecnológico), allowing us to buy equipment, take trips to do research and participate in conferences, for which we thank to them. In addition, the authors are also grateful for the support and encouragement for us to use Ferrocell made by Timm A. Vanderelli. Whithout that, we would not have done this book. Another person who helped us with discussion of ideas in the task of studying Ferrocell, assembling experiments and simulations of the experimental results was Michael Snyder. Their role can be seen in the co-authorship of some of our papers.

If you would like to contact us to make a comment about this book, you can send a message to the following e-mails, preferably both at same time, and we will respond as soon as we are available:

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Chapter 1 - Introduction

Why use Ferrocell?

The use of Ferrocell, also known as Ferrolens, is a way to encourage the study of magneto-optics in a more intuitive way. Ferrocell is a device based on a thin film of nanoparticles, which when subjected to a magnetic field, can interact the light propagation.

What is magneto-optics?

Magneto-optics is the use of magnetic fields to influence light propagation.

What is the use of studying magneto-optics?

Magneto-optical effects are used in technology to make optical switches, information storage devices, display parts and other technological applications. However, the study of magneto-optics is not so simple for beginners, because magneto-optics is a boundary between two areas of physics that involves light and magnetic fields.

What we will explore in this chapter?

We will see how the observation of patterns led us to abstract some fundamental concepts of physics. How the discovery of magnetism led some of humanity's greatest scientists to question the world around us. We will see some of the relationships between magnetism and materials, since magnetism is a basic property of matter. We will talk about the presence of magnetism from the basic constituents of matter to the stellar dimensions. How magnetism fascinated young Einstein, and how Einstein explains magnetism through relativity. We will discuss how ferrofluids are used in magneto-optics and how magnetic fields can be generated for use at the Ferrocell. The reader will notice that we try to put physics at the forefront in this chapter, avoiding as many equations as possible, following the idea of "Physics First", but we will briefly discuss obtaining simulations of magnetic fields. At the end of this chapter we indicate some references that can be explored so that the reader can advance in these subjects depending on their level of knowledge and interest.

1a. Some historical aspects and motivations to use Ferrocell

The use of the Ferrocell or Ferrolens is based on the observation of light patterns when a thin film of ferrofluid is subjected to an external magnetic field [1]. The simple observation of patterns is one of the ways that allows us to advance in the understanding of the phenomena of nature and to stimulate the technological progress. Besides the pattern formation, we will talk about the concept of field in physics.

Since ancient times, mankind has been in contact with luminous patterns that arouse their curiosity. Rainbows, halos, glories and other atmospheric phenomena are some examples of how these light patterns are present in our day lives.

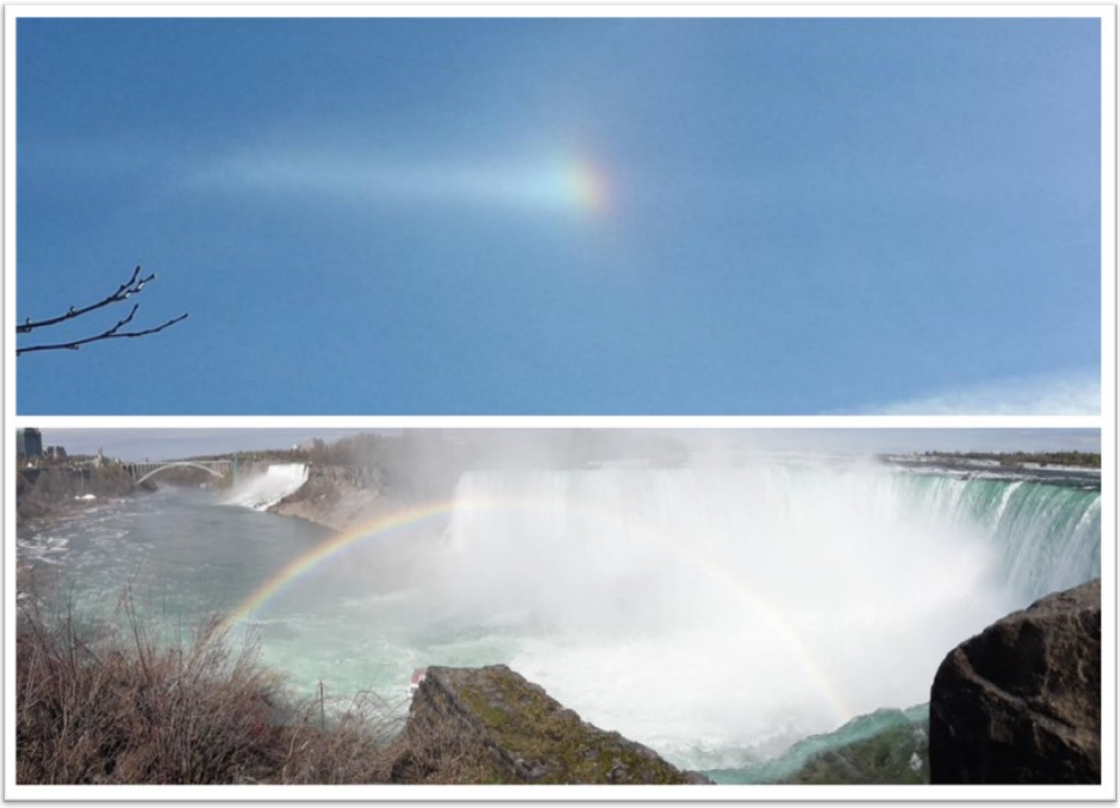

Figure 1.1 - Natural luminous patterns in nature like Sundogs and rainbows are very common.

In addition to the contemplative aspect related to these phenomena, we also have the practical results of these luminous effects, for example, some of the properties of lens optics and the development of very complex mathematical physics techniques used in engineering and science today were created by scientists who fundamentally studied rainbows. In addition to these cases, we have the serendipitous circumstance of C. R. T. Wilson, who attempted to reproduce in laboratory the Glory effect, created the cloud chamber, a device that allows to observe the presence of cosmic rays and subatomic particles, earning him the Nobel prize for Physics in 1927 [2].

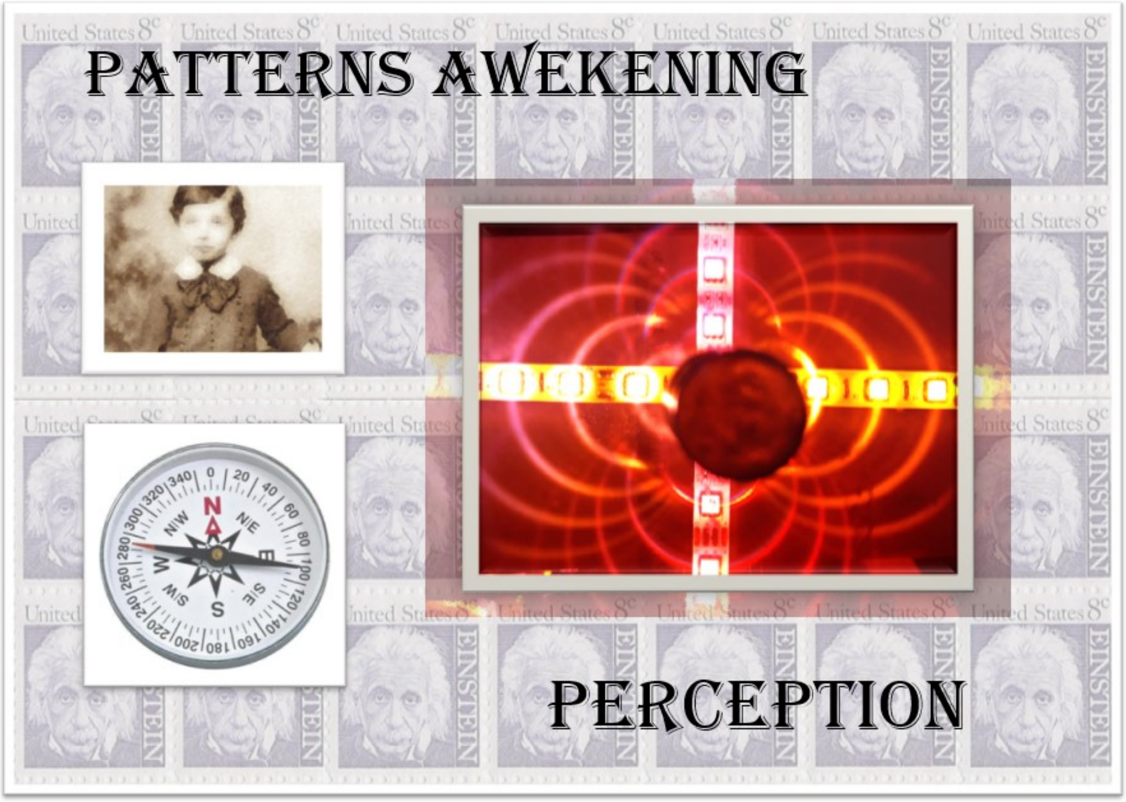

Figure 1.2 - Einstein and the compass. Image of a luminous pattern in a Ferrocell.

On the other hand, the effects of magnetism on the motivation to discover the secrets of the universe are also historically famous in science. For instance, when Albert Einstein was a child with five years old, his father showed him a compass and let the child playing with it. The observation of the motion of the compass needle, always pointing at the same direction no matter which way he turned the compass caused a such great impact on him, that as an adult, Einstein reported that this first contact with the magnetic device motivated him to understand the different aspects of physics because "Something deeper had to be hidden behind the things." Nowadays, the connection between the electricity and the magnetism is described by the special theory of relativity of Einstein [3].

The question that has baffled the young Einstein had been raised a few centuries ago by scientists like Isaac Newton: "How do bodies act on another across the space?" The answer was obtained with the concept of "Action-at-a-distance." This concept is at the root of the birth of the concept of field, another important thing to understand the motivation to use Ferrolens.

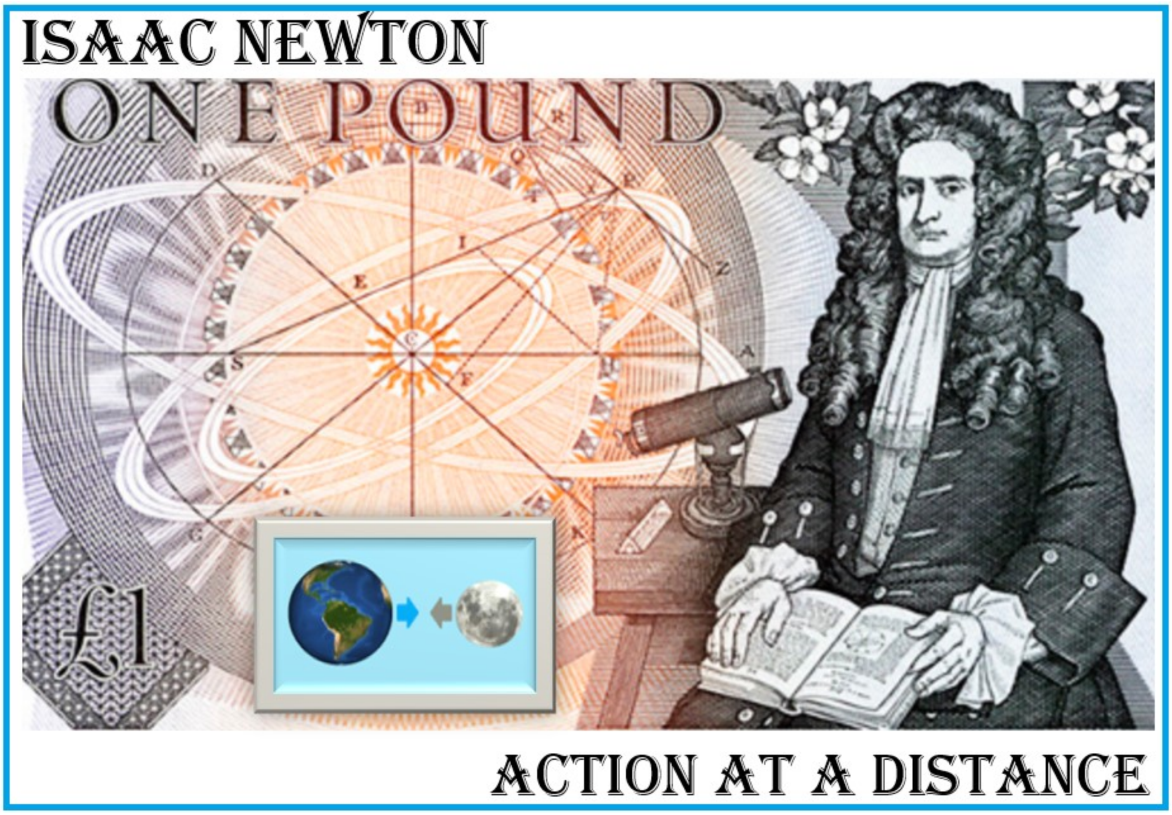

Figure 1.3 - Newton and the concept of “action-at-a-distance”.

We understand more easily the contact forces, such as we do when we touch the door handle to open it, than the forces that act without the direct contact, such as the force of gravity, the electric force and the force between two magnets, which require a little more abstraction. This kind of force reminds us that one that is used by the Jedi masters. Looks like magic! However, magic is not acceptable among the scientists as a valid answer. The answer for this kind of force is not the midi-chlorians of Star Wars, microscopic intelligent creatures, but something more subtle, the concept of “field”. The concept of field starts with the observation of patterns by Michael Faraday, which created the concept of the “lines of force” observing patterns produced by iron fillings in the presence of various magnets. The simple observation of patterns is one of the ways that allows us to advance in the understanding of the phenomena of nature and to stimulate the technological progress, and one of the most impressive concepts we knowin science is the concept of field. This is one important point to address when we talk about the use of Ferrolens, because this device shows to us some light patterns directly.

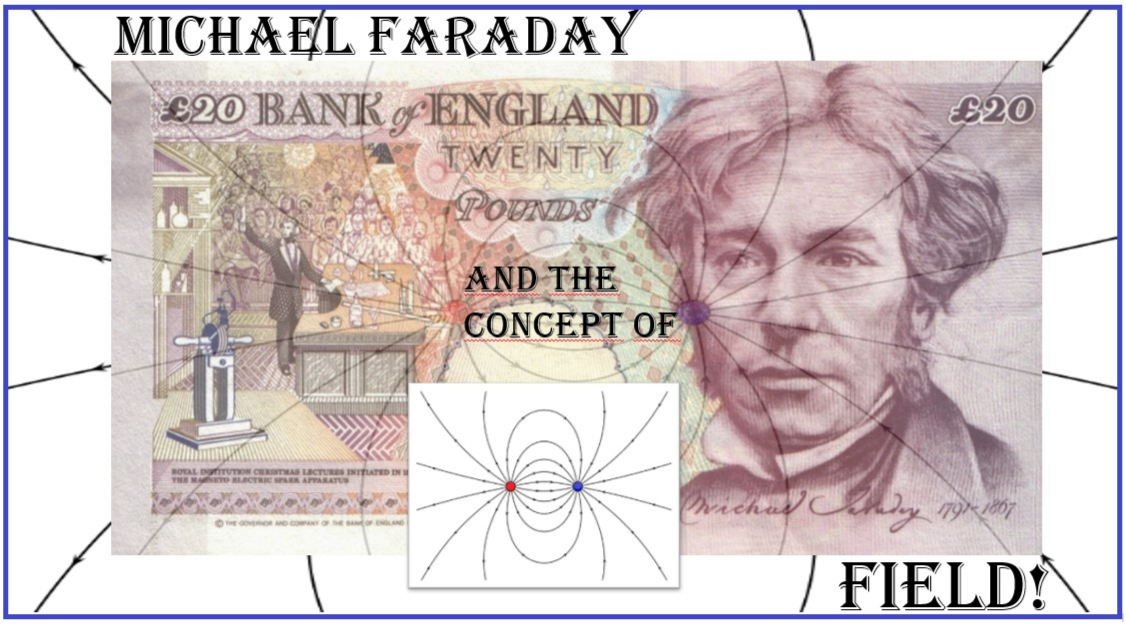

Figure 1.4 - Faraday and the concept of field.

In other words, the concept of “action at a distance” is directly linked to the observation of magnets interacting with each other by thinkers of the seventeenth century, such as Francis Bacon and René Descartes, which were inspired by the “Cosmic Magnetic Philosophy” of William Gilbert [4]. However, the idea of a body acting in a place that it is not present, or a “spooky action at distance”, baffled the philosophers and scientists that succeeded Newton, among them Michael Faraday. To solve this problem, Faraday devised the concept of “field” in reaction to the idea of “action-at-distance” theories. In this way, we have the birth of a new vision of material world. The matter is linked to the line of forces represented by the field. This field is a non-material entity with physical reality. A field is a physical quantity that changes the properties of the space around the object connected to this field, with specific values for each point in space-time. Now, beyond matter, space and time, the mankind recognized the existence of the concept of fields of force, solving the problem of the action at distance. The objects are connected by something invisible, but real, with physical meaning, associated with momentum, forces and energy.

Having this concept, it did not take long for the idea of field of force to become more important than the concept of “object” because for practical purposes, the changes in space and time are more representative than the object that created them. We are surrounded by different types of fields, each one linked to some property of matter, like mass, electricity or magnetism. Ironically, the magnetic field lines, that gave to Faraday the idea of line of force, are not considered lines of force, because unlike the electric field, they do not point in the same direction as the force acting on a charged particle.

Using iron fillings and magnets, Faraday create a new paradigm in which is based the modern physics, such as the quantum field theory which combines the classical theory of field, special relativity, and quantum mechanics, or the Higgs field associated to the Higgs boson. Using Ferrolens, magnets and light you can see a new family of patterns. The questions here are: what these patterns represent? What can be explored with this device? How the understanding of the physics behind the phenomenon can improve my knowledge of the physical reality? The aim of this book is to present the Ferrolens to the reader in a scientific context, answering some questions and motivating the reader to create new ones.

Figure 1.5 - Image of light patterns in a Ferrocell subjected to a magnetic field.

1b. Attracted by Magnetism

The study of magnetism is an old science. In James Livingston's book on magnetism [5] we find the following relationships and applications in different areas such as astronomy (magnetic fields of planets and stars), biology (magneto-sensitive animals), geology (geomagnetism and magnetic minerals), medicine and health magnetic resonance), Technology (motors, computer hard drive and memories), physics (Faraday's law), defense systems and weapons production (missiles and radars), entertainment (toys, games and magic), cinema (Star Trek and X-Men), Pseudoscience (magneto-therapy, extrasensory perception and dowsing) and literature (Plato, Gulliver's Travels and Tales of the 1001 Nights).

When we say that “magnetism is a property of matter”, does it mean that everything has a magnetic field associated? Yes, it does! Magnetism occurs in different forms and degrees. The object most associated with magnetism is a magnet. This is a common experience, and magnets can be found naturally in nature, like lodestone, which can attract iron. Using two magnets, we can verify forces of attraction and repulsion. However, you can think, “a piece of rubber cannot attract magnetically anything!” Yes, this is true because magnetism in matter has different behaviors. The classification of magnetism into magnetic materials is quite technical, with jargon names known as ferromagnetism, ferrimagnetism, diamagnetism, paramagnetism, sperimagnetism [6], and so on. Magnetism goes far beyond the "Force" case of Star Wars science fiction because it is present not only in all living things but also in all inanimate objects. As in the case of the world of Luke Skywalker and Darth Vader, the magnetism of a magnet has two poles, one called north and one called south. Curiously, all the magnets we know have the two poles always present, not being observed the presence of a magnetic monopole, that is, a north pole alone walking around. In the case of magnetism, the opposite and complementary pole is always present, so that the two sides of this force are never isolated, unlike the case of the electric charges, which can be separated, or in the case of the force of gravity, which presents only an attractive type of charge.

Figure 1.6 –The study of magnetism is an old science, as we can see in this engraving “Lapis Polaris Magnes” from Janvander Straet around 1580, showing a philosopher, Flavius Blondius, in his chamber studying the loadstone, the magnet and the development of compass [7]. The Chinese, Arabs and Persians used such compasses since the 11th century.

This is one of the basic equations of the physics of electromagnetism: the non-existence of magnetic monopoles. Just as in the case of Taoism where there is the concept of complementary opposites of Yin and Yang, there is no third type of magnetic pole, only the north and south poles. The possibility of the existence of magnetic monopoles was proposed by the brilliant British physicist Paul Dirac, and the search for magnetic monopoles is an area of immense research, since the recognition of a magnetic monopole could give a Nobel Prize, but the results obtained so far could not be conclusive [3].

Figure 1.7 – A lodestone is a naturally magnetized piece of mineral, and this lodestone is in the Hall of Gems of the Smithsonian. But how this loadstone get magnetized? According to the information of the National Museum of Natural History [8], Washington, D.C., lightning created this lodestone, a permanent magnet. Steel paper clips cling better to areas where the strongest current travelled. In this way, to make a lodestone, you need three things: 1) one iron ore, in case magnetite; 2) tiny, oriented inclusions of another iron mineral, in this case maghemite; and 3) a bolt of lightning.

This pairing of poles is called a magnetic dipole, and these dipoles can be observed from the particles known as electrons, to gigantic stars, occurring also in everyday objects such as the magnetic needles of the compasses or refrigerator magnets. How do we know this? Only by observing the magnetic fields in the objects, we cannot deduce this through the pure reasoning on these properties, we need to measure the magnetic fields. In SI units, the magnetic field is measured in tesla (T), and in gaussian-cgs units the magnetic field is measured in gauss (G), so that the conversion is 1 T =

10,000 G. Magnetometers are devices used to measure the magnetic field, and there are different types of magnetometers depending on the physical principle that it uses to measure the magnetic field.

The existence of the Earth's magnetic field is known for many centuries and it was applied for spatial orientation associated with navigation. This magnetic field exists due to the convection in the iron-nickel alloy of the outer core. The swirling metal carries an electric current and creates a magnetic field called magnetosphere, which has poles like a bar magnet, like in Fig. 1.8(a). The magnitude of the Earth's magnetic field at its surface ranges from 25 to 65 microteslas (0.25 to 0.65 gauss).This may seem little, but the magnetosphere shields Earth from harmful cosmic rays. Periodically, Earth's magnetic poles flip. The magnetic north pole moves to the geographic south, while magnetic south moves north. These flips happen irregularly, typically over spans of tens thousands to hundreds of thousands of years. Even the sun has gigantic magnetic fields, and its effects can be seen by the patterns of sunspot.

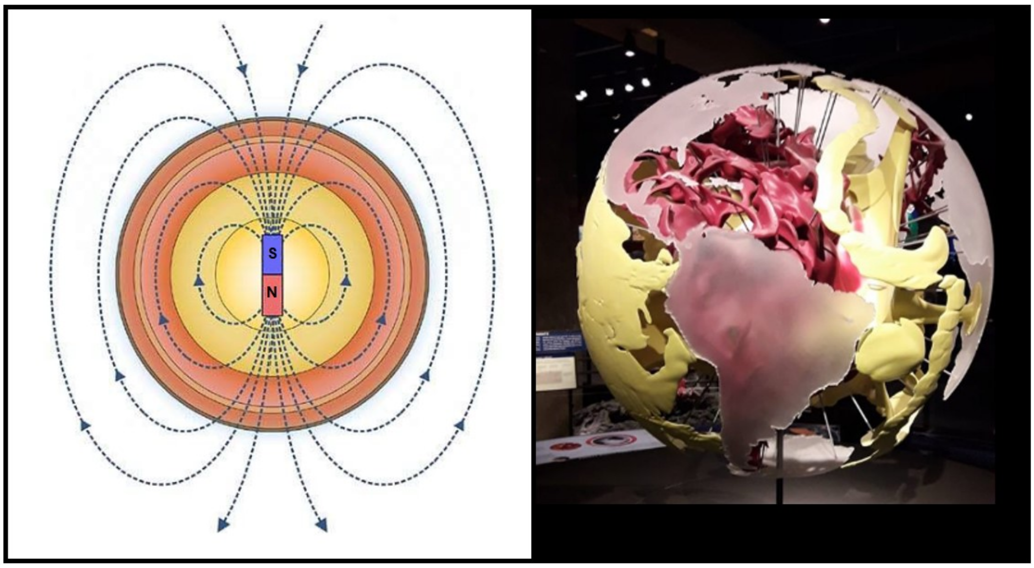

Figure 1.8 - At the center of the Earth there is a solid inner core, around two thirds of the size of the Moon and composed primarily of iron. At the temperature of 5,700°C, this iron is as hot as the Sun's surface, but the intense pressure caused by gravity prevents it from becoming liquid. On the other hand, there is the movement of liquid iron in the outer core, caused by convection and Earth's rotation, and this flow of liquid iron generates electric currents, which in turn produce magnetic fields. Charged metals passing through these fields go on to create electric currents of their own, and so the cycle continues. This self-sustaining loop is known as the geodynamo. In (b), there is the scientific model of Earth representing a snapshot in time in the American Museum of the Natural History, New York City, USA [9]. They explained their model as the follows: Solid mantle rock is represented in three ways: The hottest rock is shown as yellow; the coolest is shown as red; and the rock with temperatures in between the two is shown as empty space. Over time, as hot, less dense solid rock rises, cooler, denser solid rock sinks to take its place.

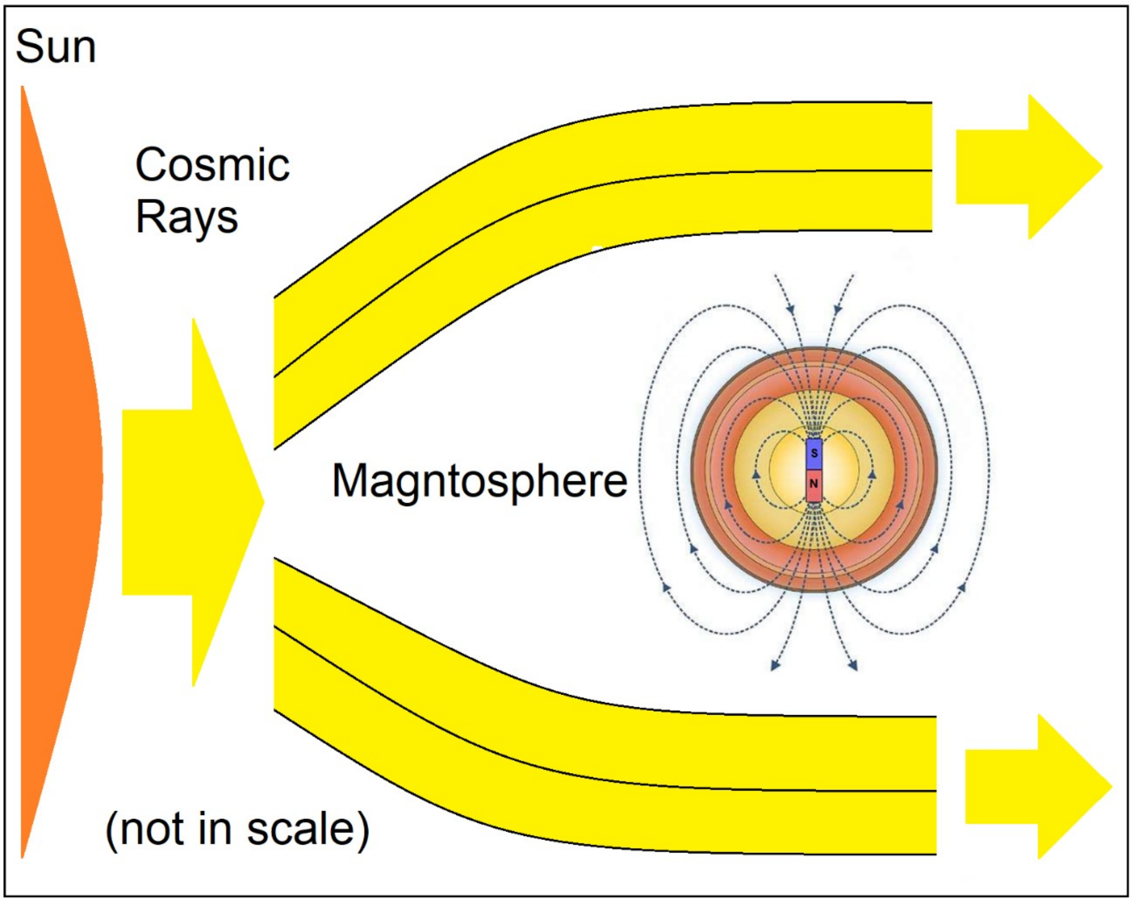

Figure 1.9 - The magnetosphere deflects the charged particles streaming toward us from the Sun [9]. Without this invisible shield, the barrage of ions from the solar wind would make Earth's surface uninhabitable. According to the information at the American Museum of natural History in New York city, the iron core of Mars, in contrast, has cooled and almost entirely solidified so Mars has only a tiny magnetic field. With little protection, Mars is bombarded by deadly ions, making life on its surface virtually impossible.

Figure 1.10 – Around 1800, Alessandro Volta invented the electric pile. Using a similar device as this pile, Oersted discovered the action of an electric current in the needle of a compass.

In this way, we can saw the existence of the magnetism from the scale of subatomic particles to the size bigger than planets or stars, showing that this phenomenon is ubiquitous and practically omnipresent, so that it raises the question: what is the essence of magnetism? The short answer for this question is that magnetism is essentially quantum and relativistic phenomenon created by the motion of electrical charges. Electricity and magnetism are intrinsically connected, and this discovery started with the invention of the voltaic pile by Alessandro Volta around 1800, as it is shown in Fig. 1.10. The availability of electric batteries has enabled the scientific community to have easy access to electrical currents in electrically conductive wires. In 1820, Oersted discovered that a long wire carrying electric current could change the natural orientation of the magnetic needle of a compass placed in its neighborhood, in a experiment exemplifying the action of the serendipity in science, as it is shown in the currency of 100 crowns (hundrede kroner) of Fig. 5. The first accurate analysis of this phenomenon was done by the French physicists Jean-Baptist Biot and Félix Savart, who were able to formulate a law describing the magnetic field produced by an electric current. Another French physicist André-Marie Ampère considered that Oersted's demonstration has represented the direct interaction between electric currents existing in the magnet with the electric current present in the wire, claiming that there is no reason to distinguish the action of an electrical current in a wire upon a compass from the magnetic action of Earth upon the compass. He went further and claimed that the same explanation is valid for the interaction between two magnets. However, if you think about permanent magnets, there is no obvious electric current, so we must describe these magnets in terms of the atoms and how they align, and this is only explained by the context of the quantum mechanics. In this way, we can see that magnetism is a quantum phenomenon. In addition to this, the magnetic properties of fundamental particles, known as spin, can be only be described as a quantum phenomenon.

We have seen that magnetism is intrinsically linked to electricity. At same way that electric current generates a magnetic field, moving magnetic field can produces electric current, and this is described by Maxwell's electromagnetic theory. This property was used by Einstein in his famous paper "On the electrodynamics of moving bodies" to motivate the discover of the Theory of Special Relativity [11]. Einstein wrote about *the moving magnet and conductor problem*:

> "It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighborhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighborhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case."

Figure 1.11 - In his thought experiment about *the moving magnet and conductor problem*, Einstein observed an asymmetry, according to Maxwell's equations, the charges in the conductor experience a magnetic force in the frame of the magnet and an electric force in the frame of the conductor, so that the same phenomenon would seem to have two different descriptions depending on the frame of reference of the observer. This was one of the problems that formed the basis of Einstein's development of the theory of relativity [3, 11-13]. The statue of Einstein holds in its left hand a paper on which are shown the mathematical that summarizes three of his most important scientific contributions, among them $E = mc^2$, which relates mass directly to energy. This equation is part of the paper beginning with the moving magnet and conductor problem.

One of the best available descriptions of how special relativity transforms the role of magnetic was done by Richard Feynman. Feynman describes an example of a electrons in a wire moving at constant velocity v through the wire, and an external electron that also moves at v nearby and parallel to the wire. Feynman points out that in classical electrodynamics, the electrons moving within the wire and the external electron both generate magnetic fields that cause them to attract. In this way, from the view of an observer watching the wire, the forces that attract the external electron towards the wire are entirely magnetic. The Youtube Channel *Veritasium* done an interesting video explaining how special relativity makes magnets work [13].

To sum up, magnetism can be understood from the perspective of classical physics, quantum phenomena and special relativity.

1c. Ferrofluids

In order to understand the magnetic properties of ferrofluids, we have to think about the magnetism in materials, and how it affects the space around. The magnetism in the materials can be studied and ordered by the way which the material responds to the presence of the magnetic field. For the purpose of this book, we can present the magnetic materials as is shown in Fig. 1.12 in a very simplified way.

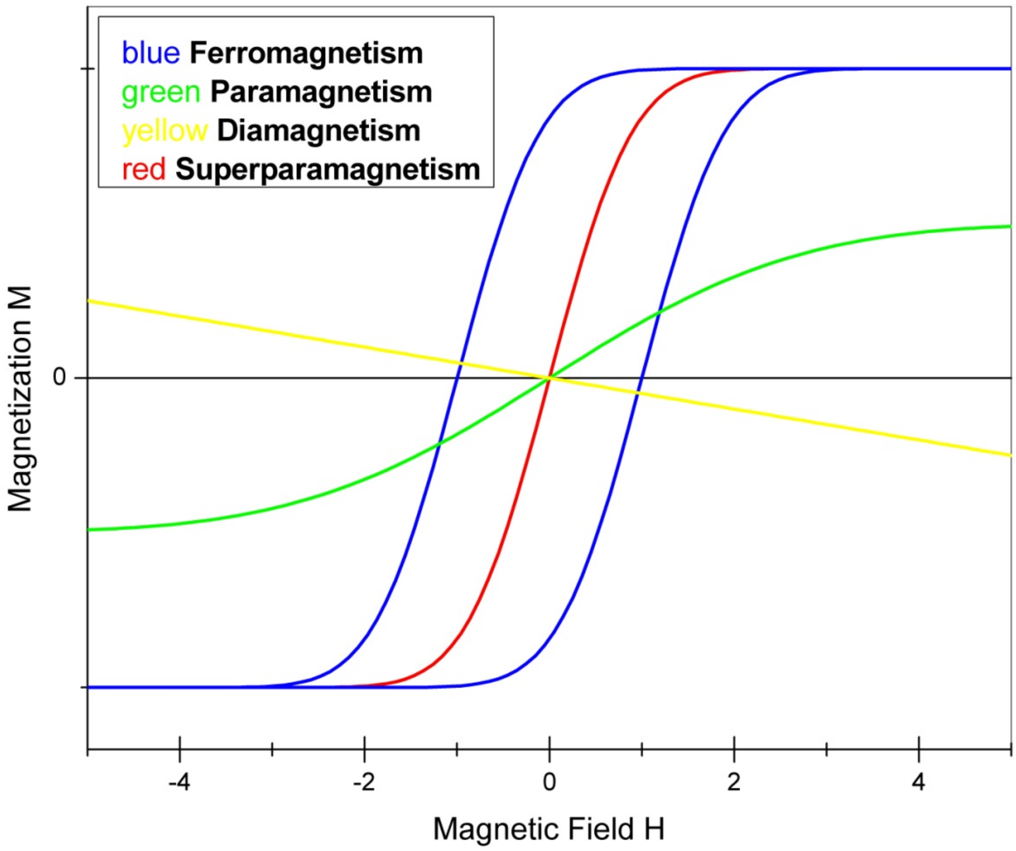

Figure 1.12 – Magnetization response of some materials for an external magnetic field H applied in the material.

When we talk about magnetic materials, the common sense about these materials thinks of iron, nickel or magnetite, represented in blue for the hysteresis curve of Fig. 1.12, known as “Ferromagnetism”.

When the magnetization is not so strong as the previous case, we have the behavior known as "Paramagnetism", like the oxygen molecule, or the majority of the elements in the periodic table, represented in green in Fig. 1.12. The temperature is a very important parameter in this classification of magnetic materials, and when you heat a ferromagnetic material it can turn in a paramagnetic material.

When a substance generates a magnetization that opposes to the applied magnetic field, it is called diamagnetic and they are associated to "Diamagnetism". By the way, all substances present the behavior of diamagnetism, represented in a very simplified way in yellow in the diagram of Fig. 1.12, however this behavior is masked by other magnetic behaviors, such as ferromagnetism or paramagnetism, and only the substances that have no traces of these responses to the magnetic field are called diamagnetic. The classification of magnetic materials is much more complex that the behaviors that we have described and they are not restricted just to the response of magnetization to the magnetic field.

Ferrofluids are made by nanoparticles of iron covered by a surfactant in a carrier liquid, such as oil or water, as it is shown in Fig. 1.13, and in ferrofluids we have the behavior known as "Superparamagnetism", and this form of magnetism appears in small ferromagnetic nanoparticles. Ferrofluid is directly linked to nanotechnology because the nanoparticles of iron are around a few nanometers.

There are some interesting mechanisms present in this material to explain its behavior in the plot in red of superparamagnetism of Fig. 1.12. First, without an external magnetic field, the magnetization can randomly flip direction under the influence of temperature in these small nanoparticles due to Brownian relaxation. The typical time between two flips is called the Néel relaxation time, and in the absence of an external magnetic field, the magnetization of the overall system appears to be zero, with the material presenting the typical behavior of the superparamagnetic state. Second, applying an external magnetic field, the particles are magnetized like what happens in a paramagnet. However, their degree of magnetization is much larger than that of paramagnets, similar to those observed in ferromagnets. This degree of magnetization is known as magnetic susceptibility, and it is a dimensionless proportionality that indicates this degree of magnetization of a material in response to an applied magnetic field. The combination of behaviors of ferromagnetism and paramagnetism creates the emergence of the superparamagnetism.

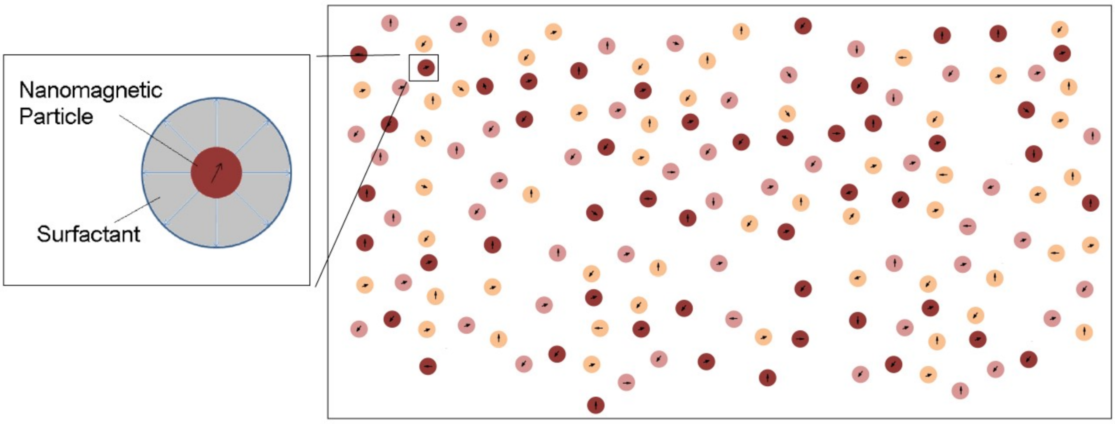

Figure 1.13 – Schematic of nanomagnetic particle dispersed in a carrier liquid whithout magnetic field. The size of the nanomagnetic particle is around a few nanometers. The different colors here have no physical meaning.

For the porpoise of using ferrofluids in magneto-optics, ferrofluid should be diluted because dense ferrofluids are opaque for light transmission. When an optically isotropic dilute nanomagnetic fluid is subjected to an external magnetic field, it can exhibits optical anisotropy, because a large number of these nanoparticles aligned forming needle-like structures. Hence, when light beams traverse a ferrofluid and the direction of propagation of light is transverse the applied magnetic field, we can observe magneto-optical effects. For example in Fig. 1.14, we are presenting a schematic of nanoparticles forming the structure of needles for a ferrofluid in the presence of a magnetic field.

There are different types of ferrofluid, for example, the type of metal used for the nanoparticles or different types of liquid carrier. In addition to this, in some cases there is the addition of non-magnetic nanospheres, or the shape of the nanoparticles. All these possibilities can change significantly the properties of the ferrofluid.

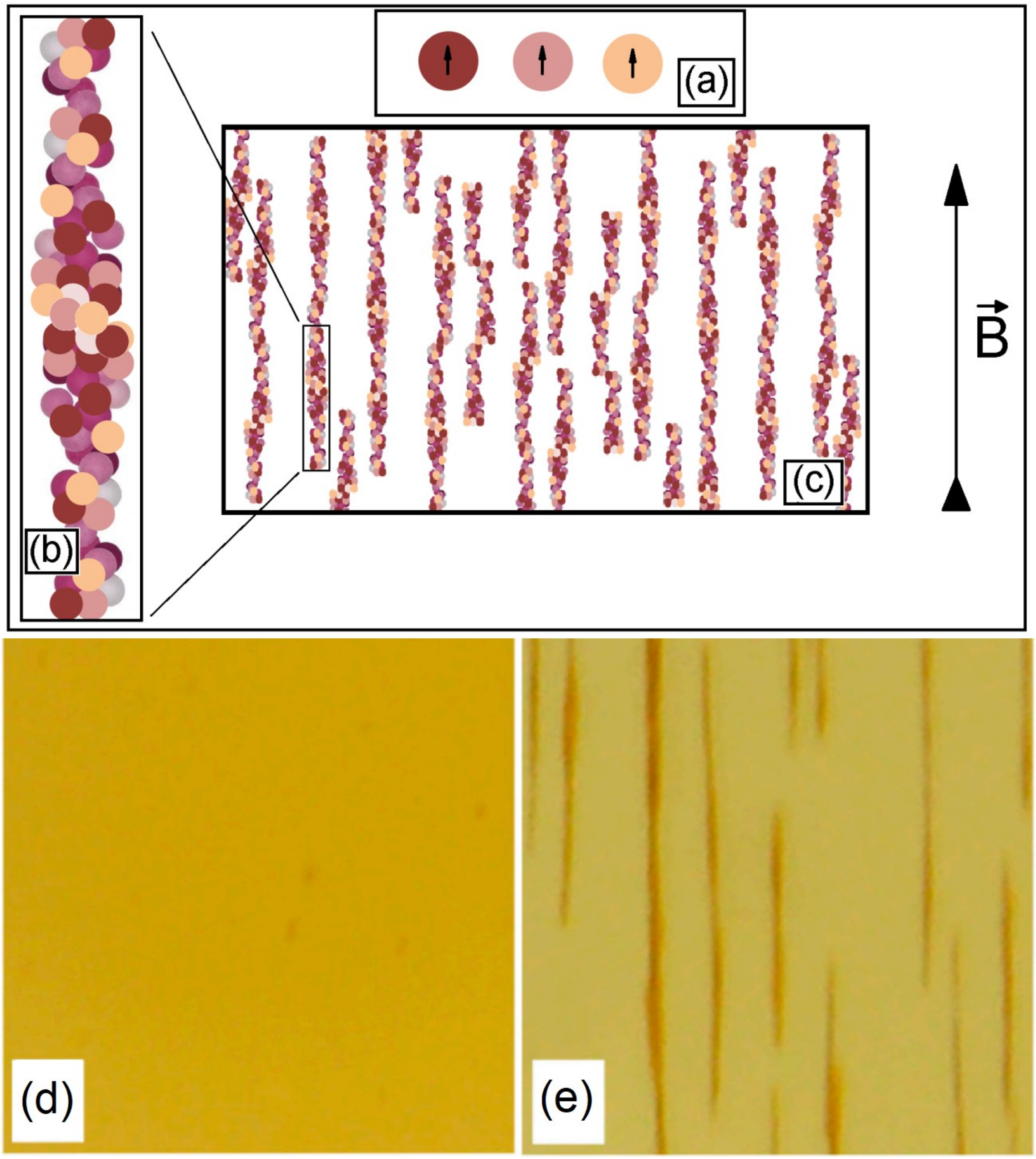

Figure 1.14 – Needle-like structures in a ferrofluid due to the presence of a magnetic field. In (a) we represented some magnetic particles with their respective magnetic orientation momentum indicated by an arrow. In (b) a needle-like structure composed by the assembly of many magnetic nanoparticles, and in (c) some of these needles aligned with the magnetic filed **B**. In (d) an image of the ferrofluid obtained with an optical microscope with no magnetic field, and in (e) the image of the formation of these needles in the ferrofluid in the presence of a strong magnetic field.

Ferrofluids are also known as a complex fluids or smart fluids, because they exhibit unusual physical responses, such as solid-like and fluid-like behavior at same time, depending on the direction that you are observing these systems. In the case that we are describing here, in the presence of the magnetic field, the ferrofluid resembles the structure of solids in the direction of the magnetic field, and behaves like a liquid in other directions, with no spatial order. This property is associated with different kinds of possible anisotropic effects in ferrofluids. One of these effects is known as "Retardance" R [14], which is related to the refraction index, and this retardance is related to the concentration of the ferrofluid, as it is shown graphically in an approximated function R(**B**) in Fig. 1.15, for different values of ferrofluid concentration, showing the general behavior of a sigmoidal curve as a function of the magnetic field. We have to consider that when the magnetic field **B** is zero, the retardance is also zero. For more information about the physical-chemical properties of ferrofluids.

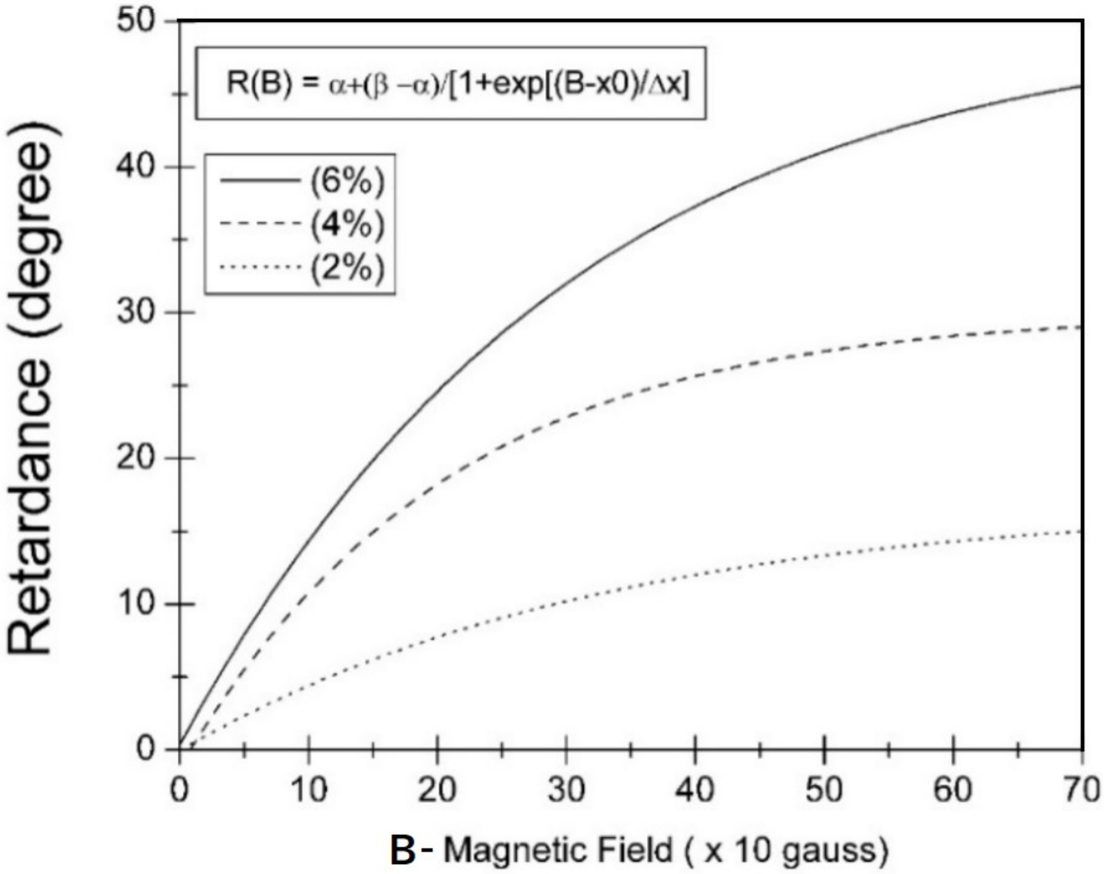

Figure 1.15 – Illustrating the retardance R in function of the magnetic field **B** using sigmoidal functions as an approximation for different values of ferrofluid concentration.

1d. Magneto-Optics

The main concept in magneto-optics is the use of magnetism to influence the light propagation. This usually involves changing the physical properties of the medium through which light is travelling, such as the polarization of the light or changing the intensity of a light beam interacting with the medium. For the case o solids the most common effects of light transmission are the Faraday effect or the Voigt effect and the magneto-optical Kerr effect. For the case of liquids, we have the Cotton-Mouton effect, and it is attributed to the “lining up” of molecules by the magnetic field. For the case of ferrofluids that we are using here is the “lining up” of nanoparticles creating microstructures like needles around 100 micrometers.

In general, all matter can generate some degree of magneto-optical effect, however the magneto-optical effects can have different magnitudes depending on the nature of the medium. For the case of diamagnetic materials, the magnetic moment induced is due to the changing of the electronic trajectories under the effect of the applied magnetic field, and consequently the magneto-optical effects associated are very weak.

In the case of paramagnetic materials, the magnetic moment results from the electronic rearrangement in the orbital states, in which the degeneracy is broken by the direct action of the magnetic field, with the Zeeman effect, in which electrons with the same energy in the absence of the magnetic field have different energy states in the presence of the magnetic field. The degeneracy breaking of the direct action of the magnetic field in the orbital momentum or the spin, and indirectly due to the coupling between the spin momentum connected to the orbital momentum, known as spin-orbit interaction. As the consequence, the magneto-optical effects in paramagnetic materials can have a strong magnitude and they are temperature dependents, because the magnetic momentum of the medium is temperature dependent.

In ferromagnetic materials, the magnetic interactions between the spin momentum are too strong, and in this case, the spin-orbit interaction is the main cause of magneto-optical effects, which are of bigger magnitude, when compared with the effects observed in the materials previously mentioned.

The magneto-optics of ferrofluids involve the properties of superparamagnetism in a complex fluid. In this case nanomagnetics particles are dispersed in a liquid, such as water or mineral oil, and light propagation through such fluid will be governed by scattering properties of individual particles. The ferrofluid is diluted in order to be sufficiently transparent for optical investigations. For example, the ferrofluid used in Ferrolens is prepared with ferromagnetic single domain particles in mineral oil. Without magnetic field, the liquid has a brownish color. When the magnetization in such particles is saturated, they behave like tiny magnets. These magnets follow the direction of applied magnetic field, forming nanostructures in the shape of needles. When light interacts with these needles, we can observe light diffraction under certain conditions. The light diffraction is perpendicular to the propagation direction of light, as it is represented in Fig. 1.16

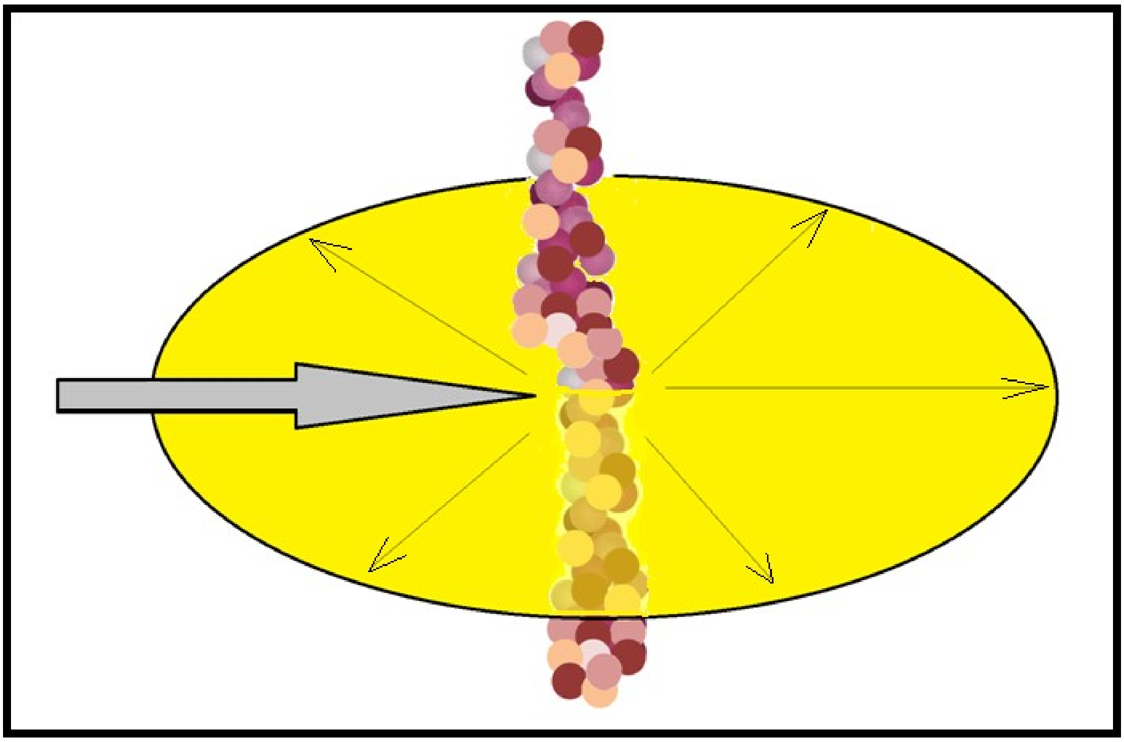

Figure 1.16 - Schematic of light diffraction in a nanoneedle, which was created in a ferrofluid subjected to a magnetic field due to the agglomeration of nanoparticles.

This light diffraction is similar to that produced by a wire. This pattern is different from that produced by a wire because there are no individual fringes in the case of ferrofluids. The absence of well-defined spacing between fringes in ferrofluids is due to multiple diffraction. For example, in Fig. 1.17 we are presenting a diagram of this multiple diffraction, and when light hits the magnetic fluid it diffracts from the first layer of needles. We have a second diffraction from the next layer, and so on. In this way, light diffracted by a spatial grating of magnetic needles is a sum of a sequence of diffraction from individual needles. The final pattern is a combination of diffraction and interference.

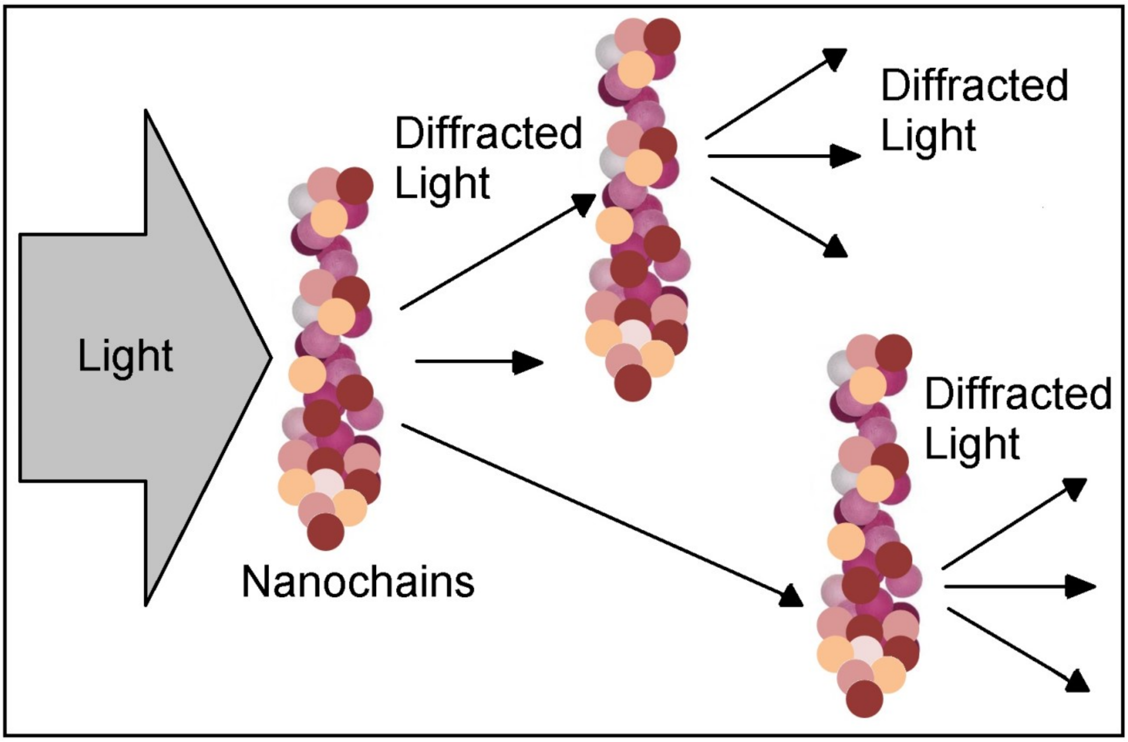

Figure 1.17 – The green arrow represents light entering in the ferrofluid, and light is diffracted by a grating of magnetic needles structures composed by nanoparticles, resulting in a combination of diffraction and interference.

In Fig. 1.18 we present three images of the light diffraction in ferrofluids using Ferrolens in the presence of a magnetic field using a green laser. In each case, we have used different orientations of the magnetic field in order to observe the effects of chain orientation in the ferrofluid.

This light diffraction depends on the light polarization caused by Faraday rotation. The Faraday rotation was discovered by Michael Faraday in 1845, when he observed changes in the light polarization of a beam of linearly polarized light sent through an isotropic dielectric placed in a magnetic field. The light diffraction is related to the direction and the intensity of the magnetic field.

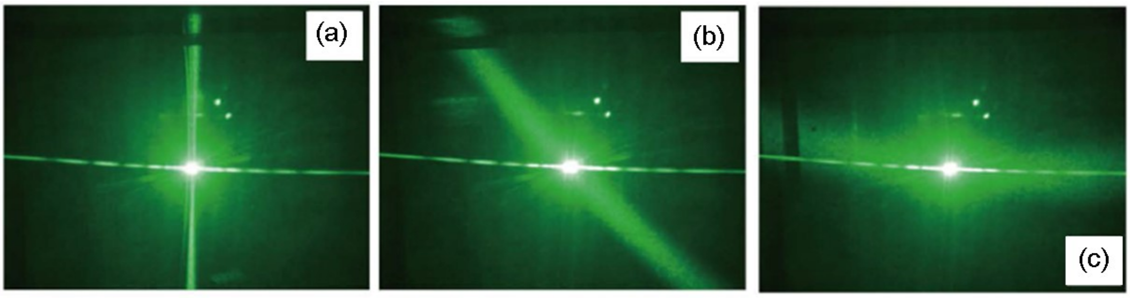

Figure 1.18 – Example of light diffraction in ferrofluid for different configurations of magnetic field.

This is a particular case of the magneto-optics of ferrofluids. Many other factors are relevant to the magneto-optics of ferrofluids, such as the nature of the nanoparticles, the type of the liquid carrier, the concentration of nanoparticles, or the intensity of the magnetic field and this is an active field of research about these materials. For example, the concentration of nanoparticles or the type of liquid carrier may favor some wavelengths, and sometimes obliterate others.

1e. Magnetostatic

Magnetostatic is the part of physics which study the properties of static magnetic fields created by different configurations of magnetic poles. One of the basic properties of this type of field is that it is a vector field with mathematical properties associated to it, like addictive property, in which the intensity of a field of one charge is summed vectorially to the intensity of another field generating charge. In many textbooks the study of magnetism is preceded by the study of electrical charges, which create electric fields, and the properties of the electric fields are analogous to the properties of magnetic field.

The magnetic field can be obtained by passing electric current in a solenoid or by the presence of a permanent magnet [15]. In this text, we use several examples of demonstrations with Ferrolens with magnet field arrays created by the combination of permanent magnets or using solenoids.

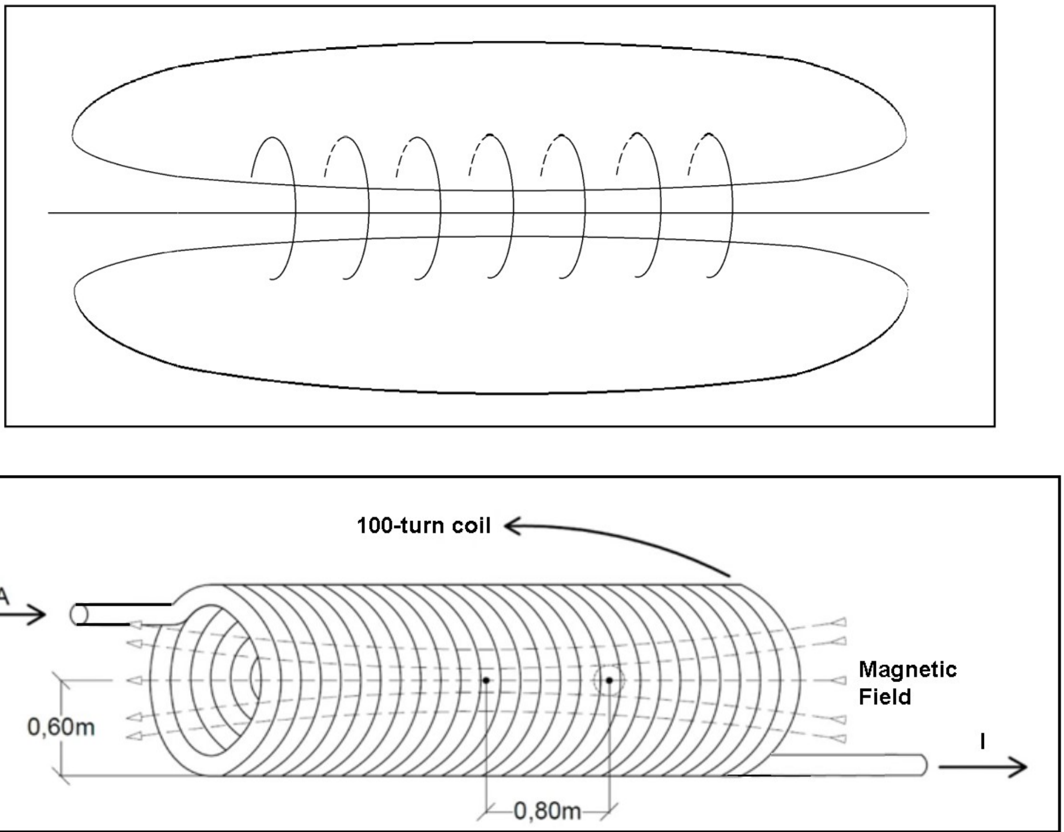

Figure 1.19 - A common and important magnetic device is the solenoid, which is a coil of wire wrapped around a cylinder in (a). The magnetic field arises when never current is run through the wire within the coil. (b) The magnetic field inside a 100-turn solenoid.

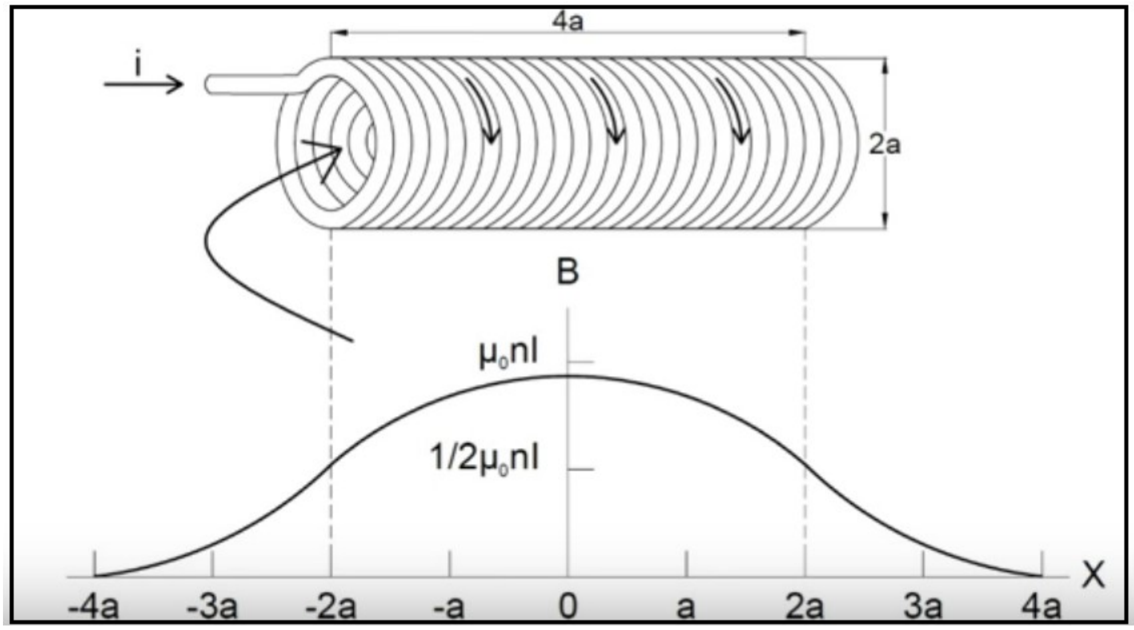

Figure 1.20 – Intensity of the magnetic field on the central axis of a solenoid.

Considering the case where the electric current is constant, we can obtain a static magnetic field with a solenoid. In this way, the magnetic field of the solenoid depends on its position on the space in relation to the solenoid. For long solenoids, those whose lenghts is much larger than their width, the magnetic field of the solenoid is more intense inside, right in the middle of the solenoid interior. This magnetic field is directly proportional to the constant μ_0 (the permeability of the vacuum) the numbel of turns of the wire in the solenoid n and the electric current I. In general, the intensity of the magnetic field in the central axis of the solenoid varies according to Fig. 1.20, For short solenoids, that is, those with a width greater than their length, the magnetic field is more intense in the regions near the wires where the electric current passes, as shown in Fig. 1.21. It is important to discuss the concept behind the permeability constant μ, which represents the constant that exists between magnetic flux density and magnetic strenght in a given medium. In certain metals, notably iron and nickel alloys, μ is substantially greater than μ_o. Because the magnetic properties of these alloys help in incresing the magnetic flux, and consequent magnetic field strenght, it is common to use such alloys as the core of the solenoids in order to increase the intensity of the magnetic filed inside the solenoid. The value of the μ_0 is:

$$\mu_0 = 1.256\ 637\ 062\ 12\ (19)\ \text{N/A}^2 \text{ or H/m (henry per meter).}$$

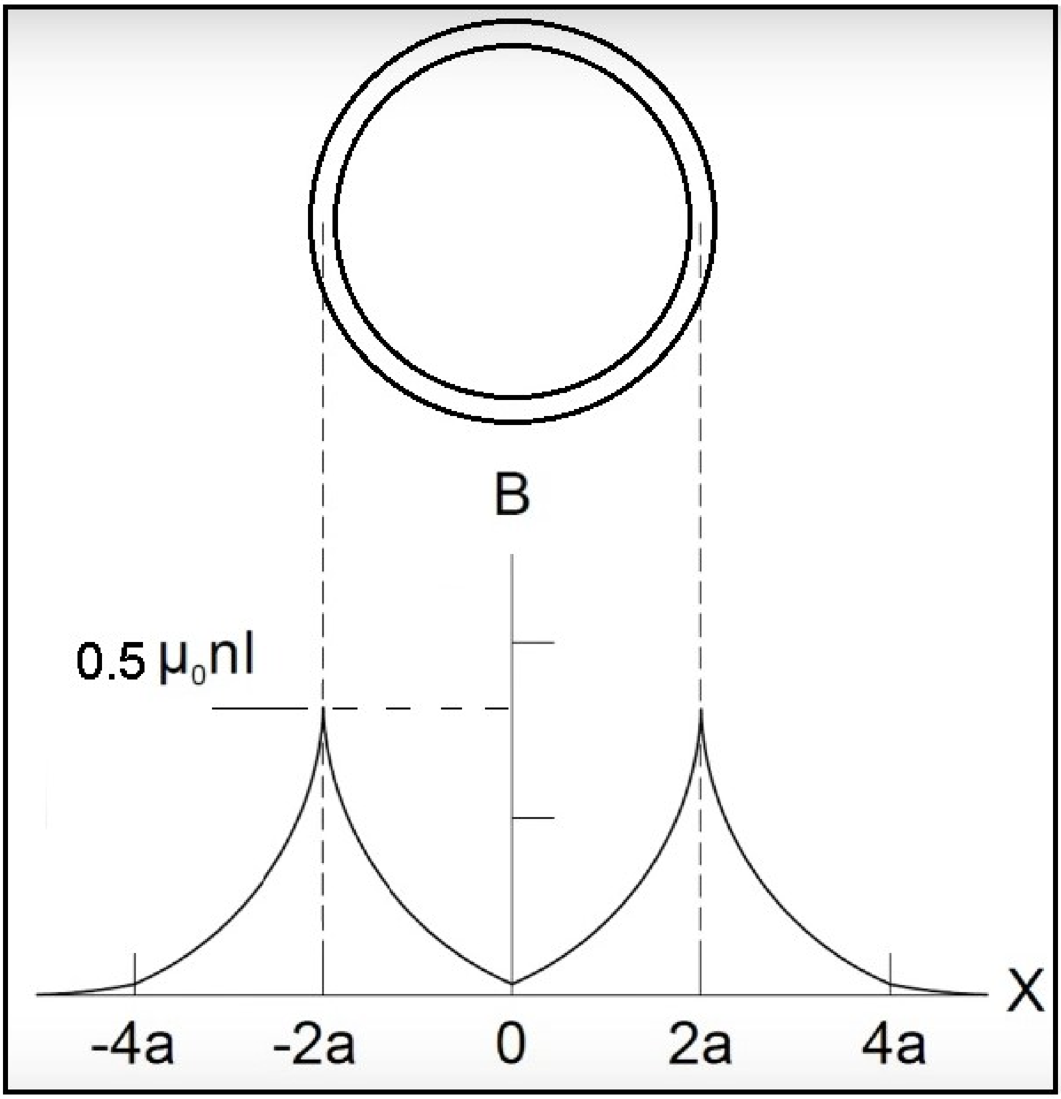

Figure 1.21 – Magnetic field of a short solenoid.

For long solenoids, those whose lenghts is much larger than their width, the magnetic field of the solenoid is more intense inside.

Now we will explore some features of the magnetic field of permanent magnets. These magnets are made from materials that possess a magnetization in the ausence of an applied magnetic field, such as rubber magnets (ferrite in a flexible base), ceramic (ferrite ceramic blends), Alnico (aluminum, nickel and cobalt), Samarian (samarium and cobalt), and Neodymiun (neodymiun, iron and boron). The need for different materials to make permanent magnets comes from the fact that there are several applications that have specific characteristics for each case, making some materials more suitable than others for each application.

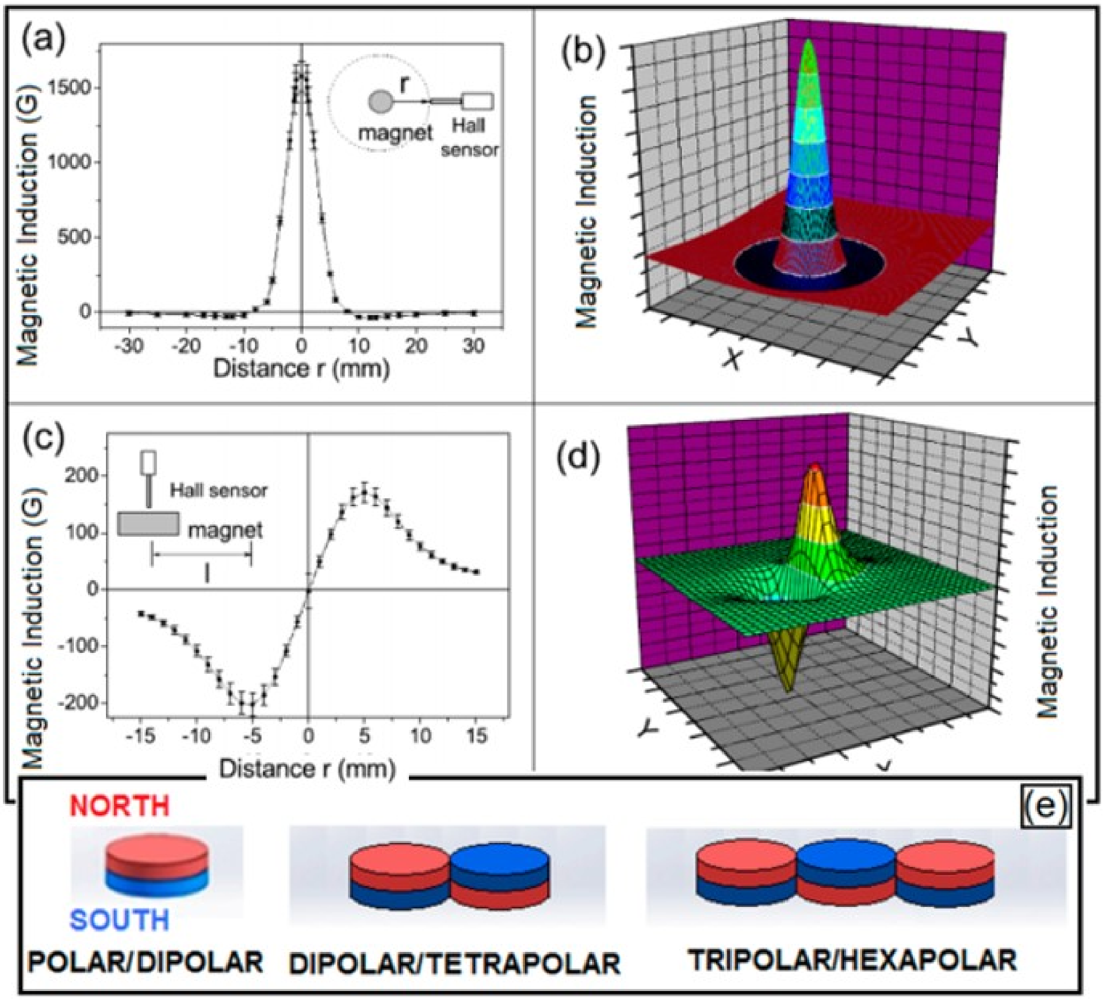

Figure 1.22. Plots of magnetic field from permanent magnets. In (a) the intensity of the magnetic field for monopolar configuration in 1D, and monopolar configuration in 2D. In (c) the intensity of the magnetic field in 1D, and the intensity of magnetic field in 2D for the dipolar configuration. In (e) some possible magnet confugurations using magneti discs.

For the case of Ferrolens, we use the magnetic field generated by neodimiun magnets, mainly because with the advent of magnets composed of rare earth material, it is possibble to obtain small magnets with magnetic fields on the order of several units of teslas. As far as we know, there is no existence of magnetic monopoles, but we consider the polar configuration of Figs. 1.22(a)-(b) when one of the poles of a magnet is facing directly the Ferrolens. The dipolar configuration is obtained whe we put a magnet with the two poles facing the Ferrolens, as it is shown in Figs. 1.22(c)-(d). Other configurations can be obtained combining different number of magnets of Fig. 1.22(e).

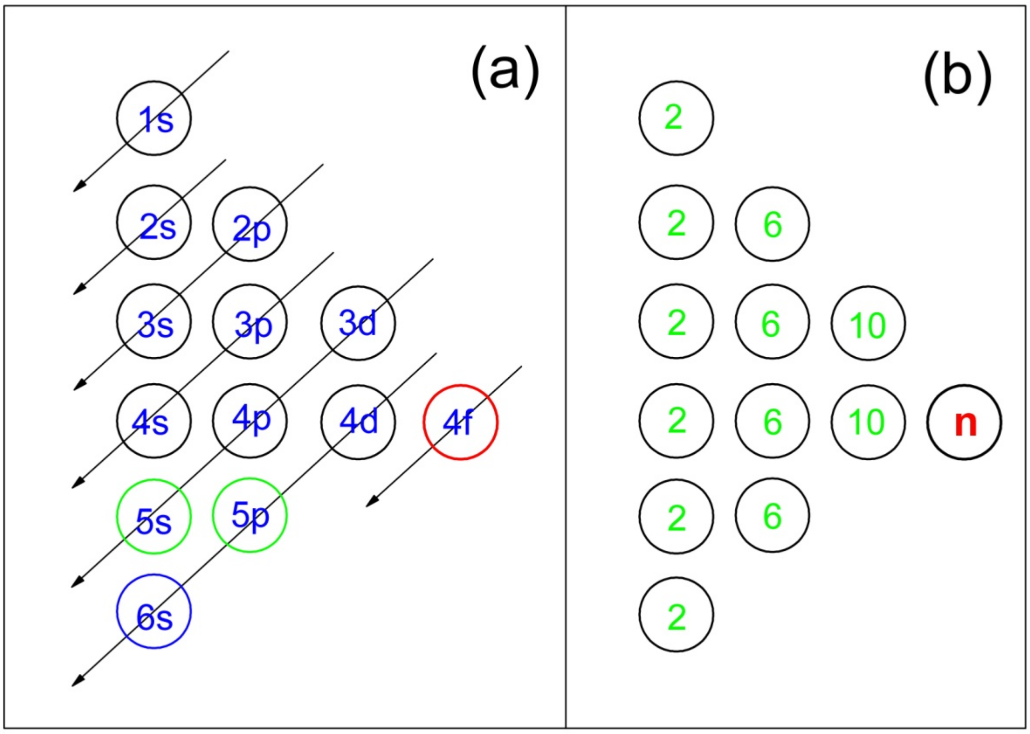

Figure 1.23. Pauli diagram of rare earth in (a). Number of electrons in each eletronic level for the case of Neodimiun n = 4, for the case of Samarium n = 6.

Why do some of these materials have intense magnetic fields? Using the Pauli diagram, we can see that a possible answer to this is because the more energetic level of these materials is further inside these atoms, with very complex configurations of level 4f, as can be seen in Fig. 1.23(a). The chemical properties of these atoms are given by the level 6s, while the electrons of level 4f are shielded by the levels 5s and 5p. In Fig. 1.23(b) we present the Pauli diagram with the number of electrons in each level for the case of rare earth elements, in which the number n = 4 for Neodimiun atom, and n = 6 for the Samariun element [16]. We show some examples of eletronic level configurations of electronic clouds of levels 2p for a single electron in Fig. 1.24. The level 4f presents electronic charges hilgly anisotropic compared with the previous orbitals, with multipolar distribution whose magnitudes and signs change the angular orbital momentum of the atom.

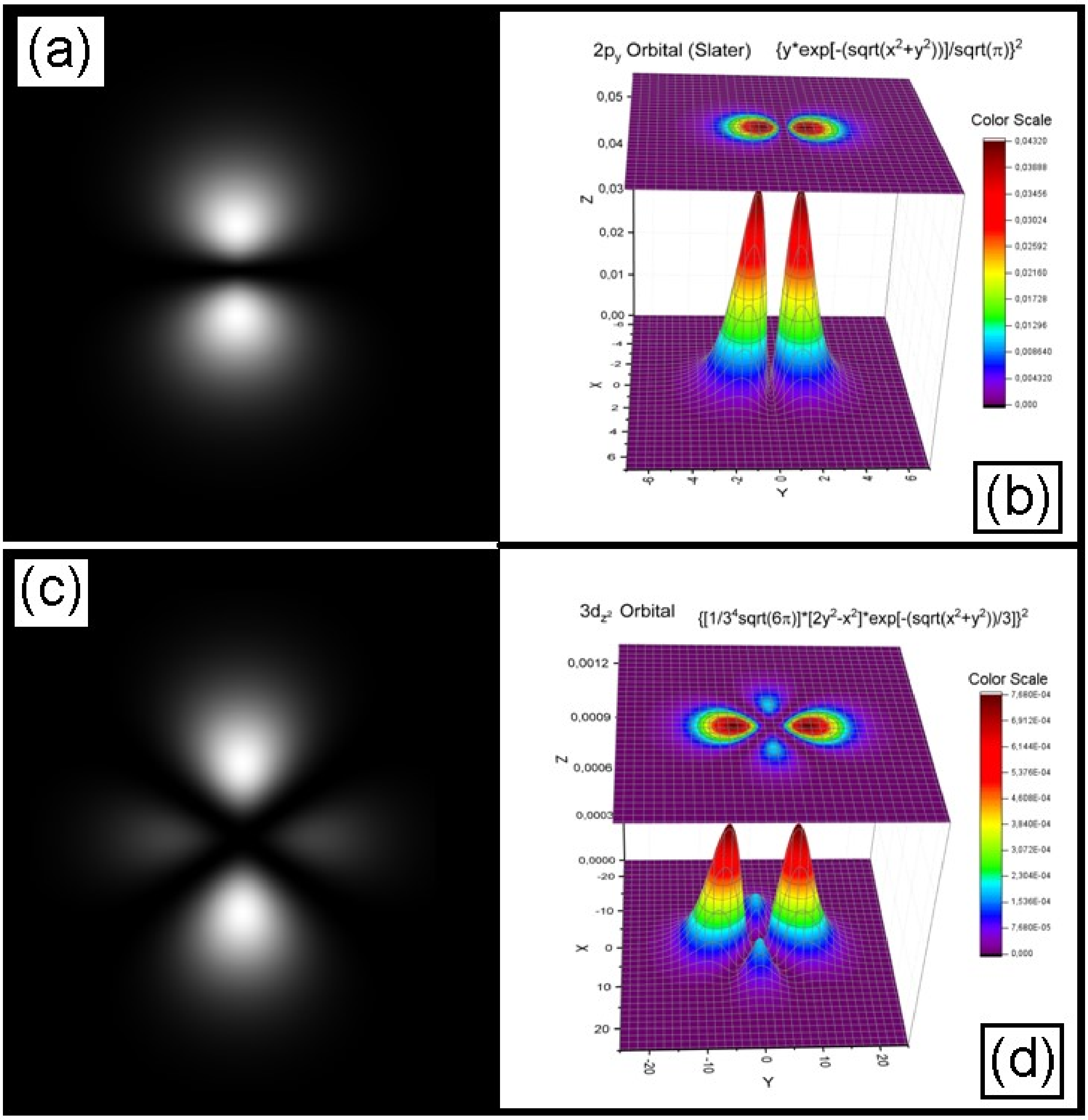

Figure 1.24 – Eletronic clouds and distributions of electrons in the levels 2p and 3d.

Using an array of magnets, we can make quantitative observations with Ferrolens by creating well-defined magnetic fields values, as it is shown in Fig. 1.25 and Fig. 1.26. The value of the magnetic field can be obtained using a magnetometer, like one that we are presenting in chapter 3.

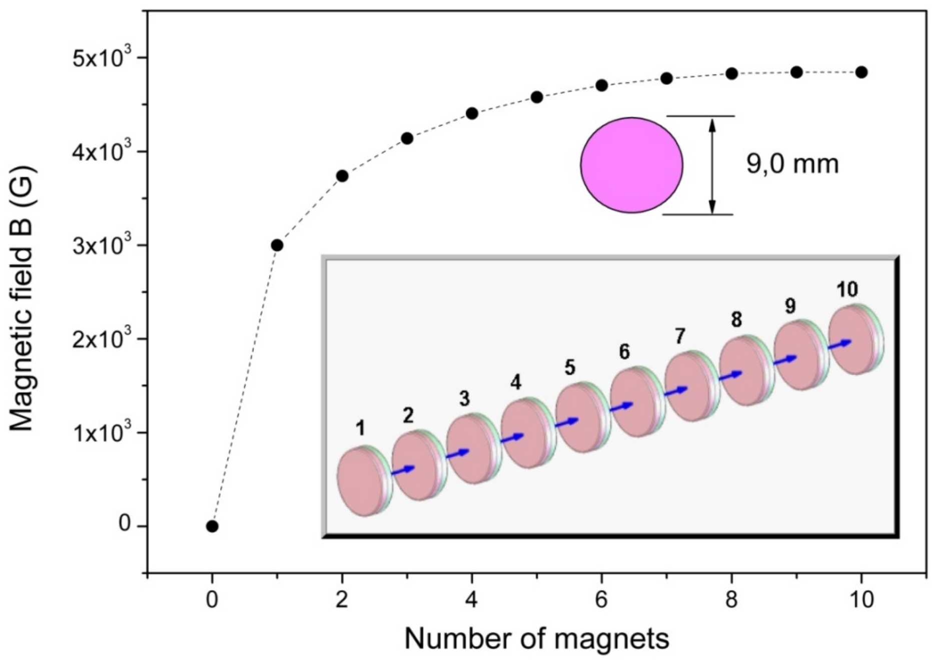

Figure 1.25 - Plot of the magnetic field intensity obtained by associating disc-shaped magnets (diameter 9,0 mm) to the point on the central axis of the first disc.

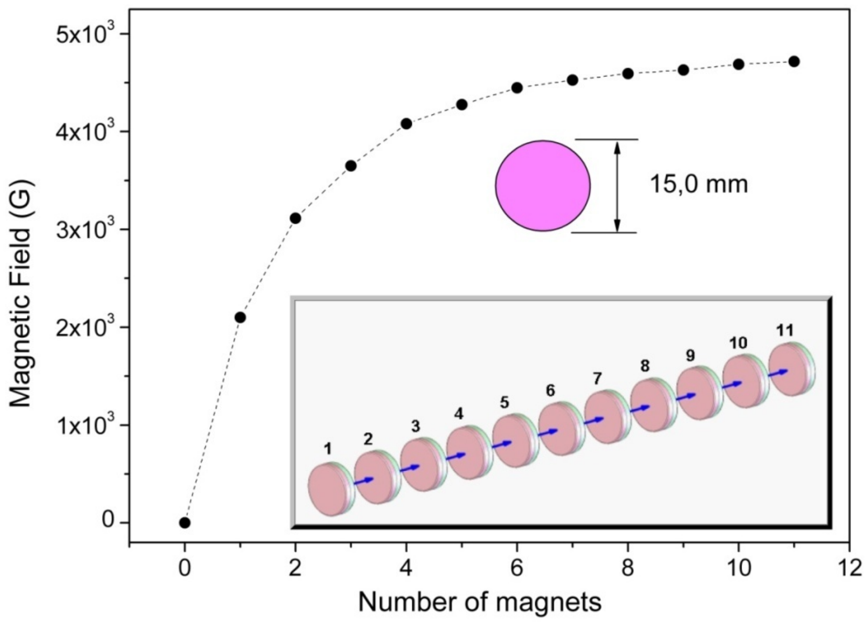

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Figure 1.26 - Plot of the magnetic field intensity obtained by associating disc-shaped magnets (diameter 15,0 mm) to the point on the central axis of the first disc.

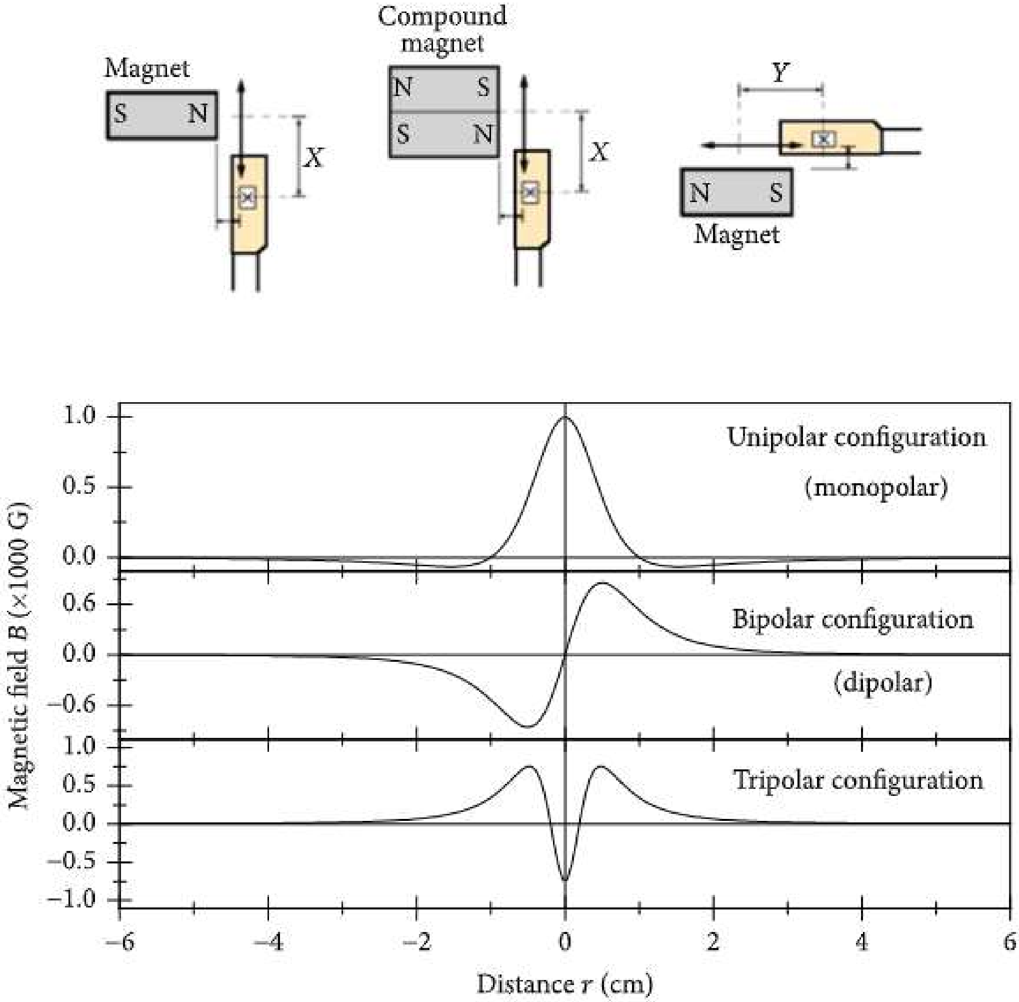

Figure 1.27 - Diagrams of magnets and Hall sensor probe. Plots of the magnetic field in at the plane of Ferrolens for monopolar, dipolar and tripolar configuration.

Using a gaussmeter, we can obtain the magnetic field intensity in some different points in the space, like the plane of the Ferrolens for the different magnets configurations of Fig. 1.27, in which is represented that the intensity of the magnetic field depends on the orientation of the Hall sensor in each point of the space.

Other magnet arrays can be obtained numerically with computer simulations, like Pic2Mag's Field Calculator made by Michael Snyder *Pic2viewer* [17] . Using this tool, we can simulate different aspects of the magnetic field, such as the vectors of the magnetic field and their related isopotentials.

Figure 1.28 – Example of simulator of magnetic field.

In Fig. 1.29 and Fig.1.30 we present some simulations using the patterns obtained with Ferrolens combined with a mirror showing the magnetic field represented by the arrows and the respective equipotentials represented by the colored lines. These simulations and patterns obtained by Michael Snyder show how the magnetic field is connected to the patterns observed in the Ferrolens. The main aspect of these comparisons is that the patterns of Ferrolens are somehow related to the equipotentials of the magnetic field.

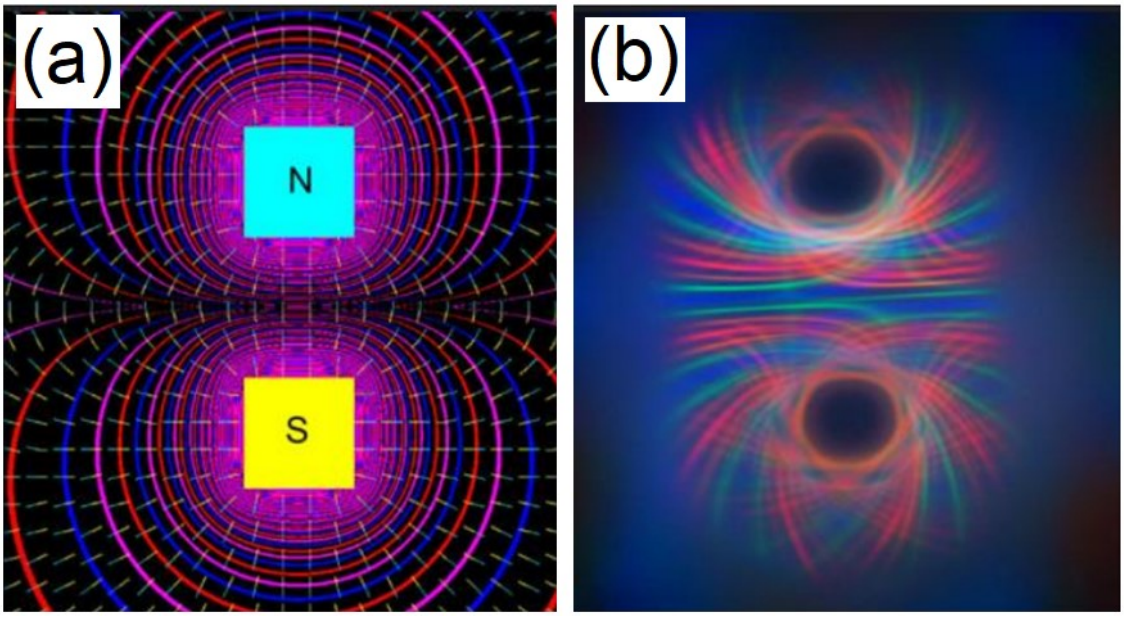

Figure 1.29 (a) Simulation of two magnets in a plane facing the north and south poles. (b) Pattern obtained with a Ferrolens with a mirror.

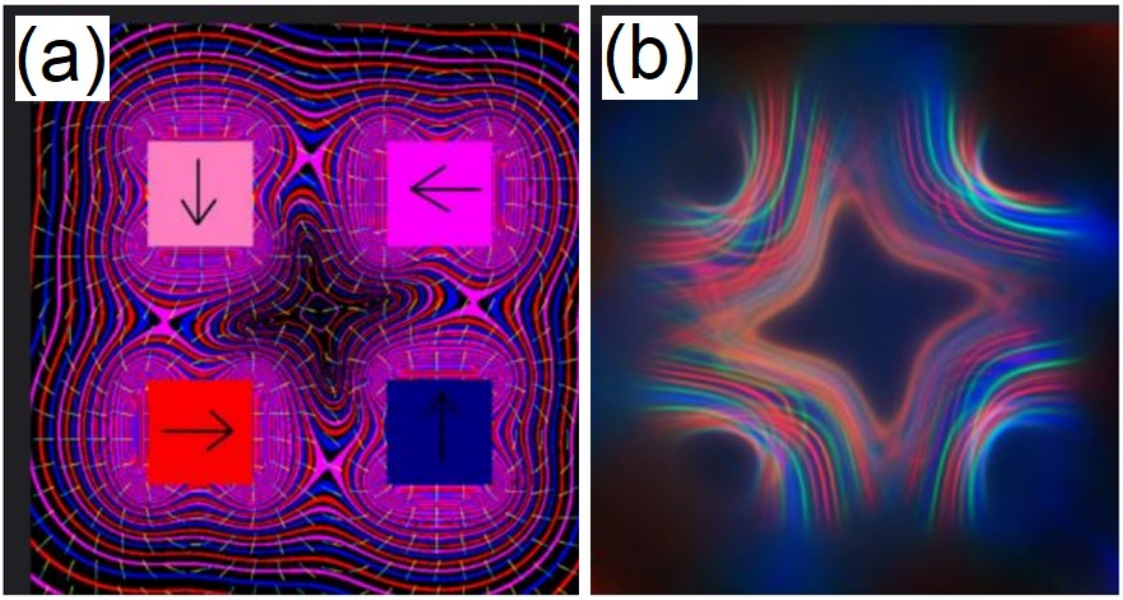

Fig. 1.30 – The star pattern. (a) simulation of two magnets in a plane facing the north and south poles. (b) Pattern obtained with a Ferrolens with a mirror.

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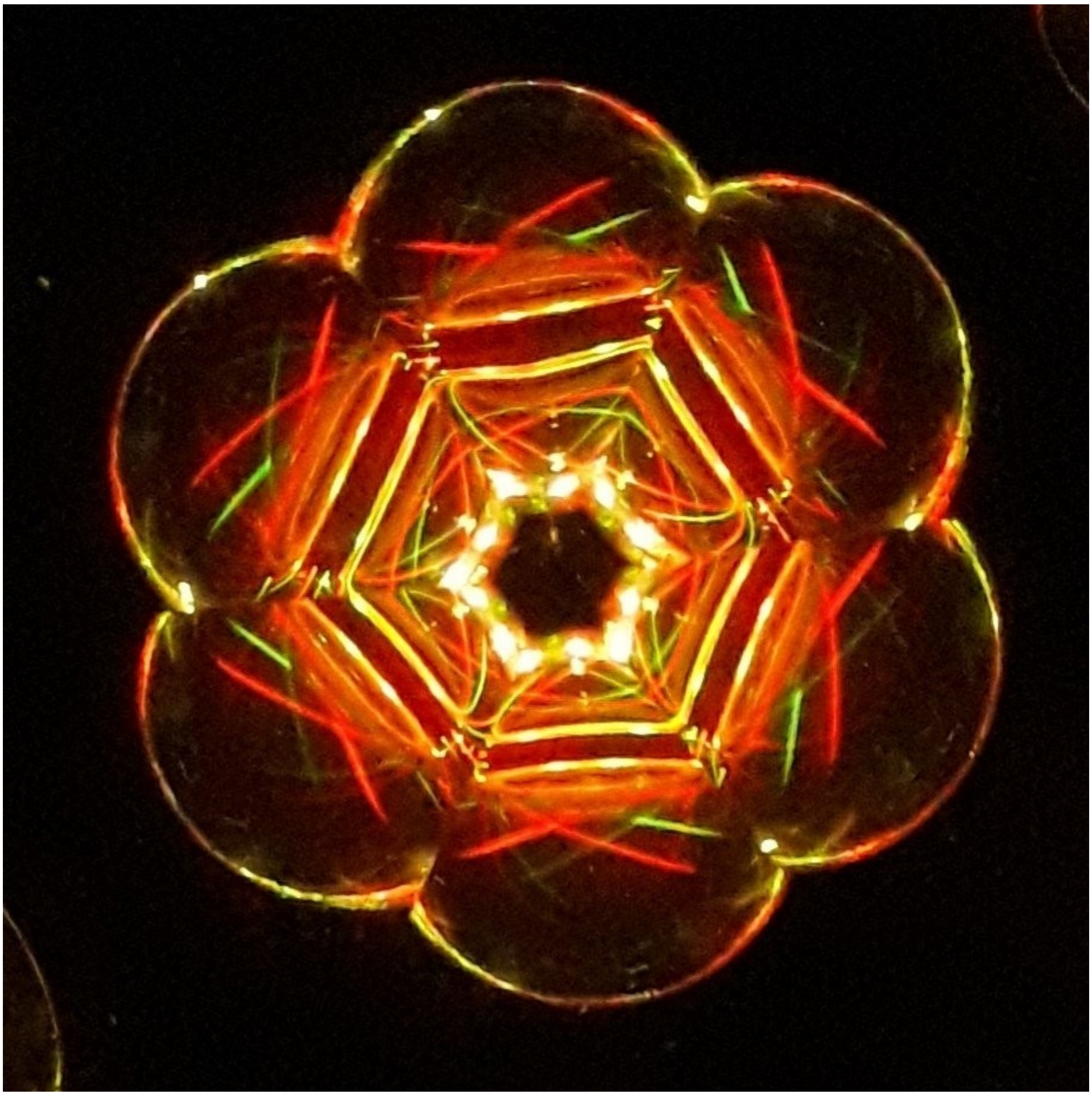


Chapter 2 – Pattern Formation

What are the luminous patterns that we can explore in Ferrocell?

When using Ferrocell, we see some light patterns simultaneously. In this chapter we will analyze what each one is. Basically, we see light patterns in the plane on which the thin film of ferrofluid is, the in plane patterns, but different light sources can confuse people who are using the device for the first time.

What are the best light sources?

In this chapter, we will explore different lighting configurations to observe the light patterns that occur with the application of the magnetic field: in plane light patterns, laser transmission and light polarization. We will see that the best light source will depend on the equipment user's interest.

How are colors 'created' in Ferrocell?

Without a light source, we don't have a light pattern in Ferrocell. Due to the physical principles involved, the colors of the light patterns are strongly linked to the colors of the light sources. Ferrocell's ferrofluid solution can mainly absorb colors closer to blue, but Ferrocell does not change the colors of the light source significantly, when the device interacts with it.

In this way, we intend to give in this chapter an overview intuitive of the formation of the luminous patterns, comparing with other equivalent physical systems existing in atmospheric optics and geology.

2a. Geometry of Patterns Projections

When you are using Ferrocell, you will see multiple patterns created by different light sources. So it is important to understand what you are seeing.

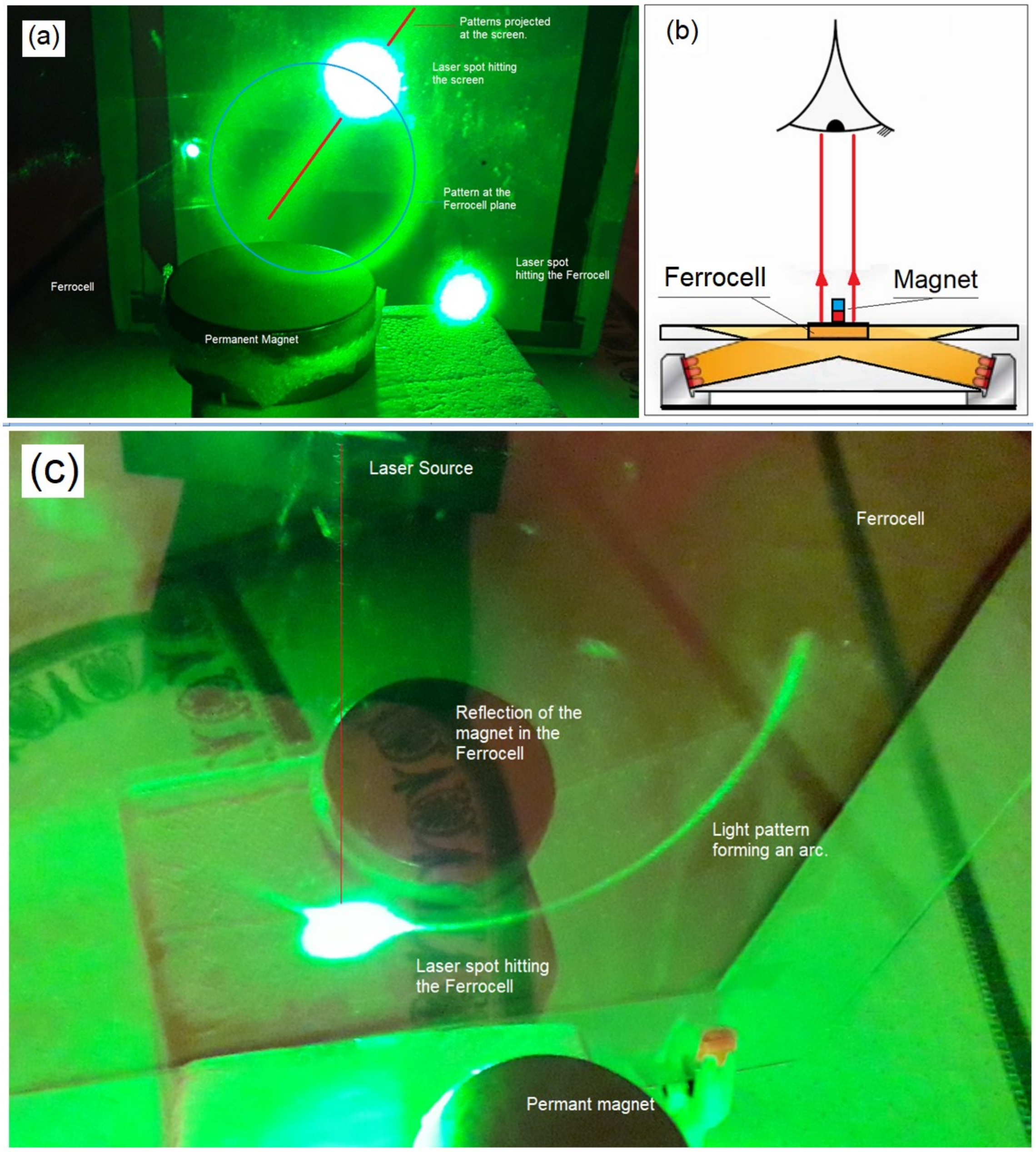


Figure 2.1 – In (a), looking through a Ferrocell: a permanent magnet behind the Ferrocell and creating some light patterns due to the interaction with the laser beam. The diagram of the dark field configuration is shown in (b). When the viewer is the same side of the magnet and the laser source is behind the Ferrocell in (c), the light pattern forms an arc at the plane of the Ferrocell.

For example, in Fig. 2.1(a), you can see a permanent magnet behind the Ferrocell interacting with a laser beam. If you look through the Ferrocell, you can see a circle crossed by a straight line.

The circle pattern around the blue line is formed in the Ferrocell plane, following the idea of the diagram of the dark field configuration of Fig. 2.1(b), while the straight line crossing the circle is formed at the screen behind the Ferrocell. Looking through the Ferrocell the viewer has the impression the both patterns are at same place, but they are in different planes. If the viewer changes his position to the other side of the Ferrocell like in Fig. 2.1(c), this viewer will see an arc-shaped luminous pattern in the image plane that coincides with the position of the Ferrocell, crossing the laser image that passes through Ferrocell. The circle is the diffracted light using as the source the image of the laser on the screen. The pattern around the red line is the diffracted light projected onto the screen by the laser spot hitting the Ferrocell, shown next to the magnet in Fig. 2.1(a).

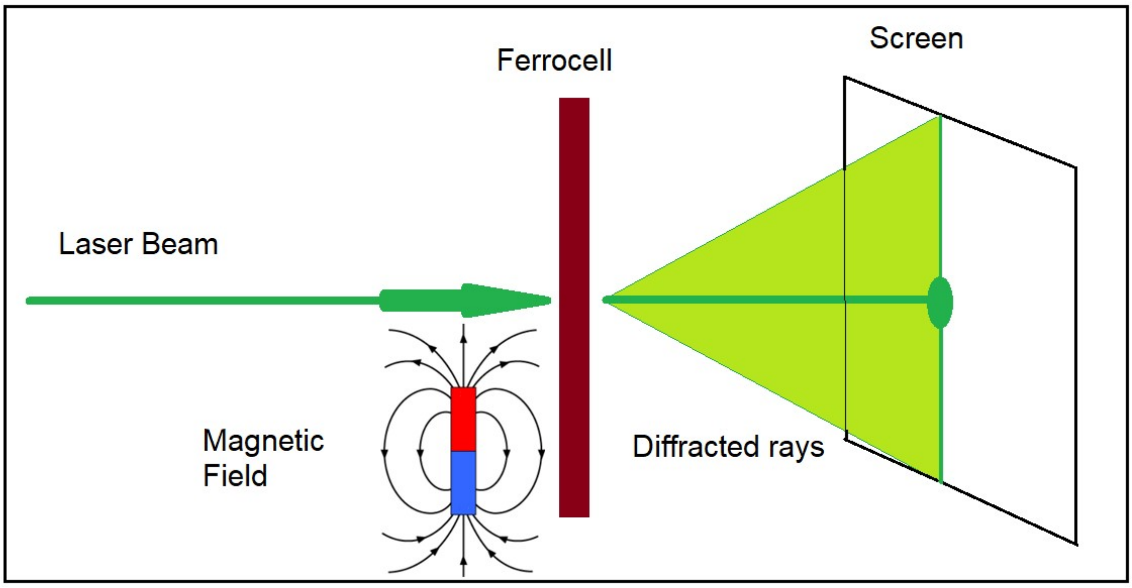


Figure 2.2 – Diffracted rays projected in a screen due to the effect of the magnetic field in a Ferrocell for the case of laser transmission.

In the next sections, we will explore in detail these configurations using the Ferrocell, in addition to the case of the light polarization.

2b. In-plane patterns

Initially, in the absence of an external magnetic field there is no light pattern because the nanoparticles in the ferrofluid are randomly distributed and thus do not scatter light that we can see any pattern. When we put a magnet on a Ferrolens and illuminate it with LED's, we can observe the formation of the light lines due to the presence of the magnetic field. The same happens if we put the magnet under Ferrolens, as it is shown in Fig. 2.2.

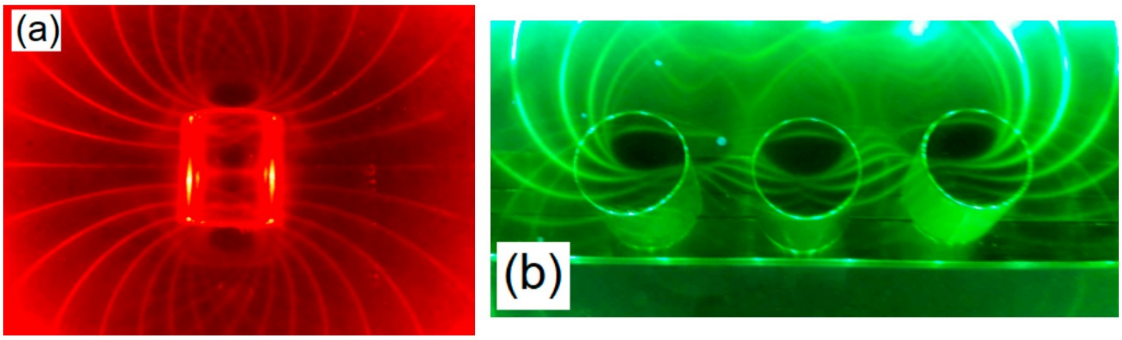


Figure 2.2- Magnetic contours observed in (a) using red light, and in (b) with green light for two distinct magnetic field configurations using the device Ferrolens.

We can observe in Fig. 2.3 that the pattern of light in it is necessarily dependent on how the illumination is arranged in Ferrolens, and this bright line that extends in space is formed by multiple light diffraction from the ferrofluid chains to the light from LED's.

This is the magneto-optical effect, and, generally speaking, magneto-optics is the use of the magnetic fields to influence the light propagation. For the specific case of Ferrolens, the magnetic field causes the particles in the ferrofluid to align with the magnetic field, as they were tiny iron filings. This makes the thin film of ferrofluid behave like a diffraction grating molded by the magnetic field. When the light coming from a LED interacts with this grid, part of it is spread towards the viewer's eye, forming the luminous pattern.

If you remove the magnetic field, the light pattern will disappear, because the thermal agitation in the liquid will cause the diffraction grating formed by the alignment of the nanoparticles to disappear by removing the magnet.

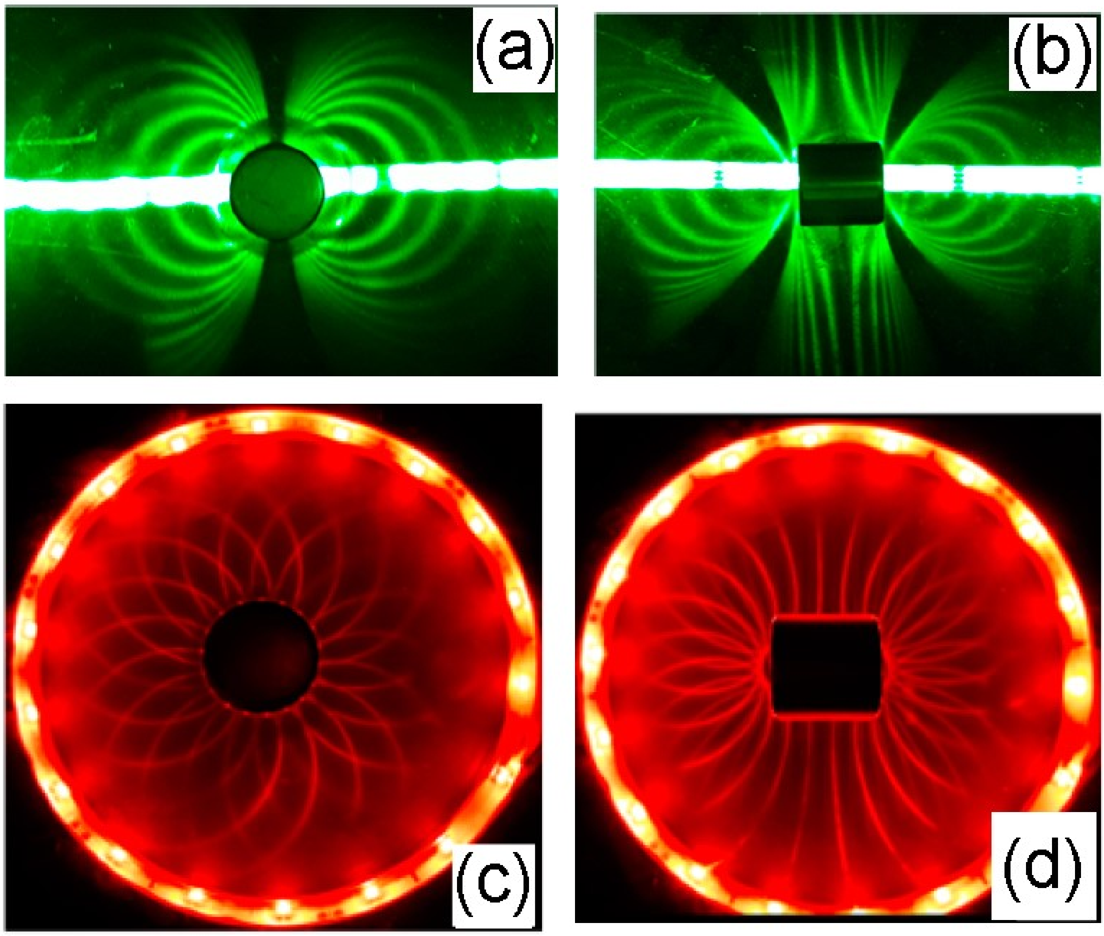


Figure 2.3 - Image of the magnetic contours obtained for a single cylindrical magnet in two orthogonal planes using the Ferrolens. Two light patterns obtained using a straight array of LEDs, in (a) for the case of polar configuration, and in (b) for dipolar configuration. In (c) the polar configuration is presented and in (d) the dipolar configuration, using LED ring lights providing radial illumination around the magnet.

A similar phenomenon occurs when you observe some light patterns obtained with the sun light reflecting on a CD, shown in Fig. 2.4(a). In this comparison we have some similarities and some differences that need to be discussed in order to qualitatively understand what is happening. First, the CD is working as a reflective diffraction grating, while the Ferrolens in the presence of an intense magnetic field is a transmission grating.

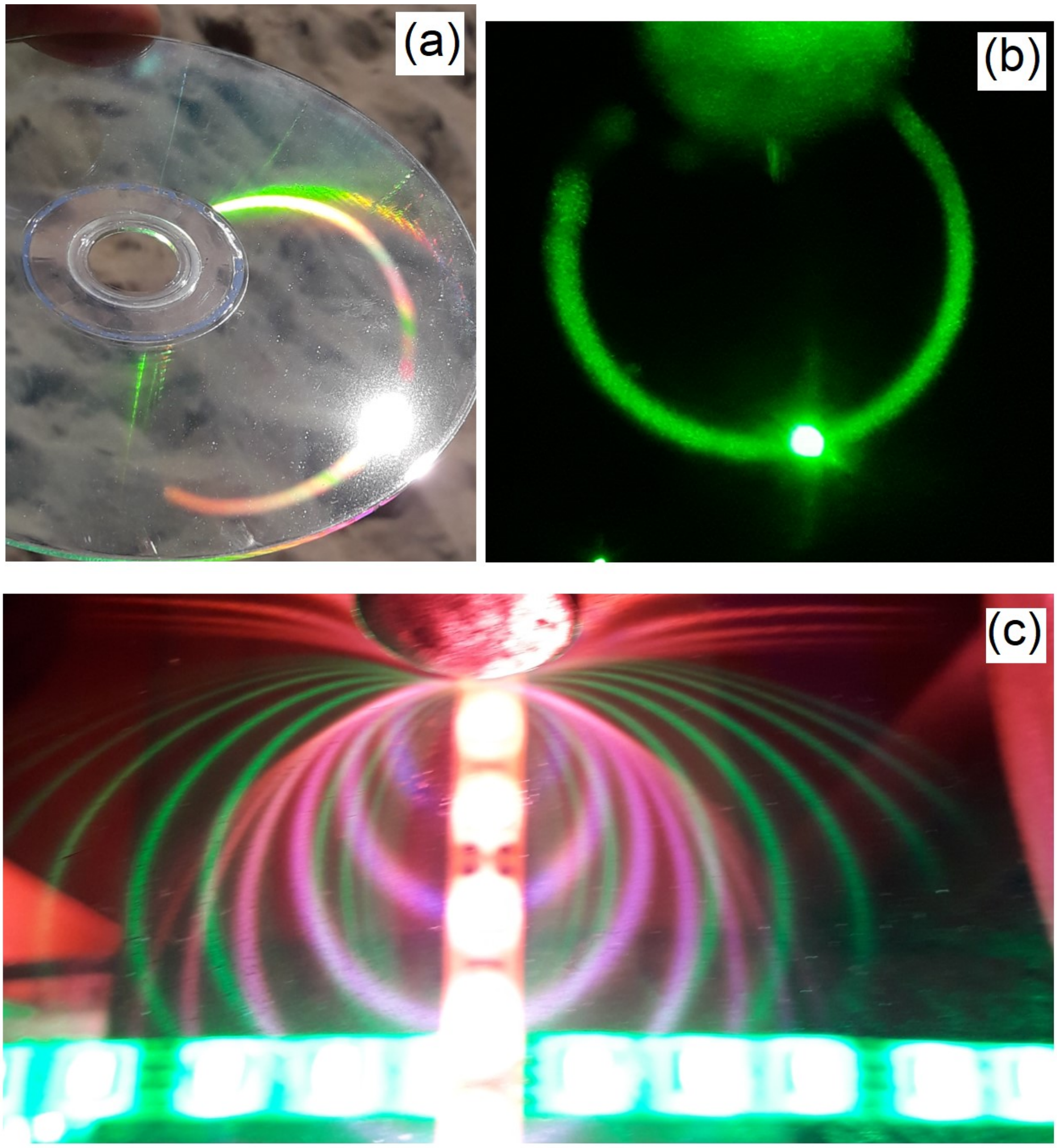


Figure 2.4 – Light pattern on a CD due to the light diffraction of the sun in(a). In this case the metal mask on the CD was removed and the CD is a diffraction grating. In (b) there is diffraction of light in a Ferrolens subjected to the magnetic field of a magnet at the top forming a similar curved pattern to the previous case. In (c) there are two LEDs strips (green and magenta) crossed with a cylindrical magnet at the top of the figure. This is an example of light crossing each other, emphasizing the influence of the source of light in the pattern formation.

Second, the light pattern due to diffraction lies in a curved line that intercepts the light source, and this is the reason why we can observe lines crossing in Figs. 2.2, 2.3 (c)-(d) and 2.4(c). Third, the regularity of the grooves in the CD is responsible for the formation of colored diffraction fringes. However, in the light patterns of Ferrolens, we have interference and diffraction occurring simultaneously, which prevents the formation of fringes, since the nanoparticles do not form such regular structures compared to the case of CD grooves. The diffraction patterns in both cases are perpendicular to the lines that form both the tracks of the CD and the structure of the nanoparticles in the ferrofluid due to the magnetic field.

For the case of a magnet in the polar configuration, we can represent the diagram of this system in Fig. 2.5. With this setup, we can see that the curved light patterns form tangent circles in the center of the magnet, and these light circles always cross the image of the light source P_n, with the distance d_n.

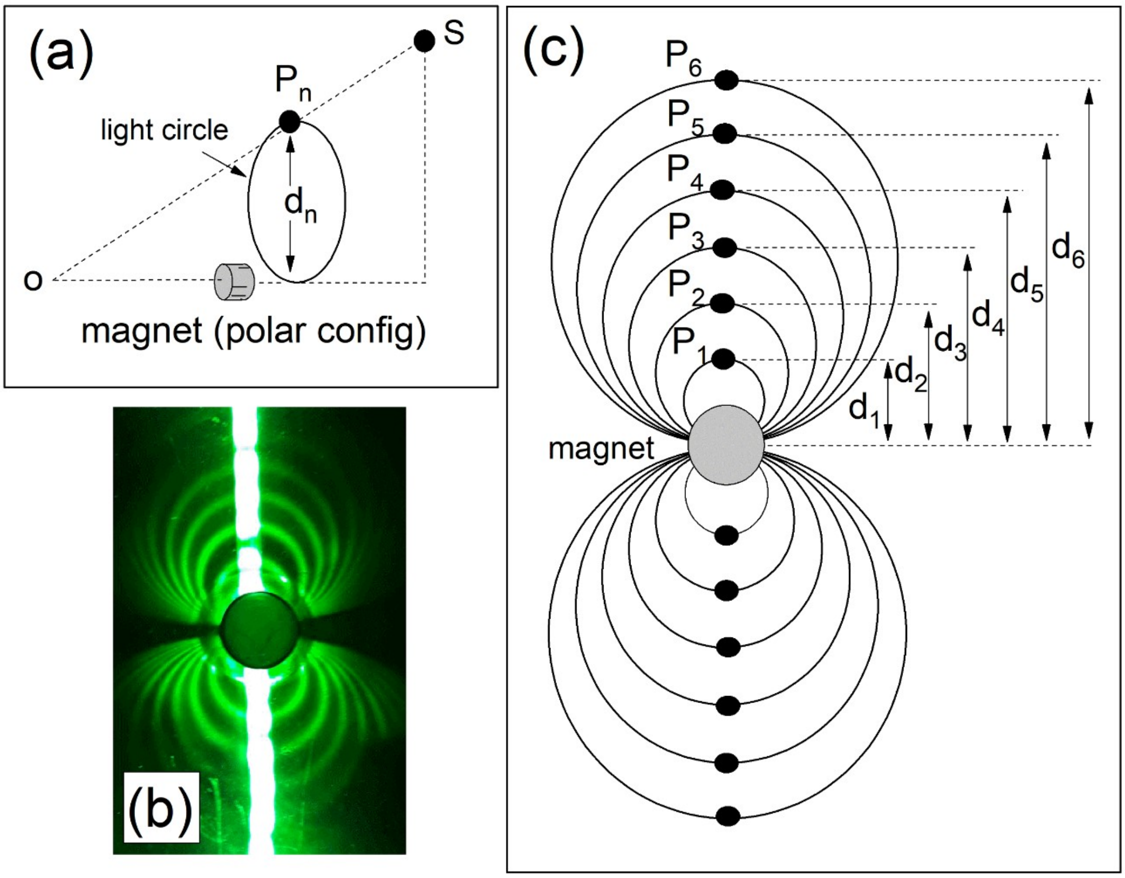


Figure 2.5 – The diagram of the eliptical pattern, with the viewr in the point o, the light source in S, for a magnet place on the Ferrolens in the polar configuratrion. The experiment is represented in (b) and the diagram of this experiment is shown in (c), with six images of the light source above the magnet Pn (from P1 to P6), each one at the distance dn from the center of the magnet (from d1 to d6).The light pattern observe in the Ferrolens plane have the image of the light source in the point Pn, with the distance dn fron the center of the magnet.

If you leave the magnet for a long time directly over the Ferrolens, this will cause the so-called "burning" effect, in which the nanoparticles agglomerate and remain fixed in some places, even after the removal of the magnet, as it is shown in Fig. 2.6. Depending on the intensity of this burning, the nanoparticles can separate due to the thermal agitation of a few hours or days, restoring the transparent appearance of the Ferrolens without the presence of the magnetic field. For extreme case, such as forgetting the magnet for several hours on Ferrolens, the burning can become permanent. This can happen due to the physical-chemical properties of the smart fluid, which represents the ferrofluid. When small magnetic dipoles are suspended in a non-magnetic fluid and the applied magnetic field causes these small magnets to line up, and form strings. These small magnetic dipoles are coated with a thin layer of surfactant, which prevents them from contacting directly against each other. For a prolonged and very intense field, this layer may rupture, causing the particles to attach to the glass or irreversibly bond to one another.

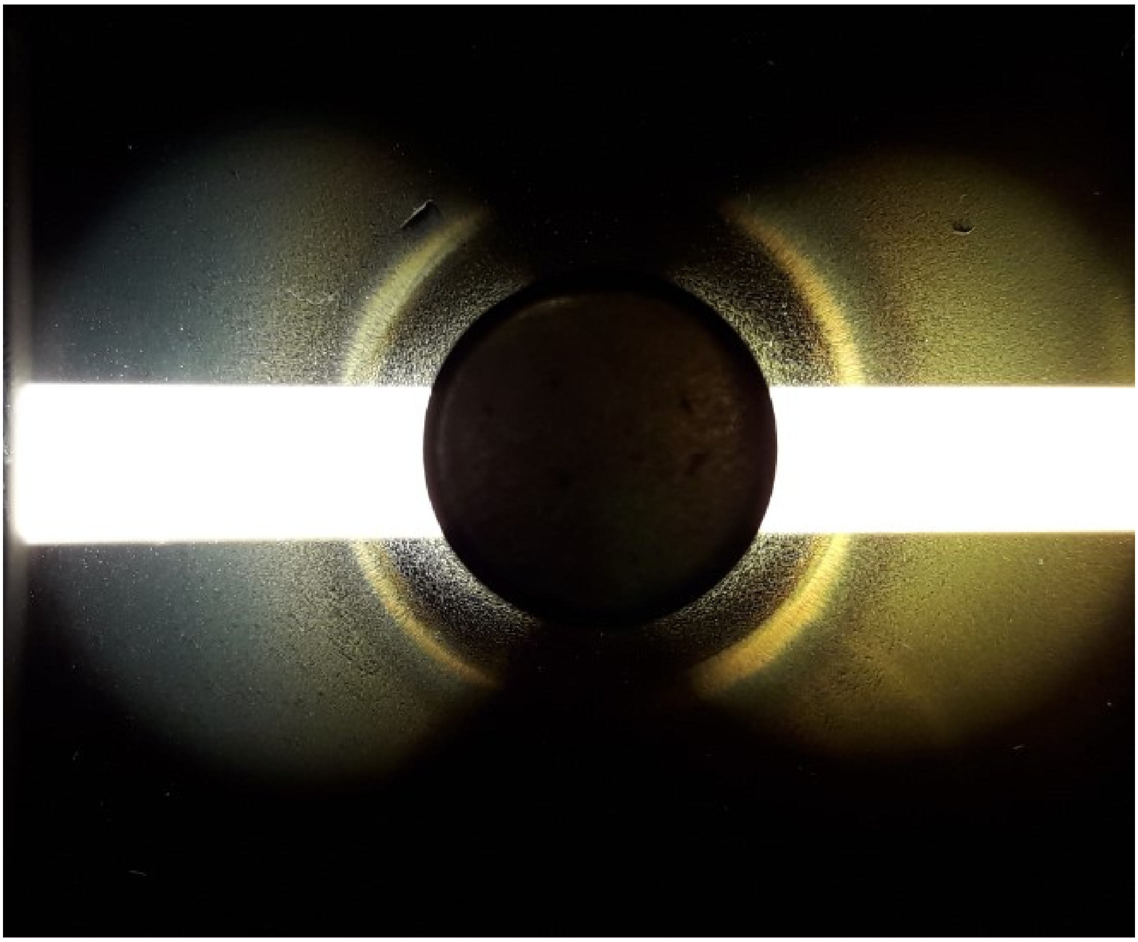


Figure 2.6 – Light pattern from a Ferrolens for a magnet in the polar configuration using a continuous white light band. In this case we have the formation of two luminous lobes. We can also observe the effect of burning with the arcs around the magnet.

In Fig. 2.7 we present a view in perspective of a setup with a circular frame of red LEDs, with a white LED within this frame. The magnet in the polar configuration is slightly away below the Ferrolens, allowing showing the overlapping of the various red lines forming a circle in the Ferrolens plane, just above the magnet. The elliptical white LED pattern appears yellowish on this figure due to the mix of white and red colors.

Note that the white LED pattern also surrounds the circular pattern mentioned previously. When we approximate the magnet in the direction of Ferrolens, this circular pattern is obtained by overlapping elliptical lines, as in the case of Fig. 2.5.

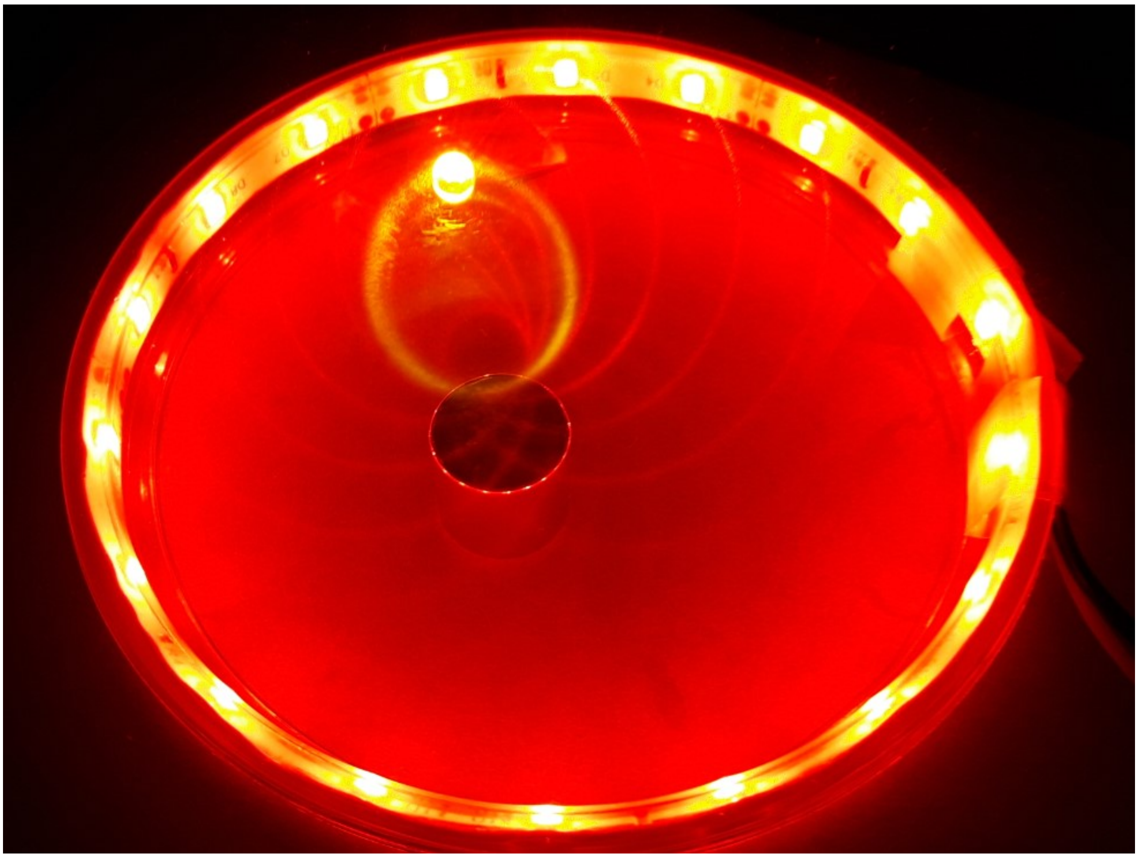


Figure 2.7 - View in perspective of a setup with a circular frame of red LEDs, with a white LED within this frame.

This darkened circular region in the center of the pattern is created by the fact that the nanoneedles in this part of the Ferrocell are in an upright position, which does not allow the light from the source to be directed at the observer.

Some of the luminous patterns observed using Ferrocell, remind us of ornamental patterns, as in this stone table of Fig. 2.8 that can be found in Vatican museum, in comparison with Fig. 2.3(c). The geometric pattern of this table is similar to the pattern of light lines observed at Ferrocell for a circular arrangement of LEDs with a pole of a magnet placed over the Ferrocell.

Figure 2.8 – Roman Marble Mosaic table ornamented with circular patterns in the Vatican Museum resembling a light pattern in Ferrocell.

This stone table can inspire us to see an optical effect on gems known as *Chatoyance* [1]. In Fig. 2.9 we see a picture of a demonstration to explain the Chatoyance, also known as the cat's-eye effect. In this demonstration, using a single LED as light source behind a grid of parallel nylon wires, the configuration forms a strip of light due to the reflection of light on each wire. In Fig. 2.10, we present two setups and a diagram explaining this demonstration. Changing the position of the viewer, the image of the light source is displaced, but the light stripe remains crossing it. The diagram of Fig. 2.10(e) presents the light rays travelling from the source of light to the observer, interacting with the grid to two different positions of the viewer, one at the top of the diagram (1), and another in the middle of the diagram (2). From the point of view of geometric optics, this effect is explained by the law of reflection in this diagram, because the reflection still occurs if the light source and the viewer are at the same side of the grid. In the specific case of chatoyancy, there are microscopic acicular inclusions in some *elbaite* crystals forming the grid.

Figure 2.9 – Demonstration of Cat's-Eye effect.

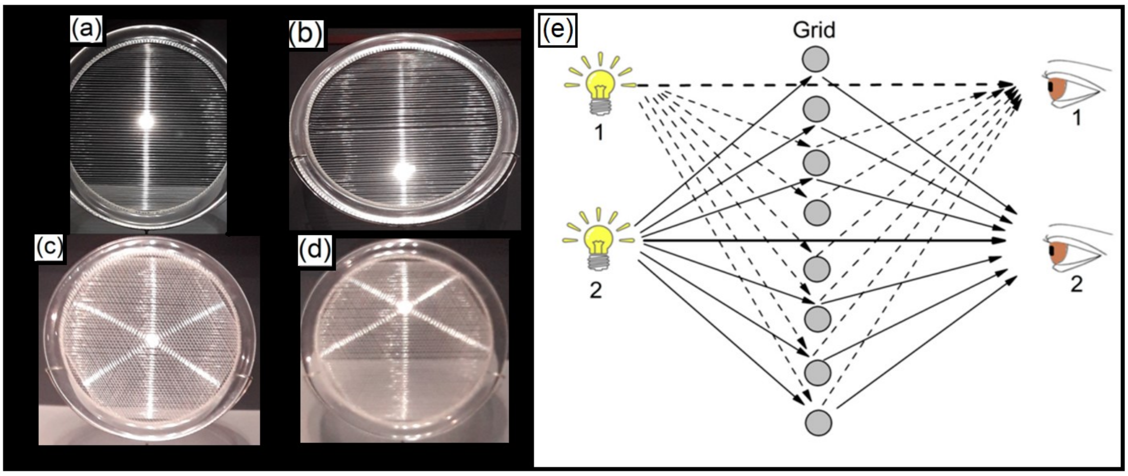


Figure 2.10 – Grid with a lamp in (a) forming a light streak. In (b), changing the position of the viewer, the image of the light source is displaced, but the light stripe remains crossing it. (c) The same effect observed previously, but now we have three crossing grids. (d) Again, the displacement of the viewer moves the pattern in the grid. (e) Diagram of the Cat's-Eye effect.

A grid of transparent tubes in Fig.2.10A shows the effect of forming light streaks with four lamps, with the streaks of light crossing each other, and in Fig. xx a brushed hemisphere light fixture with latitudinal grooves that give the Chatoyance effect.

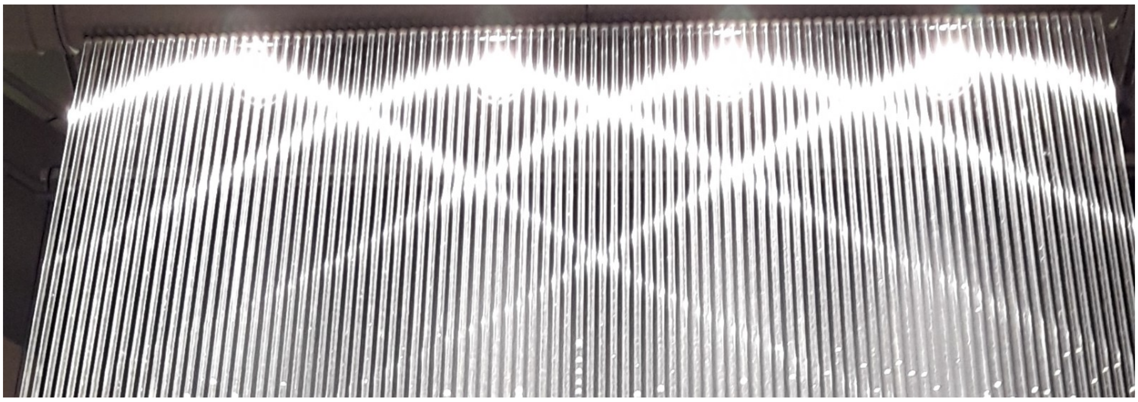


Figure 2.10A – Four lamps placed behind a grid of transparent pipes reflecting and refracting light, forming intersecting luminous patterns.

Figure 2.10B – A brushed hemisphere light fixture with latitudinal grooves that give the chatoyance effect.

To sum up, we can see that the magnetic field projected in the plane of the Ferrolens creates magneto-optical patterns that depend on the orientation of the magnetic field, the color and the arrangement of the illumination system.

2c. Laser Transmission Mode

In this section we discuss laser transmission experiments and resulting dynamic forward scattering.

When a laser beam passes through a ferrofluid in the absence of the magnetic field, the light is only slightly absorbed. This is because without the presence of the external magnetic field, there is no aggregation between the nanoparticles, which remain dispersed in the medium, due to the fact that the magnetic interaction energy between the nanoparticles in the carrier liquid is smaller than the thermal energy.

When an external magnetic field is applied, the magnetic moments of the nanoparticles are oriented along the external magnetic field, and this magnetic energy contribution dominates the thermal energy. Due to this interaction, ordered structures are formed, and consequentially there is chain formation of magnetic particles along the magnetic field, similar to the case where we have iron fillings in the presence of a magnetic field. This chain formation brings optical anisotropy in the Ferrolens, creating a linear streak when the magnetic field is applied perpendicular to the incident laser beam[2].

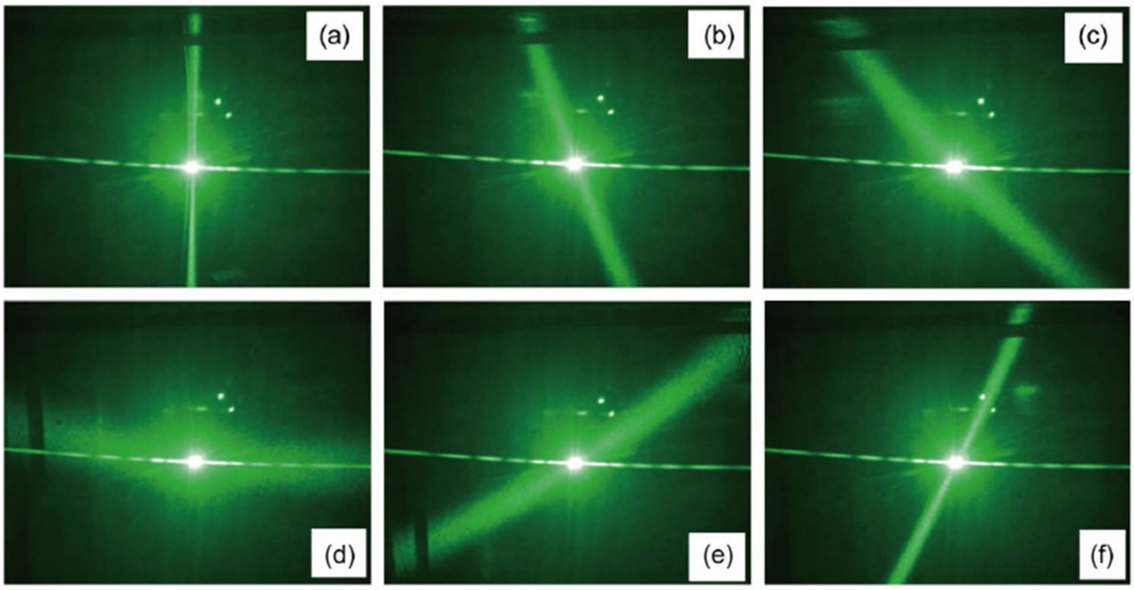


Figure 2.11 – The jumping laserdog dynamics for different orientations of needlike particles, changing the orientation of the external magnetic field. Using the fixed light diffraction of a soap film as the reference, we measured the following angles between the laser dog orientation and the reference: (a) 90°, (b) 120°, (c) 135°, (d) 180°, (e) 225° and in (f) the laserdog is rotated 245°.

We can control this light diffraction changing the orientation of the magnetic field projected in the Ferrolens. This diffraction pattern is different from that produced by a wire because individual fringes are not separate in the Ferrolens. The absence of well-defined spacing between fringes indicates that this pattern is caused by multiple diffraction. The diffraction begins in a first layer of nanoparticles when the laser enters the Ferrolens. Thereafter, this diffracted light undergoes a second diffraction from the next group of nanoparticles and so on. In this way, the light diffraction obtained from the Ferrolens is a combination of diffraction events from individual chains. Because each particle chain becomes a wave diffuser due to diffraction, and this wave interferes with each other, in this light streak we have the combination of light diffraction and interference.

We can note that the thickness of the diffraction streak changes with the orientation of the magnetic field.

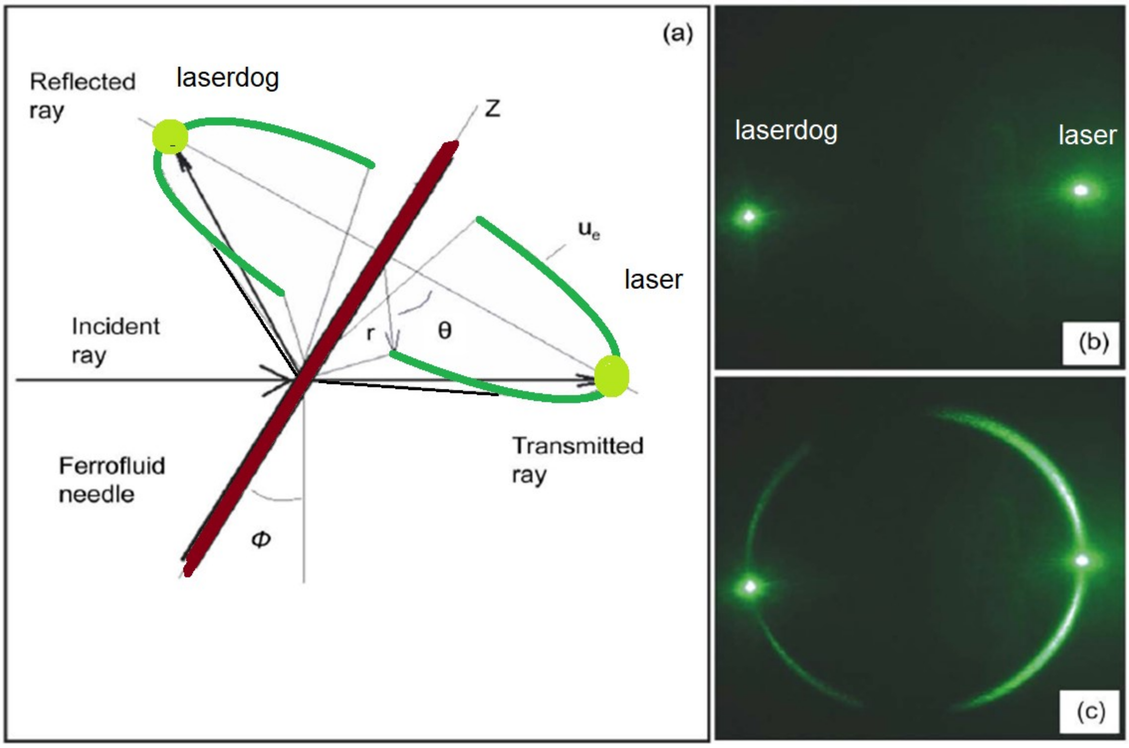
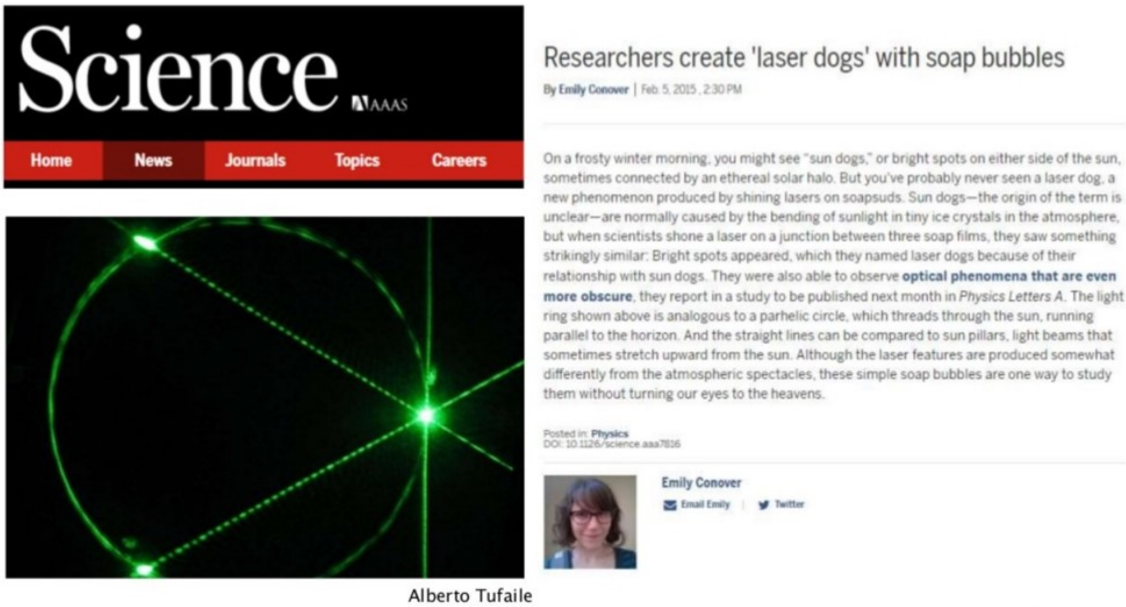


Figure 2.12 – The diagram of the laser scattering with the parlaseric circle with the laser dog pattern with nanoparticles forming a needle in (a). In (b), the laser spot and the laser dog with B = 0 gauss, and in (c) the parlaseric circle for B = 600 gauss.

When the laser reaches the Ferrolens obliquely, we have the formation of two diffraction arcs, one more intense centered on the transmitted beam at right, and another less intense in the reflected beam, at left of Fig. 2.12. These arcs are related to the parlaseric circle [3], which is a type of conical diffraction/reflection that forms circles when they are projected on a plane perpendicular to the axis of the diffraction/reflection cone. These luminous patterns are known as “Laserdogs”, because of the parallel between the “Sundogs” observed in atmospheric optics [4].



Researchers create 'laser dogs' with soap bubbles

By Emily Conover | Feb. 5, 2015 , 2:30 PM

On a frosty winter morning, you might see "sun dogs," or bright spots on either side of the sun, sometimes connected by an ethereal solar halo. But you've probably never seen a laser dog, a new phenomenon produced by shining lasers on soapsuds. Sun dogs—the origin of the term is unclear—are normally caused by the bending of sunlight in tiny ice crystals in the atmosphere, but when scientists shone a laser on a junction between three soap films, they saw something strikingly similar: Bright spots appeared, which they named laser dogs because of their relationship with sun dogs. They were also able to observe **optical phenomena that are even more obscure**, they report in a study to be published next month in *Physics Letters A*. The light ring shown above is analogous to a parhelic circle, which threads through the sun, running parallel to the horizon. And the straight lines can be compared to sun pillars, light beams that sometimes stretch upward from the sun. Although the laser features are produced somewhat differently from the atmospheric spectacles, these simple soap bubbles are one way to study them without turning our eyes to the heavens.

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Figure 2.13 –Eexample of the parlaseric circle, which represents a similar effect to the case of laserdogs.

Applying or removing the magnetic field in the Ferrolens, we will notice that there is a transient until the stabilization of the light pattern that is being observed.

2d. Light polarization

Another interesting phenomenon that can be observed with Ferrolens is light polarization. But what is light polarization? The amazing effects in 3D cinema are possible because light polarization is the property of a wave that can oscillate with more than one orientation, and it reveals one of the most important properties of the electromagnetic wave: light behaves like a vector.

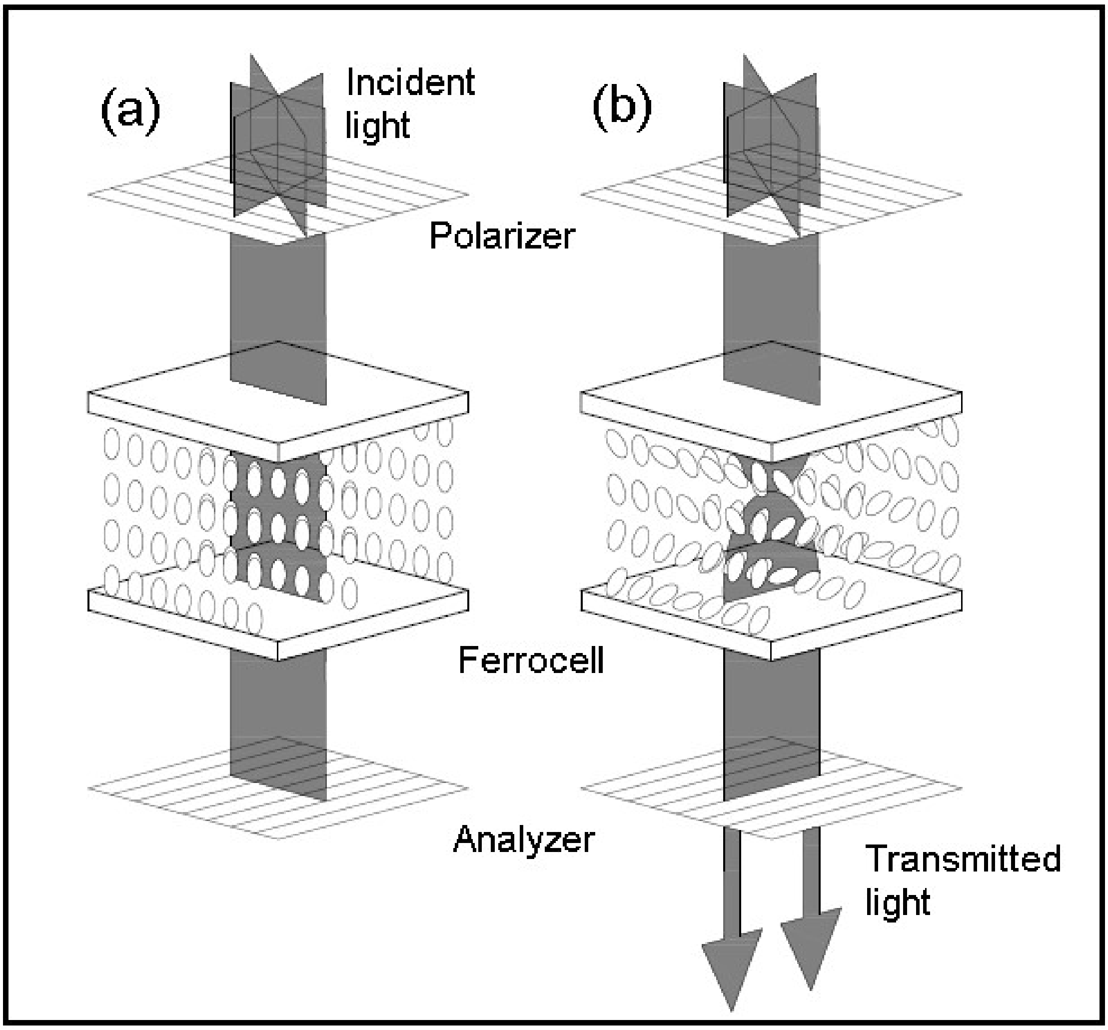

Figure 2.14 – In (a) we have the diagram of the Ferrolens between two polarizers illuminated with white backlight. In the jargon of the optics, the second polarizer is called “analyzer”. Without magnetic field, the analyzer cuts out all the light, leaving the image dark and uniform. When the magnetic field is applied, represented in (b), part of light passes through the analyzer.

This property is important because when light interacts with matter, any change in the states of this vector associated with light, brings important information about the material. This phenomenon is called optical activity, which is manifested by many natural products, such as sugars, hormones, antibiotics, just to mention some of them. In physical optics, there are some effects that relates light polarization, such as the Faraday effect, which is a magneto-optical phenomenon, or the Cotton-Mouton effect which describes birefringence in a liquid in a presence of a constant transverse magnetic field. It is also known that ferrofluids presents dichroism for different values of the applied magnetic field, in which the ferrofluid presents anisotropy for the light polarization travelling through it. For all described the above, we expect to see some effects of light polarization in ferrofluids [5].

To observe some of these properties using Ferrolens, we can start using two light polarizers, as it is shown in Fig. 2.15.

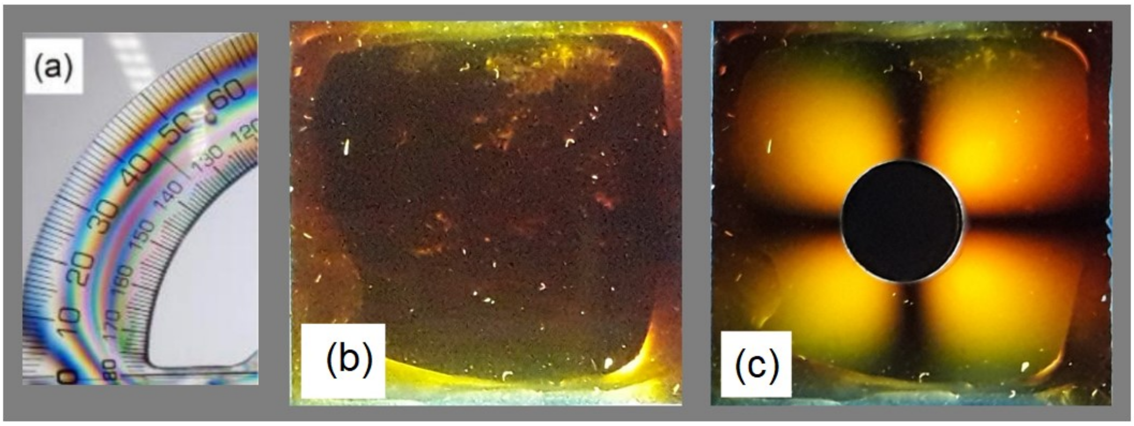

Figure 2.15 – A piece of plastic between two crossed polarizers showing different colors due to internal tensions, so we can use light polarization to study this material with a non-invasive technique. Ferrolens between two crossed polarizers in (b) with no magnetic field illuminated with white light. In (c), there is a cylindrical magnet creating a magnetic field creating a diffraction grating which polarizes the light.

We can explore some patterns using different configurations of magnetic Field in Ferrocell. For example, in Fig. 2.16 we present the patterns of polar and dipolar magnetic field configuration. For the cases of polar configuration of Figs. 2.15(c) and 2.16(a), we can see the formation of four illuminated lobes separated by dark regions in cross format, with the light intensities very similar for each lobe. In the case of the dipolar configuration of Fig. 2.16(b), we see eight illuminated regions separated by dark bands. However, in spite of the symmetry in this figure, the illuminated regions near the magnet poles of the upper and lower central portions of the sides of this pattern have a greater light intensity than the illuminated regions in the sides.

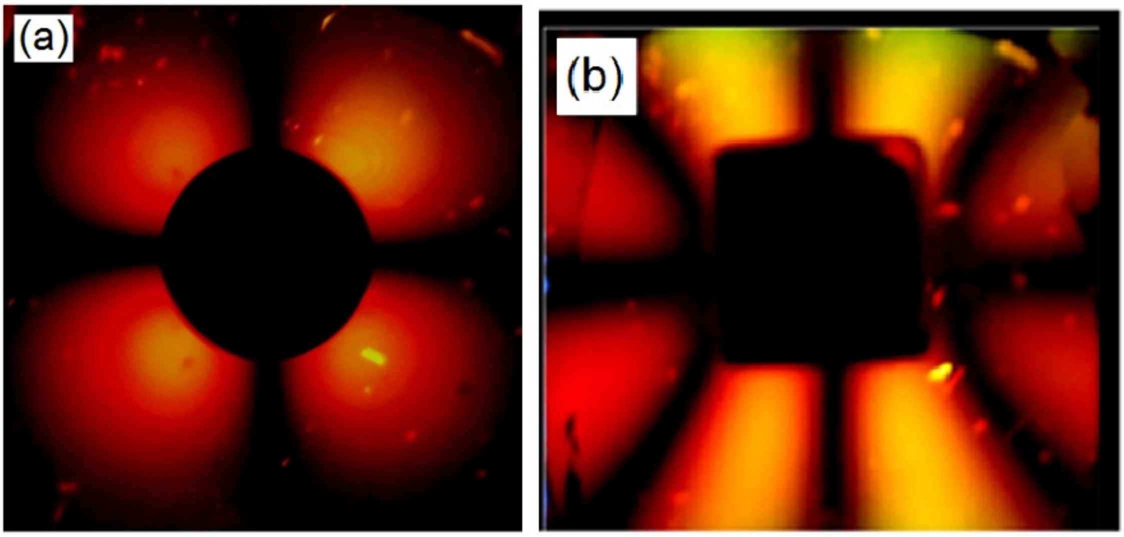

Figure 2.16 – In (a) light polarization pattern of a magnet in the polar configuration using Ferrolens, and in (b) light polarization pattern of a magnet in the dipolar configuration.

In Fig. 2.17(a) we present the polarization pattern of an axially magnetized ring. The polarization pattern of a more complex magnetic field in which two magnets placed side by side with poles in opposition, with one magnet with 900 Gauss and the small one with 200 Gauss, can be seen in the pattern obtained with the Ferrocell in Fig. 2.17(b) with the small magnet at the bottom.

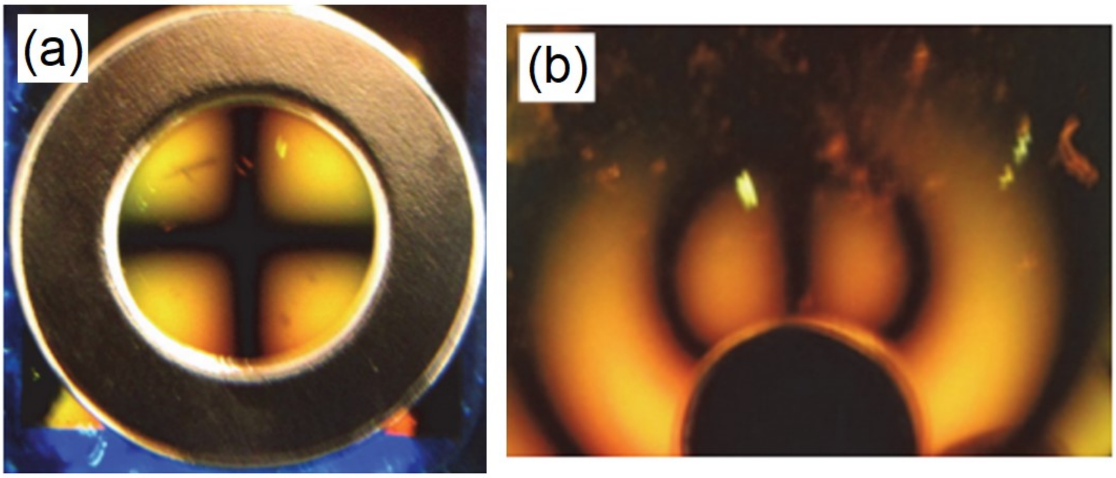

Figure 2.17 - In (a) using an axially magnetized ring, the light pattern has the form of a cross. The magnetic field of two cylindrical magnets, placed side by side with poles in opposition, one magnet with 900 G and the small one with 200 G, creates the pattern obtained with the Ferrocell shown in (b).

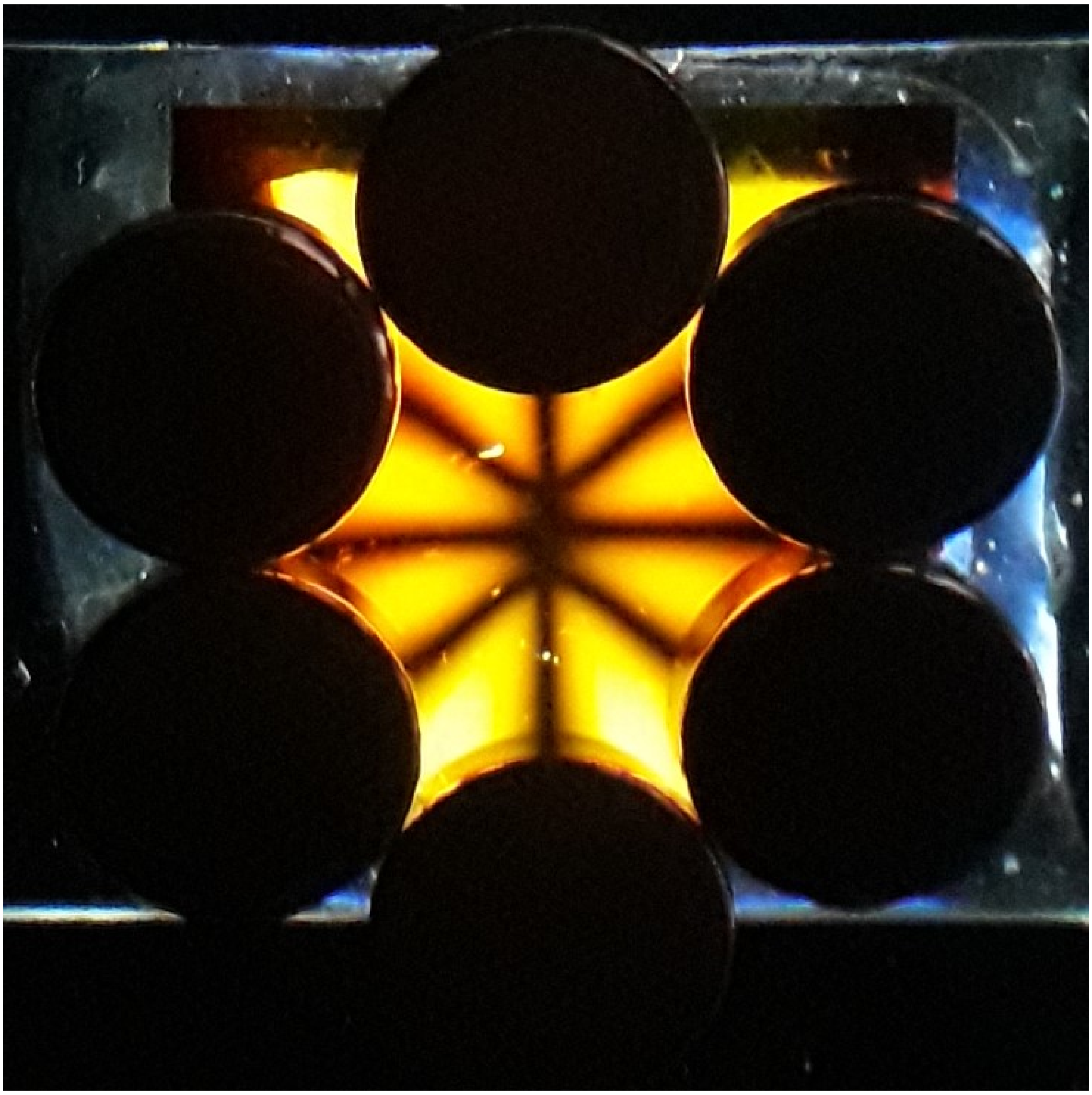

Figure 2.18 - Using six disc-shaped magnets forming a circular array, we obtained the pattern shown in this image with eightregions separated by dark lines.

Using six disc-shaped magnets forming a circular array, we obtained the pattern shown in this image of Fig. 2.18, with eight regions separated by dark lines that focus in the center of pattern.

Another interesting parallel between ferrofluids and gems is some patterns obtained using light polarization. The physical concept connecting both the physical systems is the presence of the birefringence, which is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light.

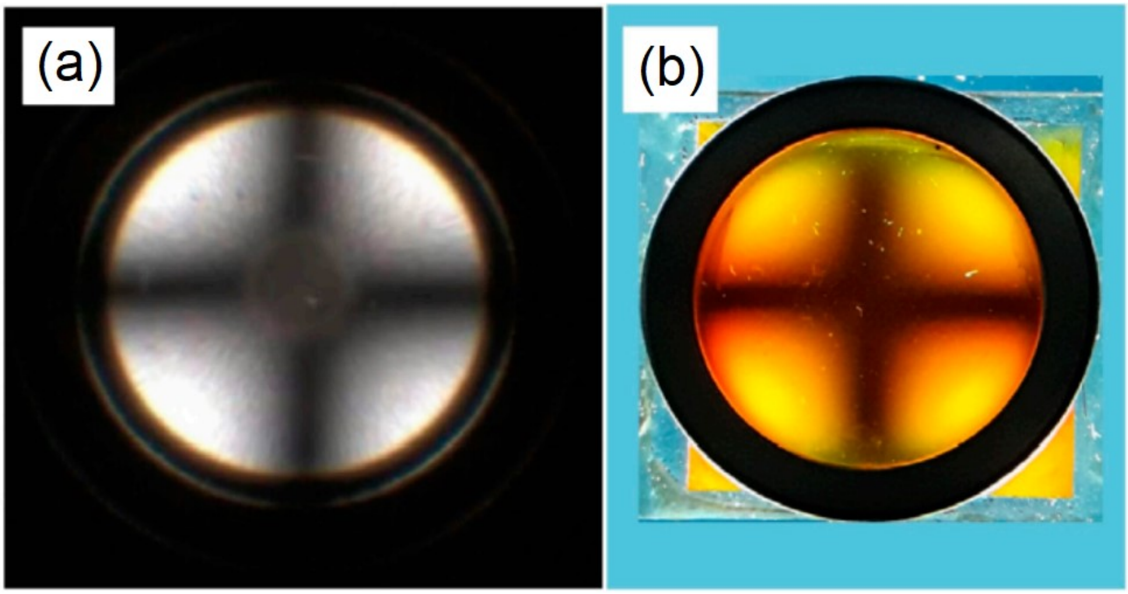

Figure 2.19 - Pattern of light polarization for quartz conoscopy showing isogyres and melatope at the center; (b) Light polarization in a Ferrolens subjected to an axially magnetized ring.

Conoscopy [1] is the study of patterns of light interference in samples of thin crystals slices in the focal plane of a microscope lens. While the ferrofluid system uses an orthoscopic illumination, with a plane wave, the light pattern obtained with quartz is obtained with a conoscopic illumination, represented by a series of concentric light cones. This type of study serves to classify the crystal structure through its optical properties. For example, in Fig. 2.19 (a) we can see the pattern polarization for quartz conoscopy showing isogyres, the two dark lines crossing forming a cross, and a melatope, the central point of the pattern. Materials like these are called uniaxial crystals. In Fig. 2.19(b) is shown the light polarization in a Ferrocell with a similar pattern. If the ring is rotated around its center, the light pattern is not changed.

Using a different magnetic field configuration, we see a set of different patterns, which are shown in Fig. 2.19, which depend on the orientation of the magnetic field. This type of patterns are similar to those observed in biaxial crystals.

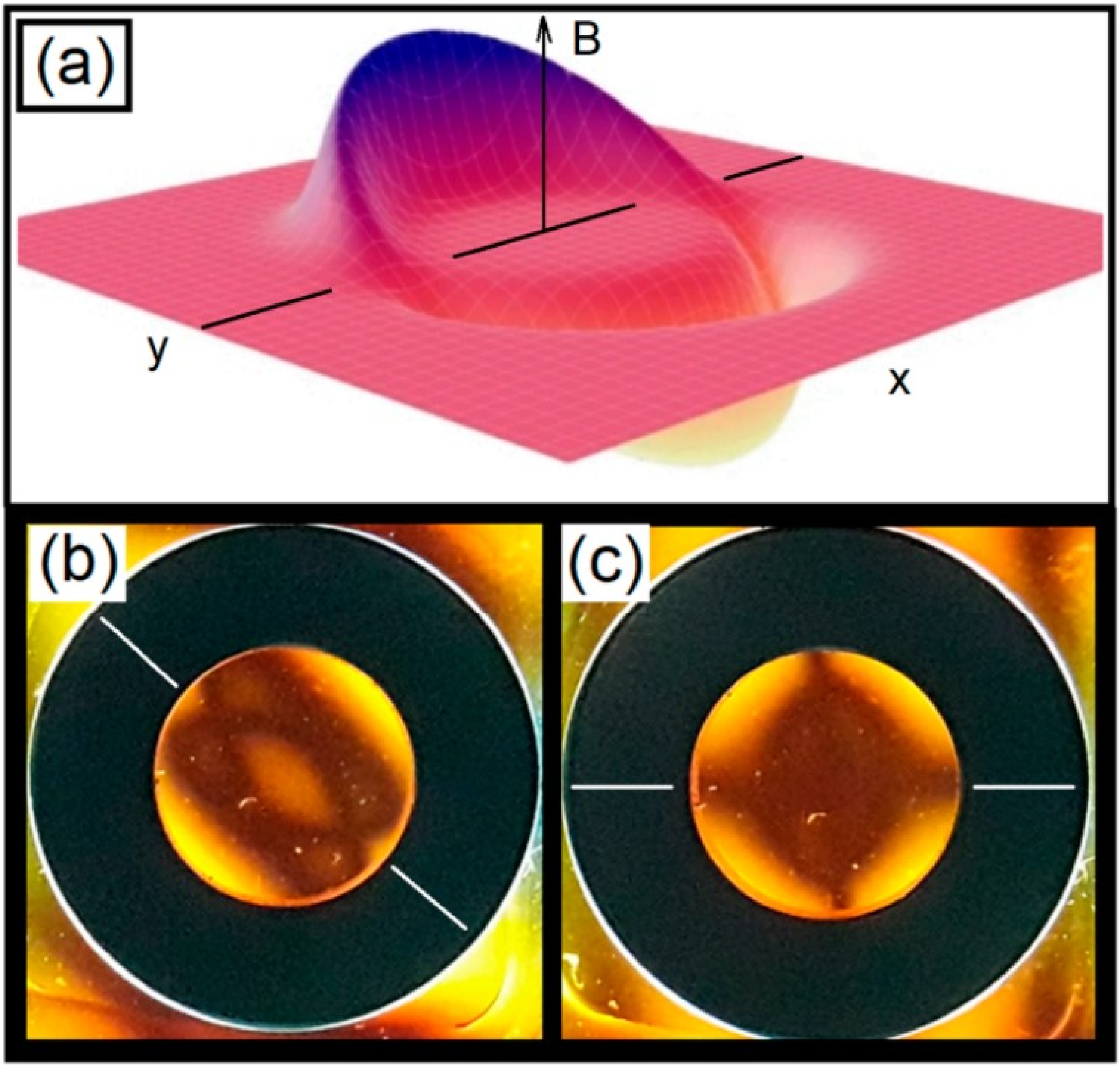

Figure 2.19 – In (a), the magnetic field intensity diagram of a magnet with a diametrically magnetization, with a line indicating the minimum field axis, (y axis); In (b), the polarization pattern obtained with the ring magnet oriented obliquely; (c) Polarization pattern with the magnetic ring axis parallel to the horizontal direction.

2e. Ferrocell combined with a mirror

Another interesting possibility is the combination of Ferrocell with a mirror, developed by Michael Snyder, shown in Fig. 2.20. This case has characteristics similar to the first case of dark field, but with an indirect lighting. Using an array of light sources with different colors, we can see an example made by Michael Snyder himself in Fig. 2.20(c), which can be compared with isopotentials simulation of the magnetic field using the Pic2Mag of Fig. 2.20(b), mentioned in the previous chapter for Figs. 1.28, 1.29 and 1.30.

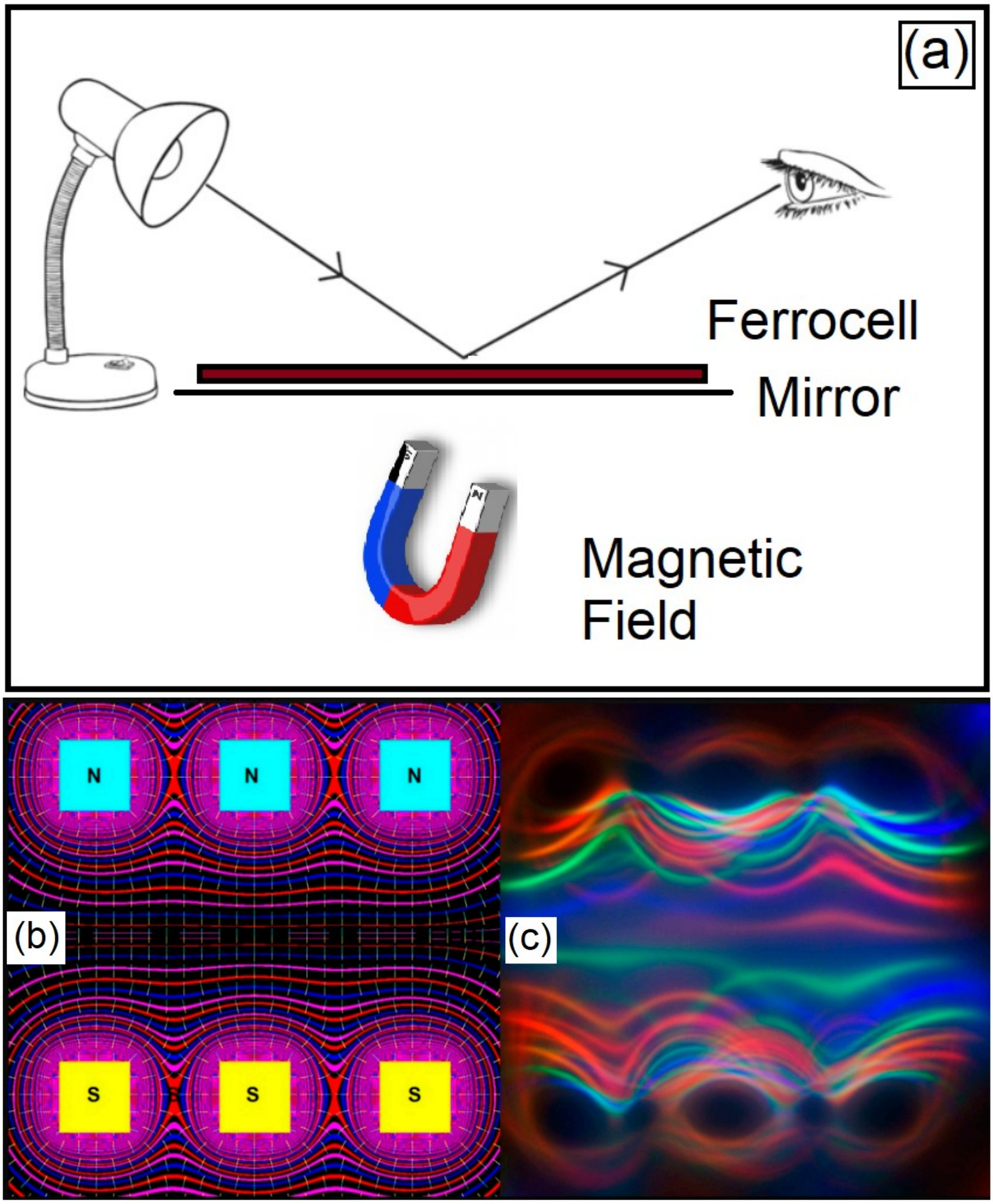

Figure 2.20 – In (a), the diagram of the Ferrocell combined with a mirror. The simulation of the isopotentials of the magnetic field of a certain array of magnets in (b). In (c), Image of the experiment of the previous simulation

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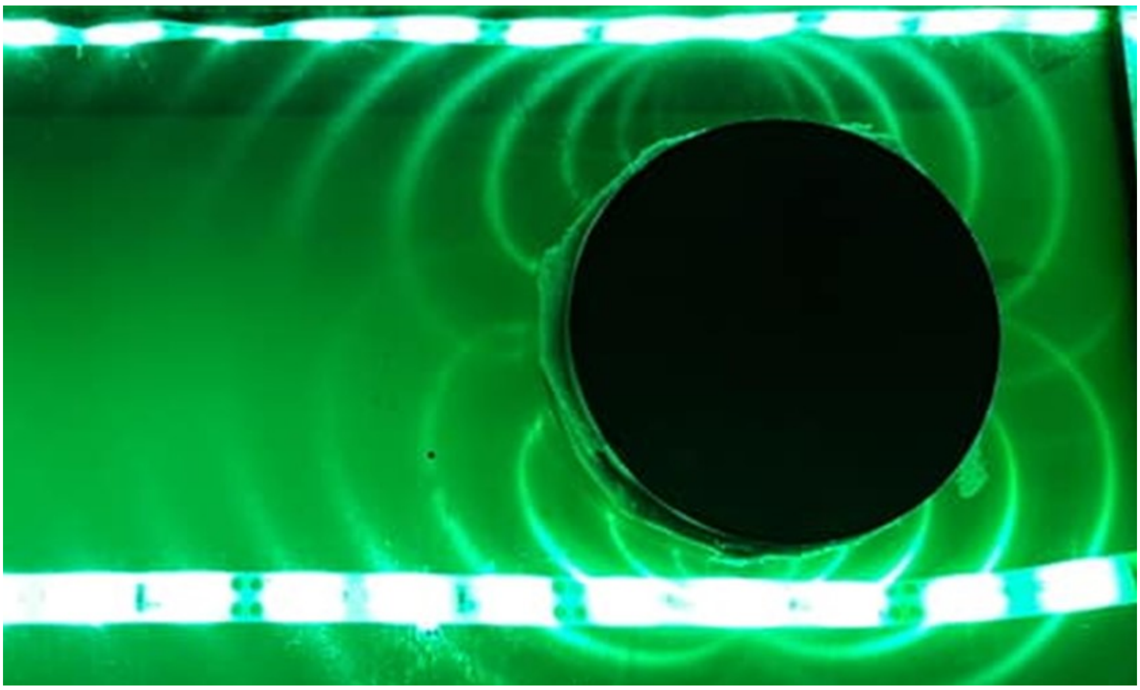

Chapter 3 - Demonstrations and Experiments with Ferrocell

What is the relationship between the magnetic field lines and the luminous pattern seen at Ferrocell?

In this chapter we will make some demonstrations using Ferrocell in order to explore this relationship.

Do we really need to worry about optics at Ferrocell?

The understanding of various optical phenomena can usually be studied with different levels of complexity and approaches in relation to existing theories. This happens since some peculiar cases involving rainbow formation, colors of birds' feather, and fabrics with structural colors and clearly applies to the case of Ferrocell. In the literature we can find several debates of this type, with authors trying to grasp the main concept that represents the phenomenon they are studying.

How can we measure the magnetic field?

Since the presence of the magnetic field is a key factor in the use of this device, we will see in the next section how to build a low cost magnetic field meter, tha allows the Ferrocell user to make quantitative measurements of the magnetic field and its effects in this chapter.

3. Introduction: Ferrocell, Are You Experienced?

In Fig. 3.Intro1 (a) we are presenting the Ferrocell. In Fig. 3.Intro (b) we have two Ferrocells with different solutions of ferrofluid. Each Ferrocell is formed by two sealed glass plates containing a Ferrofluid solution and a solvent.

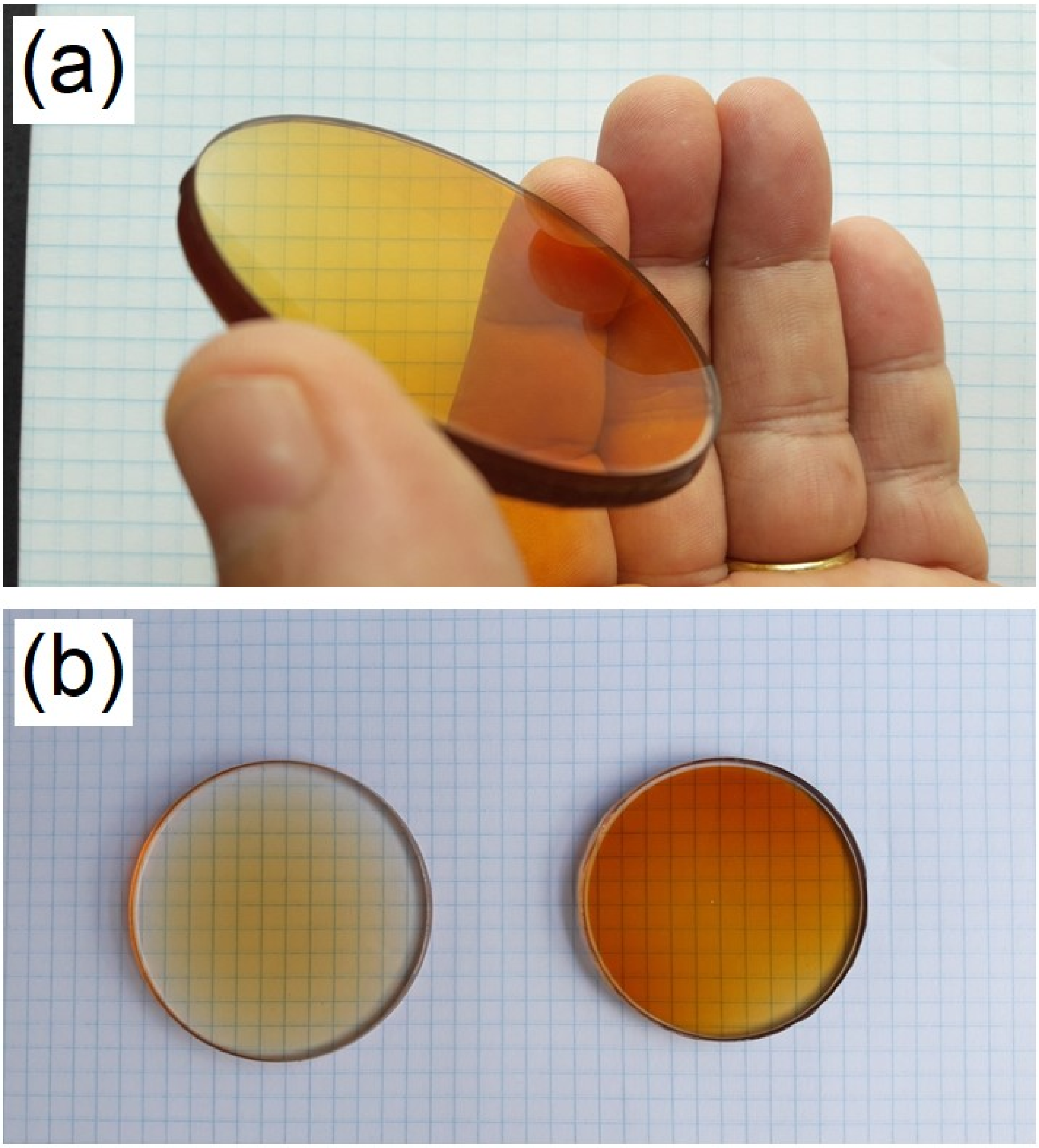

Figure 3.Intro1 – (a) Holding a Ferrocell. (b) Two Ferrocells with different solutions of Ferrofluid.

In Fig. 3.Intro2, there are two Ferrocells on supports with a ring of white LEDs and batteries. The LED lighting can be switched with an on/off button.

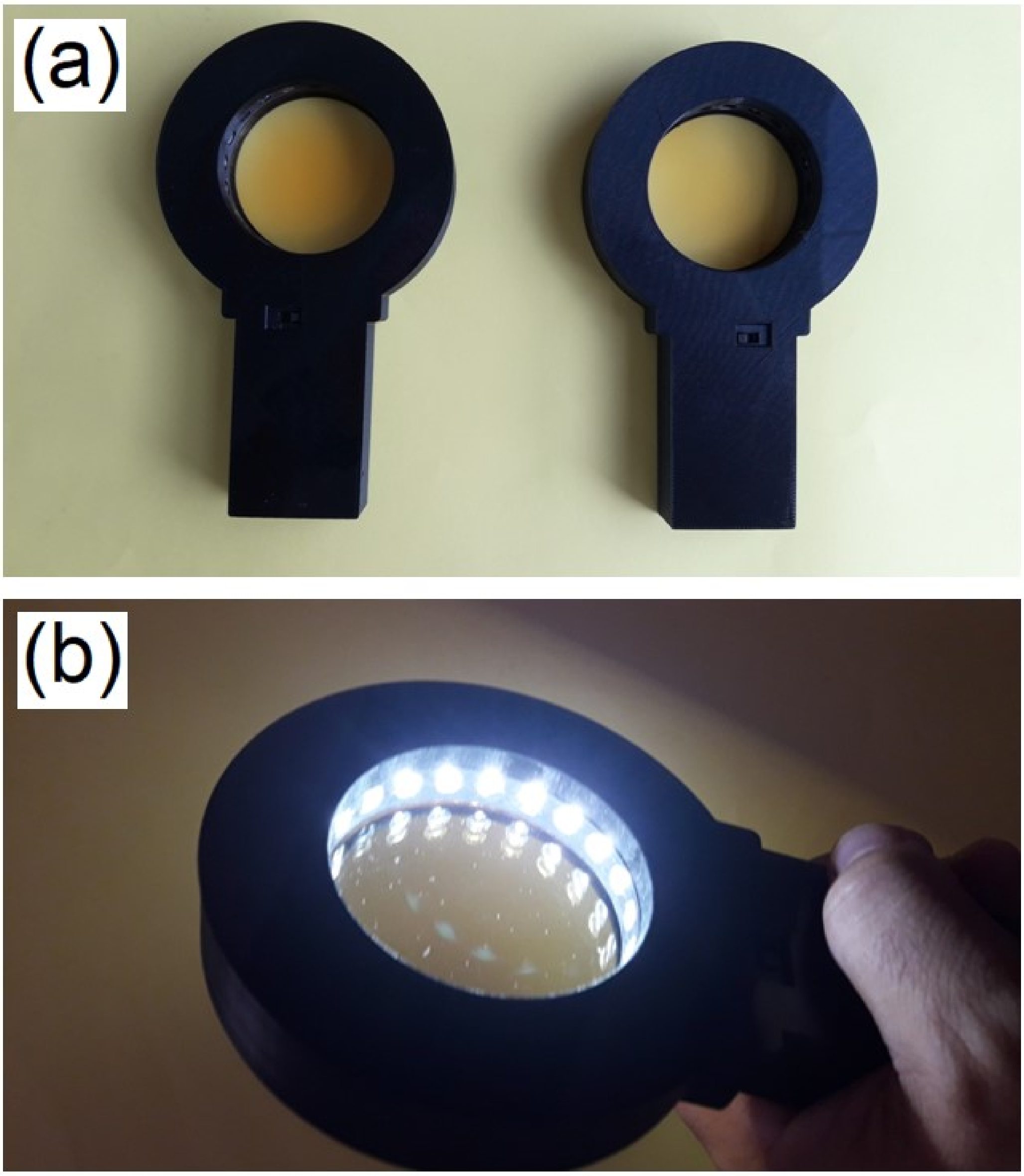

Figure 3.Intro2 – (a) Ferrolens with a support. (b) Ferrocell with a ring of white LEDs.

Now, using some permanent magnets, we are going to do some demonstrations to explore some configurations of magnetic fields.

In Fig. 3.Intro3 (a), there is a Ferrocell with a ring of RGB LEDs and batteries. Using this device we placed two magnets facing the Ferrocell.

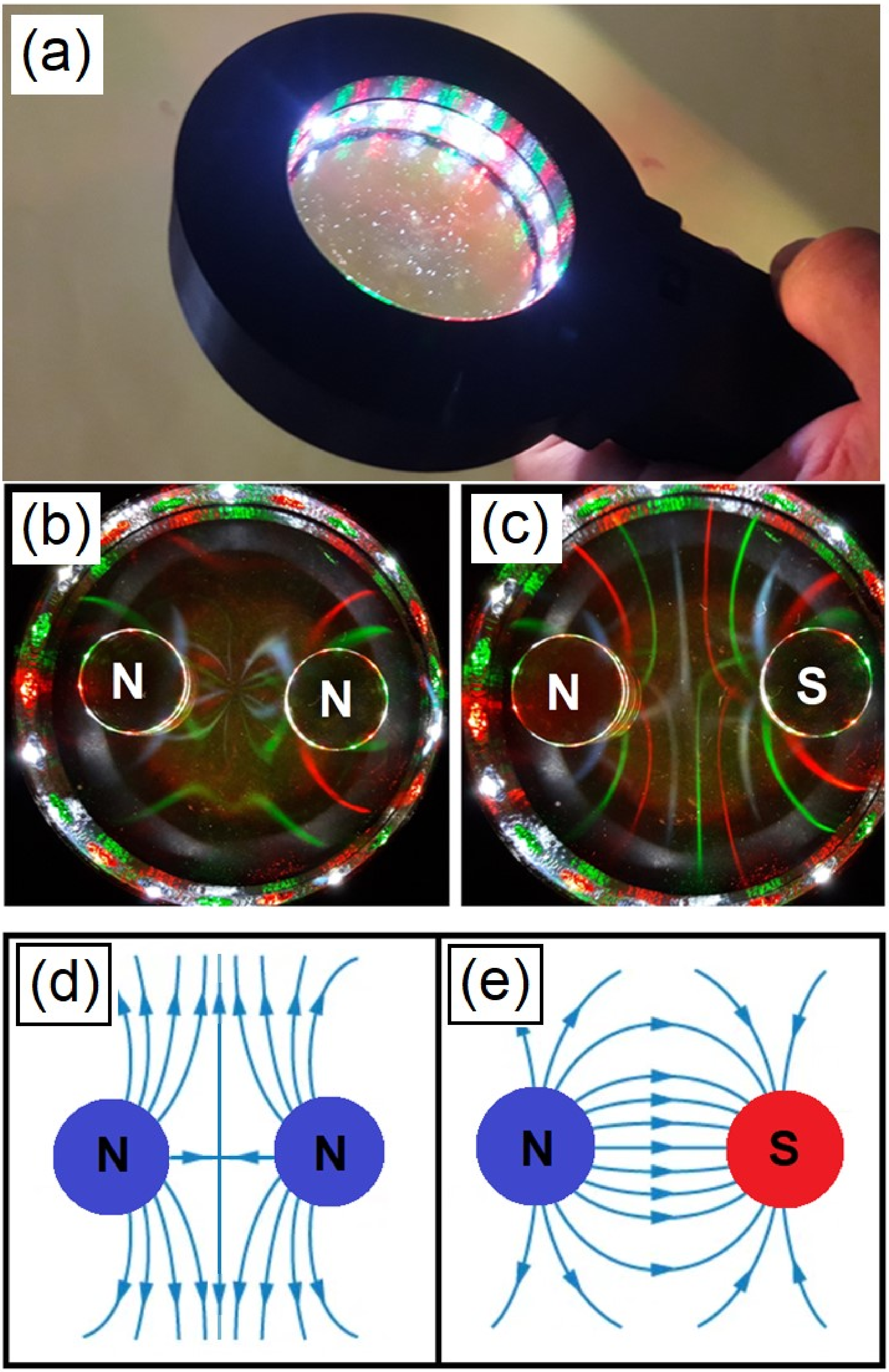

Figure 3.Intro3 – (a) Ferrocell RGB (b) North-North pattern (c) North-South pattern. Diagrams of two magnetic field lines for North-North in (d) and North-south poles in (e).

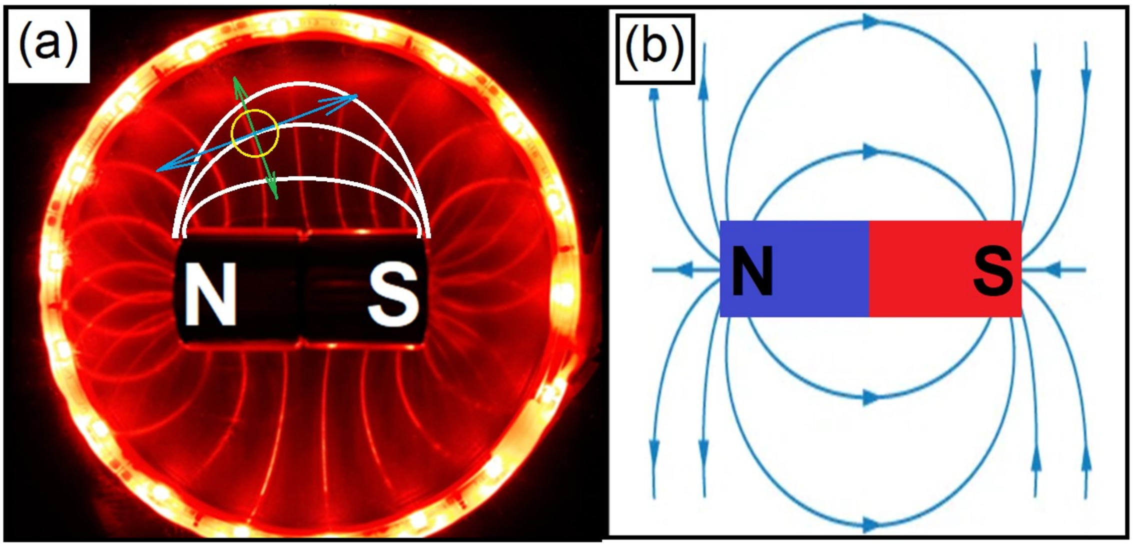

Figure 3.Intro4 – (a) Ferrocell RGB (b) North-North (c) North-South. Magnetic field line diagram for these two cylindrical magnets.

We placed two like magnets poles in Fig. 3.Intro3 (b) in a Ferrocell and in Fig. 3.Intro3 (c) two unlike poles facing the Ferrocell with the ring of RGB LEDs. You can compare these patterns with the diagrams of the magnetic field lines presented in Fig.3.Intro3 (d) and Fig. 3.Intro3 (e).

In Fig. 3.Intro4 (a) we are presenting the luminous pattern of a bar magnet, and in Fig. 3.Intro4 (b) we are presenting the diagram of the magnetic field of a bar magnet. Considering the point centered on the yellow circumference of Fig3.Intro4 (a), we see that the tangent of the Ferrocell pattern lines in green are perpendicular to the lines of the magnetic field in blue. Roughly, we can see that the lines of Ferrocell light patterns are perpendicular to the lines of the magnetic field. Recalling the optical effects discussed in chapter 2, we can see that lines of the light patterns can cross each other in some regions of Ferrocell, unlike what happens with the lines of the magnetic field, which never crosses each other. This emphasizes the fact that the light patterns we see at Ferrocell are magneto-optical effects and not just magnetic effects.

In Fig. 3Intro5, we have other light patterns at Ferrocell using one or two magnetic cylinders.

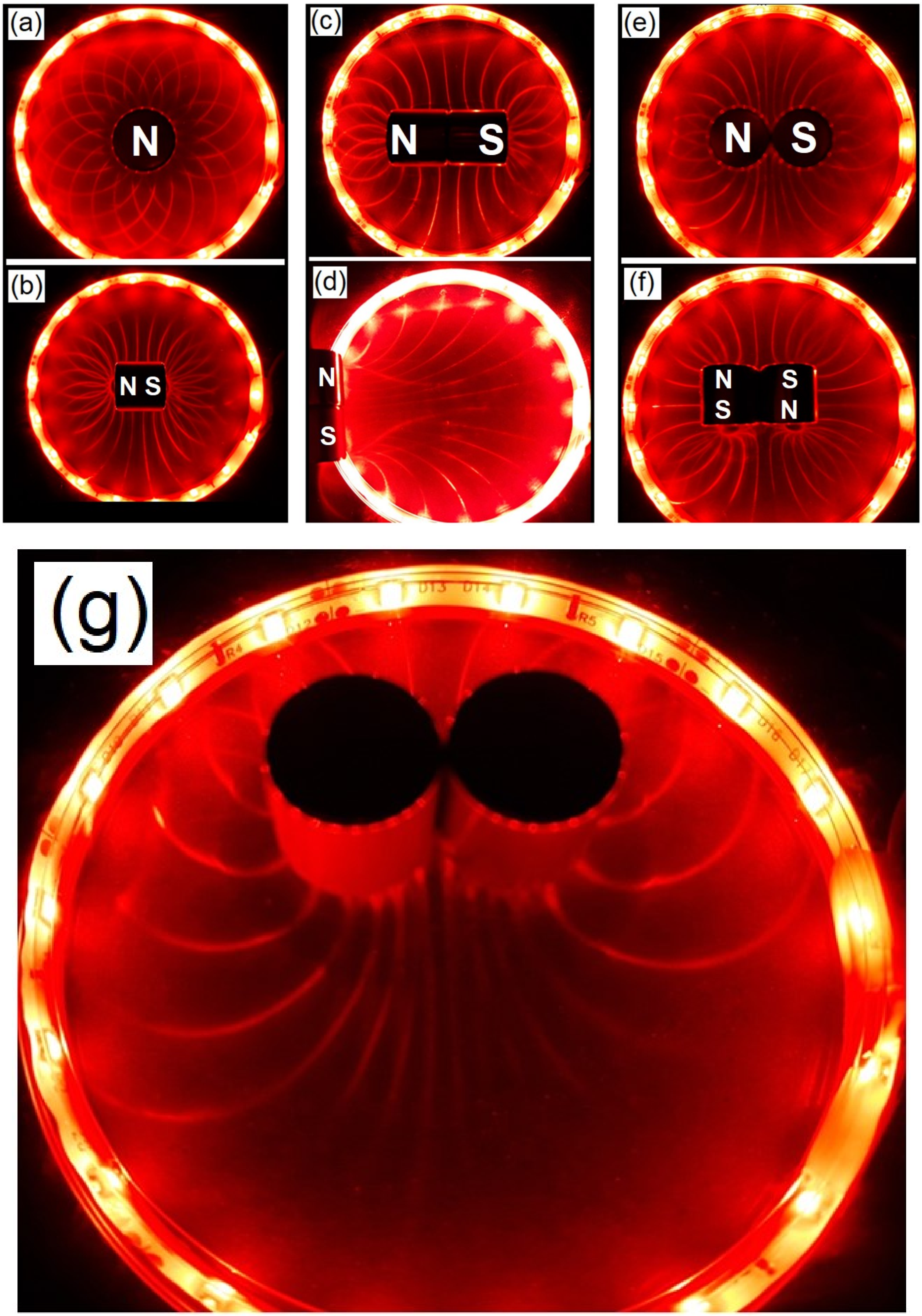

Figure 3.Intro5 – Some tests: (a) Unipolar configuration with one magnet. (b) Dipolar configuration with one magnet. (c) Dipolar configuration with two identical magnets. (d) Dipolar configuration of magnets placed on the edge of Ferrocell. (e) Another dipolar configuration. (f) Tetrapolar configuration. (g) Perspective of two magnets placed at the top of Ferrocell.

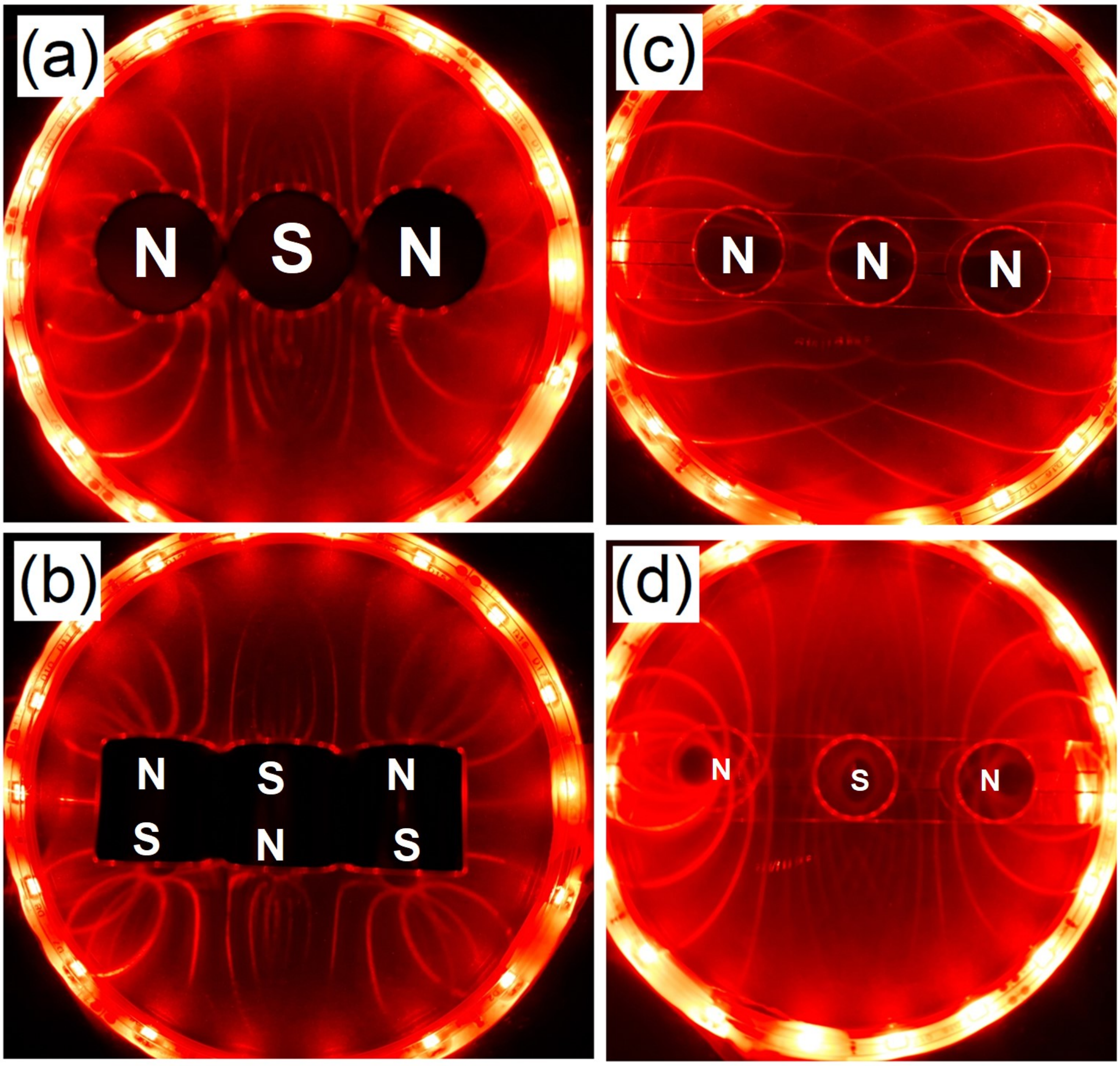

Figure 3.Into6 – Some tests using three cylindrical magnets in line. In (a), three-pole configuration N-S-N. In (b), hexapolar configuration. In (c) and (d), the magnets are placed under the Ferrocell.

In Fig. 3.Intro6 we are presenting some tests with Ferrocell using simultaneously three magnets. We can compare some of these light patterns with the respective magnetic field diagram in Fig. 3.Intro7. Pay attention to the luminous pattern of the saddle point for the case of Fig. 3.Intro7 (a), in that, each saddle point of the magnetic between each magnet is reduced to a point between each magnet in Ferrocell's luminous pattern.

In Fig. 3.Intro8 (a) we see the light pattern in Ferrocell with three-cylindrical magnets spaced by a cork. In Fig. 3.Intro8 (b), we have the light pattern obtained with three magnets in a triangular pattern.

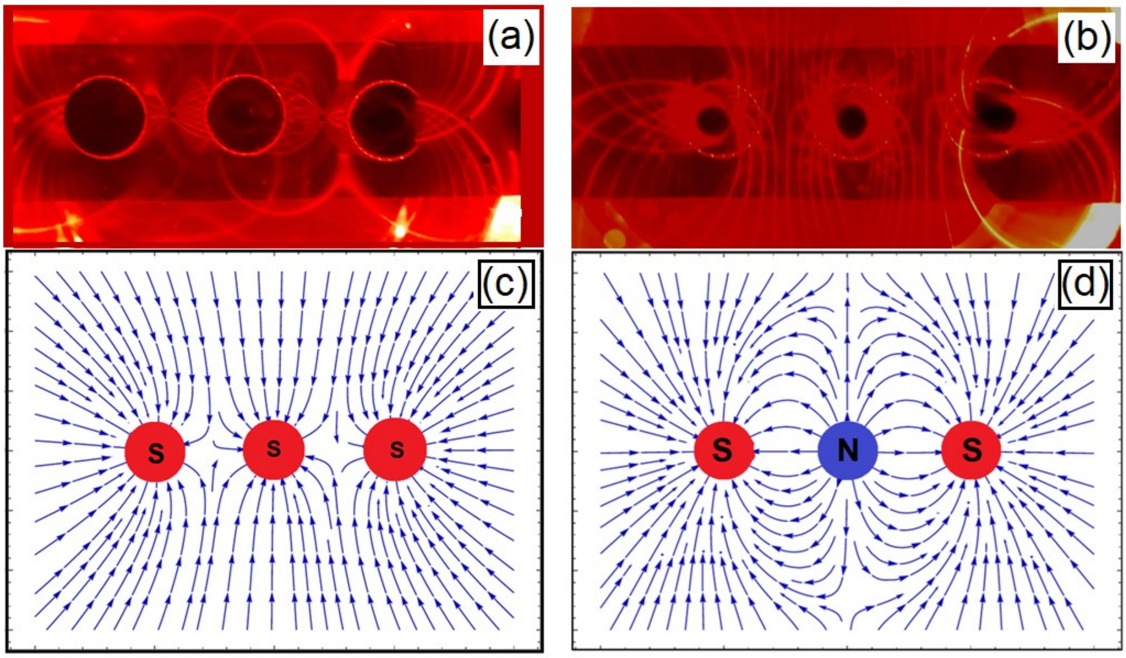

Figure 3.Intro7 – Some tests with three cylindrical magnets in line. In (a), three-pole configuration S-S-S, and in (b), three-pole configuration S-N-S. In (c), diagram of magnetic field lines for the case S-S-S configuration. In (d), diagram of magnetic field lines for the case S-N-S configuration.

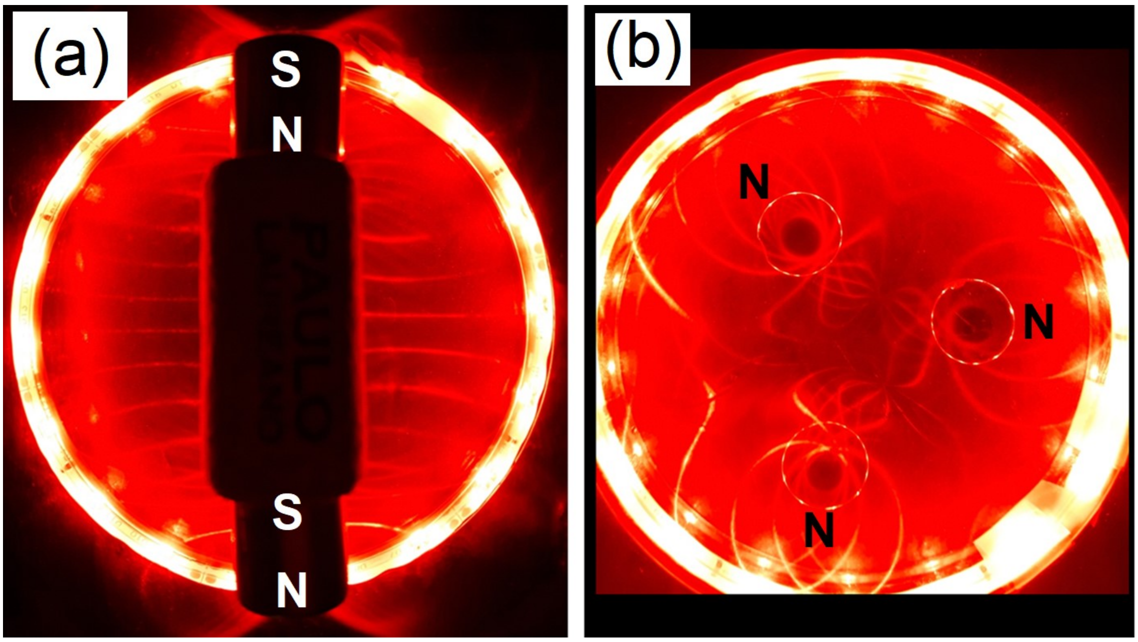

Figure 3.Intro8 – Light pattern in Ferrocell with two cylindrical magnets spaced by a cork in (a). light pattern obtained with three magnets in a triangular pattern in (b)

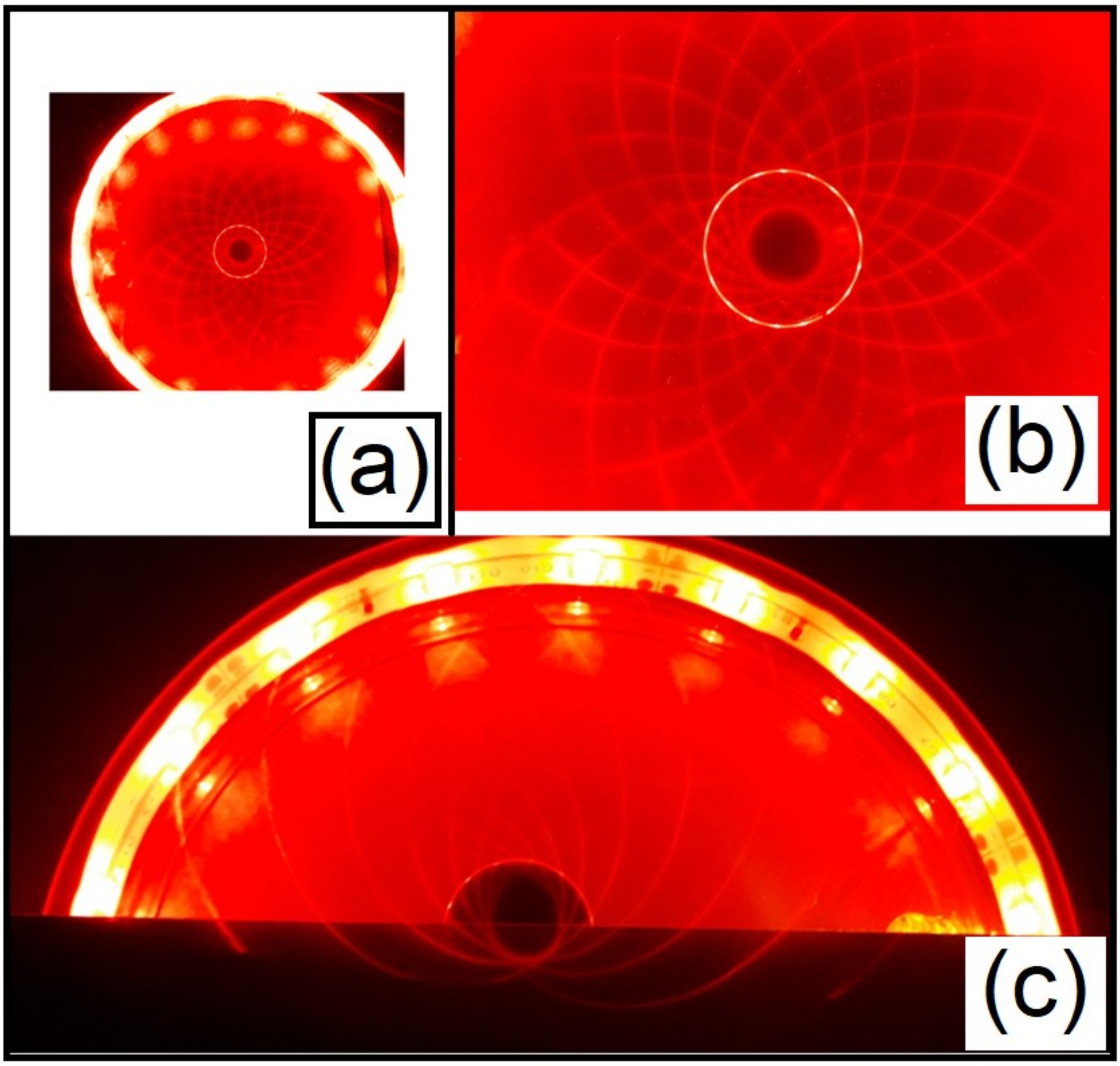

Figure 3.Intro9 – The “Black Hole” light pattern obtained placing a magnet under the Ferrocell in the polar configuration.

A pattern that intrigues many Ferrocell users and has been called by some of them as “Black Hole” is shown in Fig. 3.Intro9 (a) [1], in which a pattern in the shape o black circle around an electromagnetic pole is formed in the zoom of Fig. 3.Intro9 (b), due to the superposition of luminous ellipses of the various LEDs. This overlapping of the light sources can be perceived and followed by blocking the light coming from part of LEDs, as shown in Fig. 3.Intro 9 (c).

In Fig. 3.Intro10 we have the luminous “eye” pattern obtained using the mirror technique developed by Snyder, discussed in the previous chapter.

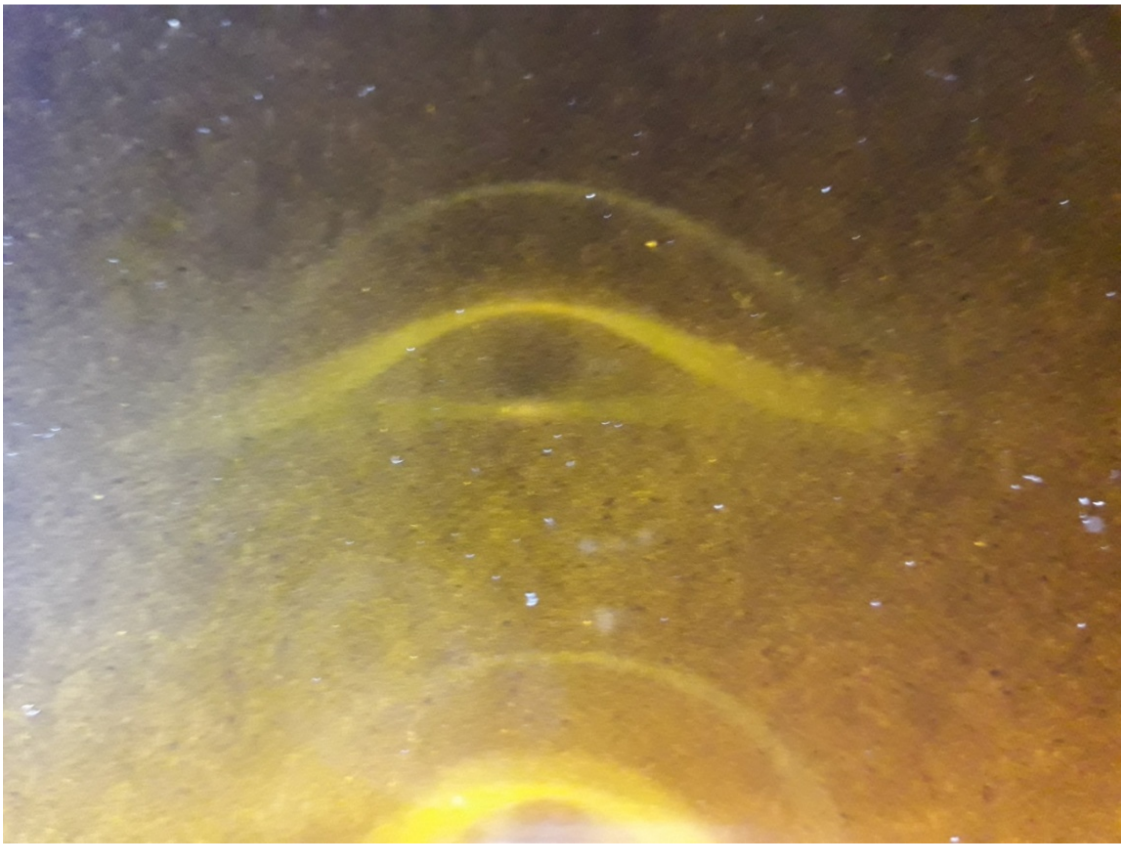

Figure 3.Intro10 – Luminous pattern from Ferrocell obtained with the use of a mirror.

We found some interesting light patterns at Ferrocell for a hexapolar magnetic field, with the system shown in Fig. 3.Intro11.

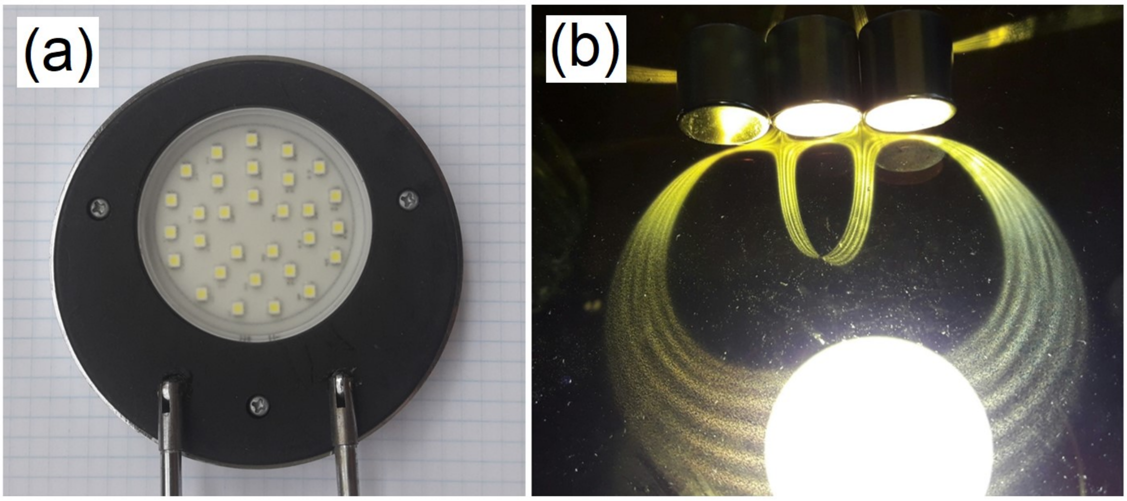

Figure 3.Intro11 – A lamp with an array of LEDs in (a) is used as light source for the case of the hexapolar magnet.

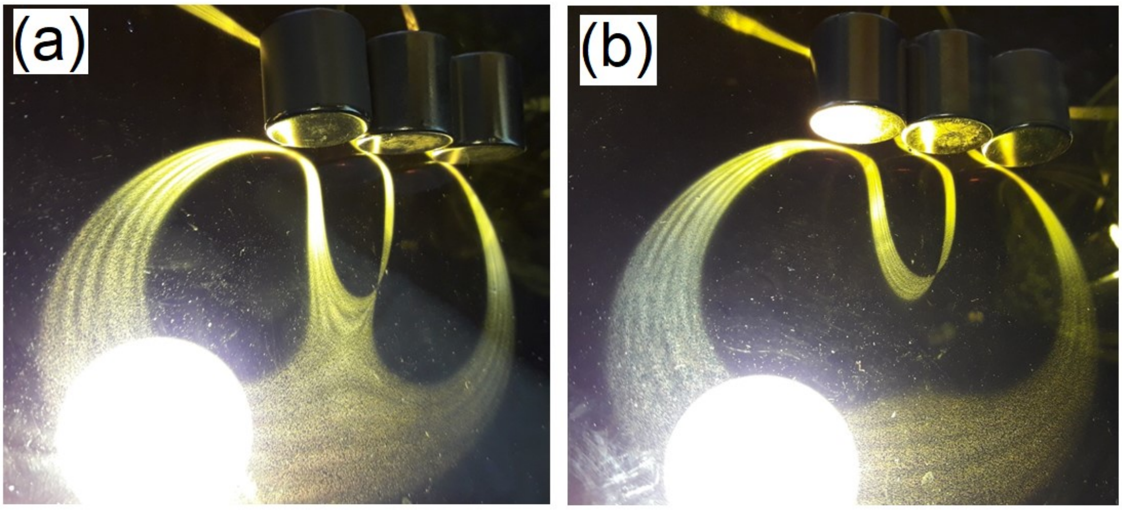

Figure 3.Intro12 – Two views of patterns for slightly different perspectives of the magnetic field applied at Ferrocell using the lamp of the previous figure.

Fig. 3.Intro12 we have two views of the light pattern of Ferrocell, using a hexapolar arrangement of magnets and the circular lamp shown in Fig. 3.Intro11, in which we see a ribbon of light formed by the light diffracted by different LEDs. Depending on the angle of view, the central part of the ribbon connects with its side.

In addition, we can see that the luminous pattern has a yellowish color , although the luminous source is white. This yellowish tone is related to absorption of light by the ferrofluid solution. Absorption becomes more intense for colors with lower wavelengths, such as blue, and less intense for higher wavelengths, such as red. Using LED lighting that allows combining colors, we show some patterns for the case of magnets in polar and dipolar configurations in Fig. 3.Intro13 and Fig. 3.Intro14 respectively.

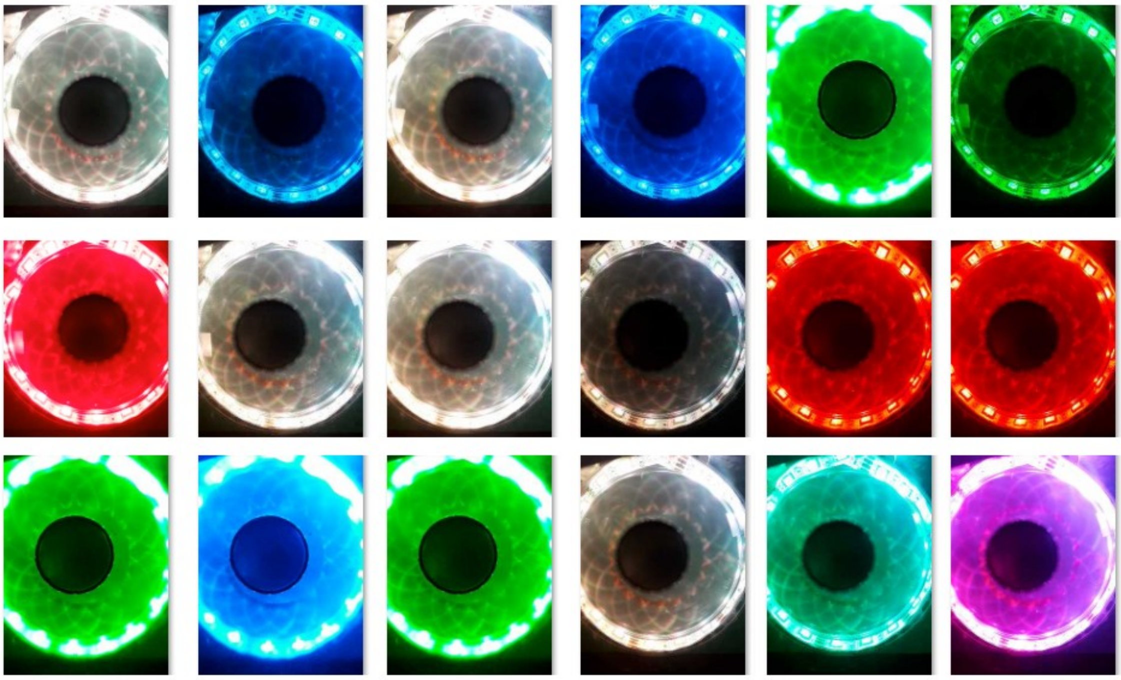

Figure 3.Intro13 – Luminous patterns with different colors obtained using polar configuration.

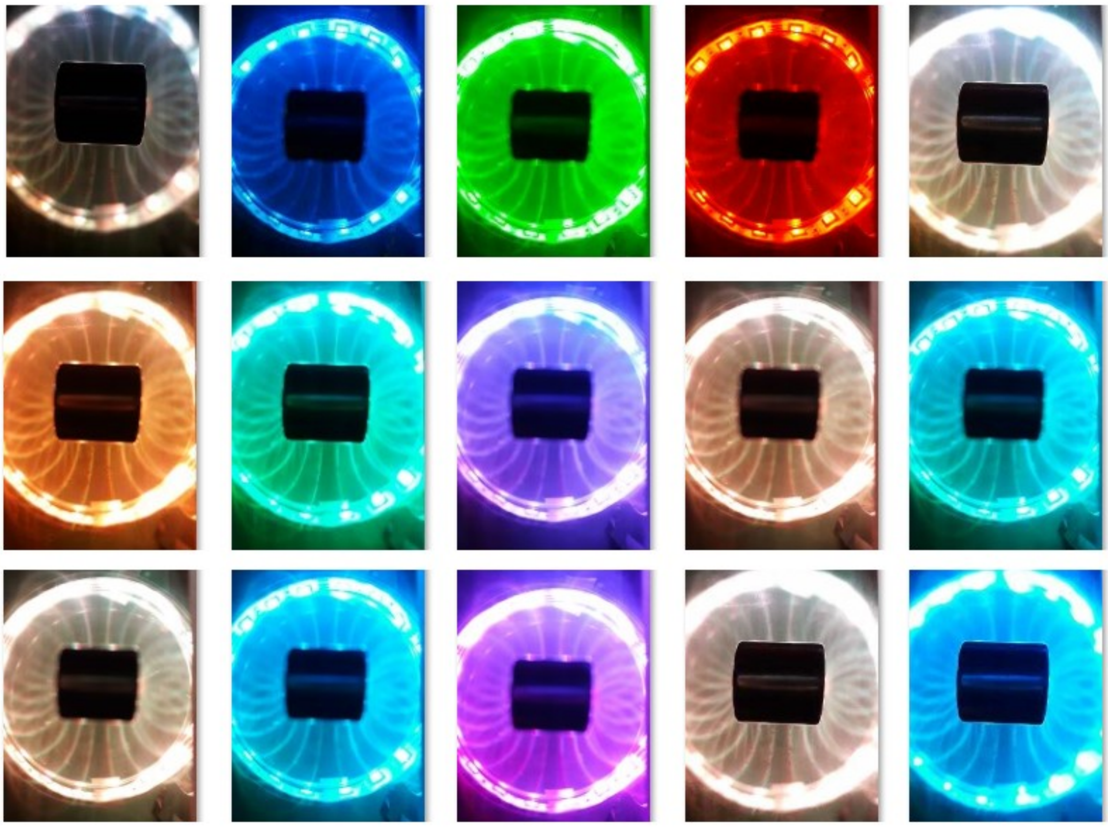

Figure 3.Intro14 – Luminous patterns with different colors obtained using dipolar configuration.

3a. Geometrical Optics, Huygens principle, Young and Geometric Theory of Diffraction

The main idea of this section is to introduce the concept of diffracted ray, which is important to understand the observation of light patterns in the Ferrolens [2-5].

Optics involves a collection of physical systems related to the propagation of light and its interaction with matter, which can represented in the diagram of Fig. 3.1. Depending on the main concept involved, we have different areas of the optics. In this way, we have the concept of ray of light and wave, and using these different concepts we have different ways to study and to understand what is happening in an optical system. For example, the concept of light ray is mainly used to understand the propagation of light and its interactions with lens and mirrors, related to the area of geometrical optics.

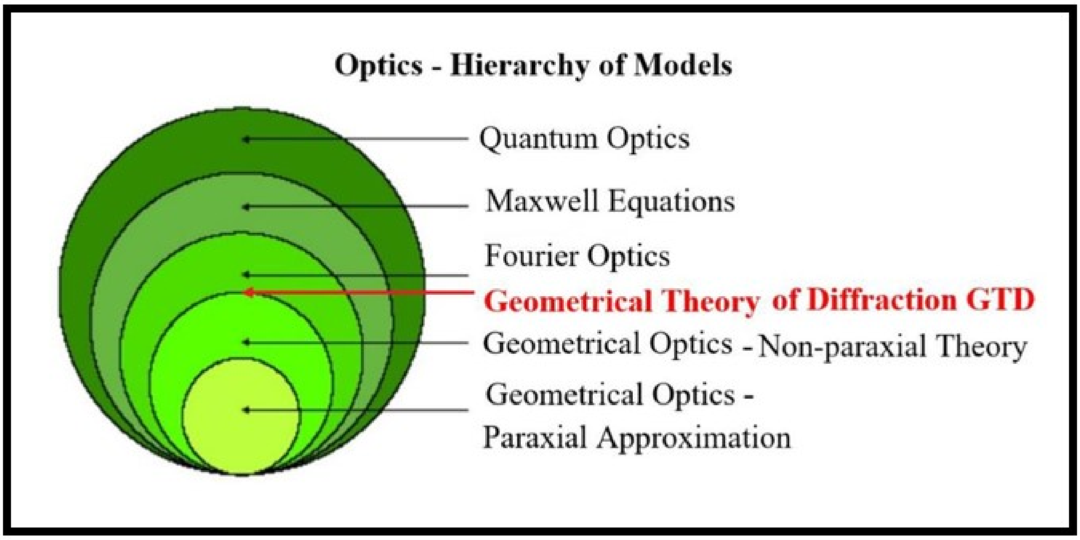

Figure 3.1 - A diagram representing the different areas of optics.

The geometrical optics in the paraxial case is used traditionally to study lenses and mirrors as in the Figs. 3.2(a)-(b). As an example of non-paraxial optics, in Fig. 3.2(c), we are presenting a sequence of rays of light, represented by R_1, with the origin at the corner at the top of the right side of the square interacting with a hyperbolic prism, in which there are reflections inside this prism by the rays R_2, followed by refractions represented by the rays R_3.

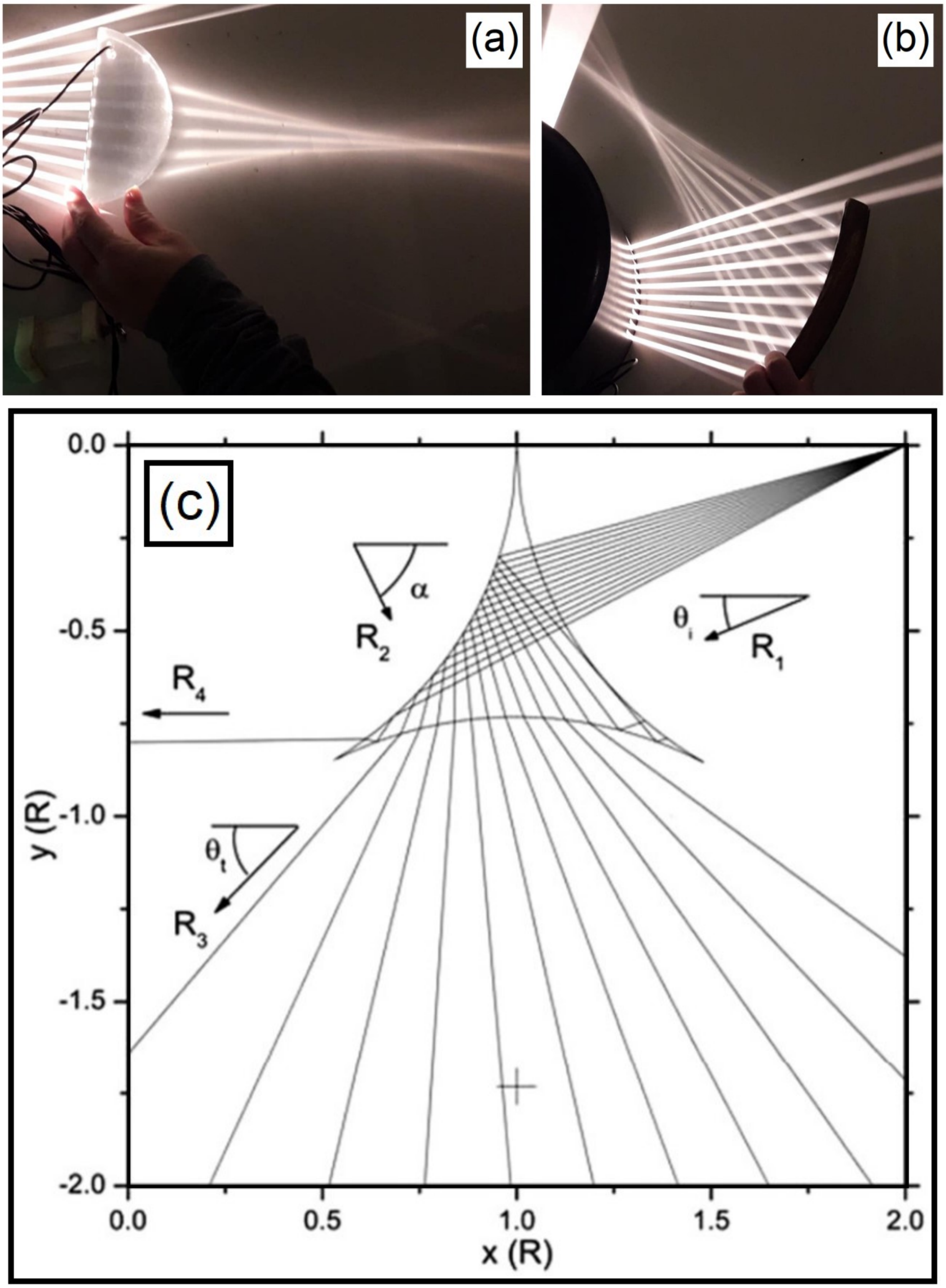

Figure 3.2 - Some experiments of geometrical optics in the paraxial representation for a lens in (a) and a mirror in (b). Representation of rays in a hyperbolic prism as an example of geometrical optics for the case of non-paraxial optics in (c) using a curved prism.

When the properties of wave are important, we are in the realm of wave optics, also known as physical optics, or Fourier Optics in the diagram of Fig. 3.1. For example, in Fig. 3.3(a) we can see the effects of light diffraction in a straight edge. For a thin single slit we have the pattern of Fig. 3.3(b), and for a large single slit, we have the pattern of Fig. 3.3(c). In this way, diffraction and interference are related to wave optics [5].

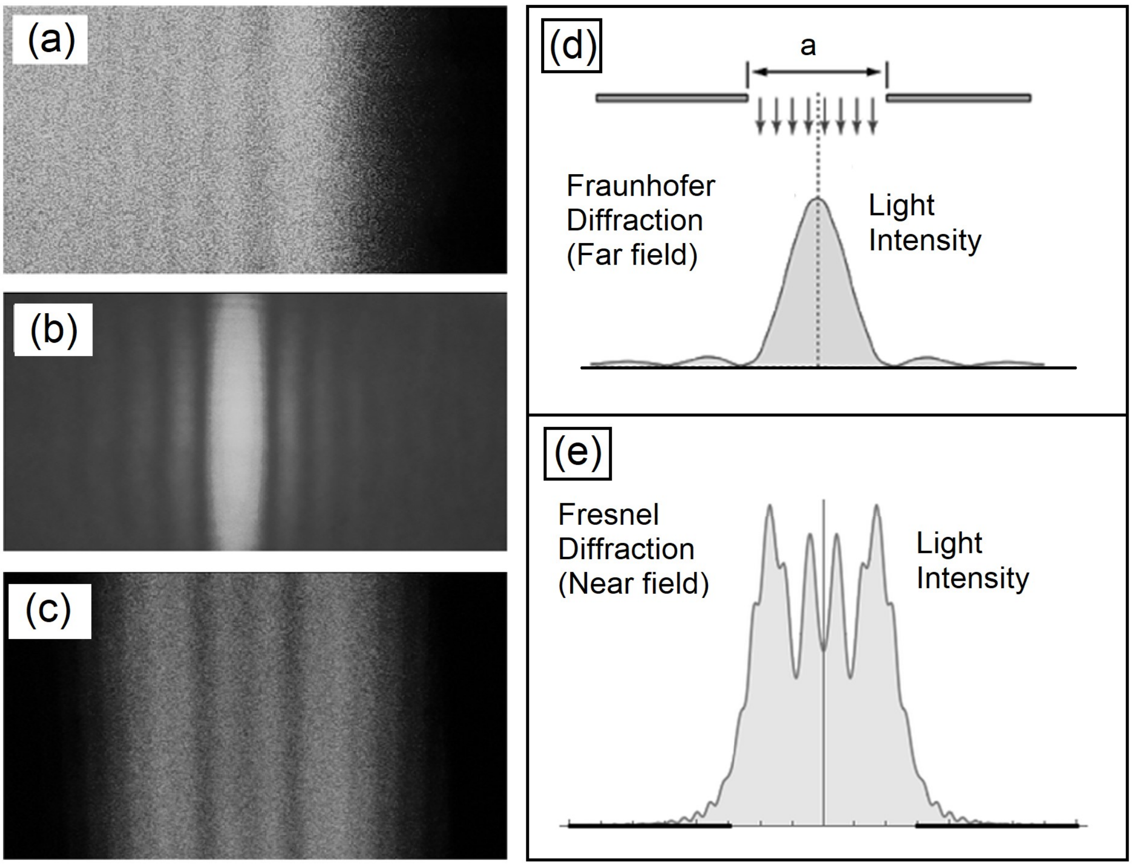

Figure 3.3 - Diffraction in a straight edge in (a). Diffraction in a thin single slit in (b). Diffraction in thick single slit in (c). Profile of light amplitudes for a single slit in near field case in (d) and for a far field case in (e).

The main principle for the case of diffraction is the Huygens principle, which states that every point on a propagating wavefront serves as the source of spherical secondary wavelets such that the wavefront at some later time is the envelope of these wavelets [4, 5].

The principle of Huygens is valid for diffraction for the far field condition, of Fig. 3.3(b)-(d). However, for the case of Fig. 3.3(c)-(d), we have to consider the near field condition, in which there is an obliquity factor due to the fact each point of the wavelet tends to irradiate in a more intense way in one direction, and consequently, the light intensity of this patterns is more complex than the previous case.

The frontier between geometrical optics and wave optics is the realm of cases where the light has the some properties of wave and light at same time, and this part was originally studied by Thomas Young and structured by Joseph Keller in the Geometrical Theory of Diffraction (GTD) [2, 5]. For these cases, we observe the laws of reflection and refraction along with far field or near field diffraction. For example in Fig. 3.4(a), we can observe the pattern of diffraction of a triangular slit, while in Fig3.4(b) we see the pattern obtained for a Plateau border, which consists of assembly of a 3D microscopic curved prism similar to the profile of Fig. 3.2(c). In both cases, we can see the existence of a pattern with six arms star, which is a characteristic of near field diffraction of triangular structures, but for the case of the Plateau border we can see the formation of a circumference, which is related to a conical diffraction occurring at same angle of incidence of the light in the Plateau border, causing a diffraction in a angle of reflection. In this way, reflection and diffraction are present at same time, with light presenting the features of ray and wave simultaneously.

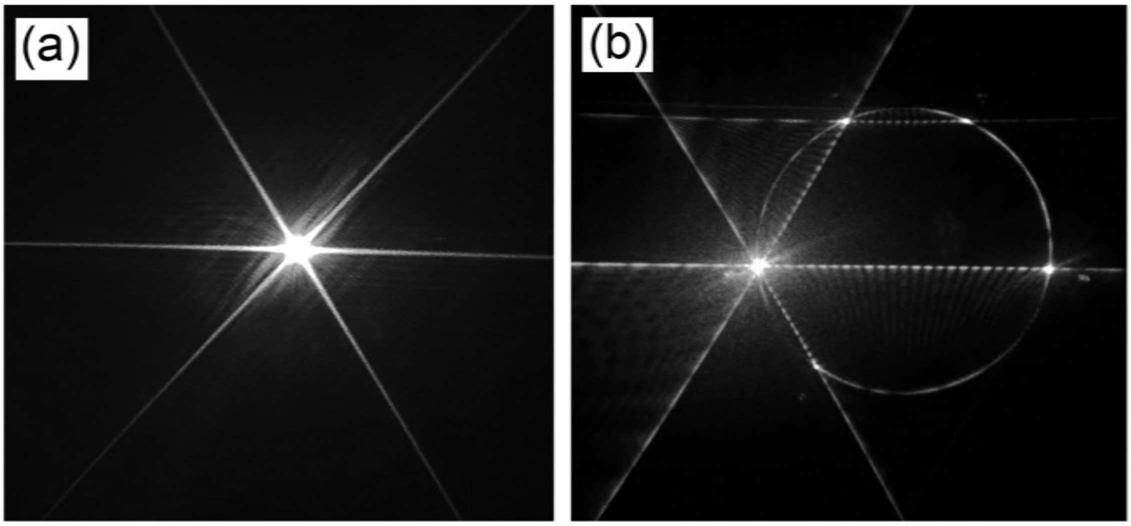

Figure 3.4 - Diffraction pattern in a triangular hole in (a). Diffraction of a laser beam in a Plateau border in (b).

The size of the magnetic structures inside the Ferrolens is similar to those present in the Plateau border. We have observed from our experiments, that the same phenomena present in the light/Plateau border system occur in the Ferrolens, and some of these ideas are represented in the diagram of Fig. 3.5.

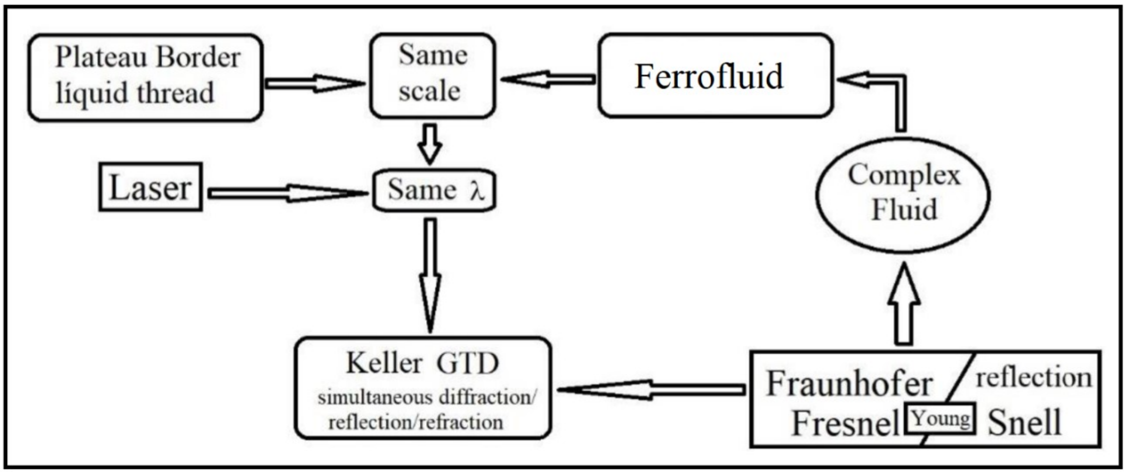

Figure 3.5 - Diagram of concepts involving light, ferrofluid and the Geometric Theory of Diffraction (GTD).

For the case of the Ferrolens, there is multiple diffraction and interference simultaneously, creating patterns observed in Fig. 3.6 for different orientations of the magnetic field, giving the impression that the light is bent [2].

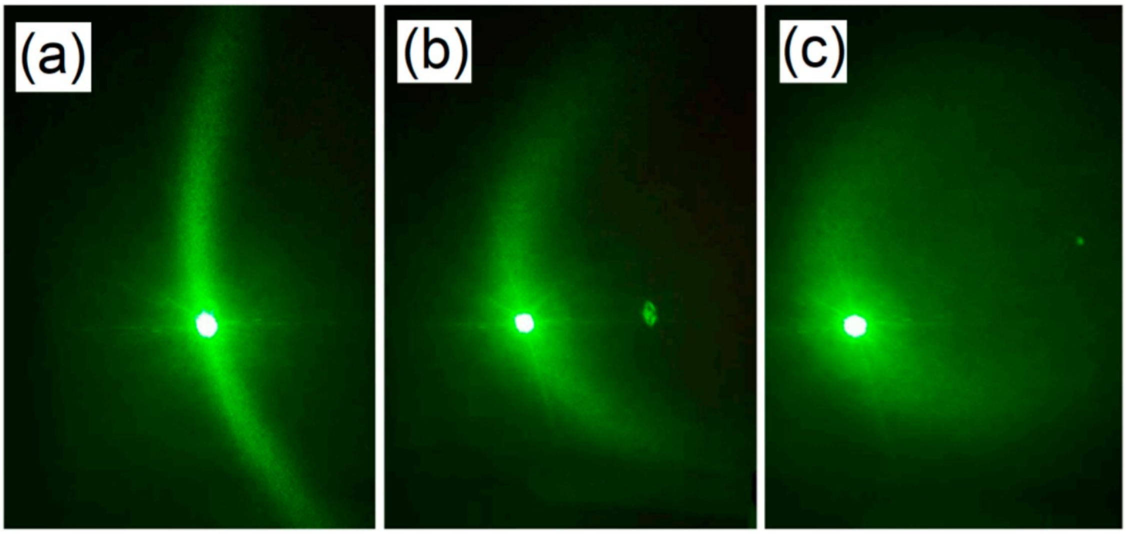

Figure 3.6 - Geometric Theory of Diffraction can be used to explain these curved patterns observed in the laser diffraction using the Ferrolens. Three images of light diffraction controlled by the magnetic field of 600 G: (a) Light scattering obliquely in the nanoneedle for different angles between light propagation and magnetic field orientation at 83°, (b) 64°, and (c) 32°.

Based in these assumptions, we can understand some of the interesting features observed in the Ferrolens, which involves some properties of magneto-optics by the observation of beautiful patterns from different perspectives, like the ones presented in Fig. 3.7.

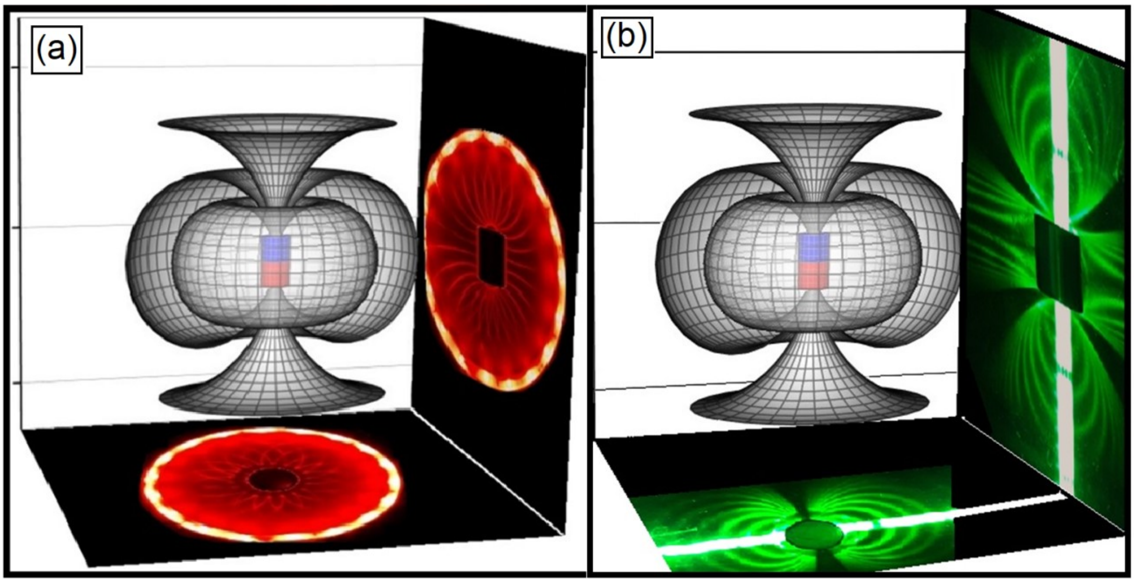

Figure 3.7 - In (a) two different light patterns obtained with Ferrolens using a magnet placed close to a ring of LEDs as the light source, and in (b) the same case as the previous one, but now using a LED stripe as the light source.

To sum up, the pattern formation in Ferrolens involves multiple concepts of Optics, such as those from geometrical and wave optics concurrently. It is important to note that the understanding of various optical phenomena can usually be studied with different levels of complexity and approaches in relation to existing theories. This happens since some peculiar cases involving rainbow formation, the colors of photonic crystals such as the feather of birds, and fabrics with structural colors and clearly applies to the case of Ferrocell. In the literature we can find several debates of this type, with authors trying to grasp the main concept that represents the phenomenon they are studying. In the case of Ferrocell, we have the addition of the magnetic field, which can cause the optics of the system to be represented by different contexts of the Optics that are in Fig. 3.1, which historically can even be considered opposed, such as the concepts of rays and waves, but that can appear at same time.

Since the presence of the magnetic field is a key factor in the use of this device, we will see in the next section how to build a low cost magnetic field meter, tha allows the Ferrocell user to make quantitative measurements of the magnetic field and its effects.

3b. Low Cost Gaussmeter

You can measure the magnitude of a magnetic field using a device known as *gaussmeter*. You can buy one, or you can do by yourself a gaussmeter. For example, we can build a gaussmeter, an equipment to measure the intensity of the magnetic field using the diagram of Fig. 3.8.

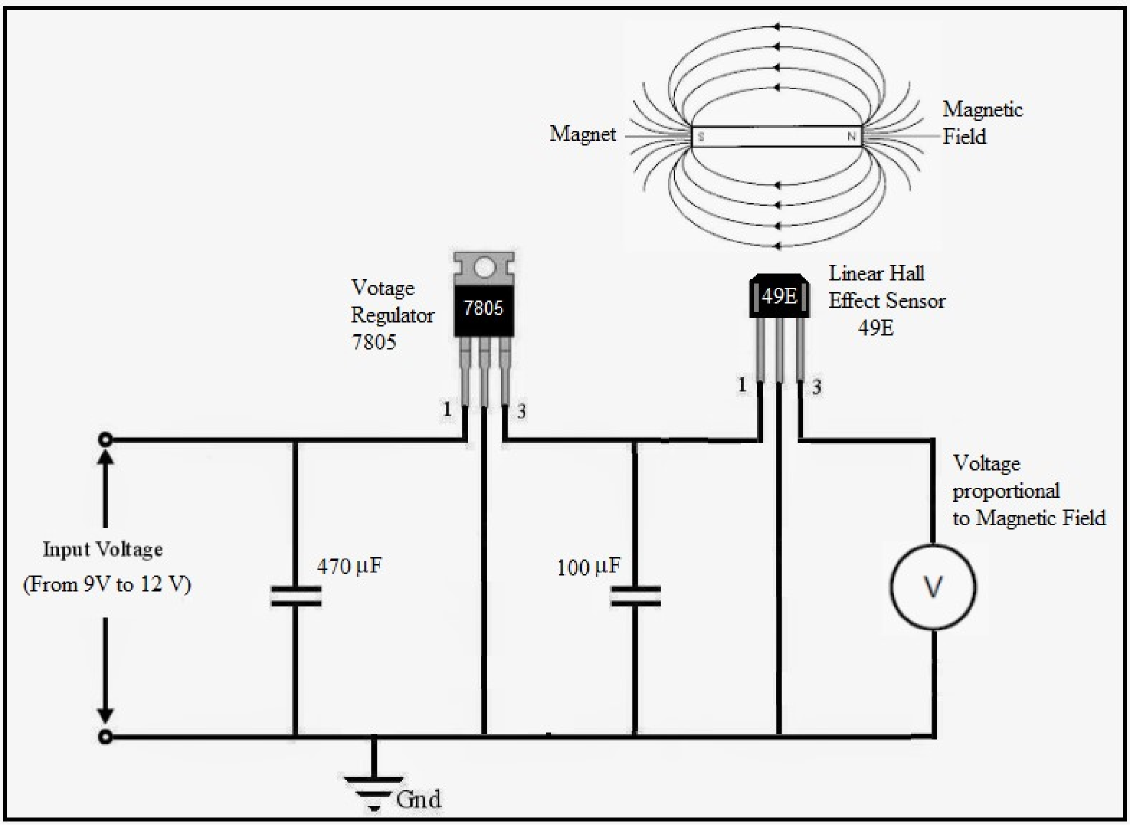

Figure 3.8 – Low cost circuit for a gaussmeter using a linear Hall sensor 49E.

The circuit of the gaussmeter is a power supply for a magnetic sensor known as "Linear Hall Sensor Effect" (SS49E) connected to a voltmeter. This is a Hall effect device that is capable of measuring the a certain range of the magnetic field of a permanent magnet or an electromagnet. The 7805 chip is a voltage regulator to power the operation of the Hall sensor. The capacitors are used to stabilize the voltage to avoid electrical noise. Using a voltmeter to measure the output of the Hall sensor, the value of the intensity of the magnetic field is proportional to the value of the magnetic field. Using a permanent magnet, we can test the functioning of this circuit. According to the manufacturer's information, this magnetic field sensor operates linearly with the magnetic field for values from 0 G to 1000 G.

We have implemented this circuit in order to test its functioning, as it is shown in Fig. 3.9.

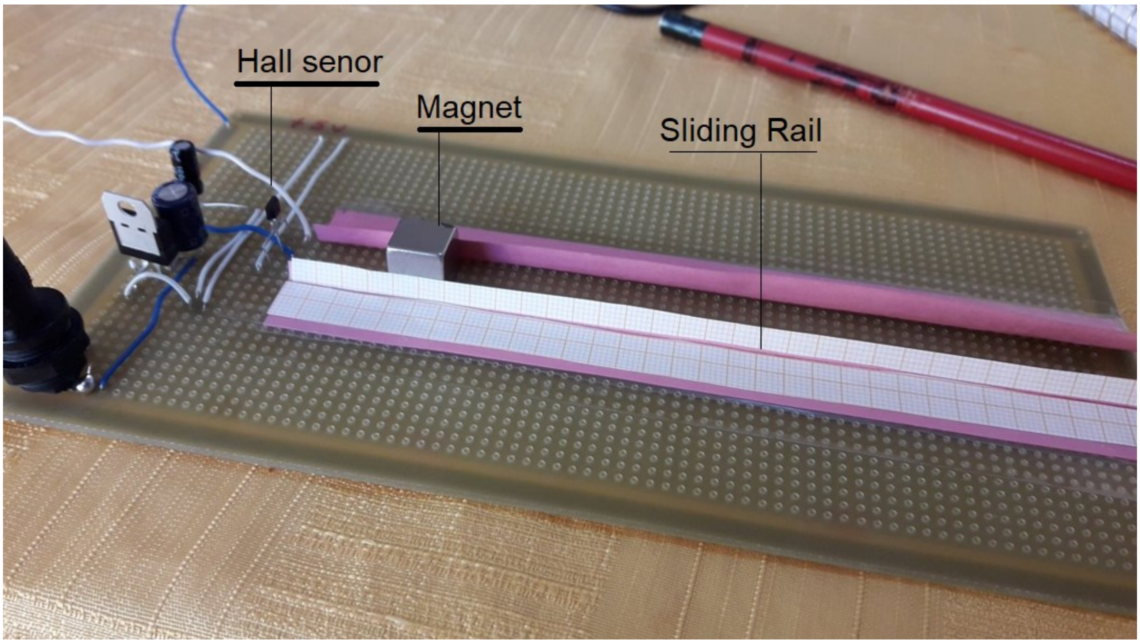

Figure 3.9 – Image of the setup to calibrate the low cost gausmeeter.

We made a small rail to slide a cubic magnet with a nominal value of 2,000 G of maximum magnetic field to test this circuit, comparing its response with a Tektronix gaussmeter that we use in our research lab. The calibration procedure was the follows: we slide the magnet into the rail, initially moving away from the Hall sensor to different positions. At each position we record the voltage value obtained with the Hall sensor. Then we approximate the magnet of the Hall sensor to observe the reproducibility and verify that there is no hysteresis effect in the low-cost gaussmeter. After that, we have done the same procedure using our Tektronix gaussmeter, recording directly the value of the magnetic field. Our measures for these two cases are shown in the plots of Fig. 3.10. The plot of the data obtained from our low-cost circuit is presented in Fig. 3.11. We have observed that this sensor is linear for the range from 0 to 1,000 G, with calibration values slightly different from the information of the manufacturer. The plot of the data obtained from our low-cost circuit is presented in Fig. 3.11.

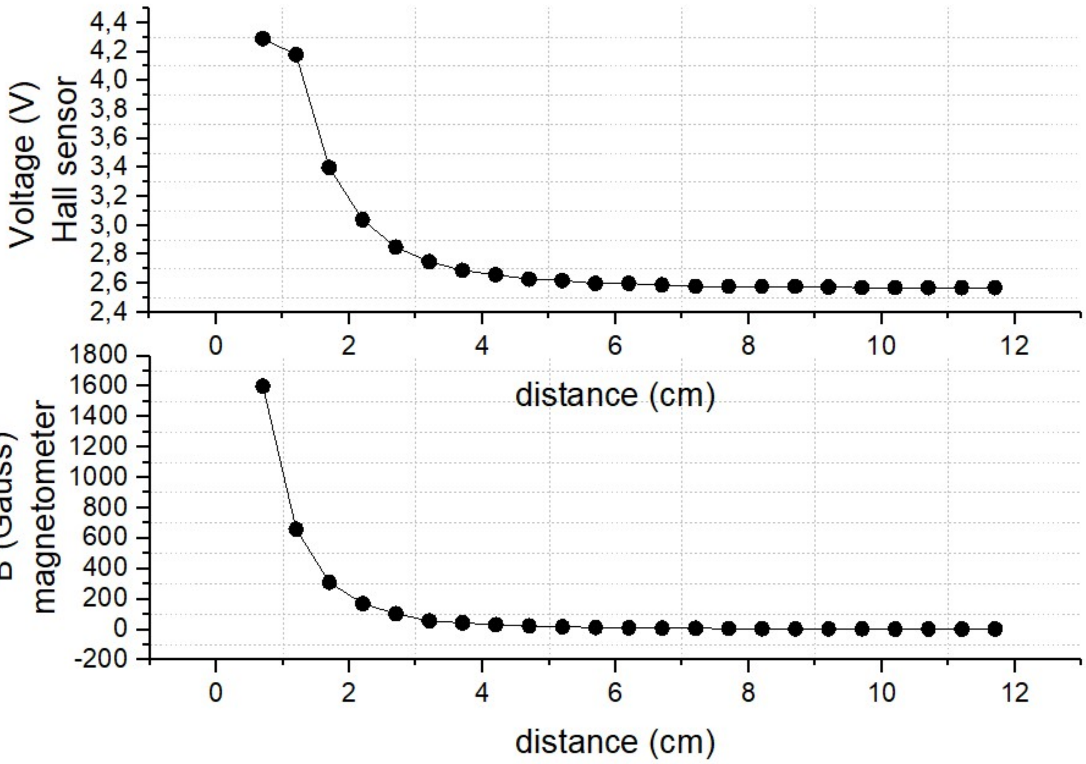

Figure 3.10 – Comparison between the Hall sensor and a professional gaussmeter using a cubic magnet (0,2 T or 2,000 G).

These calibration values were obtained for one side of the cubic magnet. When you use the opposite side of the magnet, the values obtained with our low-cost circuit begin around 2.5 V and end in 4.3 V for the range of magnetic field form 0 G to 600 G.

In this way, we have the following equation for the calibration of our Hall sensor:

B (gauss) = 365 * Voltage - 934.

The meaning of this equation is that we can transform the value that we have obtained in a voltmeter from the Hall sensor multiplying this value by 365 and subtracting 934. With a device like this you can improve your tests with Ferrolens by having an idea of the magnitude of the magnetic field in some points of the Ferrolens.

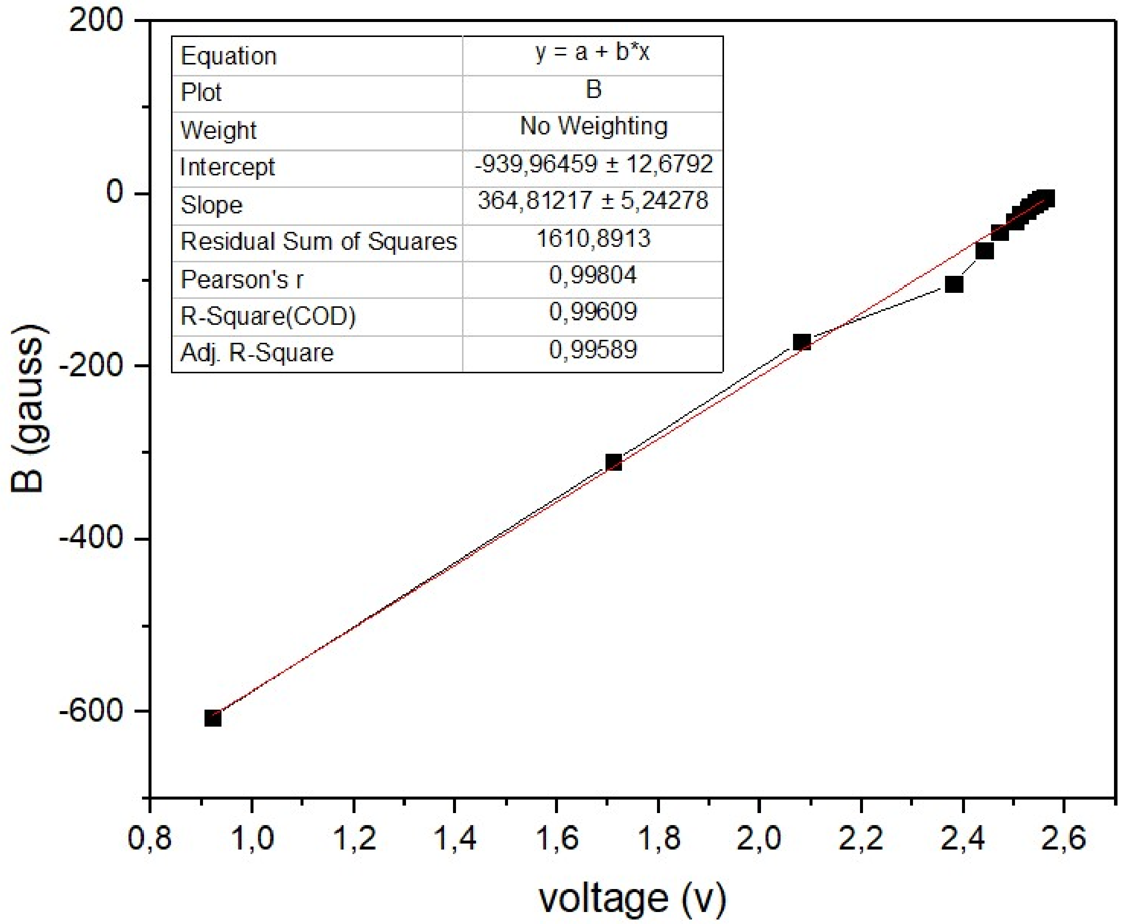

Figure 3.11 - Calibration, voltage and magnetic field intensity for the Hall sensor.

The main concept behind of the Hall sensor is that in the presence of a magnetic field, the electrical current in a conductor is displaced from its original position without this magnetic field, and this displacement of charges creates a voltage difference across this electrical conductor. This effect is a good example of the idea that electricity and magnetism are strongly connected.

3c. Recording Images of Ferrolens and Lasers

One interesting point of doing these experiments using Ferrolens is to take pictures of effects. Initially, it is necessary a camera, like the one in a cell phone. To do this, it is necessary to project the images on an opaque screen that can be made with the help of white sheet paper supported in a cardboard box, as we can see in Fig. 3.11.

Figure 3.11 - Two views of a white sheet paper supported in a cardboard box. Hanging a ruler at the bottom of the sheet helps to keep the paper well stretched to prevent deformation of the images.

Using this screen, we can observe the images of the light projected in both sides of the screen and take photos of them, as it is shown in Fig. 3.12. In order to obtain the best possible images, it is recommended to reduce the ambient lighting where the experiment is located, so that we can observe the main effects. Although the screen is opaque, we can see the patterns on both sides of the sheet of paper.

For the case of dark field configuration, the pictures can be taken directly from the device, considering the same lighting conditions of the previous case, as can be seen in several images of this book.

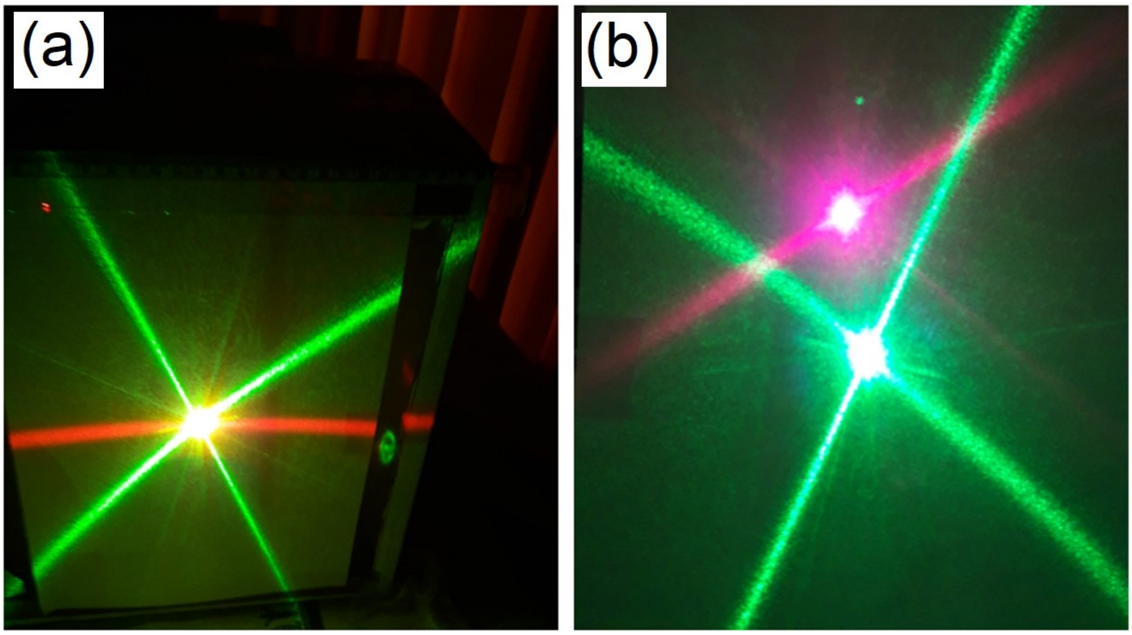

Figure 3.12 - Projecting images in the mode of laser transmission using the Ferrolens. In (a), we can see the outside of the screen, and in (b) the inside of the screen, for three lasers configurations, two green lasers and one red laser.

3d. Ferrocell: Do It Yourself

We do not intend to teach you how to make a Ferrocell in detail in this book. However, there are some videos on YouTube [6, 7] that explains how to make a Ferrocell step-by-step. If you want to build your own Ferrocell, take all the safety precautions recommended for handling ferrofluids and their solvents.

3e. Laser and Ferrolens

This demonstration is based on the concept of laser transmission using Ferrolens, so at this point it is necessary a laser, such as a laser pointer. Because of the risks posed by laser radiation, we strongly suggest that the users inform themselves about the safety measures involving the use and the risks of low power lasers, as well as the use of laser safety glasses.

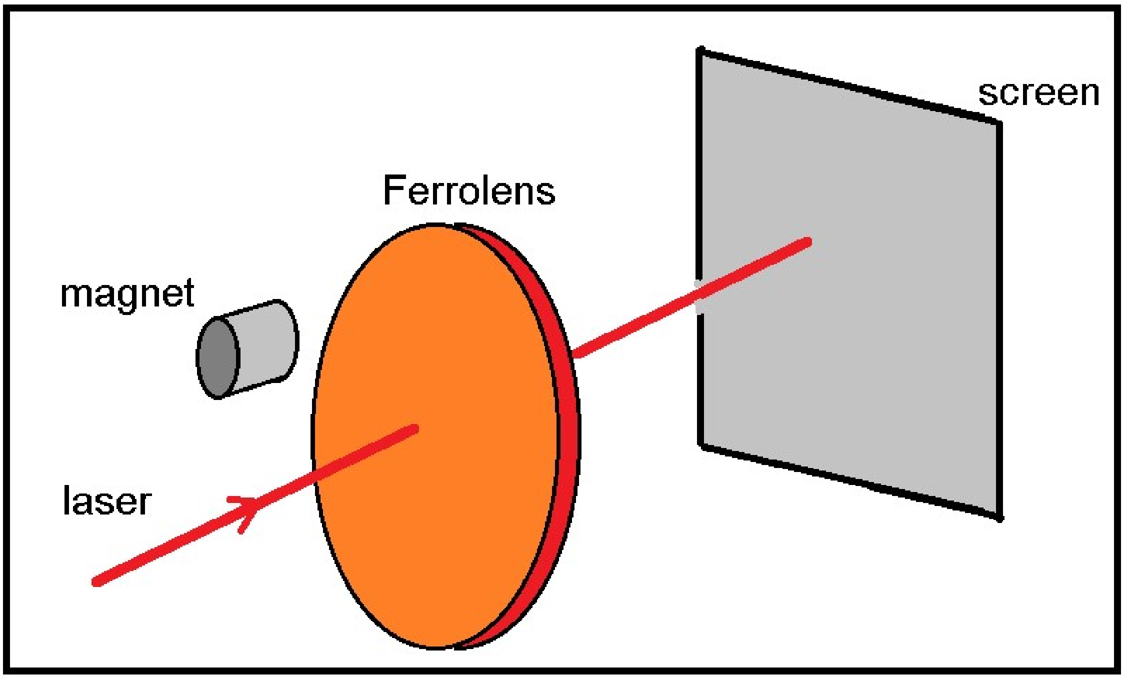

Figure 3.13 – Diagram of laser transmission demo with Ferrolens. This can be obtained using a regular laser pointer, a cylindrical Neodimium magnet, a sheet of paper along with the Ferrolens.

The main idea of this demonstration is to observe the effects of laser diffraction using a Ferrolens. In Fig. 3.13 we present a diagram to use the Ferrolens in the laser trasmission demonstration. Basically, this setup is made to observe the effects of a laser beam through a Ferrolens subjected to a magnetic field. The magnetic field can be obtained by placing a magnet near the point where the laser meets the Ferrolens. The laser is then projected onto a screen, which can be made using a sheet of whit paper in a support, so that we can observe the light pattern. To prevent the pattern from being dimmed by ambient light, the room must be slightly dark. Placing the laser beam in the center of Ferrolens will allow you to move the magnet around the beam whitout intercepting it. Mount the apparatus without the magnet, and ensure that the laser forms a dot on the screen. If any light streaks appear in the luminous pattern projected on to screen, the Ferrolens needs to be carefully cleaned.

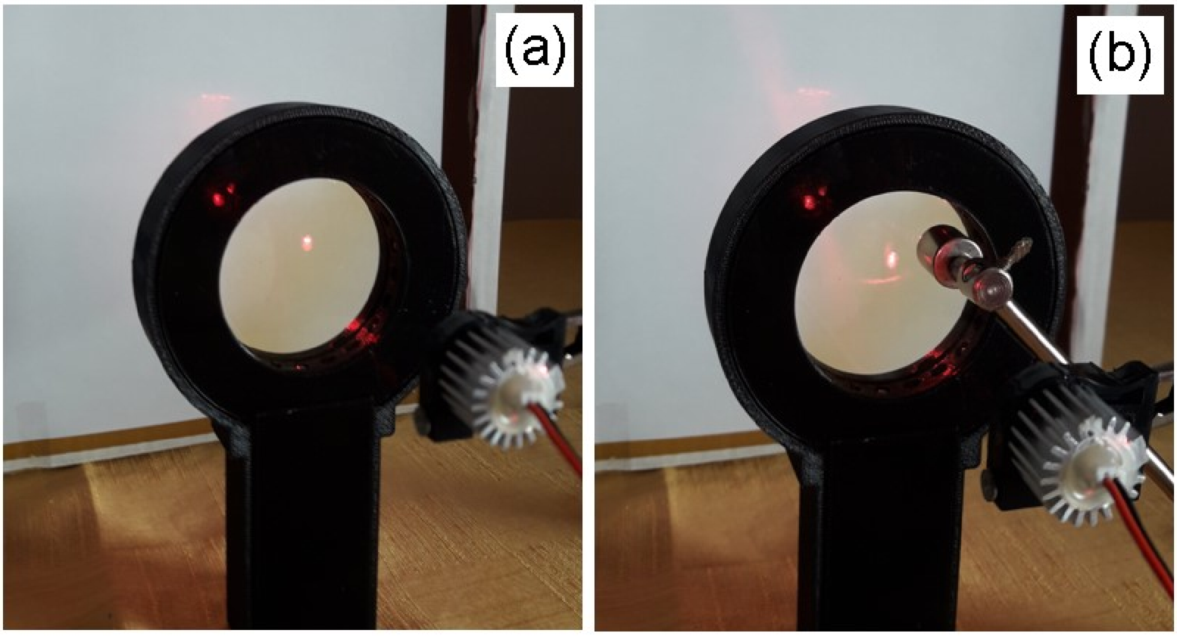

Figure 3.14 – Photos of this demonstration using Ferrolens. In (a) no magnetic field, and (b) with a magnet generating an intense magnetic field.

In Fig. 3.14(a) we present a picture of this setup without the magnet, and in Fig. 3.14(b) we have placed a magnet in the polar configuration close to the Ferrolens. A holder is keeping the magnet near Ferrolens. We have used a Ferrolens in a handholder in this case, but the light ring is turned off for this demonstration involving laser. It is important to have this type of holder in experiments involving optics, because we have to place the magnet in different positions in order to observe the effects of the magnetic field in the laser beam.

Some patterns of this demonstration is shown in Fig. 3.15. In Fig. 3.15(a) we can see the red dot on to screen, in the absence of magnetic field. In Figs. 3.15(b)-(d), we can see the formation of light streaks, when the magnet is placed near the Ferrolens in three different positions. It is interesting to explore some of these effects in the Ferrolens, changing the position of the magnet in the polar configuration.

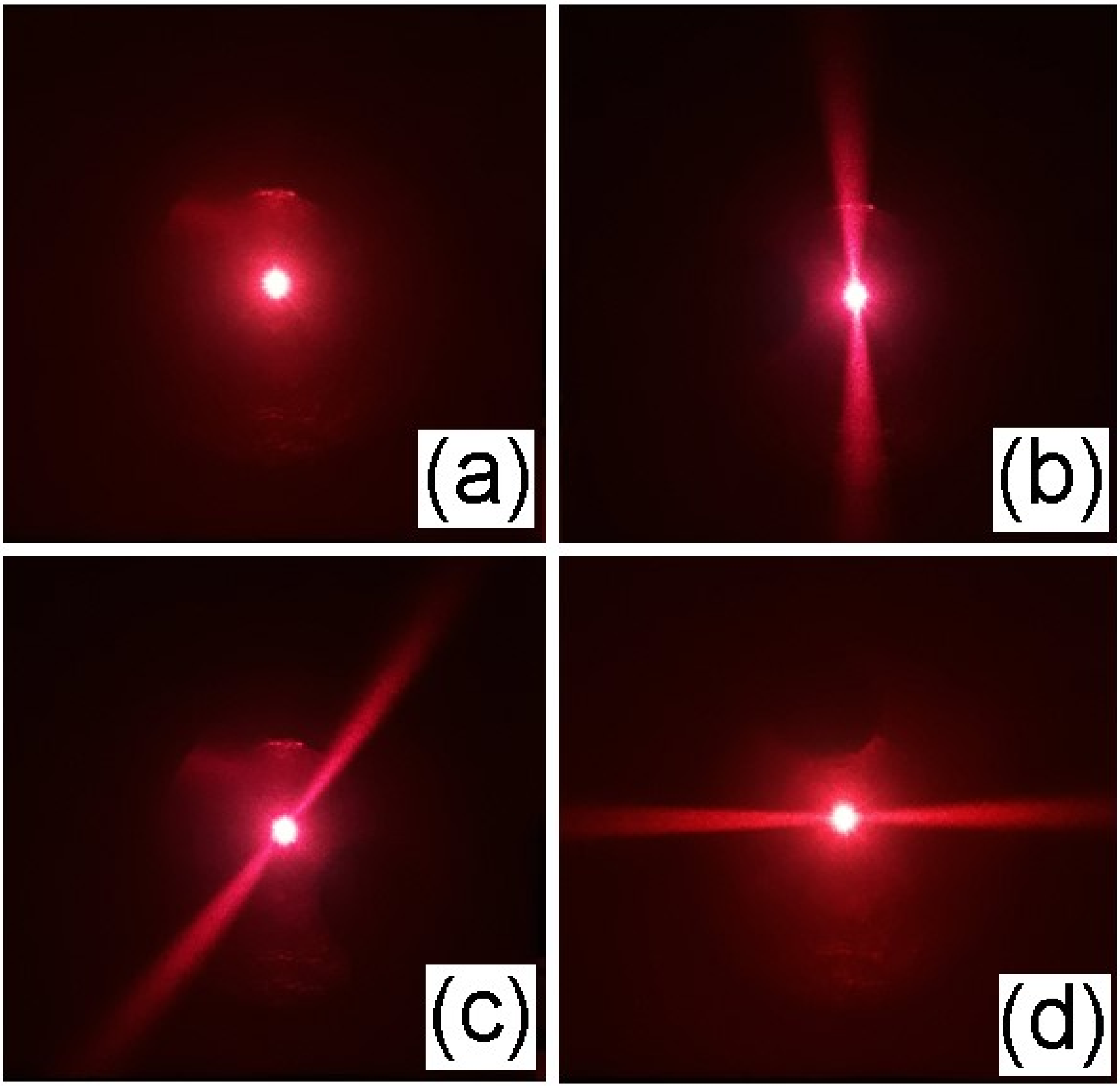

Figure 3.15 – Demonstration of laser diffraction using a red laser with the Ferrolens.

In Figs. 3.15(b)-(d), we can see that the light streaks are almost the same in these three cases, but it is in the vertical position in Fig. 3.15(b), in the diagonal position in Fig. 3.15(c), and in the horizontal position in Fig. 3.15(d). How is the position of the magnet field influencing the formation and the movement of light patterns of Fig. 3.15? To answer this question, we need to know how the cylindrical magnet was placed on Ferrolens, with the help of Fig. 3.16.

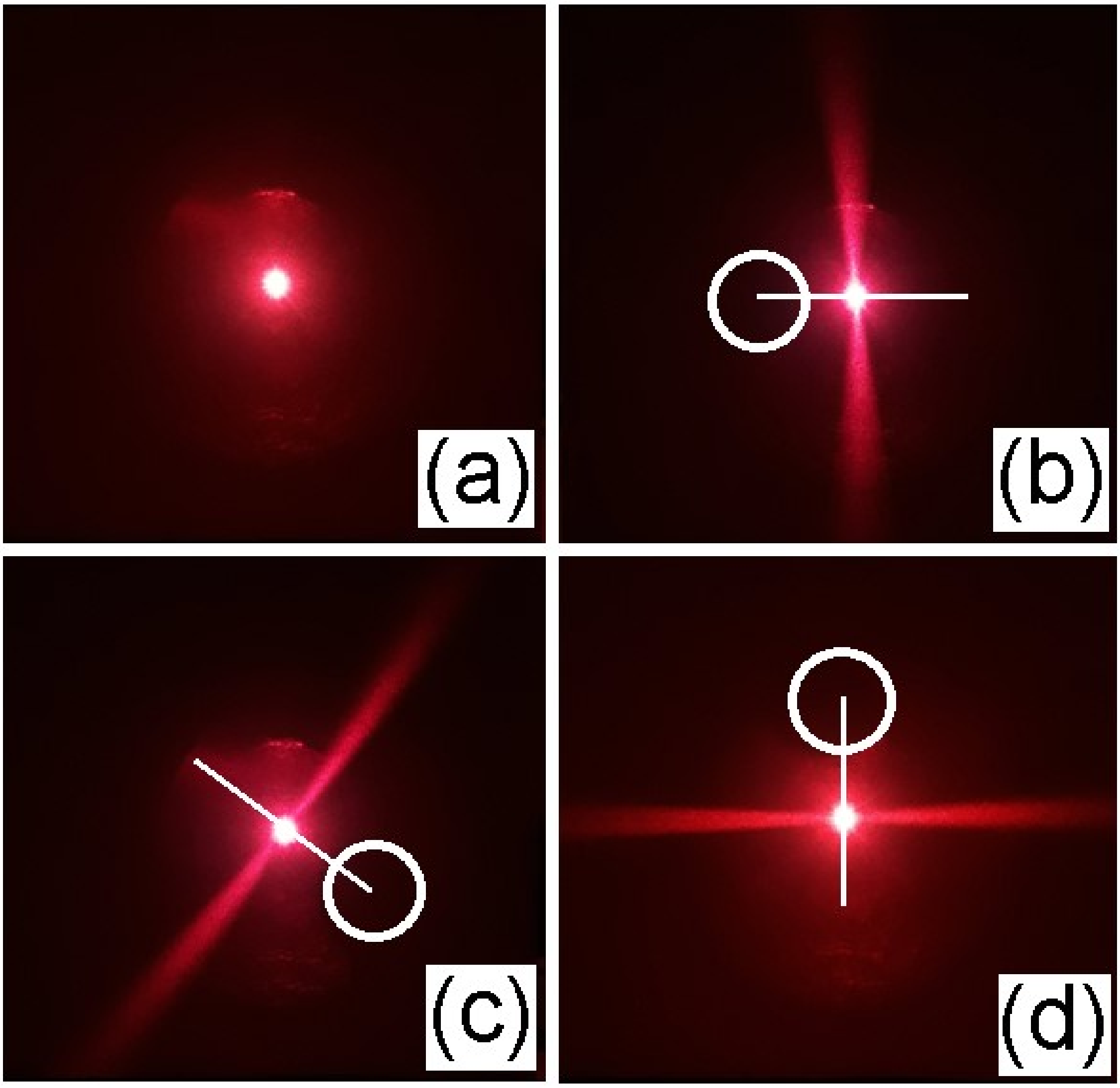

Figure 3.16 – Diagrams of the patterns with the demonstration using red laser. The white circles repesent the cylindrical magnet facing the Ferrolens. The straight white light represents the orientation of the magnetic field at the point where the laser meets the Ferrocell.

In Fig. 3.16 we can see the diagram of the magnet, the white circle, for different patterns. As discussed previously in Chapter 2, Section 2c, these light streaks occur because the magnetic field makes the iron nanopaticles take the shape of microscopic needles alligned with this magnetic field. At the point where the laser meets the Ferrolens, the microneedles are in a radial line with respect to the center of the cylindrical magnet. Thus, we see that the diffraction line that forms the pattern is always perpendicular to the laser beam and the magnetic field lines.

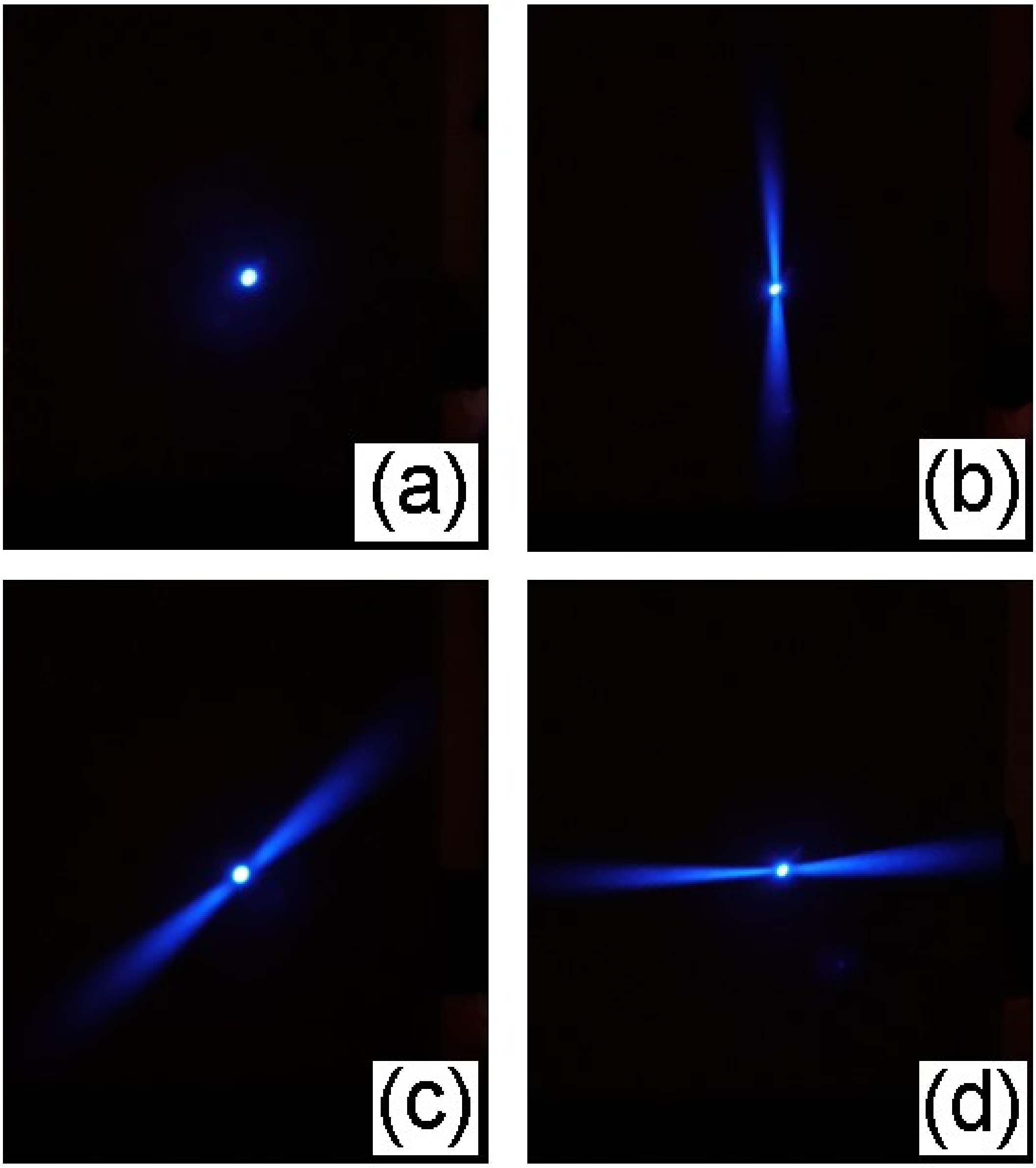

Figure 3.17 – Demonstration using a blue laser, with no magnetic field in (a) showing a blue dot, a light streak the vertical position in (b), the diagonal pattern in (c), and the pattern in horizontal position in (d).

We can also use different wavelengths to observe this light diffraction, such as the case of the blue laser of Fig. 3.17, or the green laser of Chapter 2, Section 2c. The patterns are very similar in each case.

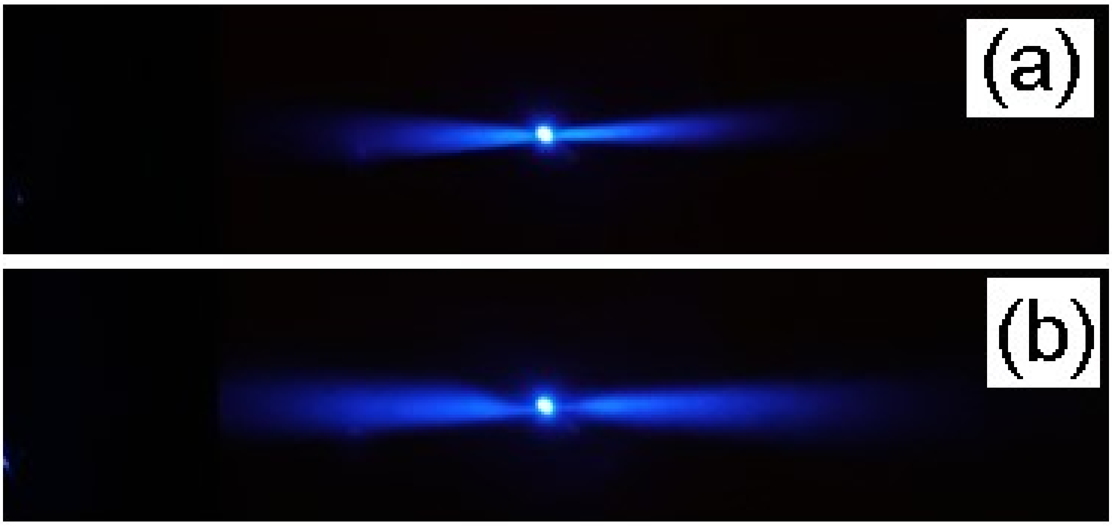

Figure 3.18 – the light pattern for different magnetic field intensities.

In Fig. 3.18, we have two light patterns for two magnetic field intensities. In Fig. 3.18(a) the magnetic field is lower than in Fig. 3.18(b). Looking carefully, we notice that the pattern is formed by two luminous lobes placed symmetrically with respect to the center point of the laser, and these lobes increase with the increasing of the magnetic field.

This occurs because increasing the intensity of the field increases the density of microneedles in front of the laser point, and consequently the space between the microneedles decreases, increasing the diffraction effect, as a narrower slit diffracts mor light than a wider slit.

Besides the case of laser transmission, we also have the case of the laser reflection in Ferrolens, which is very similar to what we have seen so far, but which allows us to observe some interference fringes on the diffraction lobes, because the ferrofluid thin film between the glass plates acts as a Fabri-Perot interferometer.

3f. Malus' Law and Light Polarization

In chapter 2, we covered some aspects of light polarization at Ferrocell, and an important physical law for the study of light polarization is Malus' law, expressed in Fig. 3.19(a).

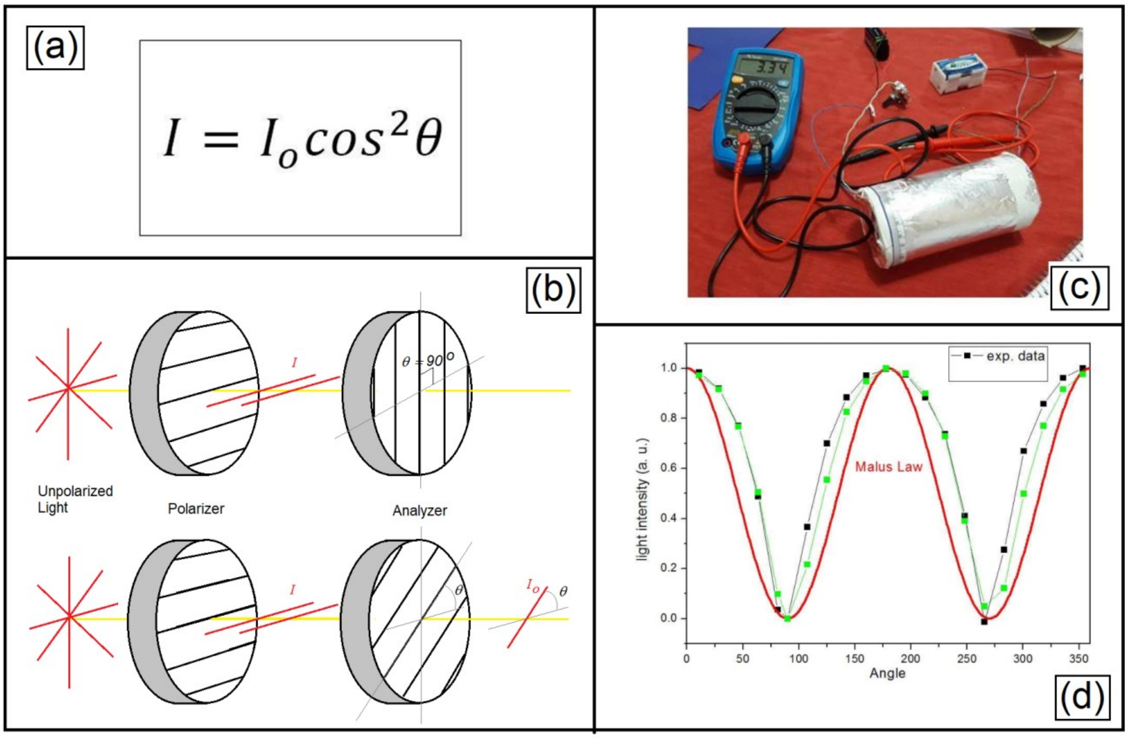

Figure 3.19 – Malus Law: in (a) equation of Malus' Law, in (b) diagram of a setup to verify Malus' Law, a low cost experiment to verify the Malus'Law. In (c) a photo of the low cost experiment to verify the Malus Law. In (d), plot of the Malus' Law in red, and two sets of data obtained by our students using this apparatus.

With Malus' Law we can verify the role of polarizing materials and their interaction with light, using two polarizers of Fig. 3.19(b). The device of Fig. 3.19(c) was constructed according to the work of Kadri, Wei, and Jaafar [2, 8] for the study Malus' Law. In Fig. 3.19(d) we can see the plot of the Malus' Law in red, along with two sets of experimental data plotted in black and in green. There is a deviation between experimental data and Malus' law, which must be related to the difference in sensitivity to different levels of light intensity by the sensor used. In general, due to the cost of the equipment, the experiment satisfactorily reproduces Malus' law.

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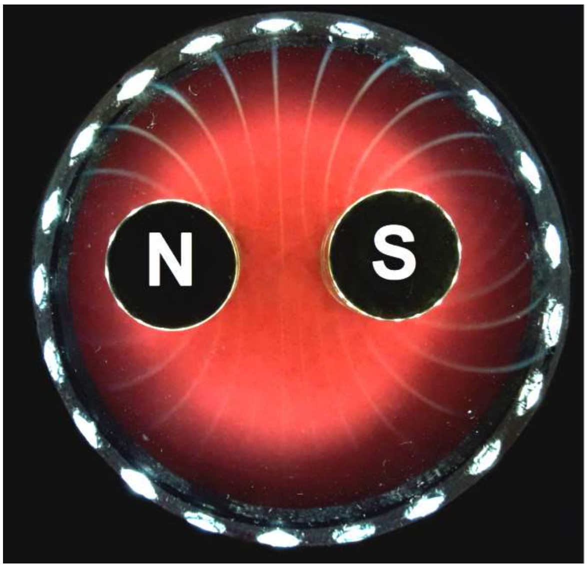


Chapter 4 – Some Presentations in Conferences

What did we do with Ferrocell?

In this chapter we will present some of our work presented at conferences around the world. Some of these presentations can be seen in some slide presentations and videos in our references. In order to integrate the research in the context of what has already been developed in some areas of research, we made comparisons and analogies with other systems ranging from Gemology to Atmospheric Optics.

For what purpose can we use Ferrocell?

One use can be by scattering light using the magnetic field as control parameter. This is a well-known application of other smart fluids, as in the case of liquid crystals, where we can control the passage of light by applying an electric field. An important aspect in the use of liquid crystals for use in optical switching is the polarization of light. So, this led us to question what are the aspects of light polarization in devices that use the Ferrocell.

How does light polarization occur at Ferrocell?

In our presentations at these conferences we showed how the magnetic field can transform Ferrocell into a diffraction grid of variable geometry, which depends on the parameters related to the magnetic field, the solution of the ferrofluid and the polarization states of light.

What is the most attractive effect of Ferrocell?

The effect that most attracts people at Ferrocell is the formation of light patterns in the presence of an external light source, subjected to a magnetic field. Thus, part of our research is to use it as a kind of display that is somehow related to a vector field with hyperbolic geometry, which can be applied for the practical study of dynamical systems. In addition, we are exploring some aspects of "vorticity", such as optical vortex, using Ferrocell. At these conferences, some people recognize the potential use of this device in the field of teaching physics.

4. Our Research with Ferrocell

We have been working with Ferrocell to understand the physical principles involved and proposing some applications. In this way, we researched and published some articles using Ferrocell, placing our work in a scientific context. Our initial idea was to recognize the phenomena that could be easily observed with Ferrocell when this device interacts with light in the presence of a magnetic field, be it static or variable.

We noticed three effects:

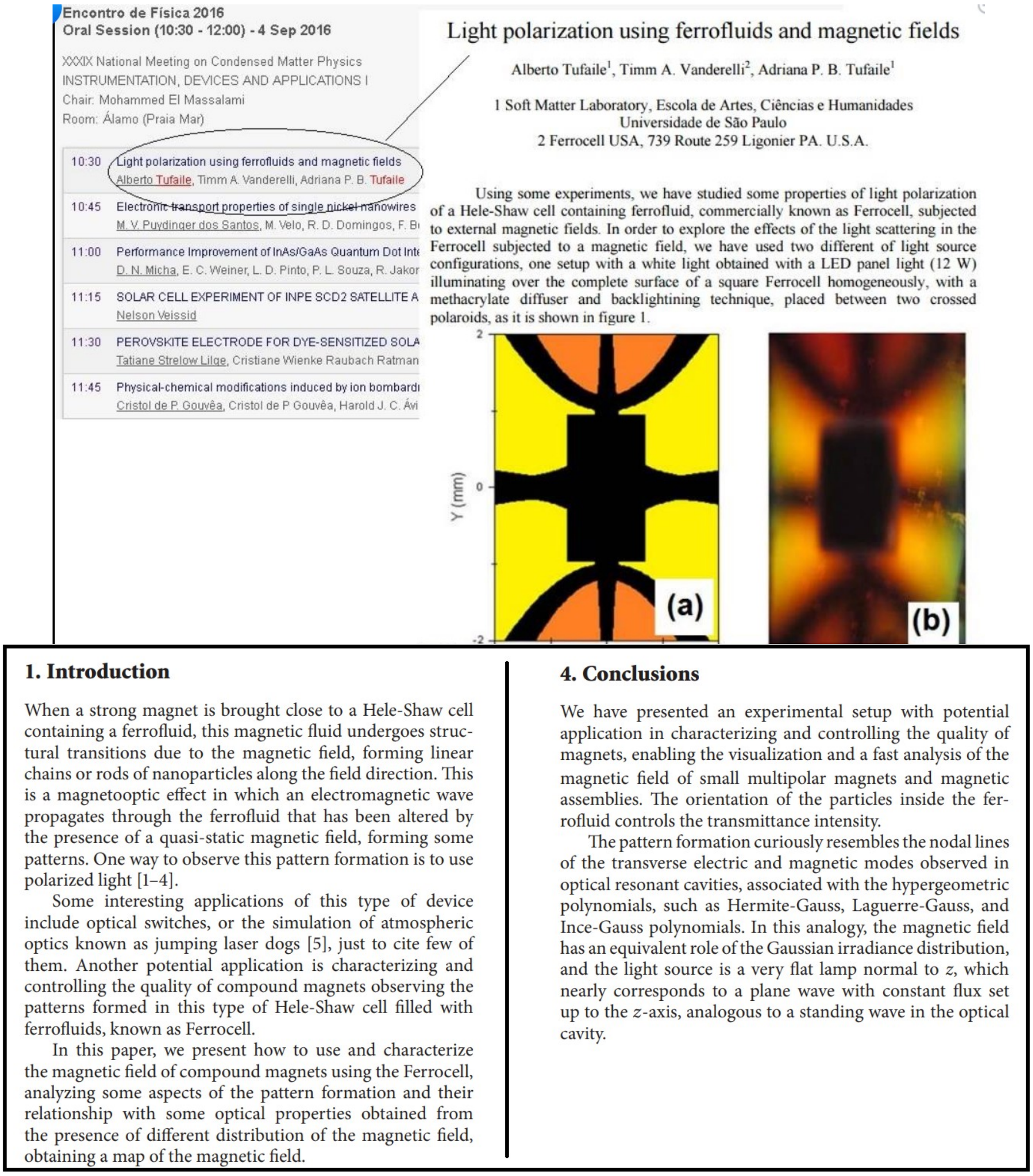
a) The formation of light patterns at Ferrocell in the presence of a magnetic Field using a set of LEDs as the light source;
b) Light from a laser being spread when it passes through Ferrocell in the presence of a magnetic field;
c) The light polarization from a light source similar to a plane wave for different configurations of a magnetic Field using the Ferrocell.

With the observation of these effects, we planned some experiments and compared them with the results that we found in the literature for the interpretation of these results. We have participated in conferences in different countries presenting this device.

We presented our first work using The Ferrocell, device and some of its effects at the Light and Color in Nature conference in 2016, with the work "Simulating Jumping Sun Dogs" [1].

Figure 4.1- Professor Adriana P. B. Tufaile starting a presentation in Granada, Spain, using Ferrocell to simulate an atmospheric phenomenon with the work "Simulating Jumping Sun Dogs", at the "Light and Color in Nature 2016" conference.

After that, we participated in the conference of the Brazilian Physics Society in 2016, in the city of Natal in Rio Grande do Norte, with the work ”Light polarization using magnetic fields and ferrofluids”[2].


Encontro de Física 2016
Oral Session (10:30 - 12:00) - 4 Sep 2016

XXXIX National Meeting on Condensed Matter Physics
INSTRUMENTATION, DEVICES AND APPLICATIONS I
Chair: Mohammed El Massalami
Room: Álamo (Praia Mar)

10:30 Light polarization using ferrofluids and magnetic fields
Alberto Tufaile, Timm A. Vanderelli, Adriana P. B. Tufaile

10:45 Electronic transport properties of single nickel nanowires
M. V. Puydinger dos Santos, M. Velo, R. D. Domingos, F. B

11:00 Performance Improvement of InAs/GaAs Quantum Dot Int
D. N. Micha, E. C. Weiner, L. D. Pinto, P. L. Souza, R. Jakor

11:15 SOLAR CELL EXPERIMENT OF INPE SCD2 SATELLITE A
Nelson Veissid

11:30 PEROVSKITE ELECTRODE FOR DYE-SENSITIZED SOLA
Tatiane Strelow Lilge, Cristiane Wienke Raubach Ratman

11:45 Physical-chemical modifications induced by ion bombard
Cristol de P. Gouvêa, Cristol de P Gouvêa, Harold J. C. Ávi

Light polarization using ferrofluids and magnetic fields

Alberto Tufaile[1], Timm A. Vanderelli[2], Adriana P. B. Tufaile[1]

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Using some experiments, we have studied some properties of light polarization of a Hele-Shaw cell containing ferrofluid, commercially known as Ferrocell, subjected to external magnetic fields. In order to explore the effects of the light scattering in the Ferrocell subjected to a magnetic field, we have used two different of light source configurations, one setup with a white light obtained with a LED panel light (12 W) illuminating over the complete surface of a square Ferrocell homogeneously, with a methacrylate diffuser and backlightining technique, placed between two crossed polaroids, as it is shown in figure 1.

1. Introduction

When a strong magnet is brought close to a Hele-Shaw cell containing a ferrofluid, this magnetic fluid undergoes structural transitions due to the magnetic field, forming linear chains or rods of nanoparticles along the field direction. This is a magnetooptic effect in which an electromagnetic wave propagates through the ferrofluid that has been altered by the presence of a quasi-static magnetic field, forming some patterns. One way to observe this pattern formation is to use polarized light [1–4].

Some interesting applications of this type of device include optical switches, or the simulation of atmospheric optics known as jumping laser dogs [5], just to cite few of them. Another potential application is characterizing and controlling the quality of compound magnets observing the patterns formed in this type of Hele-Shaw cell filled with ferrofluids, known as Ferrocell.

In this paper, we present how to use and characterize the magnetic field of compound magnets using the Ferrocell, analyzing some aspects of the pattern formation and their relationship with some optical properties obtained from the presence of different distribution of the magnetic field, obtaining a map of the magnetic field.

4. Conclusions

We have presented an experimental setup with potential application in characterizing and controlling the quality of magnets, enabling the visualization and a fast analysis of the magnetic field of small multipolar magnets and magnetic assemblies. The orientation of the particles inside the ferrofluid controls the transmittance intensity.

The pattern formation curiously resembles the nodal lines of the transverse electric and magnetic modes observed in optical resonant cavities, associated with the hypergeometric polynomials, such as Hermite-Gauss, Laguerre-Gauss, and Ince-Gauss polynomials. In this analogy, the magnetic field has an equivalent role of the Gaussian irradiance distribution, and the light source is a very flat lamp normal to z, which nearly corresponds to a plane wave with constant flux set up to the z-axis, analogous to a standing wave in the optical cavity.

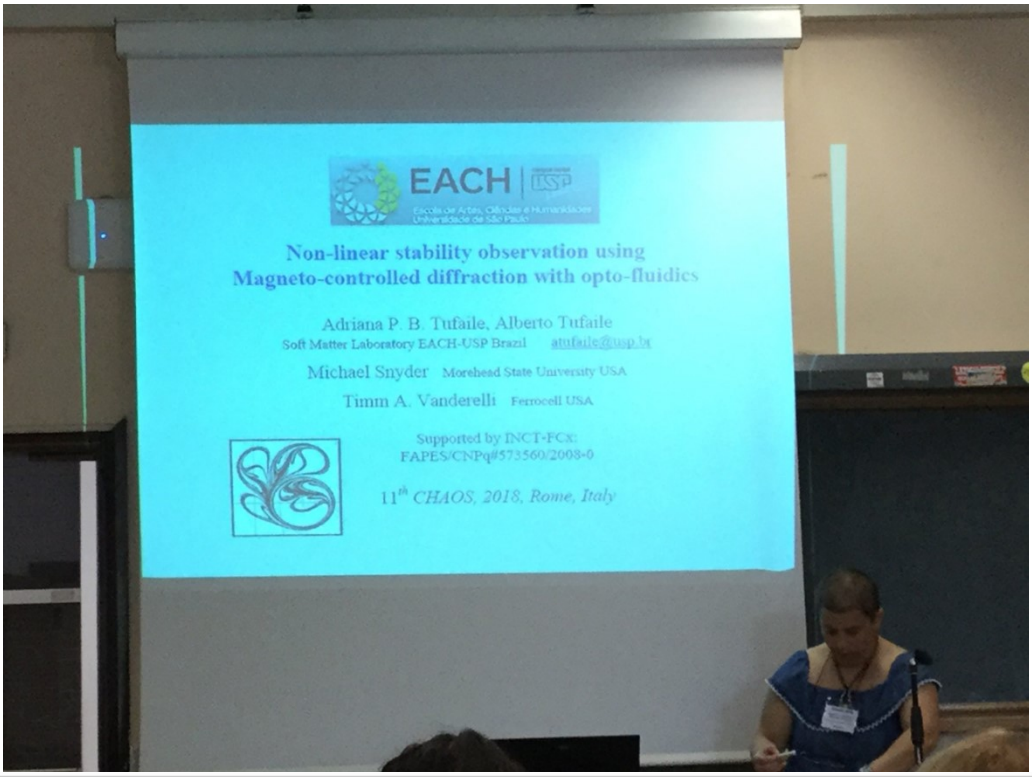
Figure 4.2 - Our participation in the conference in Brazil presented our results obtained with Ferrocell.

These two works represent the beginning of our research using Ferrocell.

In 2018 at the International Conference on Magnetism, Professor Adriana P. B. Tufaile received the *Best Poster Winner Award* for her work “Magneto-controlled diffraction to observe dynamical systems” in San Francisco, USA [3].

Figure 4.3 – Our participation in the International Conference on Magnetism in San Francisco, CA, USA. In this conference Professor Adriana Tufaile received Best Post Winner award.

In the same year of 2018 we presented the use of Ferrocell for the study of non-linear system in Rome, Italy [4].



Abstract

We have developed a magneto-optical system which simulates the stability of fixed points and the trajectories of orbits present in dynamical systems. The question of stability is significant because a real-world system is constantly subject to small perturbations, and these orbits can be observed with a Ferrocell, a device using ferrofluid, which is a superparamagnetic fluid obtained with a kind of colloid containing surfactant coated nanometer ferromagnetic particles dispersed in a carrier liquid, and this device can be used in applications of optical effects. Our magneto-optical system is based in a Hele-Shaw cell containing ferrofluid, illuminated with an external light source, such as LED. By injecting a light propagating along the in-plane direction of the liquid film, the orbits can be observed, in a way that we can bend the light. The trajectories of the orbits are obtained by the diffracted light, which consists of light patterns, and these light patterns are related to Faraday effect, linear dichroism, and linear birefringence. The diffraction pattern is different from that produced by a wire because there are no fringes in these light patterns, and the absence of well-defined spacing between the fringes indicates the existence of multiple diffraction. Under certain circumstances, these light patterns can have the same properties of the force lines of magnetic fields. The main idea of this work is to propose a device applied to non-linear systems, based on magneto-photonics. We present the patterns obtained for different magnetic fields simulating dynamical systems.

Figure 4.4 – Professor Adriana P. B. Tufaile in Rome presenting some of our results using Ferrocell and the abstract of this presentation.

In 2019 we also presented a paper using Ferrocell at TechConnect in Boston, MA, USA. This work was presented in person by Michael Snyder and Timm A. Vanderelli, and a video about this presentation can be found on YouTube [5].

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Controlling light diffraction with nanostructures

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University of Sao Paulo, BR

Keywords: Diffraction, ferrofluid, ferrolens, light polarization, polarifluid

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.

Figure 4.5 - Our 2019 participation in TechConnect in Boston, MA, USA.

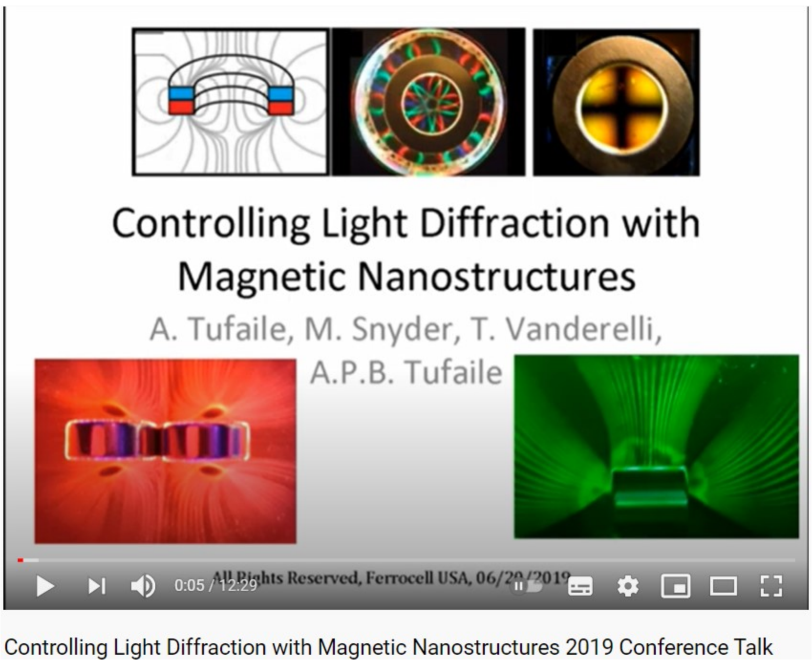

Figure 4.6 – The abstract and a video [5] of the work presented at TechConnect in Boston.

Figure 4.7 – Meeting of our Ferrocell research team in Washington, DC, USA in 2019, during FiO+LS 2019.

At this 2019 conference, during Fio+LS 2019 in Washington, DC, USA, we showed the equipment to optics community with the work "Investigation of light patterns in a Ferrolens subjected to a magnetic field" [6]. At these conferences, we took demonstrations and introduced the Ferrocell device to the audience, who in the general were very impressed with the device.

Figure 4.8 – Professor Adriana P. B. Tufaile presenting our work in optics at FiO+LS 2019. Two images of our presentation during the 2019 FiO+LS, in which Professor Alberto Tufaile shows the Ferrocell device.

Investigation of Light Patterns in a Ferrolens Subjected to a Magnetic Field

Laser Science 2019
Washington, DC United States
15–19 September 2019
ISBN: 978-1-943580-67-5

From the session
Poster Session I (JTu3A)

Alberto Tufaile, Adriana Pedrosa Biscaia Tufaile, Timm A. Vanderelli, and Michael Snyder

Frontiers in Optics + Laser Science APS/DLS   The Optical Society (Optical Society of America, 2019), paper JTu3A.17 · https://doi.org/10.1364/FIO.2019.JTu3A.17

Abstract

We have investigated the light patterns in a thin film of ferrofluid subjected to a magnetic field, in a device known as Ferrolens. We observed magnetic contours and light polarization effects.

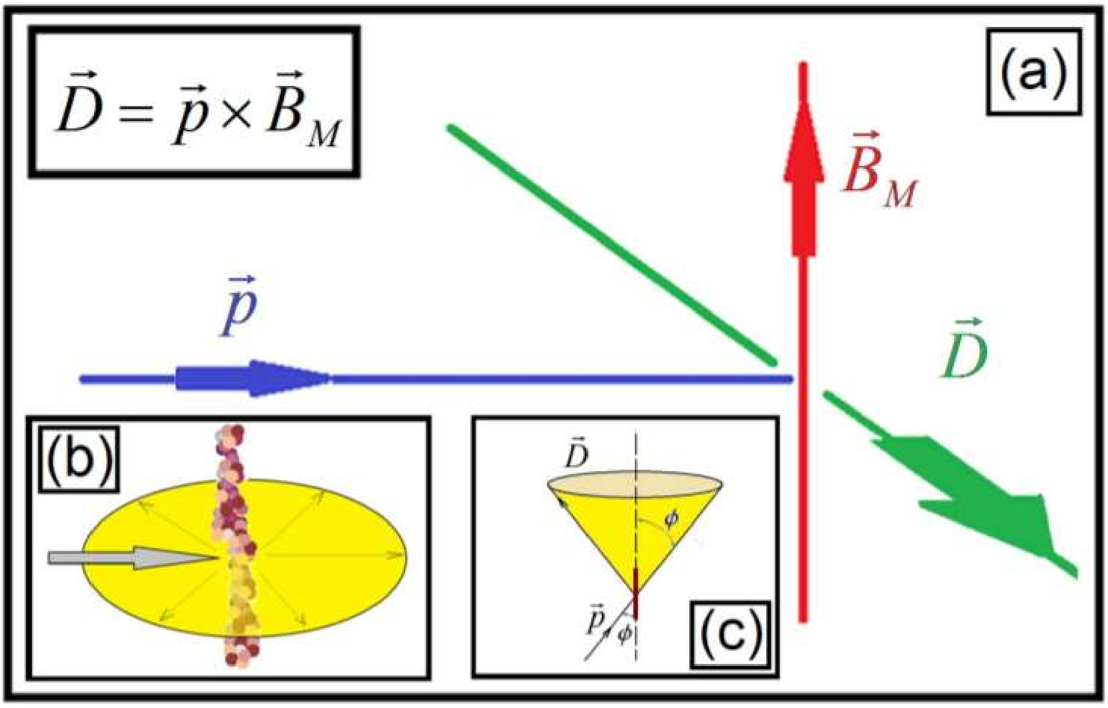

Diagram of light interacting with the magnetic field in the ferrofluid(**a**) The propagation vector ***p***, diffracts in the direction ***D***, due to the magnetic field ***B****M*; (**b**) Diagrama of the light scattering in a nanoneedle aligned with the magnetic field; (c) Conical diffraction.

Conclusions

We presented a possible connection between some patterns of the atmospheric optics and light scattering in particles with the same size of the ice crystals based in the concept of diffracted rays. In this way, the light scattered by the atmosphere is an integral sum of events from individual ice crystals, and the observed pattern can be understood as a combination of multiple scattering.

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Figure 4.9 – The abstract of our presentation at FiO+LS 2019, along with a diagram, conclusions and references [6].

Figure 4.10 – In addition to publications in scientific journals, we publicize our experiments in scientific journals such as *Revista Pesquisa* FAPESP.

This device is not very well known in the academic world until now, so we try to submit our images to scientific journals, like the "Magnetic Circles" [7]. In addition, we participated in photo contests for physics experiments and presented our most photogenic results in photo shows at our university in order to popularize this device and our research related to it.

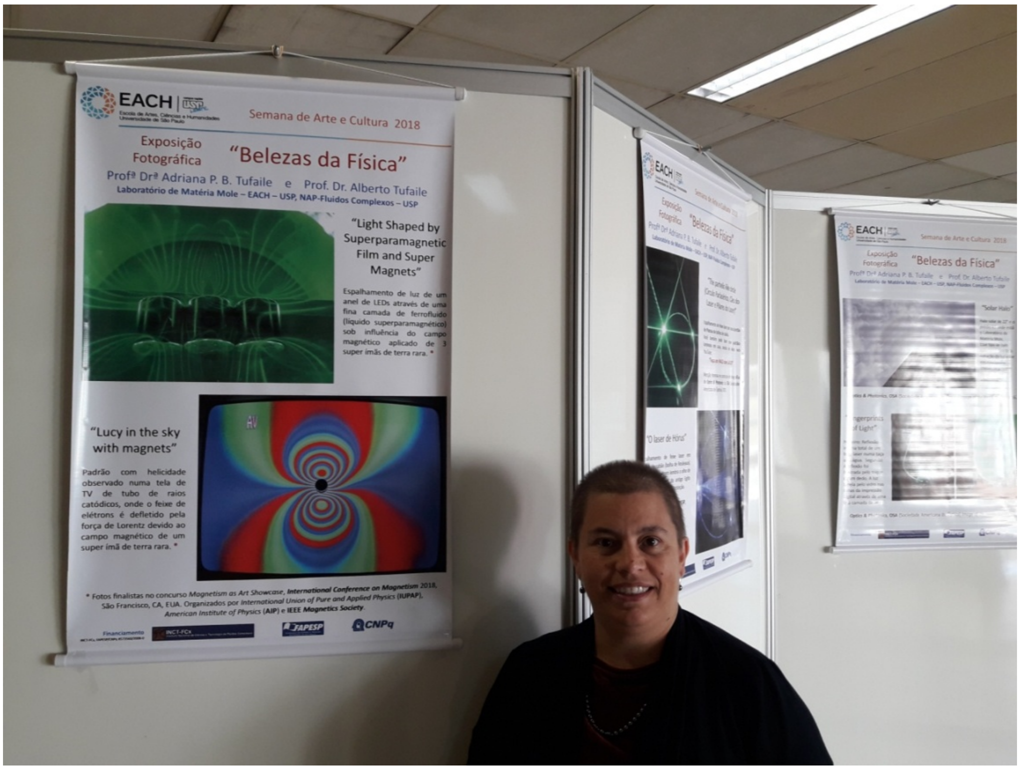

Figure 4.11 – Professor Adriana Tufaile preparing posters for our presentation on “Beauties of Physics”, in which some Ferrocell’s images were presented.

We have recently explored the possibility of optical vortexes at Ferrocell and in 2020 we presented the work “Optical Vortex and Ferrocell: A comparative study” [8].

Figure 4.12 –Our work presented at the magnetism conference in 2020 making a comparative study between Ferrocell and the optical vortexes.

References of Chapter 4

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ICM2018
SAN FRANCISCO
21ST INTERNATIONAL CONFERENCE ON MAGNETISM

Dear Alberto Tufaile,

Congratulations! Your entry to the Magnetism as Art Showcase at the 2018 International Conference on Magnetism (ICM) was selected as one of 24 entries to be posted onsite at the ICM Conference. In addition, your entry has been posted to the ICM Conference Facebook site.

Thank you for your participation in the Magnetism as Art Showcase and we look forward to seeing you soon in San Francisco, CA.

Best,

Chair, Magnetism as Art Showcase, ICM 2018

Chapter 5 – More About Ferrofluids and Magnetism

What are the main properties of ferrofluids?

In this chapter, we will delve into some properties of ferrofluids.

Can the general properties of ferrofluids be transposed to a two-dimensional system like Ferrocell?

Anyone who has worked with thin films materials in condensed matter knows that there is no simple answer to this question. Sometimes, the answer is only achieved after analyzing several experiments prepared for this question.

Probably, many of the effects that enchant people with the use of Ferrocell/Ferrolens system come from the fact that this system has dimensions of the order of centimeter in a plane and the order of micrometers in thickness.

After having discussed some optical properties of Ferrocell in the previous chapter, we will now present some of the basic backgrounds of ferrofluids, as well as the concepts of magnetic field, magnetization and magnetic charges based on the Maxwell equations. We will discuss the concepts of magnetic field, magnetic induction and magnetization, which present discontinuities and abrupt jumps in three-dimensional systems. These physical objects discussed will behave even more nonlinearly in a thin film system such as Ferrocell.

You will notice that in this chapter there will be a more intense algebraic presentation than has been shown so far in this book. The magnetism part involves integral and differential calculus. Our proposal is to avoid formulas in this book up to this point, but in this chapter the mathematical language completes what has been seen so far, as we realize that many of the discussions on social networks about the phenomena observed with Ferrocell originate from the fact that a certain lack of basic conceptual knowledge and related equations.

5a.Ferrofluids

Once people see or experience the effects of ferrofluid, they want to know more about this new material that is part of nanotechnology. Here we present the working principles of ferrofluids, of course this can be translated into various levels of depth depending on the audience.

Ferrofluids are part of a new class of magnetic materials and together with liquid crystals, they are part of complex fluids. These materials present disorder and spatial freedom as fluids and orientational order as solids.

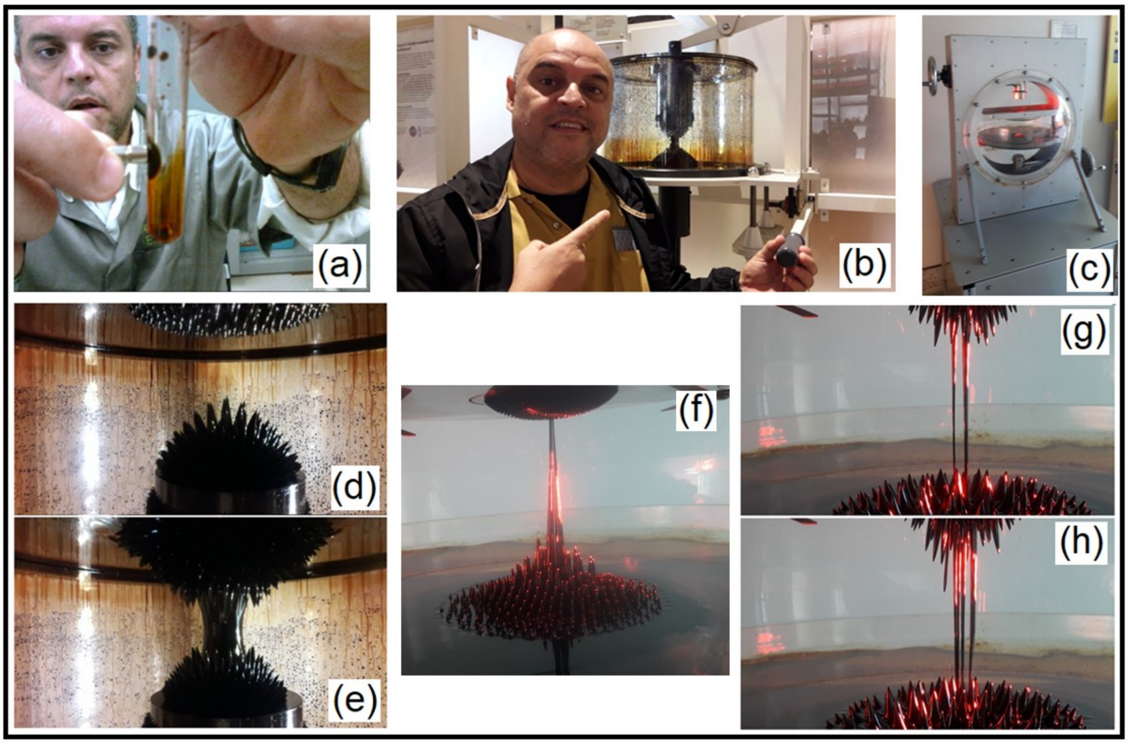

Figure 5.1. The author demonstrating that ferrofluid rises the vessel wall due to the magnetic force exerted by two small cylindrical super magnets that he holds (a). In (b), Machine for demonstrating ferrofluid at the Ontario Science Centre, Toronto, Canada. In (c), ferrofluid magnetoscope at New York Hall of Science (NYHS), USA. In (d) and (e), we are using the machine in Toronto. In (f), (g) and (h), we are using the ferrofluid magnetoscope at NYHS.

Ferrofluids are made up of colloidal magnetic nanoparticles dispersed and stabilized in a carrier liquid. The stabilization of ferrofluids produces an entropic repulsion intense enough to overcome the short-range strong attraction knows as Van der Waals force that would otherwise result in particle aggregation and consequent colloidal instability leading to precipitation [1].

We have in Fig. 5.2, a representation of a ferrofluid in the absence and presence of applied magnetic field, where the nanoparticles are oversized for illustration.

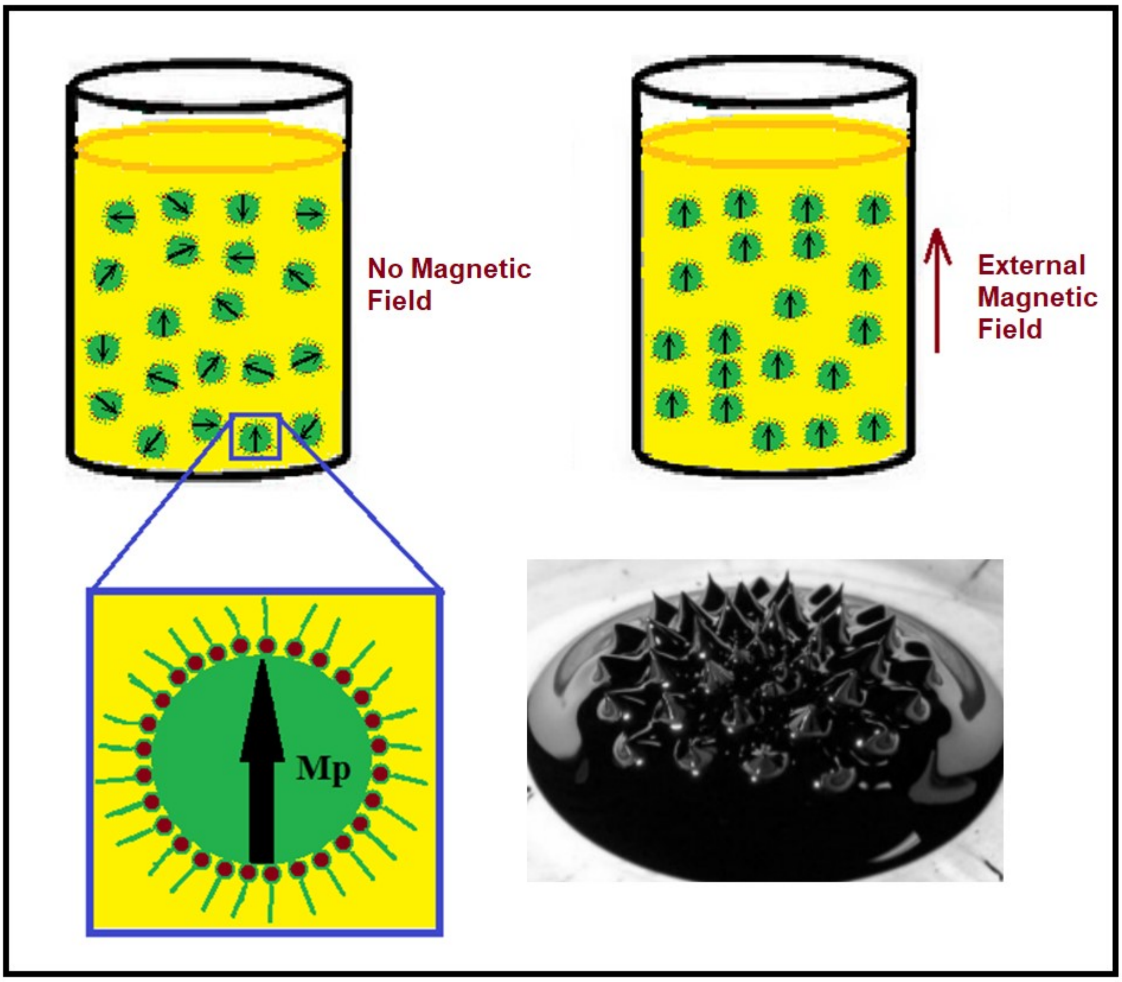

Figure 5.2. Representation of a surfactant ferrofluid, where the size of magnetic nanoparticles is exaggerated so that we can visualize the orientation of the particle magnetization (M_p) when a magnetic field is applied.

In general, magnetic materials have a Curie temperature much lower than their melting point. There is liquid He3 that can be magnetized below 2.7 mK, but this temperature is not practical at all. Paramagnetic liquid oxygen can also be considered as magnetic liquid and was used for visualization of magnetic domain walls at low temperatures. Another magnetic liquid is made of cobalt-palladium alloys with composition around Co80Pd20 in the undercooled liquid state. In this case, the material is brought by very rapid cooling to a metastable liquid state below its melting point [2].

Practically, to combine the properties of a liquid with those of a magnetic material, ferromagnetic particles are dispersed in a liquid. This idea is old, for example, Bitter powder has been used since the 1930s to visualize the walls of magnetic domains.

In the 1940s, magnetic fluids were made with iron dust in oil, the grains had sizes of the order of micrometers or more, to be used in brakes and clutches. But these liquids are not stable (particles settle or agglomerate) and when a magnetic field is applied, they become solid. It was in the 1960s that what is called stable ferrofluid was made, with particle sizes between 3 and 15 nm. They remain liquid even under intense magnetic fields and have enough magnetic susceptibility to behave like magnetic liquids [3].

5a1. Stability

One of the characteristics of a good ferrofluid is its stability. Stability against the force of gravity (particles should not decant), stability against magnetic field gradients (particles should not regroup in intense field zones), stability against particle agglomeration under the influence of dipolar forces or Van der Waals interactions.

Stability conditions lead to a particle size criterion that must be small enough that thermal agitation due to brownian particle motion opposes decantation or concentration in a magnetic field gradient. For those familiar with physics, one can get an idea of the order of magnitude of acceptable size by comparing the energetic terms at stake: thermal energy, magnetic energy, and gravitational energy, which are respectively:

Thermal energy $E_T = k_B T$, where k_B: Boltzmann constant, T: temperature,

Gravitational energy $E_g = \Delta\rho V g l$, where $\Delta\rho$: density difference between particles and the liquid, g: gravitational constant, l: height of the liquid in the gravitational field.

Magnetic energy $E_m = \mu_0 M_p H V$, where μ_0: vacuum permeability, M_p: particle magnetization, H: magnetic field, V: particle volume.

Magnetic energy E_m corresponds to the work provided to move a particle from a point where the magnetic field has H value to where the field is zero.

Stability against gravitational force requires $E_T \geq E_g$, considering spherical particles of diameter d, $\Delta\rho$ = 4300 kg/m^3 (typical for magnetite Fe_3O_4 in oil), a 0.05 m high container, T = 300 K, we obtain $d \leq$ 15 nm. Stability against a magnetic field gradient requires $E_T \geq E_m$, taking magnetite magnetization, $4{,}5 \cdot 10^5$ A/m and a maximum field of $8 \cdot 10^4$ A/m (0.1 T), we obtain $d \leq$ 6 nm. Field gradient stability then restricts particle size to values below 10 nm in diameter [3].

The stability criteria assume that the particles remain small, in other words, that they do not clump together. But they are small magnetic dipoles and the dipolar interaction tends to agglomerate them. The agglomeration by van der Waals interaction is irreversible because the energy to separate two particles once bonded is very large. Then one must find a way to keep the particles from getting too close to each other. This can be done in three ways, the particles can be coated with a layer of surfactant molecules forming surfactant ferrofluids, or the particles can be electrically charged to repel each other due to electrical force forming the ionic ferrofluids, or you can use both methods together.

5a2. Fabrication

In surfactant ferrofluids, the surfactant consists of long chains, polymers analogous to those of soap molecules, where one end is attracted to the surface of the particles and the other end has affinity for the carrier liquid. The particles are then covered with a polymer layer that keeps them at a minimum distance from each other. This type of ferrofluid, which is shown in Fig. 5.2, is obtained by grinding a coarse powder (particles in the order of 10 m) generally magnetite in the presence of the surfactant. It is the presence of the surfactant during grinding that allows such size reduction up to 10 nm and which leads to particles coated with a polymer monolayer. By this method it is possible to use different solvents as carrier liquids: water, oil, various hydrocarbons. This type of ferrofluid is the most commercially widespread.

In ionic ferrofluids, the particles carry an electric charge; they are large ions that keep their distance from each other due to electrostatic repulsion. In fact, this repulsion is partly diminished by the opposite signal ions which are present in the carrier liquid to ensure the neutrality of the assembly. This type of ferrofluid is obtained by a chemical co-precipitation reaction from iron salt solutions, generally ferrous chloride ($FeCl_2$) and ferric chloride ($FeCl_3$). The proportion of the solutions determines the particle size, using twice the ferric chloride as compared to the ferrous chloride, obtaining particle sizes around 10 nm [1]. In addition to a surfactant, various carrier liquids may be used as in the case of surfactant ferrofluids.

5a3. Superparamagnetism

The ferromagnetic particles in a ferrofluid have typical sizes on the order of 10 nm. This size is less than or equal to the domain wall thickness for the materials currently used in ferrofluids. So, there is no room for a wall in a particle, the particles are magnetic monodomains. Even materials with very strong anisotropy would have walls of a few nanometers (nm), a subdivision into domains would be very expensive in energy. The particles are then small strong magnets suspended in the carrier liquid.

Due to the thermal agitation, the particles are animated by a Brownian motion that shifts them in all directions and constantly disorients them, their orientations fluctuate in all directions and under a zero or very small magnetic field (e.g. geomagnetic field), no resulting average magnetization is observed. Ferrofluid behaves like a paramagnetic material, we call it superparamagnetic, because its particles carry great magnetic moments. L. Néel developed in 1949 the theory of superparamagnetism of small ferromagnetic particles [3-5]. When applying a magnetic field, the moments always fluctuate, but on average the magnetization component parallel to the applied field is not zero. Ferrofluid magnetizes and can reach saturation for sufficiently intense applied field when we have the highest degree of alignment possible for a given temperature.

Assuming that the particles do not interact with each other, the magnetization of a ferrofluid as a function of magnetic field H and temperature T can be written by Langevin's law. If the magnetization of the particulate material is M_p, the magnetic moment of the volume particle V is

$$m = VM_p,$$

then the average magnetic moment of ferrofluid will be [3]:

$$m_{ff} = m(\coth x - 1/x), \text{ where } x = \mu_0 \vec{m} \cdot \vec{H}/k_B T. \qquad (1)$$

Ferrofluid magnetization is equal to the average momentum per unit volume:

$$M_{ff} = \frac{\Phi}{V} m_{ff}(x) = \Phi M_p(\coth x - 1/x), \text{ where } x = x\mu_0 V\overrightarrow{M_p} \cdot \vec{H}/k_B T\ . \qquad (2)$$

In this equation, Φ is the volume fraction occupied by the particles. The saturation magnetization of a ferrofluid is therefore equal to ΦM_p and its initial susceptibility χ_i, obtained by developing the Langevin function for small x, will be:

$$\chi_i = \lim_{H\to 0}\left(\frac{M_{ff}}{H}\right) = \frac{\mu_0 \Phi M_p^2 V}{3k_B T}, \qquad (3)$$

which obeys the Curie law $\chi = C / T$, as would be expected for paramagnetic materials, where C is called the Curie constant [3].

Curie's law can be interpreted as follows: in the absence of applied magnetic field, magnetic moments point statistically in all directions and magnetization is zero. When applying a magnetic field H, the moments tend to orientate parallel to H, and if nothing opposes this effect the system acquires a large magnetization for small H (χ large). This is what happens hypothetically for temperature 0 K. However, for finite temperature, thermal agitation is opposed to parallelism, so alignment is partial, and a weak positive susceptibility is observed.

In addition to brownian motion due to thermal agitation, another effect may contribute to fluctuation of the orientation of the magnetic moments of the particles if they present uniaxial anisotropy. In this case, the magnetic moment can oscillate between two directions of easy magnetization, overcoming the energy barrier linked to anisotropy. This is a thermally activated phenomenon called the Néel mechanism. The time constants associated with these two mechanisms (Brown and Néel) depend on particle size, anisotropy constant K, viscosity of carrier liquid η and temperature. When there is a sudden variation in field H, the characteristic times due to the relaxation of magnetization are:

Brownian mechanism $\tau_B = 3V\eta / k_B T$,

Néel mechanism $\tau_N = \exp(KV/k_B T)/f_0$,

where f_0 is the frequency of attempts to cross the barrier, typically on the order of 10^9 Hz, and KV is the height of the energy barrier to reverse the particle momentum. These characteristic times are important when studying the dynamics of ferrofluid movement in magnetic fields that vary with time; their typical values are $\tau_N \sim 10^{-9}$ s and $\tau_B \sim 10^{-7}$ s [3].

5a4. Dipolar interaction between particles

If ferrofluid is not too diluted, its monodomain magnetic particles interact via dipolar interaction, which we have so far overlooked. The dipolar energy of the interaction between two particles with moments $\overrightarrow{m_1}$ and $\overrightarrow{m_2}$ is [3]

$$E_{dip} = \frac{\mu_0}{4\pi}\left[\frac{(\overrightarrow{m_1}.\overrightarrow{m_2})}{r^3} - 3\,\frac{(\overrightarrow{m_1}.\vec{r})(\overrightarrow{m_2}.\vec{r})}{r^5}\right], \qquad (4)$$

where $\vec{r}$ is the vector connecting the two dipoles.

For spherical particles of volume $V = \pi d^3/6$ and momentum $\vec{m}_1 = \vec{m}_2 = V\vec{M}_p$, the dipolar energy is minimal when they are in contact ($r = d$) and oriented both parallel to $\vec{r}$. In this case, the energy will be

$$E_{dip} = -\mu_0 V M_p^2/12. \qquad (5)$$

The thermal energy for two dipoles ($2k_BT$) will be greater than the dipolar energy if the particle size is $d< 9$ nm, where we use the magnetite magnetization value. As with most common ferrofluids, particle size has a distribution averaging about 10 nm, many particles are larger than this limit, so dipole interaction is always present for a part of the particles.

When a magnetic field H is applied, magnetic moments tend to align with the field, thermal fluctuations are less effective, and particles form chains in the direction of H, the longer the field is (even when $H = 0$, particles can form short chains in random directions). This chain forming effect under applied field action is reversible, meaning that the chains will be destroyed when the applied field is set to zero.

We describe the magnetization law of a non-interacting ferrofluid through Langevin's law and with initial type $1/T$ susceptibility. To take into account dipolar interactions, we can introduce them as a mean field created by the neighborhoods over each particle, the mean field is added to the applied field. This treatment highlights a Curie-Weiss behavior, which means that the initial susceptibility is type $1/(T-T_0)$, where T_0 is an ordering temperature. However, this applies to frozen ferrofluids, or small particle systems with dipolar interaction in a solid matrix.

In the case of a liquid ferrofluid, one should also consider the spatial correlations of moving particles that form chains, so the mean fields describing the interactions should no longer be those estimated for single particles and all the same size. The energy of the system is written as $E = E_r + E_{dip} + E_H$, where E_r is the short-range repulsion term, E_{dip} is the dipolar energy of a particle with its neighbors, and E_H is the energy term related to the applied magnetic field. The particles move and orientate in order to minimize the energy at temperature T, respecting the Boltzmann $\exp(-E/k_BT)$ distribution. This type of simulation highlights the short and disoriented zero-field chains and the formation of longer chains in the direction of the applied field (when $H\neq 0$) and finds a Curie-Weiss susceptibility, proportional to $1/(T-T_0)$.

5a5. Viscosity

As already mentioned, modern ferrofluids remain liquid in the presence of applied magnetic field, unlike the first ferrofluids. However, rheological properties are modified by the applied field and their viscosity is therefore an important feature.

Typically, the volume of a ferrofluid is composed of about 5% solid particles, 85% liquid and 10% surfactant agent [6]. The viscosity of a ferrofluid is governed by the viscosity of the carrier liquid, the possibility of choosing different solvents allows a wide range of viscosity values (water, oil, hydrocarbons, etc.). However, the presence of particles in the liquid increases this initial viscosity even in the absence of applied field.

When a magnetic field is applied, the ferrofluid is sheared, the particles tend to be aligned with the applied field, and the velocity gradients in the liquid around the particles are increased, which increases the viscosity. When the vorticity of the liquid is parallel to the applied field, the particles can spin freely, and the field has no effect on viscosity. In contrast, if the magnetic field and the vorticity are perpendicular, the viscosity increase due to the applied field is maximum.

In the presence of a strong magnetic field, for example from a supermagnet, ferrofluid that initially had low viscosity has its viscosity so increased that it behaves like a gel. This can be felt with your fingers by squeezing the tips formed in a situation like that shown in Figure 5.3. Wear latex gloves so that your fingers are not stained by ferrofluid.

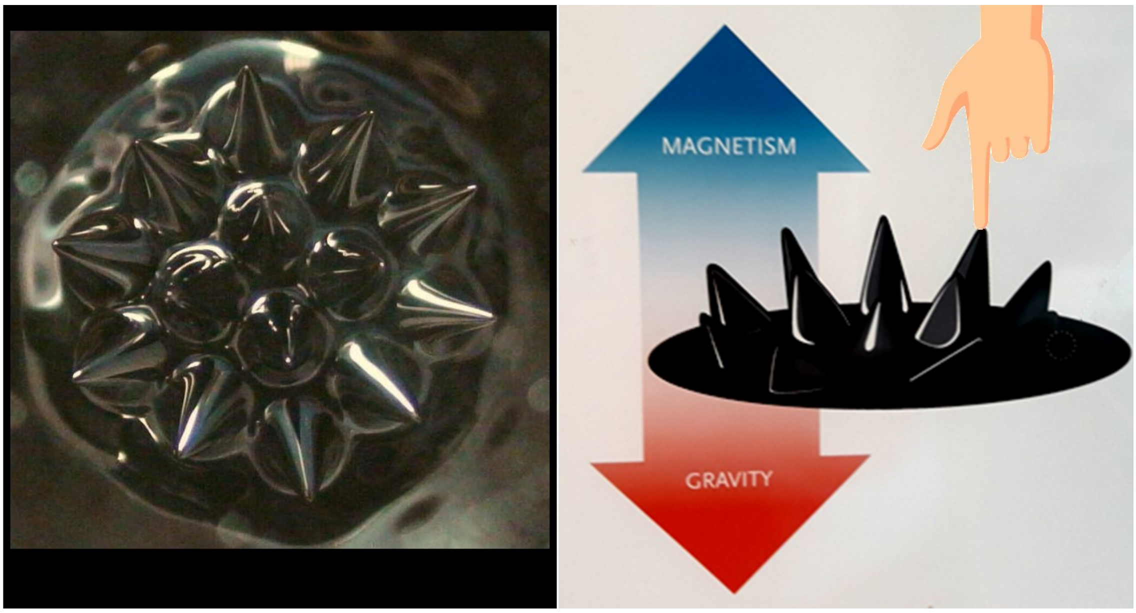

Figure 5.3 – Ferrofluid that initially had low viscosity has its viscosity so increased that it behaves like a gel in the presence of a strong magnetic field.

With all that has been discussed so far in this chapter, we see that some of the effects that occur in the Ferrocell, such as aggregation of particles in the glass or response time of the formation of light patterns with variable magnetic fields, are interesting to be studied. We are investigating these effects and intend to present our results in the form of articles in the future.

5a6. Ferrofluid Applications Beyond Ferrocell

Ferrofluids have industrial and medical applications, some are already commercial, and some are still prototyping or are under development. Their applications benefit from the characteristics of liquid and magnetic material.

Ferrofluids are commonly used in high power speakers to remove heat between the coil and the magnet and passively dampen the movement of the cone due to its viscosity. It stays where the air space around the coil would normally be and is held by the magnetic field of the magnet. As the magnetization of ferrofluid is higher at lower temperatures, the strong magnet field will always attract the coldest part of ferrofluid more strongly, forcing heat out toward the heatsink. This method does not require additional energy and we can think of it as a 'magnetic convection'.

Other applications are magnetic seals around shafts on computer hard drives; high quality and secure magnetic inks for printing, such as bank checks; manufacture of accelerometers and tilt detectors, Magnetic Domain Detection or magnetic media inspection, Material Separation (e.g..magnetodensimetric separation), Metallic Crystallization/Fracture Analysis. Among the biomedical applications are the increased contrast of images using X-rays and MRI (Magnetic Resonance Imaging)and the local heat treatment of tumors, where ferrofluid is taken to settle on the tumor and an alternating magnetic field allows it to heat locally by dissipating energy in ferrofluid, this is called hyperthermia [6, 7].

Some of the terminology discussed in this section on magnetism will be explained in the next section.

5b. Maxwell Equations: Magnetized Media and Magnetic Charges

The main idea of this book is to explore the concepts of magneto-optics using the Ferrocell. Now we will study some theoretical concepts in magnetism in the frame of Electromagnetism. To do so, we will discuss some representations of magnetism using the Maxwell Equations and explore some equations for permanent magnets [8]. The key concepts here are the magnetization $\boldsymbol{M}$, the magnetic induction $\boldsymbol{B}$ and the magnetic field $\boldsymbol{H}$. What they represent when we are using magnets and how they are generated.

Due to the existence of microscopic currents j_{micro} of its atomic structure, magnetized matter can produce by itself magnetic field in outer space. These microscopic currents are related to the electronic motion inside atoms and from the electron spin angular momentum. Considering a magnetic medium in which there is no macroscopic conduction current, the microscopic currents $\boldsymbol{j}_{\mathrm{micro}}$ in a given elementary volume ΔV around the position $\boldsymbol{r}$ confined to atomic distances give rise to the magnetization current:

$$\boldsymbol{j}_M(\boldsymbol{r}) = \frac{1}{\Delta V}\int_{\Delta V} j_{micro}(\boldsymbol{r}) d^3\boldsymbol{r}. \qquad (6)$$

This current is related with the magnetization of the body by:

$$\boldsymbol{j}_M(\boldsymbol{r}) = \nabla \times \boldsymbol{M}(\boldsymbol{r}). \qquad (7)$$

Considering that magnetic field is $\boldsymbol{H}$, and $\boldsymbol{B}$ as the magnetic induction, we can express the relation between $\boldsymbol{M}$, $\boldsymbol{H}$ and $\boldsymbol{B}$ as:

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}). \qquad (8)$$

Thus, a permanent magnet with magnetization $\boldsymbol{M}$ placed in an applied field $\boldsymbol{H}$ oriented at an angle to $\boldsymbol{M}$ produces induction $\boldsymbol{B}$ that is given as the vector sum in accord with the previous equation, in which the functional dependence of $\boldsymbol{B}(\boldsymbol{H})$ or $\boldsymbol{M}(\boldsymbol{H})$ are defined by the constitutive law of the medium. Considering the magnetostatic equations in a region of space with no conduction currents, we have due to magnetization $\boldsymbol{M}$:

$$\nabla \cdot \boldsymbol{B}_M = 0, \qquad (9)$$

$$\nabla \times \boldsymbol{H}_M = 0. \qquad (10)$$

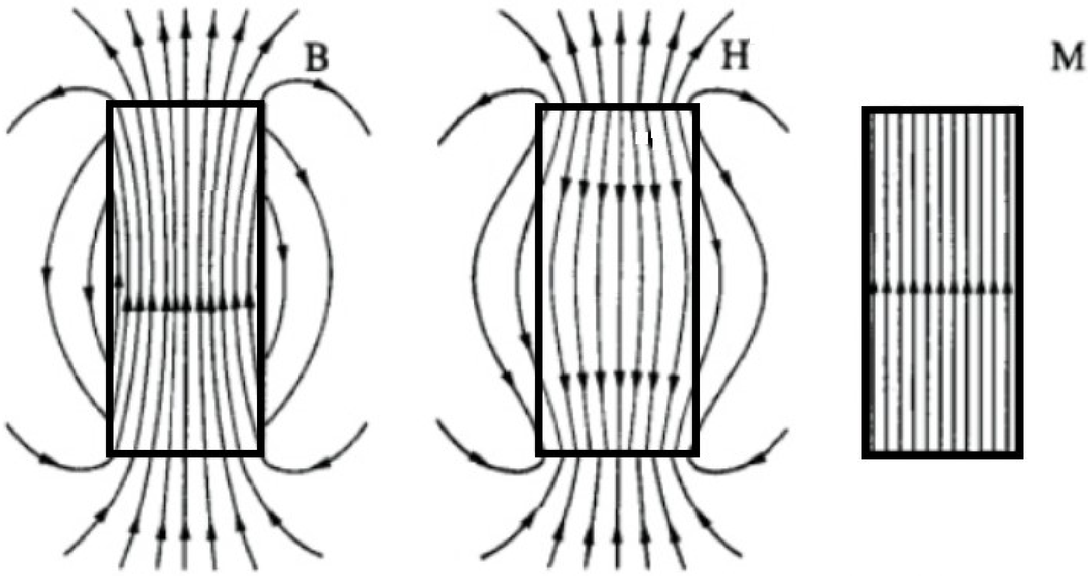

Figure 5.4. Diagrams of B, H and M in a magnet.

The field $\boldsymbol{H}$ takes the place of $\boldsymbol{B}$ in magnetized media as it is shown in Fig. 5.4, and we can write the expression of the magnetic charge ρ_m:

$$\rho_M = -\nabla.\boldsymbol{M} = \nabla.\boldsymbol{H}_M. \qquad (10)$$

The magnetic scalar potential is represented by ϕ_M, given by:

$$\boldsymbol{H} = -\nabla\Phi_M. \qquad (11)$$

The representation of the magnetic scalar potential is analogous to the electric potential. Considering a charge ρ_M moving from point A to point B between a uniform magnetic field $\boldsymbol{H} = \Phi_M d$ is the potential difference between A and B while the distance d is the distance between the two points. We have used this symmetry in our simulations to understand some of the patterns obtained with the Ferrolens because we are using magnets to generate the magnetic field. This treatment based on $\boldsymbol{H}$ is useful because it is simpler to deal with scalar potentials. This approach is only valid for the case in which $\boldsymbol{H}$ is not generated by free currents, and it is interesting to use when we are dealing with magnetic fields produced by permanent magnets.

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Chapter 6

6a – Final Notes and Conclusions

In the science fiction film “The Day the Earth Stood Still”, it is used the phrase “Klaatu Barada Nikto” by the alien Klaatu visiting Earth, that has never been officially translated by the author Edmund B. North. As there is no official translation of this phrase, each person understands its meaning in the context of the movie with their own baggage of knowledge. Following different people in different areas using Ferrocell, we feel that something similar happens in the sense of interpreting the phenomena that are observed using this device. As physicists, we try to contextualize the interaction of light in a Ferrocell exposed to an external magnetic field with the conceptual baggage already existing in physics. This task alone is not an easy one, nor do we claim that we have achieved absolute success in doing this in this book. We found several people using Ferrocell for the aesthetic appeal that luminous patterns represent, using them to answer different questions that they think are important in the world. The subjects are broad and can be of scientific or even transcendental nature. Some people focus only on aspects related to magnetism, ignoring the fact that the perspective of the optical phenomena also involves a certain degree of complexity. Other people realize that the fact of mixing a new material in a very specific geometry with optics and magnetism, leads to the area of magneto-optics that brings properties that cannot be observed in each area separately and makes the technical discussions very interesting and stimulating.

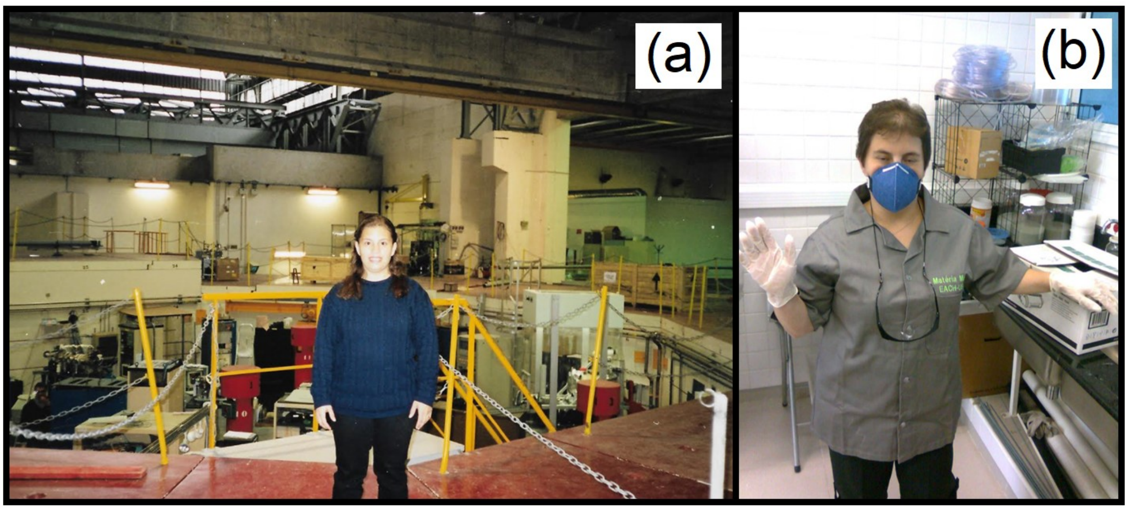

Figure 6.1 - One of the authors (A. P. B. Tufaile) at Université Paris-Sud, Laboratoire pour l'Utilisation du Rayonnement Electromagnetique (LURE) ORSAY, France in 1999, studying magneto-optics during her PhD in (a). In 2013, at Soft Matter Lab, EACH-USP preparing a ferrofluid solution.

In the movie cited previously, the alien Klaatu begs Helen Benson, the heroin of this film, to memorize the sentence, and use as a command for a alien robot Gort, explaining to her that there is no limit to what Gort could do to destroy the Earth. After she learned the phrase, Klaatu dies. This is the classic case of a new technology being learned without clearly knowing the science behind the equipment. The Ferrocell, also known as Ferrolens, was created by the American inventor Timm Vanderelli, not by an academic scientist, who introduced the device to people from different areas, selling Ferrocell and teaching us how to manufacture it. We are trying to understand the science that covers this device, in the same way that a linguist trying to see the etymology that would involve the language of Klaatu's sentence.

Part of the motivation for our work with Ferrocell is related to the evolution of our research as experimental physicists. Our research was made in material science and dynamical systems, more specifically in thin films of solid magneto-opticals materials and Chaos. In addition, as professors, we are dedicating part of our time to teaching experimental physic using ferrofluids and Ferrocell.

In our opinion, there are many other aspects that can be explored with Ferrocell and related devices, so we hope that other people will still explore these possibilities. As the central idea of this book is to provide a starting point for people who intend to interact with Ferrocell, we believe that everything presented here should be tested and verified, that is the why we try to make the experiments and demonstrations as accessible as possible, so that the people using this device can redo the experiment and draw their own conclusions, as is characteristic of the scientific method. In this way, we hope that your involvement with Ferrocell will be as fun as it was for us. Enjoy!