# Development and Application of Laser Hologram Production Techniques for the Teaching of Physics and the Public Awareness of Science

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**Abstract** (in English)

Holography is a set of techniques by which coherent light (laser light) is used to capture the phase and amplitude characteristics of light from a three-dimensional object on a two-dimensional photographic plate. Both diffraction and interference of light are directly behind its remarkable characteristics. The main objectives of this work followed two major lines: i) the development of experimental approaches for hologram production using simple and inexpensive setups, and ii) the production of holograms effectively capable of illustrating important optical instruments, physical principles and/or effects. This is for the purpose of engaging students in the study of Physics, and to reinforce the yet modest presence of optical physics (including interferometry) and modern physics in undergraduate physics courses in Angola. Here we present experimental results in hologram production obtained with a versatile setup based on a single-frequency diode-pumped solid-state laser. Even though the experimental work was performed using advanced optical and optomechanical components within a laboratory setting, we see this approach as a necessary step for the understanding and efficient application of holographic techniques, prior to developing new, simpler and less expensive setups. In this thesis, we also highlight a set of published works on applied holography that show how interference and diffraction phenomena are vital to many fields of applied physics, and how holography can be applied in different areas of science, technology and industry.

**Keywords**: Holography, hologram production techniques, optics, interferometry, teaching of physics

**Resumo** (em Português)

A Holografia é um conjunto de técnicas pelas quais a luz coerente (luz laser) é usada para capturar as características de fase e amplitude da luz proveniente de um objeto tridimensional em uma chapa fotográfica bidimensional. Tanto a difração quanto a interferência da luz estão por detrás das características notáveis da holografia. Os principais objetivos deste trabalho orientam-se segundo duas linhas principais: i) o desenvolvimento de abordagens experimentais para a produção de hologramas usando configurações simples e de baixo custo e ii) a produção de hologramas efetivamente capazes de ilustrar importantes princípios físicos, efeitos ou instrumentos óticos. Isto tem como propósito envolver os estudantes no estudo da Física e reforçar a presença da física ótica (incluindo a interferometria) e da física moderna nos cursos de graduação em Física em Angola. Apresentamos resultados experimentais de produção de hologramas obtidos com uma configuração versátil baseada num laser de estado sólido com uma única frequência bombeado por díodos. Embora o trabalho experimental tenha sido realizado com componentes óticos e oto-mecânicos avançados e num laboratório de ótica, consideramos esta abordagem importante para uma aprendizagem e aplicação eficientes das técnicas holográficas, antes de pensar no desenvolvimento de métodos novos, mais simples e menos dispendiosos. Nesta tese destacamos ainda um conjunto de trabalhos publicados na área da holografia aplicada que mostram como os fenómenos de interferência e difração são vitais em muitos campos da Física e Engenharia e em como a holografia pode ser aplicada em diferentes áreas da ciência, tecnologia e indústria.

**Palavras-chave**: Holografia, técnicas de produção de hologramas, ótica, interferometria, ensino da física.

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# 1. Introduction

## 1.1. Motivation and objectives

Along my academic journey at FCUP I had trouble in understanding all the subjects I studied due to my background in Physics and sometimes I was surprised by those subjects. When I started understanding the subjects then I felt a challenge to help my home faculty and my country in things that could help in the teaching of applied Physics and research in this area. When visiting Femtolab, I had the chance to view the hologram of Prof. Marcelo Rebelo de Sousa made by Prof. Helder Crespo. I was very surprised and was asking myself: what is a hologram and how can we make it? While looking for a subject for my master's thesis in physics, and to my good surprise, my supervisor suggested me to work in the production of holograms for pedagogical purposes in the context of physics and physics teaching and I accepted this challenge. Holography has a strong impact on viewers in showing a three-dimensional image of an object. The question is: what gives rise to that three-dimensional image obtained from a two-dimensional glass plate or film?

The interaction of light and matter has a wide range of applications in science and technology, where several important optical effects play a key role. In particular, interference and diffraction phenomena can result whenever two or more light beams are superimposed, or when light is diffracted by an object. There are many experiments that can be performed to explain the phenomenon and the consequences of the interaction of light with matter. These range from simple to more complex experiments about the behavior of matter when it interacts with radiation, such as in optical tweezers, x-ray diffraction and in many more techniques and phenomena. The practicality of these experiments in Angola is almost impossible in view of the high cost of purchasing the required equipment, the lack of qualified instructors and the reduced interest by managers of higher education institutions, who have to struggle with many different issues. Presently, what students learn in optics courses is often just the reflection and refraction of light, and this usually does not go beyond obtaining images using lenses and mirrors with simple, incoherent sources.

The objective here is to explore the phenomena of interference and diffraction of laser light by making holograms capable of illustrating important physics principles and effects in the context of teaching of applied physics to undergraduate physics students in Angola. This includes illustrations on how to make several high-precision measurements in physics and engineering, such as mechanical deformations or displacements, using optical techniques. For this work, we defined two major lines: i) the development of experimental approaches for hologram production using, whenever possible, simple and inexpensive setups, and ii) the production of holograms effectively capable of illustrating important optical instruments, physical principles and/or effects.

### 1.2. State of the art

Since the invention of holography by Dennis Gabor in 1947 [1] (for which he was awarded the Nobel Prize in Physics in 1971) and with the invention of the laser by Maiman in 1960, several new holographic techniques and applications have been devised and others are still being developed today. These range from scientific research to technological applications, such as medical imaging techniques, and also in the field of education as well as in art and/or public engagement [2], where a hologram is also seen as a way of communicating science and technology.

In the beginning of holography, as Gabor said of his invention, its main purpose was to improve optical or electronic microscopy. By recording a hologram using X-rays and playing it back using, e.g., visible radiation, the resulting magnification (given by the ratio between visible and X-ray wavelengths) would make fine details of an object visible. This invention gave rise to other fields of holography employing different techniques with different purposes depending on a particular application. Besides optical holography, also called classical holography, a new enhanced technique is also employed today where holograms are computer generated, which has become most promising in the field of applied holography.

The invention of the laser and its advances gave rise to a new way of seeing holography and led to the development of different types of laser sources for holographic applications with both continuous and pulsed lasers. Optical holography is already being applied as a security measure in important documents [3] playing a leading role in the authenticity and fidelity of information contained in such documents.

Three-dimensional (3D) display technologies are one of the most promising for the introduction of undergraduate students to basic optics courses [4] and as an art medium, where computer-generated hologram (CGH) technologies are also used. CGH is considered to be the next generation of 3D display technology [5], [6] and is considered the best solution satisfying all types of depth cues (full-parallax) among all 3D display technologies. It may represent the future of technology and communications that may affect dramatically many fields, including business, education, telecommunications and healthcare [7].

Holography is also a very effective tool for the teaching of different areas of science, from physics to life sciences, again due to its capability of reproducing 3D images [8].

Various uses of holography have been suggested by different authors for application in the field of education, from physics outreach and as a teaching tool for holography itself [9], [10], in optical image processing classes [11], in optics courses in general [12] and for math contents [13], providing a wide range of possibilities for solidifying the knowledge of middle and high schools students [14] while introducing the basic concepts of optics and photonics.

Optical Holography is the most used technique for the teaching of physics and/or public engagement because it helps understand the physics of interference of coherent light and is a very motivating tool for the teaching of applied optics. It opens valuable discussions about several subjects of daily life due to the strong impact that holograms have on a public audience. For this purpose, a color device for color holography was developed by Vaslion & Escarguel (2012) which was used by Salançon & Escarguel (2019) as an upgrade of their pedagogic tool for monochromatic holography for demonstrations or for science outreach purposes which can be used just as effectively in outdoor popular science events as in higher level physics teaching [15]. The monochromatic device is based on reflection holograms produced with a helium-neon laser of approximately 0.8 mW of output power emitting at 632.8 nm. This kit differs from standard holographic systems/setups because it does not require an appropriate/specific room for the exposure or development procedure nor a vibration-isolated optical table, and it is portable. On the other hand, it still needs adequate obscurity conditions, a power source for the laser and access to water for the hologram development.

For predicting the behaviour of diffraction gratings, which have many applications in science and technology, a model described by Olson (2013) [16] as a "simple, complete, and novel quantitative model of holography for students of science and science education" was developed that also allows understanding the principles behind wave interference.

Years & Peña (2000) [17] included holography as a tool for the teaching of optics, where they considered three key themes:

- Light radiation. Origin and main features;
- Radiation overlapping. Hologram recording;
- Light propagation in matter. Hologram reconstruction.

In the present work, we highlight how holography has been used to teach science, in particular in the teaching of physics contents at different levels, where firstly we show briefly its progress from Gabor's invention to its application in the field of education, with the purpose of showing the current state of holography and its advantage in different areas of science and technology compared to more traditional techniques.

## 1.3. Structure of this thesis

This master's thesis in physics is structured in six chapters, as described below:

- In the first chapter we present our motivation for this master's project in physics and we highlight the main objectives along two major lines that guided all the project as well as the current state-of-the art in the field;

- In the second chapter we define what is holography and a hologram and describe briefly a historical background of holography since its invention by Gabor in 1947 to the present day, where we also highlight some advances made in this area after the invention of the laser. Some important applications of holography in different areas of science and technology and in the field of education are also described;

- In the third chapter we describe fundamental physics principles and mathematical tools in which holographic principles are based as well as different types of holograms. In this chapter we also describe how holograms are recorded and reconstructed;

- The fourth chapter was dedicated to the production of holograms following Gabor's and Denisyuk's principles. Experimental details regarding the laser source as well as all optical components used to produce holograms are described and including detailed images of all experimental setups depicting the corresponding geometric configurations as well as images of the obtained holograms;

- In the fifth chapter we show how holography has been used as a pedagogical tool in the teaching of physics, highlighting some work of different authors and the impact of holography in the teaching of physics, engineering, maths, and science and technology in general.

- Finally, in the sixth chapter, we summarize our results, expectations and future work within the scope of this master's thesis.

## 2. Holography: a brief description and brief historical perspective

### 2.1. What are Holograms? How to produce them? And what is holography?

In general, a hologram is a thin flat piece of film or glass [18], or two-dimensional (2-D) surface, that can produce a three-dimensional image of a three-dimensional object when illuminated by light [19]. It is a recording of the interaction of two mutually coherent light beams, in the form of a microscopic pattern of interference fringes [20]. Holography is the set of techniques that can be used to produce holograms. For optical hologram recording of a 3D object, a laser is usually necessary, due to its spatial and temporal coherence properties. In practice, the basic condition for producing a hologram is to superimpose and record, in a holographic emulsion, the light coming from the object illuminated by a laser (the object beam), together with another beam of light coming directly from the same laser (the so-called reference beam). The reference beam and the object beam interfere with each other on a high-resolution photographic emulsion (also called a holographic emulsion), usually coated in glass or film, where the corresponding interference pattern is recorded [19] , [21]. The resulting hologram enables reconstructing a 3-D image of the object since the interference pattern encodes phase information of the light reflected by the object [22]. The obtained record, called a hologram, contains all the luminous information of the object and therefore, when properly illuminated, produces an image in every way similar to the original object. The complete wavefront of an object is recorded and subsequently reconstructed in the absence of the original wavefront and the observation of this reconstructed wavefront will give the same physical effect as the observation of the original wavefront., i.e., a 3D image is observed just as if the object was still present and being illuminated in the same way as when the holographic recording was made [23].

Besides a laser source, which is a key element in holographic recording, there are other essential optical components for the complete optical setup for hologram production. Note that, unlike in photography, no lens is used between the holographic object and the holographic film. The hologram is usually recorded using a single exposure, and the laser must be the only source of light, as shown in figure 2.1. After the light exposure (which can last from a few seconds to several minutes, depending on laser power, object and plate size, and emulsion grain size and sensitivity), the film is developed by a special process. The permanent recording thus obtained is the hologram, which, when illuminated solely by the reference beam, produces a complete three-dimensional image of the object, even in the absence of the latter.

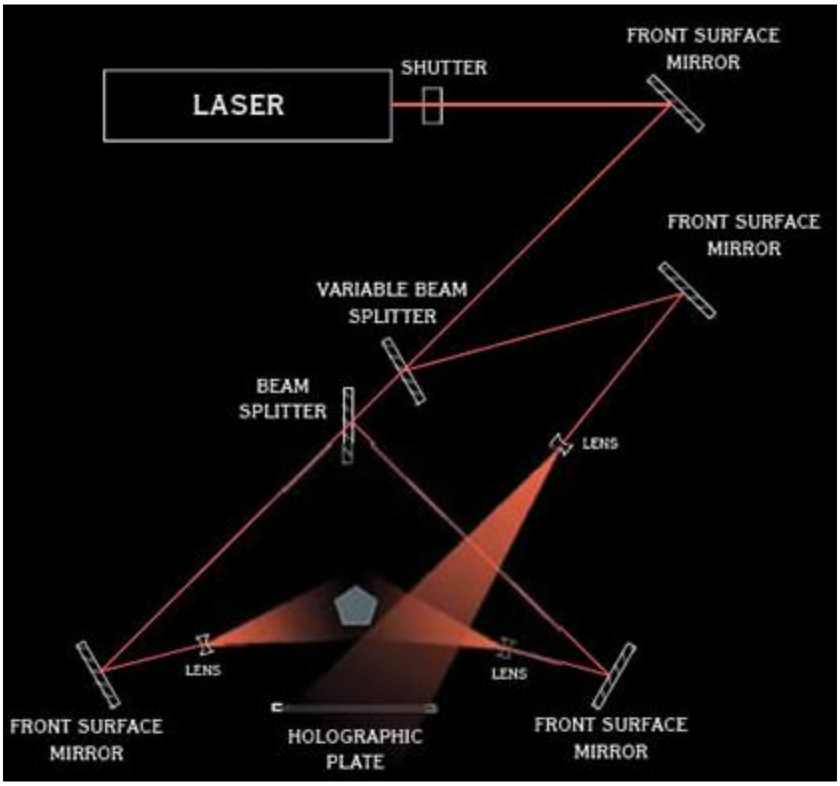



Figure 2.1: Multi-beam setup for recording a laser transmission hologram. In this case, two beams are used to illuminate the object from two sides. Note that in this configuration both the light from the object and the reference beams impinge on the same side of the holographic plate (adapted from [24]).

A crucial aspect for the realization of the hologram is the stability of all optical components used in the setup [25], including the object itself: if any of the elements move or vibrate during exposure, even for a fraction of a thousandth of a millimetre, the holographic recording can be completely destroyed.

Note that holography is not limited to the production of holograms for scientific or even artistic purposes, where the form and color of real or virtual objects are artistically or figuratively exploited. There are two major types of holography: analog and digital holography. Analog holography is performed using real reference and object beams. An example of a large analog hologram produced in Porto and used for public awareness of science is shown in Fig. 2.2. Digital holography involves simulating the interference of light using a computer, calculating the corresponding interference pattern, and performing laser optical recording, point by point (or voxel by voxel, where voxel stands for volume pixel), of the resulting hologram. It is usually used for producing diffractive optical elements (DOEs) and binary optics [26], but can also be used to produce full-color holograms of non-existing 3D objects. Several companies already provide digital holograms on demand, for scientific, technical, artistic or commercial purposes (e.g., Ultimate Holography in France, or Geola, in Lithuania).

Holograms nowadays have many and varied practical applications [27], [28], [29]. They are, for example, used as a security element in documents - credit cards, euro banknotes and football tickets, quality control (e.g. measurement of small deformations), among others (see Fig. 2.3) - and are also the basis for new and promising optical technologies for high-density data storage.

Figure 2.2: Image of the large hologram (holographic plate of 40x60 cm and image depth of more than 7 meters) produced by the IFIMUP team for the Fantaslux hologram exhibition organized by IFIMUP within the Fantasporto 2012 film festival. The composition of objects is allusive to the celebration of the 30th anniversary of Ridley Scott's "Blade Runner", as well as to the city of Porto (image courtesy of IFIMUP).

Figure 2.3: Holograms used as security elements in documents - credit cards, banknotes and in quality control. (e.g. measurement of small deformations in the automobile industry).

## 2.2. A brief historical perspective

The theoretical principles underlying holography could, indeed, have been formulated as early as in 1816, the year that Auguste Fresnel described mathematically Thomas Young's early theory of diffraction and interference [20]. In 1856, Scott Archer discovered how to produce a light-sensitive material coated on glass. So it would at that time have been just possible to make a single-beam reflection hologram of a shallow object using a narrow bandwidth light source such as a gas-discharge lamp.

The employment of Bragg interference planes [30] for the production of color photographic images was exploited by Gabriel Lippmann in the 1890s (Nobel Prize in Physics 1908), and he also showed how Fourier analysis could be applied to imagery. But holography dates from 1947 when British (native of Hungary) scientist Dennis Gabor developed the theory of holography while working to improve the resolution of an electron microscope [31] introducing "a new microscopic principle" [32] which enabled to record the amplitude and phase of an object wave in a holographic plate - Gabor coined the term hologram from the Greek words holos, meaning "whole," and gramma, meaning "message" [33] and, in 1971, Gabor was awarded the Nobel Prize in Physics "for his invention and development of the holographic method". The Gabor technique is in-line holography and consists in using nearly collinear reference and object beams in the direction perpendicular to the holographic plate (figure 2.4). This technique has been used to measure particles in large volumes giving wide depth of field relatively to conventional imaging systems [34]. On the other hand, due to symmetry reasons, two images are generated when the wavefront is reconstructed. An example of this occurs in emission electron as well as in x-ray and gamma-ray holography, where the source-to-object distances are small, and the reconstructed images of atoms are very close to their twin images from which they can hardly be distinguished [35]. The problem related with the overlapped spurious real image was due to the lack of sufficiently coherent light, and the spatial overlap with the virtual image compromised the viewing of the replayed wave front.

After the invention of the laser in 1960, Leith and Upatnieks [20], [36], [37] at the University of Michigan solved the problem of the spurious real image that occurs when using Gabor's original inline setup, by displacing the reference beam so that the unwanted image was moved out of line. When this off-axis beam (figure 2.1 is also an example of off-axis geometry) is used to replay the hologram, the unwanted image is conveniently displaced by an angle equal to twice the angle between the reference and object beams.

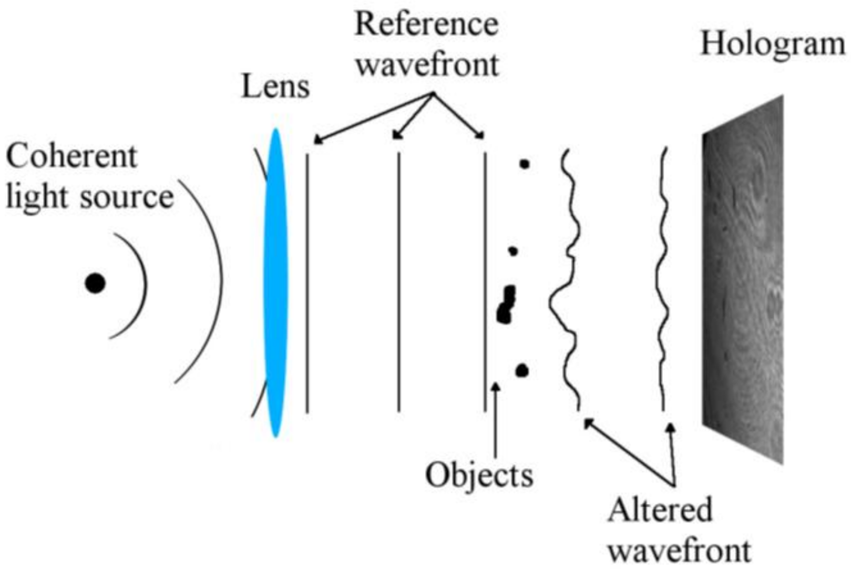



Figure 2.4: A conceptual image of the inline holography imaging setup (from [34]).

In the Soviet Union, Yuri Denisyuk was experimenting with an optical configuration that was radically different from Gabor´s. In his arrangement, the reference and object beams were incident on the emulsion from opposite directions, as shown in figure 2.5.

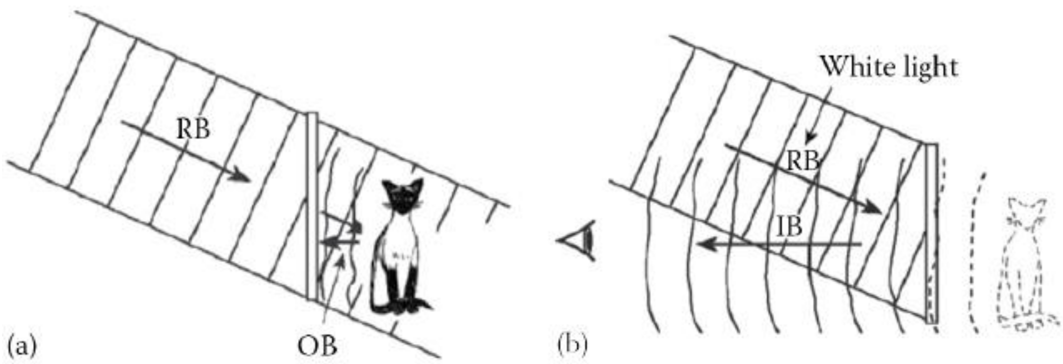



Figure 2.5: Principle of the Denisyuk (single-beam reflection) hologram. (a) In making this type of hologram, the reference beam (**RB)** passes through the emulsion and illuminates the object to form the object beam (**OB)**, which is incident on the emulsion on the side opposite to the reference beam. (b) The hologram is replayed by a reconstruction beam (**RB)** using the same optical path as the original reference beam, incident from the viewing side; the image beam (**IB)** is diffracted from the hologram (from [20]).

In 1959, Denisyuk had succeeded in producing holograms that could be replayed using a point source of white light. Due to the Bragg condition, this type of hologram and other types of reflection hologram do not have to be replayed by laser light and, when the hologram is replayed by white light, it reflects only light with wavelength approximately close to the wavelength used for recording as the other wavelengths interfere and are transmitted due to destructive interference [38]. For his first hologram, Denisyuk used a high-pressure mercury lamp source which produced sufficiently coherent light for recording a hologram of a very shallow object placed on the opposite side of the plate, which enabled the image to be viewed from the front whereas Leith and Upatniek's configurations [39], [20] required a monochromatic replay beam set up behind the hologram.  In 1962, Denisyuk's work was published in the Journal of the Optical Society of America and in 1963, Leith and Upatnieks were producing the first laser transmission holograms [40]. Figure 2.6 summarizes the recording and reconstruction geometries of Gabor, Denisyuk and Leith/Upatnieks holograms.

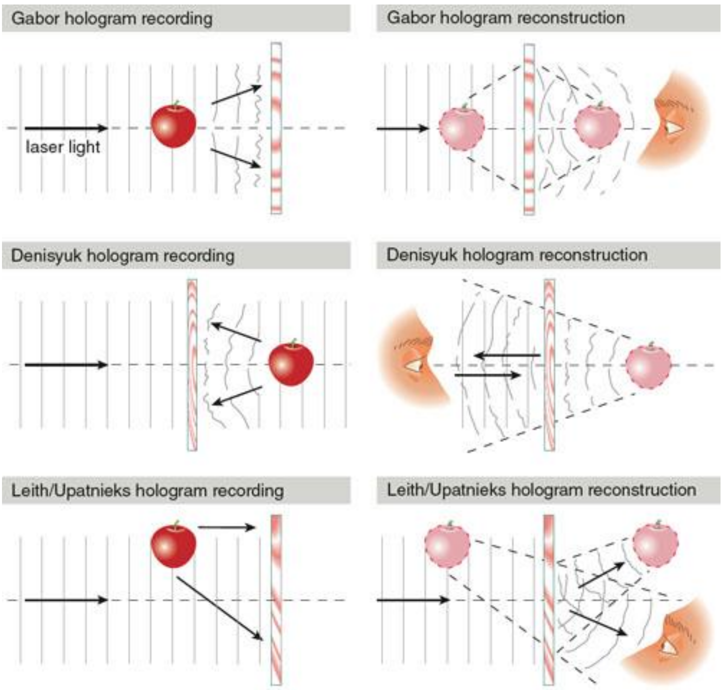



Figure 2.6: A model of wavefront recording and reconstruction illustrating the Gabor, Denisyuk and Leith/Upatnieks hologram recording geometries (from [41]).

Digital holography began years after Gabor's invention in 1947 and different techniques were being developed by many researchers in order to generate holograms using computational methods and it give another way of viewing holography as it does not necessarily require the use of a laser for optical recording and reconstruction [42].

The formation of the hologram itself can be calculated on a computer, which gives the complex field distribution to be stored as a hologram [43]. Digital holography is an important technique for studying biological cells and 3D pictures and movies have been made using this technique [44]. With the improvement of laser light sources, optical elements, and the production of high-resolution silver halide holographic plates and other holographic recording media, the quality of holographic images has significantly improved [45].

Several researchers have put significant efforts in holography. One of them is Hans Bjelkhagen who since 1968 is still working on holography for applied science and technology, artistic holography and for medicine and industry. His first work in holography as a student was at the Royal Institute of Technology in Stockholm, Sweden. A detailed historical text about his efforts devoted to holography research can be found in the proceedings of the recent $11^{th}$ international symposium on display holography – ISDH 2018, which took place in Aveiro, Portugal [46].

### 2.3. Some applications of Holography: a brief description

Since the invention of holography, various techniques for application of high-quality three-dimensional imagery have been explored and applied to different areas of science, technology, art and in education. Leith and Upatnieks [47] are some of the pioneers in advancing applied holography. In their paper entitled "Holograms: their properties and uses" they described some areas in which holographic principles could be applied. Nowadays, holography has a wide range of applications and is considered one of the most promising techniques for goggle-free 3D visualization in the near future [48]. This stems from the ideas in digital holography [49] initially proposed by Goodman and Lawrence [50] where images were reconstructed with the aid of computations from a digitized Fourier hologram [51], that was electronically detected by a video camera [50] from an optically recorded hologram; its fundamental theory was conceived by Yaroslavskii and Merzlyakov in 1980 [48].

Besides DH and optical holography there is also another type of holography - Computer Generated Holography (CGH) first proposed by Brown and Lohmann in 1966 [52], [53]. It allows the generation of holograms with the aid of sophisticated mathematical manipulations of an object that does not physically exist but can be described in mathematical terms. CGH refers to the family of techniques that generate a hologram from virtual objects using mathematical manipulations and then reconstruct the image optically using classic laser illumination methods [39], [48]. Regardless of their type, - holograms are sometimes used to engage the public in science and technology due to their 3D capability, which has a strong visual impact on viewers [54].

#### 2.3.1. Holography and information technology

The field of information technology is one area of interest in applied holography ranging from information storage [55], to communication theory, as well as optical information processing [56].

Concerning the information storage, the associative storage (figure 2.7) is a basic property of holography where either (object or reference) of the original beams can illuminate the hologram to reconstruct the other [56], where the resolution of the recording medium provides significant advantages, yielding for example many superimposed holograms in the same volume, and enabling its use in switching and optical networks [56].

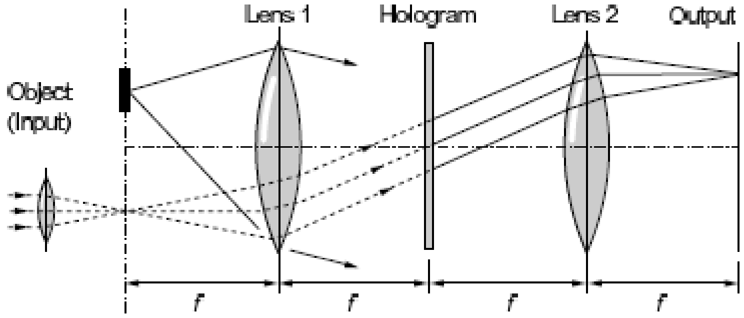



Figure 2.7. Diagram demonstrating associative storage property of holographic storage using the Fourier-transform method (from [56], [51]).

These properties can be understood in the following way: the hologram with the sought-after information, is placed in the common focal plane of the lenses [51]; the basic equation of holography for the intensity distribution I within a hologram

$$I = |r|^2 + |o|^2 + ro^* + r^*o \tag{1.1}$$

remains unchanged when exchanging the object wave **o** and the reference wave **r.** When illuminating the hologram with the object wave **o** the reference wave **r** is reproduced**,** just like **o** is reproduced by **r**. Thus, one wave or information reproduce the other. This is the property of associative storage [51], [55]. The Fourier-transform method enables information to be stored by superimposing holograms, exhibiting excellent volumetric stability, low scatter and high sensitivity for recording. On the other hand, Fourier transform and related computer algorithms are key methods in computerized modern imaging techniques [26] for image reconstruction from projections including computerized tomography [57], magnetic resonance imaging [58], and others. In this field, digital holographic (DH) microscopy is a new technology applied to optical microscopy due to its capability of producing 3D volumetric images from a single image capture.

Imaging of microscopic objects is an essential tool, especially in life sciences [45]. An important example is medical imaging, where Lagendijk *et al.* performed measurements of tumour volume in breast cancer patients using 3D automated breast volume scanner images. Their technique is based on 3D ultrasonography, which is in reality a holographic technique [59].

### 2.3.2. Holography and optical communications

Holographic principles have been also explored in the field of communication theory to enhance the transmission of information adapting it for example to fiber communications [60]. In 1961 Leith and Upatnieks [36], looked at Gabor work (a two-step imaging process which involves photographing the Fresnel diffraction pattern of an object and using this recorded pattern to reconstruct an image of this object) from the viewpoint of communication-theory, showing that the reconstruction of the hologram constitutes a sequence of three well-known operations: modulation, frequency dispersion, and a square-law detection, where in the reconstruction process, the inverse-frequency-dispersion operation was carried out in which the signal-to-noise ratio was unity.

DH has become a fundamental tool for communication technology, like in digital video holography, which combines mathematical methods to record, reconstruct and store more information in a single bit due to the properties of holograms. DH techniques are extended further to video format yielding video holograms where the concept that a bit of hologram contains full information of the original video is used to reduce the file size required for communication in terms of storage, security and speed [61].

Alresheedi et. al [62] in their paper about application of holograms in Optical Wireless Communications [48], [63], [64] showed that their adaptive fast angle and power adaptive holograms (FAPA-Holograms) system provides around 35 dB Signal-to-Noise Ratio gain over non-imaging diversity line strip multi-beam systems (LSMS).

### 2.3.3. Holography in scientific research and science teaching

Here we describe some applications of holography highlighting their importance in different fields of science and technology and in the field of education. In chapter 4 we describe the pedagogical implications of holography and its impact in the context of physics teaching.

There is significant research being carried out in holography. For example, Desse and Tribillon [65] in 2005 developed a real-time color holographic interferometry (RCHI) technique to obtain the refractive index of materials. The technique is based on using light with three wavelengths (red, green and blue) from a mixed gas (argon and krypton) laser. These wavelengths can nowadays be obtained using cheaper, more reliable and user-friendly diode-pumped solid-state (DPSS) lasers. With this technique they recorded high resolution panchromatic transmission holograms. Near-field acoustical holography (NAH) [66], [67] is another field that some researchers have explored for investigating the location of noise sources and understanding the relationship between structure vibration and sound radiation using holographic principles [68]. Another technique that has gained interest in research and application fields since the invention of holography is holographic interferometry [69], [70]. It has been used for the determination of small and/or large deformations [65], to study the problems related to aberration in holographic images [71], as a method for measuring strain caused by polymerization shrinkage of dental composite [72] and to measure microscopic displacements on the surface of an object and small changes in the refractive index of transparent objects [73], [74]. Each particular application of holographic interferometry requires a specific arrangement of the optical setup [75].

Barkhaya and Halim in their article entitled “A review of application of 3D Hologram in education: a meta-analysis “ [76], highlight the application of three-dimensional hologram technology in education which they recognized as a teaching tool in the classroom. In the following table they summarize the role of 3D holography fields. In the field of physics education, there are many physical principles (e.g., interference, diffraction, superposition principle) which can be taught and illustrated by the simple realization of a laser hologram. It is also possible to make several experiments illustrating important applications of holography, such as holographic interferometry used in mechanical stress diagnostics, angular multiplexing used in holographic data storage, “notch” filters used in Raman spectroscopy and holographic diffraction gratings used in passive spectroscopy. For example, in the basic courses on ray and wave optics at Lund University, holography has played an important role both in stimulating the students to explore the fascinating world of optics and in visualizing various interesting concepts within the courses. In Lund, students have four-hour lab sessions in holography aimed at stimulating their interest in optics, lasers and optical measurement techniques [77]; To simplify and to help the teaching of holography, a teaching kit for holography that can be packed into a small case which includes all the equipment required to produce holograms was created at Lund University. This kit is also particularly suited for science outreach, teaching of undergraduate and graduate students and continuing education [78]. Similar approaches have been followed in other countries. Holography has another advantage in the field of education when it is thought as information communication technology (ICT) medium of the teaching of sciences as pointed by Ghuloun [79] and it has been used by different researchers or educators as teaching agent or pedagogical tool in different areas of physics teaching.

| Meta-analysis of 3DH in various fields and in education | | | |
|---|---|---|---|
| Study | Field (Application) | Uses | Advantages |
| Vandembosch et.al (2005) | Cardiothoracic Surgery (Dynamic 3D echocardiography) | Observing the 3D echocardiographic data sets (normal an pathological mitral valve) in a hologram | Useful tool in clinical practice |
| Robin (2013) | Medical training-Neurosurgery (Pulse Brain Hologram) | Combine biomedical data on 3D image | Explaining planned procedure to increase patient satisfaction due to explanation |
| Romero (2015) | Neuroscience (Cerebellar control model-CCM) | Evaluation of models to control robotic origami arm | Precise and fast movement of robotic arm |
| Abin (2013) | Business (Advertisement) | Advertising and promotion | A business or product stands out from the competitors |
| Khan et al (2013) | Photo-Optical Instrumentation Engineering | HOE-based display (as far converging lens) | High resolution images, relatively bright, visible under ambient indoor lighting |
| Freeman (2010) | Pharmacology | Display the transport and effect of drugs in the several internal organs of the human body. | Help students to understand clearly how drugs work and affect the human body |
| Aina (2010) | Astronautical engineering (Genx Theatre) Farnborough Air show in 2006 | Show and discuss large engine that cannot physically fit in classroom | Very interesting technique to view different angles. |
| Jurmain et al. (2008) | Archeological study (Artifacts) | Projecting realistic images of artifacts | Archeology students are able to explore and analyse holograms of rare artifacts, hence preventing damage to the original artefacts |
| Upadhy (2013) | Engineering education (Graphics and Drawing) | A diagram of projection of hexagonal pyramid with isometric view | Increase student understanding |
| Monnin (2010) | Early childhood education ("Bugs Bunny" cartoon character) | Teaching aid/tool | Engage children |

Table 2.1. Role of holography in different fields (adapted from [76]).

## 3. The Physics behind Holography

### 3.1. Interference of light waves

Light is an electromagnetic wave and it has many scientific and technological applications; in holography, only the electric field strength is considered. Electromagnetic waves are 3-D waves, with three space dimensions and one time dimension [26], [80]. Here we represent the object wave with “o” and the reference wave with “r” and the intensity with $I$ and it is the square of the electrical field amplitude. When the object and reference wave are superimposed, they create an interference pattern which can be recorded on the holographic plate and the hologram will represent this interference pattern [81], [82].

The electric field $E(t)$ of a plane wave at a given point in space, assuming propagation in the z - direction, is given by the following equation [83]:

$$
\begin{aligned}
E(z,t) &= Acos(2\pi f t + \varphi) \\
&= Acos(\omega t + \varphi)
\end{aligned}
\qquad (3.1)
$$

where $A$ is the amplitude of the oscillation and ω is the angular frequency. The parameter $\varphi$ represents a phase factor for $t = 0$.

Figure 3.1 shows a “snapshot” of the light wave, where, $\lambda$ is the wavelength, $c$ is the speed of light, and $T$ the oscillation period of the eletric field. The reciprocal value describes the frequency $f = 1/T$. Since a point at a distance z from the point of origin starts to oscillate with a phase shift proportional to the time $t_0 = z/c = z/(f\lambda)$, the equation of oscillation at this point becomes:

$$E(z,t) = Acos(\omega(t - t_0) + \varphi) \qquad (3.2)$$

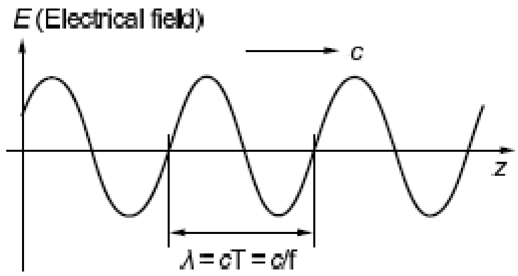



Figure 3.1: Representation of a plane wave (from [83] )

The plane wave equation can therefore be written as:

$$\mathbf{E}(\mathrm{z},\mathrm{t}) = A\cos(\omega t - kz + \varphi) = A\cos(\omega t + \phi) \qquad (3.3a)$$

where $k = 2\pi/\lambda$ is the wave number and $\phi = \varphi - kz$. Using the complex notation of Euler’s relation $e^{\pm i\phi} = cos\phi \pm isin\phi$, Eq. 3.3a becomes:

$$\mathbf{E}(\mathrm{z},\mathrm{t}) = Ae^{-i(\omega t - kz + \varphi)} = Ae^{-i(\omega t - \boldsymbol{\phi})} \qquad (3.3b)$$

Here only the real part is important and the bold character denotes the complex amplitude. The term $\omega t$ in the exponent can be left out for simplicity. The term

$$\mathbf{E}(\mathrm{t}) = Ae^{-i\phi} \qquad (3.3c)$$

is the complex amplitude and $A$ is the amplitude of the complex amplitude field.

The interference of two plane waves of a coherent light source is discussed in order to explain how volume holograms are generated [81], for example in a thick medium. Eqs (3.4) and (3.5) represent the object and the reference waves [26], and figure 3.2 depicts the interference fringes or system of standing waves as generated by the two coherent point light sources

$$\mathbf{o} = oe^{-i\phi} \qquad (3.4)$$

$$\mathbf{r} = \boldsymbol{r}e^{-i\Psi} \qquad (3.5)$$

**r** and **o** are, in this case, the field amplitudes of the respective waves at the point of superposition P. The phase $\Psi = \Psi R - 2\pi(r_1/\lambda)$ is determined by the starting phase of the wave at point R and the phase change at distance $r_1$. The same is valid for $\phi = \phi_O - 2\pi(r_2/\lambda)$.

The complex amplitude adds up at point P: $r + o$. the intensity $I$ is the square of the sum of the complex amplitudes:

$$I = |r + o|^2 \qquad (3.6a)$$

$$I = r.r^* + o.o^* + o.r^* + r.o^*$$

$$I = r^2 + o^2 + r.o\{e^{-i(\phi-\Psi)} + e^{i(\phi-\Psi)}\} \qquad (3.6b)$$

$$(3.6b)$$

If the light sources are emitting completely independently then the average of $cos(\phi - \Psi)$ vanishes since the phases vary statistically, which results in

$$I = r^2 + o^2 \qquad (3.7)$$

In this case the waves are called “incoherent.” The intensities of both waves add up, and interference does not occur.

If the value of $\Psi_R - \phi_O$ does not change, the waves are “coherent.” According to Eq. (3.6a) locations in space exist where $cos(\Psi - \phi) = \pm 1$. If the field strengths oscillate in the same phase (+) this results in

$$r + o$$

and the intensity reaches a maximum

$$I_{max} = r^2 + o^2 + 2r.o \qquad (3.8a)$$

If the fields oscillate in opposing cycles the resulting superposition is

$r - o$

and the intensity reaches a minimum

$$I_{min} = r^2 + o^2 - 2r.o \qquad (3.8b)$$

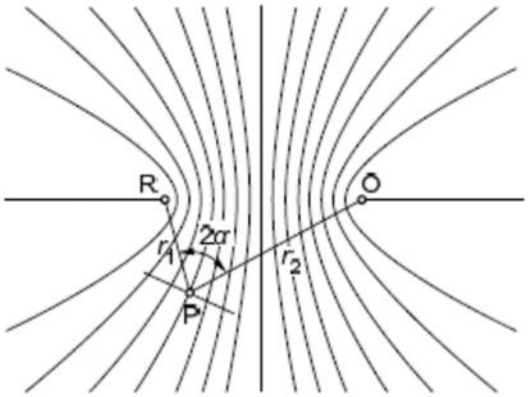



Figure 3.2 Interference fringes or system of standing waves as generated by two coherent point light sources R and O (from [83]).

The expression $r.o\{e^{-i(\phi-\Psi)} + e^{i(\phi-\Psi)}\}$ is the "interference term."

The interference pattern for $\Psi_R = \phi_O \pm N(2\pi)$ is shown in figure 3.2. The maxima of oscillation are given by

$$r_1 - r_2 = \pm N\lambda \qquad (3.9)$$

At the position of the maxima both waves oscillate in phase. Equation (3.9) describes a set of rotational hyperboloids. The distance between maxima is given by

$$d = \frac{\lambda}{2\sin(\alpha)} \qquad (3.10)$$

where $2\alpha$ is the angle enclosed by $r_1$ and $r_2$. For the connecting line $\overline{RO}$ is $\alpha = \pi/2$ and the distance of the maxima becomes $d = \lambda/2$. The so-called Fresnel zone lens appears when the interference pattern is cut perpendicular to its symmetry axis.

## 3.2. Visibility and polarization influence

For the recording of the hologram, the visibility $V$ in the interference field is determined by the ratio of the two waves $I_1 = r^2$ and $I_2 = o^2$ and is given by

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad (3.11)$$

For coherent waves and using eqs. (3.8a), (3.8b), and (3.7) one gets

$$V = \frac{2 \cdot \sqrt{\frac{I_1}{I_2}}}{1 + \frac{I_1}{I_2}} \qquad (3.12a)$$

where the maximum of visibility is reached when $I_1 = I_2$.

Assuming that the polarization of the light waves is parallel, it follows that the maximal visibility of $V = 1$ holds for $I_1 = I_2$. If the polarization directions of two linearly polarized waves enclose an angle $\psi$ the following equations result instead of eqs. (3.6a) and (3.12a):

$$I = r^2 + o^2 + 2r.o\, cos(\phi - \Psi)\, cos\, \psi \qquad (3.6b)$$

and

$$V = \frac{2 \cdot \sqrt{\frac{I_1}{I_2}}}{1 + \frac{I_1}{I_2}} cos\psi \qquad (3.12b)$$

Meaning that interference does not occur if the directions of polarization are perpendicular to each other.

## 3.3. Holographic recording and reconstruction

### 3.3.1. Recording and reconstruction

The intensity of the electromagnetic field of the light wave impinging on the photosensitive layer (figure 3.3a) is given in Eq. 3.6a, where the factor $(\boldsymbol{r} + \boldsymbol{o})^*$ represent complex functions of r and o, which gives:

$$I = r.r^* + o.o^* + o.r^* + r.o^* \qquad (3.13b)$$

here the star represents the complex conjugate. This factor contains the object wave **o** and it is particularly important for holography. The darkening of the holographic film is dependent on the intensity $I$.

The reconstruction is performed by illuminating the hologram with the reference wave **r** (Fig. 3.3b). Assuming that the amplitude transmission of the material is proportional to $I$ then the reconstruction yields the light amplitude $u$ directly behind the hologram:

$$u \sim r \cdot I = u_0 + u_{-1} + u_{+1} \qquad (3.14)$$

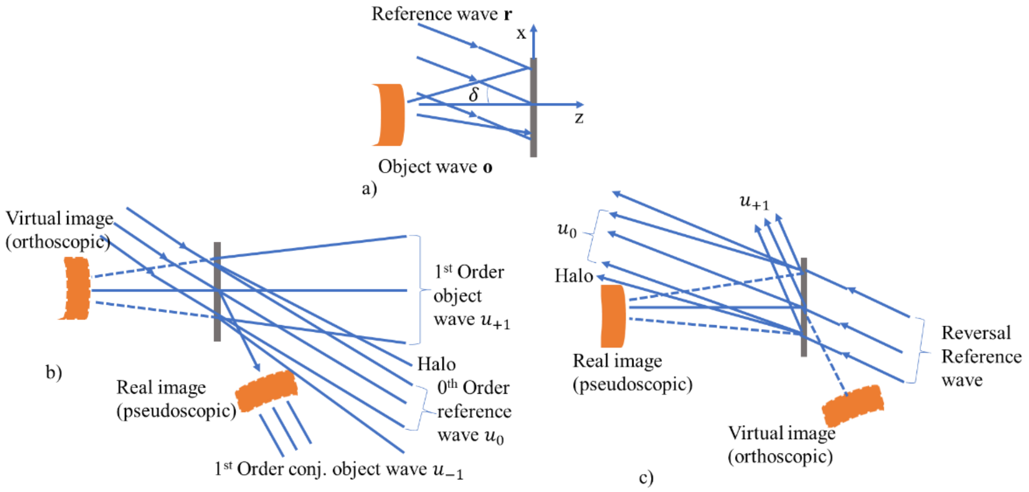



Figure 3.3 Description of holography (off-axis hologram): (a) recording, (b) reconstruction, and (c) inversion of the reconstruction wave (from [83]).

The wavefield behind the hologram is composed of three parts namely:

- $u_0$ is the zeroth diffraction order governing the reference wave which is weakened by the darkening of the hologram;
- $u_{-1}$ describes the complex conjugate object wave $o^*$ and corresponds to the $-1st$ diffraction order which gives a real and pseudoscopic image due to convergent diffraction;
- $u_{+1}$ represents the first diffraction order, where the object wave itself is reconstructed with the amplitude of the reference wave $|r|^2$ being constant over the whole hologram and proves that the object wave **o** can be completely reconstructed. This gives a virtual and orthoscopic because the diffraction is divergent.

### 3.3.2. Mathematical description of holographic recording and reconstruction

#### 3.3.2.1. Object and reference wave

The complex amplitude of the object wave $o(x, y)$ with absolute value $|o(x, y)|$ and phase $\Phi(x, y)$ depend on the coordinates $x$ and $y$ on the photographic plate. If the time dependence of the waves is not considered, Eq. (3.14) for the object wave can be written as

$$\boldsymbol{o}(x, y) = |\boldsymbol{o}(x, y)|\mathrm{e}^{-i\Phi} = o(x, y)\mathrm{e}^{-i\Phi}. \tag{3.15}$$

The phase $\Psi$ depends on the angle of incidence $\sigma$ and can be calculated by (Fig. 3.4)

$$r(x, y) = r\mathrm{e}^{-i\Psi} = r(x, y)\mathrm{e}^{+i2\pi x\sigma_r}. \tag{3.16}$$

The distance between the two maxima of the reference wave in the hologram plane is given by $d_r = 1/\sigma_r$:

$$d_r = \frac{1}{\sigma_r} = \frac{\lambda}{\sin\delta'} \tag{3.17}$$

where $\sigma_r$ is the so-called spatial frequency of the wave, i.e., the number of maxima per unit length.

### 3.3.2.2. Recording

The intensity in the plane of the photographic layer is therefore given by (see also Eq. (3.13b))

$$I = |\boldsymbol{r}(x,y) + \boldsymbol{o}(x,y)|^2$$
$$= |\boldsymbol{r}(x,y)|^2 + |\boldsymbol{o}(x,y)|^2 + \boldsymbol{r}^*(x,y)\boldsymbol{o}(x,y) + \boldsymbol{r}(x,y)\boldsymbol{o}^*(x,y) \tag{3.18}$$

$$I = r^2 + o^2 + ro(x,y)\left(e^{-2\pi i\sigma_r x}e^{-i\boldsymbol{\phi}(x,y)} + e^{2\pi i\sigma_r x}e^{i\boldsymbol{\phi}(x,y)}\right) \tag{3.19}$$

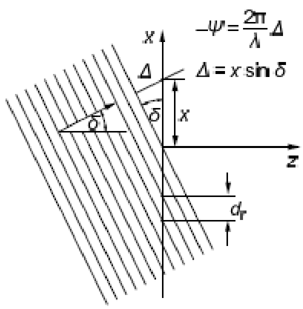



Figure 3.4: Phase $\psi = -2\pi\,\Delta/\lambda$ of an angular incident wave on a hologram (from [83])

The four summands can be calculated as

Eq. (3.19) shows that the intensity distribution in the photographic layer contains the object wave's amplitude $O(x,y)$ as well as the phase $\phi(x,y)$. The amplitude $O(x,y)$ modulates brightness while the phase modulates the distance of the fringes with spatial carrier frequency $\sigma_r = fringes/unit\ length$.

The transmission decreases proportionally to the exposure intensity I and the exposure time $\tau$. The transmission without any exposure is given by

$$t = t_0 + \beta\tau I = t_0 + \beta E. \tag{3.20}$$

The term $E = \tau I$ describes the energy density of the light, commonly called the "exposure." The parameter $\beta$ is negative and is represented by the slope in the H&D curve (Fig. 3.5). The amplitude transmission is then given by

$$t(x,y) = t_0 + \beta\tau r^2 + \beta\tau o^2(x,y) + \beta\tau r_0(x,y)e^{-i2\pi\sigma_r x}e^{-i\phi(x,y)}$$
$$+ \beta\tau r_0(x,y)e^{i2\pi\sigma_r x}e^{i\phi(x,y)} \tag{3.21a}$$

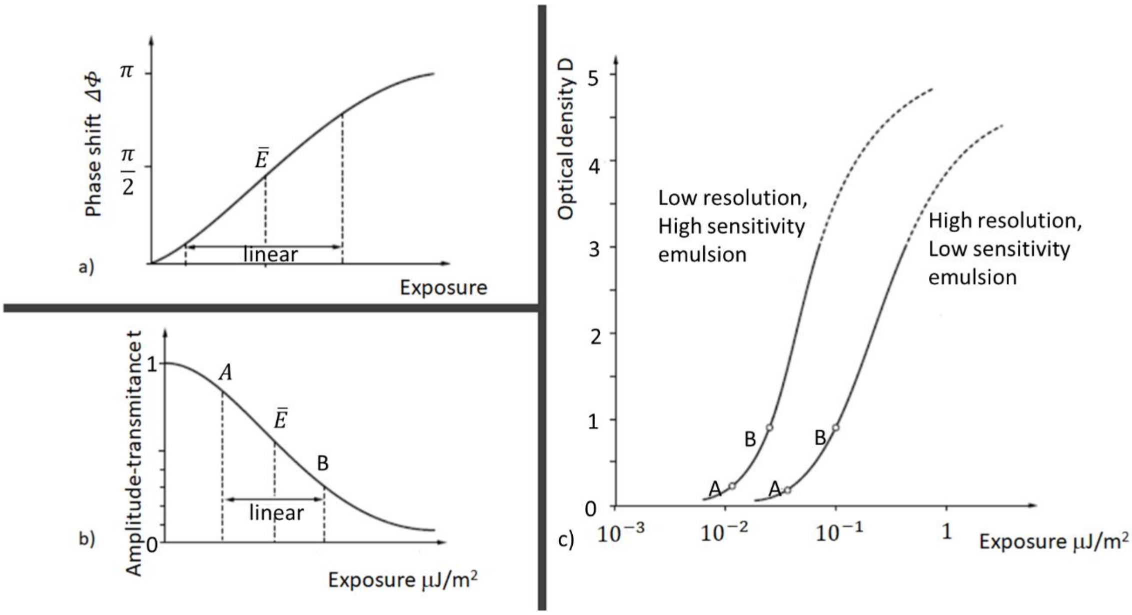



Figure. 3.5: Transparency and phase curves of holographic materials: (a) phase shift $\Delta\Phi$ as a function of the light energy $E$, (b) amplitude transparency $t$ of a holographic emulsion layer as a function of the light energy *E*, and (c) optical density $D = \log 1/t^2$ as a function of *E* (Hurler and Driffield, H&D curve), (from [83]).

### 3.3.2.3. Gratings

The transmission **t** of a plane object wave **o** which illuminates the photographic layer similar to the reference wave in eq.(3.21a) with $\phi = -i2\pi\sigma_0 x$ and the Euler equation then gives

$$t(x) = \bar{t} + t_1 \cos(kx)$$

$$k = 2\pi(\sigma_r + \sigma_0)$$

$$\bar{t}(x) = t_0 + \beta\tau(r^2 + o^2(\mathrm{x,y}))$$

$$t_1 = \beta\tau r_0. \tag{3.21b}$$

The amplitude transmission t of a hologram formed by two plane waves **r** and **o** is therefore a cosine-like diffraction grating. Hence the intensity transmission $T = t^2$ is proportional to a $\cos^2$-function.

### 3.3.2.4. Reconstruction

For the reconstruction of the object wave, the developed hologram is again illuminated with the reference wave $r(x,y) = re^{i2\pi\sigma_r x}$. The hologram $t(x,y)$ acts like a filter and the wave field $u(x,y)$ directly behind the photographic layer is given by

$$\boldsymbol{u}(x,y) = \boldsymbol{r}(x,y)\boldsymbol{t}(x,y) \tag{3.22}$$

With the help of equations (3.15), (3.16) and (3.21a) this becomes

$$\boldsymbol{u}(x,y) = (t_0 + \beta\tau r^2)\boldsymbol{r}(x,y)$$
$$+\beta\tau o^2(x,y)\boldsymbol{r}(x,y) \quad : \quad u_0$$
$$+\beta\tau r^2\boldsymbol{o}(x,y) \quad : \quad u_{+1}$$
$$+\beta\tau r^2(x,y)\boldsymbol{o}^*(x,y)e^{i4\pi\sigma_r x} \quad : \quad u_{-1}. \qquad (3.23)$$

This expression describes the effect of a hologram on a light wave during the reconstruction. It is given by four summands which are written in four lines (Fig. 3.3b).

The first summand refers to the intensity reduction of the reconstruction wave (=reference wave) by the factor $(t_0 + \beta\tau r^2)$ during reconstruction.

The second term is small assuming that we choose $o(x,y) < r$ during recording. This term is distinguished from the first term by its spatial variation $o^2(x,y)$. The $o^2(x,y)$ term contains low spatial frequencies which have small diffraction angles and create a so-called halo around the reconstruction wave.

The size of the halo is given by the angular dimension of the object. The first two terms form the zeroth diffraction order in eq. (3.23).

The third expression in eq. (3.23) denotes the object wave $o(x,y)$ multiplied with the constant factor $\beta\tau r^2$. The third term is the most important and represent the first diffraction order.

The wave travels divergent from the hologram thus creating a virtual image at the position of the original object and this image cannot be captured on a screen. The intensity (square of amplitude) of the image does not depend on the sign of $\beta$. Therefore, it is unimportant whether the hologram is processed as “positive” or “negative”.

The fourth term is the conjugate complex of the object wave $o^*(x,y)$ and represents the first diffraction order. It creates a conjugated real image. The conjugated wave $o^*(x,y)$ is mutipied with the constant factor $\beta\tau r^2$ as well as the exponential function $e^{i4\pi\sigma_r x}$. The latter means that the wave has roughly twice the angle of incidence ($2\delta$) compared to that of the reference wave (more precisely: the sine of that angle is twice as large). Since the complex conjugated wave, the phase changes its sign with respect to $o(x,y)$. Therefore, the wave $o^*(x,y)$ travels convergent and forms a real image.

### 3.4. Volume hologram

There are a number of different types of hologram, usually grouped into two main categories: transmission and reflection holograms. Reflection holograms are made with the object and reference beams incident on the holographic emulsion from opposite sides; transmission holograms are made with both beams incident from the same side [84] (see figure 3.6). Transmission holograms are reconstructed using laser light usually with the same wavelength used during recording, whereas reflection holograms can be reconstructed using white light.

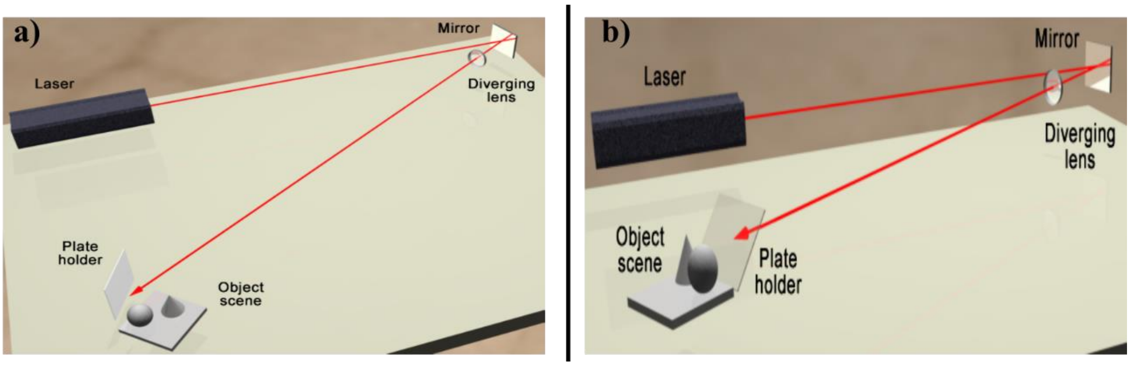



Figure 3.6: Basic single-beam transmission (a) and reflection (b) hologram setups (from [25]).

Here we briefly describe only one type of hologram that we worked on - volume holograms recorded in a thick medium. A major advantage gained with this type of hologram is that the hologram is wavelength selective and thereby also works with white light (if it is a reflection hologram) after recording and can have very high diffraction efficiency [26].

An example of the recording of a volume hologram is given in figure 3.7, where the object and reference wave interfere in a thick emulsion and the resulting pattern recorded represents a volume grating. When the same reference wave is used for the reconstruction, the object wave is perfectly replayed.

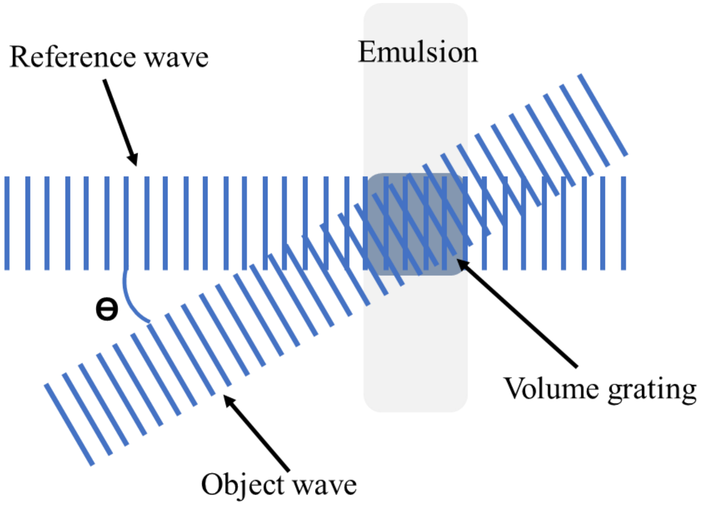



Figure 3.7.: Interference pattern of two plane waves generating a volume grating in a thick emulsion (from [26]).

One can find other types of holograms such as Fresnel and Fraunhofer holograms, Fourier holograms and embossed holograms.

### 3.5. Conjugated Object Wave

To show which properties the conjugate complex object wave $o^*(x,y)$ has behind the hologram, a plane wave with an angle of incidence $\delta_0$ is considered (see fig. 3.8). In this case the object wave can be written similar to eqs. (3.16) and (3.17):

$\boldsymbol{o}^*(x,y) = oe^{i2\pi\sigma_0 x}$ and $\sigma_0 = \sin\delta_0/\lambda$

or

$$\boldsymbol{o}^*(x,y) = oe^{i\frac{2\pi}{\lambda}x\sin\delta_0} \tag{3.24}$$

The conjugate complex object wave is formed by changing the sign of the exponent in eq. (3.24). The negative sign can then be included in the sine function:

$$\boldsymbol{o}^*(x,y) = oe^{i\frac{2\pi}{\lambda}x\sin(-\delta_0)} \tag{3.25}$$

In Figure 3.8 it becomes apparent that the conjugate complex wave $o^*(x,y)$ emerges from $o(x,y)$ by exchanging the angles $\delta_0$ and $-\delta_0$. $o^*(x,y)$ forms a real image mirrored with respect to the hologram plane.

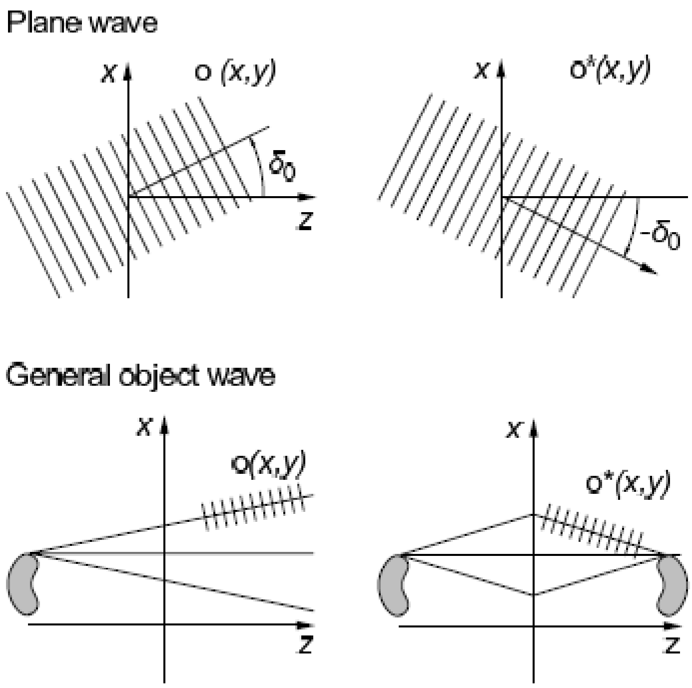



Figure 3.8: The conjugate complex object wave $o^*(x,y)$ can be created from $o(x,y)$ by mirroring at the hologram plane. $o^*(x,y)$ creates a conjugated pseudoscopic mirror image (from [83]).

Furthermore, it is noticeable that the three-dimensional images formed by $o(x, y)$ and $o^*(x, y)$ have different properties. For an opaque object, only the concave inner surface of the image produced by $o(x, y)$ can be seen (Fig. 3.8). For an image formed by $o^*(x, y)$ this surface becomes convex. This image with reversed curvatures is called “pseudoscopic.” The normal image on the other hand is called “orthoscopic.”

### 3.5.1. Position of the conjugated image

It can be calculated from the fourth term $u_{-1}$ in Eq. (3.23) if, for simplification, a plane object wave $o(x, y)$ is assumed. Therefore $o^*(x, y)$ is also a plane wave. If $o(x, y)$ has the angle of incidence $\delta_0$ (see fig. 3.8), Eqs. (3.23) and (3.25) can be written as

$$u_{-1} = \beta\tau r^2 O e^{i\frac{2\pi}{\lambda}x\sin(-\delta_0)+2\sin\delta}. \quad (3.26)$$

Here the relation $e^a e^b = e^{a+b}$ was used. Expression (3.26) represents a wave with the angle of incidence $\delta_{-1}$ with

$$\sin\delta_{-1} = \sin(-\delta_0) + 2\sin\delta. \quad (3.27)$$

As already stated, the conjugated image with $\delta_0 = 0$ (object wave impinging perpendicular on the hologram) appears at an angle of

$$sin\delta_{-1} = 2sin\delta;$$

where $\delta$ is the angle of the reference and reconstruction waves.

### 3.5.2. Reversal of the reconstruction wave

In two-stage holography also the real conjugated pseudoscopic image is used (figure 3.3b). But sometimes the image position is geometrically unfavorable and it is reconstructed in a different manner, namely by reversing the direction of the reconstruction wave (figure 3.3c). The same effect can be achieved by turning the hologram by 180◦ (around an axis perpendicular to the plane of paper). The reversal of a plane reconstruction wave like in Eq. (3.16)

$$\boldsymbol{r}(x, y) = re^{i\frac{2\pi}{\lambda}x\sin(\delta)}$$

means that $\delta$ is replaced by $180° + \delta$. From the relation $\sin(180° + \delta) = -\sin\delta$ follows that the reversed reconstruction wave is described by $r^*$ (Fig. 3.5). By reversing the reconstruction wave, Eq. (3.23) changes to

$$\boldsymbol{u}'(x, y) = \boldsymbol{r}^*(x, y)t(x, y). \quad (3.22a)$$

Instead of Eq. (3.24), the following equation results:

$$\boldsymbol{u}'(x, y) = (t_0 + \beta\tau r^2)\boldsymbol{r}^*(x, y)$$

$$+\beta\tau o^2(x, y)\boldsymbol{r}^*(x, y) \quad : \quad \boldsymbol{u}'_0$$

$$+\beta\tau r^2 \boldsymbol{o}(x,y) \quad : \quad \boldsymbol{u'_{+1}}$$

$$+\beta\tau r^2(x,y)\boldsymbol{o}^*(x,y)e^{i4\pi\sigma_r x} \quad : \quad \boldsymbol{u'_{-1}}. \tag{3.23a}$$

The terms $u'_0$, $u'_{+1}$, and $u'_{-1}$ can be interpreted analogously to the last section. The results are shown in figure 3.3c. The first and second terms form $u'_0$ in analogy with $u_0$ in Section 3.3 with the difference that the direction of the reference wave has been reversed.

The third term ($u'_{+1}$) represents the object wave $o^*(x,y)$ although the direction is angled by roughly $-2\delta$ due to the exponential function. According to figure 3.3c a virtual orthoscopic image is formed.

The fourth term ($u'_{-1}$) describes the conjugated object wave $o^*(x,y)$. This wave produces an image at the location where the object was originally placed. The image is real but pseudoscopic since it was generated with the conjugated wave. The reversal of the reconstruction wave therefore leads to a real pseudoscopic image which can be used as a new object in two-stage holography.

# 4. Experimental production of holograms

## 4.1. Laser sources and their characteristics

A laser is an adequate light source for hologram recording due to its unique properties, such as a high degree of monochromaticity, spatiotemporal coherence, brightness, directionality and, in some cases, its short temporal duration [85]. Various types of laser sources can be used in hologram production, operating either in a continuous wave (CW) or pulsed regime. Essentially, there are five types of solid-state laser technology which meet the need for long coherence length in order to produce holograms, namely: frequency-converted diode-pumped lasers (DPL or DPSS lasers), tunable frequency-converted CW optical parametric oscillators (OPOs), single-frequency and/or frequency-stabilized diode lasers, frequency-converted fiber lasers and pulsed solid-state lasers [22].

There are also gas lasers suitable for holography, namely helium-neon lasers, helium-cadmium lasers and argon or krypton ion lasers [86], although the latter are now considered obsolete technology. For our purposes, we work with a modern single-frequency frequency-doubled DPSS CW laser (CNI, model MSL-FN-532-50mW) at 532 nm (green), with 50 mW of output power and more than 50 m of coherence length.

## 4.2. Optical components and experimental details

For the production of holograms, we used two facilities: the Hololab at IFIMUP / Department of Physics of FCUP and the darkroom of the same institute, where hologram development was performed. Apart from an adequate laser source for hologram production, additional optical components are needed for the complete experimental setup. In this section we briefly describe the main characteristics and role of the main optical components we used in the production of holograms. In the first part of the thesis work, we opted to build a versatile setup capable of switching from a transmission hologram geometry (figure 4.1) to a reflection hologram geometry like in the case of figure 4.5. There is also one more setup of transmission holography for doing a holographic magnifying glass (figure 4.7).

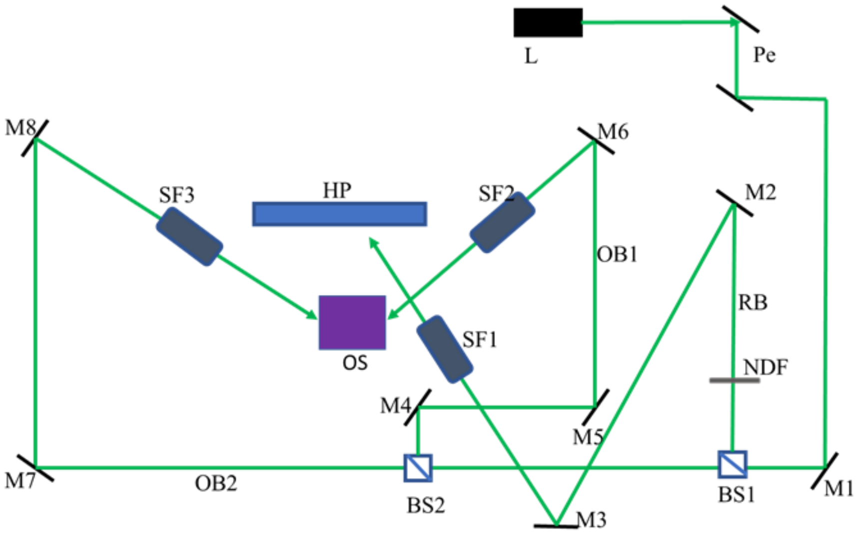



Figure 4.1: Multibeam transmission hologram setup. Laser source (L), Periscope (Pe), Mirrors (M), spatial filter (SF), reference beam (RB), object beam (OB), holographic plate (HP), Object scene (OS), beam splitters (BS) and neutral density filter (NDF). Our first object scene was a simple setup depicting a Michelson interferometer (MI) without source.

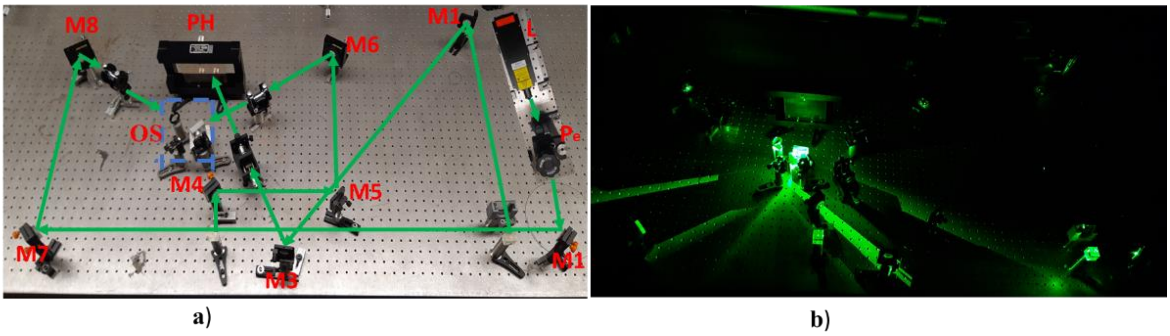



Figure 4.2: Images of the multi-beam transmission hologram setup, with laser off (a) and on (b) after recording/exposure and development procedures wherein PH is the plate holder with the holographic plate HP.

For the setup of figure 4.2, three spatial filters (equipped with microscope objectives and adequate pinholes), two neutral density filters and two beam splitters, BS1 (7/92 reflection/transmission) and BS2 (37/63 reflection/transmission), were used. The neutral density filter is used to reduce power during alignment. The reference beam was incident on the plate at the Brewster angle. A beam ratio of approximately 4:1 (reference:object) was obtained by adjusting the distances of the two spatial filters illuminating the object (SF2 and SF3). The holographic plate was an ultra-high-resolution silver-halide emulsion coated on glass (Ultimate 08) with a grain size of 8 nm, a resolution of >8000 lines/mm) and 4×5 inches in size. The sensitivity of these plates is around 100-200 $\mu J/cm^2$, which is a remarkably low value given the small grain size. The setups were built on a vibration-isolated optical table.

As our first object, we used a setup depicting a basic Michelson interferometer (figure 4.3) – a simple yet powerful optical device that can also be used to test the stability and detect potential vibrations in the optical setup itself.

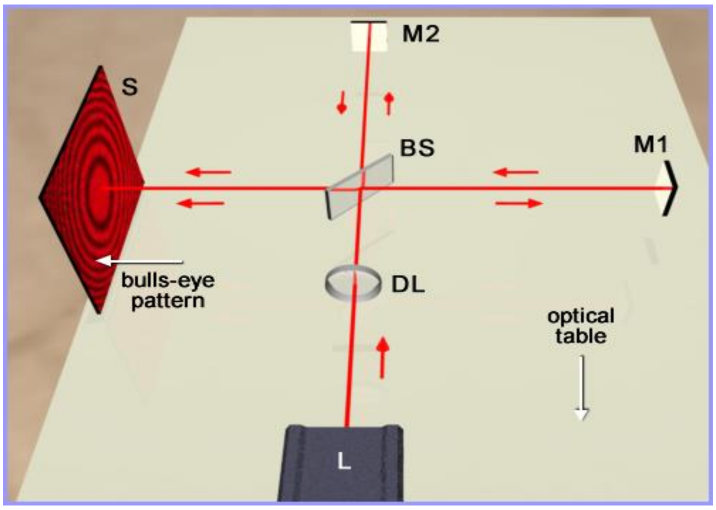
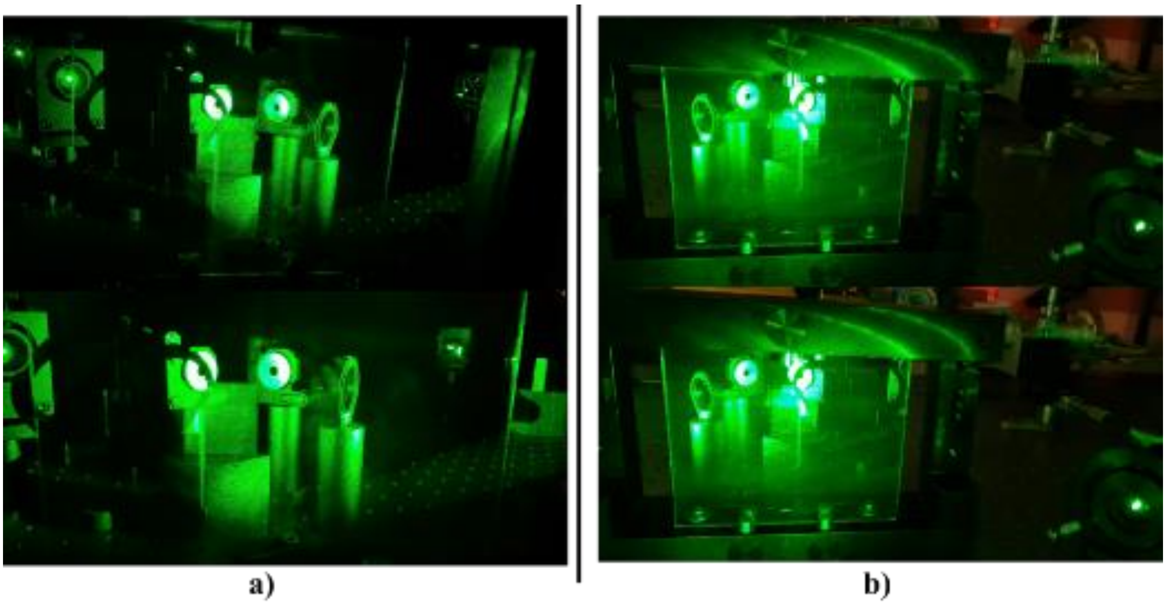



Figure 4.3: Basic Michelson interferometer for testing vibrations on optical table and optical components: laser (L), diverging lens (DL), beamsplitter (BS), mirrors (M1 & M2), and screen (S). Adapted from [25].

### 4.3. Production and replay of transmission holograms

The exposure time for the transmission hologram setup was 9 s, calculated from a total intensity (sum of reference and object beam intensities) of approximately $16\mu W/cm^2$, measured with a power meter head placed on the plane of the holographic plate holder. Processing of the exposed plate was performed in the darkroom under red safelight illumination and consisted of a proprietary developer followed by a rehalogenating bleach step, washing and drying, according to the recommendations of the plate manufacturer (for more details on the processing, see Ultimate Holography website: http://shop.ultimate-holography.com/img/cms/process%20et%20spécifications/processU08-en.pdf). The final holograms were very transparent, with very minor residual scattering, which is a good indication of correct exposure and development. The diffraction efficiency was also very high (by eye), as shown in Figure 4.4.

An image where light actually passes through it is called a real image; otherwise it is called a virtual image (like an image on a mirror). When a hologram is replayed, the virtual image is not the only image present. Figure 6 shows images of the obtained transmission hologram in two different reconstruction conditions: conjugate reference beam and normal reference beam, which produces real and virtual images of the original object, respectively. When the developed plate is returned to its original position, the holographic image is reconstructed by the reference/replay beam, and the virtual image appears in the exact position of the original object (figure 4.4b). In these conditions, the zero-order (transmitted) beam and the spurious real image (Figure 3.3a) are moved out of line, which is an important property of off-axis holography. Apart from the virtual-image beam and the undiffracted (zero-order) beam, there is a third beam diffracted toward the other side of the replay beam. This holographic image is on the viewer's side, and has some peculiar properties, namely it's pseudoscopic (i.e., concavities appear convex, and vice-versa). The real image can be projected on a target, or used as the object for making a second, or transfer, hologram [3] (as in the case of the holographic portrait of the President of the Portuguese Republic mentioned in the beginning of the Introduction, which is a second-generation reflection hologram made from a transmission hologram master).



a) b)

Figure 4.4: Real (a) and virtual (b) images of the reconstructed transmission hologram after development and exposure procedures. In (a) when the hologram is flipped the reconstruction beam becomes its conjugate, and a real (and pseudoscopic) image is formed that can be projected on a screen or photographed. In (b) when illuminated by the reconstruction beam, the image beam is a replica of the original object beam, so that the viewer sees a virtual image in the position of the original object.

## 4.4. Production and replay of reflection holograms

### 4.4.1. Single-beam reflection hologram

This is a particularly simple setup, as shown below. All it takes is a single beam that is transmitted by the plate and illuminates the object, which in turn provides the object beam.

The two beams impinge upon the plate from opposite sides, giving rise to a volume hologram composed of planes along the volume of the emulsion. This characteristic results in a Denisyuk-type hologram, where the resulting Bragg diffraction enables reconstructing the hologram using a broadband light source, such as a white bulb or a white LED.

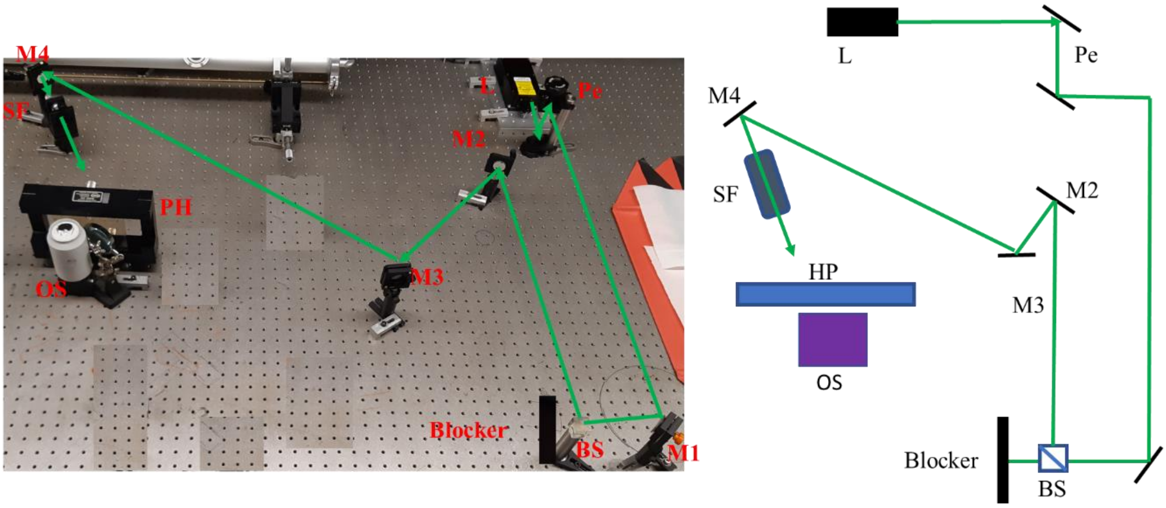



Figure 4.5: single-beam reflection hologram setup. Laser source (L), Periscope (Pe), Mirrors (M), spatial filter (SF), holographic plate (HP), Object scene (OS), beam splitters (BS) and neutral density filter (NDF). The object scene here was a beverage can (painted in white) and a magnifying glass.

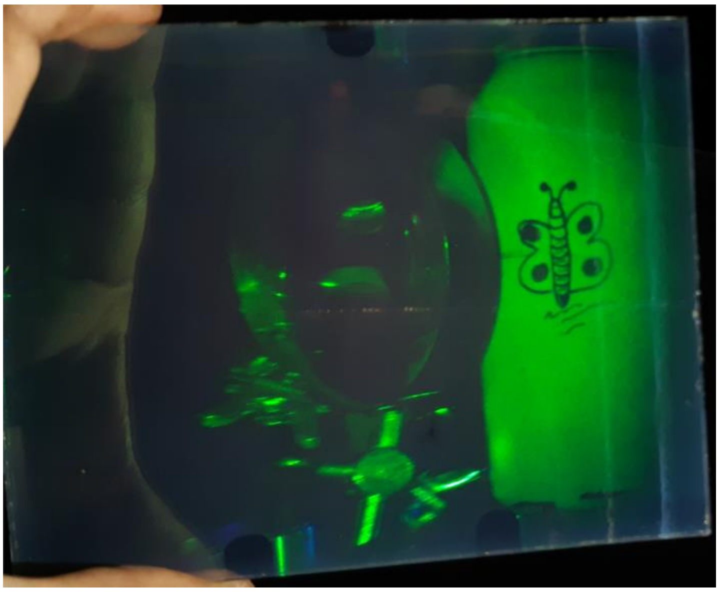


Figure 4.6. Image of the reconstructed single-beam reflection hologram.

The exposure time for this single-beam reflection hologram setup was 8 s, determined from a total intensity of approximately $18\mu W/cm^2$, measured with a power meter head placed on the plane of the holographic plate holder.

All processing of the exposed plates of all produced holograms with different arrangements were performed in the same darkroom under the same conditions as in the first case. As it can be seen from the image (figure 4.6.) the final hologram is very clear and with very little scattering, which gives a good indication of correct exposure and development.

#### 4.4.2. Holographic magnifying glass and holographic mirror

One of the most important applications of holography nowadays is to obtain holographic optical elements (HOEs) which are diffractive structures that are constructed holographically by the interference of two coherent beams of light. Typically, one beam resembles the playback beam that illuminates the HOE in the final system. The second beam corresponds to the image beam that is supposed to exit the HOE upon its playback [87], [88].

Transmission-type holograms relate to lenses, and reflection-type holograms (holographic mirrors) relate to mirrors. These holograms, besides being classified as transmission or reflection, are also classified as thin or volume and as absorption or phase holograms. The most striking characteristics of holograms as optical elements are that they strongly disperse light (usually a serious disadvantage) and that their optical configuration is independent of their substrate geometry. The disadvantage of high dispersion can be avoided using monochromatic sources or can be reduced, as in the case of holographic mirrors, since they can work simultaneously as monochromatic filters. Because of their independence from their substrates, they have found unique applications as holographic beam-splitter mirrors in head-up systems, in holographic notch filters, and in specific optical systems like the Pancake Window optical simulator [87], [88].

Holographic mirrors are optical elements that diffract light as conventional mirrors reflect light and they are volume-phase reflection-type holograms. The reflection is not a physical reflection effect, but light is diffracted by them in the same medium of incidence and they behave according to the laws of diffraction instead of reflection and can be used in optical configurations that are not achievable using conventional mirrors, enabling for instance to have produce a very thin device where the reflected light does not follow the usual laws of geometrical optics, e.g., the reflected ray does not have the same angle as the incident ray with respect to the surface of the holographic mirror.

#### 4.4.2.1. Production and replay of a magnifying glass hologram and of a holographic mirror

In this section, we made a transmission hologram of a magnifying glass (lens) and a reflection double holographic mirror (HM) with two reflection angles using multi-beam setups. This approach enabled understanding and illustrating the key differences between a hologram of a lens and a holographic mirror/lens in the HOE sense of the word.

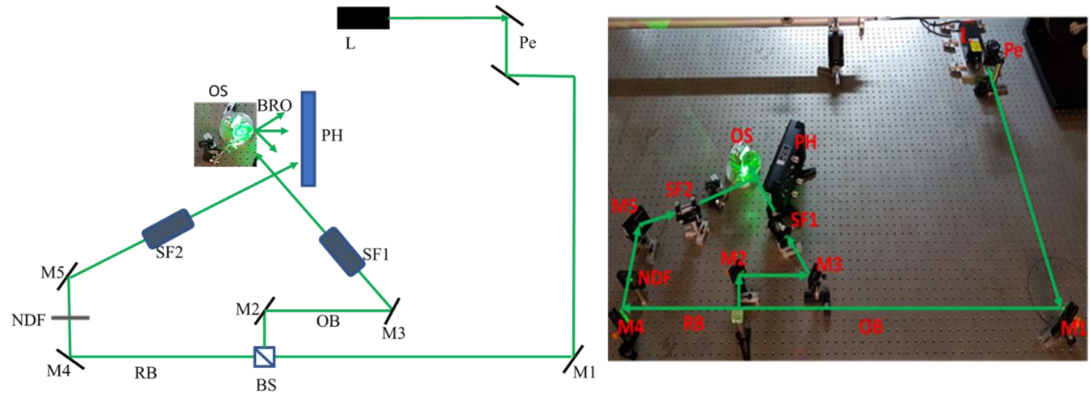



Figure 4.7: Multi-beam transmission hologram setup for a hologram of a lens. BRO is the beam reflected by the object. The object scene was a printed IFIMUP logo and a magnifying glass.

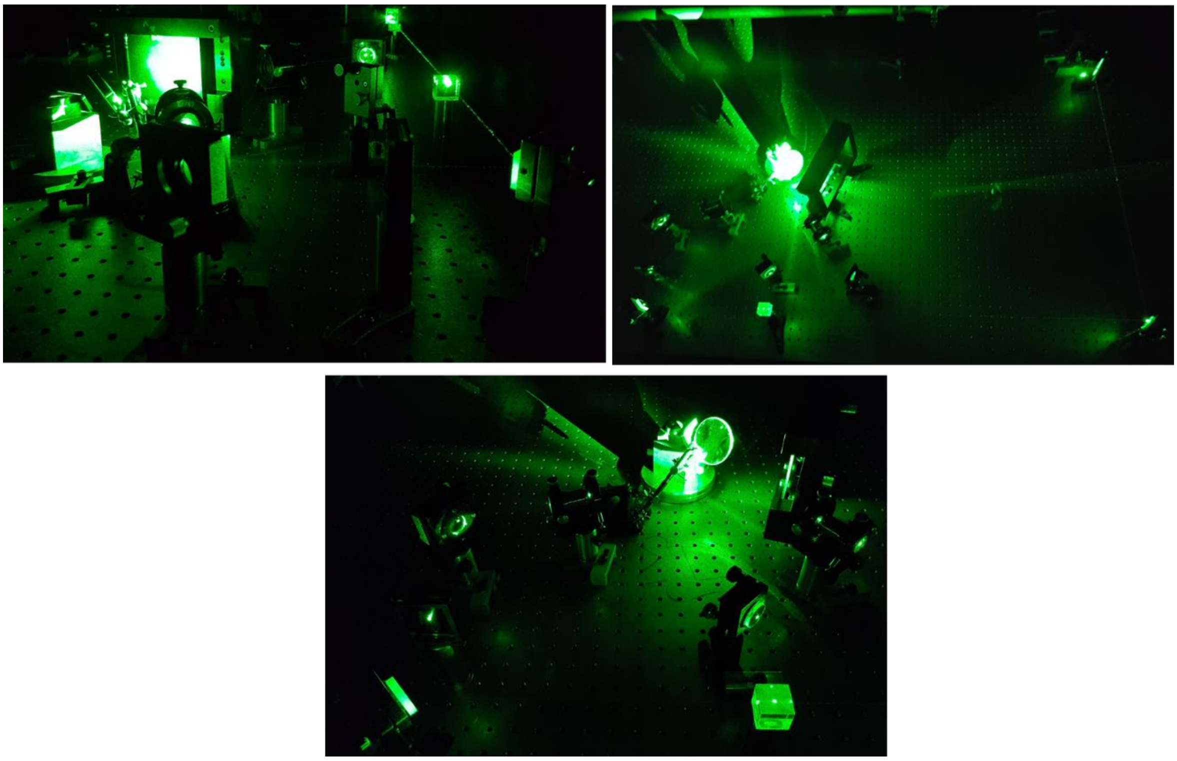


Figure 4.8: Illustrating images of the multi-beam transmission setup for the magnifying glass hologram with laser on and lab lights off.

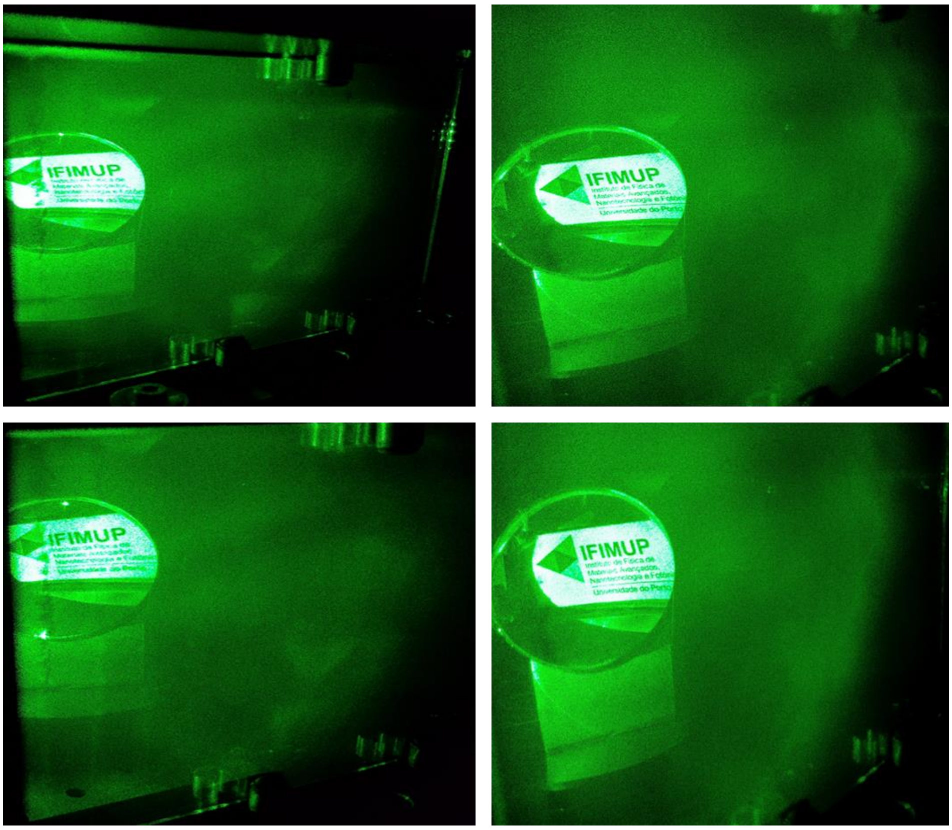



Figure 4.9: Virtual images of the reconstructed transmission hologram of a magnifying glass.

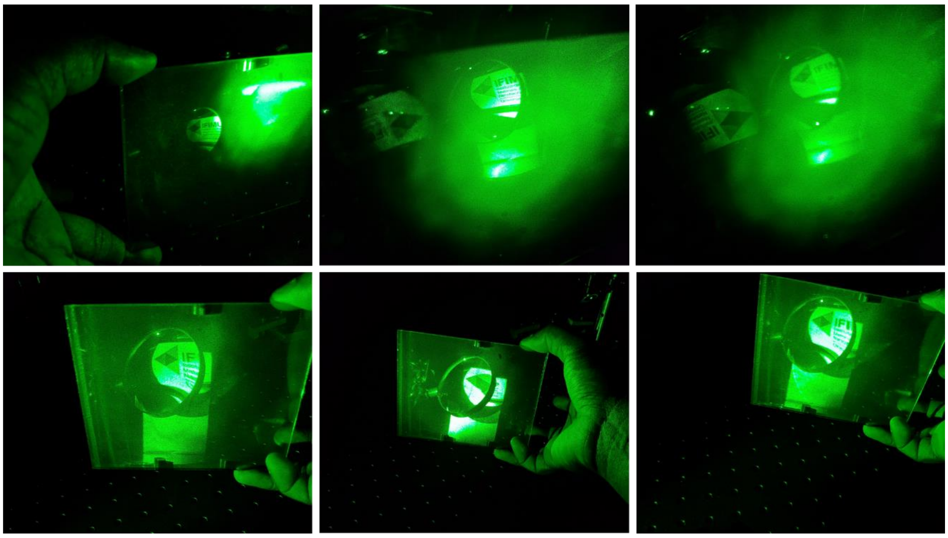


Figure 4.10: Real images of the reconstructed transmission hologram of a holographic magnifying glass, obtained by flipping the hologram in which the reconstruction beam becomes its conjugate which results in formation of a real (and pseudoscopic) image.

The development procedures of all exposed holograms are the same described in section 4.3. The exposure time for the hologram of a lens was 10 s, determined from a total intensity of approximately $25\mu W/cm^2$, measured with the same power meter head placed on the plane of the holographic plate holder; one beam splitter (38/62 ref./trans.) was used. From figure 4.9 it is possible to see how different positions of the logo are magnified while the hologram is rotated during the reconstruction (or when the viewpoint is changed). The same happens in figure 4.10.

We must point out that the hologram of a lens is not a HOE lens/mirror, since it can only magnify the object that was present during the recording. For producing a HOE, no real object is used, and the beams must be set up in order to produce the desired type of component. The setup for producing the double-angle holographic mirror is given below.

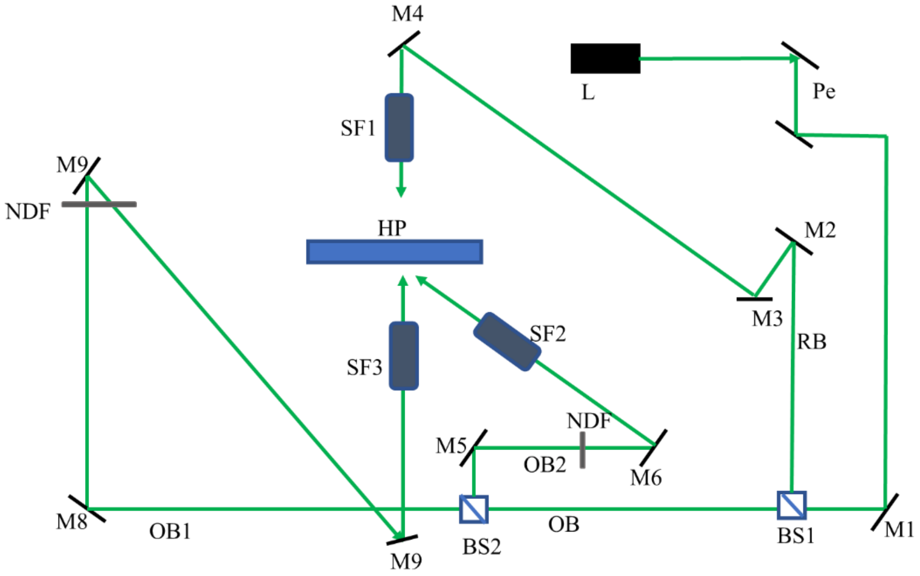



Figure 4.11: Multi-beam setup for a dual-angle holographic mirror. In this case, there is no object and three direct beams impinge upon the holographic plate, producing two reflection holographic mirrors in the same plate, as well as a spurious transmission hologram (holographic diffraction grating) due to the two “object” beams, in spite of their low intensity (1/4) compared to the reference beam.

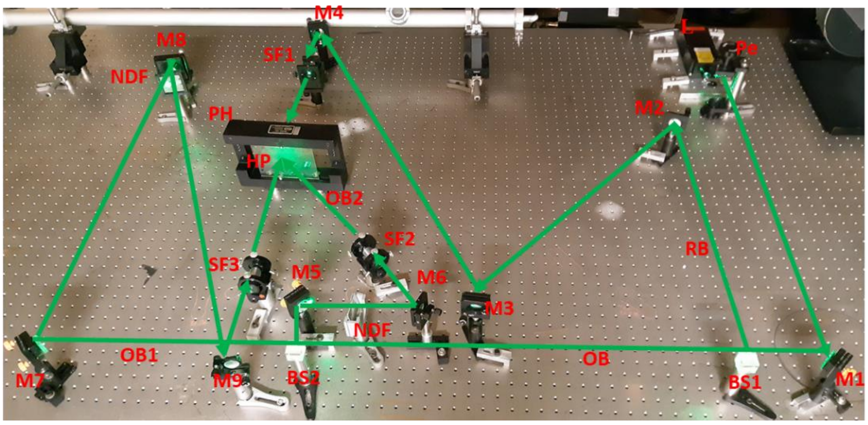



Figure 4.12: Image of multi-beam reflection hologram setup for a dual-angle holographic mirror.

For the double-angle holographic mirror, the exposure time was 8 s for an intensity of $29\mu W/cm^2$. We used a beam ratio of 4:1 between the reference beam and the two “object” beams (like in the setup of Fig. 4.2) but in this setup we used three neutral density filters to adjust the ratios and kept the same two beam splitters BS1 and BS2. The holographic plates were again ultra-high-resolution silver-halide emulsion coated on glass (Ultimate 08). The behavior of the mirror is depicted in Fig. 4.13 below.

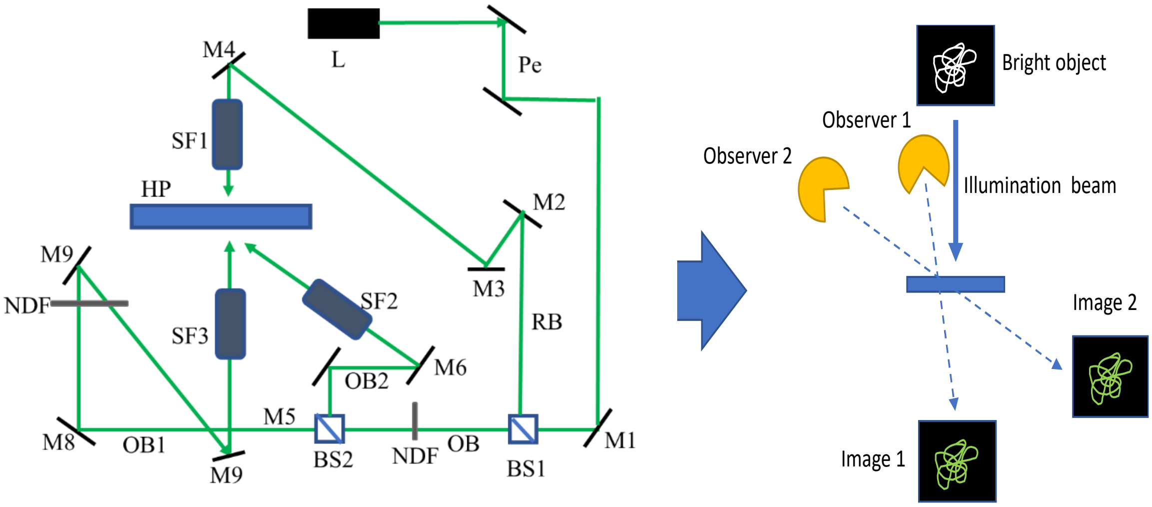



Figure 4.13: Behavior of the double-angle holographic mirror: from the setup of Fig. 4.11 (left), this holographic mirror will produce two images of a bright object than can be seen from two different angles by an observer (or camera) placed between the object and the holographic mirror.

This mirror produces two images: a first image (Image 1 in Fig. 4.13) can be seen at approximately 0 degrees (like in a normal mirror) that obeys the laws of geometrical optics; a second image (Image 2) appears when looking along the angle defined by the second "object" beam in the setup (Fig. 4.13, left), so the incidence and reflection angles are different in this case. The obtained images are shown in Figs. 4.14 and 4.15 below.

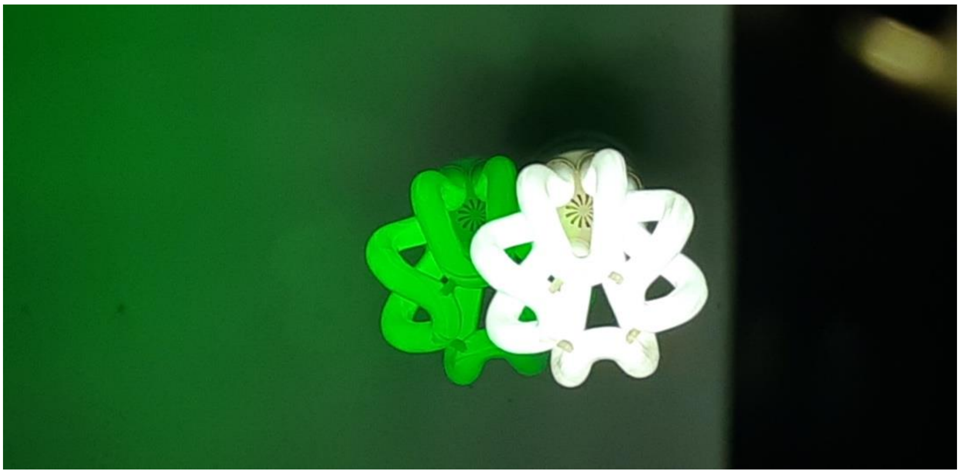


Figure 4.14: Photograph of the first image (Image 1 in Fig. 4.13) from the holographic mirror. The mirror produces a green image due to its color-selective nature. The bright white image is the partial

reflection of the object (a fluorescent lightbulb) in the glass, and appears superimposed on its holographic counterpart.

Figure 4.15: Photograph of the second image (Image 2 in Fig. 4.13), viewed at an angle with respect to the holographic plate. In this case, the green image of the object produced by the holographic mirror is totally separated from the partial reflection of the object in the glass, since it does not obey the ordinary laws of geometric optics with respect to the plane defined by the glass plate.

As a side note, replaying the holographic mirror with the original reference beam from the laser shows a spurious reflection hologram of the optical elements used in the setup (Fig. 4.16), since they end up illuminated by the reference beam, creating an additional Denisyuk recording. All mentioned spurious recordings contribute to reducing the overall efficiency of the HOE, and could be eliminated by using a purely off-axis geometry.

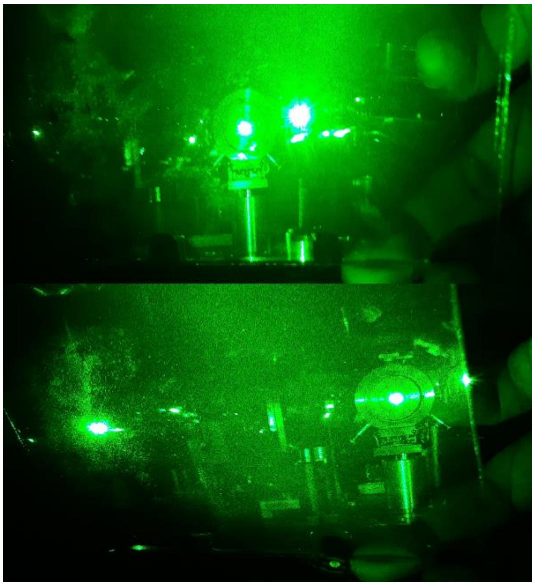


Figure 4.16: Spurious reflection holograms also recorded in the double-angle holographic mirror

### 4.4.3. Double exposure holographic Interferometry

Holographic interferometry (HI) is a technique by which microscopic changes of static and dynamic objects can be measured, e.g., by making two exposures (two holograms) of the same object in the same holographic plate. The two holographic images interfere with each other and fringes can be seen (figure 4.18, right). The two waves are from two different states of the object, one corresponding to the initial state (unstressed or stressed) and the other to the final state (stressed or unstressed). Interference phenomena, due to changes in optical path length between the two exposures, are produced when the doubly exposed hologram is reconstructed [89]. This technique consists of a holographic arrangement using a laser source for the illumination. Various kinds of HI have been developed, namely: real-time, double-exposure, and time-averaged HI. For our purpose, we made a double-exposure hologram to determine the deformation of a static object (a beverage can as object scene) caused by a rubber band placed around it. HI can be performed with one, two, or more reference waves, with the same or with different wavelengths [90].

The double-exposure technique is one of the most fundamental among other holographic interferometry techniques. When the resulting holographic interferogram is replayed, the fringe pattern (figure 4.18, right) appears superimposed as a function of the displacement/deformation (figure 4.19, left).

The main quantity used in holographic interferometry is the difference in the optical path lengths (eq. 4.2) [91] at an arbitrary point in the two exposures. The basic relation assigns this quantity either to the displacement (in case of the deformation of an opaque object) or to the path-integrated refractive index change (in case of a transparent medium) is shown in eq. 4.1. The determination of the deformation (eq. 4.1) of an opaque body by holographic interferometry is the most important engineering application in this area, since it pertains to methods of non-destructive testing. To determine the deformation of an opaque object in the double exposure technique, which find use in non-destructive testing of materials [92], we just have to count the number of dark fringes from each point where the object was deformed. To determine the amount of deformation in the double exposure technique let use the equation,

$$D_i = \frac{\lambda N_i}{(\cos\alpha + \cos\beta)} \tag{4.1}$$

where $\alpha$ is the object beam angle relative to the center of the hologram on the holographic plate holder which is of $45^0$ and $\beta$ is the viewing angle perpendicular to the hologram and is of $0^0$. $N_i$ is the fringe order number and $\lambda$ is the wavelength used during the recording. With $\alpha = 45^0$, $\beta = 0^0$ and $\lambda = 532\ nm$ the equation 4.1, can be reduced to:

$$D_i \cong (0.312\ \mu m) \times N_i \tag{4.2}$$

In this process, the exposure times are assumed to be equal for each exposure. HI techniques are also applied to measure strain, in general non-destructive testing, radiation dosimetry and vibration analysis [93] .

With minor changes and adjustments in the setup of figure 4.1 and with the insertion of one more NDF between M5 and M6 we made a double-exposure hologram using a beverage can as our object scene. The total exposure time was 8 s (4 s for each exposure) and the total intensity was approximately $15\mu W/cm^2$ with a beam ratio of 4:1 (reference : object). For the first exposure the object was unstressed and for the second exposure a rubber band was used to stress the object. After recording and replaying the hologram, a plot showing the deformation of the can was made (fig.4.19 and fig.4.20). To calculate the deformation suffered by the object due to the use of rubber band, we counted the number of dark zone (dark fringes) at each point where the object was deformed the equation 4.2 was used. The smaller the less pixels the smaller deformation at points where the object was stressed by the rubber band (fig.4.19 and fig.4.20). The image of the resulting double-exposure hologram in figure 4.18 (on the right hand side) shows high diffraction efficiency which means that all exposure and processing was well performed. The percentage of reflection/transmission light by the two beam splitters was kept and equal to the case of the setup of figure 4.1.

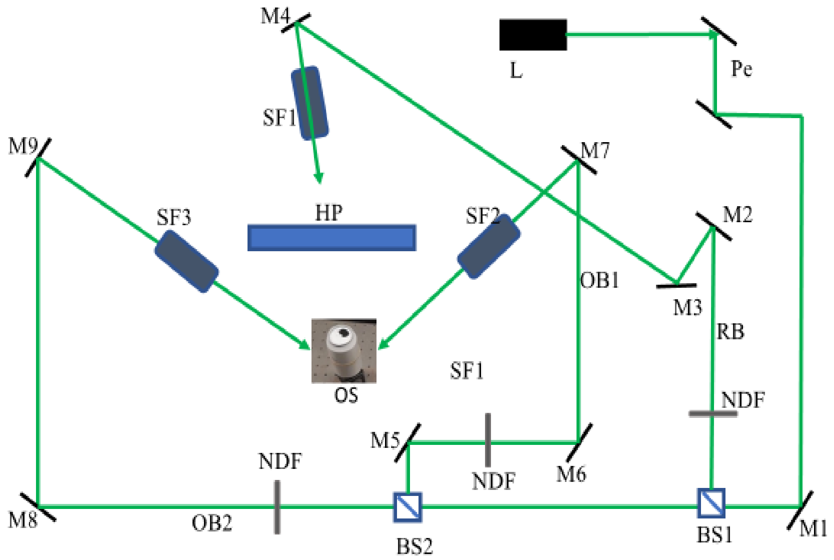



Figure 4.17: Multibeam Reflection hologram setup for double-exposure holographic interferogram. Laser source (L), Periscope (Pe), Mirrors (M), spatial filter (SF), reference beam (RB), object beam (OB), holographic plate (HP), Object scene (OS), beam splitters (BS) and neutral density filter (NDF).

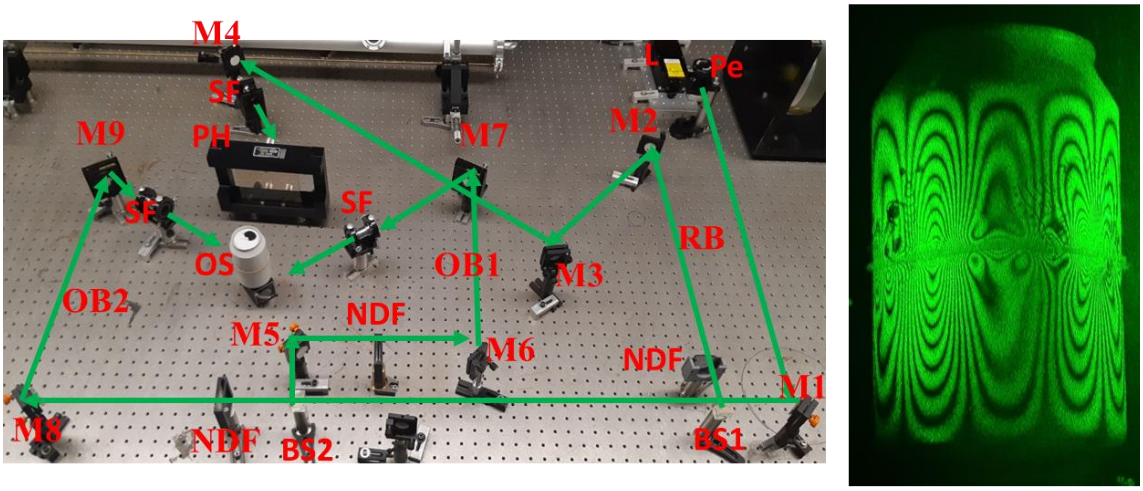



Figure 4.18: Image of multibeam reflection hologram setup for double-exposure holographic interferogram (left) and the reconstructed hologram (right).

From the interferogram on the right hand-side of fig.4.18, we choice three point (**A**, **B** and **C**) to calculate the deformation suffered by the beverage can due to the stress caused by the rubber band and using eq.4.2.

On point **A,** the deformation is zero ($D_A = 0$) and we choice this point as our reference point to determine the amount of deformation in other two points which results on $D_B \cong 5.0\mu m$ for point B and $D_C \cong 5.6\mu m$ for point C.

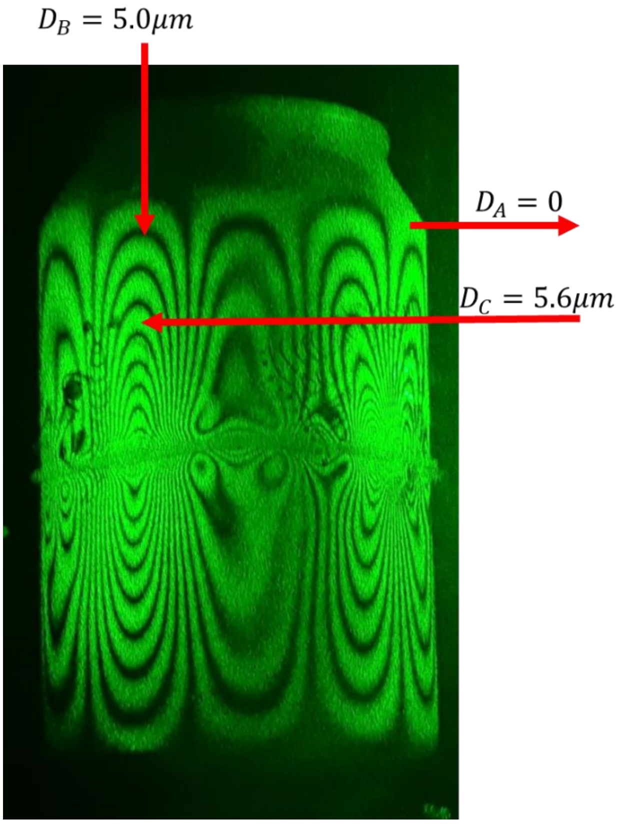



Figure 4.19: Deformation at points **A, B** and **C**

# 5. Holography in the context of Physics teaching

## 5.1. Holography as a pedagogical tool for the teaching of Physics

Lasers are an essential tool in the process of producing holograms. We would first like to ask how holography can be used as a pedagogical tool for the teaching of physics. Like in other scientific disciplines, the nature of light is important and has a long history in science and technology. Holography is a subject that, from the physics viewpoint, fits into the context of modern and applied physics. Modern physics is a curricular discipline in the Angolan physics undergraduate course and there are contents about the interaction of light with matter and also on the interference and diffraction of light. However, experiments to explain these phenomena, consequences and other physical properties of light are not performed to ensure the proper understanding and consolidation of the subjects. In the context of optics, the production of holograms will encourage and motivate the teaching of optical physics, which is not taught in undergraduate physics courses at my faculty in Angola. Geometric optics is taught without any reference to the wavelike properties of light and without any use of lasers. Interferometry is not taught in any undergraduate level in Physics. This makes it very difficult to understand different phenomena that involve light interaction with matter and, when faced with scientific literature in the field of modern and coherent optics, students are not able to understand it.

The impact of holography as a teaching tool has been analyzed in several works. One expectation is  that in the future, various learning environments (school, clinical and public), systems (direct, emergent and augmented reality) and telecommunication devices (computers, tablets, cellphones, TV) will be used to measure the short and long-term effects of using holograms as teaching agents for learners of all ages [94] while it is becoming a fundamental tool for the teaching of different areas of science [8] due to its capability of producing 3D images. Holography can also be used to accomplish experimental classes if included in the program of laboratory classes and/or optics courses.

Using holography for the teaching of physics will give the possibility of introducing undergraduate physics student to the basic principles of applied optics and photonics and to learn more about light phenomena and to make some measurements that can only be made using holographic/optical principles, which also has implications for the industrial development of my country.

### 5.2. Pedagogical implications of Holography

What benefits can be taken from holography? In what physical contents can holography make an impact in undergraduate physics students? As mentioned previously, holography can link the student's theoretical classes about interference and diffraction phenomena with experiments, hence highlighting the mathematical concepts behind these phenomena [95]. In addition, holography can raise public awareness to the fields of science, technology, engineering and mathematics (STEM). The work of Orcos and Magreñán [13] assessed the use of a hologram in enhancing the meaningful learning of cellular division contents and found that holography has great potential in the classrooms and in the creation of collaborative work environments from a constructivist point of view. Science concepts have to be taught in such a way that arouses the interest of students and provides a deeper understanding that enables solving real-world problems. STEM pedagogical methodology in the classroom is crucial as it aims to approach interdisciplinary learning based on problem solving. This type of methodology brings important benefits when carried out in an appropriate way, since it allows transferring the knowledge and skills of the student to the real world in which they live [13].

The pedagogical implications of holography range from the deepening of students' knowledge to the diversification of teaching of modern physics teaching and the motivation of students to continue their studies in the area of physical sciences and engineering. The students themselves may, through their own financial resources, acquire inexpensive material to produce their own holograms, beyond the formal laboratory activities within a course. For example, in the manual by Unterseher [96] there are many suggestions of holographic setups that can be carried out without the need of expensive equipment, and there are many examples of amateur holographers around the world that have developed their own holographic studios.

## 6. Conclusion and perspective

With the aim of encouraging undergraduate physics students in Angola and to motivate the inclusion of optical physics in undergraduate physics courses and to illustrate potential applications in several fields, we worked on the production of holograms to explore the phenomena of interference and diffraction of light as well as the interaction of light with matter. With this project, the teaching of interferometry is recommended in order to link the phenomena of interference, diffraction and interaction of light waves in applied optics and photonics. Several types of holograms produced by different arrangements, forming a solid ground for developing many of the ideas further and for creating simpler and less expensive setups within the reach of schools in Angola. It will be possible to use it for the teaching of some physics contents if included in laboratory experiment classes. And we believe that the implementation of optical physics and interferometry experiments in Angolan physics undergraduate courses has strong potential in encouraging students to enroll in the study of physics and to pursue further work in optics.

In future, apart from the teaching applications, I expect to work on holographic techniques for medical applications combining it with spectroscopic methods for detecting and treatment of cancerous diseases.

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