I learned it through the hologram

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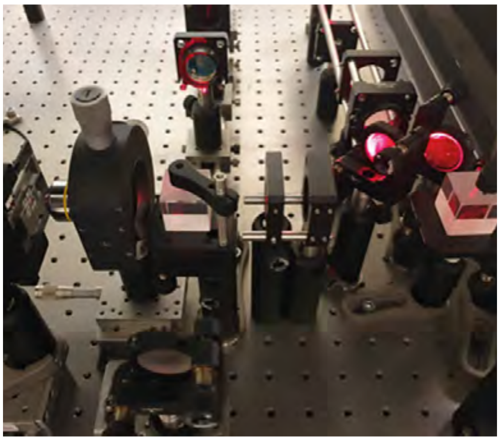

Holography is an advanced coherent imaging technique that records and reproduces 3D images using the principles of interference and diffraction. It finds numerous applications in fields such as biomedicine, engineering, art, and microscopy. Teaching holography at university provides students with a unique opportunity to learn more about optical physics. Moreover, it fosters creativity and innovation, as students can explore the potential of Digital Holography for their own future research.

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The generation of three-dimensional images remains one of the major challenges of advanced imaging techniques today, even though holography, invented by Denis Gabor in 1948 (Nobel Prize in Physics 1971), is one of the leading approaches in this field. Holography is a powerful coherent imaging technique that can record and reproduce 3D images with stunning detail and realism. Unlike traditional photography, which captures only a 2D representation of a scene, holography allows us to capture the full depth and complexity of the visual world. Holography is based on the principles of interference and diffraction, which describe how light waves interact with each other to create complex fringe patterns up to nanoscale. The Optics Department of the FEMTO-ST Institute at the University of Franche-Comté in Besançon, France, is one of the laboratories that pioneered laser manufacturing and holography techniques in the early 1960s [1]. These achievements were made possible in part by P.M. Duffieux, who founded the Optics laboratory in Besançon, and who is recognized as one of the pioneers of modern optics thanks to his book on Fourier optics which was published in 1946 [2]. Duffieux laid the foundations of an extensive series of activities within the French research community that have touched on nearly every aspect of contemporary optics and photonics, such as optical information processing, digital holography, and optical computing.

Digital holography (DH) is a modern form of holography that uses solid-state cameras and/or 2D digital display to record or reconstruct images in phase and in amplitude. DH offers several advantages over classical holography to carry out laboratory experiments, including greater speed, sensitivity, and the added flexibility associated with digital processing. DH is therefore an extraordinary means of getting students to perform a wide variety of experiments related to advanced optical instrumentation and complex image formation.

Overall, holography and DH are powerful imaging techniques with wide-ranging applications in areas such as advanced microscopy and in high-performance display technologies for screens. As technology continues to evolve and improve, holography constitutes an extraordinary means to teach and •••

illustrate photonics concepts and computational imaging to undergraduate and graduate student in physics. Therefore, at the University of Franche-Comté, the Physics undergraduate programmes continue to include the concepts of classical holography within the Fourier optics course. This then allows the introduction at master's degree level of the principles of DH and advanced unconventional imaging, through practical and project-based learning. Students are also involved in outreach and exhibition designing with artists in visual art where holography techniques are also implemented [3].

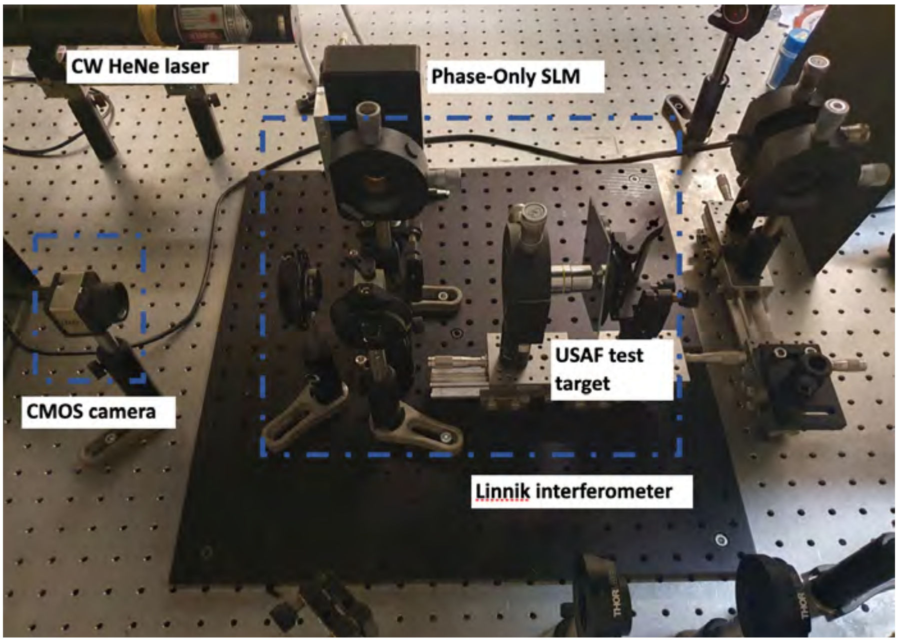
Theoretical background and basic concept in holography with undergraduate students

The theoretical approach used to introduce holography can begin from different points of view depending on the background of the students in a class. For students without a solid background in mathematics and physics, it is usual to emphasize the Huygens-Fresnel principle and to write this principle in a mathematical form, namely that the diffracted field at a point M in space is estimated from a sum of secondary spherical waves weighted by the amplitude of the initial field A(P) and an obliquity term K(P). Here P are points on the wavefront, k the norm of the wave vector, and r is the distance between points P and M:

$$A(M) \propto \int_{wavefront} \frac{e^{ikr}}{r} K(P) A(P) dP \qquad (1)$$

For more mathematically inclined students, the demonstration of the diffraction integral in the framework of Helmholtz-Kirchhoff theory allows the application of Green's theorem and works on the formal limits of the diffraction integral.
Another starting point is the angular spectrum method, expanding a wave field into a sum of infinite plane waves of the same optical frequency (the monochromatic condition) and different directions (angular frequency). This point of view allows us to propose a framework where the Fourier transform (FT) in two dimensions (2D) - generally approached mathematically - becomes a tool directly related to the physical properties of the waves and involved in the formation of an image. It allows the introduction of the free space transfer function and the usual convolution tools used in the field of linear filtering [4]. The propagation then becomes a convolution between the initial field and the 2D FT of the free space transfer function [5]. This formalism constitutes a robust approach to teach DH and its applications.

Figure 1. Example of a digital holographic microscope setup in a Linnik configuration.



Digital holography and advanced instrumentation with graduate students

DH can be presented as a lensless computational coherent imaging method that consists of displaying a volume image (using *e.g.* a spatial light modulator) or recording the optical wave diffracted by an object onto a sensor [6]. The diffracted field from the object can be computed numerically to display a computer-generated hologram on the spatial light modulator, but it can also be reconstructed numerically by back-propagation of the recorded wavefront from a digital hologram registered by a solid-state camera. Off-axis or in-line configurations are typical geometries for DH depending on the targeted applications. Off-axis DH provides a simple way to overcome the drawbacks of the twin image superposition and DC term. To record a digital off-axis hologram onto a 2D sensor, an interferometer is required, and it offers the advantage of a single frame acquisition. In-line configuration allows to display or to record a Gabor hologram thanks to a simplified arrangement, but complex image processing is necessary to remove the DC term, and the twin image mixing. Multi-frame acquisition is also possible

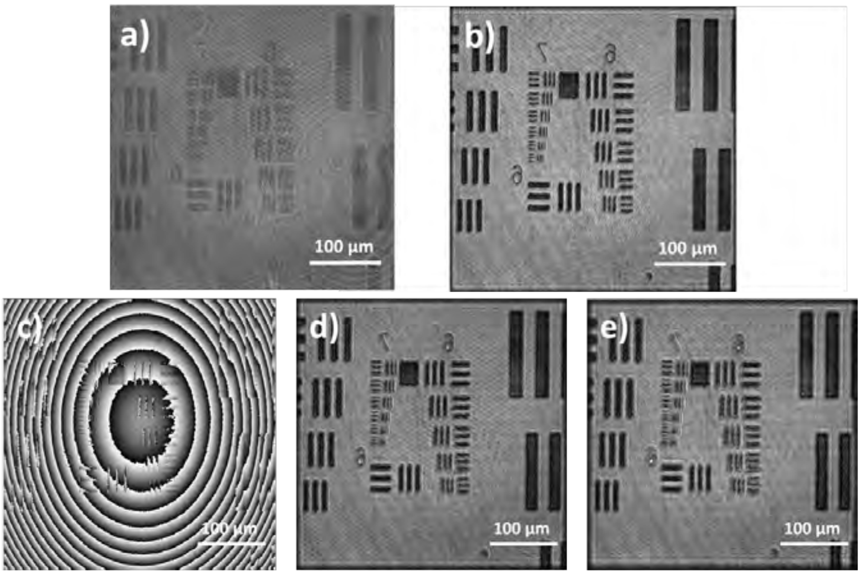
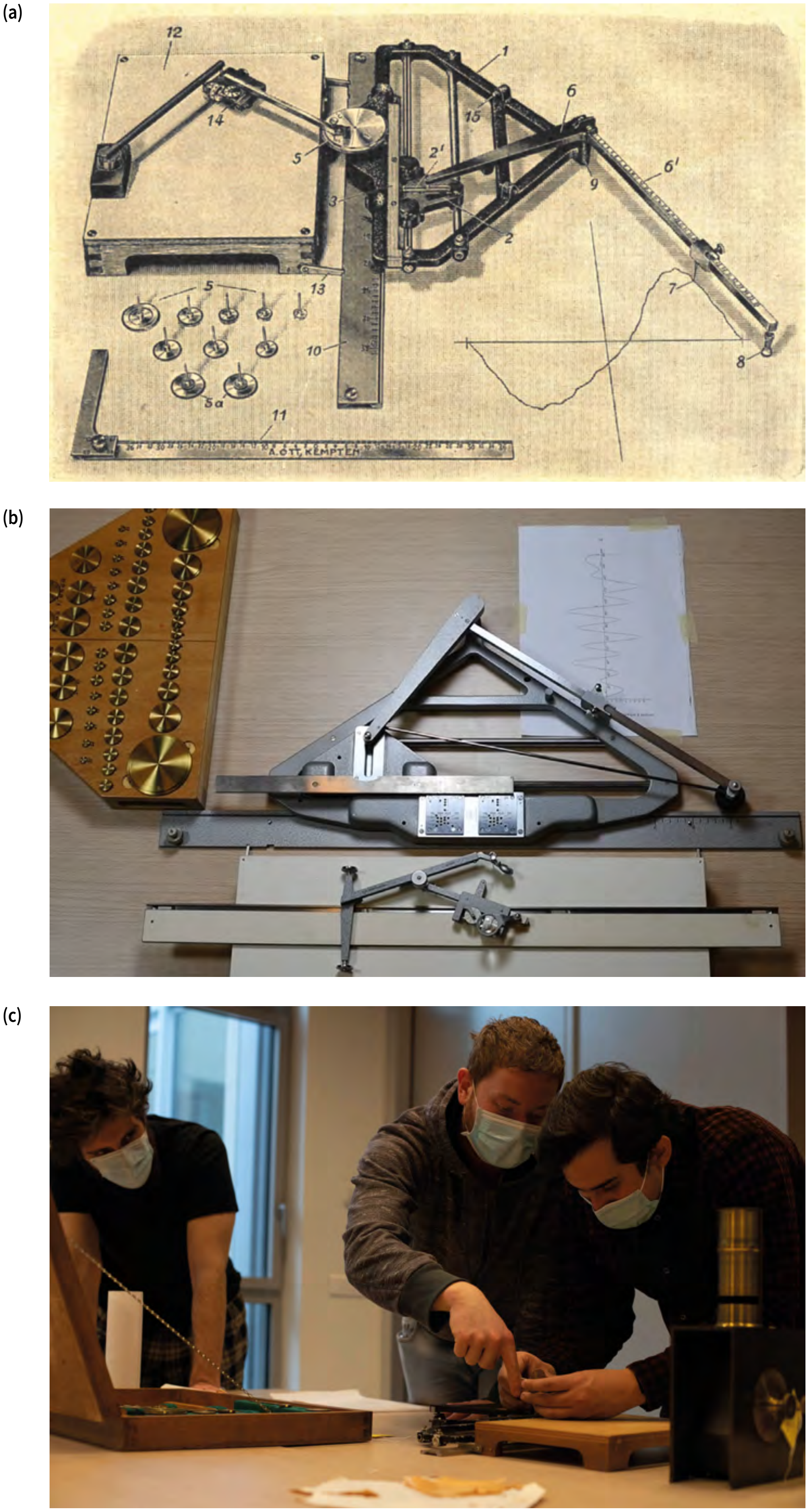


Figure 2. a) Example of a Digital hologram registered with a DHM set-up. In focus image restitution of an USAF test target at a distance of 81 µm b) in amplitude c) in phase, with spherical aberrations. Defocus images reconstructed at distances of d) 121 µm and e) 161 µm.

with in-line DH to overcome this issue by using a phase-shifting approach, but it requires a static object. Of course, when micro-scale objects are studied, microscope objective lenses are used to realize a Digital Holographic Microscope (DHM). For the past ten years at the University of Franche-Comté, various digital holographic set-ups have been developed with graduate students as part of a class devoted to advanced optical instrumentation, but also during individual laboratory immersion projects set up as part of the EIPHI Graduate School. The objective is to teach students two-dimensional optical metrology through structured light methods and/or interferometric approaches such as holography or interferometry. The concepts of physical optics are studied in combination with the principles of information theory and digital image processing, numerical modelling of the propagation of the diffracted light field in free space. These studies involve considering limitations imposed by the instrumentation and devices used, such as the physical size and number of pixels of a camera or spatial light modulator, but also challenges in DH such as numerical autofocusing or phase contrast imaging. The research immersion project in the master's programme complements the teaching in order to ensure that the students are effectively trained in the skills targeted by the courses. It also allows an opening to research carried out within the Optics department of the FEMTO-ST Institute. These DH set-ups also illustrate experiments resulting from research carried out at FEMTO-ST in DH [7] and in spatial shaping of complex Bessel-type or accelerating laser beams [1].

For each new academic year, a different DH setup can be proposed to the students to be studied, modeled and associated with a specific application in microscopy, optical metrology or laser beam shaping. The first step for the students is to design the numerical simulation programs using the angular spectrum method (ASM) or the Fresnel diffraction approach. The second step consists of applying the codes to various configurations of the experimental holographic setup to be realized, and working with experimental digital holograms. Figure 1 shows a typical setup for a DHM in an off-axis configuration, with a reference beam dynamically driven by a phase-only spatial light modulator (SLM). Hologram acquisition is performed on a 5Mp CMOS 2D sensor using a Linnink interferometer. The objects studied are of millimetre to micrometre



size. The amplitude and phase restitution of the image is numerical (Figure 2b and c). It is shown that this process allows the measurement of optical path differences with resolutions of up to ten nanometres. The insertion of an addressable element (SLM) in the setup gives great flexibility for the main reason that a dynamic correction of the wavefront can be applied. In this context, this dynamic digital holography bench is a great pedagogical tool for master students to explore the potentialities of computational imaging, to explain dynamic aberration correction or digital autofocusing in automated microscopy.

A key-point of DH for students to learn is to note that, instead of an image of the object, it is the propagating wavefront incident on the image sensor that is recorded (see Figure 2a). The distance of the object does not impact the recording quality, it only changes the recorded wavefront. The object distance represents a computation parameter that is numerically tunable over an extended range (Figure 2b, d, e). This specificity makes the range of working distances allowed by DH much larger than that allowed by usual refractive imaging devices. The reconstruction distance leading to the optimally-focused image has to be determined for each position of the object along the z-axis. There are various techniques for defining image-formation sharpness-criteria that apply to DH [7]. One advantage of DH is to provide numerical autofocusing without any mechanical displacements. Overall, students readily appreciate the great

Figure 3. The Mader-Ott Harmonic Analyser used from 1909 to 1960. a) Illustration of how the harmonic analyzer works. b) Mader-Ott Harmonic Analyser from Optics department lab collection, FEMTO-ST Institute, Besançon. c) Master students from graduate school EIPHI during labwork with the harmonic analyzer.

potential of DH to generate or record an image, and learn that quantitative information can also be extracted from the phase image for 3D optical profilometry for example.

Early instruments from lab collection for active learning with graduate students

As already mentioned, a well-known approach to describe the physics behind holography is via the angular spectrum method. This elegant and mathematically simple approach considers that an intensity distribution at a plane is the result of the interference of an infinite number of plane waves of different orientations and phases (Equation (1)). The calculation of these different plane waves uses Fourier methods, but unfortunately, the Fourier transform remains sometimes mathematically abstract for students. Yet when Joseph Fourier developed his harmonic analysis in the 19th century, he saw it as a simplification of complex physical problems involving periodic signals. Many analogue analysers were then rapidly developed, including the Mader-Ott from the early 20th century. We are fortunate to have one of these historical instruments in the optics department of FEMTO-ST (Figure 3). As part of an art and science project in the first year of the masters' programme in 2021-2022, we offered students the opportunity to rediscover the history and operation of this instrument, and how to highlight this with the help of an artist affiliated to the laboratory. During four days, they managed to make it work from scratch and link it to the history of harmonic analysis. The feedback received was clearly that working with such a hands-on analogue instrument greatly improves their intuitive understanding of the Fourier transform.

Conclusion

Physical optics constitutes a large part of undergraduate and graduate physics. As a result, it is sometimes difficult for students to assimilate the wide variety of concepts covered and the multitude of associated experiments. This is why themes such as holography give meaning and motivation to students around a wide variety of topics: 3D imaging and optical instrumentation, coherence of a source, optical information processing and the scalar diffraction theory. An equally important aspect of our students' training is their ability to perform experiments based on theoretical concepts. It also involves interpreting the results obtained and comparing them with the results of numerical simulations. ●

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