Introduction

Holography was invented in 1947 by the Hungarian physicist Dennis Gabor during his research into electronic microscopy [GAB 48, GAB 49]. This invention won him the Nobel Prize in physics in 1971. It took until 1962 [LEI 62, LEI 61, DEN 62, DEN 63] for the first lasers used for this technique to find concrete applications [POW 65, COL 71]. Holography is a productive mix of interference and diffraction. Interference encodes the amplitude and relief of a 3D object, and diffraction works as a decoder, reconstructing a wave that seems to come from the object that was originally illuminated [FRA 69]. This encoding contains all the information on a given scene: amplitude and phase – thus relief. Practically, the execution of a "Denisyuk" type [DEN 62, DEN 63] "analog" hologram is carried out in three steps: the first step concerns the recording of the interference pattern on a photosensitive support, typically a plate of silver gelatin; the second step involves the chemical process of development/treatment of the support (which typically lasts around a quarter of an hour with silver gelatin plates); and the last step is the process of the physical reconstruction of the object wave, where the laser is diffracted by the sinusoidal grating encoded in the photosensitive support, making the initial object "magically" appear. The magic of holography is explained by wave optics [GOO 72, BOR 99, COL 71, HAR 02, HAR 06]. Considering the constraints involved in the treatment of holograms (an essential stage of their development), which make their industrial use difficult for quality control in production lines, for example [SMI 94], the replacement of the silver support by a matrix of the discrete values of the hologram was envisaged in 1967 [GOO 67]. The idea was to replace the analog recording/decoding by a digital recording/decoding simulating diffraction by a digital grating. Holography thus became "digital" [HUA 71, KRO 72]. The attempts of the time suffered from a crucial lack of technological means permitting the recording of holograms while respecting sampling conditions and allowing the reconstruction of the diffracted field with a reasonable calculation time. From the 1970s up to the 1990s we witnessed a veritable boom of holography, as much from the point of view of applications [JON 89, RAS 94, SMI 94, KRE 96], as from the holography of art [GEN 00, GEN 08]. Some industrial systems based on dynamic holography are even currently commercialized [OPT 11]. The material used for the recording is a photoreactive crystal [TIZ 82]. Nevertheless, the difficulty of the treatment of the holograms and the relative complexity of the devices have impeded a real industrial penetration of the methods developed in the laboratory in the past 30 years. In parallel, at the same time, we witnessed the development of interferometry techniques (Twyman–Green and Fizeau interferometry) for the control of optical surfaces using phase-shifting methods [WYA 75, CRE 88, DOR 99]. The reader will notice that in the literature several terms have been used to describe "holography", often among which is the term "interferometry". With the advent of image sensors, the rapid development of "digital" interferometry [BRU 74] and of "TV holography" [DOV 00] has blurred the distinction between holography and interferometry. Holography was initially, and foremost, a non-conventional imaging technique permitting a true 3D parallax, whereas interferometry was a useful tool for the analysis and the measurement of wave fronts. With the development of laser sources and the increase in the resolution of image sensors, from which both disciplines have benefited, the frontier between Michelson interferometry, Mach–Zehnder interferometry, Twyman–Green interferometry, and holographic interferometry is henceforth much less marked than previously. The common objective of these methods is to record/reconstruct the smooth or speckled optical wave front. This means that these disciplines are intimately linked by the connectedness of their fundamentals. Thus, in this book, we can use the terms "holography" and "interferometry" interchangeably.

Even though the concepts of the implementation of digital holography had been known for some time, it took until the 1990s for "digital" holography based on array detectors to come about [SCH 94]. In effect, at the end of the 1980s, we witnessed important developments in two sectors of technology: microtechnological procedures have allowed the creation of image sensors with numerous miniaturized pixels, and the rapid computational treatment of images has become accessible with the appearance of powerful processors and an increase in storage capacities. These advances were made possible by the video games industry that boomed in the middle of the 1980s. From 1994, holography found new life in the considerable stimulation of research efforts. Figure I.1 shows graphs demonstrating the number of scientific publications in the domain of digital holography between 1993 and 2011 (keywords "digital holography", source: ISI – Web of Sciences, 2011). The database lists more than 2,300 articles, of which 57 have been cited more than 57 times.

The most cited articles concern the methods of reconstruction, digital holographic microscopy, secure encoding, and metrological applications. The development of digital holographic microscopy from 1999 has led to commercial systems [LYN 11]. Figure I.1 shows that the explosion of digital holography dates from the start of the 2000s. This revival is explained in part by the appearance on the market of numerous laser sources (laser diodes or diode-pumped solid-state lasers), at moderate cost, giving the opportunity to develop compact and versatile systems. Thus, 10 years after this boom, it seems an opportune time to propose an introductory book on digital holography. This book describes the mathematical fundamentals, the numerical calculation of diffraction, and the reconstruction algorithms, and precisely explains a certain number of techniques and applications that use the phase of the reconstructed field.

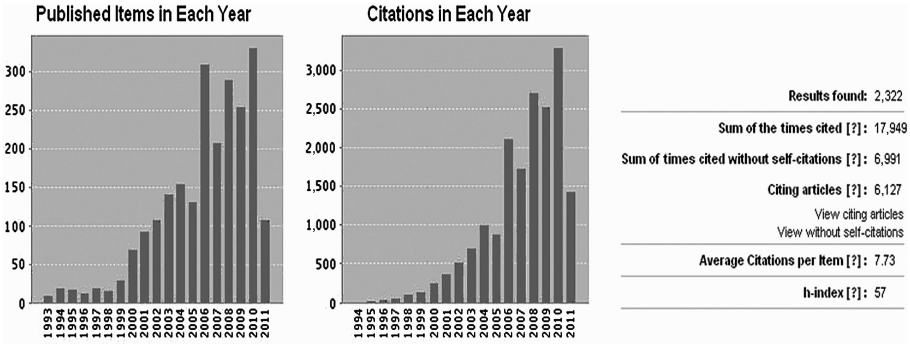

Figure I.1. *Graphs of the number of articles published and of citations since 1993*

Analog or digital holography is closely related to the diffraction of light. However, in practice, it is often difficult to obtain analytical solutions to diffraction calculations, leading to the use of computational methods in order to obtain numerical results. The spectacular development of computational methods in recent years offers everybody the opportunity to calculate the Fourier transform of any image rapidly. Currently, very few works on optics are dedicated specifically to numerical calculations of diffraction, which is fundamental to digital holography. This is why we wish, with this book, to present the fundamentals of diffraction, summarize the different existing techniques of calculation, and give practical examples of applications. This book is for engineers, researchers, and science students at master's level, and will supply them with the basics for entering the vast domain of digital holography.

This book is structured in seven chapters, an appendix, and a list of bibliographical references. The first chapter is a reminder of the mathematical prerequisites necessary for a good understanding of the book. In particular, it describes certain widely used mathematical functions, the theory of two-dimensional linear systems, and the Fourier transform as well as the calculation of the discrete Fourier transform. Chapter 2 introduces the scalar theory of diffraction and describes the propagation of an optical field in a homogeneous medium. The classical approaches are presented and the chapter is concluded with Collins' formula that is used to treat problems of diffraction in waves propagating across an optical system. In Chapter 3, we develop the methods for calculating diffraction integrals using the fast Fourier transform, and we discuss sampling conditions that must be satisfied for the application of each formula. The fundamentals of holography are tackled in Chapter 4; we describe the different types of hologram and the diffraction process that leads to the magic of holography. The fundamentals being outlined, Chapter 5 presents digital Fresnel holography and the algorithms of reconstruction by Fresnel transform or by convolution. We also present methods of digital color holography. This part is illustrated by numerous examples. Chapter 6 is an extension of Chapter 5 in the case where the field propagates across an optical system. The seventh and last chapter considers digital holographic interferometry and its applications. The objective is to propose a synthesis of the methods that exploit the phase of the reconstructed hologram to provide quantitative information on the changes that any object (biological or material) is subjected to.

The Appendix proposes examples of programs for diffraction calculations and digital hologram reconstruction with the methods described in Chapter 5.