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Creating holography: 75th anniversary of Gabor's invention

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Dedicated to Prof Maria J Yzuel

The year 2022 marks the 75th anniversary of Dennis Gabor's invention of the holographic method and for which he received the Nobel Prize in Physics in 1971. The year 2022 also marks the sixtieth anniversary of the publication in 1962 of two seminal papers in the field of holography. In one of them Yuri Denisyuk introduces the reflection hologram and in the other paper Emmeth Leith and Juris Upatnieks describe the holographic process from a communication-theory viewpoint. In this paper, we carry out a brief description of the different "origins" of holography, making special mention to the way Gabor, Denisyuk y Leith established the basis, which made possible the spectacular development of holography from the invention of the laser at the beginning of the decade of 1960.

Keywords: Hologram, Holography.

1 Introduction

In 2022, it will be 75 years since holography began to take its first step in a laboratory of an electrical engineering company in Rugby, England, where Dennis Gabor was working on improving the electron microscope [1]. However, it was not until the invention of the laser in 1960 that holography proved to be a highly productive and attractive area of research. Since then, the many applications of holography in many different scientific and technical areas have given rise to "hot topics" [2] and the basic principles involved in the recording and reconstruction of holograms continue to give rise to exciting innovations in a wide range of areas: three-dimensional imaging, holographic interferometry, pattern recognition, image processing, holographic portraits, communications, optical elements, head-up displays, acoustic holography, particle detection, optical storage, solar energy conversion, optical encoding, digital holography, security, packaging, sensing... and much more. The year 2022 also marks the 60th anniversary of the publication in 1962 of two seminal papers in the field of holography: the introduction of the reflection hologram made by Yuri Denisyuk [3], and the description of the holographic process from a communication-theory viewpoint made by Emmeth Leith and Juris Upatnieks [4].

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To commemorate these three holography anniversaries, we remember in this paper how holography was invented and reinvented over and over again, and how its three main players made their inventions and discoveries with no knowledge of the work of the others. Although in the development of holography we can find many heroes and even some occasional villain, the truth is that three researchers were its main protagonists [5-8]. The first was Dennis Gabor, a Hungarian engineer living in England, inventor of holography in 1947, who received the Nobel Prize in Physics in 1971 "for his invention and development of the holographic method"; Yuri Denisyuk in the former Soviet Union and Emmett Leith in the United States. However, there is still another protagonist that we must mention because it was the trigger that reactivated holography in an "explosive" way in the early sixties: the laser, one of the most important and versatile scientific instruments of all time.

2 Dennis Gabor and the microscopy by reconstructed wavefronts

Dennis Gabor (1900-1979) was born on 5 June 1900 in Budapest, Hungary (Fig 1). Although physics fascinated him, he finally decided to study engineering. Later he wrote: "Physics was not yet a profession in Hungary, with a total of half-a-dozen university chairs – and who could have been presumptuous enough to aspire to one of these?" [9].

(a) (b)

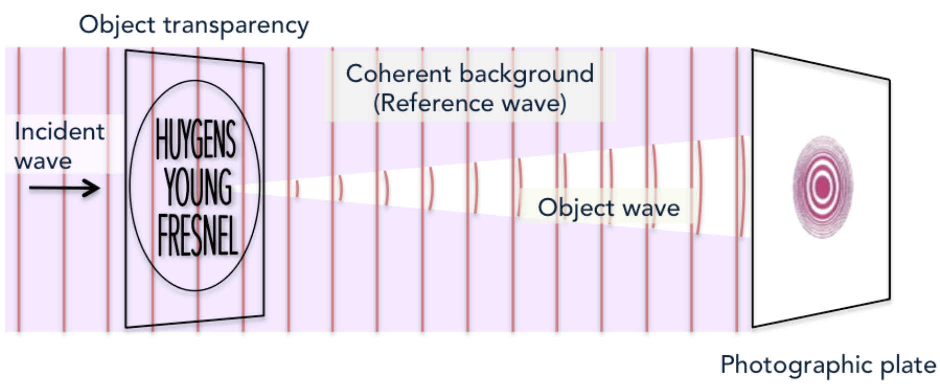
Fig 1. Dennis Gabor (in Hungarian: *Gábor Dénes*) commemorative plaques: (a) Dennis Gabor's birthplace in Budapest. Rippl Rónai Street No. 25. (b) Xántus János Secondary School (formerly *Royal Hungarian State Secondary School*), where Gabor completed his secondary studies. Markó Street No. 18-20. Credits: A. Beléndez.

In 1918, he began studies in electrical engineering in Budapest which he finished at the Technical Hochschule Berlin-Charlottenburg, Germany, where he obtained a Diploma in Electrical Engineering in 1924 and the degree of Doctor of Engineering (Dr-Ing.) in 1927 with a thesis related to the development of one of the first high speed cathode ray oscillographs [10]. In the same year, he joined one of the physics laboratories of the Siemens & Halske AG in Berlin, where he began to develop some of his many inventions. As proof of his fruitful work as an inventor, he filed 62 patents between 1928 and 1971 [11]. In 1933, after

Hitler came to power, Gabor left Germany and in 1934 he went to England, where he got a job with the British Thomson-Houston Company in Rugby.

Throughout his entire life Gabor always said that he was an engineer and inventor rather than a scientist, even though his work was almost always related to applied physics. But Gabor was also a humanist in the sense of the Renaissance [12]: voracious reader, writer, essayist, man concerned about the technological society in the late twentieth century and member of the Club of Rome, a platform of diverse thought leaders who identify holistic solutions to complex global issues and promote policy initiatives and action to enable humanity to emerge from multiple planetary emergencies. Since 1958 he devoted much of his time to study the future of our industrial civilisation on which he published, among others, the book *Inventing the Future* [13], in which he stated that the future cannot be predicted, but futures can be invented.

But let's go back to 1947, when holography begins to take its first steps in a laboratory of an electrical engineering company where Gabor was working on improving the electron microscope. This instrument had increased the resolving power of the best optical microscopes by a hundred times and was very close to resolving atomic structures, but the systems were not quite perfect. Their main limitation was related to the spherical aberration of the magnetic lenses of the microscope. To solve this problem Gabor asked himself: "Why not take a bad electron picture, but one which contains the whole information, and correct it by optical methods?" [12].



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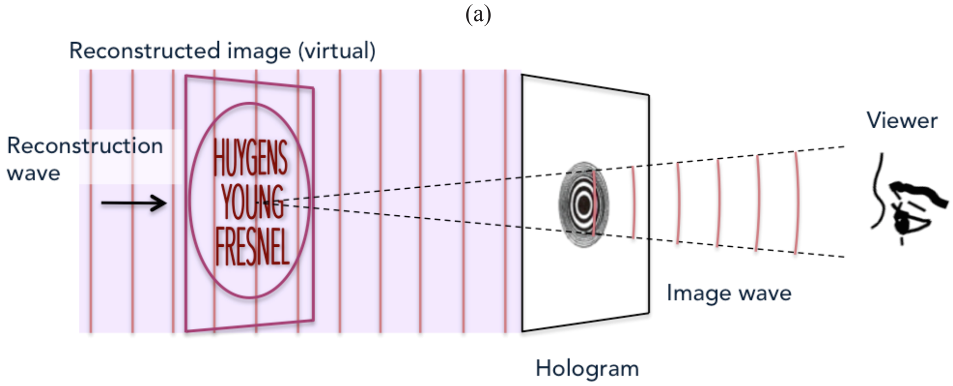


(b)

Fig 2. (a) Recording and (b) reconstruction of an in-line hologram (Gabor's hologram).

Gabor came up with the answer to this question while he was waiting for a tennis court on an Easter day in 1947 [14]. His central idea was to consider a two-step process: the wavefront recording and reconstruction (Fig 2). In the first stage, the recording, the interference pattern between a coherent electron beam (the object wave) and a "coherent background" (the reference wave) is recorded on a photographic plate. Gabor called this interference pattern "hologram", from the Greek word *holos*, the "whole", because it contained the whole information (amplitude and phase) of the object wave. In the second stage, the reconstruction, the hologram is illuminated with visible light and the original wavefront is reconstructed, so that the aberrations of the electron optics can be corrected by optical methods. Gabor called his method "Microscopy by reconstructed wavefronts". Therefore, the physical principles of holography are based on the wave nature of light. These physical principles are interference (in the recording step) and diffraction (in the reconstruction step). Gabor spent the rest of the year working on his 'new microscopic principle'.

To obtain contrast interference fringes it is necessary to use a light source of high coherence, which did not exist in times of Gabor (the first laser emission was obtained by Theodore Maiman on May 16, 1960). Due to this, Gabor made his first hologram in 1948 using a light source that consisted of a mercury arc lamp with a narrow-band green filter, one of the best coherent light sources before the laser. The object was a tiny circular transparency (1.4 mm diameter) of opaque lettering on a clear background containing the names of Huygens, Young and Fresnel (Fig 2), who were important to Gabor because they developed the physical basis for his new technique.

In 1948, Gabor published a short paper in *Nature* entitled "*A New Microscopic Principle*" [15] and the same year a longer paper ("*Microscopy by Reconstructed Wave-Fronts*") was presented to the Royal Society of London. In this paper, which was published the next year in the Proceedings of the Royal Society of London A, Gabor stated [16]: "*The name* '*hologram*' *is justified because the photograph contains the total information required for reconstruction the object, which can be two-dimensional or three-dimensional*". In the abstract of this paper Gabor clearly outlines, in a simple way, what is and how works holography [16]: "The subject of this paper is a new two-step method of optical imagery. In a first step the object is illuminated with a coherent monochromatic wave, and the diffraction pattern resulting from the interference of the coherent secondary wave issuing from the object with the strong, coherent background is recorded on a photographic plate. If the photographic plate, suitably processed, is replaced in the original position and illuminated with the coherent background alone, an image of the object will appear behind it, in the original position."

In September 15th, 1948 the New York Times carried the first-ever news story introducing the hologram: "New Microscope Limns Molecula; Britons Impressed by Paper Combining Optical Principle With Electron Method" [1]. The wavefront reconstruction was well received among scientists as Lawrence Bragg and Max Born, both Nobel laureates in physics, and Charles Darwin, grandson of the evolutionist and Director of the National Physical Laboratory [6], and this was a key factor in improving Gabor's career. In 1949, Gabor was appointed to take up the newly created Mullard Readership in Electronics at the Imperial College of London, and he became the director of a new Electronics laboratory.

During the following years, the wavefront reconstruction technique was studied by Gordon Rogers in England, Adolf Lohmann in Germany, and Paul Kirkpatrick, Albert Baez and Hussein El-Sum at Stanford University in the United States. El-Sum held the first doctoral thesis on holography in 1952 and about fifty articles on Gabor's technique were published during the period between 1948 and 1955 [1].

However, only small and blurry images were obtained so that by the year 1954 Gabor was frustrated to the point of desperation. His problem was that the reconstruction step of the hologram was imperfect: Gabor's method produces an in-line hologram whose quality is poor due to the overlap of the virtual image and the real or conjugate image. When the hologram was reconstructed, a virtual image appeared in the position of the original object but, unfortunately, the view of the image was marred by the presence of a spurious real image in line with it. In 1955, after investigating various optical set-ups to minimize the effect of the conjugate image, Gabor abandoned his research about holography. Gordon Rogers, perhaps the most enthusiastic researcher in holography in those years, wrote in 1956: "*As far I am concerned, I am quite happy to let Diffraction Microscopy die a natural death. I see relatively little future for it, and I am looking forward to doing something else*" [17]. Gabor himself thought holography was no longer important that when he was appointed to a Chair of Applied Electron Physics at the Imperial College in 1958, he barely mentioned his work on 'microscopy by wavefront reconstruction' [6].

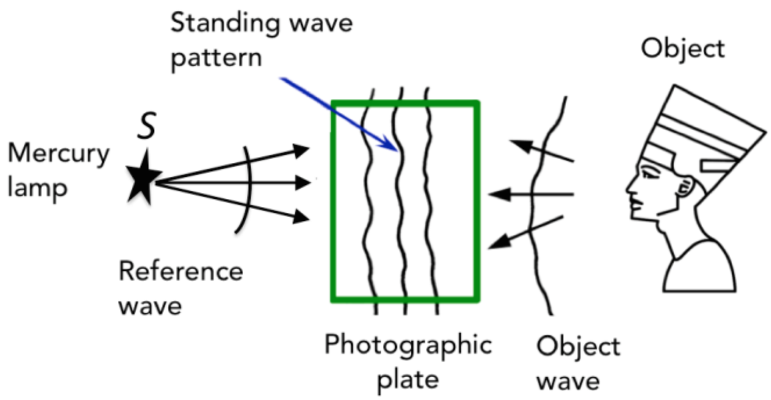
3 Yuri Denisyuk and the wave Photography

At the time, the Gabor wavefront reconstruction concept was being reinvented in a different context, another researcher was conducting a series of similar studies at the most important optical research centre in the former Soviet Union. His name was Yuri Denisyuk (Fig 3) and he initiated the second research on holography around 1958 [6].

Fig 3. Yuri Denisyuk (1927-2006) with his holographic reflection portrait (H J Caulfield (Ed), The Art and Science of Holography. A Tribute to Emmett Leith and Yuri Denisyuk, SPIE Press, Bellingham, Washington, back cover image (2004) [doi: 10.1117/3.2265060].

In 1954, under the supervision of Alexander Elkin, Denisyuk started working for the Soviet Navy in the field of optical instrumentation at the Vavilov State Optical Institute in Leningrad. In 1958, he decided to pursue a doctorate, so Elkin allowed him to devote part of his time to carrying out research for his doctoral thesis under the direction of Eugenii Iudin. Although Iudin died a few months later, during the following years Denisyuk was able to continue his doctoral thesis without a supervisor and under the sole supervision of Elkin, who provided him with a small stipend and some material to continue the laboratory experiments that Denisyuk himself designed.

Denisyuk placed the object next to one side of the photographic plate and illuminated the other side with light from a mercury arc lamp. The light wave, after passing through the plate, is reflected by the object and interferes with the incident wave, giving rise to a standing wave pattern that can be recorded on the photographic plate. This plate, once developed, is illuminated with white light and the object appears in its original position and in the colour of the light used in the recording (Fig 4).



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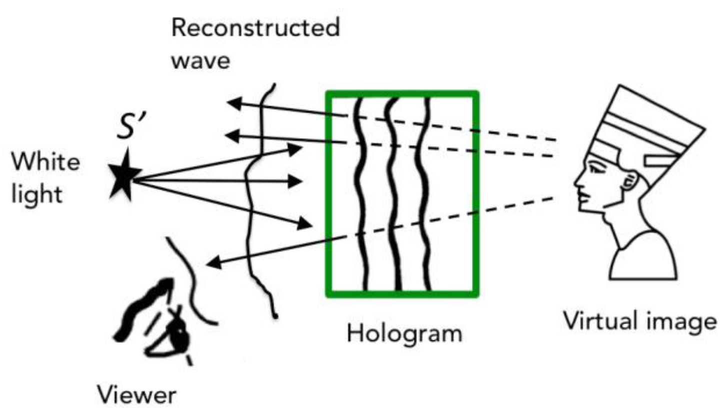


(b)

Fig 4. (a) Recording and (b) reconstruction of a reflection hologram (Denisyuk's hologram) using a mercury lamp and white light, respectively.

Fig 5. Reflection holograms of the Treasure of Villena made by J A Quintana at the University of Alicante (Spain) in 1984. Credits: A. Beléndez.

This type of hologram, the reflection hologram, played a major role in the future evolution of holography and it's the technique commonly used for recording holograms of three-dimensional objects. This type of holograms has the advantage that, although they are recorded using a laser, their reconstruction is carried out with white light. Denisyuk type holograms were used in the former Soviet Union and other countries, within the framework of a vast programme of collaboration between physicists and museologists, to conserve works of art considered archaeological treasures. In fact, the Denisyuk technique is often used to substitute the original objects by holograms in travelling exhibitions. In 1984, at the University of Alicante (Spain), a series of reflection holograms of the Treasure of Villena were made (Fig 5). The fidelity of reproduction of shapes, colours and brightness is so spectacular that it is difficult to tell whether we are looking at the object itself behind a glass window or at a holographic reproduction.

In 1962, Denisyuk published his discovery [3], which he called wave photography, and after completing his doctoral thesis, he returned to his former research on optical instrumentation, so his opportunities to continue his work on wave photography were very limited [18]. Research in this technique languished in the Soviet Union in the following years and for his colleagues the connection of his work with Gabor's wavefront reconstruction was marginal and, moreover, both schemes seemed sterile and without possible applications.

4 Emmett Leith and the lensless photography

In 1971, in his Nobel Prize Lecture [12], Gabor stated that around 1955 holography went into a long hibernation until the invention of the laser in the early sixties. However, this statement is not correct. Emmett Leith (Fig 6), the third main actor in our history, pointed out that it was wrong to think that research on holography had disappeared between 1955 and 1962, but that it was actually carried out clandestinely in two different laboratories [4]. One such environment totally invisible to the West was the Vavilov Institute in Leningrad, where Denisyuk worked on his wave photography. The other one was the Willow Run Laboratory at the University of Michigan, near Ann Arbor, in the United States, a classified laboratory in which Leith made the third independent formulation of holography and where he had entered in 1952 to work on a secret military programme called Project Michigan related to synthetic aperture radar [19].

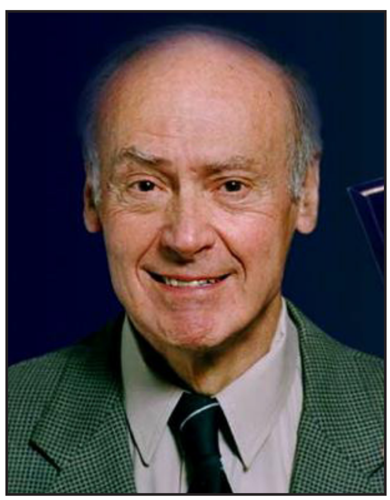
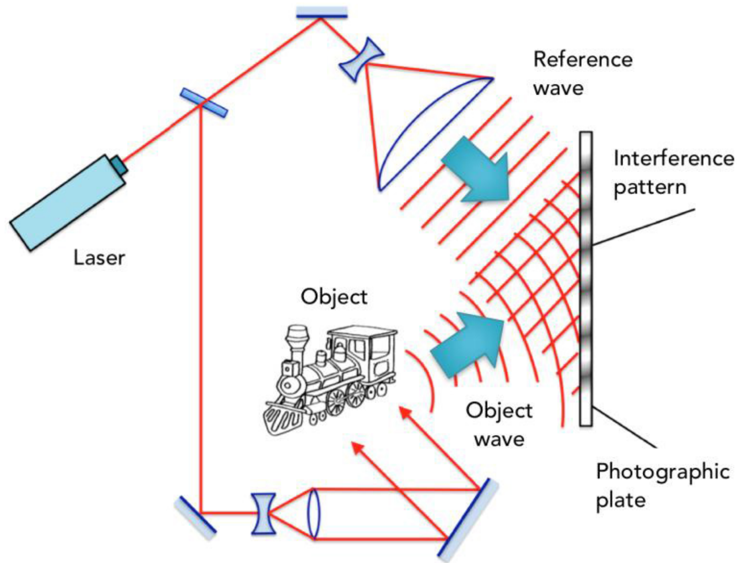


Fig 6. Emmett Leith (1927-2005). (H J Caulfield, Ed, The Art and Science of Holography. A Tribute to Emmett Leith and Yuri Denisyuk, SPIE Press, Bellingham, Washington, back cover image (2004) [doi: 10.1117/3.2265060]).



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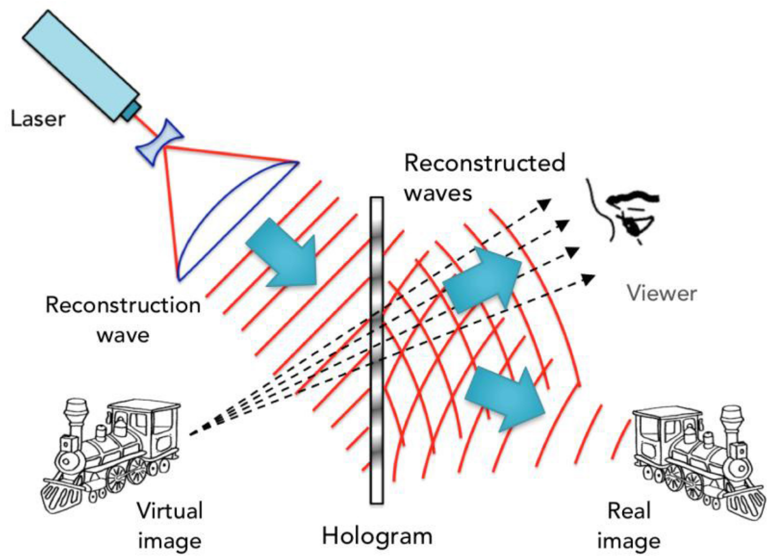

(b)

Fig 7. (a) Recording and (b) reconstruction of an off-axis hologram (Leith and Upatnieks' hologram).

During 1955 and 1956, Leith reformulated the theory of synthetic aperture radar in terms of physical optics. As he analysed the mathematics of the process, he found that he was recording an interferential pattern of radar waves. Leith had just reinvented holography, developing a complete theory of it in the microwave region. Shortly after, he learned about Gabor's work and found that it was related to his radar research. In 1960 Juris Upatnieks (1936) started working as Leith's assistant and they both repeated Gabor's experiments, first using a mercury lamp as a light source and then a helium-neon laser. They had an advantage over Gabor and Denisyuk in that by the early sixties lasers had been invented and highly coherent light was already available. Leith and Upatnieks solved the twin image problem of Gabor's in-line hologram and came up with the tilted reference beam technique: they had just invented the off-axis hologram, in which the object and reference waves impinge on the same face of the photographic plate, but at a certain angle to each other (Fig 7). In this hologram the virtual and real images are angularly separated in the reconstruction and the Gabor problem of twin images is solved. This new geometry was crucial to the advancement of holography as a really useful technology. In 1963, Leith and Upatnieks published their results under the name of lens-less photography and their first holograms were of two-dimensional objects: texts and photographs in black and white [20].

A fundamental difference between photography and holography is that in the latter instead of storing a two-dimensional image of an object formed by a lens or system of lenses, sufficient information is stored to allow the object wave itself to be reconstructed. As we can see in Fig 7 (a), the interferential pattern of two waves is stored on the photographic plate. It may be said that holography makes it possible to "freeze" the object wave and subsequently "set it in motion again." Consequently, the three-dimensional character of an object is maintained. It is possible to move your eye around the reconstructed image of the original object and see different perspectives, making the parallax effect obvious (Fig 8).

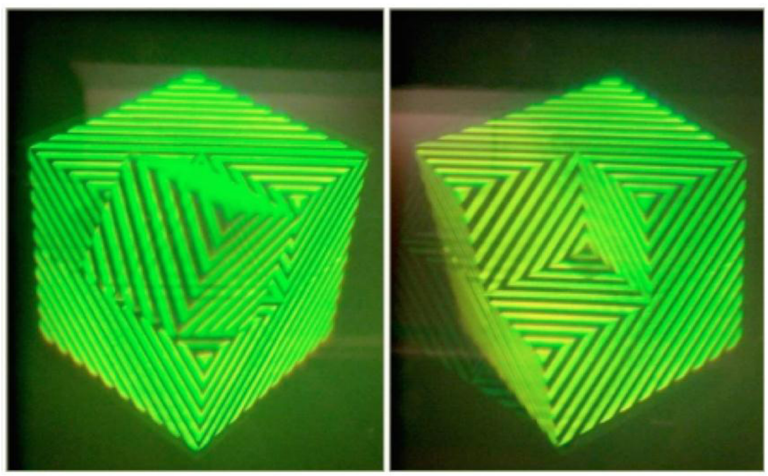

Fig 8. Views from different angles of the image reconstructed by a hologram, showing changes in perspective. The hologram is on display at the Deutsches Museum (Munich). Credits: A. Beléndez.

On Friday, April 3, 1964, at the last session of the Optical Society of America meeting held in Washington, Upatnieks presented the new work on holograms of three-dimensional objects. At the end of his presentation he announced to the attendees that they could see one of these holograms in the hotel lobby. It was the famous hologram of the train. When the hologram was properly illuminated with the laser, a three-dimensional image appeared that had all the properties of the original object. It was not the Upatnieks talk, but the observation of this hologram that really shocked everyone at the meeting. We can imagine a long queue of optical specialists waiting anxiously for their turn to see the hologram. All of them were confused and most found it impossible to believe what they were seeing: the little toy train looked real behind the photographic plate, as if the train was actually there [21,22]. Many asked them "Where's the train?", and Leith said "It's back in Ann Arbor" [23,24]. The truth is that the train never left there. By combining laser with off-axis holography technique, Leith and Upatnieks not only opened holography to the real world of three-dimensional objects, but it was also possible to develop many scientific and technological applications in different areas. In fact, the hologram off the Leith-Upatmieks axis gave rise to holography as it is known today. As Gabor himself points out in his Nobel Lecture, the success of Leith and Upatnieks "was due not only to the laser, but to the long theoretical preparation of Emmett Leith, which started in 1955 (…). Their [*from Leith and his collaborators*] results were brilliant" [12].

5 Conclusions

In the almost two decades between 1947 and 1964 holography was a collage constructed from different perspectives [1]. Gabor's wavefront reconstruction concept as a new form of microscopy, Denisyuk's wave photography as a way to obtain three-dimensional images, and Leith's lensless photography initially formulated from research on synthetic aperture radar. In 1964, the exciting vision of Leith and Upatnieks' three-dimensional hologram "explosively" reactivated the interest in holography. Hundreds of researchers began to link the works of Gabor, Denisyuk and Leith, and in the years following the presentation of the train hologram more than a thousand scientific papers on hologram recording were published [1]. It was necessary, however, to find a single name for this new field that encompassed what had previously been known in three different ways. It is not clear who coined the term "holography" to designate this new area, but it is certain that holography, a field with extraordinary potential, had just been born.

The holographic explosion, which originated mainly thanks to Leith and Upatnieks and other researchers at the University of Michigan, also rehabilitated the figure of Gabor, who went from being virtually unknown to being awarded the 1971 Nobel Prize in Physics "for his invention and development of the holographic method". Gabor, aware that the work of many other researchers had played a key role in this award, finished his Nobel Lecture recognizing that the contributions of other researchers helped him to win the Nobel Prize [12]: "I am one of the few lucky physicists who could see an idea of theirs grow into a sizeable chapter of physics. I am deeply aware that this has been achieved by an army of young, talented and enthusiastic researchers, of whom I could mention only a few by name. I want to express my heartfelt thanks to them, for having helped me by their work to this greatest of scientific honours".

Although the reconstruction of an image in three dimensions giving the perfect sensation of relief is undoubtedly one of the most spectacular and well-known achievements of holography, there are many other applications. Emmett Leith stated on more than one occasion that "*holography by itself is a somewhat narrow field, but combine it with others and it makes an area big enough to spend a lifetime in*" [25]. Proof of this is the fact that holography has provided and continues to provide innumerable applications in a multitude of scientific and technical fields. Holographic interferometry, holographic optical elements, holographic displays, scanners, computer generated holograms, acoustic holography, holographic memories, solar holography, security holograms, colour holography, holographic portraits or holographic sensors are just some of the numerous applications of holography [26]. In 1966 Leith and Upatnieks made a hologram in collaboration with the photographer and artist Fritz Goro for Life magazine [1], and in 1968 a paper titled "*Holography: A New Scientific Technique of Possible Use to Artists*" [27] was published in the Leonardo magazine. In this paper the possibility of using holography as a new art form was discussed, and since then several artists began to experiment in this field. This made holography one of the "rare" scientific fields that provided a medium for art.

Seventy-five years after its invention, and despite its erratic beginnings, we can say that holography has shown a great past and a magnificent present, but it is certainly undeniable that its future is still very promising.

Acknowledgments

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