1 Holography Reinvented

Stephen A. Benton
MIT (USA)

This chapter is titled "Holography Reinvented" to emphasize that each of the three best-known names in holography made his discoveries and inventions with no knowledge of the work of others; that is, each of them invented or reinvented holography, as it were. This chapter is largely a presentation of anecdotal remarks drawn from conversations, observations drawn from historical documents (including some from the Museum of Holography files now at the MIT Museum), and observations drawn from the author's own experiences as holography has evolved. As such, any errors of fact or interpretation are entirely the author's own, as is the slant toward imaging or display holography that will be conspicuous. The three main players are Professors Dennis Gabor, Emmett Leith, and Yuri Denisyuk. A few other names will come into the story as well, notably Pieter van Heerden (my former colleague at the Polaroid Research Labs) and Hussein M. A. El-Sum.

1.1 Dennis Gabor

By now, most holographers are familiar with the story of the first invention of holography. The story goes that Dennis Gabor was waiting for a tennis court in Rugby, England, on a fine Easter day in 1947 when the solution to the wavefront recording and reconstruction problem came to him in a flash of insight. The central idea was, of course, to use the reference beam to record relative phase. It is interesting to contemplate what subconscious stimuli might have been present for this insight, although it is hard to imagine how bouncing balls played a role. Gabor had been born in Budapest, Hungary (June 5, 1900), educated as an electrical engineer in Berlin, Germany (Dr. Ing., 1927), fled Hitler's regime and moved to England in 1934, where he was an inactive alien during World War II. He was awarded the Nobel Prize in Physics in 1971, an unusual accomplishment for an electrical engineer. It suffices to say that he had something of a nonlinear career path, a pattern that is also repeated in holography's history.

Quite some skepticism greeted Gabor's 1948 publication in *Nature* magazine, because many had been trying to solve similar problems for years. Pieter van Heerden was an assistant professor at Harvard University at the time, and he remembers rushing into Julian Schwinger's office to proclaim the solution of the optical phase reconstruction problem.[1] Schwinger (who became a 1965 Nobel Laureate in Physics) quickly rebuked van Heerden, saying that it was well known that such a thing was impossible, and that young Pieter should have read the article more carefully. “But Julian,” Pieter said, “he shows pictures!” To which, Schwinger read the article for himself and recognized its importance. The cry of “Show me the hologram!” has been a continuing theme in the field ever since.

Gabor pursued optical holography for several years after 1948, especially in terms of holographic microscopes, but this led nowhere and he eventually abandoned the field. It is remarkable that he had not anticipated holography’s potential as a 3D imaging technique until the work of Leith and Upatnieks, considering that during the war he had worked on a no-glasses form of 3D that involved projection onto lenticular screens and was a fan of 3D pictures (a topic he returned to later in his life).[2] His subsequent work at Imperial College instead turned toward information theory and flat color television tubes. He returned briefly to holography when his former student, Peter Goldmark, invited him to the CBS research labs in the USA. Again at Imperial College, he dabbled in futurology (not very fruitfully) near the end of his life. He did manage to visit the Museum of Holography in New York City in 1978, and bequeathed some of his Nobel Prize materials to it (although not the prize medal). He died on February 9, 1979, after a series of strokes. Although Professor Gabor could seem quite imperious at a distance, he was actually a warm and welcoming person one-on-one. He once published an article on optical character recognition that more or less duplicated one of Pieter van Heerden’s publications. When van Heerden pointed this out, Gabor replied, “I hang my head in shame.” This was a remarkably heartfelt apology for so prominent a scientist!

1.2 Emmett N. Leith

Emmett Leith was still a young researcher, having gained his master’s degree in physics from Wayne State University in 1952, when he reinvented holography in 1956.[3] Unfortunately for the rest of us, his work was done as part of a top-secret high-resolution radar-imaging project (Project Michigan, a synthetic-aperture radar system), and news of his work emerged only slowly from that dark world several years later. Leith was given the job of designing the optical processor for the data as a result of his having taken four courses in optics—something that would be impossible for most engineers today! He perceived the analogy between optical and radar-wave phase reconstruction and introduced the idea to the Willow Run Lab as a new way to think about how the optical processors worked, and how they could be improved. Later, the parallels between his thinking and that of Gabor became clear, and the optical processor research moved into new directions that were more explicitly holographic. They were finally allowed to begin publishing their nonradar results in 1961, although most scientists had forgotten about Gabor’s holography by then and didn’t know what to make of the new research. It was only when the continuous-wave He-Ne laser became available to them that the recording of front-lit solid objects with photographic quality became possible. Leith and his assistant, Juris Upatnieks, realized that the images should be 3D, but somehow the dramatic visual impact was missing. Kodak 649-F spectroscopic plates were being used at the time, on account of their very high resolving power, and were available as 50 × 50-mm (2 × 2) plates, which Leith and Upatnieks were using, and as larger 100 × 125-mm (4 × 5) plates. The first plates were too small for both eyes to see through simultaneously, but with the larger plates, the vivid 3D nature was immediately apparent. A colleague of mine, William Houde-Walter, later browsed the cabinets full of holographic tests at Michigan. He noted that the angle between the object and reference beam grew with time as Leith and Upatnieks tested the limits of their new technique, leading up to the well-known image called Bird and Train, now in the collection of the MIT Museum.[4]

The age of display holography as we know it began in the Fall of 1963, as Leith and Upatnieks gradually introduced their discoveries to the scientific world, first locally and then nationally. The curtain truly rose at the Spring 1964 meeting of the Optical Society of America, in Washington, D.C.[5] There, Leith and Upatnieks gave a short oral paper on their 3D holograms, and invited the attendees to view a hologram in the hotel suite used by the Spectra-Physics company, who made most of the early holography-capable lasers. A line of optical scientists and engineers wound down the hallways of the hotel as they patiently waited to see the 3D images that were absolutely unprecedented in their realism and accuracy. Quite a rage of interest in holography ensued, and many promises were made then that have yet to be kept! Emmett Leith was awarded America's National Medal of Science in 1980, and was appointed to full professor at the University of Michigan in 1968, where he is still active today.

This author's first glimpse of a display hologram came in March of 1965 at Polaroid Corporation. Edwin Land had been on a photographic expedition with Ansel Adams in Arizona when they came across a seminar on holography being given by Prof. George Stroke, also of the University of Michigan. Land had been fascinated by Gabor's original work, and quickly invited Stroke to give a seminar at the Polaroid Corporation. There, he showed a dim hologram of a coffee mug (which had been made by Douglas Brumm while a student with Prof. Leith[6]), an image that is still vivid in my memory (does anyone forget his first glimpse of a hologram?). Coffee mugs and cups have been a favorite motif in my holography classes ever since. That night, my wife Jeannie and I, with John and Mary McCann, cobbled together a laser and some film and made the first of many holograms to come at Polaroid.

Emmett Leith's research since the heyday of the 1960s has delved into various exotic applications of holographic concepts, including triple-grating interferometers and imaging through breast tissue. Nevertheless, he has been a generous supporter of display holography throughout the modern history of the field, always willing to appear at art and science conferences to encourage young holographers to advance their work. This has also been true of Yuri Denisyuk, and seems to be an attribute not just of great holographers, but of great human beings as well.

1.3 Yuri Nicholaevitch Denisyuk

Yuri Densiyuk was born in Sotchi, on the Black Sea (a favorite resort town of citizens of the then Soviet Union) on July 27, 1927. As a boy, he was a resident of Leningrad (now Saint Petersburg), and was caught there during the infamous siege of 1943. As we know, that was an occasion of terrible hardship, and Madame Denisyuk was advised to stop feeding her sickly son, as he seemed doomed not to live for long. Somehow, our dear colleague survived, and still has the strength and vigor of a much younger man.

Denisyuk was also launched on a fairly typical research path after gaining his bachelor's degree in 1954 from the Institute of Fine Mechanics in Leningrad. However, he had a persistent inspiration from a science fiction story burning in his mind. The well-known Soviet author I.Y. Efremov wrote several books that have been translated into English, one of which, titled "Stories," includes the short story "Stellar Ships."[7] In this tale, two scientists exploring an alien planet find a polished layered-metal disk that displays a 3D image of the head of a humanoid, thought to be seventy million years old. Denisyuk pondered this possibility for a few years, knowing well of Lippmann's work on interference photography, and commenced his own experiments in 1958. Lasers were some years away, so he made do with a specially constructed mercury discharge tube as a light source (now on display at Moscow's Technical Museum).

Denisyuk's first images of reflections from convex mirrors proved his theory of wavefront reconstruction by reflection, but his ideas were not warmly accepted at the time. After their publication in the Soviet Union in 1962,[8] a young researcher at the Institute of Physical Problems (directed by Peter Kapitsa) wrote a scathing review that greatly impeded Denisyuk's further research for several years. In the late 1960s, during the furor of interest in Leith's and Upatniek's work, his comrades realized that a form of holography had been previously invented in the Soviet Union! Kapitsa personally compelled his young colleague to write a positive review of Denisyuk's work in 1968, and holography joined the pantheon of glorious accomplishments of the worker's paradise. Indeed, Prof. Denisyuk was awarded the Lenin Prize in 1970, an enormous honor comparable to the Nobel Prize in the west, and was elected a member of the Soviet Academy of Science. Denisyuk has chronicled some of this in the journal *Leonardo*.[9]

I first met Yuri Denisyuk in 1978, at a holography conference in Ulyanovsk, on the shores of the River Volga in Russia. For several of us visiting the Soviet Union for the first time, it was a welcome surprise to find that Professor Denisyuk was willing to meet with us at length, to describe his experiments on ultrafine-grained emulsions and new holographic techniques in detail, and to be generous and welcoming in general. Since his first visit to the USA in 1989, under the auspices of H. John Caulfield and myself, he has been a regular visitor here and a generous supporter of young holographers entering the field.

Lest stories of such suppression of work in holography strike anyone as a peculiarly Soviet phenomenon, I might mention here the work of my friend, Pieter van

Heerden. His ideas on volume holography were developed while he was a scientist at the celebrated General Electric Research Labs in Schenectady, NY. So deep was the skepticism about his ideas that another scientist was commissioned to test them by computer simulation, and he proved that they were bunkum. Van Heerden was invited to resign from GE, and was quickly recruited by Dr. Land at Polaroid. Pieter published his ideas in *Applied Optics* in 1963,[10] before anyone in the USA had seen or heard of Denisyuk's earlier work, which was not published in English until later in 1963.[11] For many of us, it was van Heerden's articles that provided the earliest understanding of volume holography. Van Heerden went on to create other highly controversial theories about the fundamentals of mathematics and physics, which he published privately.

To return to Professors Denisyuk and Leith, it is also remarkable to me how they are so beloved by their many former students in their respective countries. One cannot converse about holography for long in either environment without soon finding a one- or two-degree-of-separation link with either Emmett Leith or Yuri Denisyuk, followed by fond approbations. Holography is a field that has attracted a variety of idiosyncratic thinkers, including its founders, and a spirit of warmth and generosity has often prevailed, also exemplified by Profs. Leith and Denisyuk.

Neither Leith nor Denisyuk knew anything of the work of Gabor at the time that their unique insights were formed. Nevertheless, there is a common link between both of them and Gabor: they both learned about holography via the work of Hussein M. A. El-Sum, a former student of Paul Kirkpatrick at Stanford University, who was a dedicated X-ray holographer throughout the 1950s. Leith learned of a paper by El-Sum sometime after his 1956 work on the optical processor, and Denisyuk learned of a talk by El-Sum from a colleague newly returned from an overseas conference just as he was preparing to send off his 1962 manuscript for publication. This author was also a careful reader of El-Sum's doctoral dissertation, the first such in holography, so there are many of us who are in his debt as an apostle of holography.[12]

It would be very difficult for an optical researcher today to claim ignorance of the work of Gabor, Leith, or Denisyuk, thanks to our shrinking world and a wider appreciation of holography; so the epoch of reinventing holography is probably over. However, it is the next wave of holographically inspired inventions that we are all hoping to see. For this author's part, I am hoping that the same 3D realism can be found in new quasi-holographic techniques that rely on holography mainly for their inspiration, as volume holography did on Efremov's story. Holography has come to take on two meanings in our culture. Firstly, it means wavefront reconstruction by interference and diffraction/reflection. More widely, it has come to mean the ultimate 3D imaging method of the future, and it stands as an optimistic hope for the progress of our science and technology relating to everyday life. Hopefully, future reinventions will be as productive and useful as holography's evolution has been.

15 Color Conical Holographic Stereograms: Recording and Distortion Compensation Methods

Luis Manuel Murillo-Mora
Toppan Printing Co., Ltd. (Japan)

Katsuyuki Okada*, **Toshio Honda**
Chiba University (Japan)

Jumpei Tsujiuchi
Tokyo Institute of Technology (Japan)

15.1 Introduction

Holographic 3D displays were first proposed by Leith et al.[1] in 1964, but practical applications were delayed because of the difficulty of both recording and reconstructing holograms. This difficulty was solved by white-light reconstruction holograms and by the use of pulse lasers for holographic recording.

White-light reconstruction holograms were an outgrowth of the rainbow holograms developed by Benton[2] and the thick reflection holograms developed by Denisyuk.[3] Both of these techniques made large contributions to the development of the holographic 3D display.

It was also very difficult to eliminate vibrations during the exposure of holograms, and pulse lasers such as ruby or YAG lasers were employed to record holograms of moving objects like animals and to record holographic portraits of human bodies. However, large-scale objects such as landscapes and architectures are still difficult to record in a hologram.

A holographic stereogram synthesized from a series of ordinary photographs was first proposed by McCrickerd et al.,[4] and was later accomplished as a cylindrical stereogram with white-light reconstruction by L. Cross. The chief advantage of the holographic stereogram is to make 3D display holograms of any object possible. Objects of primary interest include large-scale objects like landscapes and architectures, medical images,[5,6] and computer-synthesized virtual objects.

Various configurations and techniques[7–12] have been applied thus far in holographic stereograms. The original images for synthesizing holograms are usually

* passed away on October 4, 1996.

provided by ordinary still or movie cameras, but computer-generated or processed images are also employed for more flexible applications.[13–15]

This chapter will describe details of the color conical hologram, which is considered an interesting configuration for a holographic 3D display because it offers some special features not found in other types of holograms. In a conical hologram, there exists the possibility of displaying 360 deg of perspective of a real image of the object in the center of the cone, as shown in Fig. 15.1. With the added possibility of observing a reconstructed color image, clearly the conical holographic stereogram is suitable for holographic 3D displays.

15.2 Methods of Color Holographic Stereogram Synthesis

The proposed method to obtain a color holographic stereogram consists of recording three rainbow holograms on each slit hologram. The angle of the reference beam is modified when the three sets of 2D images are recorded to obtain the superposition of three vertically displaced rainbows in reconstruction. The combination of these rainbows will yield a full-color image at the right viewing position.

15.2.1 Original 2D images

The three sets of 2D images can be obtained using three color filters (red, green and blue) and a black-and-white camera, as indicated in Fig. 15.2. The object is placed on a turntable, and a camera is set at the proper position and angle according to the perspective of the conical hologram. Each color view is taken with the camera and stored in computer memory. Once the three color images have been saved, the turntable is rotated an angle $\Delta\beta$, and the next view of the object is presented to the camera. The process continues until a total number of N images have been taken.

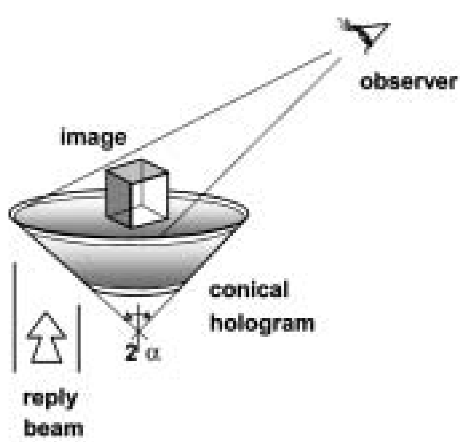

Figure 15.1 Conical hologram.[16,17]

These images will subsequently be referred to as “r,” “g” and “b” images, although they are not color images.

15.2.2 Hologram-recording method

The procedure followed to record a color holographic stereogram is shown in Fig. 15.3. It allows formation of a rainbow hologram in a single step. Each 2D

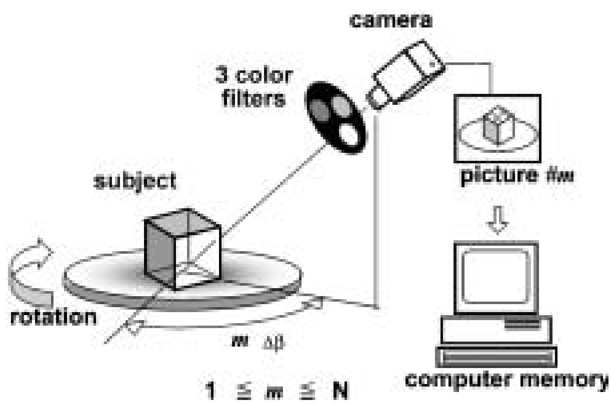

Figure 15.2 The procedure to obtain the set of object perspectives.[16,17]

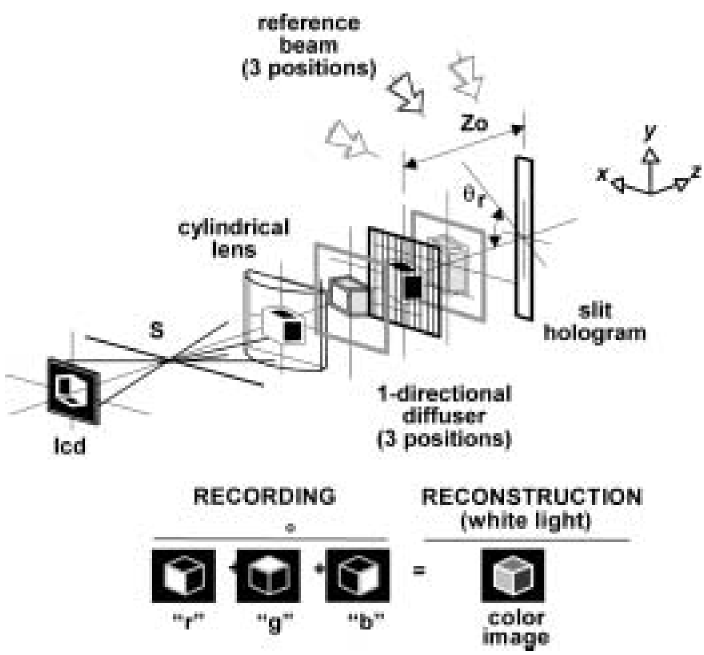

Figure 15.3 Recording method for a color holographic stereogram.