15. Holography

History

- Dennis Gabor (1948, 1949, 1951) ••• Nobel Prize in Physics (1971)

  holography

  "whole recording"

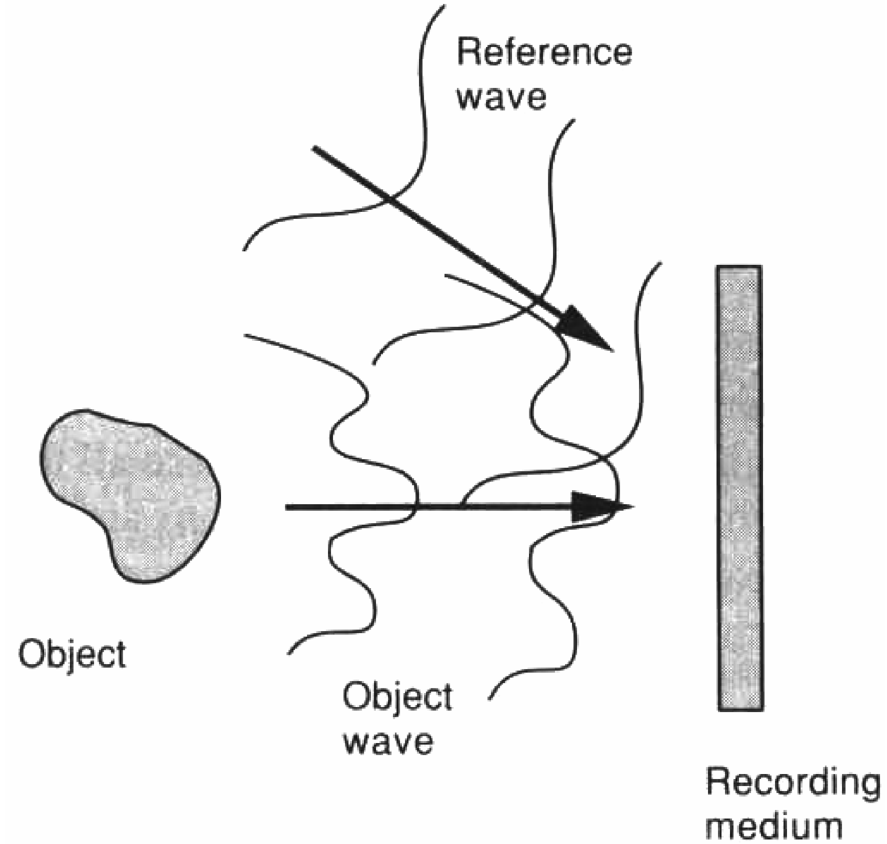
  - On-axis hologram

- E. N. Leith and J. Upatnieks (1962, 1963)

  - Off-axis hologram

- Y. N. Denisyuk (1962, 1963, 1965)

Recording Amplitude and Phase



Object Beam

$$a(x,y) = |a(x,y)|\exp[-j\phi(x,y)]$$

Reference Beam

$$A(x,y) = |A(x,y)|\exp[-j\psi(x,y)]$$

Interference

$$I(x,y) = |A(x,y)|^2 + |a(x,y)|^2 + 2|A(x,y)||a(x,y)|\cos[\psi(x,y) - \phi(x,y)]$$

Reconstruction of Wavefront

$$t_A(x,y) \propto I(x,y)$$

$$t_A(x,y) = t_b + \beta'\left(|a|^2 + A^* a + A a^*\right)$$

For the reading (probe) beam of $B(x,y)$,

$$B(x,y)t_A(x,y) = t_b B + \beta' a a^* B + \beta' A^* B a + \beta' A B a^* = U_1 + U_2 + U_3 + U_4$$

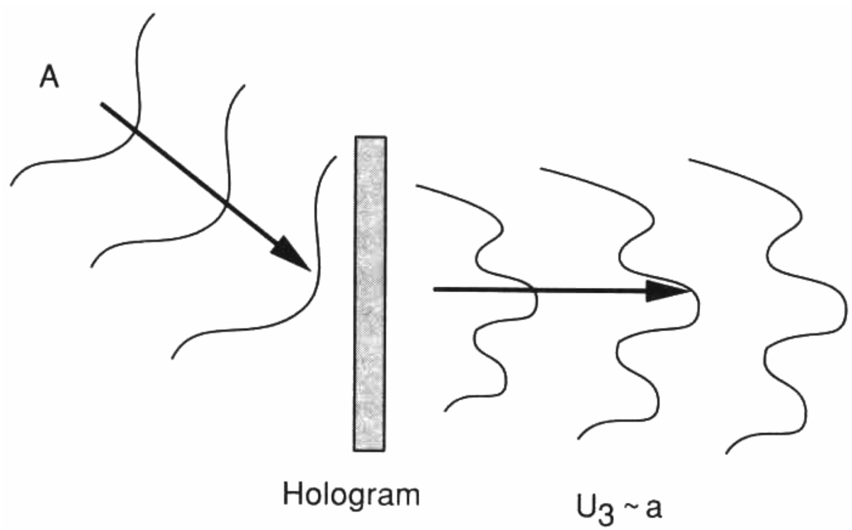
For $B = A$

$$U_3(x,y) = \beta'|A|^2 a(x,y)$$

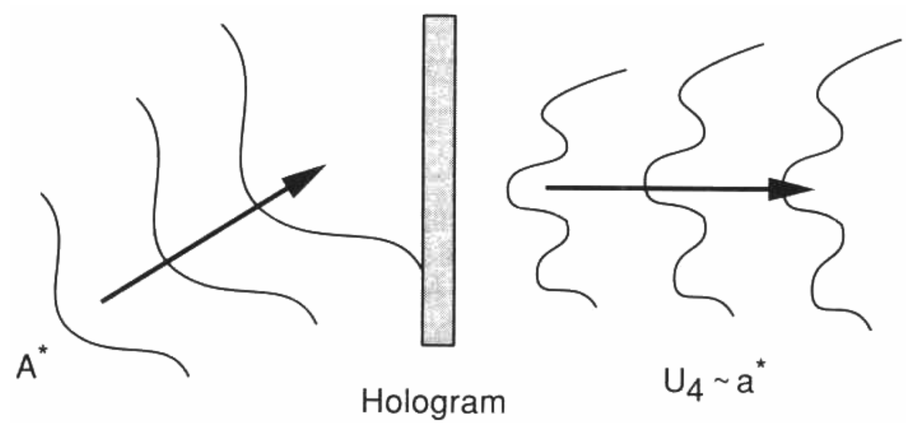
For $B = A^*$

$$U_4(x,y) = \beta'|A|^2 a^*(x,y)$$

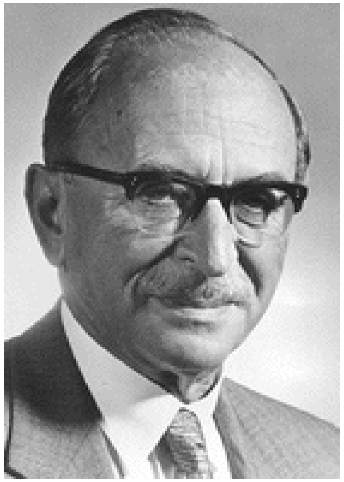
Original Referencing & Conjugate Referencing



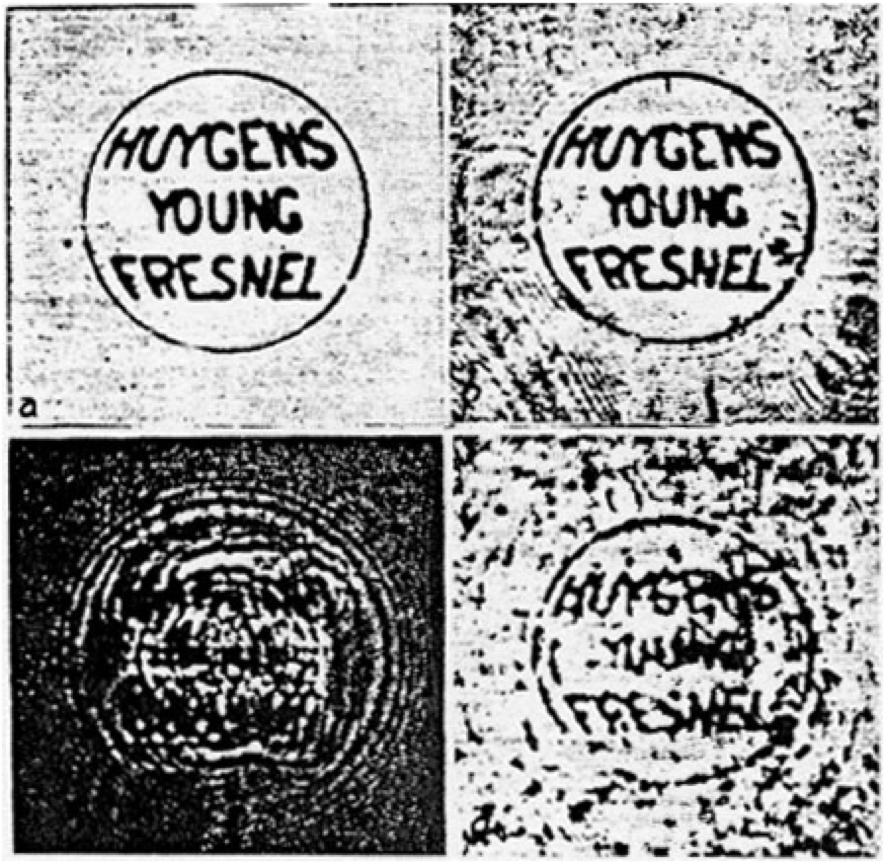
(a)



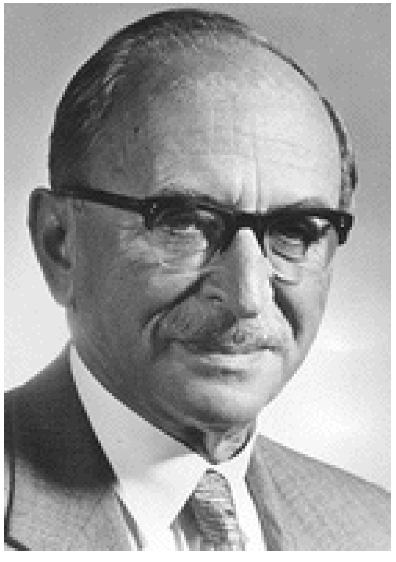
(b)



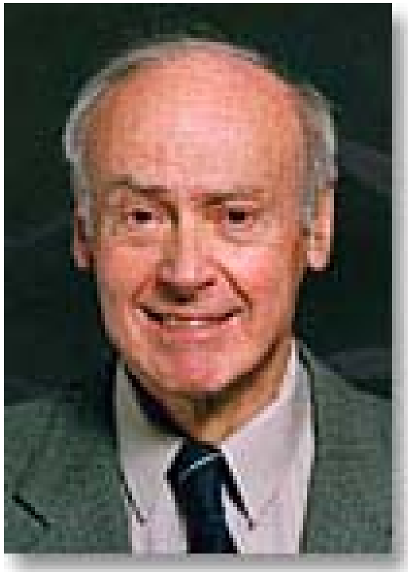
Gabor Hologram



Pioneers of Holography



Dennis Gabor
(1900-1979)



Emmett Leith
(1927-2005)

Yuri Denisyuk
(1927-2006)

Stephen A. Benton
(1941-2003)

Benton

In Memorium (by Andrew Woods)
Stephen A. Benton
Dec. 1, 1941 - Nov 9, 2003

Professor Stephen A. Benton (Steve to his many friends) passed away on Sunday evening (9 November 2003) after a long struggle with brain cancer.

Stephen A. Benton was Professor of Media Arts & Sciences at Massachusetts Institute of Technology (MIT) (Cambridge, Massachusetts) and Head of the Spatial Imaging Group, MIT Media Laboratory. He invented white-light "Rainbow" holography, holographic video, edge-lit holography, and other vast improvements in holographic stereography.

After finishing his undergraduate degree at MIT in 1964 and his Doctorate in Physics at Harvard University in 1968, he went to work beside Dr. Edwin Land at Polaroid. He worked on many projects at Polaroid, especially holography.
He pushed the field from its start and collaborated with artists to show the power of these techniques. He produced some of the most memorable images in holography. He was able to instruct artists, without technical backgrounds, in the new techniques he was inventing, which allowed more people to immediately use his new inventions. One of his most significant inventions is the "Rainbow Hologram," which led to accurate color control in transmission holography.

Benton became a professor at MIT in 1982 and was a founding professor and academic head of the MIT Media Lab in 1984. He also started the Spatial Imaging Group (SPI) at MIT. In this group he provided the only place in the world where students could come to learn the rigorous math, science, and engineering of holographic display systems.

At the Media Lab, Benton and his students invented holograms with 180-degree fields of view, holographic video systems, reflection hologram precise color-control, edge-lit holograms, and extremely high-quality holographic stereograms. These inventions comprise most of the technical advances in the field for the past 20 years.

Benton holds several patents and has published numerous articles and books including his 2001 compilation "Selected Papers on Three-Dimensional Displays". He was a fellow of SPIE, OSA, and IS&T and has held positions of leadership at various professional societies. He was chair of the Practical Holography conferences from 1989 to 2002 and co-chair of the Stereoscopic Displays and Applications conferences from 2000 to 2003.
Steve leaves his wife Jeannie, son Jamie, and daughter Julia. He was 61.

Leith

In memoriam: Emmett Leith
30 December 2005

Holography pioneer Emmett Leith died suddenly on 23 December 2005 after suffering a stroke. He was born in 1927 and received the BS and MS in physics and the PhD in electrical engineering, all from Wayne State University, Michigan, and also an honorary Doctor of Science degree from University of Aberdeen. He had worked at the University of Michigan since 1952.
His research was in the areas of synthetic aperture radar, optical processing and holography. His work on optical information processing of synthetic aperture radar data led him to independently discover the principles of holography in the mid-1950s. Leith made this development unaware of the work of Dennis Gabor, who approximately eight years earlier had proposed "in-line" holography.
Numerous applications of holography developed from the work of Leith. In 1962, working with Juris Upatnieks, Leith produced the first three-dimensional laser transmission hologram, of a toy train and a bird.
Leith authored or coauthored about 200 papers. He was named a Fellow of SPIE in 1985. He received the Society's Gold Medal in 1990, and the Dennis Gabor Award in 1983. He was also a member of the National Academy of Engineering.
Charles M. Vest, professor of mechanical engineering and president emeritus of the Massachusetts Institute of Technology, said that Leith was "one of the most inventive and unique individuals I have ever known. His scientific reasoning was based on an remarkable ability to visualize the physics of whatever he was working on in deceptively simple ways."
Vest recalled a meeting with Leith after the two had not seen each other for a long time. He mentioned an article of Leith's that he had seen published some years earlier on the history of the Willow Run Laboratory, and asked if it would be possible to get a copy of it sometime.
"Emmett said 'Sure,' reached into his pants pocket, pulled out a copy of the article and handed it to me."
Leith and Yuri Denisyuk were honored with the publication of a tribute volume entitled The Art and Science of Holography (H. J. Caulfield, editor) in 2004. In it, the late Steve Benton wrote that Leith was always "a generous supporter of display holography throughout the modern history of the field."

Leith target=_blank>http://spie.org/Announcements/2005.html#Leith

Leith

In Memoriam: Emmett Leith

Emmett Leith, the Schlumberger Professor of Electrical Engineering and Computer Science at the University of Michigan died on December 23 at the age of 78 after suffering a stroke the previous day. Professor Leith made seminal contributions that established the place of coherent optics in radar systems and is credited, along with his colleague Juris Upatnieks, of developing modern holography in the early 1960's. The holographic techniques developed by Leith and Upatnieks allowed the images of 3-D real world objects to be captured on photographic film. When the film was viewed under proper illumination, the full 3-D images reappeared, and these images had all the properties of the original objects, including full parallax. According to Leith, "One could move one's head and peer behind obscuring structures, to see what was hidden behind, just as if one were viewing the original objects themselves." The results, as reported at the Annual Optical Society of America Meeting in 1963, were dramatic and created a worldwide interest in holography.

Much of Leith's holographic work was an outgrowth of his research on synthetic aperture radar (SAR) performed while a member of the Radar Laboratory of the University of Michigan's Willow Run Laboratory beginning in 1953. This earlier work had military value and remained classified until 1968. As part of this effort, Leith contributed to the development of new optical techniques to process SAR data, allowing high-resolution radar images to be obtained for the first time. These contributions included the first coherent cross-correlator, the introduction of the wavefront reconstruction view-point to explain SAR optical processing, and the introduction of coherent optics to perform pulse compression of chirped radar pulses. The concept of wavefront reconstruction was, unbeknownst to Leith, closely related to the work performed eight years earlier by Dennis Gabor. Gabor had performed his work as a means of improving the quality of images in electron microscopy, and he received the Nobel prize in 1971 for his wavefront reconstruction principle, dubbed holoscopy.

Born in Detroit, Leith received a B.S. and M.S. degree in physics and a Ph.D. in electrical engineering all from Wayne State University located in Detroit, Michigan. He spent his entire 52 year scientific career at University of Michigan and was due to retire at the end of last year. Leith supervised more than forty Ph.D. students during his career, many of who went on to make significant scientific and engineering contributions.

Leith received the National Medal of Science from President Jimmy Carter in 1979. He was a member of the National Academy of Engineering, a Fellow of the Optical Society of America (OSA), and a member of OSA since 1961. In addition, he was the recipient of the OSA Fredric Ives Medal in 1985. This medal recognizes overall distinction in optics and is the highest award of the Society. Leith also played an active role in the organization, serving various OSA Committees during his time as a member.

Leith is survived by June, his wife of 49 years, and their two daughters, Pam Wilder of San Jose, Calif., and Kim Leith of Baltimore, as well as three grandchildren.

This obituary was contributed by OSA member Kim Winick, a long-time friend and colleague of Emmett Leith.

Leith.asp target=_blank>http://osa.org/news/release/01.2006/Leith.asp

Denisyuk

In memoriam: Yuri Denisyuk 1927-2006

On May 14, Yuri Denisyuk died peacefully in St. Petersburg, Russia. The loss to the optics community of this brilliant, humble, and generous man is immeasurable. Coming as it does less than six months after the death of his friend and colleague Emmett Leith, his death marks the end of an era. The two beloved founders of modern holography are gone and somehow the field they created and nurtured for over forty years must determine how it can honor them by continuing to thrive.

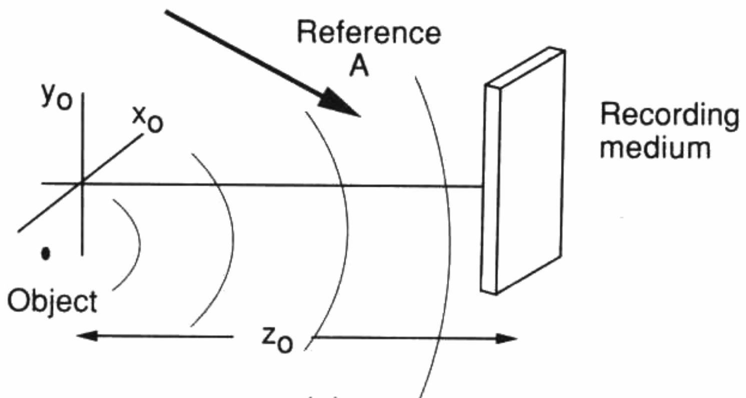
Professor, academician, and friend to all in his field, he was best known for the Denisyuk hologram -- the holograms that produce the wonderful, often-colored 3D images hovering just behind the plane of the hologram. His other contributions in the field of coherent optics and holography were also of great importance. During the last years of his life, he had turned his attention to optical logic, high density data storage and non-linear optics where he also made significant contributions.

Denisyuk began experiments in interference photography in 1958 and published his work in 1962 in the Soviet Union. But his research was not well received until the work of Leith and Upatnieks began to generate excitement in the late sixties. In 1970 he was awarded the Lenin Prize and was elected a member of the Soviet Academy of Sciences. Denisyuk and Leith received the first Dennis Gabor Award from SPIE in 1983.

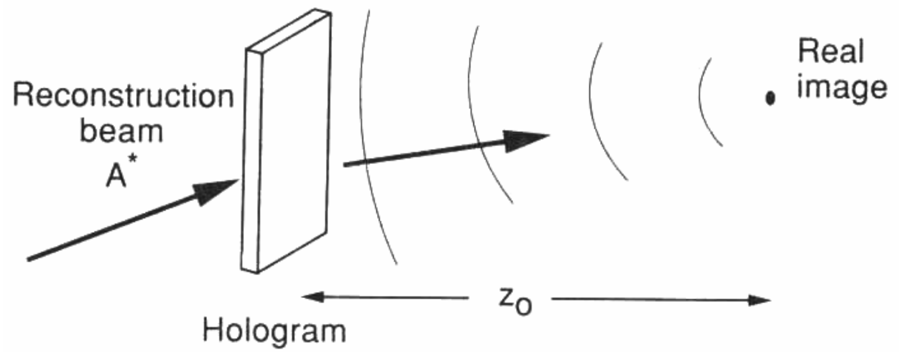
SPIE will honor him and Professor Leith with a special conference as part of the Optics and Photonics Symposium this summer in San Diego.

http://newsroom.spie.org/x3181.xml?highlight=x509

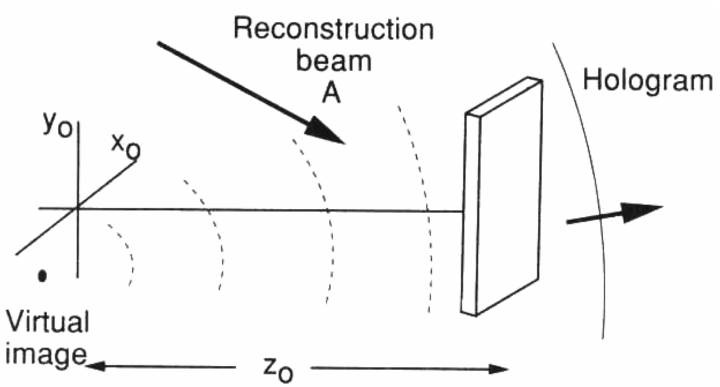
Image Formation by Holography



(a)



(c)



(b)

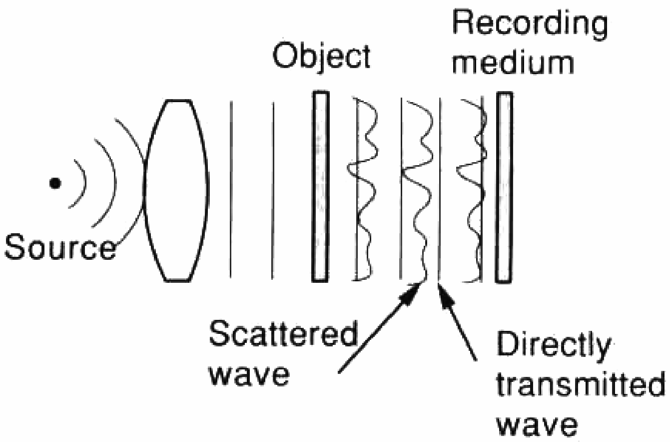
Virtual image

$$a_0 \exp\left[jk\sqrt{z_0^2 + (x-\hat{x}_0)^2 + (y-\hat{y}_0)^2} \right]$$

Real image

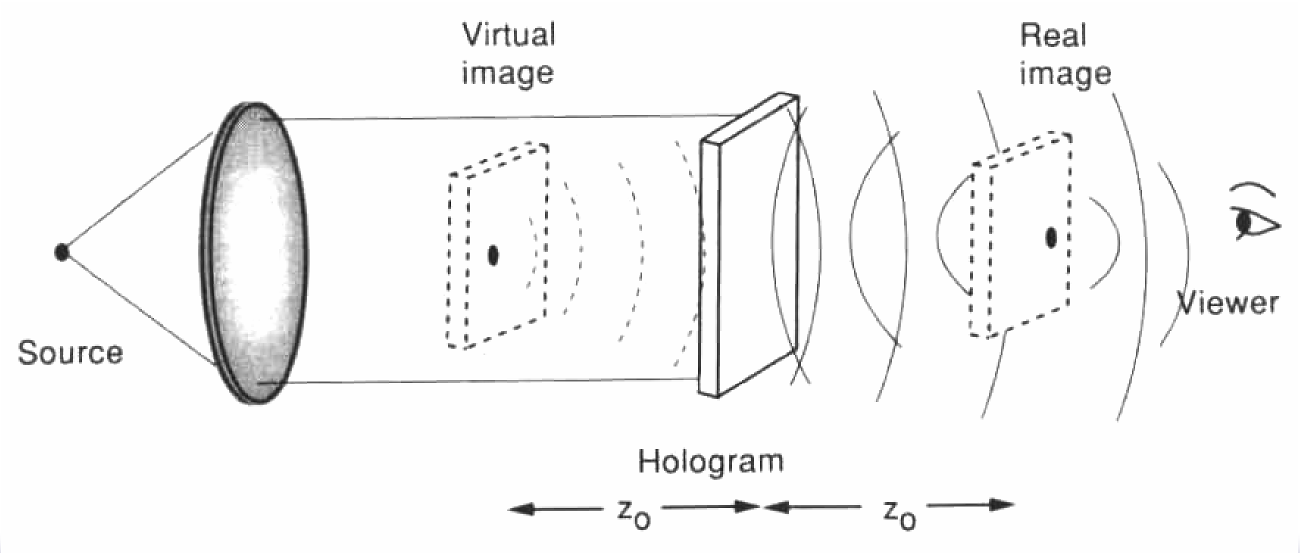
$$a_0^* \exp\left[-jk\sqrt{z_0^2 + (x-\hat{x}_0)^2 + (y-\hat{y}_0)^2} \right]$$

Gabor Hologram

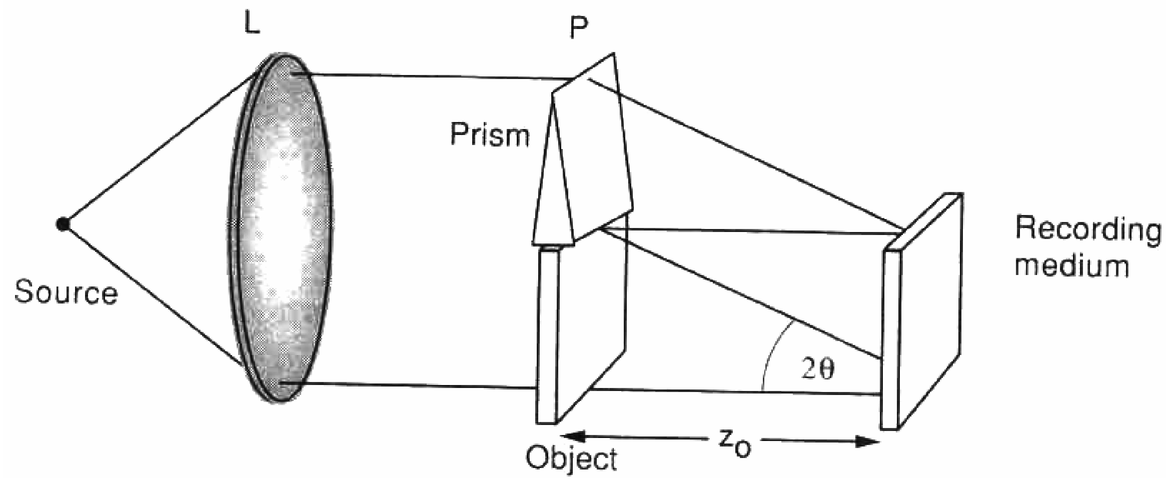


$$I(x,y) = |A + a(x,y)|^2$$

$$= |A|^2 + |a(x,y)|^2 + A^* a(x,y) + A a^*(x,y)$$



Leith-Upatnieks Hologram (I)

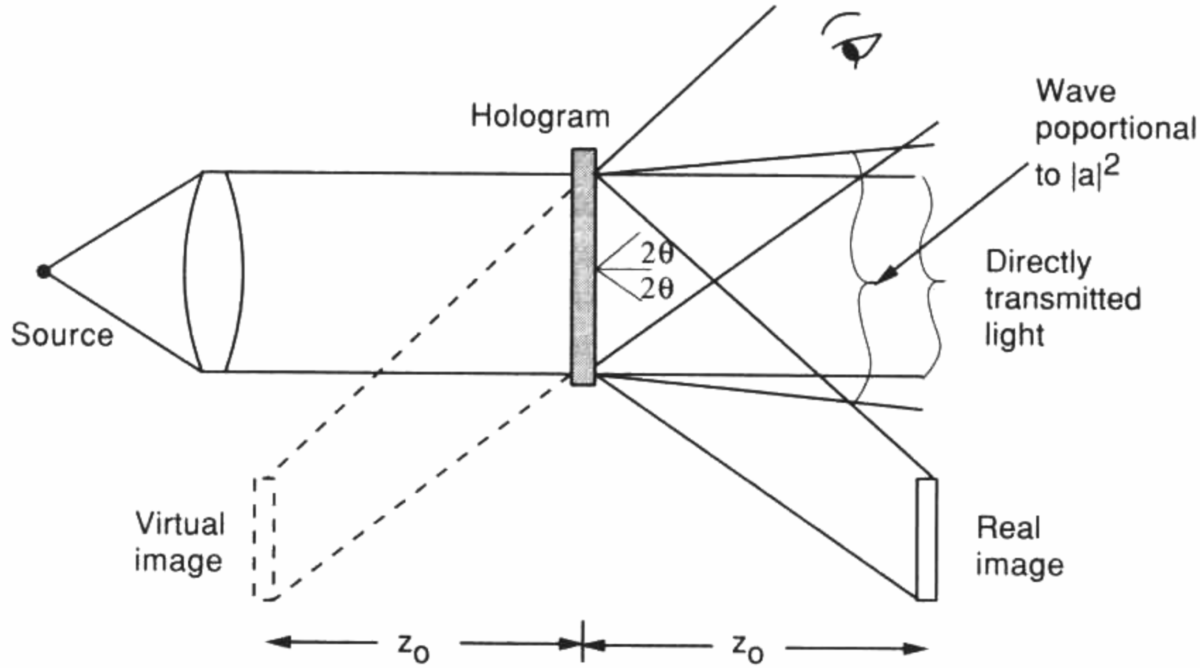


$$U(x,y) = A\exp(-j2\pi\alpha y) + a(x,y)$$

$$\alpha = \frac{\sin 2\theta}{\lambda}$$

$$I(x,y) = |A|^2 + |a(x,y)|^2 + A^* a(x,y)\exp(j2\pi\alpha y) + A a^*(x,y)\exp(-j2\pi\alpha y)$$

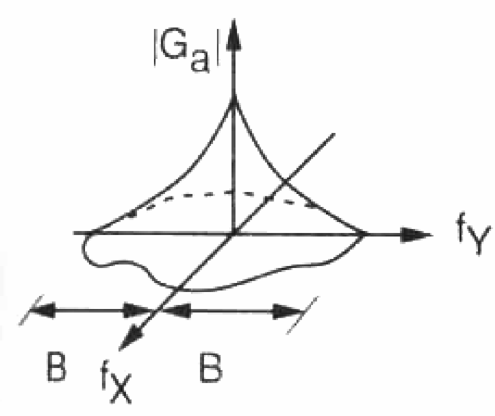
Leith-Upatnieks Hologram (II)



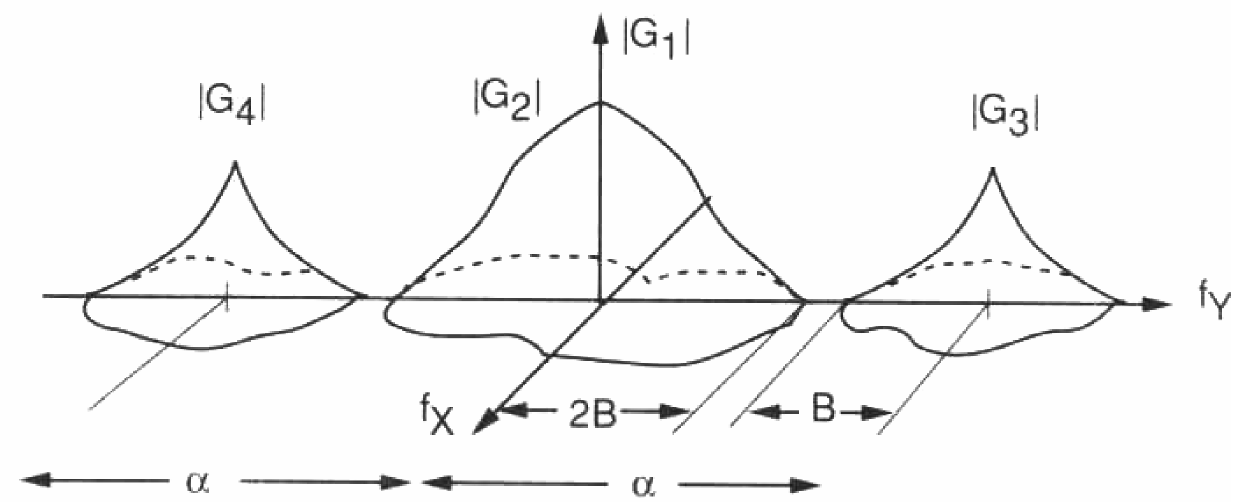
$$U_1 = t_b B \qquad U_3 = \beta' B A^* a(x,y)\exp(j2\pi\alpha y)$$

$$U_2 = \beta' B |a(x,y)|^2 \qquad U_4 = \beta' B A a^*(x,y)\exp(-j2\pi\alpha y)$$

Requirement of Reference Beam Angle



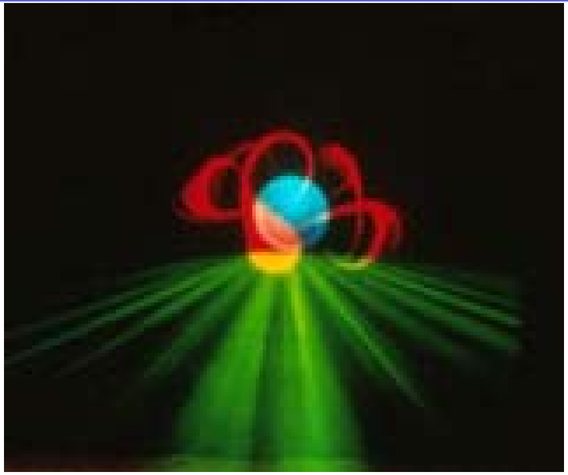
(a)

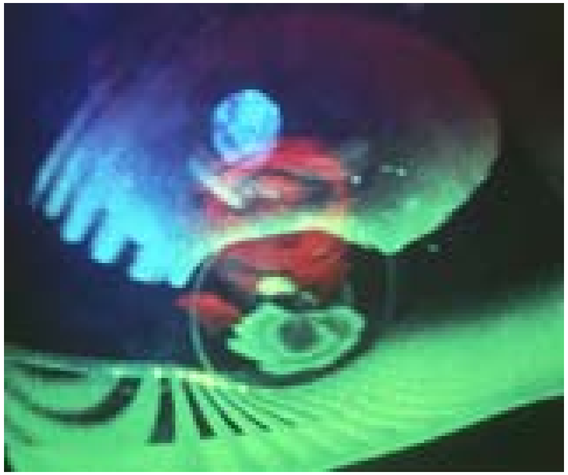


(b)

$$2\theta_{\min} = \sin^{-1}(3B\lambda)$$

Hologram Examples

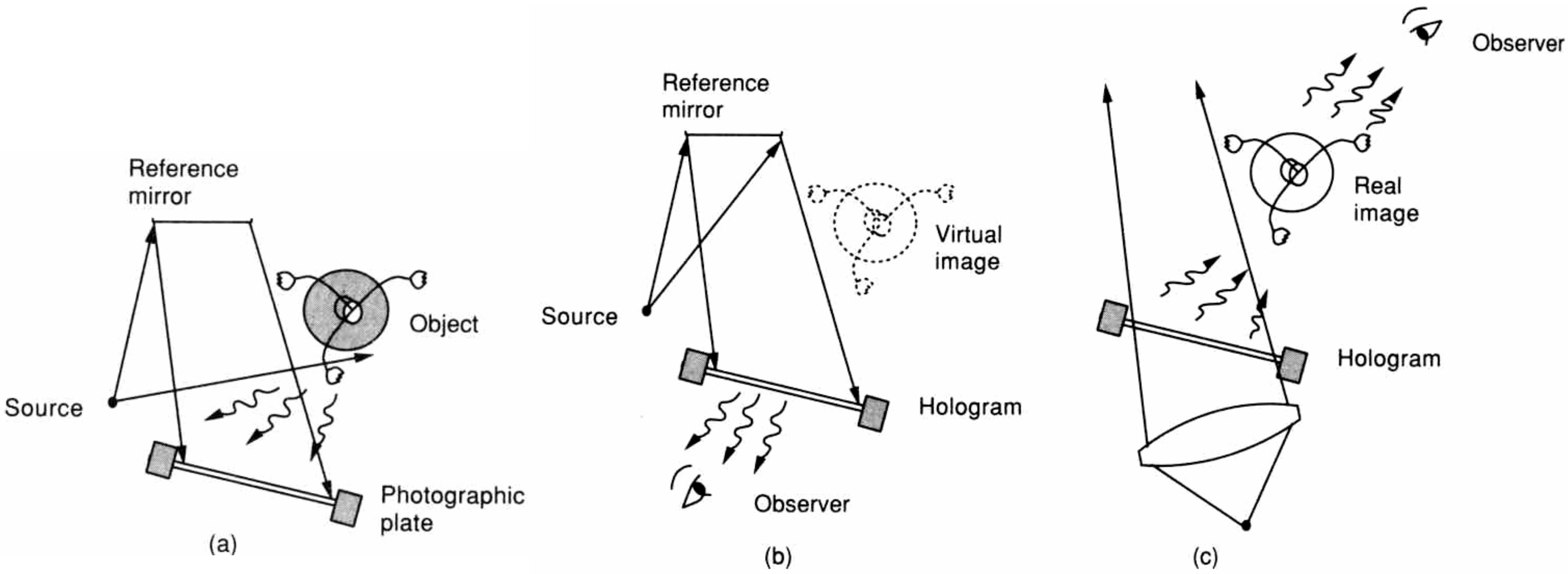




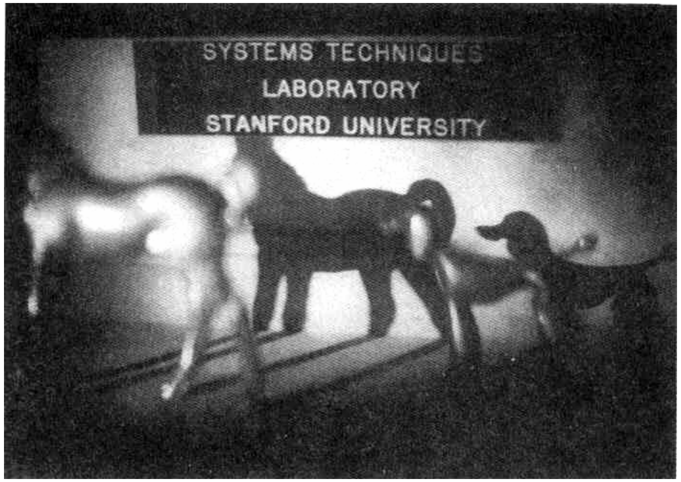
Bird and Train, by Emmett N. Leith and Juris Upatnieks, 1960, one of the earliest laser transmission images.

The Seed, an abstract white light transmission hologram by Dan Schweitzer, 1980.

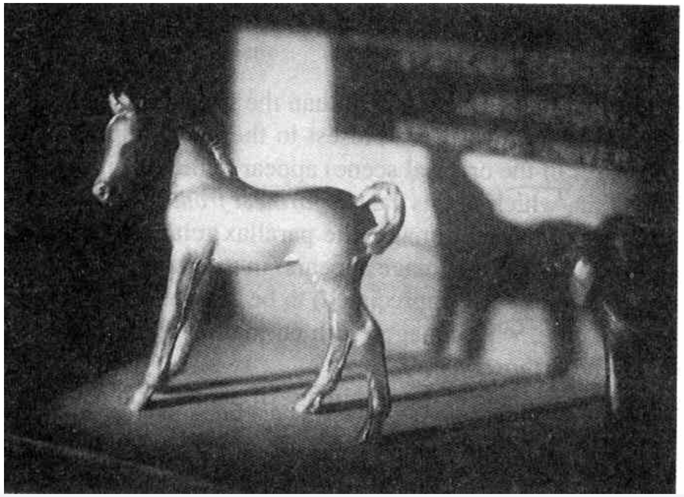
Holography of 3D Scenes (I)



Holography of 3D Scenes (II)



(a)



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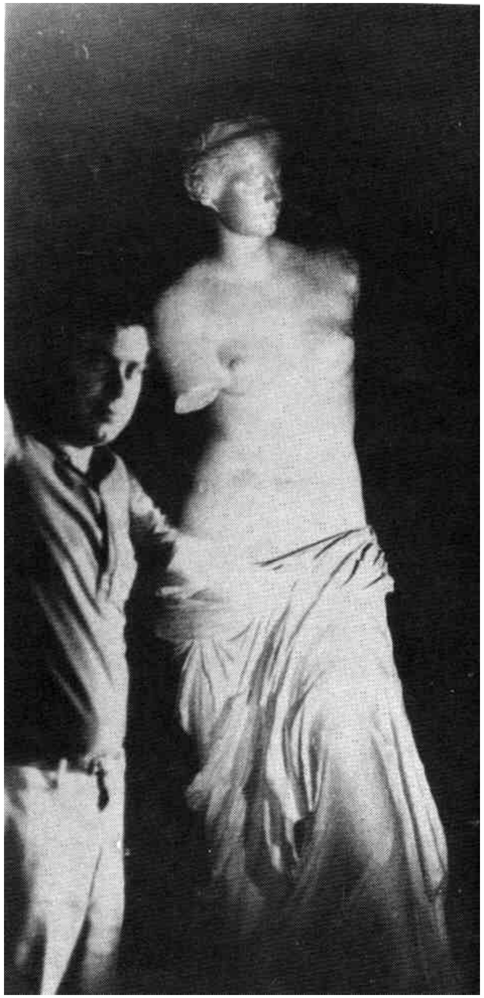
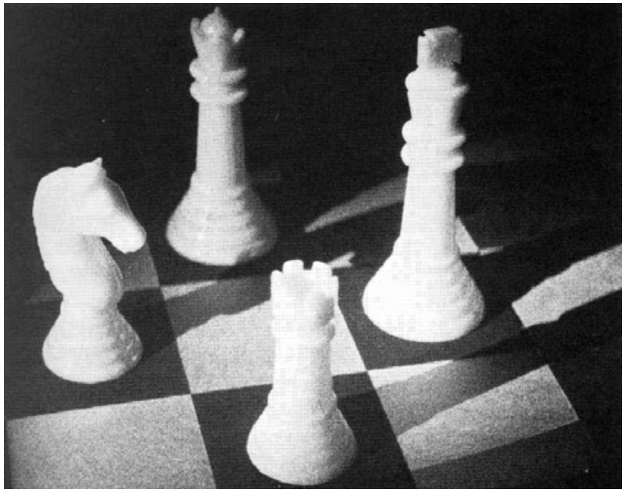
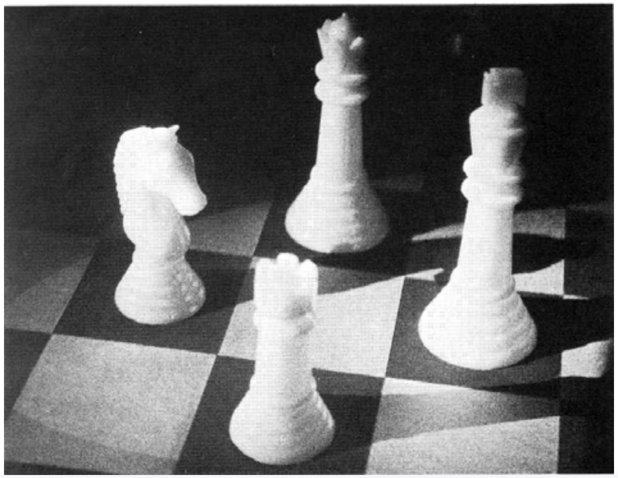


Parallax in Holograms





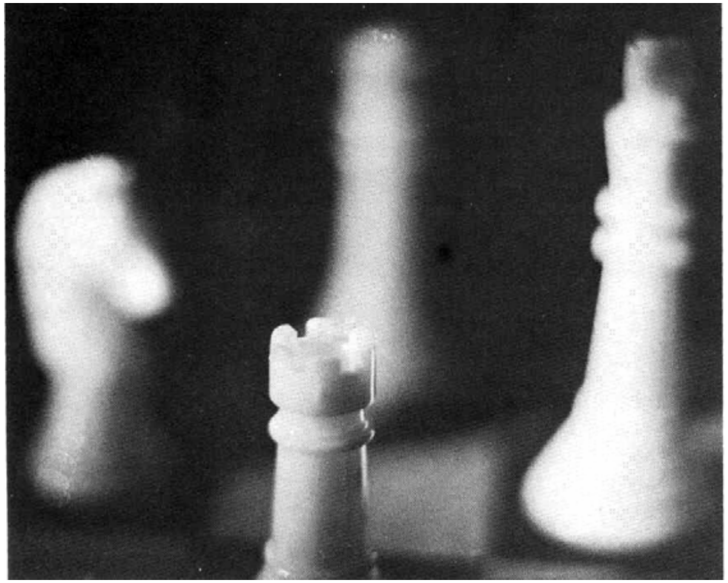
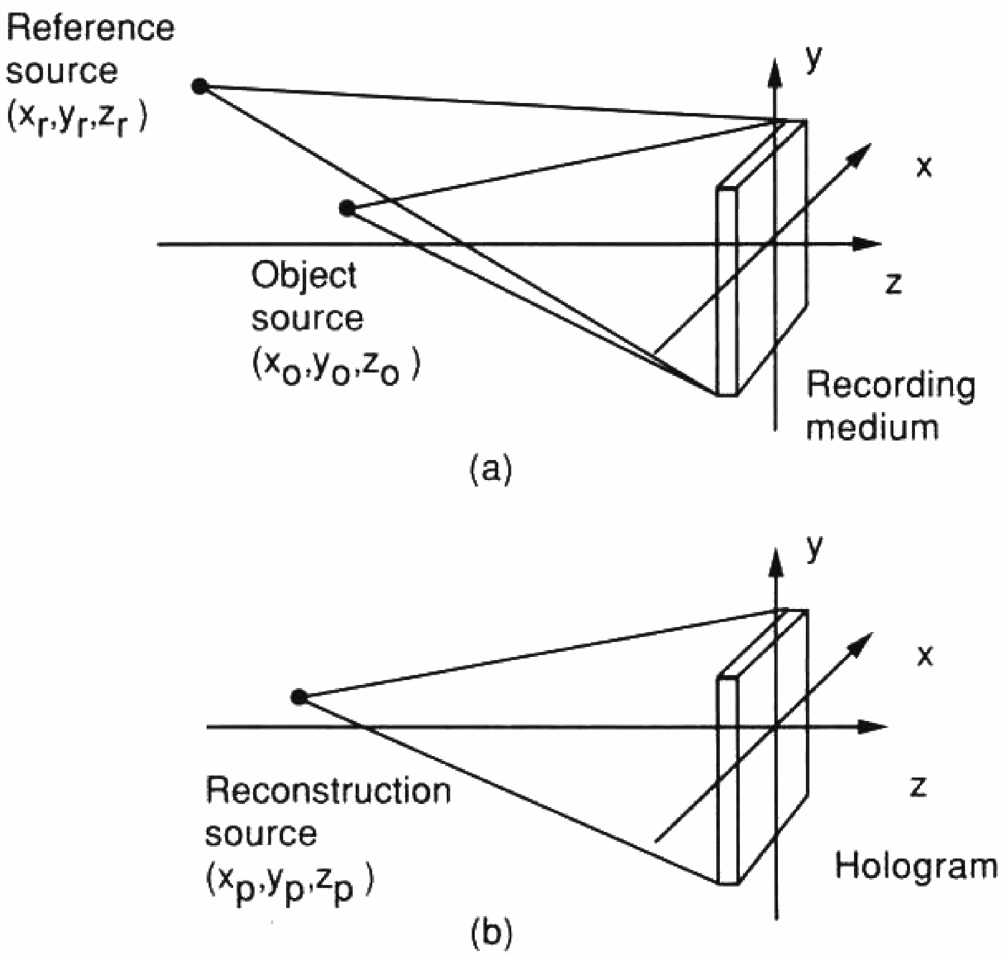


Image Location



$$z_i = \left(\frac{1}{z_p} \pm \frac{\lambda_2}{\lambda_1 z_r} \mp \frac{\lambda_2}{\lambda_1 z_0} \right)^{-1}$$

$$x_i = \mp \frac{\lambda_2 z_i}{\lambda_1 z_0} x_0 \pm \frac{\lambda_2 z_i}{\lambda_1 z_0} x_r + \frac{z_i}{z_p} x_p$$

$$y_i = \mp \frac{\lambda_2 z_i}{\lambda_1 z_0} y_0 \pm \frac{\lambda_2 z_i}{\lambda_1 z_0} y_r + \frac{z_i}{z_p} y_p$$

Image Magnification

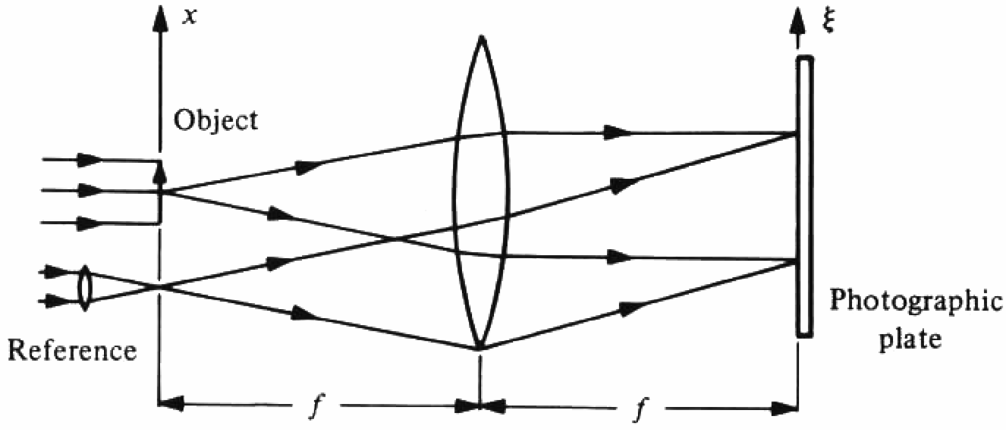
Transverse Magnification

$$M_t = \left|\frac{\partial x_i}{\partial x_0}\right| = \left|\frac{\partial y_i}{\partial y_0}\right| = \left|\frac{\lambda_2 z_i}{\lambda_1 z_0}\right| = \left|1 - \frac{z_0}{z_r} \mp \frac{\lambda_1 z_0}{\lambda_2 z_p}\right|^{-1}$$

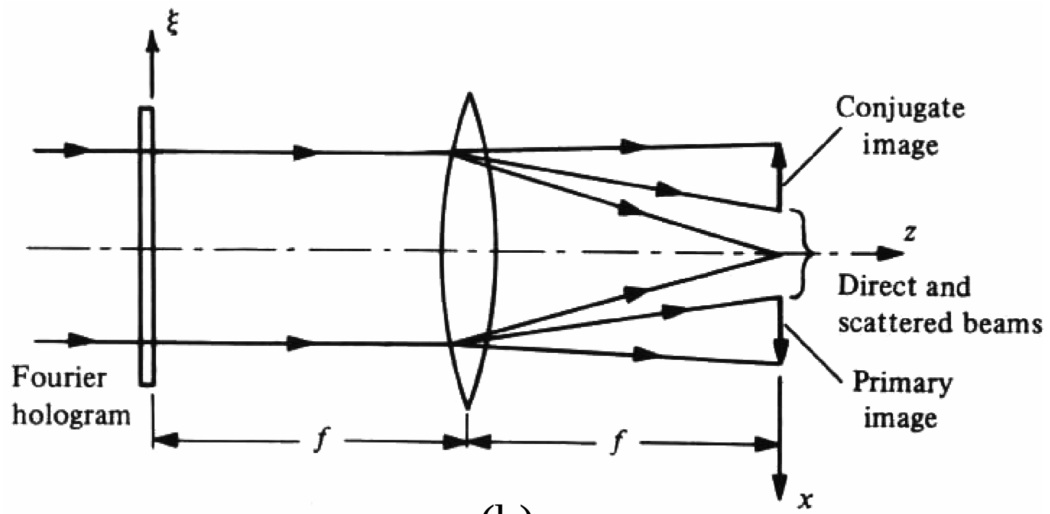
Axial Magnification

$$M_a = \left|\frac{\partial z_i}{\partial z_0}\right| = \left|\frac{\partial}{\partial z_0}\left(\frac{1}{z_p} \pm \frac{\lambda_2}{\lambda_1 z_r} \mp \frac{\lambda_2}{\lambda_1 z_0}\right)^{-1}\right| = \frac{\lambda_1}{\lambda_2} M_t^2$$

Fourier Hologram (I)

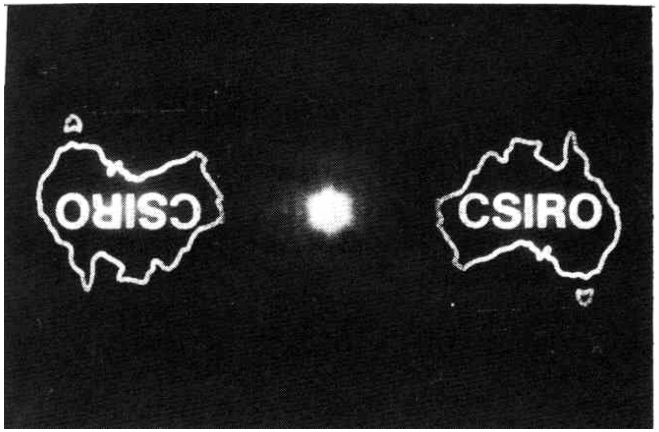


(a)



(b)

Fourier Hologram (II)



Lensless Fourier hologram

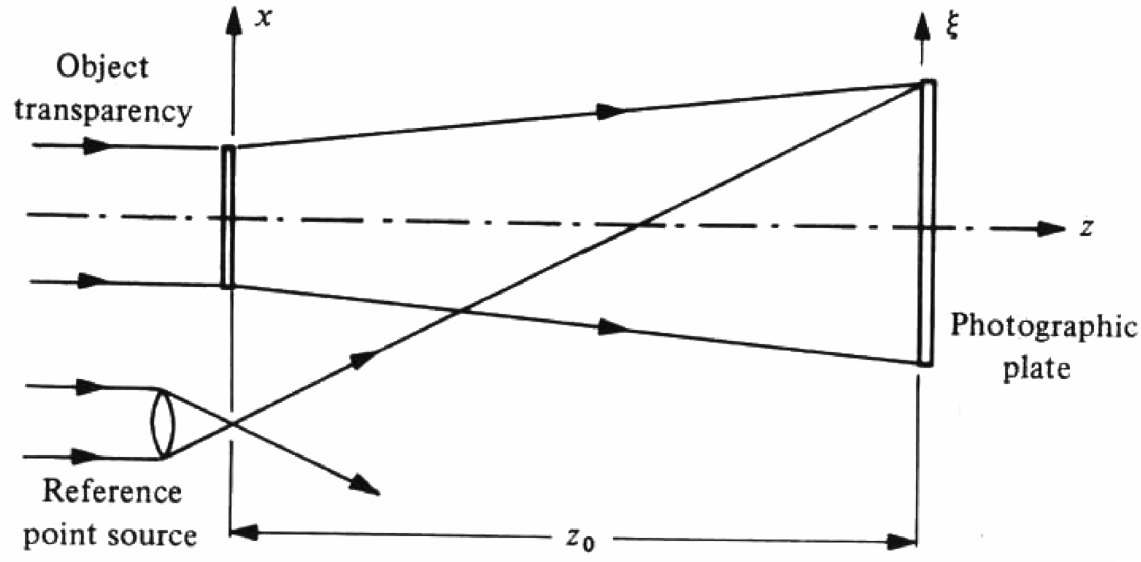
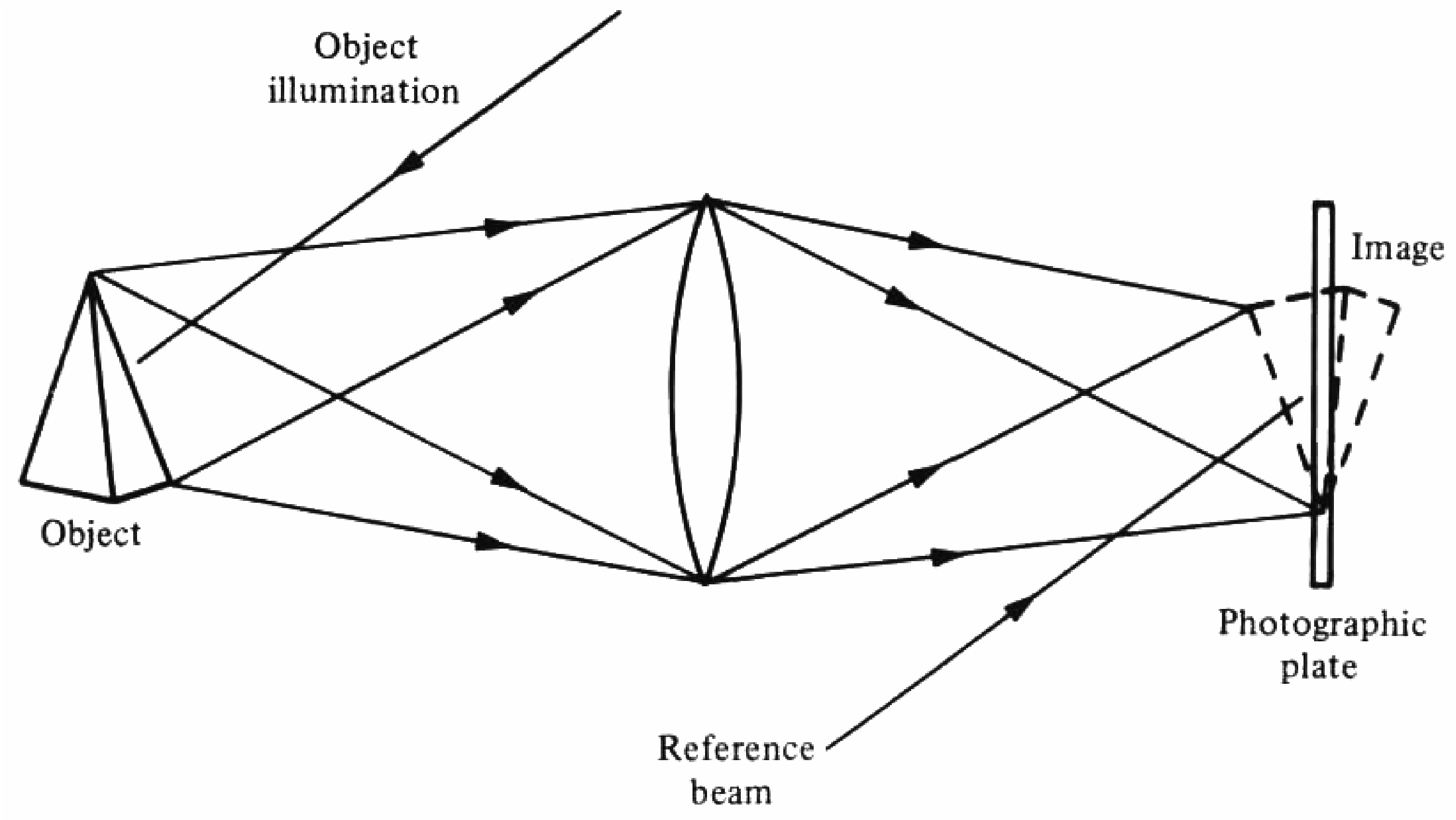
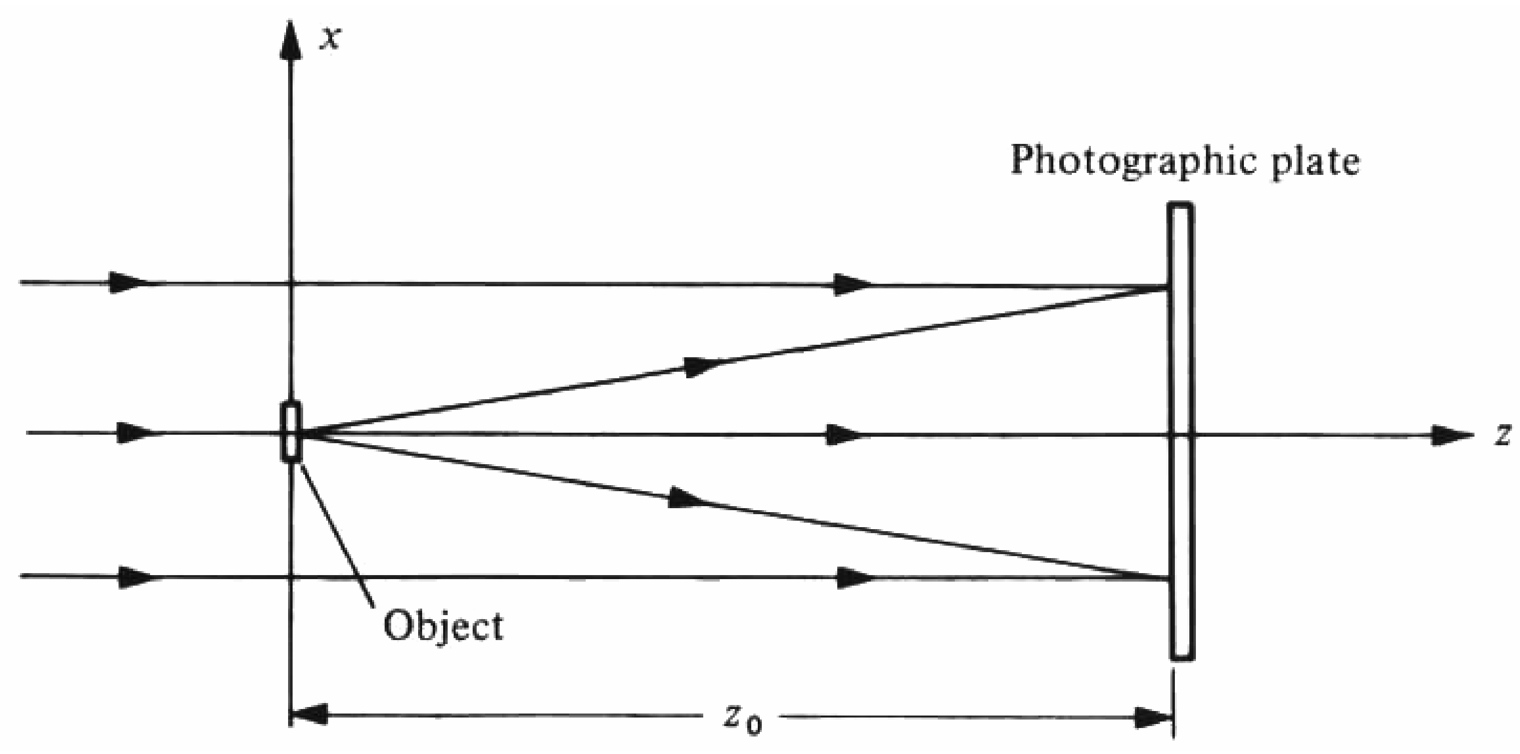


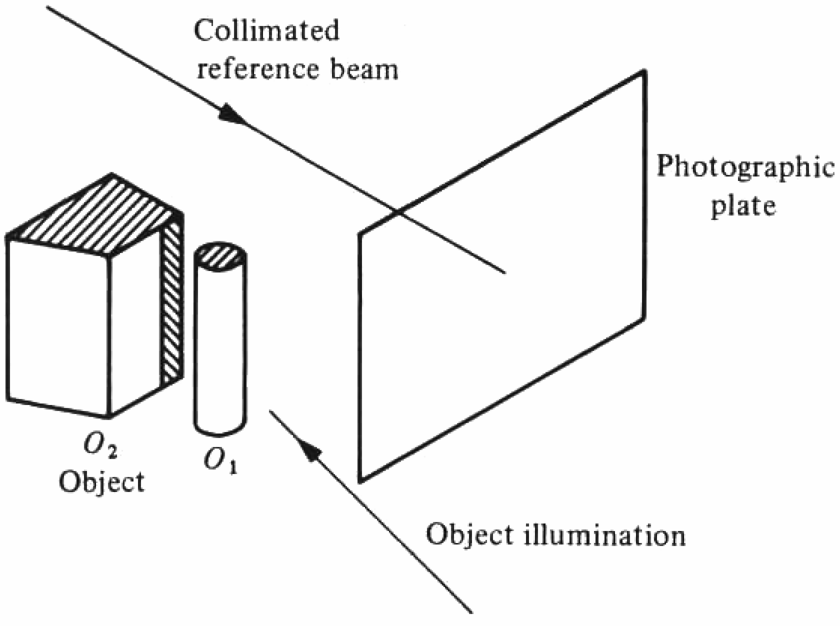
Image Hologram



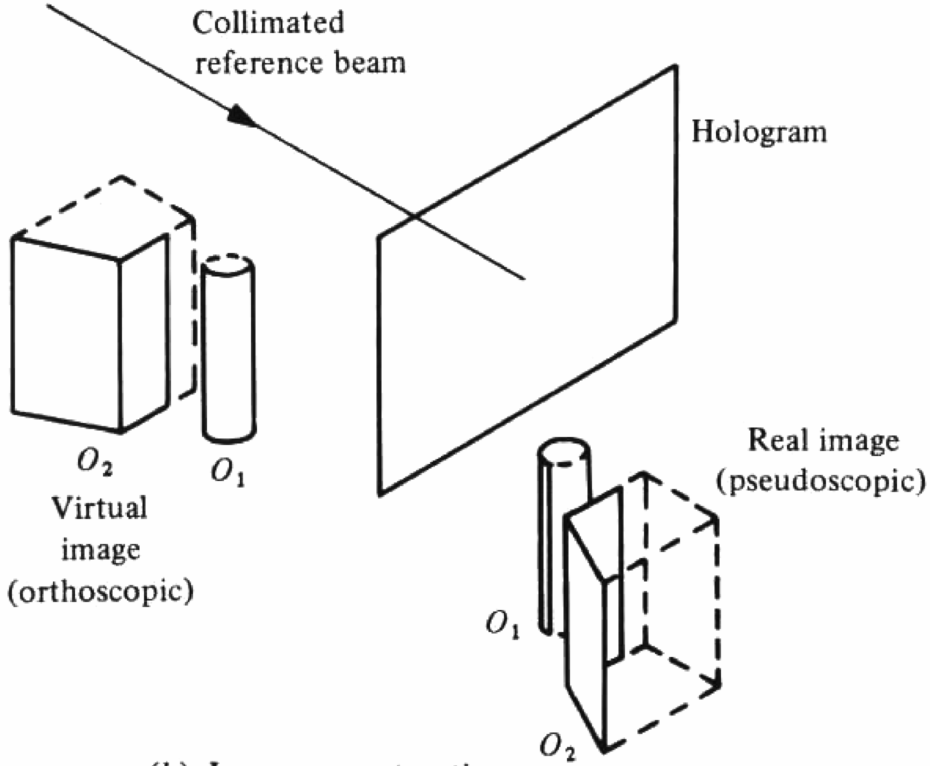
Fraunhofer Hologram



Orthoscopic and Pseudoscopic Images



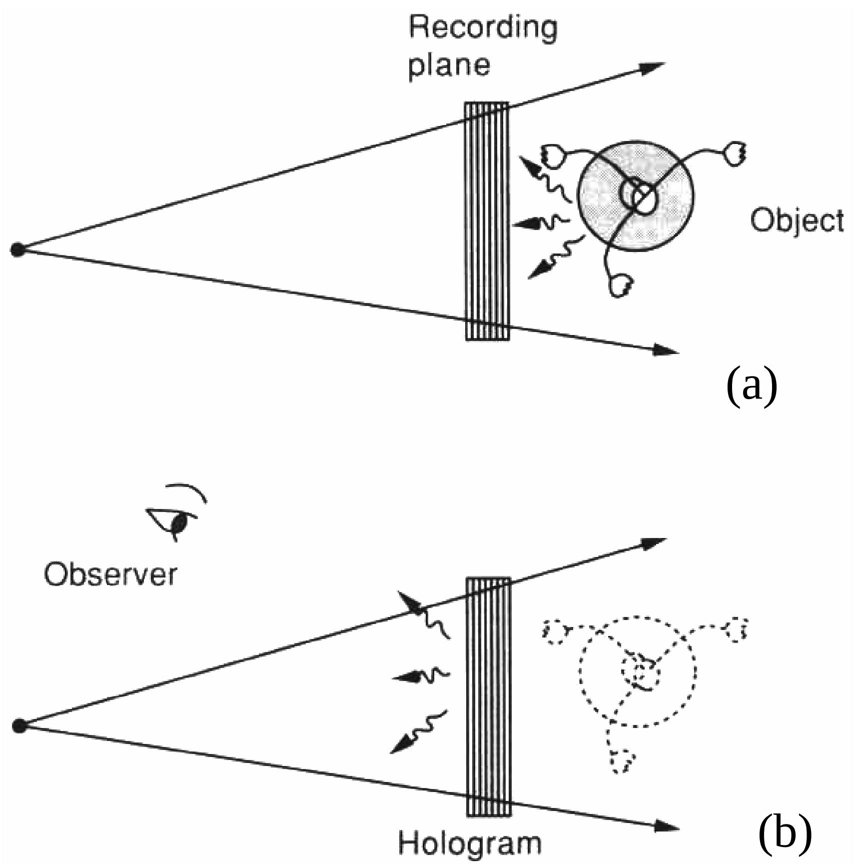
(*a*) Hologram recording

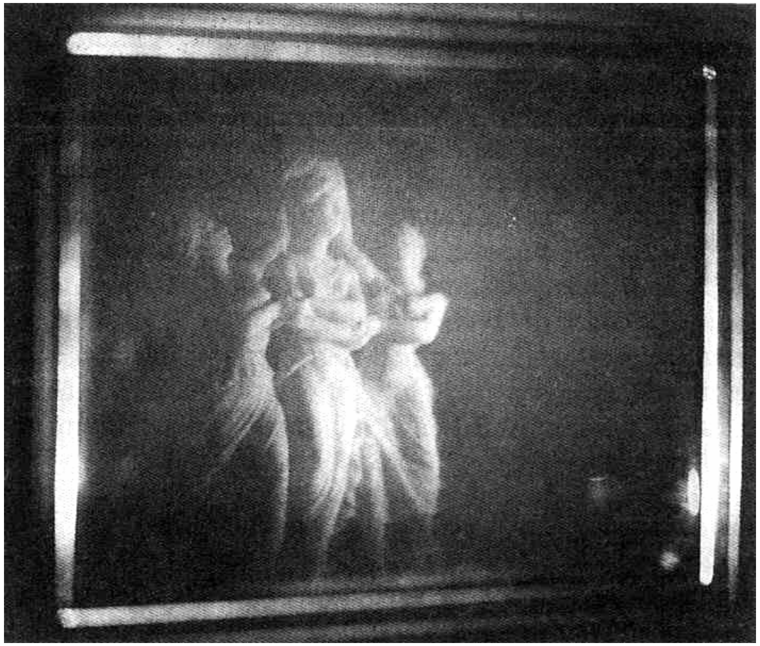


(*b*) Image reconstruction

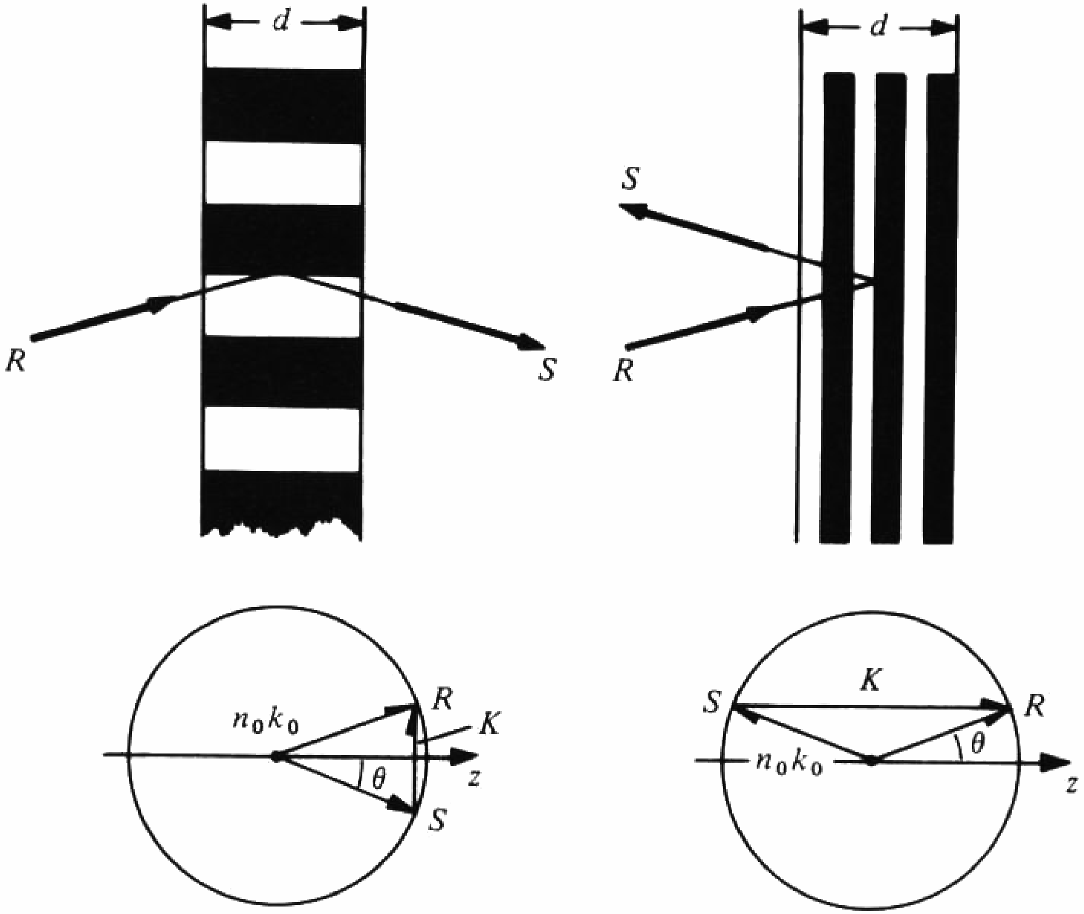
Transmission and Reflection Holograms (I)

• Reflection hologram





Transmission and Reflection Holograms (II)



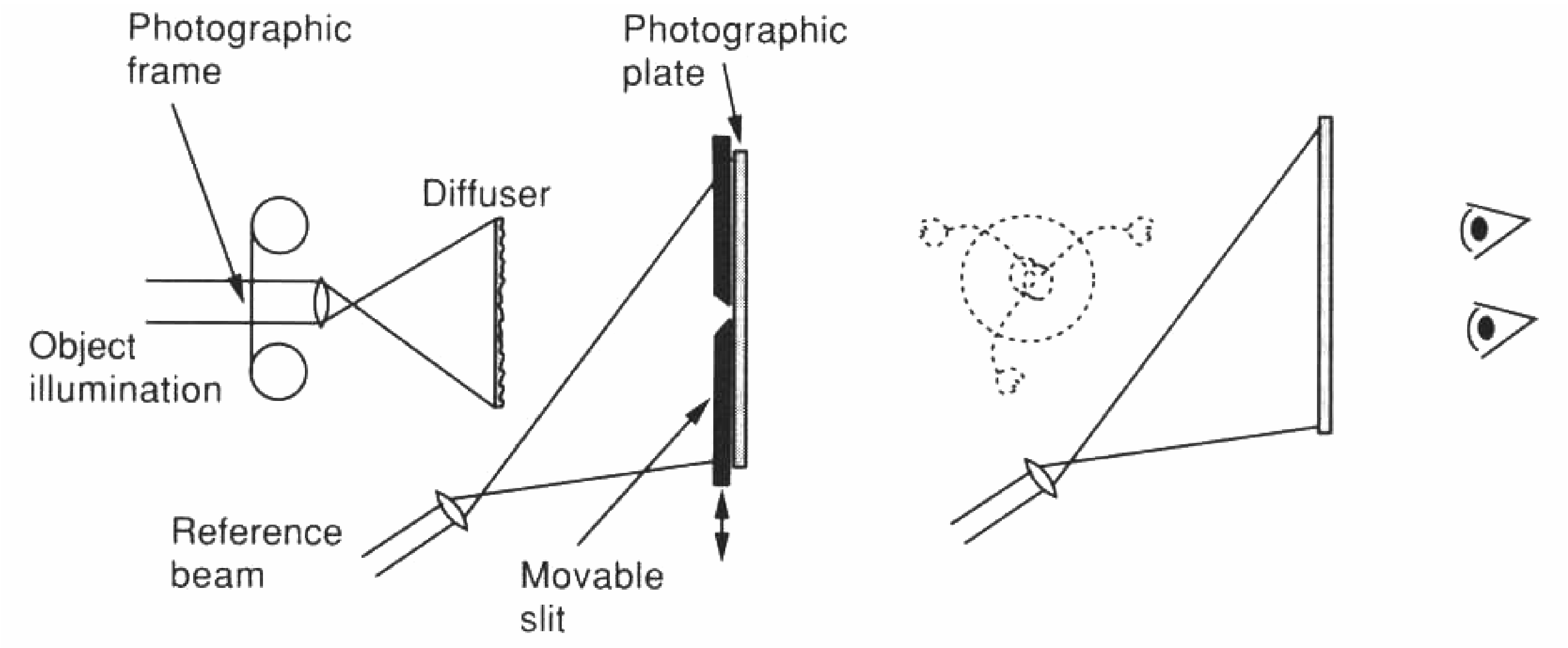
Transmission grating

Reflection grating

Maximum Theoretical Diffraction Efficiency

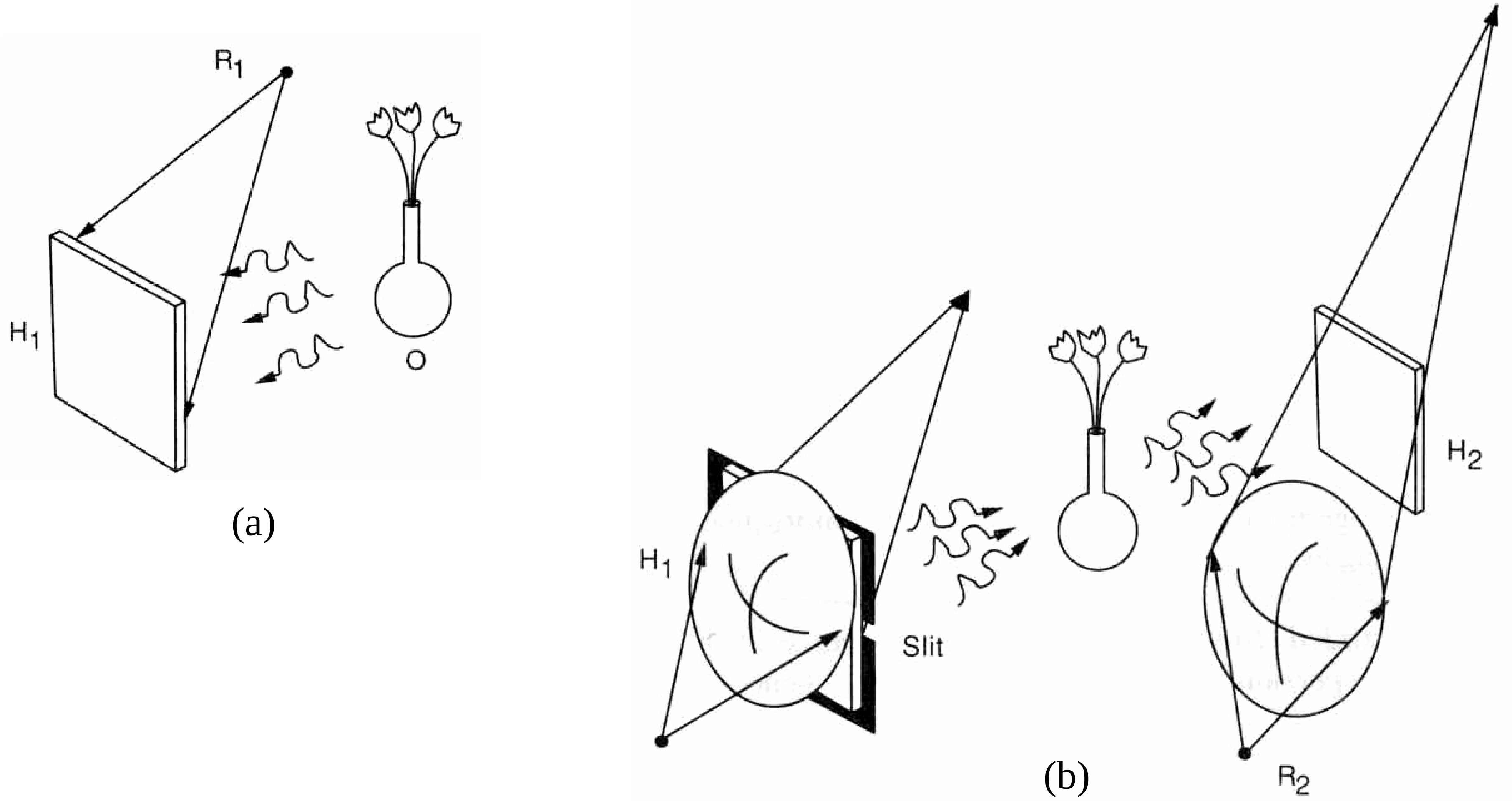
Type of grating	Thin transmission		Volume transmission		Volume reflection	
Modulation	Amplitude	Phase	Amplitude	Refractive index	Amplitude	Refractive index
ε_{max}	0.0625	0.339	0.037	1.00	0.072	1.00

Holographic Stereogram

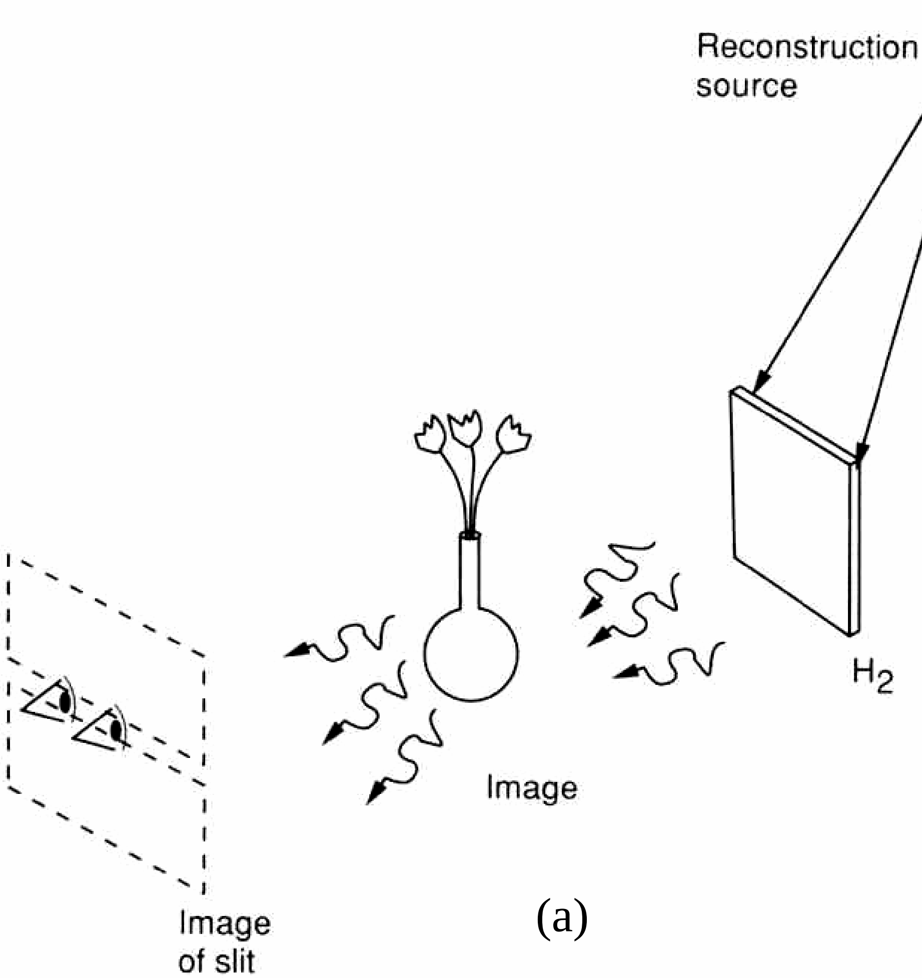


(a) (b)

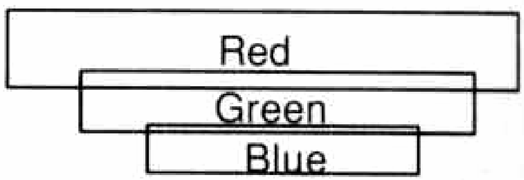
Rainbow Hologram (I)



Rainbow Hologram (II)

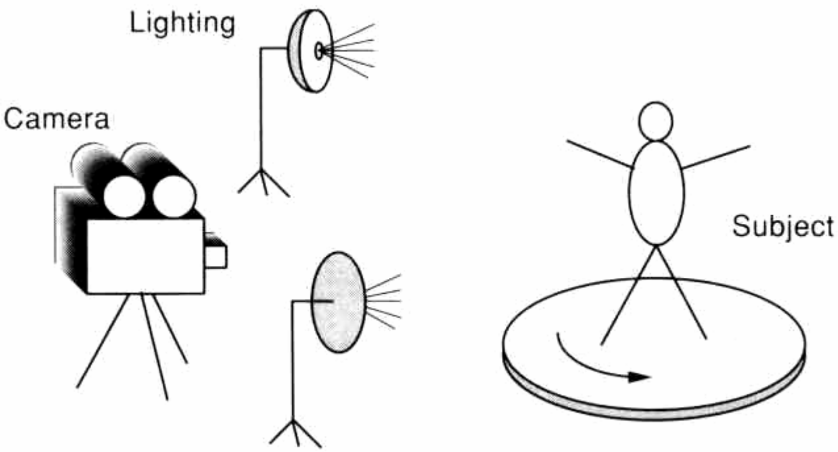


(a)

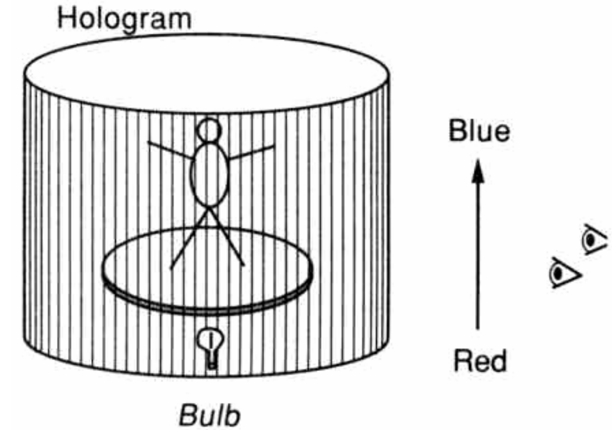


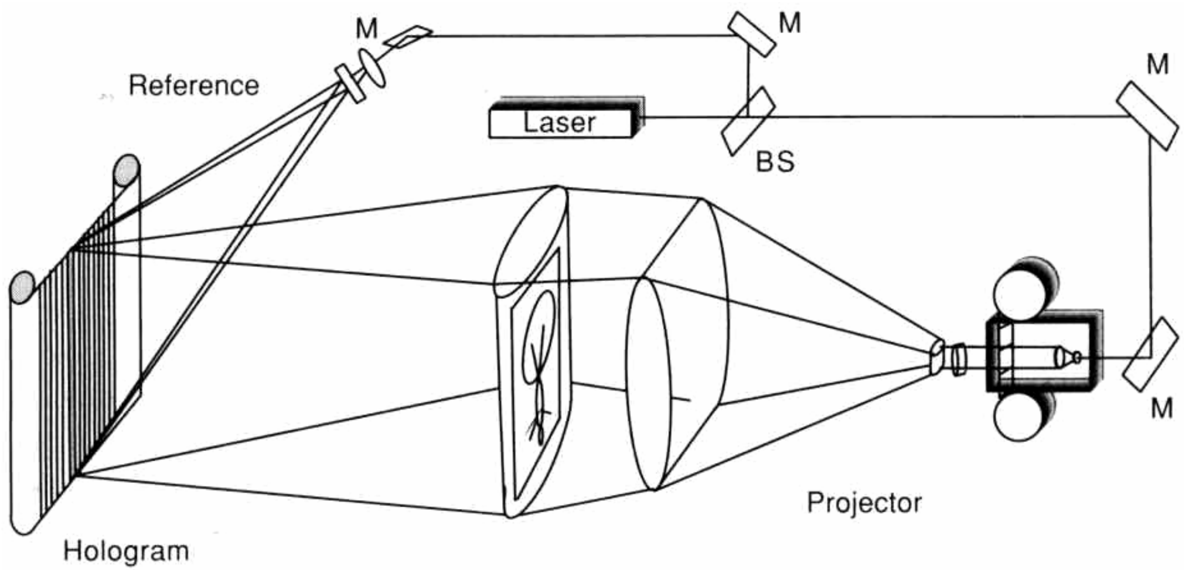
(b)

Multiplex Hologram



(a)





(b)

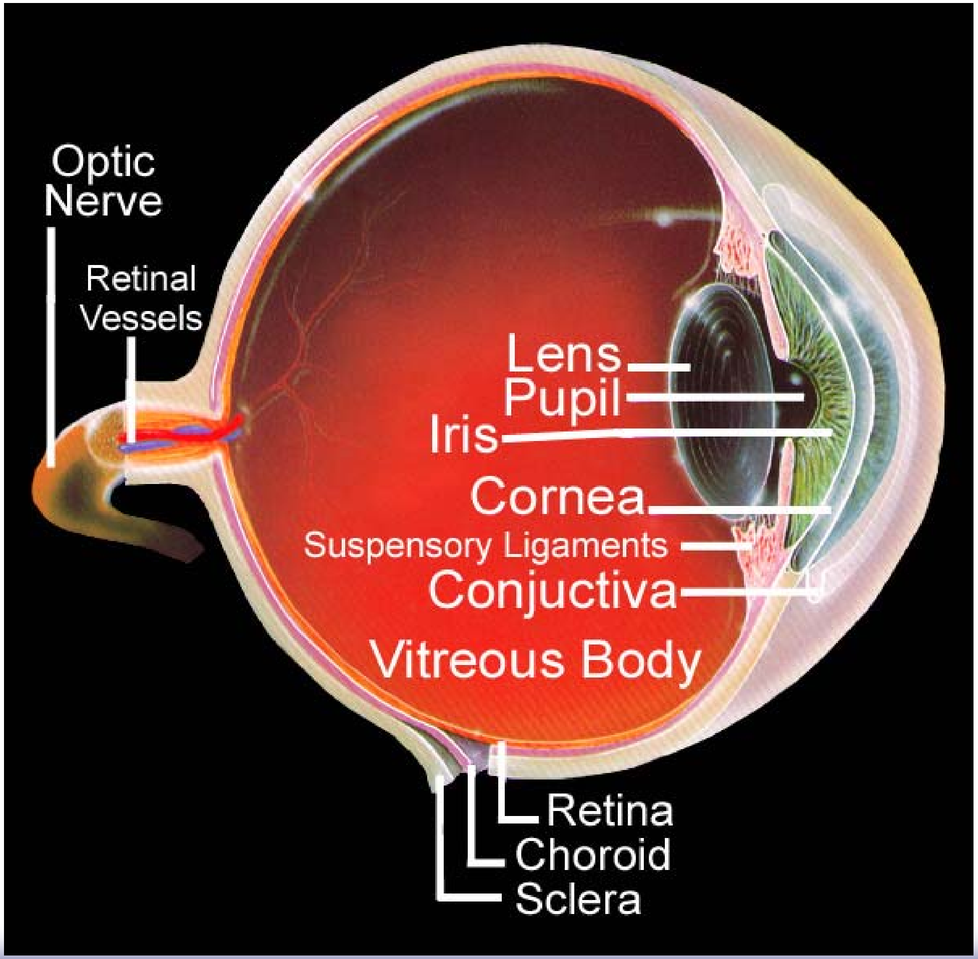
Holographic Materials (I)

Material	Reusable	Processing	Type of hologram	Exposure required J/m^2	Spectral sensitivity nm	Resolution limit mm^{-1}	Max. diffraction efficiency (sine grating)
Photographic emulsions	No	Wet chemical	Amplitude (normal) Phase (bleached)	5×10^{-3}–5×10^{-1}	400–700	1000–10000	0.05 0.60
Dichromated gelatin	No	Wet chemical	Phase	10^2	350–580	>10000	0.90
Photoresists	No	Wet chemical	Phase	10^2	uv–500	3000	0.30
Photopolymers	No	Post exposure	Phase	10–10^4	uv–650	200–1500	0.90
Photochromics	Yes	None	Amplitude	10^2–10^3	300–700	>5000	0.02
Photothermoplastics	Yes	Charge and heat	Phase	10^{-1}	400–650	500–1200 (bandpass)	0.30
Photorefractive							
$LiNbO_3$	Yes	None	Phase	10^4	350–500	>1500	0.20
$Bi_{12}SiO_{20}$	Yes	None	Phase	10	350–550	>10000	0.25

Holographic Materials (II)

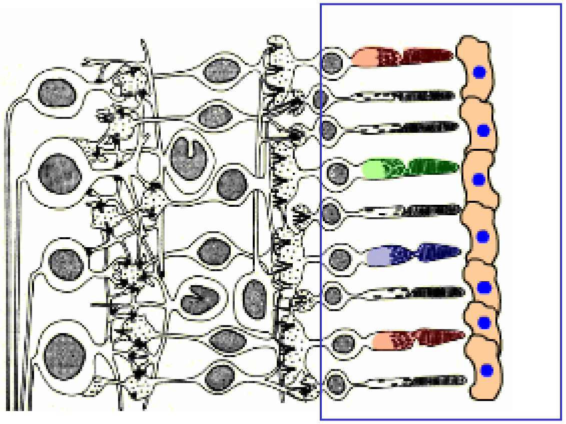
Type: Plates	Type: Film	Spectral sensitivity	Exposure (J/m^2) for $t=0.5$	Emulsion thickness μm: Plate	Emulsion thickness μm: Film	Grain size nm	Resolution limit mm^{-1}
Agfa-Gevaert (Holotest)							
10E56	10E56	Blue–green	10^{-2}	7	5	90	3000
10E75	10E75	Red	5×10^{-3}	7	5	90	3000
8E56HD	8E56HD	Blue–green	2.5×10^{-1}	7	5	35	> 3000
8E75HD	8E75HD	Red	10^{-1}	7	5	35	> 3000
Eastman Kodak							
649F	649F	Panchro	5×10^{-1}	15	6	60	> 3000
120-01/02	SO-173	Red	2×10^{-1}	6	6	50	> 3000
125-01/02	SO-424	Blue–green	5×10^{-2}	7	3	65	1250
131-01/02	SO-253	Red	3×10^{-3}	9	9	70	1250

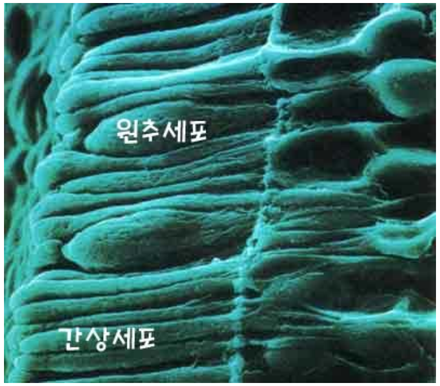
Eye

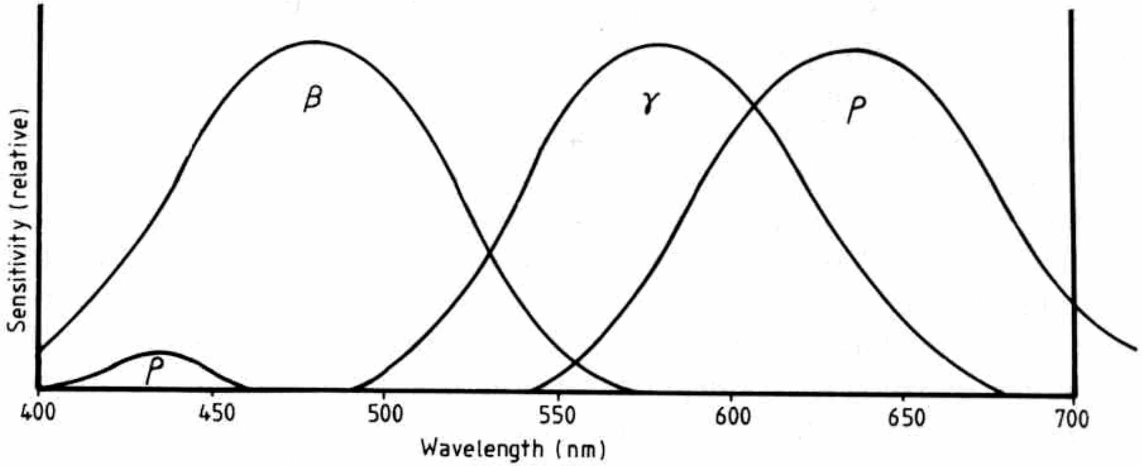


Optic Nerve
Retinal Vessels
Lens
Pupil
Iris
Cornea
Suspensory Ligaments
Conjuctiva
Vitreous Body
Retina
Choroid
Sclera

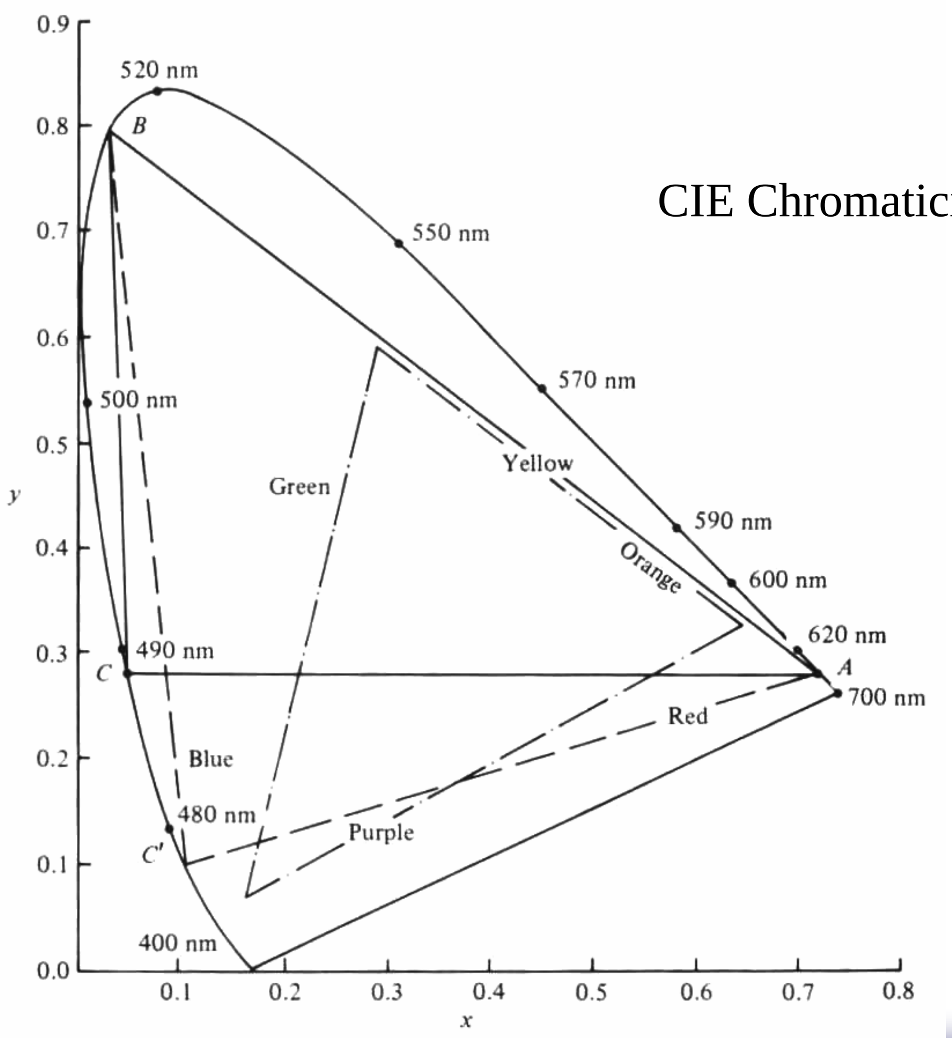
Color




원추세포
간상세포

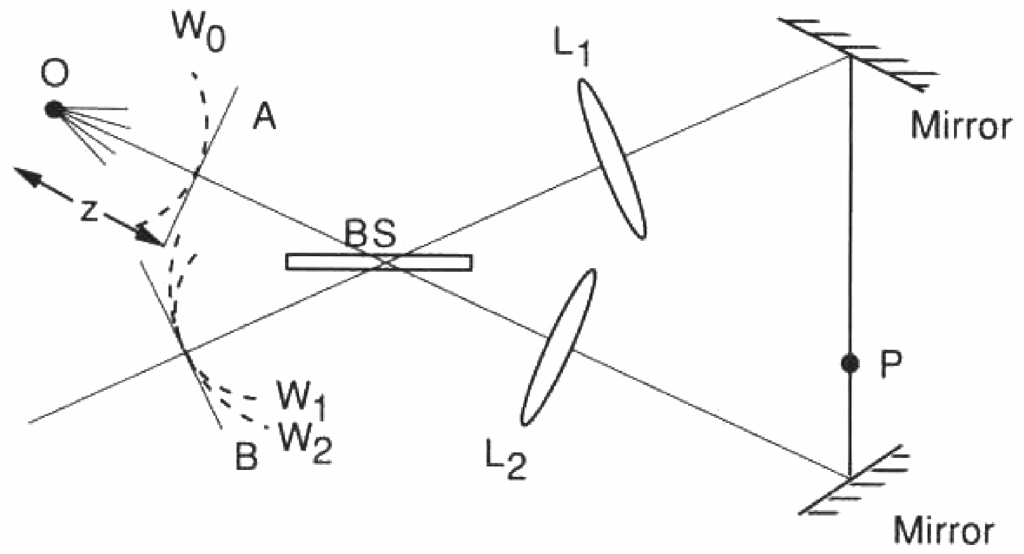

β
γ
ρ
ρ
Sensitivity (relative)
400
450
500
550
600
650
700
Wavelength (nm)

Color Holography



CIE Chromaticity diagram

Incoherent Holography



$$M_1 = -\frac{f_2}{f_1}$$

$$M_2 = -\frac{f_1}{f_2}$$

$$U_a(x,y) = U_0 \exp\left[j\frac{\pi}{\lambda z}\left(x^2 + y^2\right)\right]$$

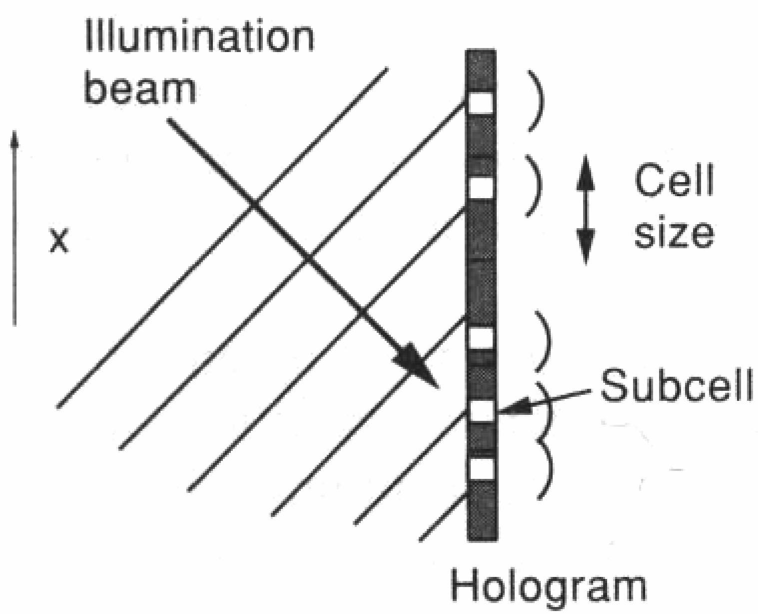
$$U_b(x,y) = U_1 \exp\left\{ j\frac{\pi}{\lambda z}\left[\left(\frac{x}{M_1}\right)^2 + \left(\frac{y}{M_1}\right)^2\right]\right\} + U_2 \exp\left\{ j\frac{\pi}{\lambda z}\left[\left(\frac{x}{M_2}\right)^2 + \left(\frac{y}{M_2}\right)^2\right]\right\}$$

Computer-Generated Hologram (CGH)

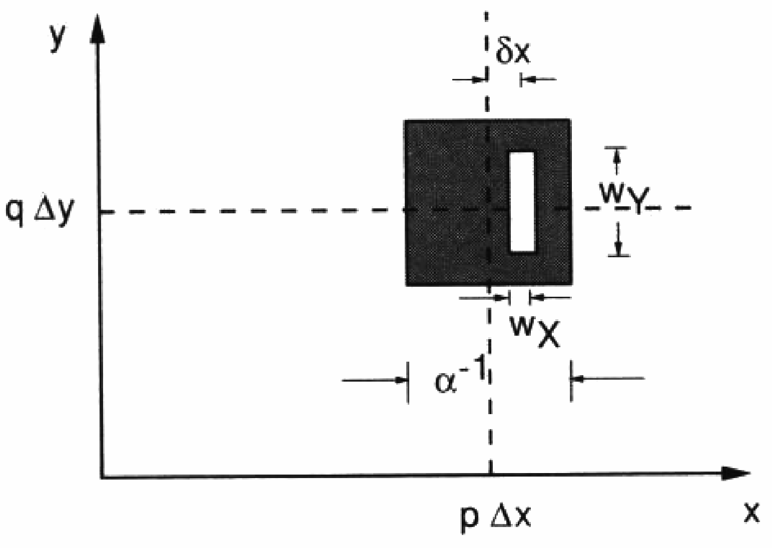
Type	Preparation	Gray levels	Comments
Superimposed FZP	Multi-exposure photo	Continuous	Limited number of points
Detour phase	Plotter output	Binary	Both phase and amplitude are quantized
Delay sampling	CRT display	Continuous	Fourier hologram
Synthetic interferogram	CRT display	Binary	Phase only
Kinoform	Bleached photo of plotter output	Plot- continuous Final result- transparent	Phase only, Special film treatment
ROACH	Bleached photo on triple-emulsion film	Continuous	Special film, Special treatment

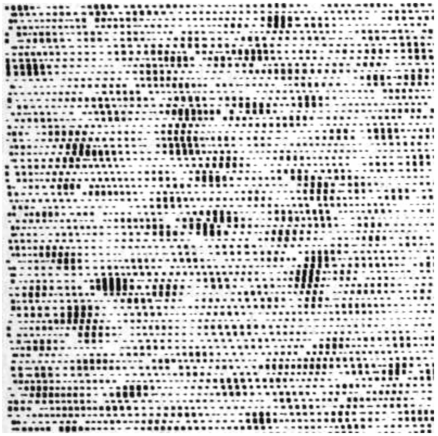
Detour-Phase Hologram (I)

$$U_f(u,\upsilon) = \sum_{p=0}^{N_X-1}\sum_{q=0}^{N_Y-1} |a_{pq}| e^{j\phi_{pq}} \exp\left[j\frac{2\pi}{\lambda f}(up\Delta x + \upsilon q\Delta y)\right]$$

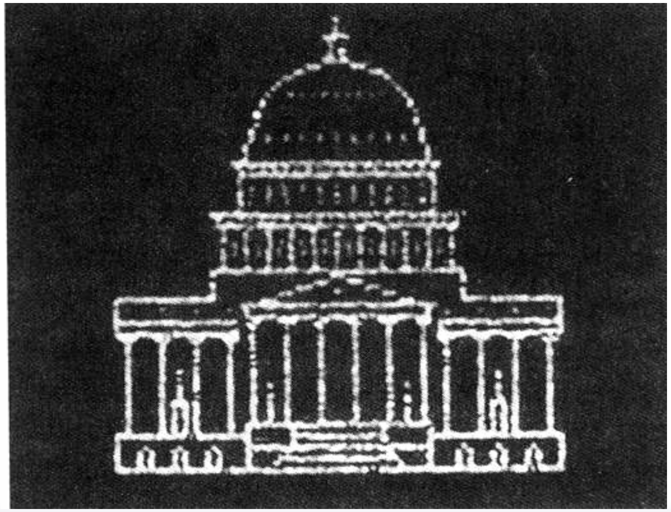


Detour-Phase Hologram (II)



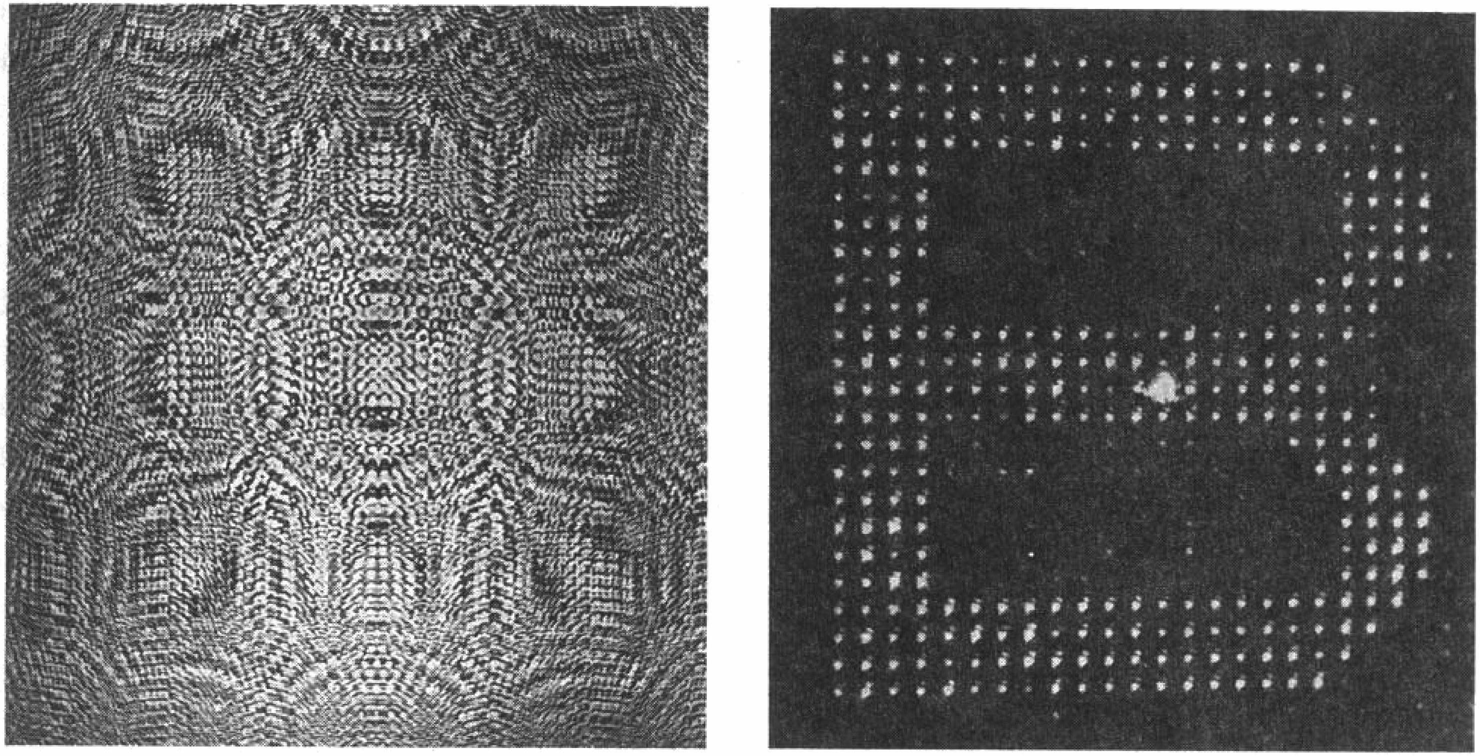


(a)



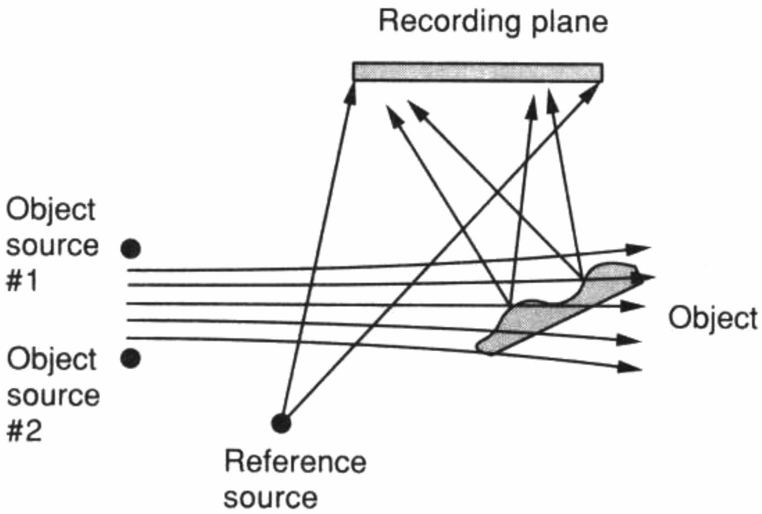
(b)

Kinoform



(a) (b)

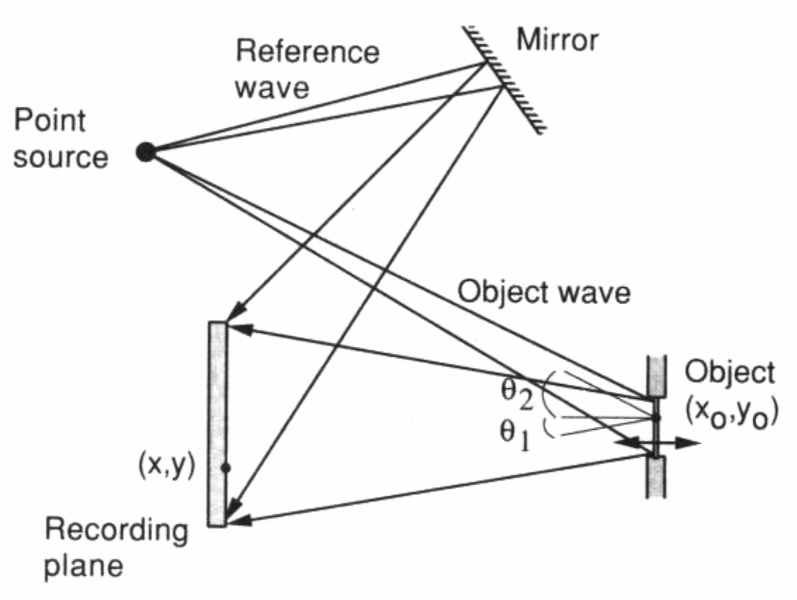
Contour Generation

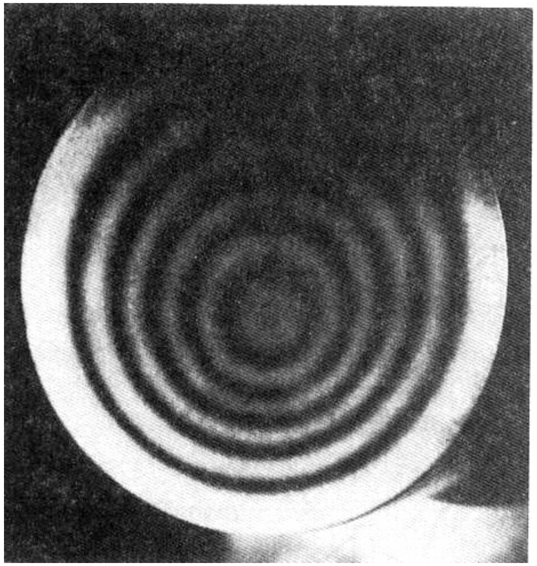


(a)

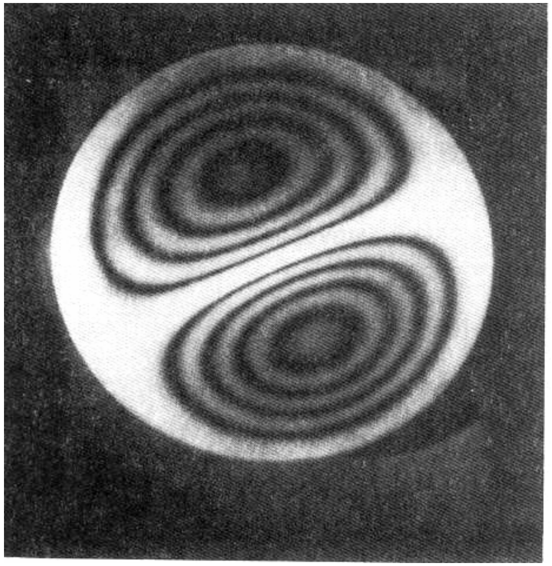
(b)

Vibration Analysis



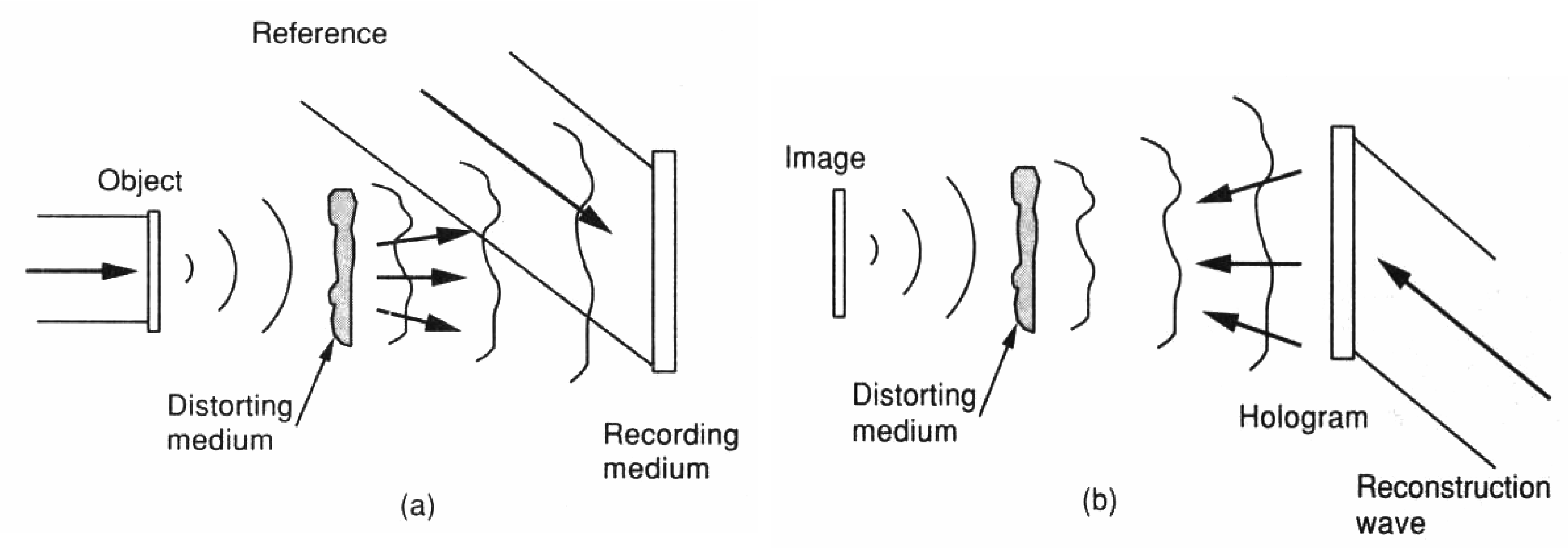


(a)

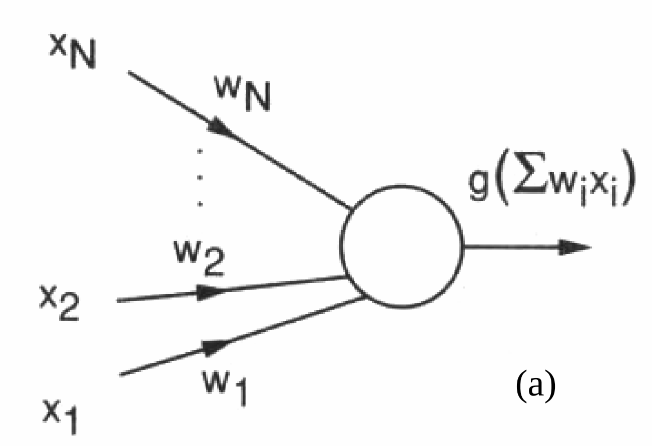


(b)

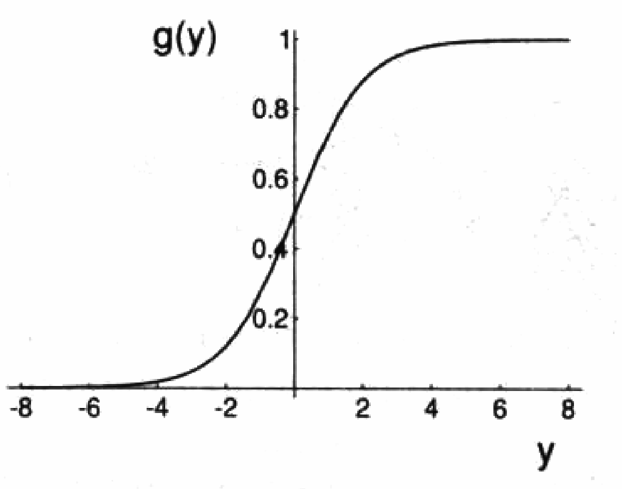
Aberration Compensation



Artificial Neural Networks



(a)



(b)