Kirk-Othmer Encyclopedia of Chemical Technology.

HOLOGRAPHY

Holography involves an image recording technique whereby the complete wave information (optical or other wave phenomena) emanating from a three-dimensional scene is captured in a suitable material and a reconstruction step where the information is replayed to reconstruct the true three-dimensional character of the recorded scene. The three-dimensional character of scenes reconstructed with a hologram is illustrated by photographs of the reconstruction from a single hologram taken from different viewing angles as shown in Figure 1. Each picture captures a unique perspective of the true scene as if the original scene were being viewed, to the extent that a properly prepared holographic portrait can seem very much as if the person were being viewed directly. In fact, a properly prepared hologram can exactly duplicate a particular wavefront at a specified wavelength. This is radically distinct from conventional photography where the film records only the intensity fluctuations of a flat projection (image) of the original scene with complete disregard of the relative phase distribution which stems from the wave nature of light. As implied by the name hologram which literally means "whole record," a hologram contains the complete intensity and phase information associated with a given scene.

In optical holography, the phase information carried by an object wave to be recorded is transformed into a complex interference pattern by combining it with a mutually coherent reference beam. The resulting nonuniform intensity distribution is then recorded with either standard photographic film or other specialized materials for holography. This indirect method of capturing both the intensity and phase information is necessary because the extremely high frequencies of light make direct sensing and recording impossible. This is in sharp contrast to acoustic and microwave phenomena where direct coherent sensing and recording are performed routinely with coherently phased array sonar and radar.

With the advent of new materials including polymers and photorefractive media, which require less handling complexity, relatively recent applications involving the storage and manipulation of information have been introduced. Significant advances in optoelectronics such as the introduction of compact semiconductor and solid-state lasers have also helped to fuel such new applications. This article describes a variety of such applications in addition to display holography which is more familiar and widespread. Before addressing the applications topics, however, the basic concepts of holographic recording and reconstruction must be addressed as well as the variety of materials and recording/reconstruction geometries that are currently available. There have been excellent discussions of the history behind the invention and development of holography which by itself is both fascinating and enlightening (1, 2).

0.1. The Holographic Principle

Holography involves the recording of the mutual interference pattern due to two mutually coherent optical fields. A generic holographic recording experiment is shown in Figure 2: an expanded and collimated laser beam is split into two paths, with one falling directly on the holographic material and the other scattering off an object to be collected on the same material. The first is called the reference and the second the object. Although variations of this basic arrangement exist, its simplicity is most suitable for the present discussion.

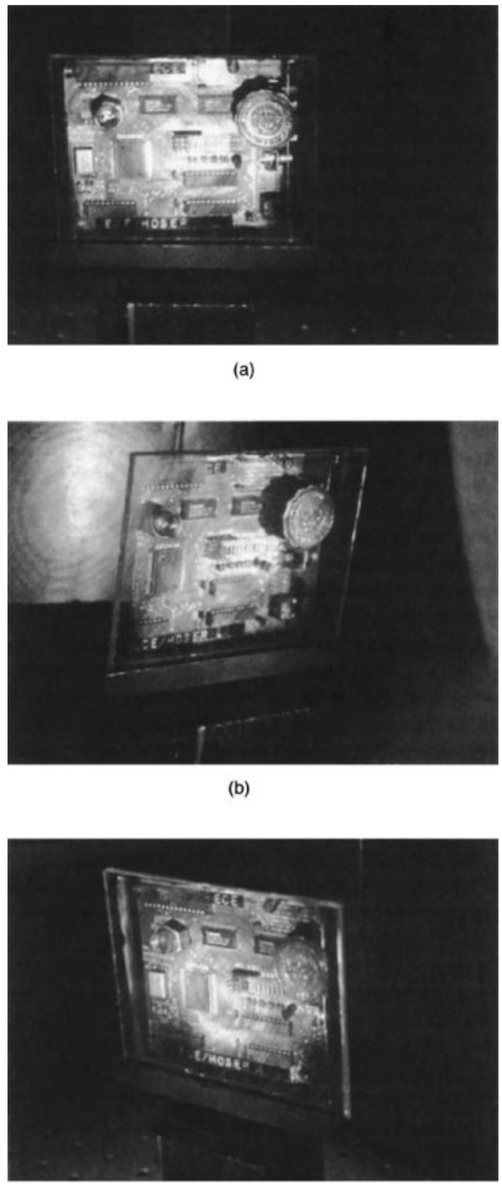

Fig. 1. Reconstructions from a hologram. (a) Normal viewing angle; (b) viewing from left side; (c) viewing from right side. Courtesy of Mr. Tae Jin Kim.

The intensity distribution falling on the film is given by equation 1, where S is the object wave amplitude and R represents the plane wave reference.

$$I \propto |S+R|^2 = |S|^2 + |R|^2 + SR^* + RS^* \qquad (1)$$

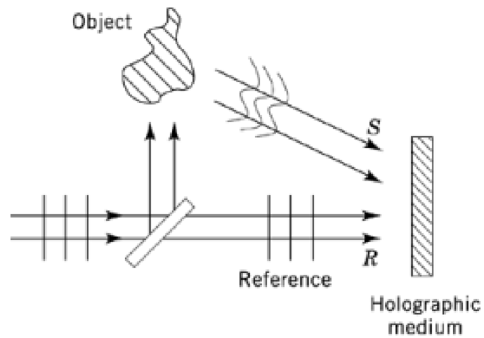

Fig. 2. Holographic recording system. S is the object wave and R the plane wave reference.

Film and other holographic recording media respond to the overall exposure or total optical energy per unit area deposited during the exposure time τ given by $\epsilon = \tau I$. An assumed linear relationship between the exposure and the transmittance of the film after exposure and development is given by equation 2, where t_0 is the average transmittance of the film and κ is a constant that depends on the material and processing.

$$t = t_0 + \kappa\tau\left(|S|^2 + |R|^2 + SR^* + RS^*\right) \tag{2}$$

The last two terms in the transmittance expression enable the holographic reconstruction process.

Reconstruction of the object wave is achieved by illumination of the developed hologram with the reference wave as shown in Figure 3**a.** The diffracted wave amplitude from the hologram is given by equation 3, where the first term represents the attenuated reference wave after passage through the hologram.

$$A_{\mathrm{diff}} \propto tR = \left[t_0 + \kappa\tau\left(|S|^2 + |R|^2\right)\right]R + \kappa\tau|R|^2 S + \kappa\tau R^2 S^* \tag{3}$$

The second term represents a virtual image of the original object signal which can be viewed by an observer looking at the hologram along the original object signal direction. The last term represents an unfocused wave which carries the complex conjugate of the signal amplitude emerging at a distinct angle from the hologram as shown in Figure 3**a.** This term can be brought to a focus by reconstructing the hologram with a plane wave traveling in exactly the opposite direction as the original reference wave as shown in Figure 3**b.** If $R = e^{ikx}$ represents the original plane wave reference, then $R^* = e^{-ikx}$ represents a wave traveling in the opposite case. In such a case, the diffracted wave amplitude is given by equation 4, where the last term represents a real image formed precisely at the location of the original object.

$$A_{\mathrm{diff}} \propto tR^* = \left[t_0 + \kappa\tau\left(|S|^2 + |R|^2\right)\right]R^* + \kappa\tau R^{*2} S + \kappa\tau|R|^2 S^* \tag{4}$$

Yet another variation in the reconstruction is to use the object wave to reconstruct the reference wave. This will be pursued further in a later section that describes the use of holography for pattern recognition.

0.2. Hologram Varieties

The rich variety in the types of holograms stems from the specifics of how the interference patterns are recorded. Although a more complete classification of the various hologram types is possible, the most important classification parameters are the material perturbation (amplitude or phase), material thickness (thin or thick), and the recording format (transmission or reflection). Most holograms can be classified using a combination of

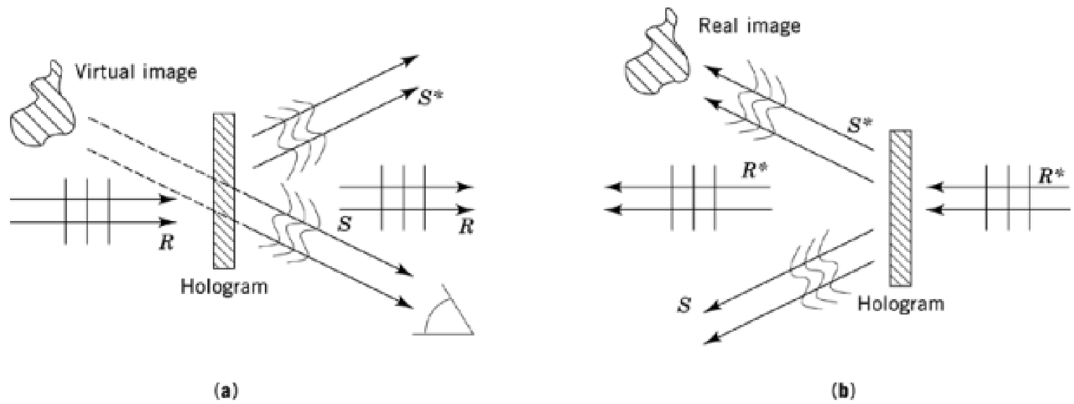

Fig. 3. Holographic reconstruction. (**a**) Reconstruction of virtual image of object; (**b**) reconstruction of real image of object.

these three parameters. In describing the basic hologram types, only the simplest planar gratings recorded by two intersecting plane waves are considered. These results can be generalized using the principles of coherent optics theory to address more complex problems involving nonplanar waves.

0.3. Material Perturbation

Exposure of a suitable holographic material to recording waves must induce perturbations of its optical transmission properties to record holograms. The perturbations may include a complex set of physical effects (3), but in most cases they can be lumped into one of two categories: (*1*) absorption perturbations and (*2*) phase perturbations. A unit amplitude plane wave at wavelength λ passing through a homogenous material of thickness T, refractive index n, and absorption constant α emerges with amplitude A, where the first multiplicative term describes the effect of material absorption and the second represents the imposed change in phase of the wave.

$$A = e^{-\alpha T} e^{i \frac{2\pi}{\lambda} nT} \qquad (5)$$

Holographic information can be recorded by spatially modulating either (or a combination of) the absorption or phase (index or thickness change).

In choosing a material for a particular application, the relative merits of each candidate must be considered. The material sensitivity, which can be loosely defined as the energy density that is required to induce a perturbation in either absorption or phase that represents a significant portion of the operating range, is an important characteristic. Holographic resolution defined as the number of line pairs per millimeter that the material can support is another important consideration. These parameters along with other less prominent but still important quantifiers are used to describe holographic materials in Table 1. In the following discussion the physical mechanisms that enable holographic recording in the materials are presented.

0.3.1. Absorption Materials

Materials that respond to incident exposure by absorption perturbations include photographic film and photochromic glasses/crystals (see Photography; Chromogenic materials, photochromic). The ideal absorption material would respond with an amplitude transmittance (the first multiplicative factor in eq. 5) that is linearly proportional to the recording exposure. All materials exhibit such a linearity only over a limited range of

Table 1. Characteristics of Holographic Materials

Material[a]	Reference	Sensitivity, J/cm^{2b}	Resolution, lines/mm	Wavelength, nm	Processing method
silver halide emulsion[c]	4	3.5×10^{-7}–5×10^{-4}	1000–5000	450–700	wet/bleach
DCG[d]	2	1.5×10^{-2}	5000	355–700[e]	wet
photopolymer	5,6	$80 - 100 \times 10^{-3}$	5000	400–700	uv/heat
thermoplastic	2,4	10^{-5}	750–1500[e]	350–700	heat
photorefractors					
semiconductors	7	5×10^{-5}	1000[f]	700–1300	none
sillenites	8	1.5×10^{-2}	1000[f]	400–700	none
ferroelectrics	9–11	$10^{-2} - 10^{f}$	5000[f]	400–700	none

[a] Subject to phase perturbations unless otherwise noted.
[b] To convert J/cm^2 to dyn/cm, multiply by 10^7.
[c] Also absorption perturbations.
[d] DCG = dichromated gelatin.
[e] $\lambda > 550$ nm requires sensitizing dyes.
[f] Due to the wide variability of material parameters, these figures represent only rough estimates.

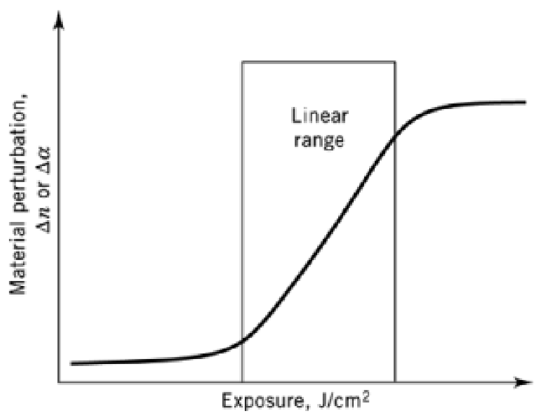

Fig. 4. Material exposure response curve.

exposures as illustrated by the exposure response curve shown in Figure 4. The nonlinearities are manifested as spurious gratings and result in reconstruction distortions.

Photographic film consists of fine grains of silver halide compounds and sensitizing agents imbedded in gelatin. The film is coated on a substrate which is a transparent plate or sheet (glass or plastic). The typical thickness of the coatings range from 5 to 15 μm and the size of the photosensitive grains are typically less than 0.1 μm. Exposure to light and subsequent wet processing converts the silver halide into metallic silver which modifies the absorption. Although the wet processing that is required to develop the holograms is inconvenient, this medium is still the most popular because of its high sensitivity ($0.3 - 10\ \mu$J/cm^2 to effect 50% change in transmission), commercial availability, capability of sensitizing to various wavelengths, and high resolution (1000–3000 line pairs/mm). An additional feature is that by a bleaching process, the developed absorption hologram can be converted into a phase hologram where the absorptive silver is changed into a transparent compound.

0.3.2. Phase Materials

Phase holograms can be recorded in a large variety of materials, the most popular of which are dichromated gelatin, photopolymers, thermoplastic materials, and photorefractive crystals. Dichromated gelatin and some photopolymers require wet processing, and thermoplastic materials require heat processing. Photorefractive crystals are unique in that they are considered to be real-time materials and require no after-exposure processing.

Dichromated gelatin (DCG) as a holographic recording medium offers a large index modulation capability, low absorption/scattering, and high resolution, and is a popular material for display holograms. The only drawbacks are that it requires wet chemical processing, plates must be fabricated since they are not commercially available in ready-to-use form, and the developed plates must be sealed as the material is hygroscopic. A DCG plate consists of a gelatin layer (typically 1–15 μm thick) with a small amount of ammonium dichromate ($(NH_4)_2Cr_2O_7$) spun on a glass substrate. Standard photographic plates can also be converted into a DCG plate by a well-known process (12). Exposure to light ($\lambda = 488$ nm for DCG without sensitizing dyes) causes the gelatin to harden with unexposed areas remaining relatively soft. Wet processing produces an index modulation through the introduction of vacuoles (voids whose sizes are smaller than the wavelength) (13) with the resulting index variation being as high as 0.08 (12).

Certain polymers doped with appropriate dyes can also be used to create phase holograms. Typically, exposure to light causes local polymerization of the material causing spatial variations in the monomer to polymer ratio, which after appropriate processing leads to index perturbations that can be almost as high as that achieved in DCG. Polaroid's DMP128 (14) and Du Pont's Omnidex (4, 5, 15) materials are among the most popular. Photopolymers can be spun or rolled onto substrates or cast into molds, depending on the particulars of the material. The Polaroid material requires wet processing while the Du Pont material is developed after exposure by uv light and heat treatment.

Holograms can be recorded in certain thermoplastic materials in the form of surface relief gratings. The so-called photothermoplastics (6) usually consist of a thermoplastic on top of a photoconductor layer, all deposited on a glass substrate. The medium is prepared by uniformly applying a static charge on the top layer (thermoplastic) usually through corona discharge methods. Exposure to a holographic interference pattern then causes a relaxation of the static charge where the intensity is high and thus imprints a spatially varying electric field across the thermoplastic layer. Heating the entire structure causes the thermoplastic to physically deform in response to the intensity of the local electric field, thus creating a surface relief pattern which can be read out holographically. The medium can then be reused by heating to erase the recorded gratings. Complete systems to record holograms using thermoplastics are available (6).

The photorefractive effect can be used to record holograms in a variety of materials which exhibit a combination of impurity levels in the band structure, charge transport mechanisms, and the linear electrooptic (Pockel's) effect. This includes semiconductors (7), sillenites (8), ferroelectrics (9–11), and most recently, polymers (16) and exotic multiple quantum well semiconductor structures (17). In such materials, the holographic interference pattern causes a spatially nonuniform excitation of charges out of the impurity trap levels into the conduction (or valence for holes) band where they move under the influence of diffusion and drift to be retrapped in relatively darker regions. The multistep process is repeated until a steady state is reached yielding a grating in the form of variations in the space charge field. The space charge electric field in turn modulates the local refractive index via the linear electrooptic effect resulting in a phase hologram. The time required to reach the steady state is approximately inversely proportional to the exposure intensity, and the proportionality constant depends on the material that is used. At modest intensity levels of 1 W/cm^2, the time constant can range from many seconds in the slowest ferroelectrics to microseconds in the fastest semiconductors. Recent developments in these materials have yielded thermal and electrical techniques of fixing such holograms so that they are impervious to further exposures of light (18–22), making the materials useful for not only real-time applications but also for long term storage.

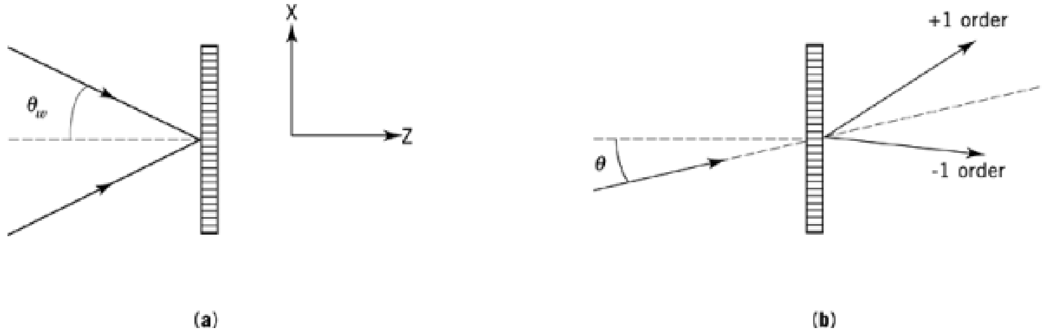

Fig. 5. Uniform plane wave grating where (**a**) is the recording, and (**b**) the readout.

0.4. Material Thickness

Holograms recorded in a material whose physical thickness is small when compared with the grating spacing is considered a thin hologram; the effect on an incident optical wave is characterized by a spatially varying transmittance function. The output of such a hologram can be determined by multiplying the input field with the transmittance of the hologram and analyzing the resultant diffraction using the principles of coherent optics theory. The most prominent features of thin gratings are lack of strong angular selection in reconstruction and limited diffraction efficiency. A quantity that is often used to delineate the boundary between thin and thick holograms (thick implies that angular/wavelength selectivity effects are exhibited) is where n_0 is the average refractive index of the hologram, Λ_g is the grating spacing, and T is the physical thickness of the hologram.

$$Q = \frac{2\pi\lambda T}{n_0 \Lambda_g^2}$$

Values of $Q < 1$ imply a thin hologram and $Q > 1$ imply a thick hologram (23).

0.4.1. Thin Holograms

A thin amplitude grating (recorded in, for example, silver halide film) formed by two plane waves at wavelength λ_{w}, intersecting at a half angle θ^{w} as illustrated in Figure 5**a,** can be characterized by the transmittance *t,* where Λ_g is the grating spacing and $t_0 = t_1 = 0.5$ represents the ideal case of full modulation depth.

$$t_a = t_0 + t_1 \cos\left(K_g x\right), \qquad K_g = \frac{2\pi}{\Lambda_g} = \frac{4\pi}{\lambda_w}\sin\theta_w \qquad (6)$$

A uniform plane wave at wavelength λ, incident at an angle θ as shown in Figure 5**b,** has a complex amplitude given by equation 7 at the hologram plane.

$$A = e^{i\frac{2\pi}{\lambda}\sin\theta x} \qquad (7)$$

The diffracted field from the hologram is then given by the amplitude function as shown in equation 8.

$$A_{\mathrm{diff}} = At_a = t_0 A + \frac{1}{2}t_1 e^{i\alpha_+ x}e^{i\beta_+ z} + \frac{1}{2}t_1 e^{i\alpha_- x}e^{i\beta_- z},$$

$$\alpha_\pm = 2\pi\left(\frac{\sin\theta}{\lambda} \pm \frac{1}{\Lambda_g}\right) = 2\pi\left(\frac{\sin\theta}{\lambda} \pm \frac{2\sin\theta_w}{\lambda_w}\right), \qquad \beta_\pm = \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - \alpha_\pm^{\alpha}} \qquad (8)$$

This is easily derived by expanding equation 6 in terms of complex exponentials. The first term represents the undeflected passage of the readout beam whereas the second and third terms represent the waves diffracted by the hologram. Although there is a range of parameters θ, λ, λ_w, for which one or both diffracted orders are exponentially attenuated and thus do not propagate, such a thin grating can be reconstructed from a wide range of angles and wavelengths, albeit with some distortions in the case of information carrying holograms. The maximum efficiency with which energy is diverted into the diffracted orders is $\eta = 1/16$ for the ideal case of full modulation grating ($t_0 = t_1 = 1/2$).

If the index of refraction of a thin material were modulated in lieu of its absorption, the resultant transmittance function for a grating prepared as in the absorption case is given by equation 9 where n is the average index of the thin film, Δn is the amplitude of the index perturbation, and T is the thickness of the film.

$$t_\phi = e^{ia\cos K_g x} a = \frac{2\pi}{\lambda}\Delta n T \qquad (9)$$

The diffracted amplitude from illuminating such a grating with a unit plane wave normal to the surface is easily calculated again by resolving equation 9 into complex exponentials (as in eq. 10) where $J_m(a)$ is the mth Bessel function.

$$A_{\text{diff}} = \sum_{m=-\infty}^{\infty} J_m(a)(-i)^m e^{imK_g x} e^{i\sqrt{k_0^2 - m^2 K_g^2}z} \qquad k_0 = \frac{2\pi}{\lambda} \qquad (10)$$

The chief factor that distinguishes phase and absorption gratings is the appearance of multiple diffraction orders. Although the expansion has an infinite number of terms, the diffraction amplitude is zero beyond a certain number due again to evanescent waves. Each of the first diffraction orders (corresponding to $m = \pm 1$) has a diffraction efficiency of $[J_{\pm 1}(a)]^2$ whose maximum value is approximately equal to 0.34. Thus the maximum diffraction efficiency from a thin sinusoidal phase grating is 34%. By using optimized blazed phase profiles, the diffraction efficiency into the first order can approach unity as is done for diffraction gratings for spectroscopy (1).

0.4.2. Thick Holograms

When the recording medium is significantly thicker than the grating spacing, the recorded hologram is said to be a volume hologram and is marked by high diffraction efficiencies and strong angular–wavelength selectivity during reconstruction. The interference patterns are recorded as either absorption or index gratings throughout the volume of the material. The two basic configurations for recording volume holograms are transmission and reflection geometries as illustrated in Figure 6. The distinction between the two is simply that in recording transmission gratings, the two interacting waves enter from the same side of the medium, whereas the recording waves enter from opposite faces to prepare the reflection hologram. The resultant grating planes are nominally perpendicular to the hologram face in the transmission geometry and they are parallel in the reflection case.

Because the losses tend to be excessive in volume absorption gratings, volume holograms are realized in most cases using index (phase) gratings. The maximum achievable diffraction efficiency (theoretical value assuming ideal parameters) from an absorption transmission grating is 3.7 and 7.2% from an absorption reflection hologram (1). Much higher diffraction efficiencies can be obtained using phase volume holograms; basic expressions for estimating them are given below.

The most distinctive feature of thick holograms is the angular and wavelength selective reconstruction. With increasing thickness of the hologram, such effects (also known as Bragg effects which are analogous to the angularly selective x-ray diffraction in solid-state physics) become more pronounced. The Bragg effect also suppresses higher diffraction orders which are prevalent in thin-phase gratings. Maximum diffraction efficiency is achieved when the reading beam matches the angle and wavelength of one of the beams used to write the grating. Small deviations $\Delta\theta$ and $\Delta\lambda$ from the Bragg angle and wavelength yield rapid decrease in the diffraction efficiency. A measure of the total detuning from the optimum angle and/or wavelength is given

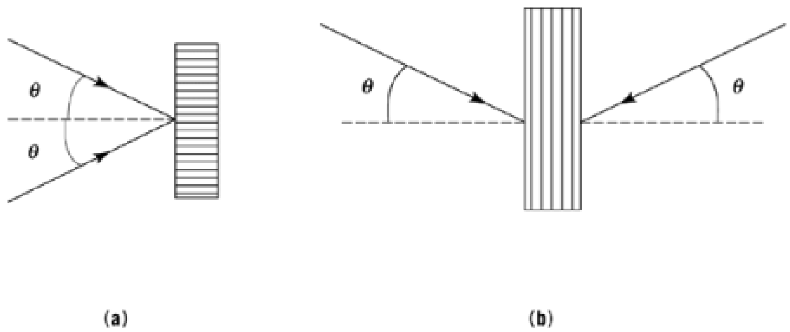

Fig. 6. Volume hologram recording where (**a**) is the transmission, and (**b**) the reflection.

by the phase mismatch function $\Delta\varphi$ (24), where T is the thickness of the grating, Λ_g is the grating spacing, n_0 is the average refractive index in the hologram, θ is the half-angle defined in Figure 6, and $\psi = \pi/2$ for transmission holograms and 0 for reflection holograms.

$$\Delta\phi = \frac{\pi T}{2\Lambda_g \cos\theta}\left[2\Delta\theta \sin(\psi - \theta) - \frac{\Delta\lambda\pi}{\Lambda_g n_0}\right] \qquad (11)$$

The diffraction efficiency for the transmission geometry is given by equation 12 (24) where n_1 is the amplitude of the index grating.

$$\eta_{\mathrm{trans}} = \frac{\sin^2\sqrt{\phi^2 + (\Delta\phi)^2}}{1 + \left(\frac{\phi}{\Delta\phi}\right)^2}\phi = \frac{\pi n_1 T}{\lambda\cos\theta} \qquad (12)$$

For the reflection geometry shown in Figure 6**b,** the diffraction efficiency is given by equation 13.

$$\eta_{\mathrm{refl}} = \frac{1}{1 + \frac{1-(\Delta\phi/\phi)^2}{\sinh^2\sqrt{\phi^2-(\Delta\phi)^2}}} \qquad (13)$$

For both geometries the diffraction efficiency approaches unity in value for $\Delta\phi = 0$ with the transmission hologram exhibiting a periodic behavior (24, 25) efficiency as a function of the grating strength φ, whereas the reflection efficiency exponentially approaches unity.

0.5. Computer-Generated Holograms

Instead of physically recording an object wave by mixing it with a reference on a suitable recording medium, holograms can be prepared in the following two steps. First, the desired object wave distribution can be calculated across the plane where the holographic plate would have been positioned. The object can be real or fictitious since a computer is used to simulate the effects of diffraction. Next, a transparency is produced using computer-controlled photolithography, which can be as simple as a laser printer with proper photographic demagnification, that yields a reconstruction of the object when properly illuminated. Because of the flexibility introduced by the computer in the calculation stage, either off-axis or on-axis holograms with high efficiency and quality can be prepared (26). Although the former variety is done quite routinely by optical means, preparation of on-axis holograms optically introduces undesirable noise terms which severely degrade the reconstruction quality. Such is not the case for computer-generated on-axis holograms because the physical limitations of the recording geometry are removed.

In principle, masks with complex valued transmittance functions can be prepared using a composite of two masks, with one implementing only the amplitude perturbations and the other having only a phase distribution via surface deformations; usually one method or the other is used. The binary detour-phase method (27) and its variants (28, 29) yield masks which have a collection of transparent holes in an opaque background where the size of the holes encode the amplitude and whose spatial position within some predefined limits encode the phase. Because of the binary nature of the masks thus produced, such holograms typically yield higher order diffraction and diffract only a small percentage of the light into the useful first order.

Kinoforms are phase-only masks which are prepared by setting the amplitude values to unity and changing only the phase across the hologram (30). The kinoform has the advantage that proper preparation can lead to holograms which can diffract almost all of the light into the useful first order.

By using electrically addressed spatial light modulators (31) in place of photolithographic masks, the preparation of holograms can be made essentially real-time with the reconstruction changing dynamically as fast as the computer calculations and the spatial light modulator response allow (32). Typically, however, the limited resolution in such devices leads to a sequentially synthesized reconstruction where the entire object field is divided into smaller units and a sequence of reconstructions performed rapidly appears as a large field reconstruction to the observer. An impressive real-time holographic display system using a Connection Machine (a parallel supercomputer) for the calculations has been demonstrated at MIT (33).

1. Display Holograms

Display holography is by far the most familiar and well-developed holographic application to date with several museums dedicated to holographic art. These holograms range from extremely simple ornaments to large color portrait holograms with strikingly real appearance. The one practical feature of all display holograms is that they be observable with white light so that potentially dangerous laser beams need not be used.

1.1. Reflection Hologram

Perhaps the simplest such hologram is a reflection hologram (34). A laser beam is passed through a holographic plate to scatter off a nearby object as shown in Figure 7. The beam that passed through the plate mixes with the backscattered waves to form the holographic fringes which are recorded. When developed, the plate can be illuminated with an incoherent point source of light and the observer sees the object with full parallax through the plate. Because the hologram was made with a single wavelength laser beam, the reconstruction, as dictated by the Bragg effect, will be primarily at one wavelength, although, depending on the spatial information that is recorded, various colors may be observed across the reconstruction. As the observer changes his viewing angle, a corresponding shift in the color is noticeable. This geometry has been widely commercialized for ornaments and jewelry.

1.2. Achromatic Hologram

Transmission holograms present a challenge for white light viewing since the dispersive nature of holographic gratings result in the various colors smearing the reconstruction unless special care is taken. The simplest

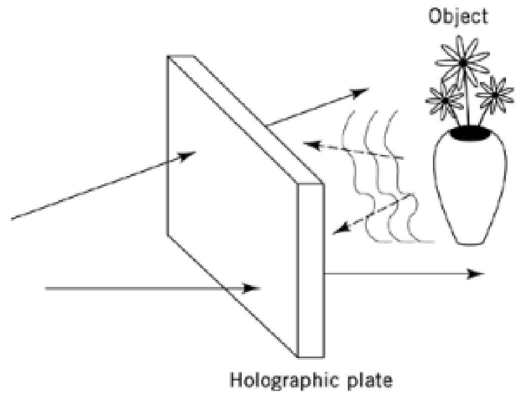

Fig. 7. Reflection display hologram (34).

realization of an achromatic transmission hologram is to use a lens to form an image of the object on the holographic plate (35). A collimated white light beam illuminating the developed hologram then reconstructs the object where the various color components diverge due to grating dispersion. When the observer focuses on the holographic plate, however, the diverging colors come back into registration and form an achromatic reconstruction. This technique, however, works well only for objects with very limited depth since points on the object whose image points are not precisely at the plane of the holographic plate result in color smearing. A better technique is to use a diffraction grating whose spatial frequency is equal to the average spatial frequency of the transmission hologram to precompensate the white light illumination (36). If the $+1$ diffraction order from the grating is used to illuminate the hologram to yield a -1 order, the dispersive action of the hologram is compensated by the opposite sign dispersion from the grating. The grating must be sufficiently close to the hologram to minimize color separation, while the unwanted diffracted orders from the grating must be suppressed.

1.3. Rainbow Hologram

For the reasons just described, the transmission hologram that is most popular in display applications is the rainbow hologram (37) which achieves object monochromatic reconstruction under white light illumination with depth not possible using other methods. The only drawbacks are that vertical parallax (with respect to the observer) is sacrificed, and the recording process requires either a two-step procedure (37) or a complex one-step apparatus (38). The first drawback does not represent a serious problem since vertical parallax is not appreciated as much as horizontal by human observers. Instead of seeing vertical parallax when the observer moves the viewing angle up and down, the reconstruction changes in color. The second problem has been solved for the most part by process optimization, and large beautiful holograms with striking detail and depth have been produced (39).

1.4. True Color Holograms

To record holograms in full color (of objects under white light illumination) as viewed by an observer, three suitably chosen separate laser wavelengths are required. The three colors are chosen such that when mixed in proper proportions, the entire color range of the object to be recorded is covered. The most easily obtained combination which yields good results is the He—Ne laser which emits red light ($\lambda = 633$ nm) used with an argon ion laser emitting both green ($\lambda = 515$ nm) and blue ($\lambda = 633$ nm) light. A wide range of wavelengths can also be obtained with a dye laser system.

The method for recording color holograms is essentially a simple procedure whereby three separate holograms, each formed at a different wavelength, are prepared in the same medium. Readout using the three lasers yields a superposition of three separate reconstructions whose colors are mixed by the observer's eye to yield the desired true colors. Recording the three holograms in a common medium is important for color registration, and care must be taken to keep the object fixed with respect to the holographic plate between the exposures lest color smearing result during the reconstruction.

The simultaneous reconstruction using three different colors yields cross-talk noise components in addition to the desired color reconstruction since a given color will access not only the hologram that was recorded at the same wavelength but also the other holograms. Volume holograms have been used to effectively suppress such cross-talk (40) via the Bragg effect which allows efficient reconstruction only for the particular color and angle that was used during recording.

1.5. Composite Holograms

For applications where lasers cannot be used for the recording process, for reasons of safety or convenience, composite holograms (41) can be prepared from regular photographs of an object taken from a number of different perspectives (along an arc centered on the object). A series of contiguous, narrow strip holograms are then exposed using these photographic slides as the object so that each narrow strip presents a slightly different view to the observer. When properly illuminated, the composite hologram presents a view which changes with the observation angle. Animation effects can be included by moving the object between each photographic exposure. The composite hologram prepared with such a set of pictures then presents a view which appears to move with the observation angle.

1.6. Holographic Applications

1.6.1. Holographic Interferometry

An important industrial application of holography involves the interference of reconstructed and real object waves to measure surface and internal stress and deformations in solid objects (42). The measurement method is nondestructive and can yield highly accurate results. In holographic interferometry, a hologram of the object to be tested is recorded. After it is developed, the hologram is replaced in exactly the same position in which it was recorded. When the object is illuminated, as during the recording phase, and the hologram is illuminated to yield a reconstruction, the virtual image from the hologram coincides with the waves emanating from the object. The two waves interfere, and slight changes in the object's position or shape from its recording conditions result in shifts and deformations in the interference fringes. When fringe pattern is properly interpreted, it yields important information about the detailed changes in the object's shape. A variant of this procedure using time-averaging techniques has been used to study spatiotemporal oscillation modes of vibrating surfaces (43, 44).

1.6.2. Holographic Optical Elements

Although holography has served niche roles in the fabrication of gratings and filters for spectroscopy (45) and the manufacture of distributed feedback semiconductor lasers (46), a wider role is being filled by holographic optical elements to replace or improve traditional imaging components (47, 48). By using patterned grating structures which can be produced optically or by means of computer controlled lithography/etching techniques, diffractive elements can be produced to implement a wide range of imaging functions ranging from simple lenses to complex heads-up display systems for modern avionics. Because of rapid advances in lithography/etching techniques developed mainly for the production of electronic circuitry, complex grating structures can be prepared to implement diffractive lenses and beam splitters whose refractive counterparts would be difficult to fabricate. Moreover, the diffractive lenses are much thinner and lighter than their refractive counterparts.

The production of master molds of such structures can lead to the mass production of such elements using embossing techniques which are already being used to prepare holographic insignia on various credit cards. Diffractive structures can also be prepared on the surface of refractive lenses to cancel various aberrations including chromatic and spherical aberrations (49).

1.6.3. Holographic Data Storage

Advances in holographic materials and device technologies such as spatial light modulators and detector arrays are fueling developments in the use of holography for information storage and retrieval (see Information storage materials, optical). For reasons of compactness and storage capacity, the most favorable approach uses a volume hologram in which data is multiplexed using either reference angle (50–54) or wavelength variations (55, 56). As opposed to other long-term storage media such as magnetic or optical disks, data in holographic systems are usually organized as pages with each page recorded and retrieved as one entity. In the angular multiplexing scheme, for example, a spatial light modulator is programmed with the data to be recorded (as a spatially varying transmittance function). The object beam passes through the spatial light modulator (also known as the page composer) to acquire the data and is recorded in the holographic medium (thick) with a plane wave reference beam. The next page of data to be recorded is then impressed into the spatial light modulator and a new hologram is recorded in the same medium but with a reference wave whose direction is slightly detuned from the first. After a series of such holograms are exposed, the hologram can be interrogated to yield any particular page of information by illuminating it with the corresponding reference wave. The ability to record and independently access any particular page is a manifestation of the Bragg effect described earlier. Another multiplexing technique uses the wavelength of a tunable laser source to record and access information in a reflection hologram geometry. Instead of the angular orientation of the reference wave being varied, the wavelength of the laser is carefully tuned to record and access data which is also another manifestation of the Bragg effect. Experiments using photorefractive crystals as the recording medium have demonstrated the storage and recall of 5000 pages of information, with each page of information consisting of 320×200 pixels (51). The information can be reconstructed with high fidelity (leading to low error rates) as evidenced by the pictures shown in Figure 8 (51).

1.6.4. Holographic Pattern Recognition

Whereas the holographic memory application uses the reconstruction of the object beam by illuminating the prepared crystal with a properly oriented reference wave (for the angularly multiplexed case), an object beam can be used to illuminate the crystal to reconstruct the reference waves (57–59). If, as illustrated in Figure 9, a series of patterns are recorded holographically in a crystal using reference waves multiplexed in one orientation, the illumination of the crystal with an arbitrary object pattern yields an array of reconstructed reference waves which are focused to an array of spots using a lens. The amplitude value of each focused spot is proportional to the degree of correlation between the input object beam and the object pattern that corresponds to that particular reference wave. By locating the highest valued intensity spot, the stored object that is closest to the input object can be quickly identified. This holographic technique yields an extremely rapid method of comparing patterns since the output information is produced in parallel.

2. Coherent Optics Theory

The principles of coherent optics theory are essential to study and problem-solving in holography (60). The propagation and diffraction of light are described by Maxwell's equations in terms of the amplitudes of the associated electromagnetic field. For the current purpose, discussions can be limited to deal solely with monochromatic light (single wavelength) which can be realized approximately with lasers. By assuming then that the electric

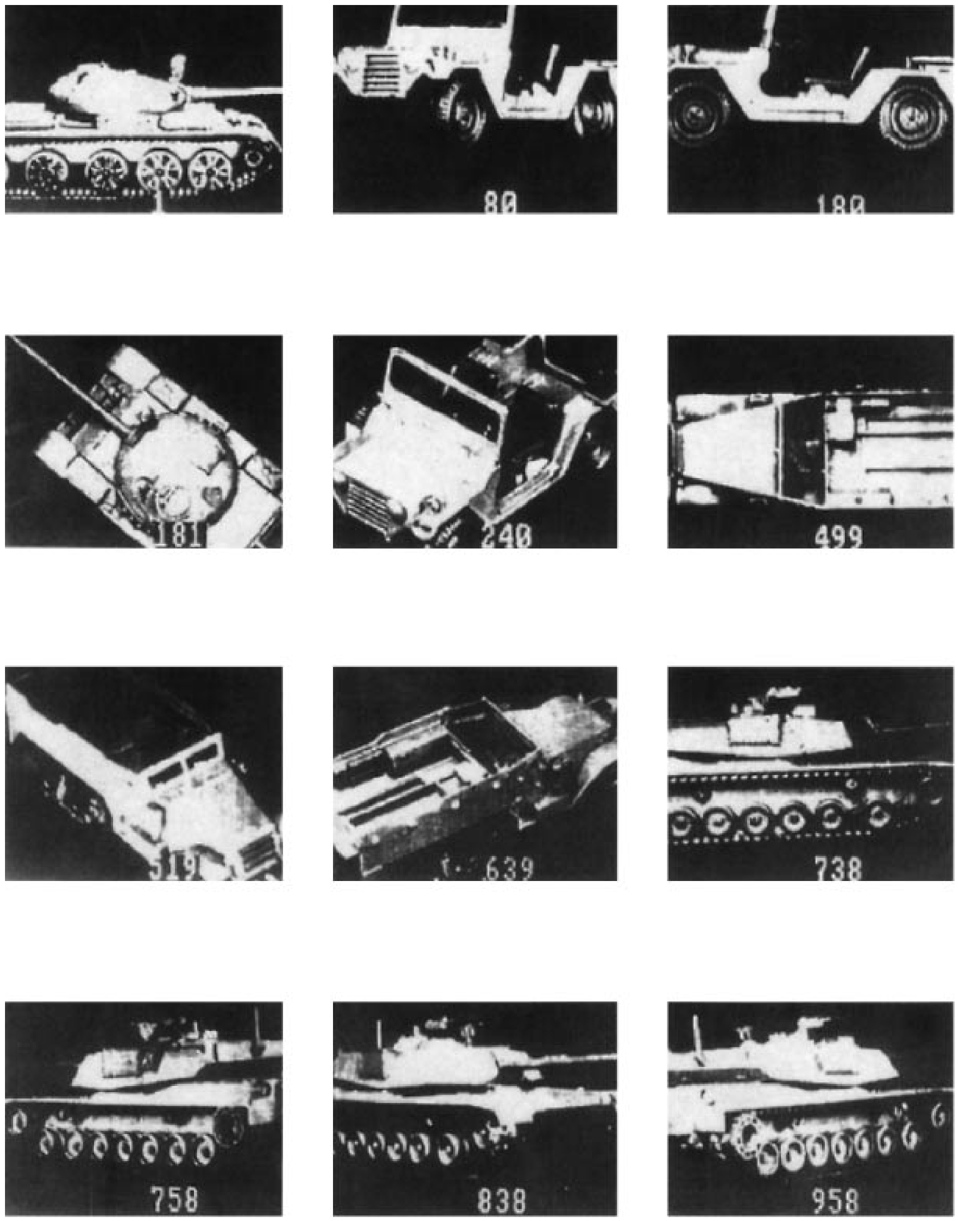

Fig. 8. Holographic data storage experimental results photographs of holographic reconstructions from a multiplexed hologram (51).Courtesy of Dr. Fai Mok.

field amplitude of the light of frequency v follows the form of equation 14,

$$E = Re\left\{E(x)\,e^{-i2\pi vt}\right\} \qquad (14)$$

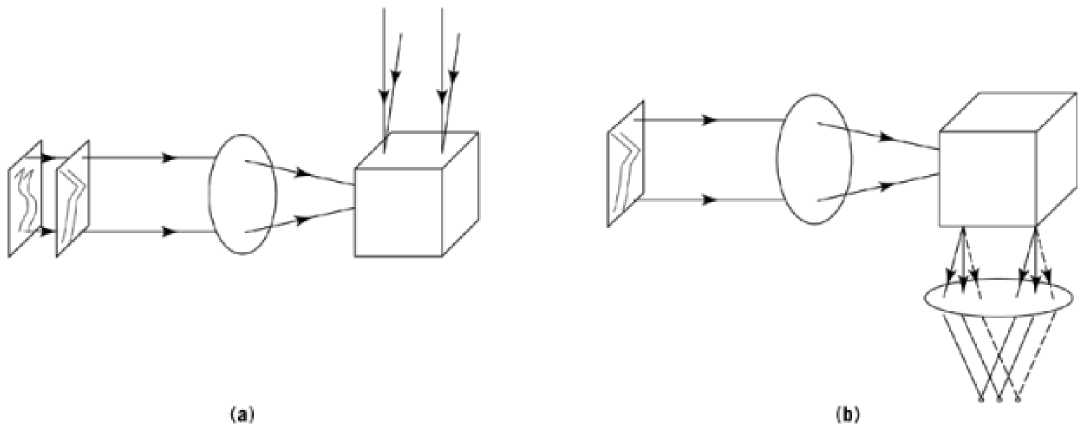

Fig. 9. Holographic pattern recognition system. (**a**) Recording an angularly multiplexed hologram; (**b**) forming correlation outputs using arbitrary input object pattern.

Maxwell's equations can be combined (61) to describe the propagation of light in free space, yielding the following scalar wave equation:

$$\nabla^2 E(x) + k_0^2 E(x) = 0 \qquad (15)$$

where E is the complex electric field amplitude, c is the speed of light in vacuum, and $k_0 = v/c = 2\pi/\lambda$ is essentially the photon momentum at wavelength λ. The simplest solution to this equation is the uniform plane wave traveling in an arbitrary direction denoted by the vector **k:**

$$E(x) = e^{ik \cdot x} \qquad (16)$$

where the propagation vector is required to satisfy $|k| = k_0$.

Any field amplitude distribution and associated propagation effects can be described equivalently by a superposition of plane waves of appropriate amplitude and direction provided that every component plane wave satisfies equation 16. If, for example, an optical field amplitude given by the function

$$a(x, y) = \frac{1}{2\pi} \int \int_{-\propto}^{+\propto} A\left(k_x, k_y\right) e^{i\left(k_x x + k_y y\right)} dk_x dk_y \qquad (17)$$

is imposed across the input plane as in Figure 10 where $A(k_x, k_y)$ is the Fourier transform of $a(x, y)$, then the solution describing the effects of propagating along a distance z is given by the amplitude distribution

$$\hat{a}(x, y, z) = \int \int_{-\propto}^{+\propto} A\left(k_x, k_y\right) e^{i\left(k_x x + k_y y\right)} e^{iz\sqrt{k_0^2 - k_x^2 - k_y^2}} dk_x dk_y \qquad (18)$$

If $a(x, y)$ is spatially bandlimited in extent so that

$$A\left(k_x, k_y\right) = 0, \quad \text{for } \sqrt{k_x^2 + k_y^2} > \frac{2\pi}{\Delta} \qquad (19)$$

where Δ essentially measures the finest spatial feature in the amplitude distribution $a(x, y)$, the exact diffraction integral can be reduced to the familiar Fresnel form as long as the associated assumption relating Δ, λ,

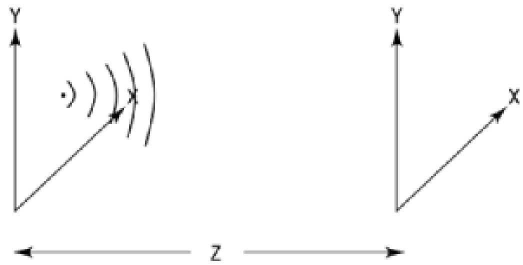

Fig. 10. Diffraction analysis coordinate system.

and z is met:

$$\hat{a}(x, y, z) = \frac{\pi e^{ik_0 z}}{i\lambda z} \int\int_{-\propto}^{+\propto} a\left(x', y'\right) e^{i\frac{ik_0}{2z}\left[\left(x'-x\right)^2+\left(y'-y\right)^2\right]} dx'\, dy' \qquad (20)$$

provided that

$$\frac{z\lambda^3}{2\Delta^4} < 1$$

This expression is the main tool used in describing diffraction effects associated with Fourier optics. Holographic techniques and effects can, likewise, be approached similarly by describing first the plane wave case which can then be generalized to address more complex distribution problems by using the same superposition principle.

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