

Holography

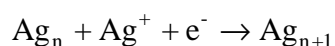
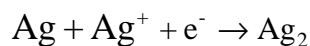
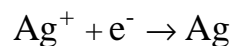
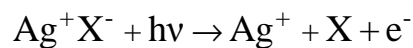
Holographic materials

“Common holographic materials include: silver halide photographic emulsions, dichromated gelatin, photoresists, photopolymers, photothermoplastics and photorefractive materials.

Explain the nature of each of these materials. Your answer should include any advantages/disadvantages and uses of the materials.”

Silver halide emulsions have been in use by photographers for over 150 years, consequently their manufacture, processing and optical response have been studied and optimised considerably. They are highly available – for example, Fujifilm offers a panchromatic silver-halide film in a variety of sizes¹. They provide excellent resolution (30-40nm according to the Fuji datasheet), diffraction efficiency in excess of 45% and are sensitive across the visible spectrum (from HeCd 442nm to Ruby 694nm).

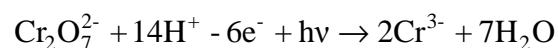
Ionic silver halide crystals (grains) are dispersed to form an emulsion (commonly, in gelatin). Commonly, iodide and bromide (Ag^+I and Ag^+Br^-) are used. Light absorbed by the crystals oxidises the halides, i.e. a valence electron is excited to the conduction band and flows away, leaving halide atoms and Ag^+ ions. The liberated electrons are then trapped in crystal defects, the gelatin or absorbed by silver ions. After exposure, a developer (containing a reductant) provides electrons to reduce silver ions. Silver ions in proximity of negative halide ions will be less likely to reduce than silver ions surrounded by neutral halide atoms, so silver ions in regions of a grain that absorbed more light will develop faster. Clusters of thermally stable metallic silver atoms will appear darker than silver ions, however the silver ions may still develop slowly as they absorb electrons photoexcited from halide ions.



The development stage is followed by a stop-bath, which removes developer from the emulsion. This may simply be a water bath, but is often accelerated with other solvents. Next, the unexposed (and still photosensitive) silver halide crystals are washed out via the *fixer*, to prevent them from darkening in response to light. The fixer is then washed out, and an image is left on the film, with clusters of metallic silver grains forming dark regions in the gelatin. While development is a multi-stage process and the films are not re-usable, the chemicals are readily available making this holographic material and its development process relatively simple.

This method produces amplitude holograms, however bleaching the film between application of the developer and the final wash converts the transmittance profile to a refractive index profile, allowing production of phase holograms too (~10x higher diffraction efficiency).

Dichromated gelatin may achieve near-100% diffraction efficiency and spatial resolutions greater than those of silver halide (>10000 mm⁻¹). A consequence of this high resolution is a greater SNR ratio, compared to silver-halide. For one source³, a diffraction efficiency in excess of 75% may be obtained, with strong response in the blue-cyan range of the spectrum. Resolutions range from 100-5000² mm⁻¹. The shelf life of dichromated gelatin films is short (around a year for one source, when refrigerated³; a “few” hours according to #4), so the often must be produced on-demand reducing their popularity. Dichromated gelatin produces an image by reduction of hexavalent chromates to trivalent chromium, causing a local change in refractive index.



Consequently, only phase holograms are generally produced with this material. They require an exposure of 100-1,000 times that of silver halide emulsions. Intensity holograms are however possible, according to #4.

Photoresists respond to light (typically deep blue to UV) with a change in solubility. After processing with a solvent, soluble regions are dissolved away, leaving the image (or a negative image) as a relief profile (resulting in a phase hologram). This may then be used to produce masters in order to mass-produce the image. The diffraction efficiency of Photoresists is theoretically limited to 33%, and they require a similar exposure to dichromated gelatin, with resolution comparable to silver-halide emulsions.

Photopolymers are theoretically capable of diffraction efficiencies up to 100%⁴, however the spatial resolution is limited by non-local responses (as modelled in source #4), with materials in source #4 reported to have spatial resolutions ranging from 2750-6000 mm⁻¹.

Photothermoplastics are sensitive from blue/near-UV to mid-red (400-650 nm), with diffraction efficiencies up to 30%. They are reusable and produce phase holograms. They consist of a transparent conductive layer on a photoconductive polymer, with a layer of thermoplastic on top, all on a glass or film substrate. The thermoplastic layer is first charged negatively and uniformly (by corona discharge⁵). When light is incident on the photoconductive layer, it locally alters the conductivity of the layer, allowing charge to flow from the thermoplastic towards the transparent conductor (where a positive charge is maintained). After exposure, the thermoplastic layer is recharged. A current is then passed through the conductive layer to heat the thermoplastic. The electrostatic attraction between the negatively-charged thermoplastic and the positively-charged transparent conductor causes the thermoplastic layer to deform, becoming thicker in the unexposed regions. Cooling the film then freezes this relief image in. By heating the plate while exposing to light, it may be “erased”, ready for re-use. As the hologram is recorded via changes in conductivity in the presence of an electric field, the hologram is optically stable once discharged. This material may not be as easy to use as others, as it requires machinery to apply uniform charge, and to electrothermally develop.

Photorefractive crystals are also reusable, may achieve 100% diffraction efficiency (although ~20% is more typical for common materials such as LiNbO₃) and resolutions comparable to silver halide emulsion (1000-10000 mm⁻¹). They do however require a stronger exposure (thousandths to tens of joules per square centimetre) than silver halide film (microjoules to tenths of millijoules per square centimetre). They may be used or produce phase holograms in real-time.

In these materials, electrons are trapped in centres (analogous to grains). Intense light (maxima in the diffraction pattern) liberates the electrons, allowing them to flow, until they are trapped in diffraction minima (dark regions). The accumulation of negative charge in these regions results in a Pockels effect, causing local changes in refractive index, resulting in a phase hologram.

The trapped electrons will slowly escape their traps (either due to excitation by ambient light or tunnelling), resulting in the image fading away. This may take from a fraction of a second to many years depending on the photorefractive material in use, allowing photorefractive crystals to produce static-image holograms requiring minimal processing or real-time holographic video. Colour-hologram recording in real-time has been demonstrated⁶ with photorefractive crystals. Holograms may be forcefully erased by exposure to bright and uniform light, in order to liberate the trapped electrons and disperse them. Holograms may be fixed by heating, in order to replace trapped charge with ion clusters. Owing to the lack of complex processing, high resolution (2000-10,000+ mm⁻¹) and high diffraction efficiency (~100% in some materials such as LiNbO), up to a thousand holograms may be recorded onto one crystal⁷.

1 "Silver Halide Holographic Film Products",
<http://www.fujihunt.com/fuji/testjb.nsf/pagesbykey/HOLOGRAPHY>, 20-03-2011

2 "Dichromated Gelatin for Hologram recording",
<http://www.hololight.net/dcg.html>, 20-03-2011

3 "PGF-04.pdf Dichromated Gelatin Holographic Plates",
<http://www.integraf.com/Downloads/PFG-04.pdf>, 20-03-2011

4 "Photopolymer holographic recording material", JR Lawrence, FT O'Neill, JT Sheridan

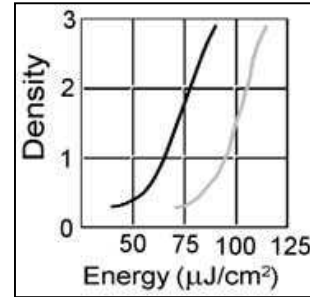
5 "Holographic Storage Materials",
<http://www.hololight.net/thermoplastics.html>, 20-03-2011

6 "3D, true color photorefractive hologram",
CA Heid, BP Ketchel, GL Wood, RJ Anderson, GJ Salamo, Nonlinear Optics '98: Materials, Fundamentals and Applications Topical Meeting, pp.182-184, 10-14 Aug 1998

7 "Photorefractive materials",
<http://www.hololight.net/photorefractive-materials.html>, 20-03-2011

Beam intensities

“Examine the graph of optical density against exposure for the Geola plates used in the holography lab. Suppose in the course of making a sinusoidal grating, one wanted to keep the exposure strictly between 73 and 77 $\mu\text{J}/\text{cm}^2$ in order to achieve an undistorted sinusoid. Calculate the necessary ratio of incident beam intensities for the two plane waves. Your answer might surprise you.”



Energy and power are proportional to amplitude squared :

$$\frac{E}{\text{area}} = \frac{P}{\text{area}} t = I t = A^2 t = \langle A_r(x,t) + A_o(x,t) \rangle^2 t$$

Exposure conditions for constructive and destructive interference:

$$(A_r + A_o)^2 t = 77 \mu\text{J} / \text{cm}^2$$

$$(A_r - A_o)^2 t = 73 \mu\text{J} / \text{cm}^2$$

Which leads to two simultaneous equations:

$$A_r^2 + A_o^2 + 2A_r A_o = 77\alpha$$

$$A_r^2 + A_o^2 - 2A_r A_o = 73\alpha$$

These provide the following relationships between object and reference beams:

$$A_r^2 + A_o^2 = I_r + I_o = 75\alpha$$

$$A_r A_o = \alpha \rightarrow I_o = \alpha^2 / I_r$$

Combining the two gives a quadratic in reference beam intensity:

$$A_r^2 + A_o^2 = I_r + \frac{\alpha^2}{I_r} = 75\alpha$$

$$I_r^2 - 75\alpha I_r + \alpha^2 = 0$$

$$I_r = \frac{\alpha}{2} \left[75 \pm \sqrt{75^2 - 4} \right]$$

Which allows us to calculate the ratio of beam intensities, using the amplitude relationship found previously:

$$\frac{I_o}{I_r} = \frac{\alpha^2 / I_r}{I_r} = \frac{\alpha^2}{I_r^2} = \frac{2}{75^2 \pm 75\sqrt{75^2 - 4} - 2} \approx \frac{2}{75^2 \pm 75^2 - 2} \approx \frac{1}{75^2}$$

$$I_o \approx \frac{I_r}{5000} = 0.0002 I_r$$

i.e. the reference beam should be approximately five-thousand times more intense than the object beam!