Chapter 15: Practical Issues in Rainbow Holography

As impressive as the first white-light transmission “rainbow” holograms were, with their simplified illumination and bright, clear images, artists and designers soon tired of their single-color look. Also, even though the transfer process was quicker and easier than shooting masters, rainbow holograms were still expensive to make. This chapter describes work on several of these points, with the goal of helping bring rainbow holograms into the practical worlds of art and commerce.

Multi-color rainbow holograms

A discerning public expects its modern graphics to be in color! And by this we mean multiple colors, not just the single pure color of a simple rainbow hologram. But indeed there is considerable confusion about what we do mean by “color holography,” and first we will establish the vocabulary we intend to use in these notes:

> <u>single-color</u>, or <u>monochrome</u>: means that the image appears in a single wavelength, or a band of wavelengths narrow enough to give the impression of a single saturated color or spectral hue. The color may vary with viewer position, as in rainbow holograms, or be relatively constant, as with volume reflection holograms.
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> <u>achromatic</u>, or <u>black-and-white</u>: means that the same image information, or gray scale, appears in a waveband wide enough, or in a mix of complementary colors suitably chosen, as to appear substantially neutral or unsaturated in hue, as a black-and-white photograph or television image does. This can be accomplished by viewing a rainbow hologram with a line-shaped source, or by properly processing a volume-reflection hologram.
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> <u>multi-color</u>: means that more than one hue appears in the image at the same time, usually in a posterized fashion. Each hue is saturated, and the regions are usually not carefully registered. This is the type of imaging that is often decried as “neon-light imagery.”
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> <u>full-color</u>: means that primary colors are carefully mixed so that pastel and non-saturated hues are attained. This requires careful registration of primary-color images. However, the term usually includes images in which the colors vary with viewer position, as with rainbow holograms.
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> <u>natural-color</u>: means a full-color image in which the hues shift very little with viewer position, so that they can represent the actual hues of subjects. The term applies even to computer-generated images of imaginary objects that have no “natural” color, etc.
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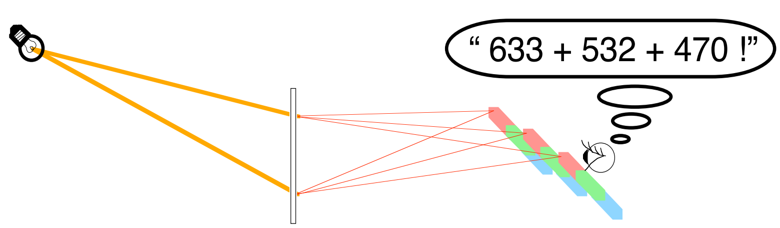
> <u>true-color</u>: a presumptuous term that describes holograms made with multiple wavelengths of laser light, and viewed in the same wavelengths (usually volume reflection holograms). It has to be said that objects illuminated in multiple-wavelength laser light do not often appear natural, or in their normal colors, due to irregularities in their reflection spectra that are uncovered by narrow band light. Every imaging process modifies colors to some extent, which is why there are color consultants on movie productions—holography is no exception.

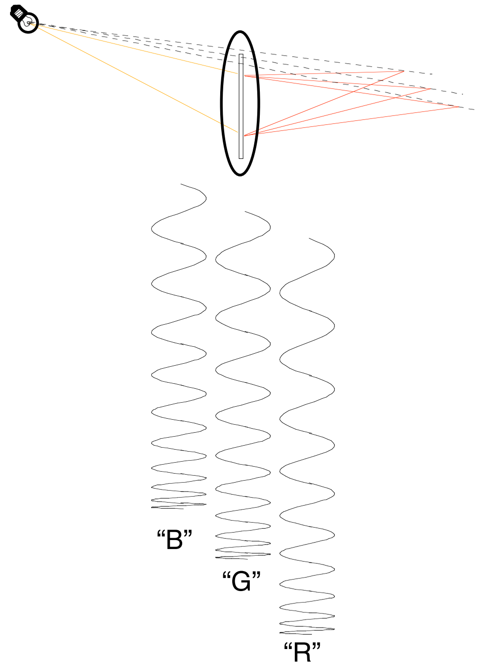
This chapter will be concerned with white-light transmission “rainbow” holograms exposed with a single wavelength of light (most holographers can afford only one type of laser!), so that we are limited to “multi-color” holograms. This is because registration is very difficult when we expose in one wavelength and view in another (the goal of color imaging), and in any case the colors will vary with viewer height.

We can think of this as a problem of creating several overlapping “component” holograms in a single emulsion, each chosen to bring a different wavelength to a focus at the viewer’s position. Thus their “red” foci are stretched of For purposes of simplicity, we will discuss only three wavelengths, intended to represent “red” and “green” and “blue” light. However, we hasten to point out that making a strong link between the wavelength of an image and its perceived color is very risky in view of the research of Edwin Land. The best choices of “token” primary-color wavelengths are themselves quite controversial in the field of color holography. For sheer convenience, we will chose 633□m, 532□m, and 470□m as our primary-color wavelengths.



The component holograms are designed so that their red, green and blue segments overlap in space, which means that their red “ends” are arrayed along an imaginary line in space, tipped at the “achromatic angle” that we found for the spectrum of a single point in space. Taking this angle into account is one of the keys in understanding how to achieve effective multi-color holograms.

The hologram itself is then a composite of slightly offset, slightly-differently-scaled component holograms. Each of these is separately created by one of two different techniques. Either the reference beam is changed for each, and the object beam kept constant, or the reference beam is unchanged, and the object beam moved about. Each technique has its particular advantages, and is used to match the set of tradeoffs chosen for a particular imaging application.



<u>Multiple-reference-beam holograms:</u>
In this technique, the master hologram is not moved for the various component hologram exposures, and the reference beam is moved from place to place. In principle, all the reference beam exposures could be made at once to produce an achromatic hologram, but the interference patterns formed between the reference beam sources (considered two at a time) would give rise to a very strong diffraction pattern, which would cause "spill light" to come into the image and unacceptably degrade it. Thus the exposures must be created as three separate exposures. In practice, the three reference beams are set up at the same time, and unblocked one at a time (it is not practical to reset a reference beam while a plate is waiting to be exposed!). This also offers an opportunity to change the H1 between exposures, so that different image components can be presented in each of the three wavelengths.

The reference beam angles and distances are calculated in a straightforward way, using the sin-θ and $\cos^2$-θR formulae, once the object beam angle and distance are determined. The object beam angle follows from the shrinkage considerations mentioned earlier and again at the end of this chapter, and the best choice follows from careful modeling and calculation.

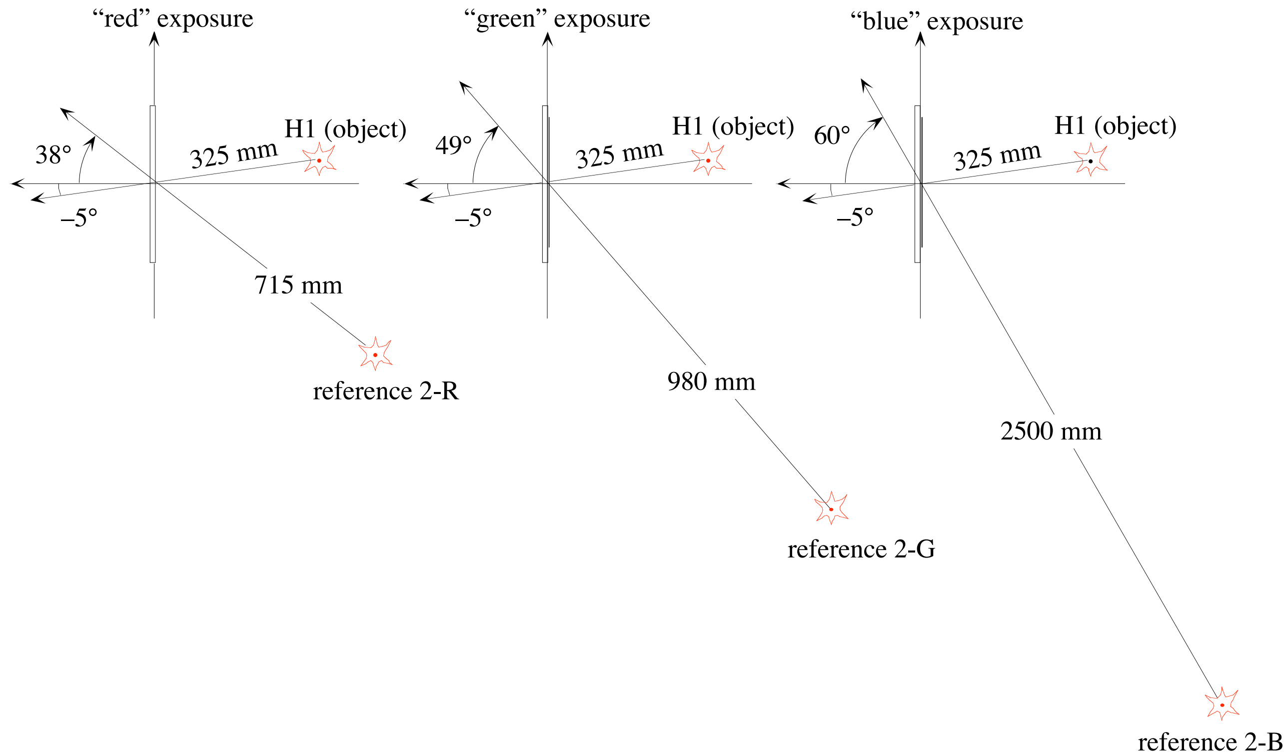
A typical choice for the object beam angle is –5.2°. Use of the sin-θ equation yields reference beam <u>angles</u> of:

$$\theta_{\text{ref-RED}} = 38°,\ \theta_{\text{ref-GREEN}} = 49°,\ \theta_{\text{ref-BLUE}} = 60° \,. \tag{1}$$

The next step is to get the reference beam distances from the $\cos^2$-θR equation, yielding

$$R_{\text{ref-RED}} = 715\text{ mm},\ R_{\text{ref-GREEN}} = 980\text{ mm},\ R_{\text{ref-BLUE}} = 2500\text{ mm} \,. \tag{2}$$

This geometry is sketched just below. In practice, all the reference beams would be put in place, and the appropriate beam ratios established, before the exposure sequence begins by blocking two reference beams at a time.



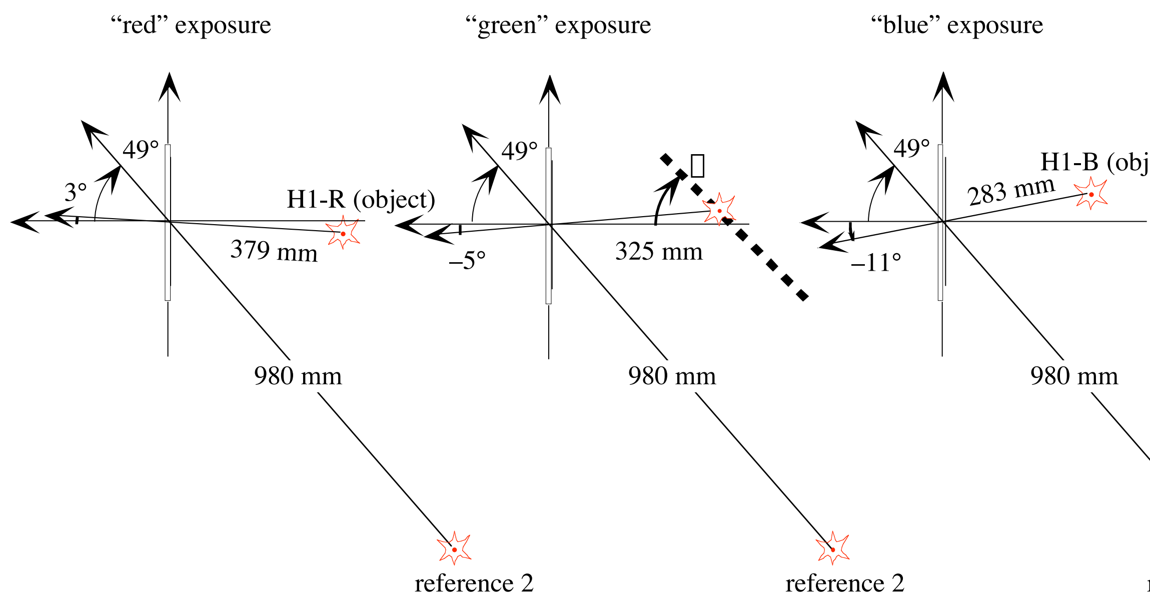
<u>Multiple-object-beam holograms:</u>

In this method, the object beam angle and distance is changed instead. Because the interference between the object beams produces a random pattern, which produces only a weak and diffuse scattering of illumination light. Thus all three object beams can be present at the same time, simplifying the exposure process.

Assuming the same shrinkage conditions as in the previous section, we find that the “green” exposure geometry will be the same as for the previous section. But we use first the sin-θ and cos^2-θ/R equations to find the object-beam angles and distances for the “red” and “blue” exposures.

$$\theta_{\text{obj-RED}} = 3°,\ \theta_{\text{obj--GREEN}} = -5°,\ \theta_{\text{obj-BLUE}} = -11°\ . \tag{3}$$

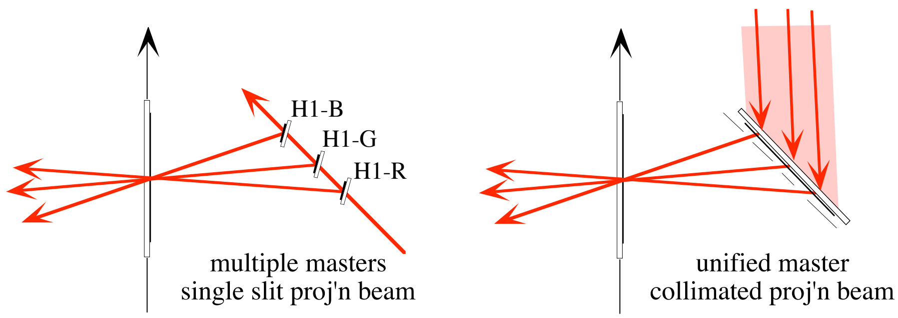
$$R_{\text{obj-RED}} = 379\ \text{mm},\ R_{\text{obj-GREEN}} = 325\ \text{mm},\ R_{\text{obj-BLUE}} = 283\ \text{mm}\ . \tag{4}$$



Note that the locations of the slits are on an approximately-straight line tilted at an angle that is the same as the "achromatic angle" derived previously, roughly given by:

$$\tan \square = \sin \square_{ref} \quad . \tag{5}$$

Because they are on a line, the H1 holograms can all be projected with a single slit-beam of illumination that passes through all of the H1s, or the H1s can be exposed upon a single large plate or film hologram and illuminated with a single wide collimated beam.



Advantages and disadvantages of the multi-color methods:

There are advantages and disadvantages to both of the two methods we will discuss here. A simple array of some of this can be shown as a table:

	Advantages	Disadvantages
Multiple-reference beam	easy registration good for photoresist	low diffraction eff'y long "blue" ref beam
Multiple-object beam	single exposure high diffraction eff'y simple table layout	tricky registration

Registration is a key issue because the careful "matching up" of the various color components is important to the aesthetic appeal of the result. For a multiple-reference-beam hologram, all three H1 holograms are shot at the same location, with the same overall perspective upon the subject scene. Parts of the scene are typically either covered with black velvet, painted black, or have their illumination blocked from one exposure to the next. When each H1 is projected back to the H2, these parts appear side-by-side as originally seen. When the image is viewed in a wavelength different from the one it was exposed in, there is some change in side-to-side magnification away from the hologram plane, but overall registration remains quite good. In the case of a multiple-object-beam hologram, however, the several H1 holograms are shot from different up-to-down vantage points, and "see" different parts of the tops and bottoms of the scene. When these images are projected back on top of each other

The "one-over-N" law:

Multiple incoherent exposures of a hologram causes the brightness of each of the resulting holograms to drop off in brightness, and the drop-off goes as $1/N^2$, where N is the number of incoherent exposures. Because there are N such sub-holograms, the diffraction efficiency of the total hologram drops off as 1/N, which is the origin of this name of the law. One way to think about it is that the dynamic range of the transmittance of the hologram is limited (from zero to unity, say), and that splitting that range among N sub-holograms requires that the modulation of each drops as 1/N. The diffraction efficiency of a hologram goes as the square of the modulation, and so forth. Another point of view is that the average of each exposure, or its "DC bias," adds to that of the others, and it is the "bias buildup" that requires the exposure times to be divided roughly uniformly. Or, we could point to a previously proven equation that the diffraction efficiency of a hologram simply varies as the square of the exposure time. The phenomenon is fundamental, and is an important limitation to what kinds of practical optical elements can be built up by multiple exposures of a hologram.

The "order effect" amendment to the 1/N law:

As though multiple exposures didn't pay a high enough holographic price, some peculiarities of the physics of the silver halide process cause the first exposure to dominate in holographic effect[1]. If three equal sub-hologram exposures are given to a composite hologram, the first-exposed sub-hologram will be brighter than the second, which will be brighter than the third. An approximate compensation can be made by giving them unequal exposures in the ratios of

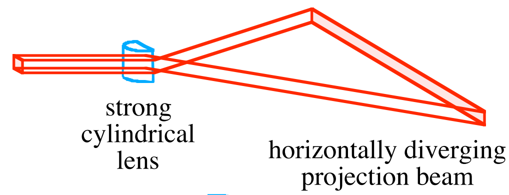
$$t_1 : t_2 : t_3 = \frac{2}{9} : \frac{3}{9} : \frac{4}{9} \quad . \tag{6}$$

Different materials, and even newer silver halide materials, will display different “order effects” or perhaps no order effect at all. For example, it is often the case in photoresists that only the last substantial exposure matters, and for photopolymers it is only the very first exposure that matters.

The question of “incoherence” among holographic exposures often comes up. Basically, if it is impossible for the object beams for the various sub-holograms to interfere with each other, they are effectively “incoherent.” In this case, they are separated by time, but they can be separated by polarization, by wavelength, and other effects.

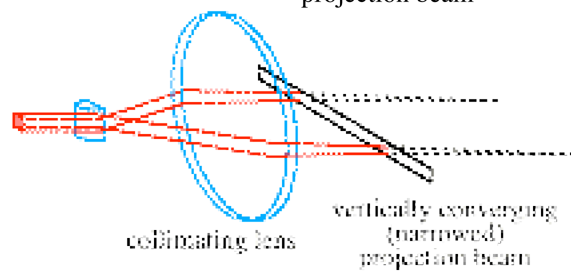
Slit-illumination beam forming

Rainbow holograms are created by limiting the amount of the H1 “master” hologram used to a narrow horizontal slit, usually accomplished by a combination of masking of the H1 and concentrating the light illuminating the slit thus formed. However, it is important to control the radii of the illumination in both the horizontal and (less important) vertical directions by a suitable choice of optics. This is usually easy if the slit width is roughly the diameter of the raw laser beam, but more careful shaping of the beam requires more elaborate optics.



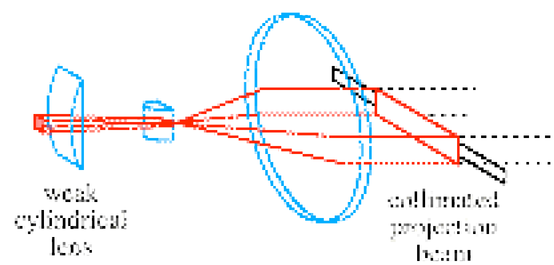
<u>simplest case: diverging the raw beam:</u>

The usual starting point is simply the horizontal spreading of the raw laser beam by the use of a vertical cylindrical lens (all directions are with respect to the hologram frame; typically the slit is vertical on the table, and the cylindrical lens’ axis is horizontal). Although very good short-focus (ca. 10mm focal length) cylindrical lenses are available in the optics catalogs, a small glass test tube filled with mineral oil, or a polished glass rod, will often do just as well. The only caution is that the mineral oil may start to flow if too strong a laser beam is used, which will degrade the holographic recording.



<u>collimating the slit illumination beam:</u>

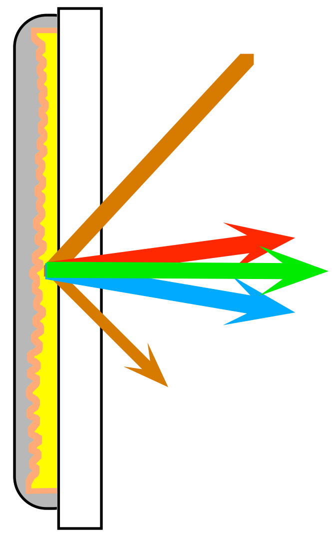
Whenever possible, we would prefer to illuminate the H1 with a collimated beam so as to minimize the distortion in the resulting image. However, simply putting a collimator one focal length from the diverging cylindrical lens is not usually adequate, because the beam will start to converge in the vertical direction downstream of the collimator. The result will be a narrower slit than before, and increased speckle in the image. To keep the beam of constant width, which allows as much distance between the collimator and the H1 as needed, and to increase the beam width when desired, use a long-focus cylindrical lens upstream of the diverging lens, spaced so that the foci of the two lenses coincide. The ratio of long to short dimension of the slit beam will then be the ratio of the focal lengths of the cylindrical lenses, which can be varied widely.



Embossed holograms

We have spoken of diffraction gratings and holograms mainly as repetitive variations of absorbance or transmissivity, but recall that repetitive variations of light delay or phase modulation will also cause diffraction. In bleached holograms, this is mainly due to variations of the refractive index of the emulsion, but the same effects can be produced by variations in the thickness of the emulsion. These two effects usually accompany each other, but it is possible to make holograms that only thickness variations, which are usually called “surface relief” holograms.

One nice feature of surface relief holograms is that they can be simply and cheaply replicated simply by transferring the thickness variations to a piece of transparent plastic by some combination of heat, pressure and perhaps softening agent. However, surface relief holograms are vulnerable to physical damage, such as by scratching, so it is also useful to mirrorize the surface-relief side (by vacuum evaporation of aluminum, for example), and then view the hologram in reflection mode. This causes endless confusion between true "volume reflection holograms" (the Denisyuk sort of thing) and "reflective rainbow holograms" (the Benton sort of thing), which you will sometimes have to sort out by context.



Making a stamping master:

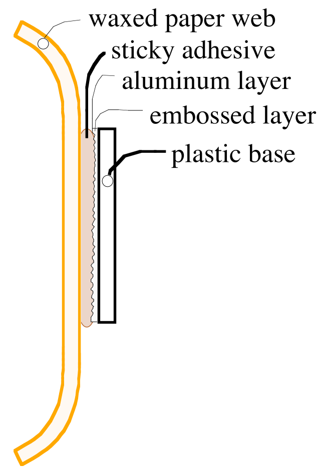
Silver-halide materials may be processed so as to produce a prominent surface relief pattern, usually by using very strongly hardening chemicals, and by rapid drying. However, the depth of the pattern is very dependent on the spatial frequency of the pattern, and is not usually prominent beyond a few hundred cycles per millimeter.

For commercial hologram production, special materials have been developed that only produce surface relief, and they are called *photoresists*. These are either photo-polymers, which are cross-linked by exposure and thus made less soluble in a developer bath (called positive-working photoresists), or resins that become more soluble with exposure (deep blue light breaks bonds in long molecules; they are called negative-working photoresists). Negative-working photoresists are the type usually used for microelectronic fabrication, and the same materials have been adapted for holographic use. Because these materials are sensitive mainly to deep-blue light, only krypton (413 nm), helium-cadmium (442 nm) and argon (458 nm) laser lines are useful. The large shift between exposing and viewing wavelengths makes careful compensation for wavelength effects essential. And because these materials have low sensitivity (20 mJ/cm^2 is typical), very careful technique is required.

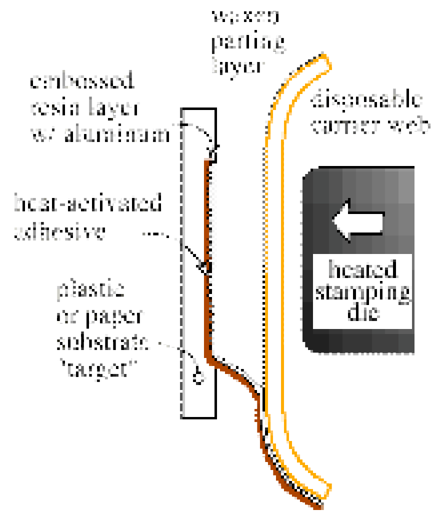
"Development" is usually accomplished by washing in weakly alkaline water bath for half a minute or so, and then drying so as to leave no spots. The resin is itself too soft to serve as a mold or stamper, and so is replicated by coating with nickel metal that is peeled away to be the stamper or shim. The nickel is electrically deposited to a thickness of a millimeter or two, but there must first be a "starting electrode" that is either vacuum deposited gold or aluminum, or "electrode-less nickel" that is formed by a chemical reaction. The first nickel shim is often used as a "mother" to replicate several "daughter" shims, which in turn may give birth to "grandaughters," so that a single photo-resist exposure may produce millions of eventual embossed holograms.

Early evaluation of an embossed hologram also represents a considerable challenge, but is essential if exposure, beam ratio, and development are to be properly chosen. Transmission viewing of the dry photoresist master will give a certain RMS hologram phase modulation (luckily, the photoresist development can be resumed after drying!). Viewing of the dry nickel master will give about four times as much modulation, and viewing of the final embossed hologram will give about six times as much modulation. The trick is to wind up with a high modulation, and thus high image brightness, without overmodulating, which causes a milky white blur to appear. Only an experienced embossing holographer can accurately judge the outcome when looking at the photoresist plate while still in the lab!

There are two types of embossed holograms in common production. The first, historically, is the thick "sticker" hologram that is stuck to a waxed paper carrier, and transferred (often by hand) to a product surface. However, this is too slow and expensive a process for very large product run, so a newer process has been evolved from the traditional hot-stamping foil process. The foil has a very thin surface relief layer on it, which is stuck onto the product surface by a combination of heat and pressure. If conditions are right, the hologram can pressed below the surface of a credit card, which makes it almost impossible to remove without destroying both it and the card. Because hot-stamp holograms are so thin, they are especially sensitive to the texture of the product surface, so that coarse paper cannot be used because its texture overwhelms the surface relief of the hologram!

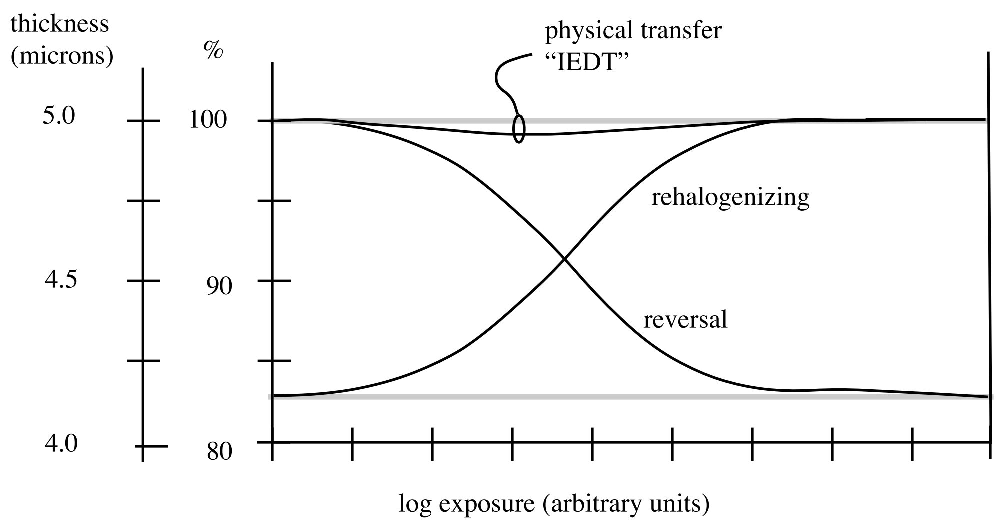


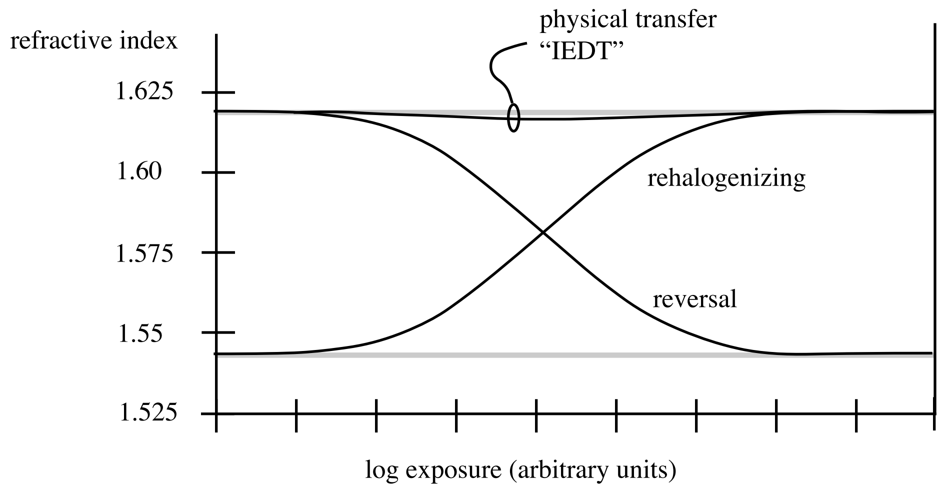
A newer process impresses surface relief in the coating that is often applied to fine paper while it is being manufactured, and then the whole roll is aluminized and varnished to protect the hologram layer. The resulting diffraction paper can be printed upon, so that instead of adding a hologram to a page, it is "removed" by being printed over! The results are so cheap that they are often used for wrapping paper and other wide-roll applications. However, it is fair to say that the surface quality is not high enough to allow deep three-dimensional images to be reproduced. The old-fashioned "sticker" holograms still provide the best image quality for that purpose.



Shrinkage compensation:

When holographic materials are exposed and processed, they typical undergo a change of average thickness and refractive index. For silver halide materials, both changes are due to the fact that some materials are removed from the emulsion. About 17% of the volume of a holographic emulsion is silver bromide microcrystals, of refractive index 2.25, and 83% is gelatin, of refractive index 1.54. Depending on how the emulsion is processed, up to half of the silver halide may be gone at the end, so that the layer mechanically collapses (depending on how it was hardened during the processing) and drops in refractive index. The following diagrams suggest how this might change as a function of exposure for three common process types (assuming no hardening occurs):

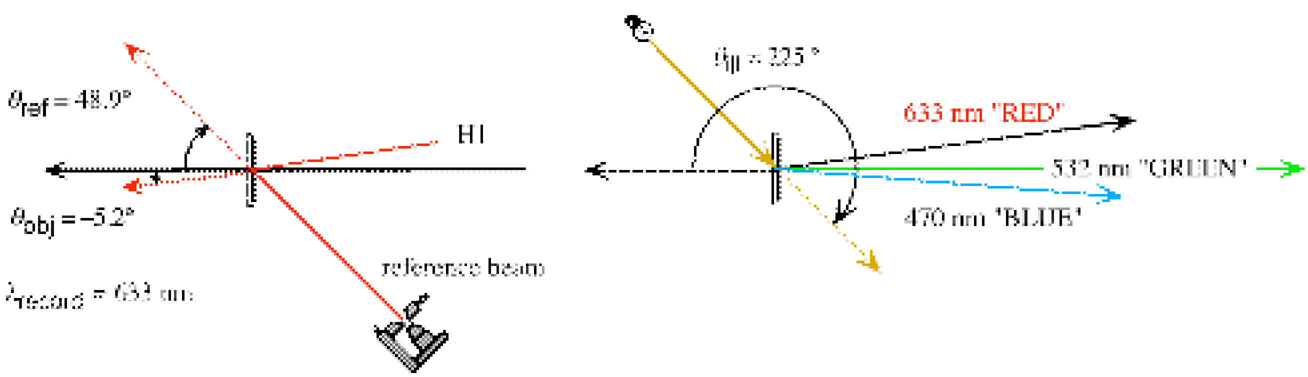




The results of applying the “t-shrink” model to these conditions yields the following recommendations for object and reference beam angles for producing a 532□m “green” image on axis.

SHRINKAGE	θ_{obj}	θ_{ref}	θ_{total}
minimum. t2 = t1 n2 = n1 = 1.62	-4.17 °	50.52 °	54.69 °
50% t2 = 0.92 t1 n2 = 1.58	-5.20 °	48.93 °	54.13 °
maximum: t2 = 0.84 t1 n2 = 1.54	-6.30 °	47.29 °	53.59 °

If we specify a “50%-shrinkage” process (there are several options for such) then the appropriate exposure geometry will be:



In this case, only the 532□m green light will be maximally diffracted. The tip angle of the fringes is not quite right for red and blue rays, and even for five micron thick emulsions some falloff due to “Bragg angle mismatching” will be apparent—but not so much so as to detract from the beauty of the hologram.

References:

1. Johnson, K.M., Hesselink, L., Goodman, J.W., “Holographic reciprocity law failure,” *Applied Optics*, **23**, pp.□18-227 (1984).