Matching a Phase Material to an Application

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The choice of a phase recording material strongly affects the utility of the final recording. For display holograms properties such as brightness, contrast, color range and color saturation might dominate and the choices are part art and part science. For holographic optical elements (HOEs), the extended range of properties that may require manipulation and the choices of materials to obtain each property in the required quantity makes a working knowledge of what can be done extremely useful. We present the fundamental properties of phase recordings and the fundamental properties of many phase materials so that a choice that will get you from plan to product can be more readily made. Recipes are not given but references to recipes are and modifications or procedures that can modify a well-known material may be described. The object is to make the reader aware of both the strong functions of these materials and the weak or subtle properties so that a design may be reviewed for feasibility a little more thoroughly, and hopefully the route to a functioning product will be shorter and less costly.

Introduction

The phase recordings we consider are the simple transmissive sinusoidal volume plane grating, the powered or focusing volume grating, the general reflective volume grating with the two special cases of a conformal reflection recording and a strong spherical wave recording, and finally, the large class of surface phase gratings so popular because of the supposed ease of fabrication. We first identify as many of the properties of these phase structures as we can, then discuss the variations and mix of these properties that may be required in a well functioning final copy. At this point we define the minimum performance required of the end product and then list some popular media to choose from. To make a good first choice we need to know the intrinsic properties of these materials and their limitations, strong and weak points, cost, availability, and perhaps what would be termed their "nuisance factor." This last factor is the cause of plenty of work. Very often the art gets in the way of the science, the recipe has too many variables, the learning curve is a little too long and the literature a little too short and probably

ambiguous and contradictory. We use charts and graphs as much as possible and keep things as simple as possible, steering clear of any exhaustive validations of claims made for different materials or the chemistry involved. The reference material can be used to satisfy these other needs. Only simple algebraic equations or approximations are used without formal justification.

Basic Phase Diffracting Structures

Each of the Figs. 1 through 5 represents a common spatial phase modulator. The simple plane grating covers a wide terrain, wide enough to include transmissive display holograms made in bleached silver grain films that can be thought of as consisting of very many superposed plane gratings or as many tiny spatially multiplexed gratings. The reflective grating covers just about everything else that could be made but we have to consider the subtleties of various configurations and some special cases. Surface phase gratings are not just thin volume gratings, they have become a large class of optics themselves, referred to as diffractive optical elements (DOEs) and they enjoy considerable popularity at the present time. Some materials in common use today can be used to fabricate all of these diffraction structures, but none will cover all possible constructions within every class. Within the description of the properties of the HOE that is to be fabricated is the description of the material that will have to exist to make it. In most cases the material does exist and may be available in some form, but not always on the right substrate and in the right thickness. In real materials the direction that light transits through the HOE makes a difference, sometimes a large difference, the efficiency of a grating can actually be greater in one direction because gradients in the modulation and holographic mirrors reflect different spectra on each side with different intensities.

Basic Transmissive Volume Holographic Gratings. Figure 1 depicts an edge view of a section of a plane grating of thickness T of fringe spacing d, at the surface and of fringe tilt or Brag tilt B. The fringes themselves are regions of high and low index n with the differences referred to as (Δn). The product of ΔnT is the total modulation of the grating, but the diffracted light in each order also depends on angles a and b and wavelength λ, which together define d. The change in index is usually not uniform through the film.

It is common wisdom that the thicker the grating, the narrower the angular bandwidth and the better the suppression of higher orders, if they can exist. The other half of that assumption is that the value of Δn is small enough to make the product of ΔnT just large enough to diffract all of the light. If in fact the product is two or three times that high, the grating will behave as a three or four times thinner grating. Materials that require wet processing almost always have a gradient in index that can be very high, further reducing the effective thickness of the grating. Even
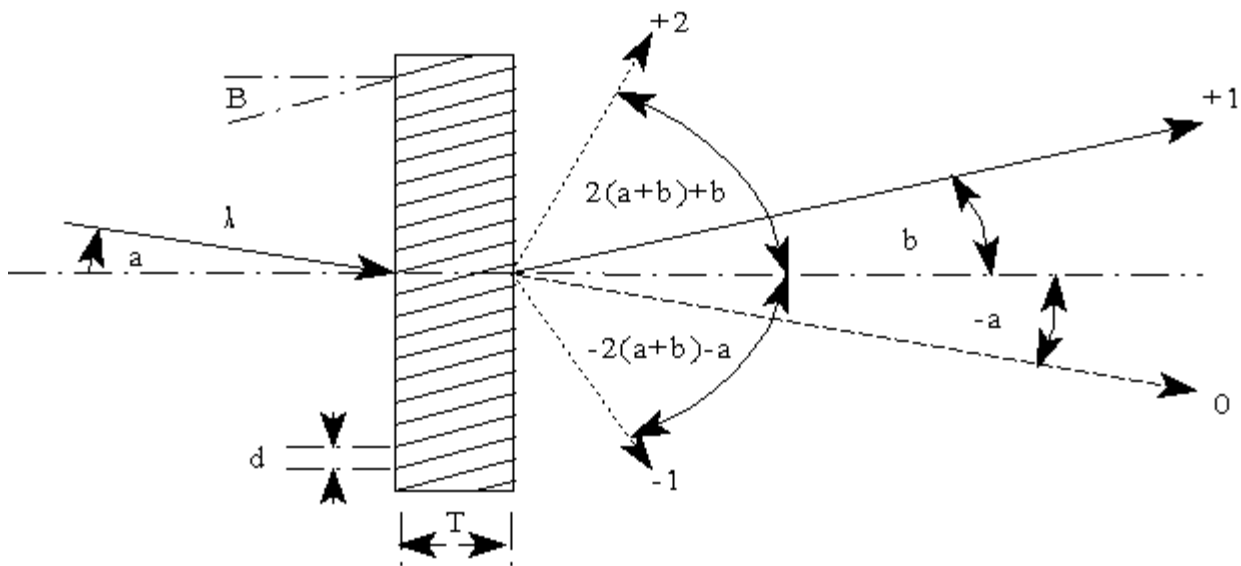
Figure 1. The simple plane volume phase grating with properties: $\sin a + \sin b = \lambda/d$; DE $\propto \sin^2(\Delta nT)$; power lost to higher orders $\propto \Delta n^2$; fringe or Brag tilt $B \propto T$ and n.

real-time recording materials, including photorefractive crystals, have a gradient in index from absorption and behave as if they were much thinner than they are. The power lost to higher orders is proportional to Δn^2 so if modulation is excessive then not only is a thick grating rendered thin but it may diffract most of the incident power into useless orders.

Another problem in dealing with thick gratings is the wandering Brag tilt B. Whenever wet processing is used there is a high probability that the original tilt made during exposure will play back at some other angle. In very thick gratings this error can exceed the angular bandwidth of the grating and render a nonuniform grating that is useless. Thick gratings made in low shrinkage photopolymers and photocrosslinkers that require no processing seem to work well enough. If the intended use of the grating requires a thin structure with a broad angular and spectral response, then the angles must be chosen so that higher orders cannot exist. This can begin when a and b both equal 30 deg and the second order becomes evanescent at 90 deg. The –1 order may still exist but is not entitled to receive much power at modulation levels near optimum for 99% diffraction efficiency (DE). When any of these gratings show excessive B error, there is usually a preexposure fix that can be done to compensate or a postprocessing bake down or swell up for each material. A special case of this grating is the total internal reflection (TIR) geometry that requires extreme control over fringe tilt error. It should also be remembered that TIR gratings will not diffract P polarized light very well or at all for the same reason that Brewster's angle works.

Figure 2 shows a common variance on a plane grating, a grating with a spatially varying spatial frequency such that rays of a certain λ and a common input direction will be diffracted to a common point on the output side. We may have seen this in text books as an off-axis equivalent lens, which is generally assumed to be a practical application of holography. For the fast optic shown, the output could be a family of points, half of them virtual and half of them real and all related geometrically to the fundamental focal length. Note that from top to bottom the spatial frequency ($f_0 = 1/d$) varies from very low, perhaps 200 l/mm

to very high, perhaps 2000 l/mm. In the plane grating we only had to consider the modulation product of ΔnT but now we have to add the term f_0, which also modifies DE. Note also that higher orders are nearly impossible to suppress at the top of this HOE and are nonexistent at the bottom.

The difference in spatial frequencies could be compensated for in most materials by adjusting exposure energies in some way so that the lower end received less exposure and so create lower modulation than the top. This would solve the modulation balance except that now even more energy will be lost in the higher orders for only a small gain in the +1 because the losses at the top are proportional Δn^2, which just went up. Then the better fix is to try to keep Δn constant and vary the T from top to bottom such that the product of ΔnTf_0 is everywhere the same. Obviously you cannot buy such a material commercially, so this special coating is very experimental. The processing also has to be tailored because it is not likely that the thicker portions can be processed in the same time frames as the thinner portions. What about real-time materials that saturate? Perhaps if available in liquid form, this HOE could be made.

As the f# goes to 2.5 or higher, this lens becomes a fairly good performer in most materials. Only the really fast f#1 and lower optics are an art to construct and are probably best made in pieces if possible. An on-axis lens made in any volume material at any f# will have a dead zone in the middle where almost no light can be diffracted because the spatial frequency falls to zero. One way around this dilemma is to work with a material that forms a surface phase structure at low spatial frequencies so that the HOE transitions from a surface phase HOE in the center to a thin and then thick phase HOE as the radial distance increases. A few materials will do this to some degree.

Figure 3 depicts a simple slanted reflection grating. If it were unslanted we would call it a conformal mirror with about the same properties found in dielectric stack mirrors. All reflection HOEs share one advantage over all transmission HOEs, the efficiency just keeps going up with increasing modulation rather than cycling up and down. The suppression of higher orders is also better at high Δn
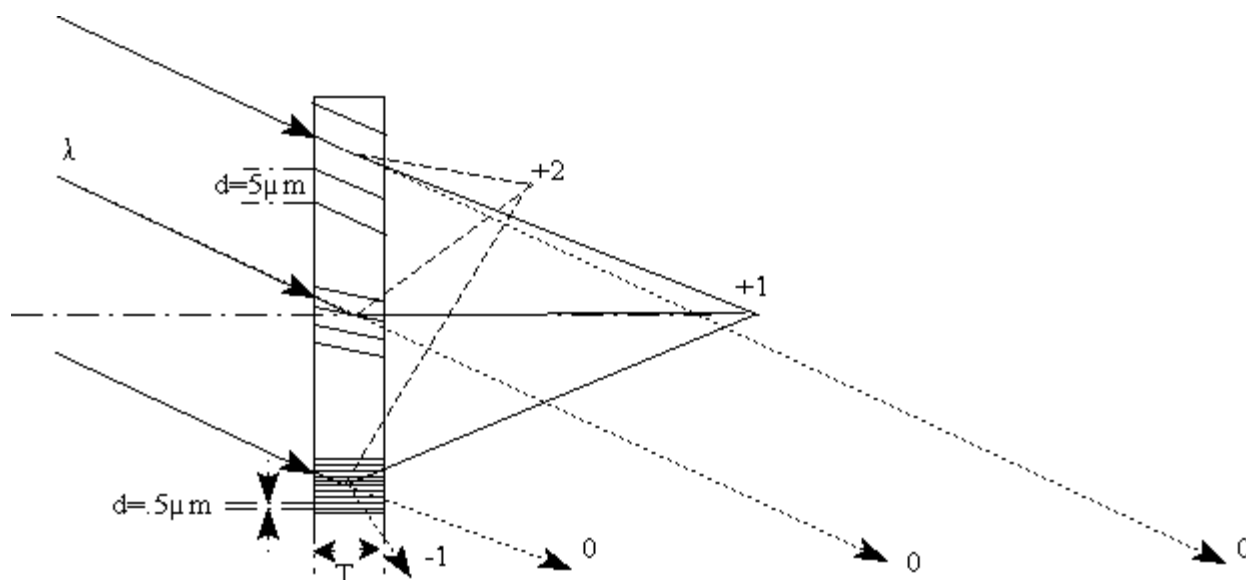
Figure 2. The case of a fast off-axis focusing HOE with these additional properties: DE varies from top to bottom if ΔnT is a constant; Brag or fringe tilt error is typically not uniform; higher orders often rob power from regions of large d spacing such as near the top; and $S + P$ (random polarization) efficiencies cannot be as high at the bottom as in the middle.
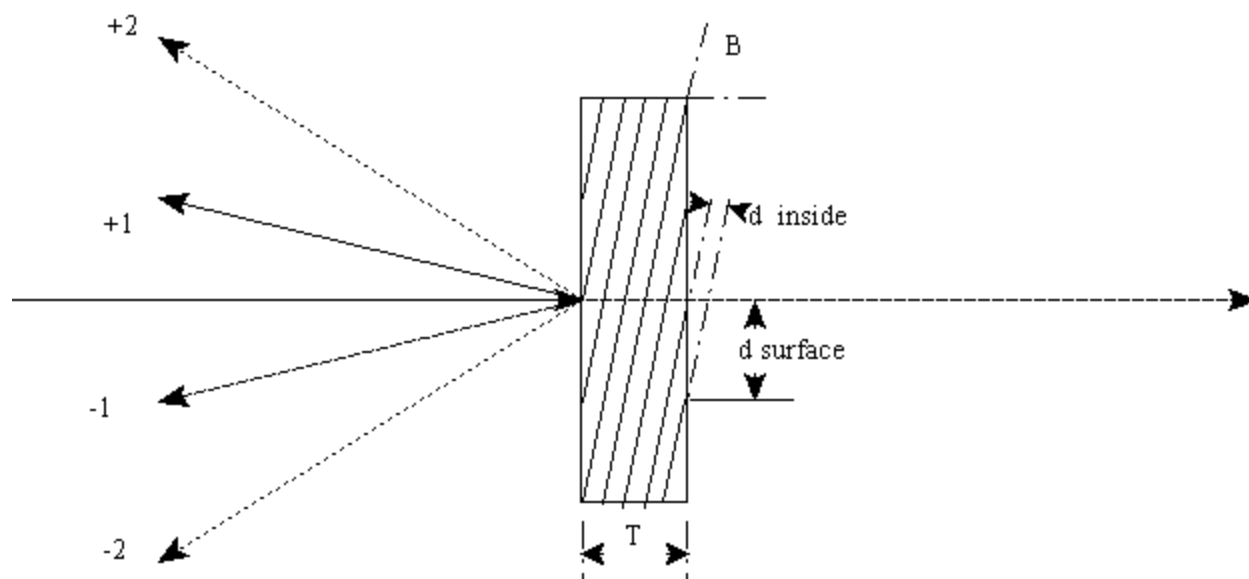

Figure 3. The simple reflection grating with the properties: DE $\propto \Delta nT$; $\lambda \propto nT$ + any gradient in d spacing; $\Delta\lambda \propto \Delta n$ + any gradient in d spacing; surface grating strength is always nonzero except for a conformal reflector; and power lost to -1 and higher orders is usually negligible even at high Δn.

but the fringe spacing is a new variable affecting color and fringe tilt and it is nearly impossible to record an off-axis reflection HOE without also recording a fairly strong transmission HOE. The idea of suppressing the unwanted transmission HOE by somehow index matching it out is only wishful thinking. The plane where the fringes meet the substrate must necessarily contain the same periodic changes in index that makes the HOE efficient, so the only case where a transmission HOE is not formed is the special case of the conformal reflector. This effect is of course minimized in materials of low Δn that rely on significant T to get sufficient modulation. In an HUD design the surface grating produces serious flare light when flying at certain angles to the sun. For that reason alone,

practically all holographic HUDs are conformal reflectors.

Figure 4 is an illustration of a fast focusing reflection HOE. In this case the surface grating changes from high to low frequency but the reflection grating is more or less constant everywhere so that the efficiency is high everywhere. The efficiency falls off for p polarized light when the internal angle of diffraction or reflection approaches 90 deg, so if this is important to the design a denser material would be better than a less dense material. As the average n (roughly equivalent to density) of the film falls to low values, the internal diffraction angles grow larger and account for many HOE failures. One of the errors this geometry is prone to is a variable fringe spacing and tilt induced by processing. Occasionally the distortion in the
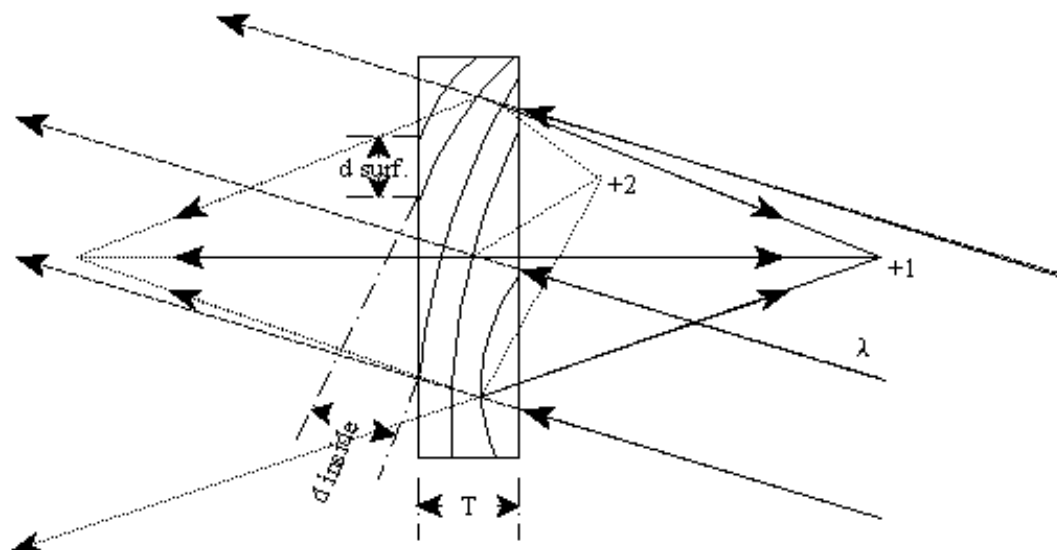
Figure 4. The very fast non conformal reflection HOE with the properties; DE $\Delta \propto nT$; λ may vary with position from process induced distortions; surface grating can be very intense, producing a "transflection hologram;" and higher orders are suppressed much better than in transmission equivalent with mirror backing.

fringe structure is so large that constructive wave coupling fails and the HOE loses nearly all efficiency in spite of a large modulation level. Often the color is variable across the surface indicating a nonuniform internal d spacing or average n. HOEs exhibit more severe aberrations in the reflection mode compared to the transmission mode, much like conventional optics. The choice of materials and processes to control them is particularly important when designing reflection optics or reflection art work. Full color display films have to have the required sensitometric characteristics as well as true reconstruction characteristics and only a few do. There are none that do it all with high efficiency but that is not a show stopper for anything but multiwavelength notch filters and such that can usually be made with some other material.

Surface Phase Recordings

Figure 5 is a representation of the surface profiles common to diffractive optics. Each has been recorded in one or more phase materials and copied in many more phase materials. The single biggest advantage of surface phase structures is that they can be replicated in a dozen or more ways that do not involve the use of lasers. In fact many are made as originals without laser light or at least without interference effects. Since they can often be made optically with lasers, we have to consider them and mention the common materials with their properties and uses. The three most common surface profiles are shown as sinusoidal, square, and sawtooth. The sinusoidal are natural continuous phase interference patterns, the square waves could be made by interfering a lot of odd harmonics in phase but are better copied from masks generated in typeset machines or on chrome masks exposed to E-beams. The sawtooth is deeper and is sort of the equivalent to a single side band transmitter with a suppressed carrier. This shape or its interferometric equivalent, that appears more rounded, is the only one that puts nearly all the light into one order. An exception to this is the deep square or sinusoidal grating that is high enough in spatial frequency to have no possible higher orders and is deep enough to have some volume type wave-coupled interaction that results in high efficiency.

The sawtooth shape has long been machined into materials to form blazed gratings and now diamond-turned blazed zone plates have become common on plastic lenses where the hybrid is effectively color corrected and has reduced spherical aberration. The blazed zone plate may also be made with a single exposure through a gray scale mask in photoresist, in some photopolymers, and with lesser performance in silver grain and dichromated gelatin (DCG) films. This general class of optics includes binary optics, embossed rainbow holograms, embossed full parallax holograms, kinoforms, and all other DOEs.

Matching Materials

The broadest class of phase recording materials would fill a book or two, so we only want to consider generic silver grain films, DCG, Polaroid photopolymers, DuPont photopolymers, PVA, PVK, and Shipley photoresist. Reference texts and papers are listed in the bibliography for recipes and other details.

Silver-Halide in Gelatin. By far the most popular materials to work in are products from Agfa, Kodak, and a handful of smaller producers around the world. Some are panchromatic, some have extremely fine grains, all are comparatively fast, and a few have been made to work in the near IR. They are the first choice of most artists because of the sensitivity to commonly available lasers of all colors and because they may be repeatably exposed and processed to produce the widest range of visual effects. The upper range of Δn is on the order of 0.1 and the grain size varies from a low of about 10 nm to over 100 nm. Grains are a significant source of scatter and therefore produce noise in the recordings, especially at short wavelengths. This is a major consideration for most applications and for all but the smallest grain films. Just about any HOE and some DOEs may be made in silver films but they will rarely be optimized for enough properties, and if they are bleached to get the highest efficiency then other sources of noise begin contributing and grain size may grow as well. A well worked out plan for a product may utilize the speed and panchromatic properties to produce a master HOE that can then be contact copied into a material with appropriate final properties. These films can be left
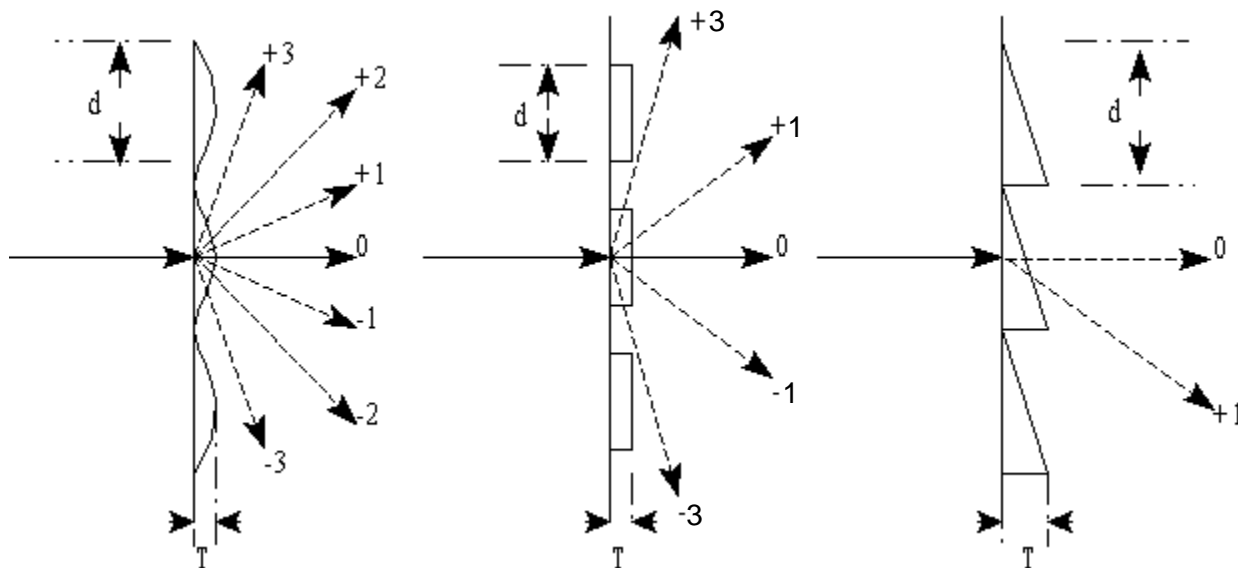
Figure 5. The general surface phase structure with the properties: Angular bandwidth ($\Delta\theta$) is much larger than in volume holograms; power distribution in higher orders is a strong function of fringe shape and depth T; T is roughly equivalent to Δn and depends on n, except for metalized reflective shapes; and computer generated DOEs are now common and practical, HOEs still rule at high f_0.

as clean amplitude holograms or converted to "no silver halide in gelatin" (SHG) with simple chemistry, and the resultant optic will be free from scatter caused by the grains of silver. The SHG masters are especially good when copying in the blue region where the lower Δn works well and silver grains often produce excessive noise.

A good example is the making of a HOE like Fig. 2 that must perform well at 680 nm. If it were made at any other wavelength other than 680 it would play back with aberrations, so we either have to precompensate for those aberrations or make a master at 680 nm. Both Agfa and Kodak make films that are sensitive to 680 nm and that can also readily be processed into SHG masters with a simple weak chrome bleach followed by a fix and some hot alcohol baths. Then the master can be copied at 488 into DCG or a suitable photopolymer or the much slower photoresist. Display masters may also be made this way, taking advantage of the speed of silver (as low as 3 μJ/cm^2) and then creating a photoresist submaster in a more stable set up using 442-nm light. Contact copies of even a weak hologram can be very bright when transferred to DCG, provided that the ratio of reference to object light is no less than 10:1 at the bright points and the scatter from all sources is very low. We highly recommend this general procedure for any exposures that have to be made at wavelengths longer than 514 to about 750 nm. Diode lasers can easily be made to operate in a single mode for a long enough time to make a good recording and ion lasers or cadmium lasers can do all the copying.

DCG. By far the most versatile of the phase materials, DCG in its simplest form can be used to create almost any type of HOE as long as the exposure is allowed to be done at blue green or shorter wavelengths. A few people have even made good quality HOEs with dye sensitized DCG also known as DSDCG, using krypton red or big HeNe lasers. The disadvantage there is the low sensitivity of the material and low availability of strong red sources. DSDCG may require from 50 to 1000 mJ/cm^2 at 647 nm, while DCG can be used with as little as 4 mJ/cm^2 at 442 nm to about 100 mJ/cm^2 at 514 nm. In general all the photopolymers and all the photocrosslinkers are at least 1000 times less sensitive than silver halide products. We are

fortunate that low scatter can be had from both mediums or else copying from one to the other would be useless. The intrinsic noise from a highly efficient DCG HOE of moderate thickness in the 5 to 8 μm range is 1 or 2%, a very low number. The sources of noise can be controlled to that level for simple grating like structures, but surface noise from dirty beams, intermodulation noise found in multibeam or diffuse object recordings, dust on and in the film, and nonlinearity noise through the bulk can all contribute to the best of the materials and not all noise sources can be eliminated.

The two greatest advantages of using DCG are the intrinsic low scatter, (if hardened sufficiently), and the tolerance for many reprocessing or postprocessing steps to fine tune the end product. The biggest disadvantage is that one has to devote time and space to a clean coating facility and the end product is extremely sensitive to high humidity. Some products require a careful tailoring of the thickness and juggling of the sensitizer, and in those cases the requirement to coat your own is a big advantage. We work with standardized mixtures and coating methods that produce 5-, 8-, 10-, and 25-μm thick coatings that have been sufficient to make almost any HOE for the visible and near IR regions, from 450 to 1500 nm.

When the material is used without much hardening it produces hazy holograms that exhibit broad spectral and angular bands, but as it is hardened it also narrows and at some point it crosses into the no-scatter zone quite suddenly, with no attendant change in other properties. This point is where even unexposed gelatin can no longer be dissolved out with warm water, leaving scattering centers behind. At all levels of hardness, the Δn near the surface can be pushed to 0.25 but as in most other media that number cannot be extrapolated to thicker films. Films as thick as 100 μm have been made and processed but they behave no differently than 50 μm films, which in turn behave thicker than 25 μm films but have a ΔnT product that is actually lower than what is achievable at 25 μm. We think 25 to 30 μm is about the practical limit for HOEs made in DCG, which means notch filters made in DCG can trade off bandwidth for density up to that thickness but top out at a ΔnT product of about 2.5, no matter how

thick or thin the film is. DMP-128 from Polaroid tops out at about 2 also, bleached silver film is about 0.7, PVA is about 0.8 after wet processing, and DuPont products go to at least to 1.

DCG has been used successfully with all the basic configurations, including the surface relief structures. For spatial frequencies below 500 l/mm, DCG and silver halide films both form efficient surface relief profiles. This works best with softer gelatin, and in silver film is enhanced by repeated bleach and develop steps. In DCG the effect is enhanced by using thick film and a longer soak in a 86% SG alcohol and 14% water mixture before final dehydration in straight alcohol. Fixing after the first processing can improve the gel hardness without destroying the relief image and then the gel can be used as an embossing master with solvent softened plastics. Hardened silver halide films work about as well.

The problems related to nonuniform spatial frequencies or just nonuniform exposures can be fixed if they are only off by 10 or 20% by postprocessing DCG in baths of hot soapy water and in fixer where areas that require more modulation are dipped in hot water and areas that are too well done can be brought down with fixer. Local zones may be repeatedly painted with fixer or a 5% solution of Triethanolamine (TEA) and then reprocessed in water and alcohol to balance out the plate. If an area is known to be overexposed before processing, it may be effectively unexposed with an ordinary incandescent lightbulb held close to it for a few minutes. All of these manipulation methods are experimental and the rules are loose and vary greatly from thick to thin in time and intensity. Baking at about 150°C will cause the gelatin to densify and if tilted fringes are present they will appear to lay down. Baking also makes the gel much more stable and a little less hygroscopic. While it is still hot a glass cap or at least an epoxy coating can be applied without trapping too much moisture in the film. Trapped moisture can become active on heating and cause the gel to collapse. Mysterious color shifts in capped reflection holograms can be explained by the action of trapped moisture and lack of 150°C bake down.

The sensitivity to moisture is not the only drawback to using DCG. It will easily distort in thick films, and in large area recordings in thin films it is very difficult to process uniformly. The processing leaves the fringe planes at slightly random positions and usually the film expands so that the fringes stand up while the bulk n goes down. In gratings made at near 64 deg in and out for either reflection or transmission the diffraction efficiency for incident P polarized light is near zero, because n has dropped to about 1.3. Unless one was building a polarization separator this would not be desirable. In fact the low n means that the difference between S and P efficiencies is always larger than in more dense media. DMP-128 also has a low average n for about the same reason, the Δn is created by producing low density voids in the film during dehydration, much like the making of aerogels.

DMP-128 Photopolymer from Polaroid. This film has enjoyed success as a flexible film used for great looking reflection and transmission display holograms. It is also useful for making high density reflectors, and because of the unique open structure it can be filled with liquid crystals to make disappearing HOEs and DFB lasers and narrowband filters. It is easier to stabilize than DCG and has about the same high modulation in films of 7 to 15 μm. All of the wet processed films seem to work best in the thickness range from 5 to 15 μm, probably owing to limited diffusion rates in DCG and in DMP-128. This material is used mostly with red light but can be made panchromatic more easily than DCG and is much more sensitive, requiring only about 25 mJ/cm^2 to fully expose.

This material is saturable, once the polymerizeable material is used up the effects of exposure are nonexistent. This is a great advantage in production because overexposure has almost no effect, except to maybe compress the contrast range a little. This is true of all the migratory photopolymer systems, including all of DuPont's photopolymer products. The light used to expose the hologram need not be perfectly uniform to get a uniform copy. The ratio of the reference to object wave is the primary determinant of how much modulation an area will have after an overexposure. It is a sort of self "dodging" film with a hard limit on modulation related to beam ratio. This implies that to get maximum performance a reflection or transmission master has to be as bright in its hot spots as the reference.

One disadvantage of this material is that it is on a substrate that has a higher index than the unexposed film. so that all recordings have a mirror in them and the film is not generally available in liquid form as of this writing. Environmental controls are important at the exposure station, because the film has to be activated by a fairly precise percentage of water or it will produce noisy holograms. The low average n may be a disadvantage for some HOEs, and the material tends to shrink during or after processing and needs to be babied a little to get it to reconstruct with perfect fidelity. The display holograms are the best and brightest among the mass-produced products and last a very long time.

Polaroid has announced the introduction of another photopolymer that also has a high Δn but needs no wet processing and therefore is much more suitable for precision HOE making. It will be a great boon to some if they market the film as DuPont does, coated and in liquid form. We do not know how it is used or how well it performs. Photopolymers, because of the dynamics of monomer migration, may make pretty poor sequential hologram recordings, each successive shot adds noise to the previous shot, and if angles are not changed sufficiently between shots in a real-time material, then more than one recording will be made at a time as previous recordings reconstruct and rerecord with new ones. Latent image recordings do not have this problem and some real-time materials do not have migration occurring.

DuPont Photopolymers. These are all real-time recording materials with migration of monomer. They work as-is or may be enhanced with postexposure baking and with the addition of a monomer to swell them to a thicker state. Swelling shifts playback color and angle in reflection holograms. The sensitivity of some films is down to a few mJ/cm^2, but as with DMP-128 they cannot be overexposed. Some films are panchromatic and good full color holograms can be made in them. The available Δn is about 0.06 on a good day in the best of films, so to get good brightness the films are over 8 μm thick, more typically about 20 μm. They play back with smaller bandwidths but look clear in about any light. The normal backing is mylar and is birefringent, causing some problems with production and making it difficult to make HOEs with high integrity. The liquid film has been made available so that it can go on glass and then good quality HOEs are possible. A very large number of display holograms have been produced in this material, which is sold in sheets and rolls with machines to expose and process it.

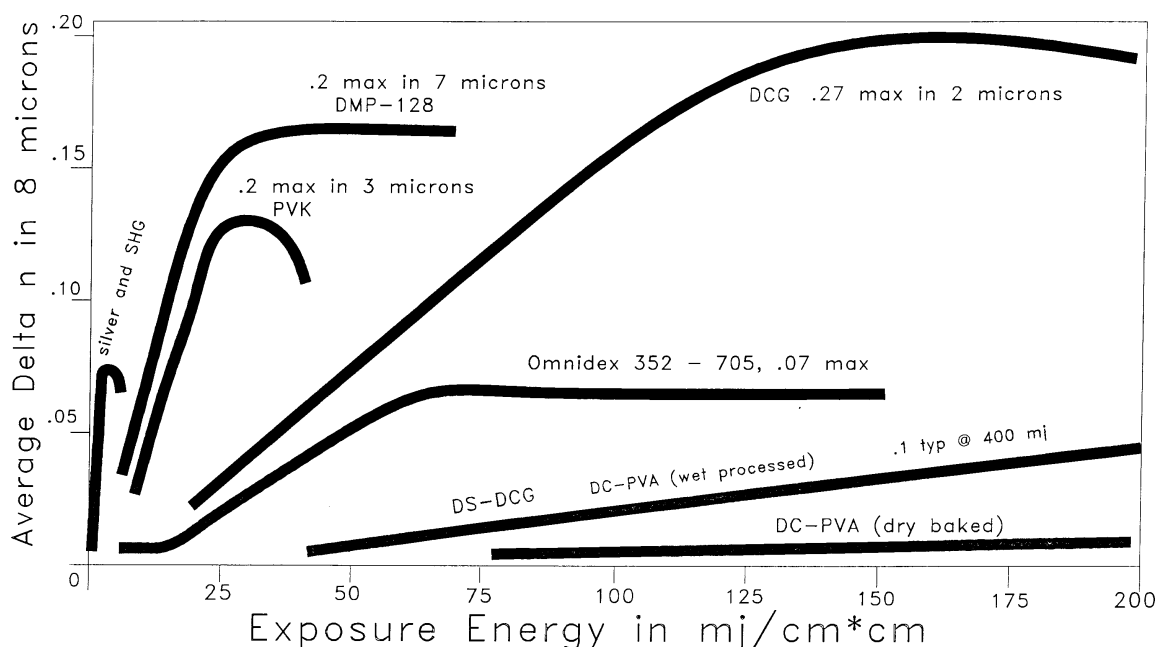The limited modulation prevents this material from

Figure 6. Phase material modulation reference for common materials.

being used in some tasks, but it is a big plus for others. When high angular selectivity or a narrow notch filter is needed, it is the material of choice, especially if you can get coatings of 50 μm or more. Optical memories have been made with it and could flourish. We made diffraction-limited gratings with it. The dye never bleaches all the way out of some of their films so it is useless at short wavelengths, as is DCG and polyvinyl carbazole (PVK). Most if not all holographic recording materials naturally absorb strongly in the UV region both long and shortwave.

One of DuPont's materials forms an excellent embossed surface on exposure and is great for copying binary or possibly shaded masks. The shading may copy with poor linearity depending on light intensities, spatial frequencies, and migration rates and distances, all considerations that could be negative. We copied a binary mask in non-embossing material and found that it was self guiding because of the real-time formation of the higher index light fringes. The first light through the slits forms a guide for the rest, and the usual diffractive spreading does not occur and the copied HOE is excellent except for the plastic substrate it is usually on. This is very easily used material, and stores for years in a refrigerator.

Polyvinyl Alcohol and PVK. Polyvinyl alcohol (PVA) has been dichromated and used as a real time material fixed with heat for many years. It is easy to get, mix, coat, and use this way. It is also possible to enhance the modulation greatly by dipping it in water and alcohol, similar to DCG processes. It can also serve as a binder for a monomer and act more like other photopolymers. In its dichromated form it is a photocrosslinker like DCG and as such has no migration, but the latent image in PVA is many times better than the latent image in DCG. Images and HOEs are easily seen as they form in films as thin as 5 μm. The integrity of the recordings is very high with very little damage done by overwriting multiple times. As a crosslinker it is not a saturable media and can be overexposed, however it requires about a 100 mJ/cm^2 to form a strong recording and about 1000 more to begin to undo it.

One disadvantage is that it does not adhere well to glass or plastic, which makes it a perfect candidate for a trans-

fer hologram. It is possible to form a conformal mirror in it on flat glass or plastic in a production environment and then lift it off and transfer it to a spherical surface in another off-line process. It is soluble in water and unstable at high humidity but it may be possible to stabilize chemically by converting at least some of its molecules back into polyvinyl acetate or by adding crosslinking agents to a last bath. Borax is used to crosslink PVA and form "slime." Baking a wet processed PVA hologram causes it to return to its original latent image state and stabilizes it somewhat against moisture. Other uses include protecting and cleaning optics and it is a common mold release agent.

PVK is not soluble in water but dissolves in chloroform and is sensitized by halogens to become a photocrosslinker. It is processed in xylene and hexanes or a monobath of miscible but differentially volatile solvents. It should only be used where maximum resistance to water is needed. It will work well in 5 μm layers, has a short shelf life and a high Δn but is hard to process uniformly. It is sensitive to blue green light and requires only a few mJ/cm^2. It requires the use of noxious chemicals, some of which are known carcinogens.

PVK is also a commonly used photoconductor that could be used to form relief holograms in thermoplastics and for light intensifiers. If used for holography it has to be sensitized at the same time it is dissolved or it will not work. The fastest sensitizer is carbon tetraiodide and it is extremely unstable.

Shipley Photoresist. Many use this as a standard for embossing masters. It can be obtained on plates commercially from several sources, has a long shelf life, and reasonable sensitivity to blue and UV light. We have jars of material that are 20 years old and still work about as well as they ever did. This is the most common material used to make binary optics from metal masks and it is easily metalized for production of embossing shims. We make masters from epoxy molds lifted from the resist and then mold copies in other epoxies and plastics. It is possible to make features as deep as 4 or 5 μm with little effort, and resist masters may be directly converted to glass masters

with reactive ion etching or with diluted HF. Some people are able to get very high aspect ratios in it and form high frequency, high efficiency gratings in it. The integrity of the recording is rarely compromised in processing, but very high frequency gratings may close over at the top if they are exposed to common organic solvent fumes. Resist is user friendly and one never has to even dim the lights while working with it.

All surface phase DOEs and HOEs are readily made in this material. It is often advisable to make a clean master in DCG to copy from because the exposures for reasonable size copies can run from several minutes to an hour, during which time a contact copy on three legs may not move but most optical setups of any size will. The required exposure is on the order of 2000 mJ/cm^2 at 488 nm. Clean glass and primers and bakeouts are sometimes necessary to keep the resist on the glass, and since most resists used are positive, exposure to UV after processing will break bonds and leave the material prone to falling off. There is a lot more to be said about designs and materials but no more room or time to say it. ▲

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