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A.J. Hunt

November 1982

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ASSESSMENT REPORT

HOLOGRAPHIC WINDOW COATINGS FOR SOLAR CONTROL AND DAYLIGHTING

by

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1. INTRODUCTION

A significant fraction of the energy used for space heating, cooling, and lighting can be saved by using window coatings to control radiant heat flows to and from buildings. Direct sunlight may be partially rejected by a window coating to reduce cooling loads. Alternatively, sunlight can be directed into the room to provide task or general lighting. A window coating may act as a heat mirror to reject the infrared portion of the sunlight while passing the visible spectrum. Sunlight may also be controlled by using the angular position of the sun, rejecting or passing light at either high or low angles depending on the need.

Current methods to obtain radiant control are often expensive, unwieldy, or self defeating. Present window coatings typically consist of a metalized layer that is used to reflect a large fraction of the sunlight to reduce cooling loads. While this is effective in reducing the solar heating, it also significantly reduces the visible light, thereby increasing the requirement for interior lighting. The additional electrical lighting then creates heat that increases the cooling requirements, offsetting the original energy savings. Architectural devices such as light shelves or reflective slats are sometimes used to reflect or scatter light further into the room. Control of sunlight by the angle of incidence is usually achieved (if at all) by external devices; e.g., by the use of louvers, awnings, orientations, or window setback.

This report investigates a new approach to the control of sunlight passing through windows, based on the *diffraction* of light. In this approach, Holographic Optical Elements (HOE's) intercept sunlight and diffract it in a desired direction. As a window coating that may be applied to an existing structure, a HOE can provide angular acceptance or rejection of the incoming sunlight, it can direct sunlight deeply into a room to provide task lighting, and it can select the portion of sunlight with the greatest visual efficicy. (visual effectiveness of light per watt).

The most familiar form of hologram is a photographic plate that produces a three dimensional image of an object, usually viewed with a laser as a light source. However, a hologram can also be made to function as an optical element with unusual properties. For instance, a HOE can direct the visible portion of sunlight onto a ceiling to provide general illumination. A HOE may be used to direct sunlight to a specific area of a house (e.g., a kitchen) to provide warmth in the early morning hours but later in the day it can function to reject unwanted sunlight. To fulfill these different functions, holographic window coatings will have different characteristics depending on the window orientation and nature of the heating and cooling loads. However, holographic window coatings can be manufactured by the same basic process but with properties that vary to meet many different needs.

In the past, the use of HOE's in optical systems has been limited for two reasons. First, because they rely on diffraction, they are necessarily wavelength sensitive, and introduce large chromatic aberrations when used with white light, severely reducing the quality of the images. Second, the techniques and emulsions used in the past have generally resulted in rather low efficiencies. However, in the past few years, techniques have been developed to reduce or exploit chromatic effects and increase diffraction efficiencies.

The preceding examples of the applications of HOE's to sunlight control are by no means exhaustive. The unusual and fundamentally different nature of HOE's suggest that there may be many solar applications that have not yet been conceived. It is highly probable that a continuing research program will uncover other possibilities.

The LBL Solar Group has been studying the properties and uses of HOE's for solar applications for the past two years as part of an internal program to investigate the optical properties of materials of small dimensions. Both theoretical and experimental studies were performed to determine the advantages and limitations of diffractive optical systems for use in solar applications. The applications and analysis contained in this report reflect the approach and work performed as part of our program.

2. STATE OF THE ART

A. Diffractive Optical Devices

Diffraction phenomena have been known for a long time. Leonardo da Vinci first described diffraction in the 15th century. The diffraction grating was invented by Fraunhofer in 1819 and was used to spectrally separate sunlight into its colors. The hologram, a device based on interference and diffraction, was invented by Gabor[1] in 1948 as a way of improving the resolution of an electron microscope. A hologram is formed when *interference patterns* produced by coherent light *are recorded on photographic film.* Because coherent light is required to create a hologram, the concept remained largely unexplored until the invention of the laser. The information stored in the hologram is reconstructed when it is illuminated with monochromatic light. As light passes into the hologram it is diffracted by the submicroscopic interference fringes to reconstruct the original wavefront or produce a new one. The result may be a three dimensional image in space or the *hologram may act like an optical element.*

A Holographic Optical Element (HOE) is a particularly simple form of hologram that acts like a powerful, thin lens to change the direction of incoming light. If the pattern of fringes varies in a particular way across the film, light can be forced to go to a certain point (focused), or if the pattern is constant, in a certain direction (deflected). Because the effect relies on the interference of diffracted waves, holograms are necessarily wavelength sensitive.

A HOE may be made by dividing a laser beam into two or more components, expanding those components into converging or diverging wavefronts, and then recombining the wavefronts in a region that contains a photographic emulsion. During the time the emulsion is being exposed the wavefronts must be very stable, not moving over a fraction of a wavelength. After the exposure, the hologram is removed and may be developed in a number of ways, depending on the desired qualities. The developed hologram contains interference fringes that are composed of variations in either the optical properties or in the thickness of the film.

The HOE may be used as it is, after sealing the emulsion, or may be used as a master to produce other holograms[2]. Copies of the original hologram may be made several ways. Contact printing may be used to reproduce several types of holograms. The original hologram, if developed so as to cause diffraction by variations in the thickness, may then be used to make a master hologram that can emboss thin plastic sheets for low cost applications.

Types of Holograms

Holograms are divided into two general types depending on the thickness of the fringe structure[3]. If the hologram has interference fringes over a depth small compared to the wavelength of light, it is referred to as a thin (or surface) hologram. If the thickness of the fringe pattern is many times the wavelength of light, it is referred to as a volume (or thick) hologram. A volume hologram has more selective angular and spectral characteristics than a thin hologram. Because a volume hologram can direct more light into a single diffraction order[4], it is also generally more efficient (where efficiency is the fraction of incident light that is redirected in the desired direction). However,

high diffraction efficiencies are not always necessary or desirable, especially for window coating applications were just a portion of the incident sunlight is still sufficient for interior lighting.

A simple volume HOE that acts like a lens can be made by interfering a plane parallel wavefront with a coherently related spherical wavefront originating from a point source. If the light from the two wavefronts impinges from opposite sides of the emulsion, the HOE will act as a converging mirror (reflection hologram); if from the same side, a converging lens (transmission hologram). Typical optical arrangements for making holograms for these two cases are illustrated in Figure 1. A large variety of optical components can be produced by variations in the position, angle, and strength of the optical elements. These include off-axis converging and diverging optical elements, beam deflectors, and beam splitters.

Recording Media

The intensity distributions produced by the interference of coherent light may be recorded with high resolution silver halide photographic emulsions, dichromated gelatin emulsions, photopolymers and embossable plastics. Silver halide emulsions are widely used because they are readily available and combine good resolution with ease of use. High efficiencies are attainable when the hologram is bleached to produce a phase contrast hologram. Dichromated gelatin emulsions provide extremely good efficiencies[5] and resolutions but are more difficult to make and must be sealed to protect them from the environment. Photopolymers demand extremely high intensity exposures and thus require a powerful laser to produce. Inexpensive embossing techniques may be used to make thin holograms by duplicating master holograms much in the same way that phonograph records are mass produced.

Holographic recording techniques can be classified by the property of the medium that is being modulated. They fall into three categories: amplitude modulation, phase modulation, and refractive index modulation. In *amplitude modulation,* the *absorption* of the medium is used to modulate the intensity of the reconstructing beam. This technique severely limits the efficiency because of the loss of energy in the emulsion. An example of this technique is a normally developed (unbleached) silver halide emulsion.

Better efficiencies may be obtained by using the *phase modulation* technique. In this case the *optical thickness* of a thin hologram is varied to cause phase changes in the reconstructing beam. Since there is little or no absorption, efficiencies can be considerably improved[6]. Typical holograms produced using this technique are bleached silver halide emulsions[7,8] and embossed plastic films.

The highest efficiencies can be obtained by *modulating* the real part of the *refractive index* throughout the volume of a thick hologram. By using this technique, the reconstruction beam undergoes multiple diffractions due to the variation in refractive index as it propagates through the hologram[9,10]. In theory, a thick hologram may be 100% efficient. Dichromated gelatin emulsions exploit this technique. Dichromate holograms are also desirable because of the high resolution possible.

Properties of HOE's

The simplest type of HOE has parallel fringes of equal spacing. This is basically a type of diffraction grating. When this HOE is illuminated with a beam of parallel light,

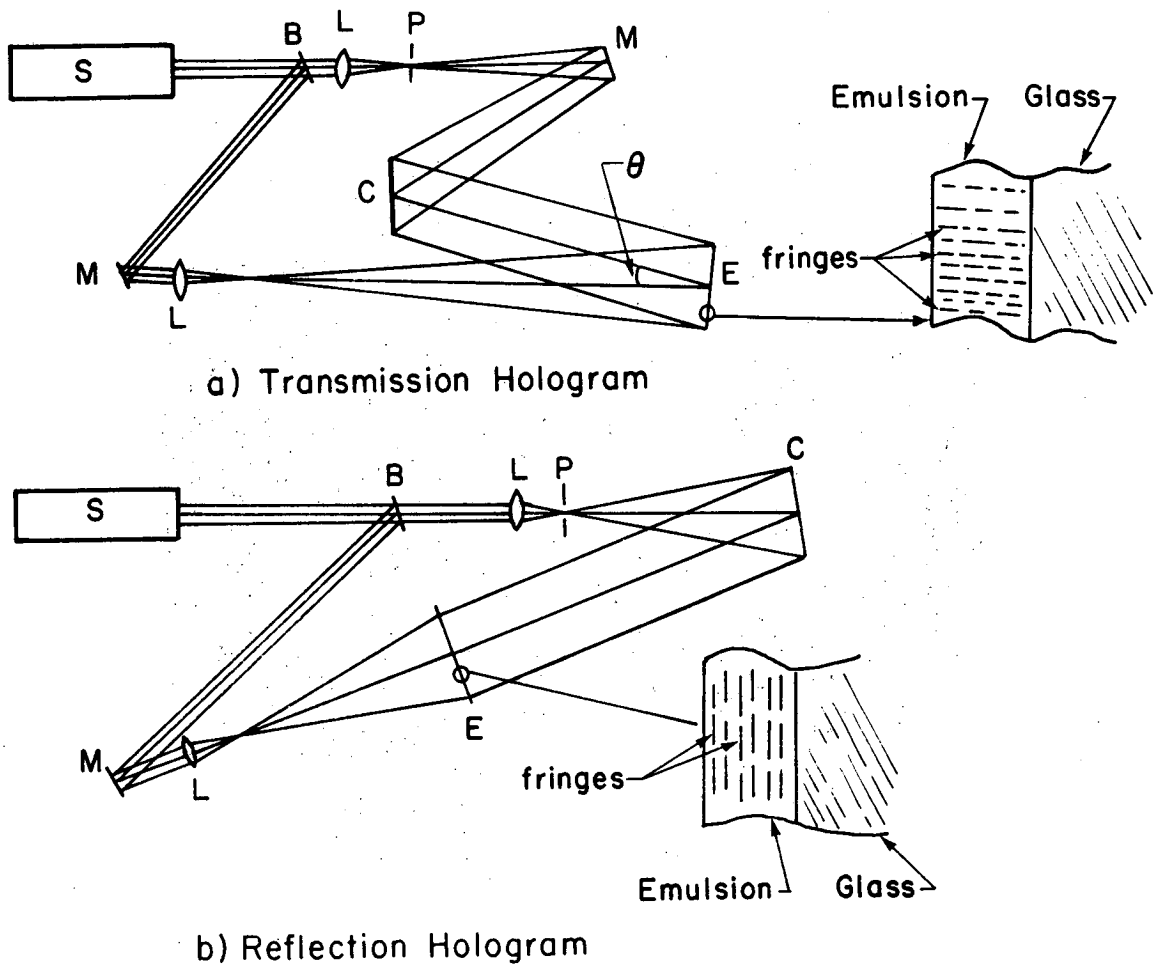

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Figure 1. Typical holographic set up for a) transmission hologram and b) reflection hologram. Extreme enlargements of the cross sections of the emulsions are shown below the diagrams. The components illustrated are the laser source S, beam splitter B, plane mirrors M, pin hole P, collimating mirror or lens C, emulsion E, and lenses L.

the beam will be deflected through an angle that is determined by the angle of incidence, the wavelength and the spacing of fringes.

A simple holographic *lens* may be made by interfering light from a point source and a plane wave as illustrated in Figure 1. The resulting hologram has fringe patterns shaped like ellipses with eccentricities determined by the angle between the two beams. When this angle is zero (an on-axis hologram), the fringes form concentric circles. This pattern is identical to that of the Fresnel zone plate, except that the optical density of the HOE varies continuously over each zone rather than disjointly. An example of an on-axis hologram made at LBL, produced analytically with a computer operating a graphics device, is illustrated in Figure 2. The secondary patterns are artifacts of the computer technique and do not significantly affect the performance of this optical element.

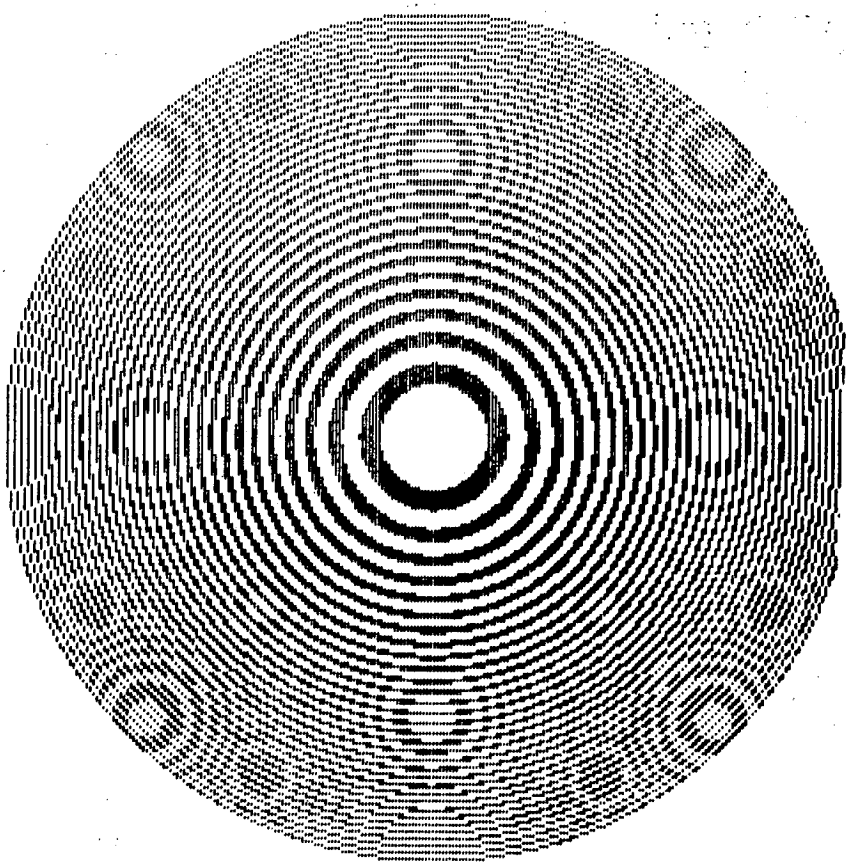

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Figure 2. An on-axis point focus hologram created analytically with a computer and graphics device at LBL.

In a thick hologram, the fringes form three dimensional patterns in space, something like submicroscopic venetian blinds. The orientation of these fringe planes with respect to the surface of the hologram is also dependent on the inter-beam angle. The fringes are roughly perpendicular to the surface for an on-axis transmission hologram and parallel to the surface for an on-axis reflection hologram, as was illustrated in Figure 1. The geometry of the fringes for more complex HOE's is a superposition of many of these zone patterns, one for each point on the object. For a hologram of a real object, the pattern of exposed fringes is exceedingly complex and appears, by observation through a microscope, to be a random distribution of exposed photographic grains.

An important aspect of a HOE is the number of interference fringes per unit distance (spatial frequency). The spatial frequency is important because it affects both the diffraction efficiency of the HOE and the resolution requirements of the holographic medium. If the spatial frequency is too small, (large spacing between fringes), little diffraction occurs and the hologram efficiency will be low. If the spatial frequency is too high, the recording medium will not be able to resolve the individual fringes, and the efficiency will again suffer. For the point source HOE, the fringe spatial frequency rises rapidly as the inter-beam angle increases. For moderately off-axis beams, the fringe spatial frequency can easily be several thousands of lines per millimeter.

Considerations in Using HOE's for Solar Collection

One of the issues in using HOE's for solar applications concerns the effects due to the wavelength dependence of diffraction. The relatively broad spectrum of the solar irradiance requires that a device used for solar collection must operate over a wide range of wavelengths. For visible light applications, this requirement is less stringent.

To illustrate this wavelength dependence, consider an example. In a simple plane diffraction grating with a spatial frequency f, the angles of incidence and diffraction are related by the grating equation:

$$\sin\phi - \sin\theta = m\ f\lambda \qquad (1)$$

where m is zero or a positive or negative integer called the order number, λ is the wavelength of light, and the angles are given in Figure 3. It can be seen that, for a fixed incoming angle and order number, the direction of the diffracted wave depends on wavelength.

A thin hologram with a constant fringe spacing has angular dispersion characteristics very similar to those of the conventional diffraction grating described above. However, with different fringe patterns and spatial frequencies, a wide variety of behavior can be obtained. A thick transmission or reflection hologram can be made to direct light in a particular direction, independently of the direction of the incident light. This behavior is very useful in daylighting applications where it is desired to project deeply into a room the light falling on a window. The rate at which diffraction efficiency falls off as the direction of the incoming beam changes is related to the thickness of the hologram. For a surface or thin hologram, this angular-wavelength selectivity is relatively small but may be augmented by blazing (controlling the shape of the surface contour of the grating to maximize the amount of light diffracted in a certain direction). Angular-wavelength selectivity increases with hologram thickness. For a thick hologram, the diffraction efficiency may be very high and maximum in one direction.

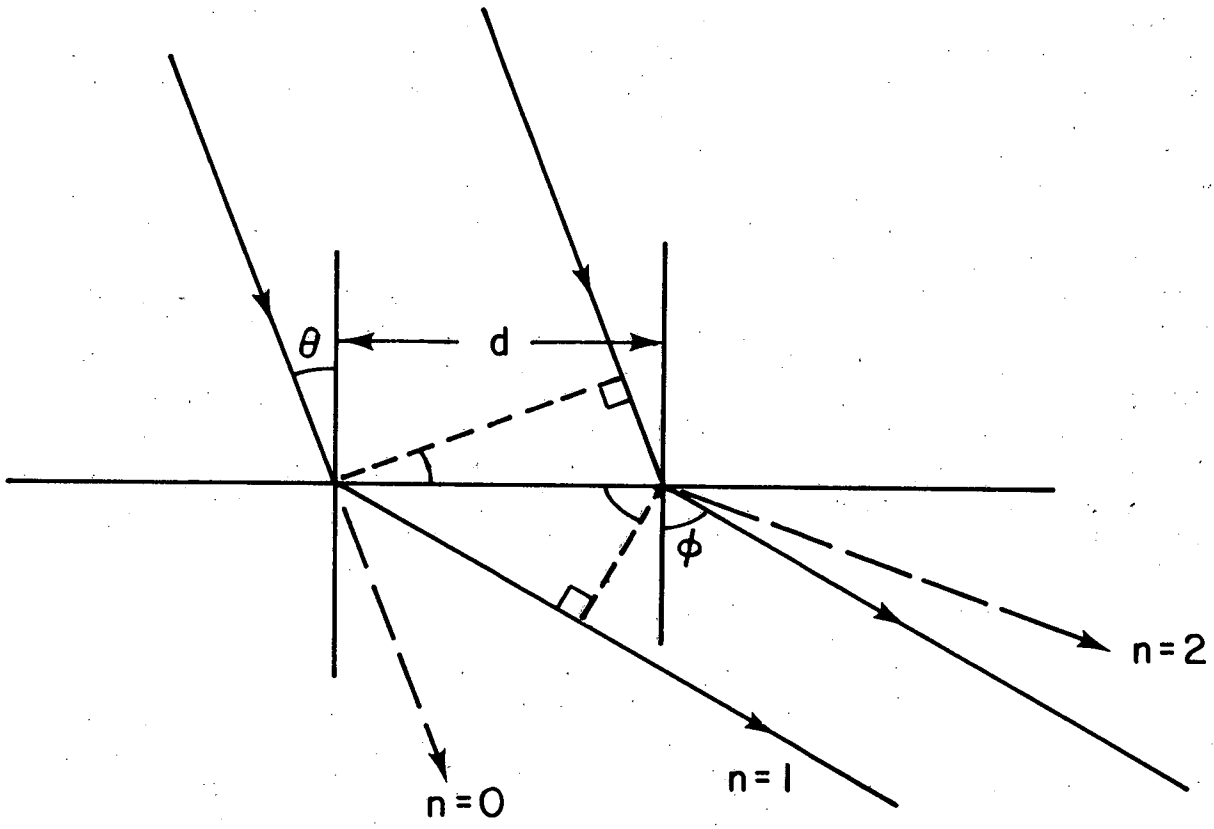

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Figure 3. Geometry for diffraction from a periodic structure with spatial frequency f = 1/d.

Diffraction Efficiencies

Table I lists the theoretical and experimental efficiencies for thick and thin holograms made using the various recording techniques. The diffraction efficiency is defined as the power in the first diffraction order as a fraction of the power in the incident beam.

A final issue regards the definition of *solar efficiency* of a HOE. The conventional definition, in terms of energy in the first diffracted order, may not be suitable for a given solar application because of the combined effects of spectral dispersion, light from more than one order being effective, and non-ideal reconstruction conditions. Due to these factors it is quite possible to have effective solar efficiencies that are higher or

TABLE I

MAXIMUM EFFICIENCY FOR VARIOUS HOLOGRAM TYPES*

Hologram medium:	Thin		Thick		Thick	
Mode of diffraction:	Transmission		Transmission		Reflection	
Property modulated:	Amplitude trans-mittance	Phase shift	Absorp-tion constant	Refra-tive index	Absorp-tion constant	Refrac-tive index
Maximum theoretical efficiency (%)	6.25	33.9	3.7	100	7.2	100
Maximum efficiency obtained experimentally (%)	6.0	32.6	3.0	90	3.8	80

*From "Optical Holography," Collier, Burckhardt and Lin, Academic Press New York, 1971.

lower than the first order diffraction efficiencies. A useful definition of the solar efficiency is likely to be dependent on the application.

B. Applications

In this section we will examine applications of HOE's associated with management of energy in the form of sunlight that enters a building through its windows. The three major applications considered here are *daylighting* (use of sunlight to replace or augment existing electrical lighting), *solar control* (selectively accepting or rejecting sunlight), and *solar heating* (use of sunlight entering a building to heat thermal mass in the building).

HOE window coatings function by selecting or rejecting sunlight based on either its angular or spectral characteristics. Table II illustrates how the three applications apply to the four control strategies. While this table offers a convenient way of categorizing the control techniques, it should be remembered that the angular and spectral effects are not in general independent.

To gain a clearer idea of how a HOE window coating would function, consider the examples given in Figure 4. Figure 4a illustrates the effect of a simple, uniformly spaced, linear holographic diffraction grating placed on the window of a building. In this case the direction of the diffracted beam is given simply by Equation 1. It can be seen that the coating acts to deflect the incoming sunlight to the ceiling of the room to provide illumination or heat.

TABLE II

CONTROL STRATEGIES AND APPLICATIONS

	Specular Control	Angular Control
Acceptance	Daylight	Daylight Heating
Rejection	Control Daylight	Control

In Figure 4b, a thick hologram acts to selectively direct the sunlight to a specific part of the room, regardless of the direction of the incoming sunlight. In Figure 4c, a thick hologram acts selectively to accept or reject the sunlight depending on the angle of the sun. These two cases illustrate the action of HOE window coatings when illuminated by a narrow band of wavelengths. By using multiple exposures with different wavelengths, it is possible to direct a major part of the visible spectrum in the same direction.

Figure 4d illustrates the behavior of the same coating as in Figure 4a when it is illuminated with a wide band spectral source like the sun. It can be seen that different wavelengths are deflected to different directions, but, because of the relatively large size of the window, the spectral components (colors) mix together on the ceiling. The color of the resultant light will depend on the details of the coating and geometry, but sufficient mixing can occur to provide good visual lighting.

The examples in Figure 4 illustrate only a few of the possibilities provided by HOE window coatings. In these examples the coatings were simply diffraction gratings. Holographic window coatings can be made with parallel fringes, as in Figure 4, but with fringe spacing that varies from the top to the bottom. Using this type of coating, the incoming light may be directed to a specific linear *band* for enhancing the penetration of light deeply into the room. In a more general case, where the fringes are not restricted to be parallel, light may be focused to a single *spot* in the room. Thus a holographic coating may be used to redirect the incoming light, focusing it in one or two dimensions.

Holograms possess further characteristics that result in qualities unobtainable using conventional optical systems. One of the most fascinating possibilities involves the use of the multiple exposure properties of a hologram. Because a hologram is very much like a photograph, it is possible to make double, triple, or a greater number of exposures. Each exposure acts like a separate optical element and the composite exposure combines all of their behaviors. For example, several exposures may be superimposed, each of which would focus the sun to the same spot for differing positions of the sun in the sky. Thus the hologram would behave like a stationary focusing collector. However, there are serious drawbacks when using such a hologram as a solar collector. Due to fundamental limitations in optics, the exposures interfere with

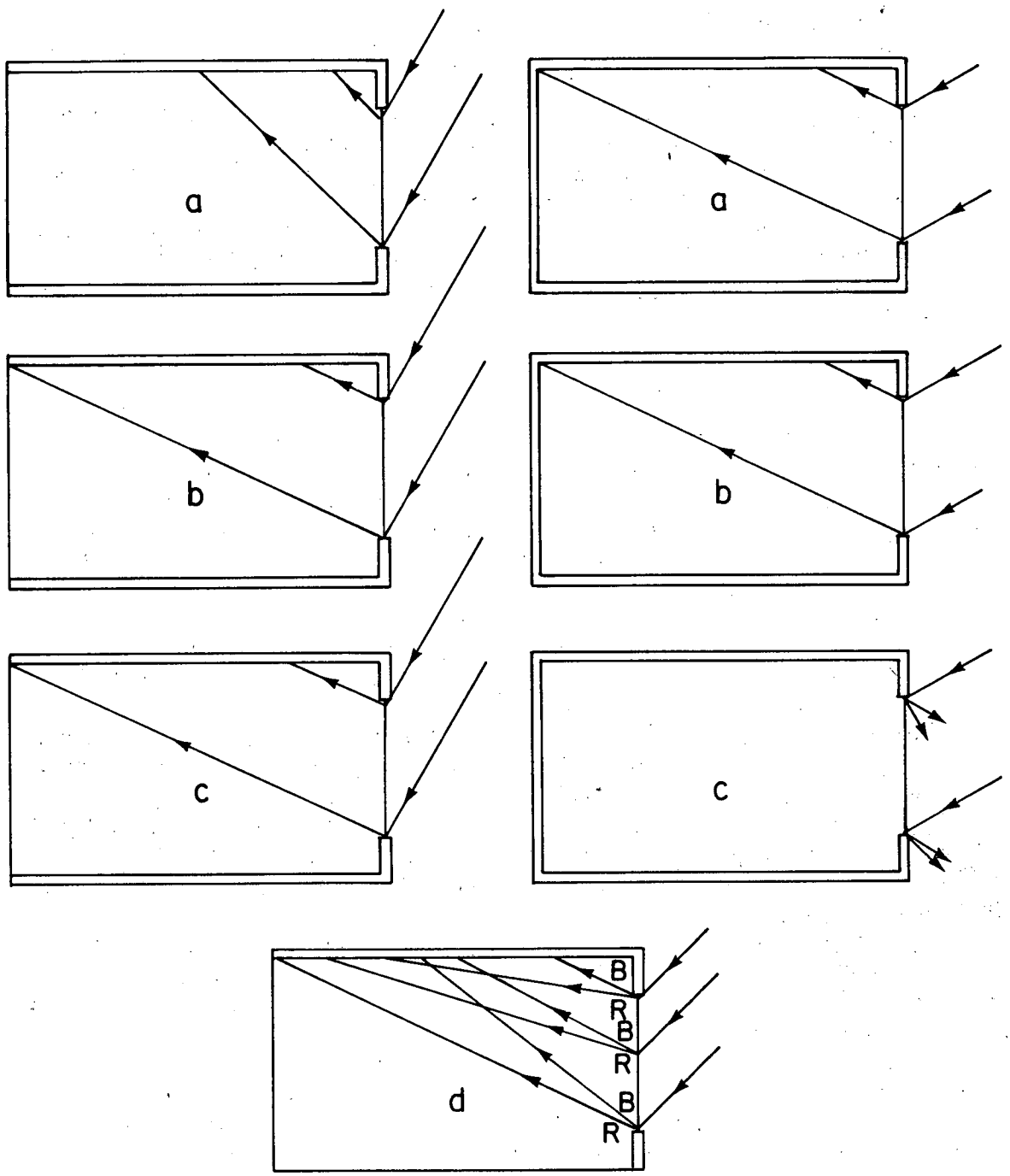

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Figure 4. Holographic diffraction gratings for window coatings. Figure 4a illustrates the action of a thin hologram with constant fringe spacing on light of one wavelength, 4b shows the use of a thick hologram to direct light to a portion of the room independent of the solar angle, 4c illustrates angular rejection of sunlight by a thick hologram, and 4d illustrates the spectral recombination with sunlight using a thin hologram.

each other so that the efficiency of each separate exposure is significantly reduced. However, there may be applications for which lower efficiencies are acceptable if certain focusing behavior is desired.

Sunlight may be rejected by holographic coatings if the beam is diffracted back out from the window or if it is absorbed by the coating. Volume holograms can be made so as to pass only light from a limited angular range. In general, thin holograms allow allow a significant fraction of the light to pass through the film.

From the above and previous discussions it can be seen that the holographic optical element is a uniquely versatile device. Because of the tremendous variety of characteristics exhibited by HOE's, it is certain there will be future applications not anticipated in this report.

Daylighting

Daylighting refers to the use of natural lighting to replace or augment internal (electric) lights. Daylighting appears to be a excellent application for holographic window coatings for several reasons. Holographic window coatings have the ability to redirect light to the ceiling or deeply into a room as illustrated in Figure 4. This results in a reduction in the electric lighting required from that needed if the light simply passes through the window and strikes the floor.

As mentioned earlier, holograms are quite spectrally sensitive: the angular deflection and efficiency of HOE's vary widely with wavelength. Holograms will show much less variation in properties over the relatively narrow band of visible light, (than over the broad wavelength range of the full solar spectrum) making their behavior relatively predictable and attractive for daylighting applications. Another, related benefit in using holograms for daylighting is that it is possible to further use the spectral properties of holograms to transmit only the portion of the visible spectrum for which the eye has the greatest response (while still appearing to be white light). This maximizing of the visual efficacy of light entering a room produces the greatest visibility in a room with the minimum amount of heat. This is an important consideration in cooling loads in air conditioned buildings.

Because of the spectral selectivity exhibited by volume holograms, they are an excellent match for daylighting applications. By using double exposure techniques that utilize two different laser wavelengths, it is possible to provide high diffraction efficiencies and uniform angular response over most of the visual spectrum (Tin, 1982).

So far we have only considered deflecting holographic window coatings with fringes that are oriented horizontally. There are applications where different orientations may result in enhancement of interior lighting. For instance, in south facing windows, it may be desired to deflect morning sunlight to the eastern end of a room. This is quite possible by using a holographic coating with the proper orientation. Clearly, there is a broad range of possible configurations, with each being quite site and application specific.

Holographic coatings may also be used in conjunction with sky lights, light shelves, or on exterior surfaces to redirect light through a window that receives no direct sunlight. Because of the large number of possibilities, it is not possible to explore all these applications at the present time. Therefore, the best approach may be to concentrate on a few specific examples and study the properties of holographic coatings for those cases, but keeping in mind the rich number of possibilities presented by this technology.

Sunlight Control and Rejection

Similarly to the methods by which holographic coatings may be used to redirect sunlight into a room, they can act to reject the sunlight when it arrives from a range of angles. The most obvious application of this is the use of films to reject the light from setting sun falling on west-facing windows. This application can have significant impact on energy use for air conditioning, obviate the requirement for controllable blinds, and make the interior environment more pleasant.

Solar Heating

Holographic coatings may be used, as was indicated early in this section, to deflect light to desired areas within a room. This energy may be used for heating areas of the interior of the structure. An application for this approach would be to redirect sunlight to heat storage tiles in the ceiling or walls. It may be possible to use the focusing ability of a HOE to *concentrate* light falling on the windows onto an absorbing and storage structure. However, it must be remembered that, because of the spectral dispersion of sunlight, the incoming light may be dispersed over a range of angles. Thus it is likely that only a fraction of the light can be directed to a specific area. This may not be a serious drawback for applications that are distributed over the room interior.

Side Effects of Holographic Window Coatings

The most important side effect of window coatings is probably the interference with visibility. Because there are many types of HOE's, their effects on visibility may vary considerably. Simple angular deflectors using thin holograms will only have a secondary effect on visibility, causing some haziness with possible rainbow effects and a decrease in directly transmitted light. Similarly, bleached volume holograms optimized for simple deflectors without strong angular selectivity will allow clear viewing with a reduction in brightness not dissimilar to the effects of solar reflector films currently on the market.

If strong angular or spectral selectivity is desired of the coating, there will be more severe effects on the visibility. These effects will vary considerably with viewing angle. It is difficult to estimate these effects in detail until prototype films are produced and visual observations may be made directly.

The appearance from within and from outside will probably be quite similar, the differences occurring because of the different viewing angle of the observer. Some polarization of the transmitted and diffracted light will occur. This will probably not be apparent to a casual observer. If polarizing eyeglasses are used to view the coatings it is possible that there may be some interesting visual effects.

3. ECONOMICS AND TECHNOLOGY DEVELOPMENT

A. Energy Savings

The use of holograms to supply illumination in buildings that would otherwise be provided by electric lighting has several attractions. Lighting consumes about one quarter of the primary energy used in commercial buildings in the U.S. and nearer to one half of the energy used in office buildings. There is adequate light falling on the building to illuminate its interior if it could be properly redirected. Sunlight can provide more visually effective light per watt than electric lamps.

A recent study[11] performed by the Passive Solar Group at LBL evaluated the energy savings possible from various strategies to utilize daylight to reduce the total energy consumption in commercial buildings. The base case used in the calculation was a 10000 square foot single story building equipped with roof monitors (a type of skylight) to provide lighting for the interior. The object of the study was to determine the optimum ratio of roof monitor glazing area to floor area in order to minimize the total yearly energy usage for the building. The results of this rather complete simulation can be adopted to obtain a rough idea of the possible energy savings if holograpic window coatings were used instead of the monitors. This is an appropriate comparison because the holographic window coatings could be used on a narrow strip of the exterior glazing to provide light deeply into a multistory building. If the width of the strip is expressed as a fraction of the floor area the results may be used directly (with a few qualifications).

The results of the study showed the maximum energy benefit when the glazing area was about 2.5 percent of the floor area. The absolute value of the energy costs varied with location, but the savings resulting from the daylighting strategy were similar at about $0.50 per square foot of floor area per year. To determine the fraction of this value that holographic window coatings could supply requires some assumptions about how deeply into the space the redirected sunlight can penetrate and what the average efficiency of the coatings is. A hologram designed to cover the visible spectrum has a corresponding divergence of about 12 degrees. A 12 degree spread from a narrow strip on the wall would reach a height of about 10 feet in a run of 50 feet. Because light can enter the east, south, or west windows of the building this penetration could effectively light almost the entire building. The same hologram can have a peak efficiency of over 50% for the entire visible range. The average efficiency will be less because of varying solar directions, and is estimated at 75% of the peak efficiency because the coatings face three directions (the view factors are relatively good). With these assumptions, the net savings from using a strip of holographic coating about 18 inches high is about $0.18 per year per square foot of floor area. Multiplying this amount by the inverse of the 2.5% aperture ratio gives a savings of $7.20 per year per square foot of window coating. For a ten year pay-back this means that the coating should cost less than $72 per square foot.

B. Economic and Technical Barriers (Commercial Development)

This section describes the technological approaches to the commercial development of several types of holographic window coatings. Portions of this section are necessarily speculative because of the difficulty in predicting the most viable production methods for undeveloped processes. In the same vein, it is premature to attempt to analyze the economics of production beyond estimates of relative costs for different approaches and the costs of the materials. We have tried to determine if any bottlenecks to development exist or if there are critical pathways for product development. A description of some of the competing technologies is included in this section to provide a background, but is brief due to time and space limitations.

Holographic window coatings are unique because within a *single manufacturing process* films can be produced *for a variety of applications.* Thus HOE's can provide functions that, if other technologies were used, would require several different processes or products. The same process may be used to make holographic coatings that deflect light, act as a lens, or function as an angular shutter, simply by changing the submicroscopic fringe patterns in the hologram. Different patterns are produced by varying the optical design of the holograms, not by changes in materials or construction. The optical properties are contained in the original or "Master" hologram that is produced by interfering light; this Master may then be used to produce large numbers of copies, the copies being the HOE's actually used in applications. This flexibility in design combined with uniformity in manufacture makes the use of HOE's for commercial development very attractive. It should be pointed out, however, that determining how to make the the Master hologram is one of the most challenging aspects of this field. We will return to this point later.

Once the Master hologram is produced it may be copied in a number of ways. The medium and process for copying determines the characteristics and costs of the final product. Holograms may be made in any size, but the technical difficulties increase progressively with sizes greater than a few feet. However, this is not a serious drawback because a Master may be used in a mosaic fashion to produce coatings of arbitrary size. In the following, the production of thick and thin HOE's from an original master are discussed. It should be remembered that thick and thin are relative concepts: both types of HOE are much thinner than the coating or film used to support them.

Thin HOE Window Coatings

A thin hologram for window coating applications is attractive because of the potential for low cost through mass production methods. The type of thin hologram most likely to be adopted for window applications is simply a thin plastic sheet with thickness variations produced by embossing one or both of its surfaces. The production process begins by using a special technique to transfer the patterns from the master into contours in metal forms. The forms are then mounted on a pinch roller assembly. When a plastic sheet is drawn between the rollers, it is embossed with the the pattern originally created by beams of interfering light. While this process is basically simple, the patterns must be very fine in scale, so this process still requires some development work. (Present methods to produce phonograph records utilize embossing techniques of comparable resolution.)

The process of producing the films from the master is always the same. By changing the master a wide variety of differing wavelength and angular properties may be encoded onto the film. The film only needs to be a few mils thick to provide the mechanical strength for mounting to a window. The films can be backed with an adhesive so that they can be retrofitted to windows in a simple manner. The product materials costs will be comparable to usual costs for thin plastic films and adhesives.

Embossing techniques for commercial holograms are presently under development for display holography. These techniques have been used to produce holographic *images* of acceptable quality on thin plastic and metal coated plastic films. HOE's for window coatings probably will not demand the quality of embossing required for image holography because the patterns are much less complex. For this reason the development of production processes for embossed holographic window films looks promising and could evolve rather quickly if it were perceived that a market exists for the product.

Thick HOE Window Coatings

Thick or volume holographic window coatings based on modulating the real part of the index of refraction offer significant performance advantages over thin HOE's, as was illustrated in Table I. However, processes for their mass production are more complex than for embossed thin holograms. Thick holograms may be manufactured directly as illustrated in Figure 1. This process yields high quality holograms, but is not well suited to mass production. A simpler method of reproduction that yields copies of excellent quality[12] is based on contact printing of the master. Either laser or incandescent light source may be used during exposure, depending on the master and the printing process. Either silver halide or dichromated emulsions may be used as the recording medium. Processes similar to those used in conventional photography are used to develop the film.

The diffractive coatings may placed on plastic or glass substrates. The emulsions used for these coatings are water sensitive, and therefore must be sealed before being exposed to the environment. Dichromated emulsions have been successfully sealed and exposed to the elements for periods of years without showing undue degradation[13].

Other Window Coatings

Non-diffractive window coatings presently available or under development include those with reflective, absorptive, heat mirror (infrared reflective), and refractive properties. The functions of the reflective, absorptive, and heat mirror coatings do not essentially overlap those provided by diffractive coatings. If desirable, these other film properties may be combined with diffractive films to augment their performance.

The window coating closest in behavior to holographic coatings is the Fresnel lens. The Fresnel lens operates on the principle of refraction of light using small facets embossed into a plastic plate. These much thicker coatings do not exhibit strong spectral properties and therefore are not capable of controlling the spectral content of the transmitted light. Fresnel lens coatings can be used to deflect sunlight into a room in a manner similar to the diffractive coatings, but with different angular characteristics. Fresnel coatings do not exhibit the angular shutter properties discussed for HOE coatings. The optical characteristics of Fresnel coatings are such as to destroy the visibility through the window. Alternatively, holographic coatings can perform most

functions provided by Fresnel lenses, use significantly less material, and may have only a minor effect on visibility through the window.

C. Research Requirements for Laboratory Bench Scale Tests

To perform meaningful bench scale tests of HOE window coatings requires four basic steps. First, a specific application of interest must be identified. Next, analytic calculations must be performed to determine the holographic setup required to produce a film with the required characteristics. Third, the HOE must produced. Last, the HOE must be evaluated. It cannot be overemphasized that a systematic approach is essential to achieve meaningful conclusions from a test program in this area. Holograms have been made for a number of years for display art applications. Several individuals and groups have developed, largely through trial and error, techniques to produce excellent quality display holograms. However, the criteria for good display holography are considerably different than for HOE's of the type discussed in this report. A systematic approach to the design of the holographic window coating must be based on a careful evaluation of the needs and techniques to produce them, and should not simply adopt techniques developed for other applications. The major steps for a test program are discussed below, followed by specific needs in terms of time and support.

From the earlier discussion it should be clear that there are many possible applications for holographic window coatings; in fact, choosing among the applications is one of the most difficult aspects of this approach. However, a test of a HOE window coating should act more as a proof-of-principle than a final determination of an applications niche. A suitable choice for testing would be a linear volume holographic grating based on the silver halide emulsion. This choice provides a baseline for a number of applications but requires less effort for design and sample production than other approaches.

Once the basic configuration has been chosen, it is necessary to optimize the HOE design for a specific function. A deflector to enhance light penetration to a ceiling would be a choice consonant with the program objectives. The design effort would then focus on determining the optical setup parameters to maximize the efficiency for visible light deflection. This could be done using the analytic models that have been developed at LBL and that have been implemented on the LBL computer system.

Once the design has been determined, making a hologram requires a laser, an optically stable table, a variety of optical elements, holders, and dark room facilities. The approach would then be to use the calculated setup conditions and experiment with the exposure and development conditions. The goal would be to produce a bleached, volume hologram that was optimized to redirect visible light efficiently. For the laboratory test, it is only necessary to produce holograms of a size sufficient for evaluation purposes.

The testing phase of the program should have two objectives. First, laser measurements should be performed on the film to accurately determine the efficiency as a function of angle and position on the test sample. These tests allow comparison with predicted performance, and determine whether the design goals have been met in a quantitative way. The second major test objective is to study the performance of the test sample using real sunlight under controlled conditions. The Passive Solar Group at LBL has developed a highly instrumented model structure capable of simulating a wide variety of daylight conditions. This type of test bed would be ideal for evaluating

variety of daylight conditions. This type of test bed would be ideal for evaluating realistic performance parameters of holographic window coatings.

The time and cost to design, produce and evaluate a test holographic window film at LBL would depend somewhat on the scope of the work and the approach. Carrying out the program outlined above at LBL would have the advantages of the design tools already being in place and access to the automated daylighting test bed mentioned above. Assuming this approach, it would take two investigators about a year to carry out the work and report the results. There is an additional requirement of setting up the laboratory facility for generating and photographically developing the hologram. The cost of the above program, instituted in FY 1983 would be in the neighborhood of $280K. A report of the results should be available about one year after the start of the program. At the end of the period, the program would be in a position to support and evaluate the full range of possibilities for holographic window coatings. In addition, the work would establish a National Laboratory involvement for program guidance and a base for technology transfer to the private sector.

4. RESOURCES AND EXPERIENCE IN THE FIELD

A. Current Research in Holography

The field of holography expanded rapidly from almost nothing in the mid 1960's to an active field encompassing both scientific and artistic endeavors. First viewed as a curiosity, it quickly found application in a number of unrelated technical fields, including nondestructive testing, fabrication of diffraction gratings, computer memory elements, battlefield infrared viewers, and checkout counter laser scanners, to mention but a few. Because of the variety of applications there is not a very cohesive community of holographic investigators. A small but active band of people have been developing holographic art for commercial and purely aesthetic reasons. Thus, while there is a variety of experience in the private sector, most of the activities are directed toward specific product lines, usually associated with the field of electrooptics.

Recently there has been interest in HOE's for solar collectors. Their use as concentrators for solar photovoltaic cells is quite promising because of their ability to concentrate different colors (wavelength bands) to different locations. By using HOE, concentrated light is directed to a series of photocells that match the wavelength characteristics of sunlight. This spectral decomposition improves the combined theoretical performance of the cells considerably. At present, work on spectral matching for photovoltaics is taking place mostly in Germany. There is a program to investigate HOE's for solar thermal conversion presently funded by the Basic Energy Sciences of DOE. NTS corporation is investigating this approach under the leadership of Dr. Hla Tin. This group has expressed interest in exploring the window coating idea within the past two years but received no DOE funding for this work. With the possible exception of this group there is very little, if any, work going on in the use of holograms for solar control and daylighting applications.

As mentioned earlier, there is a wide ranging group of investigators working in general holography. A few of the university, industrial, and governmental groups investigating general topics in holography are listed in the upper part of Table III. The lower part of the table contains a list of groups working on solar energy applications of HOE's.

B. Technology Transfer

After a successful test and evaluation of the concept of holographic optical coatings, it is anticipated that there will be private sector interest in the technology from at least two groups. In the current economic and regulatory climate, the power utilities have shown great interest in implementing conservation measures to reduce the need for new generating capacity. The development of holographic window films offers potential daytime energy savings that impact the peak loads on many utilities. It is reasonable to assume that either the utilities themselves or their research organizations (EPRI, GRI) will have an interest in continuing a research and development effort on the concept.

The second group that will undoubtedly show interest in continuing work on holographic window coatings consists of window film and window manufacturers. If it can

TABLE III

SOME GROUPS INVESTIGATING HOE's

Group	*Interest*
General Holography (miscellaneous topics):	
Bell Laboratories	General
China Lake Naval Weapons Center	HOE's
Holographics	Display Art
Hughes Research Laboratory	Military
IBM	Business Machines
Jodon Engineering	Optical Instr.
University of Michigan	General
University of Arizona-Optical Sciences Center	General
Holography for Solar Collection:	
Apollo Optics	Kinematics, Inc.
Farrand Optical	Solar & Instr.
Lawrence Berkeley Laboratory	Solar & Cons.
NTS Corporation	Solar
University of Stuttgart	Photovoltaic

be demonstrated to this group that the manufacturing process is amenable to existing technology, it would be quite surprising if they didn't want to pursue this work themselves. A main uncertainty in this case is how the manufacturers perceive the patent situation, and what coverage they can obtain. At present there is at least one patent granted for a solar concentrator based on HOE's and very likely several patent applications have been filed on related concepts. As of the present time we know of no patent or application covering the use of holograms for window coatings, but it is certainly possible that one has been filed.

Other groups that may express interest are architectural organizations and individuals. This approach offers a new approach to building energy management that may be of interest to such groups. Building materials representatives may also be interested in investigating the possibilities this approach offers.

5. FUTURE APPLICATIONS AND SPINOFFS

Because these devices are basically extremely flexible optical elements, potentially any aperture that can benefit from the control of radiant energy flowing through it is a potential user of diffractive control systems.

One large class of cases that has not yet been discussed involves the control of infrared radiation. The use of holograms in the infrared offers no conceptual difficulties, but very little work has been done on producing infrared HOE's. A factor gravitating against using HOE's for infrared control is that most infrared radiation is from thermal sources and is therefore diffuse (arriving from a distribution of angles) and has a wide spectral distribution. As we have seen earlier, the angular and spectral effects can be quite significant in diffractive systems. Thus potential infrared applications must be examined in detail to determine their usefulness.

Another related application that has not been discussed in any detail is the use of holographic coatings as solar augmentation devices. For instance, a reflection hologram could be mounted outside a window and act to redirect or refocus sunlight into the window. Using the multiple exposure characteristics of holograms could make this an attractive approach in some cases.

As we better understand the advantages and limitations of HOE's for building applications, other, uses that are unforeseen at the present, may well become apparent.

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