Holographic Diffusers:
Diffusers with low backscatter

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Abstract

Holographic diffusers have been produced with very low back diffusion in comparison with diffusion in the forward direction. Reduced back diffusion was achieved by lamination and index matching procedures which minimized the formation of Bragg planes parallel to the film surface. Photopolymer media were used as phase media.

1. Introduction

Diffusion of light can be readily achieved using ground glass or wavy glass as a refractive diffuser. Transmissive diffusion characteristics of several diffusers has been examined [1-3], but the back diffusion of these diffusers is not so well characterized. Holographic diffusers have also been examined [4], and they offer the possibility of considerable control over the angular distribution of diffusion. In some applications, it is required that light be diffused only in the forward direction; backward (reflective) diffusion is problematical. For example, a backlit display device may incorporate diffusers [5]. If it is viewed in full sunlight, any back diffusion of the sunlight will reduce contrast of the image. Back diffusion can be reduced by the use of polarization type isolators [6] provided that the diffuser in question preserves polarization; however there is a penalty of loss of intensity in the forward direction due to the absorption of light by the polarizer.

In this article we examine holographic diffusers in which back diffusion is suppressed by the elimination of spurious Bragg planes during the formation of the holographic optical element (HOE).

2. Methods and Materials

2.1. Formation Rationale

The formation of HOE's which diffuse light primarily in the forward direction and with minimal back diffusion can be achieved as follows. In a thick emulsion, diffraction of light from the HOE is primarily by Bragg diffraction. Therefore forward diffusion is enhanced by preferential formation of transmissive Bragg planes or gratings which are nearly perpendicular to the surface of the photosensitive material (film) and avoidance of reflective Bragg planes which are nearly parallel to the surface. Transmissive Bragg planes are formed when the input light rays intersect on the same side of the film; whereas reflective Bragg planes are formed when the input light rays intersect on opposite sides of the photopolymer as seen in Fig. 1. Illumination of the developed plate by a light ray in the same direction as one of the original light rays results in reconstruction of the other input ray. This may be in either transmissive or reflective form depending on the conditions during formation of the HOE (Fig. 1).

During HOE formation, light rays are reflected from interfaces where there is a change in refractive index (n) as indicated by the film sandwich formation procedure of Fig. 2. Rays which are reflected back from the photopolymer can interfere with input light, and this interference gives rise to reflective Bragg planes.

Reflective Bragg planes may be eliminated by removing extraneous layers which give rise to partial reflection due to discontinuity in refractive index. The reflective Bragg planes are also reduced by index matching any remaining discontinuities. The Mylar (polyethyleneterephthalate) cover sheet may be removed for direct lamination of the photopolymer to the glass plate. Any birefringence of that material will be removed as well. The photopolymer is tacky which facilitates the lamination procedure. The back reflection from the air interface on the right in Fig. 2 may be eliminated by laminating the film to an anti reflection coated plate. A lamination method was used rather than an index matching tank since lamination was simpler and also eliminated spurious reflections during the reconstruction and use of the diffuser plate. The final diffuser plate would not be used with an index-matching tank.

Back diffusion also arises from scattering of light from inhomogeneities within the film. Such scattering may be reduced by choosing a film which approximates a pure homogeneous phase medium as well as is possible.

2.2 Formation Procedures

Three diffusers were formed with different procedures of attachment to a substrate, to compare the effect of reflections from interfaces during formation. Interfaces involving a change in refractive index are: film lamination to a glass plate, film lamination to an anti reflective plate, and a film sandwich. These cases are shown in Fig. 3. For the glass plate laminated and antireflective laminated diffusers, the Mylar cover sheet was removed and the photopolymer laminated directly to a glass plate or anti reflection coated glass plate respectively. For the sandwiched diffuser, the film (Mylar-photopolymer-Mylar) system was sandwiched between the glass diffuser and a glass plate. For each of these diffusers, DuPont 600-10 film [7] was placed in direct contact with a ground glass source diffuser which was illuminated from behind by a collimated laser beam; these therefore had a 180° field angle of input rays. A film exposure of 55 mJ/cm^2 was made at 514 nm from an argon-ion laser (Coherent Innova model 300) for formation of each HOE. The film was given a flood light exposure followed by a 2 hour bake at 120 °C, as recommended by DuPont.

Lamination was performed using the following procedure recommended by DuPont. Cleanliness is very important in this procedure, therefore the glass substrate was cleaned by dragging a piece of lens paper with reagent grade methanol applied across the glass surface. Immediately following cleaning the glass plate, the cover sheet was removed from a piece of holographic recording film by peeling in a slow continuous motion. Care was taken to de-laminate the cover sheet in a slow, even manner to avoid de-lamination between the photopolymer and Mylar base. While holding the leading edge of the film off the glass plate, a soft rubber roller (Printmasters No. 4126, Hunt Manufacturing Co., Statesville, N.C.) was used with a strong constant pressure to roll the film onto the glass. Care was taken to avoid trapping air bubbles between the glass and photopolymer. Some HOE specimens were deliberately delaminated from the glass substrate and were re-measured.

For the photopolymer sandwich, four back reflections are possible from four interfaces: photopolymer/ Mylar, Mylar/air, air/glass, and glass/air as seen in Fig. 3. Two reflections are possible for the photopolymer laminated to a glass plate: photopolymer/glass interface and glass/air interface (Fig. 3). Assuming that the anti reflective coating allows no reflection, only one back reflection exists between the photopolymer/ glass interface when the film is laminated to an anti reflective plate (Fig. 3c). That back reflected ray does not generate an interference pattern within the photopolymer.

A further series of holographic diffusers was made in DuPont photopolymer HRF-150-38 laminated to an anti-reflection coated glass plate. Exposures were made at 514 nm with different input cone angles of diffuse light, with 180° corresponding to contact between the diffuser and the film. Smaller angles were achieved by moving the illuminated diffuser back from the film. Following exposure, the diffusers were given a 60 second ultra violet cure, but no heat treatment, since it is not required for this film. This photopolymer is one of the thickest available from DuPont, with a thickness of 38 µm. A drawback of using HRF-150-38 photopolymer is its high exposure energy of 130 mJ/cm^2 at the sensitized wavelengths of 488 and 514 nm. Previously used DuPont photopolymers recommended exposure energies of 20 mJ/cm^2.

3. Results and Discussion

3.1. Ring Structure

A ring structure consisting of several rings of light with the innermost one the brightest, brighter than the diffuse background, and centered on the incident beam axis was observed in the back diffused light of HOE diffusers sandwiched between a glass plate and source diffuser during formation. A particular specimen was exposed at 55 mJ/cm^2. The light diffused forward was much stronger (as intended), and any ring structure in the forward direction was overwhelmed by the overall diffusion. The ring structure was too faint to measure the ring diameters accurately. Another HOE diffuser was therefore formed as above, but exposed at 25 mJ/cm^2 instead of 55 mJ/cm^2 to enhance the back reflection. This exposure resulted in a ring pattern in the back diffused light which could be measured easily. The innermost ring subtended an angular radius of about 8°.

The inner ring structure in the back diffuse light is indicative of interference from light reflected from the various layers in the film. Analysis of this light was performed, idealizing the interference as that of a holographic zone plate. A holographic zone plate lens of focal length f arises from laser point sources at distances u and v from the recording film. The resulting interference pattern consists of circular zones of radius r_n,

$$r_n = \sqrt{2n\lambda f} = \sqrt{2n\lambda \frac{1}{\frac{1}{u} - \frac{1}{v}}}$$

in which n is an integer.

In the context of the multi-layer holographic film, we do not have point sources, however offset images of the diffuse light can be expected to generate diffuse rings by a similar interference phenomenon.

We find, following calculation, that an inner ring of radius 8.3° corresponds to a separation between effective source images of about 60µm. The Mylar backing was found to be 20 µm thick; the emulsion is quoted as 10 µm thick and the overall thickness of the film was about 60 µm thick. Therefore the back diffusion in the DuPont material is attributed to spurious Bragg planes arising from reflections among the layers.

3.2. Diffusion Results: Dependence on Attachment Procedures

The above ring pattern did not appear when the film was laminated to an anti-reflective plate. Diffuse transmission results for the HOE diffusers with three different procedures of attachment to the substrate are plotted in Fig. 4. Results are given in the form of normalized diffused light power per solid angle, vs angle with respect to the normal; the incident beam was normal to the plate in all cases. The meaning of the angle is shown in the inset in Fig. 4. Transmission values are very close to each other at all spatial frequencies. The attachment procedure has no significant effect on transmission characteristics of the HOE diffusers. This was expected since the attachment procedures used do not affect the transmissive object beam ray field during formation.

Diffuse reflection results for the HOE diffusers with three different attachment procedures during formation is seen in Fig. 5. As expected, back diffusion increased in the sandwich diffuser due to reflections of light from the various layers forming extraneous Bragg planes. The lowest back diffusion values were obtained when the photopolymer was laminated to an anti reflective plate followed by glass plate lamination. The glass plate sandwich diffuser gave the highest values of back diffusion.

The diffuse transmissive values of Fig. 4 were divided by the diffuse reflective values of Fig. 5 resulting in the transmission versus reflection (T/R) ratio graph as seen in Fig. 6. Since the transmission values are about the same and the reflection values vary greatly, the T/R graph is dominated by the reflection characteristics.

The diffuser made by lamination to an anti reflective plate was then de-laminated from the anti reflective plate following exposure to study the effects of de-coupling. It was observed that the photopolymer was no longer tacky and that further direct lamination to a substrate would not be possible. Further lamination would require the use of a cement. Index matched cement is available which would serve this purpose. It should be noted that transmission values decreased from 2.7 to 0.91 mW/Sr mW and reflection values increased from 0.0043 to 0.10 mW/Sr mW as a result of delamination.

The zero order beam ratio is the ratio of light intensity directly transmitted (at an angle of zero degrees), to the incident light intensity. Zero order beam ratios for each HOE diffuser in DuPont 600-10 film with different attachment procedures are given in Table 1. Zero order beam ratio is about the same for each laminated diffuser, and much lower for the glass plate sandwich diffuser. The low zero order ratio results for the glass plate sandwich diffuser are a result of reflective Bragg plane formation causing more light diffraction and thus a lower zero order beam ratio.

Zero order beam ratios for DuPont HRF 150-38 film depended on exposure energy, and the lowest zero order beam ratio (0.27) was observed at the recommended exposure energy.

3.3. Diffusion Results: Dependence on Field Angle

Results for the 150-38 film are shown in Table 2. The T/R ratio (ratio of diffusely transmitted to diffusely reflected light) was only 11 for 150-38 film laminated to a plain glass plate at a 180° field angle. By contrast, a restriction of the field angle and lamination to an anti-reflection coated plate gave rise to T/R values as high as 630. The HOE's made with restricted field angles less than 45° did not exhibit much diffusion in either the forward or the backward direction at 45°.

Upon delamination of the 34° HOE diffuser from its glass substrate, it was observed that the photopolymer was no longer tacky and that further direct lamination would not be possible. Following delamination, diffuse transmission at 10° decreased and diffuse reflection increased, resulting a T/R ratio drop from 630 to 9.1.

Suppression of back reflection is therefore necessary at reconstruction as well as during formation of the HOE. The reason is that during reconstruction, a portion of the light which is diffused forward by the film can be reflected back by interfaces which contain a discontinuity in refractive index. Suppression of these reflections is therefore necessary during reconstruction, if back diffusion is to be minimized. This suppression is achieved by using the same index matching procedure during reconstruction of the HOE as was used during its formation. We also recognize the possibility that distortion of the photopolymer after removal from its substrate could have reduced the diffuse transmission. Use of an index matching tank is not considered practical in this context since index matching is needed during reconstruction as well as during formation; and during reconstruction the diffuser would be part of a larger device.

4. Discussion

Use of an anti-reflection coated plate in laminating the DuPont 600-10 holographic film results in T/R ratios exceeding 100 at small angles (10°) and about 18 at 45°, as shown in Fig. 6. T/R of 630 was achieved in DuPont 150-38 film at 10°; this was prepared with a field angle of 45°. This is to be compared with T/R ≈ 3 at 10° for DuPont 600-10 film exposed in a sandwich of glass plates with no particular precautions. In prior studies [4], the DuPont film, although it is a high quality phase medium, was found to exhibit significant back diffusion when prepared as a diffuser. Even when a polarization based optical isolator was used, the best T/R which was obtained at 10° was 26. By contrast, the ground glass used as a source to make the HOE's exhibits T/R of 28 at 10° and 1.7 at 45. Other ground glass exhibits T/R = 80 to 90 at 10° and 2 at 45°, depending on wavelength; and a white plastic diffuser [4] exhibits T/R ≈ 0.8 to 1 at 10° and 0.8 to 0.9 at 45°.

In order to achieve levels of back diffusion even lower than those reported here, the present procedure could be combined with an optical isolator based on polarization. Study of back diffusion due to light scattering by particles [8] may be of use. Another possibility is the use of Polaroid photopolymer. Finally, use of higher quality anti-reflection coating in the present method will also be helpful.

5. Conclusions

Lamination of the photopolymer film to an anti reflective plate effectively reduced diffuse reflections in holographic diffusers.

Diffusers with the lowest values of back diffusion were prepared by moderately restricting the field angle of incident light during formation.

Acknowledgment

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Table 1 Zero order beam ratios comparing attachment procedure during formation.

Diffuser type	Zero order beam ratio I_z/I_{in} λ =514 nm (formation and playback)
1: glass plate sandwich	0.054
2: glass plate lamination	0.17
3: anti reflective plate lamination	0.14

Table 2. Performance of holographic and ground glass diffusers. The following HOE's were exposed at the recommended exposure energy of 130 mJ/cm^2 at 514 nm. Diffusers were given ultraviolet flood cure for 60 sec. with a halogen projector lamp. No heating process was required following UV. cure.

Diffuser type	λ(nm)	Forward transmittance (mW/sr mW) 10°	45°	Back reflectance (mW/sr mW) 10°	45°	Forw/back T/R 10°	45°	Zero order beam Iz/Iin
1:DuPont 150-38 180°, with glass plate	514	0.89	.0065	0.084	.0014	11	4.6	0.27
All HOE's below laminated to anti-reflection coated plate								
2:DuPont 150-38	514	1.2	.0050	.0058	.0007	210	7.1	.35
180° Field Angle	633	0.81	.0034	.0052	.0005	160	6.8	.49
3:DuPont 150-38	514	1.8	.0019	.0055	.0008	330	2.4	.17
60° Field Angle	633	1.7	.0008	.0054	.0006	310	1.3	.36
4:DuPont 150-38	514	3.8	.0015	.0072	.0006	**530**	2.5	.093
40° Field Angle	633	2.2	.0009	.0047	.0005	470	1.8	.27
5:DuPont 150-38 34° Field Angle	514	2.7	.0011	.0043	.0005	**630**	2.2	0.25
6:DuPont 150-38	514	0.79	.0014	.0051	.0007	150	2.0	.12
30° Field Angle	633	0.61	.0005	.0036	.0003	170	1.7	.32
7:DuPont 150-38	514	0.95	.0020	.0073	.0010	130	2.0	.21
20° Field Angle	633	1.2	.0010	.0051	.0006	240	1.7	.39
8:DuPont 150-38	514	0.071	.0011	.0030	.0007	24	1.6	.45
10° Field Angle	633	0.050	.0005	.0013	.0003	38	1.7	.61
9:Glass Diffuser as source for 1-7.	514	2.3	0.034	0.083	0.020	28	1.7	.0093

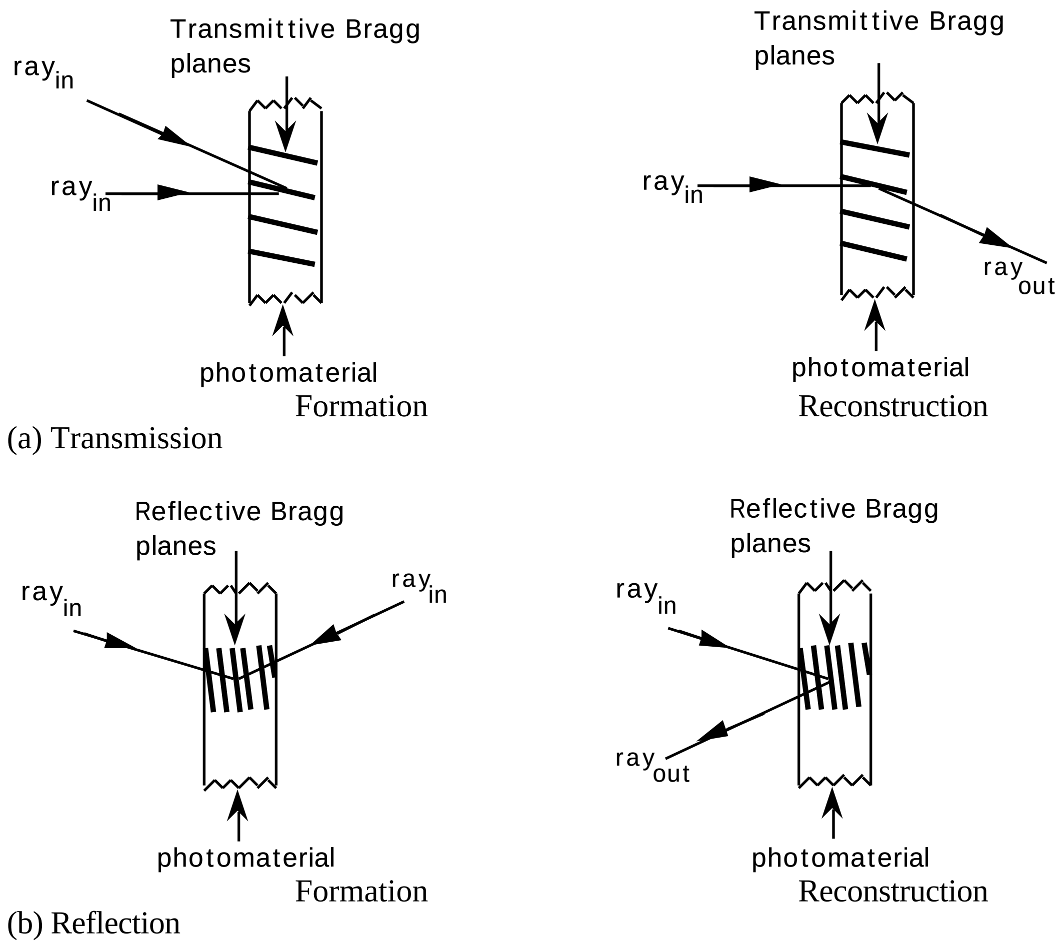

Figure 1 Bragg plane formation and reconstruction. (a) Transmissive Bragg plane formation and reconstruction (b) Reflective Bragg plane formation and reconstruction

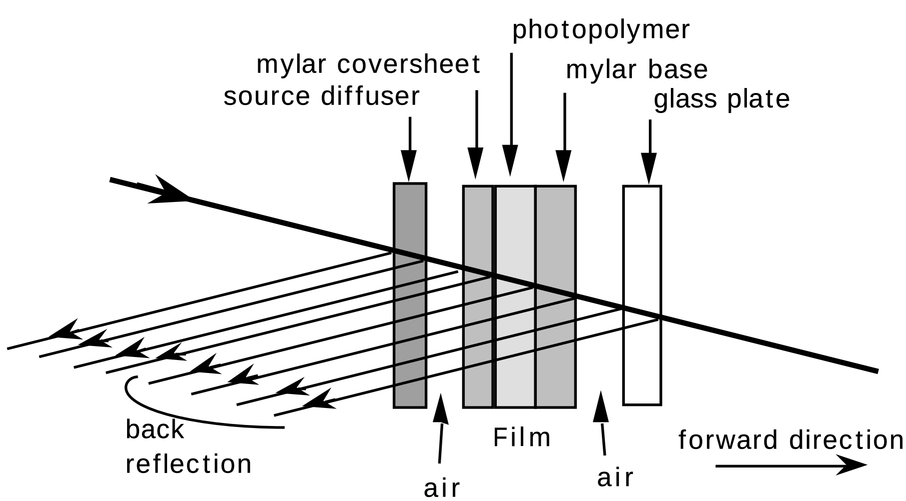

Figure 2 Ray diagram of formation layering indicating reflections from interfaces at which the index of refraction changes. Rays which are reflected back from the photopolymer can interfere with rays traveling in the forward direction to form reflective Bragg planes.

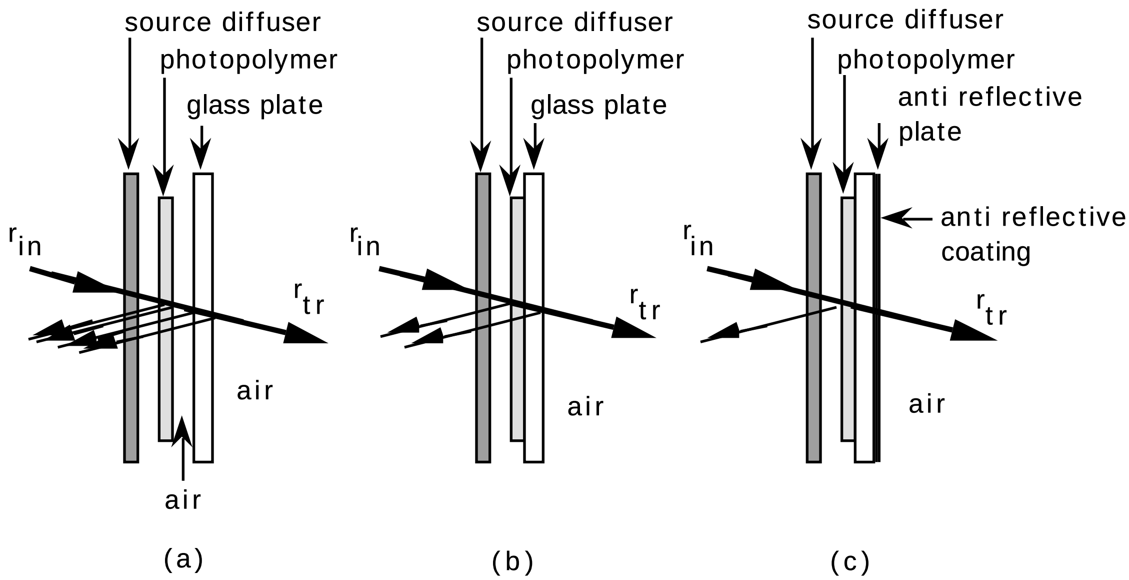

Figure 3 Ray diagram of three layering systems indicating back reflections from interfaces where the index of refraction changes. Reflections are not drawn from interfaces in front of the film. (a) Photopolymer sandwiched between source diffuser and glass plate. (b) Photopolymer sandwiched between source diffuser and laminated to a glass plate. (c) Photopolymer sandwiched between source diffuser and laminated to an anti reflective coated plate.

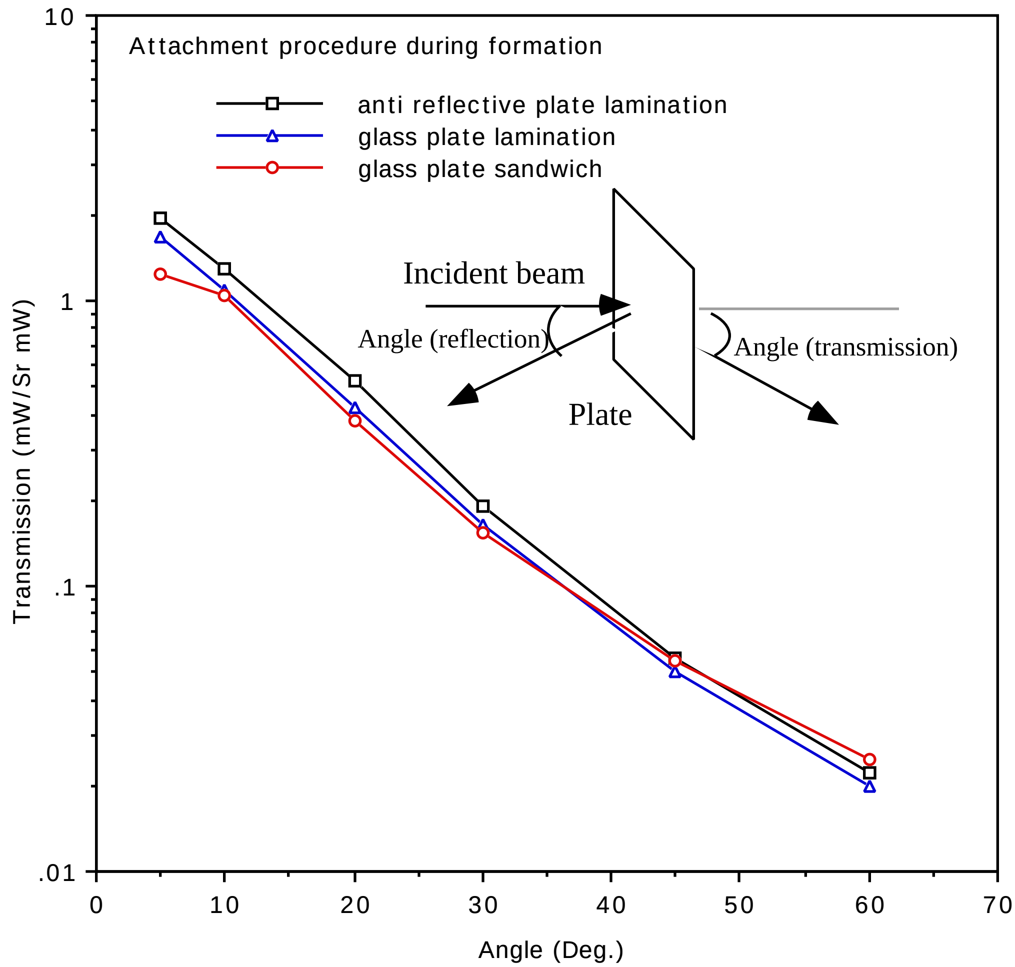

Figure 4 Diffuse transmission results for different procedures of attachment of film to substrate during formation in DuPont 600-10 film with a 180° field angle. Formation and playback wavelength of 514 nm.

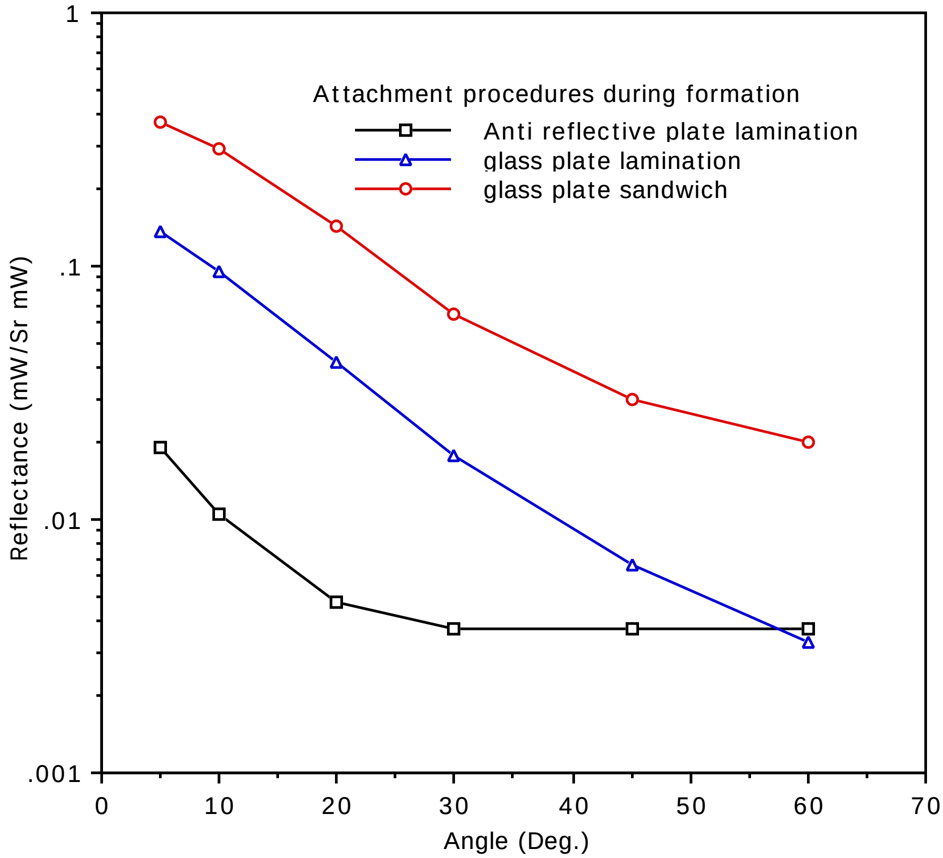

Figure 5 Diffuse reflection results comparing attachment procedure during formation in DuPont 600-10 film with a 180° field angle. Formation and playback wavelength of 514 nm.

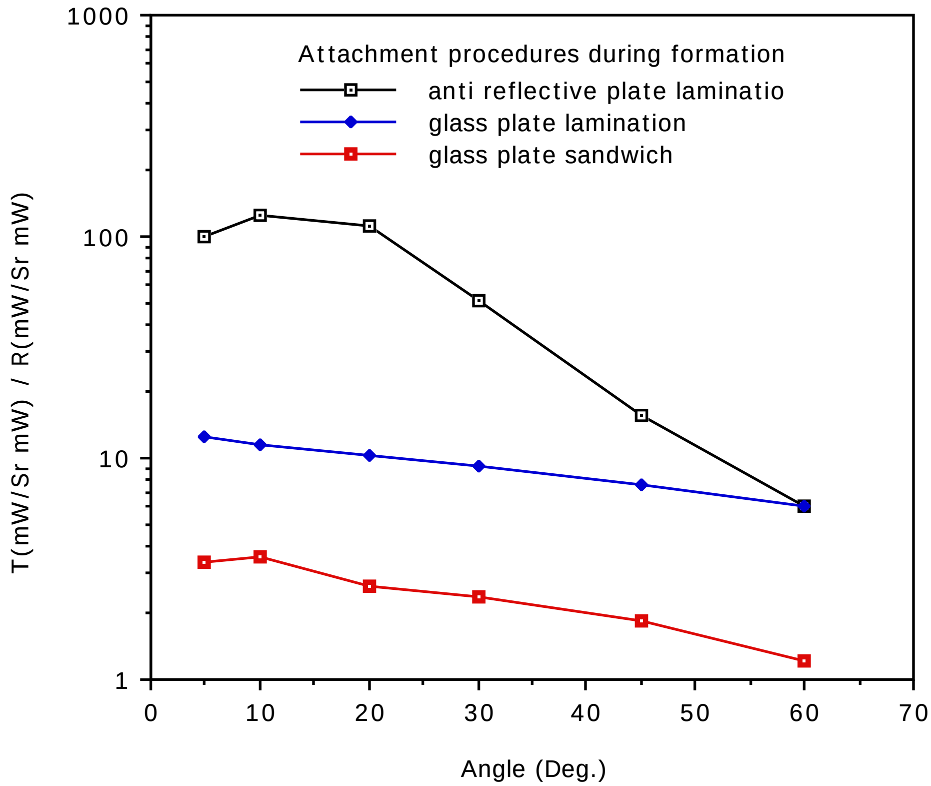

Figure 6 Diffuse transmission / reflection ratio (T/R) results for different attachment procedure during formation in DuPont 600-10 film with a 180° field angle. Formation and playback wavelength of 514 nm.