INSTITUTE OF PHYSICS PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY

Meas. Sci. Technol. **14** (2003) 346–355 PII: S0957-0233(03)39968-0

A method of characterization of diffusing thin films used as active elements of optical systems

J Sánchez-Capuchino and J Arasa

Centro de Desarrollo de Sensores Instrumentación y Sistemas (CD6), Universitat Politécnica
de Catalunya, Campus de Terrassa, Rambla San Nebridi No 10, 08222, Terrassa,
Barcelona, Spain

E-mail: jorgesc@oo.upc.es and arasa@oo.upc.es

Received 25 July 2002, in final form 9 January 2003, accepted for publication 20 January 2003
Published 18 February 2003
Online at stacks.iop.org/MST/14/346

Abstract
A large number of optical systems use diffusing thin films as active elements. Evaluation of the performance of an optical system that contains diffusing elements requires the characterization of the diffuser in its task environment. In this paper, a method of characterization of a diffusing thin film whose properties allow its inclusion in an imaging optical system is presented. The characterization is carried out by establishing a measure protocol that describes the diffusing thin-film properties. The characteristics of the film are determined in an image translation application: evaluating the amount of transmitted energy, the diffused pattern and the contrast variation introduced.

Keywords: diffuser characterization, diffusing thin films, optical design

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Diffusing thin films with particular light diffusion properties are used a great deal. In particular, a low-absorbance diffuser that diffuses light in a uniform way constitutes an important optical element. Such diffusers see use in multiple applications, such as in projection systems, microscopy illumination systems, display fabrication and projection screens. The use of diffusing thin films requires characterization of the descriptors determined by the working environment. The performance required in the application governs the quality criteria that must be used to evaluate a particular thin film. In our chosen application (translation of images), a group of measures governed by the intended utility of the thin film has been established. The characterization results should also be valid for analogous applications of diffusing thin films. The characterization process comprises the experiments described below.

1.1. Experiment I. Quantification of the energy transmitted by the diffusing thin film

An important item of information in the characterization of an optical element is the energy transmission capability. In the case of a diffusing thin film, this parameter is obtained by comparing the transmitted energy to the incident energy.

1.2. Experiment II. Analysis of the diffused energy distribution produced by the diffusing thin film

A diffusing thin film transforms the diffused energy distribution. By analysing the diffused distribution, it is possible to determine the energy transfer pattern associated with the diffusing thin film for characterization purposes.

1.3. Experiment III. Evaluation of the contrast variation in the transmission of the diffusing thin film

The use of test targets to evaluate or calibrate an imaging system's performance is standard. One quality descriptor

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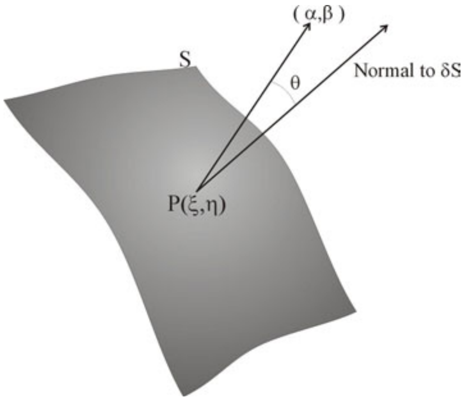

Figure 1. The energy transmission from a surface element.

applied to optical imaging systems is the capacity of an element to vary the contrast for different resolutions. Use of an appropriate test target allows one to characterize the quality of an element in terms of contrast and resolution.

2. Organization of the paper

The paper has been organized in the following way. First of all, in section 3 we recap on the concepts of diffusing thin-film theory and subjects related to the thin-film characterization experiments presented. Section 4 describes the experimental procedure for the thin-film characterization. In section 5, representative experimental results from each of the experiments are detailed and analysed. Finally, the conclusions drawn are presented.

3. Theoretical fundamentals

Radiant energy is energy emitted, transmitted or received in the form of electromagnetic waves or photons [1]. The field of science whose focus is the measurement of radiant energy in general is radiometry [2]. In many optical systems, it is acceptable to neglect the intensity and wavelength when using the energy propagation law (the geometric approximation). In such cases, the description of the energy propagation is formulated in geometrical language.

In radiometry, the energy is studied by investigating the radiant energy emerging from a surface portion S [2] (figure 1). We set $P(\xi, \eta)$ as a point on the surface, represented in a coordinate system (ξ, η) appropriate for S. The energy emerging from the element ds of the surface S at the point $P(\xi, \eta)$, making a solid angle dΩ in the direction given by the polar angles (α, β), can be expressed as [1][1]

$$\delta^2\Phi = L\cos\theta\,\delta S\,\delta\Omega. \tag{1}$$

θ is the angle between the direction (α, β) and the normal to the surface S at the point $P(\xi, \eta)$ (figure 1).

$L(\xi, \eta; \alpha, \beta)$ is a factor called the radiance at the point $P(\xi, \eta)$ in the direction (α, β).

From (1), the emergent energy $\delta\Phi$ (see footnote 1) can be resolved using

$$\delta^2\Phi = \delta I\,\delta\omega. \tag{2}$$

Comparing (1) and (2), we obtain

$$\delta I = \frac{\delta\Phi}{\delta\omega} = L\cos\theta\,\delta S. \tag{3}$$

The integral

$$I(\alpha, \beta) = \int L\cos\theta\,\delta S \tag{4}$$

over the surface S is called the radiant intensity (see footnote 1) in the direction (α, β). If the radiance L is isotropic and if the surface S is a plane, equation (4) reduces to

$$I(\alpha, \beta) = I_0\cos\theta, \qquad \text{where } I_0 = \int L\,\mathrm{d}S. \tag{5}$$

From (5), we find that the radiant diffused intensity in a given direction varies as the cosine of the angle between this direction and the normal to the thin film. Equation (5) is known as Lambert's law. A body whose primary or secondary radiance fulfils equation (5) is known as a perfect transmitter or diffuser provided that its surface is a transmitter or diffuser, respectively. The thin films that satisfy Lambert's law (5) are called Lambertian diffusing thin films.

The substrate on which the thin film is deposited can introduce variations in the assembly's final performance. In the methodology used, the optical properties of the substrate cause a transmitted energy redistribution due to the energy limit angle, which moves from the interior substrate to the exterior substrate (the limit angle effect). This effect is produced when some of the energy diffused by the film falls on the substrate's back surface with an incidence angle higher than the limit angle θ_L (figure 2). This energy is completely reflected at the surface, returning to the film and falling again onto the back surface. Similarly, the energy that again falls on the film with an incidence angle higher than the limit angle θ_L is again reflected. This again returns to the substrate back surface and the behaviour continues to repeat. This effect redistributes the energy transmitted by the film, increasing the amount of contrast loss (equation (10)) that can be caused by the diffusing thin film. In the case of a point object, the effect is observed in the form of a dark circle encircling a shiny zone.

The proportion of the incident energy that is diffused by the diffusing thin film is characterized in the experiment that quantifies the transfer of energy that occurs (experiment I). In the case of a Lambertian surface, the diffused energy pattern obeys equation (5). This pattern is determined by the physical characteristics of the film.

With the aim of evaluating the difference in performance between a generic film that one wishes to characterize and a Lambertian film (experiment II), it is convenient to consider two aspects:

- First, the diffused energy distribution produced by a Lambertian surface (5) is related to the incident energy through the cosine of the diffused energy angle. With the aim of quantifying the difference in a diffused pattern in order to characterize the performance of a generic

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[1] The notation is as recommended by ANSI standard Z-7.1-1967(RP-16). See for example [9] or [10].

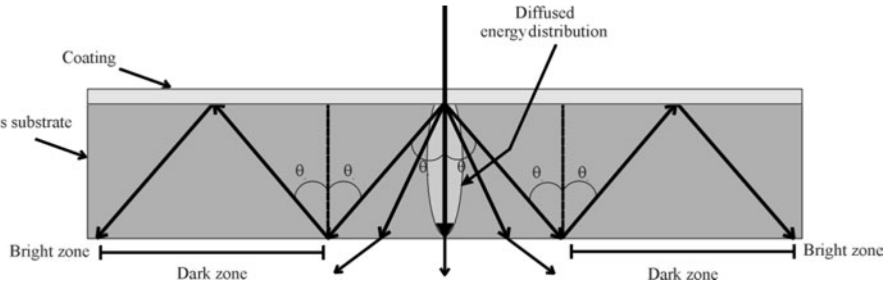

Figure 2. The limit angle effect for a section of the diffusing thin film.

film with respect to the Lambertian case, one defines the Lambertian diffusion coefficient (LDC) (6). The LDC is a measure of the difference between the diffused energy pattern (I_j) of the thin film being analysed and the diffused pattern produced by a Lambertian diffusing surface (I_{Lj}) represented by equation (5). This parameter is determined for incidence of the energy perpendicular to the diffusing thin film. The LDC value is obtained by calculating the average of the differences $I_j - I_{Lj}$ [11]. In the expression for the LDC, R stands for the residue associated with the experimental uncertainty or due to individual elements used in the measurement. The expression is

$$\mathrm{LDC} = 1 - \sum_{j=1}^{j=n} \frac{|I_j - I_{L_j}|}{(n-2)} \pm \mathrm{R} \tag{6}$$

where

$$\mathrm{R} = \sum_{j=1}^{j=n} \frac{\sum_{j=1}^{j=n} \frac{|I_j - I_{L_j}|}{n} - |I_j - I_{L_j}|}{(n-2)} \tag{7}$$

and where j is a sampling element; its values correspond to each pixel in the image sensor. The possible values of j must satisfy $j \neq (I_j)_{min}$ and $j \neq (I_j)_{max}$. n is the number of samplings. I_j is the intensity of the energy diffused by the thin film in the sampling element j. I_{L_j} is the intensity of the energy diffused by a Lambertian diffuser in the sampling element j. LDC ≈ 1 if the pattern is close to showing Lambertian performance. LDC ≈ 0 in the opposite case.

- Secondly, in the case of a Lambertian film, the diffused energy distribution is independent of the incident energy direction. The variations introduced in the diffused pattern of the thin film because of the influence of the energy incidence direction are quantified using the adirectionality coefficient (AC) (8). The coefficient AC gives the difference between the diffused pattern with incident energy normal to the diffusing thin film under evaluation (I_{Nj}) and the diffused pattern with incident energy non-normal to the same film (I_j). The AC value is obtained by calculation of the average of the differences $I_j - I_{Nj}$ [11]. In the expression for the AC, R stands (as in expression (6)) for the residue associated with the experimental uncertainty or due to individual elements used in the measurement. The expression is

$$\mathrm{AC} = 1 - \sum_{j=1}^{j=n} \frac{|I_j - I_{N_j}|}{(n-2)} \pm \mathrm{R} \tag{8}$$

where

$$\mathrm{R} = \sum_{j=1}^{j=n} \frac{\sum_{j=1}^{j=n} \frac{|I_j - I_{N_j}|}{n} - |I_j - I_{N_j}|}{(n-2)} \tag{9}$$

where j is a sampling element; its values correspond to each pixel in the image sensor. The possible values of j must satisfy $j \neq (I_j)_{min}$ and $j \neq (I_j)_{max}$. n is the number of samplings. I_j is the intensity of the energy diffused by the thin film in the sampling element j. I_{N_j} is the intensity of the energy diffused by the thin film with normal incidence in the sampling element j. AC ≈ 1 if the pattern is close to showing Lambertian performance. AC ≈ 0 in the opposite case.

Finally, to evaluate the influence of the thin film on the quality descriptors for the imaging systems, it is essential to establish a measure associated with the resolution. One of the quality descriptors widely applied to optical imaging systems is the contrast variation introduced by the system or each of its elements [5, 6]. This descriptor is represented by the modulation transfer function (MTF) of the element that one seeks to characterize—in this case a diffusing thin film.

There are many test targets used to evaluate or calibrate imaging systems as regards contrast and resolution—for example, star targets, sinusoidal patterns and the USAF 1951 test. The latter allows one to analyse the film, in a bidirectional way (horizontal and vertical), to high frequencies, where the contrast modification in the application is characterized (experiment III). The measure of the contrast transmitted by the assembly (USAF test + thin film) characterizes the thin film as regards contrast and resolution. The variation in contrast for each frequency is determined using equation (10), where I_{max} and I_{min} correspond respectively to the zones with higher and lower energy flux:

$$C(\omega) = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}. \tag{10}$$

In an optical system, the ratio of the contrast variation caused by a system element to the contrast of its object, depending on the frequency, is the MTF (11). A plot of the MTF against frequency ω is universally used to display the quality of an image-forming system [5, 6]. One particular advantage of the MTF is that it can be cascaded, by simply multiplying the MTFs of two or more unconnected components to obtain the MTF of the combination:

$$\mathrm{MTF}(\omega) = \frac{C_{image}(\omega)}{C_{object}(\omega)}. \tag{11}$$

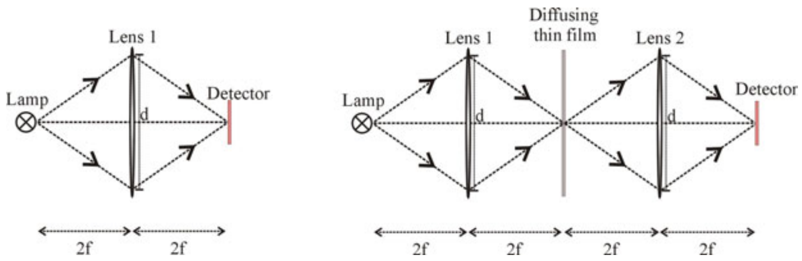

Figure 3. A transmitted energy measuring tool. This system works with an equivalent aperture number of $N = 4$ and a lateral magnification of $m = -1$. (a) Initial energy detection without the diffusing thin-film contribution. (b) Detection of the proportion of energy transmitted by the diffusing thin film.

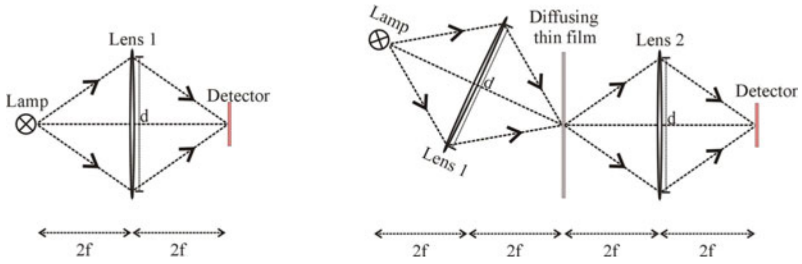

Figure 4. A transmitted energy measuring tool with the light incident at 60° with respect to the optical axis of the assembly.

4. Experiments

4.1. Experiment I. Quantification of the energy transmitted by the diffusing thin film

The image translation application used as an example in this article determines the type of characterization of the diffusing thin film that is required. The use of the thin film as an intermediate element in a process of formation of images requires knowledge of the quantity of energy that arrives at the detector of the system in the image plane.

The energy distribution that arrives at the intermediate plane where the thin film is situated depends on the application conditions. A test that measures the energy transmitted by the system must be carried out under conditions similar to those in which it should work in real applications. In view of this, a good parameter for characterizing the ratio of the transmitted energies that arrive at the detector is the f-number (N) [6]. N corresponds to the ratio of the effective focal length (efl) of the system to the diameter of the entrance pupil (d_{EP}):

$$N = \frac{\text{efl}}{d_{EP}}. \tag{12}$$

With the aim of approximating the working conditions of the diffusing thin film in the experimental situation, we have chosen a system that presents a situation equivalent to one with an f-number of $N = 4$ with unitary lateral magnification, such systems being widely encountered in image formation.

Evaluation of the diffused energy of the film with respect to the incident energy needs a procedure wherein they will be related. The characterization of the diffused energy of the film must be carried out in similar conditions to the image transport ones—from the intermediate plane of the thin film to the system image plane, where the detector is situated. In most systems, there is unitary lateral magnification (or close to unitary lateral magnification and with $N = 4$); therefore the assemblies were constructed with these conditions.

In figure 3, experiment I, which characterizes the energy transmitted by the diffusing thin film, is represented. In the assembly, the energy that will fall on the thin film is determined by means of a detector placed in the antiprincipal image plane ($m = -1$) of lens 1. What this detector registers (measure 1) will be useful as a reference for subsequent detections.

Next, the reduction in the transmitted energy, compared to measurement 1, caused by the diffusing thin film is measured. For that purpose, the surface for characterization is located in the plane in which the detector had been situated before—that is, in the antiprincipal image plane of lens 1. Lens 2 (identical to lens 1) is situated such that its object antiprincipal plane coincides with the lens 1 antiprincipal image plane. In the antiprincipal image plane of lens 2, the quantity of energy transmitted by the diffusing thin film is detected (measure 2). Ignoring experimental limitations, the relation between the two measures (measures 1 and 2) determines the proportion of the energy transmitted by the diffusing thin film.

For the measurement, the light source is situated on the axis of the optical system. As a result, this characterization is valid only for systems that have $N = 4$ and where the field is small. However, there are systems in which the emergence or incidence angle variation can have a large range. For these systems, the use of diffusing thin films is necessary, because for them it is not possible to locate a detector in the image plane of the system. These systems are those where, in spite of the aperture being equivalent to that in the case with $N = 4$, the incident beam is not centred on the axis of the optical system and makes a large angle with respect to the axis. To treat these systems, we repeated the previous experiment, but with the light incident at 60° with respect to the optical axis of the assembly (figure 4). In the interesting applications in image transport, the diffusing thin film is always perpendicular to the detector. Our characterization suggests that such films could be made use of in a much wider range of image transport applications.

4.2. *Experiment II. Analysis of the diffused energy distribution produced by the diffusing thin film*

It is considered that those surfaces whose primary or secondary radiance fulfils Lambert's law (5) are perfect or Lambertian diffuser surfaces. Figure 5 shows an assembly where the degree of similarity between a generic diffusing thin-film behaviour and Lambertian behaviour is characterized. The LDC and AC measures quantify the differences from Lambertian behaviour of the film for characterization.

The diffused energy distribution produced by the diffusing thin film with normal incidence is described by the LDC. To measure the LDC, a 5 mW He–Ne beam laser is used to irradiate the thin film, with perpendicular incidence (figure 5). The diffused energy is detected on a screen situated nearby. The knowledge of the laser incidence point on the thin film and the distance to the screen allow one to determine the emergence angle for the diffused energy. The energy distribution and its emergence angle are captured through an objective with a CCD detector, registering the energy projected on the screen. The CCD-detected distribution represents the diffused energy pattern of the thin film. The pattern shape indicates the influence of the film on the diffused energy and determines the LDC.

From equation (5), the diffused energy distribution produced by a Lambertian diffused surface must be independent of the incident energy angle. However, the diffused distribution produced by a generic diffusing thin film can have a certain dependence of the incidence angle. The influence of the incident energy direction on the diffused energy is represented using the AC. This measure is obtained by repeating the previous experiment before but with a changed He–Ne laser angle of incidence on the thin film. Comparison of the two diffused energy patterns with incidence at different angles establishes the angular dependence and determines the AC. The alterations of the detected intensity patterns show the variation of the diffused energy effected by the thin film.

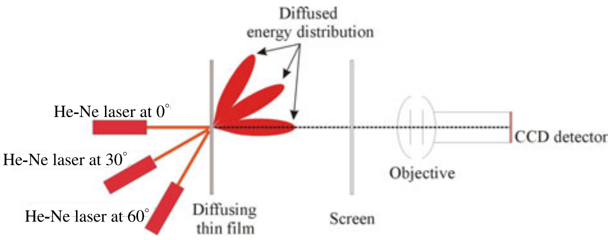

Figure 5. The diffused energy distribution measuring tool.

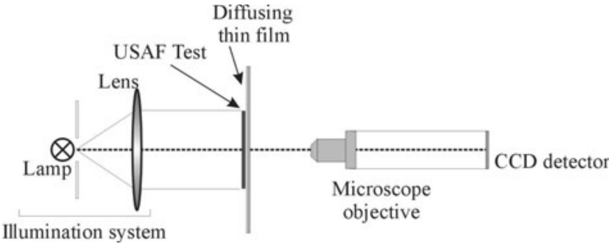

Figure 6. The influence of the diffusing thin film in the contrast loss measuring tool, with collimate light at normal incidence.

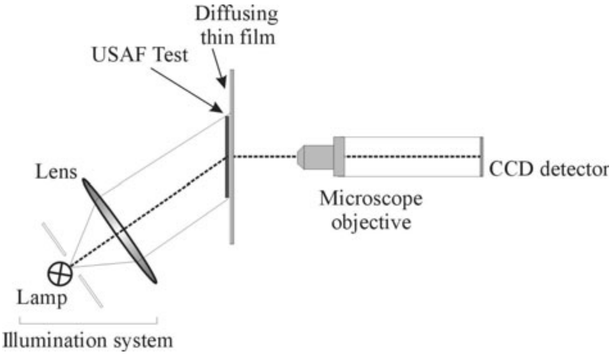

Figure 7. The influence of the diffusing thin film in the contrast loss measuring tool, with collimate light at 60° incidence.

4.3. *Experiment III. Evaluation of the contrast variation in the transmission of the diffusing thin film*

One quality descriptor widely applied to image-forming systems is the thin-film MTF [5, 6]. The MTF is obtained by means of the experiment shown in figures 6 and 7. The illumination system of the assembly has to simulate the surface illumination conditions that characterize the working environment, like in the experiment that quantifies the film's transmitted energy (section 4.1). However, the contrast variation is highly dependent on the test incidence direction. To ensure some degree of equivalence of the conditions for all the test measurements, in addition to using the same diffusing film, the illumination must be with a collimated beam light and, with the same intention, the detection system must be set up to have the smallest possible influence on the detected energy. In this assembly, the detection system includes a microscope objective that passes the test image to a CCD detector. The special conditions of illumination in the experiment are required because the microscope objective detects energy from all the emergence angles of the thin film; these conditions match those used in image-forming systems. In such systems, the image contrast variation measured through the MTF is realized in similar conditions to the ones that we used to obtain this measure.

In this experiment an incident energy distribution is generated on a USAF 1951 test, whose test surface is joined to the thin film. The collimated light beam in incident perpendicularly on the surface in figure 6 and at 60° in figure 7; the intention was to obtain information on the contrast variation with non-normal incidence.

The application of equation (10) to each selected frequencies group determines the contrast variation for that particular frequency group. The ratio of the contrast measured with the thin film to the USAF 1951 test's original contrast is, for each frequency, the MTF (equation (11)).

5. Experimental results

Sample description

The diffusing thin films used in this study were prepared by depositing coatings on glass substrates (Schott glass[2] BK7,

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[2] Certain commercial equipment is identified in this paper in order to adequately describe experimental procedures. Such identification does not necessarily imply that the equipment is the best available for the purpose.

Table 1. Composition, mixing ratio and thickness for the samples evaluated. D700 is an acrylic used as a coating; D847 Scansealer is a transparent high-performance sealer, which is used as an adhesion promoter as well as a traditional sealer; D807 is a medium thinner; D841 is a polyisocyanate used as medium hardener; D759 is an acrylic cellulose used as a flattening paste.

Sample A (vol)	Sample B (vol)	Sample C (vol)
D847 (4) D759 (2) D841 (1.7) D807 (2.7)	D847 (4) D841 (1) D807 (2)	D847 (4) D700 (0.4) D841 (1) D807 (2)
Thickness: 15 μm	Thickness: 15 μm	Thickness: 13 μm

Table 2. Incident versus transmitted photon ratios for the samples evaluated. The values are rounded to whole numbers.

Diffusing thin film (sample)	Incident:transmitted	
	Incident light normal	Light incident at 60°
A	206:1	1797:1
B	1704:1	1898:1
C	493:1	1682:1

Table 3. Equivalent f-number (N) if the original N is $N = 4$.

Diffusing thin film (sample)	Equivalent N	
	Incident light normal	Light incident at 60°
A	57	169
B	165	174
C	88	164

5 mm thickness). The rms roughness of the coating is ≈1 μm. Coating films of three kinds on the same glass substrate, 100 mm × 100 mm × 5 mm, have been used. The surfaces of the glass substrates were carefully cleaned before the thin films were deposited [8]. The composition, the mixing ratio and the thickness are detailed in table 1 for each coating film. The different coating films in the samples were deposited in the order of listing in table 1. The sedimentation process, where each coating film was deposited upon the substrate and its previous coating films, was carried out by PPG Industries, Incorporated (see footnote 2). All the coating films were also provided by PPG Industries, Incorporated (see footnote 2).

5.1. Experiment I. Quantification of the energy transmitted by the diffusing thin film

The results of the analysis of the relation between the quantity of energy transmitted (measure 2) and the incident energy (measure 1) are given next. The ratio determines the proportion of energy diffused by the diffusing thin film. The experiment was carried out on the three samples described above. Tables 2 and 3 show the results obtained with the light source placed on the optical axis (perpendicular) and on an axis tilted at 60° to the optical axis. In these results, there are experimental errors, but these have not been computed since they affect the two measures equally.

The way in which the transmitted energy quantity has been expressed is one that allows an easier interpretation for our application. Tables 2 and 3 show the results of this experiment in two formats:

- Table 2 shows the transmitted energy with respect to the number of photons that must arrive at the thin film to diffuse one photon. This representation is useful in the computation scenario, with the current generated by a CCD detector.
- In table 3 the transmitted energy is shown as an equivalent f-number (N_{eq}) (equation (12)). This second form is especially useful in the working environment of photographic objectives; therefore it was considered of interest to carry out a conversion from the other form (table 2). The conversion was done assuming that without the diffusing thin film the optical system works in conditions with f-number $N = 4$. The inclusion of the diffusing thin film in the optical system introduces energy loss that can be reinterpreted as the optical system working in conditions with a new f-number, always higher. The new f-number (N) of the optical system that forms the image (with the thin film included) has an inverse proportionality with the photon-transmitted energy:

$$N^2 \propto \frac{1}{\text{number of transmitted photons}}. \tag{13}$$

To carry out the conversion, it has been assumed that in the ideal case, the thin film transmits all the photons that impinge on it and its f-number is $N_0 = 4$. The equivalent f-number (N_{eq}) is determined by relating this to the ideal f-number N_0 (table 3):

$$\frac{N_{eq}^2}{N_0^2} = \frac{1/\text{number of transmitted photons}}{1}. \tag{14}$$

The results presented show that, with normal incidence, sample A is the one which transmits the highest proportion of the energy. However, for an incidence angle of 60°, the transmission is decreased considerably. This indicates that sample A has a high sensitivity to the direction of incidence on the diffusing thin film.

Sample B causes a substantial loss of transmitted energy for both incidence angles; of all the samples evaluated, it is the one which transmits the least energy.

Sample C transmits a slightly lower proportion of the energy than sample A. It is observed that the outcome for this sample is less sensitive to the tilt variation of the incident energy.

For the three diffusing thin films evaluated, samples A and C are the ones which transmit the higher proportions of the energy. With perpendicularly incident energy, sample A causes less energy loss, while for tilted energy incidence, sample C is the one which transmits the highest proportion of the energy. The results from experiment II will establish whether the energy transmitted by samples A and C is diffused in a manner providing the Lambertian distribution pattern of interest.

5.2. Experiment II. Analysis of the diffused energy distribution produced by the diffusing thin film

The results of experiment II, which evaluates the differences between the diffused pattern and those produced by Lambertian

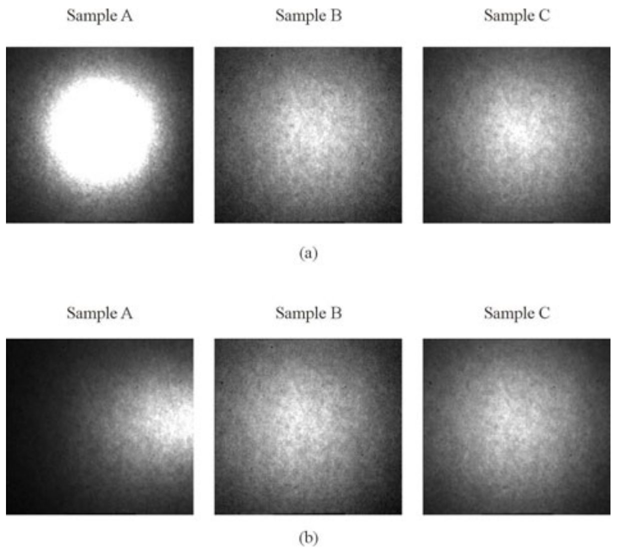


Figure 8. The energy diffused by the diffusing thin film detected with the measuring tool of experiment II. Energy incidence angle: (a) normal or 0°; (b) 60°. Initially, the image captured was an 8-bit (256-level) greyscale. To show the effect of the diffuser on all the samples, the initial captured image has been matched to the next transformation. Sample A: the lowest level (0) corresponds to level 47; the highest level (255) corresponds to level 103. Sample B: the lowest level (0) corresponds to level 47; the highest level (255) corresponds to level 63. Sample C: the lowest level (0) corresponds to level 47; the highest level (255) corresponds to level 93.

Table 4. The LDC and its associated residues.

Diffusing thin film (sample)	LDC (%)	R (%)
A	50.85	20.2
B	23.51	0.7
C	32.09	3.5

Table 5. The AC and its associated residues.

Diffusing thin film (sample)	AC (%)	R (%)
A	65.87	27.9
B	99.42	0.41
C	97.26	2.83

diffusers, are presented next. Figure 8 shows the diffused energy patterns registered in experiment II. Due to the differences in diffused distribution between the samples, the captured images have been matched to facilitate analysis of the differences.

Figure 9 shows vertical cut plots of the diffused pattern images in the higher-transmission columns for three incidence angles (see figure 5). These are constructed from the results registered in the CCD detector plane. In them, the diffused energy intensity (as a greyscale) versus detector position (mm) is represented. The intensity at each pattern position gives the amount of energy detected at that point. The plots in figure 9 relate to the LDC (table 4) and to the AC (table 5) for each sample evaluated.

The results revealed show that a high proportion of the energy is transmitted by sample A in the direction of incidence of the energy. There is also a high proportion of energy transmitted for the tilted incidence case, but with a substantial displacement of the diffused distribution. These results indicate that sample A has a low diffusion capability and a high sensitivity to the energy incidence direction. This behaviour is verified by examining the LDC and the AC in combination. The LDC of sample A indicates 55.85% similarity to the Lambertian pattern for perpendicular incidence. However, a high proportion of the transmitted energy is not diffused, saturating the CCD image sensor (figure 9(a)). In this case, the LDC value is influenced by the similarity between the Lambertian pattern and the distribution generated as a result of the detector saturation. AC = 65.87% represents the biggest sensitivity to incident energy direction found among all of the incident energy directions examined. This value shows that the transmitted energy direction is near to the incident energy direction (figure 8), confirming the low diffusion capability of sample A.

Experiment I allows us to see that sample B causes a high loss of transmitted energy for any incidence angle. Likewise, experiment II confirms the results given above and indicates that the small proportion of energy that is transmitted is not diffused following Lambert's law. LDC = 23.51% expresses the fact that the diffused energy distribution production by sample B is not close to a Lambertian performance. AC = 99.42% shows that a low proportion of the energy transmitted by sample B is diffused, independently of the incident energy direction.

As regards sample C, the results indicate that—uniquely—only a small proportion of the energy transmitted for normal incidence is not diffused, showing a reasonable diffusion capability. The LDC indicates that the sample C diffused pattern shows an about 32.09% match with the Lambertian diffuser one. The AC indicates a low sensitivity to non-perpendicular incident energy directions, approximating the energy pattern for a perpendicular incident energy direction at the 97.26% level. This indicates that, in the case of tilted incident energy, sample C introduces uniquely insignificant modifications of the diffused distribution produced with a perpendicular incidence direction.

The diffusing thin films with higher unidirectional transmission capability are the ones which have poorer diffusion capabilities, so the performance will be unlike the Lambertian one. Sample A transmits a great proportion of the incident energy in a unidirectional way (even saturating the detector), showing a low diffusion capability. On the other hand, sample B is not very close to showing Lambertian performance and transmits a very low proportion of the energy. However, the appreciable proportion of the energy transmitted by sample C is diffused with a distribution near to a Lambertian one for perpendicular energy incidence. Moreover, the diffused distribution obtained with an incident energy direction that is not perpendicular to the diffusing thin film is very near to the Lambertian one.

5.3. Experiment III. Evaluation of the contrast variation in the transmission by the diffusing thin film

The quality descriptor selected to evaluate the variation of the diffusing thin-film transmitted contrast is the MTF.

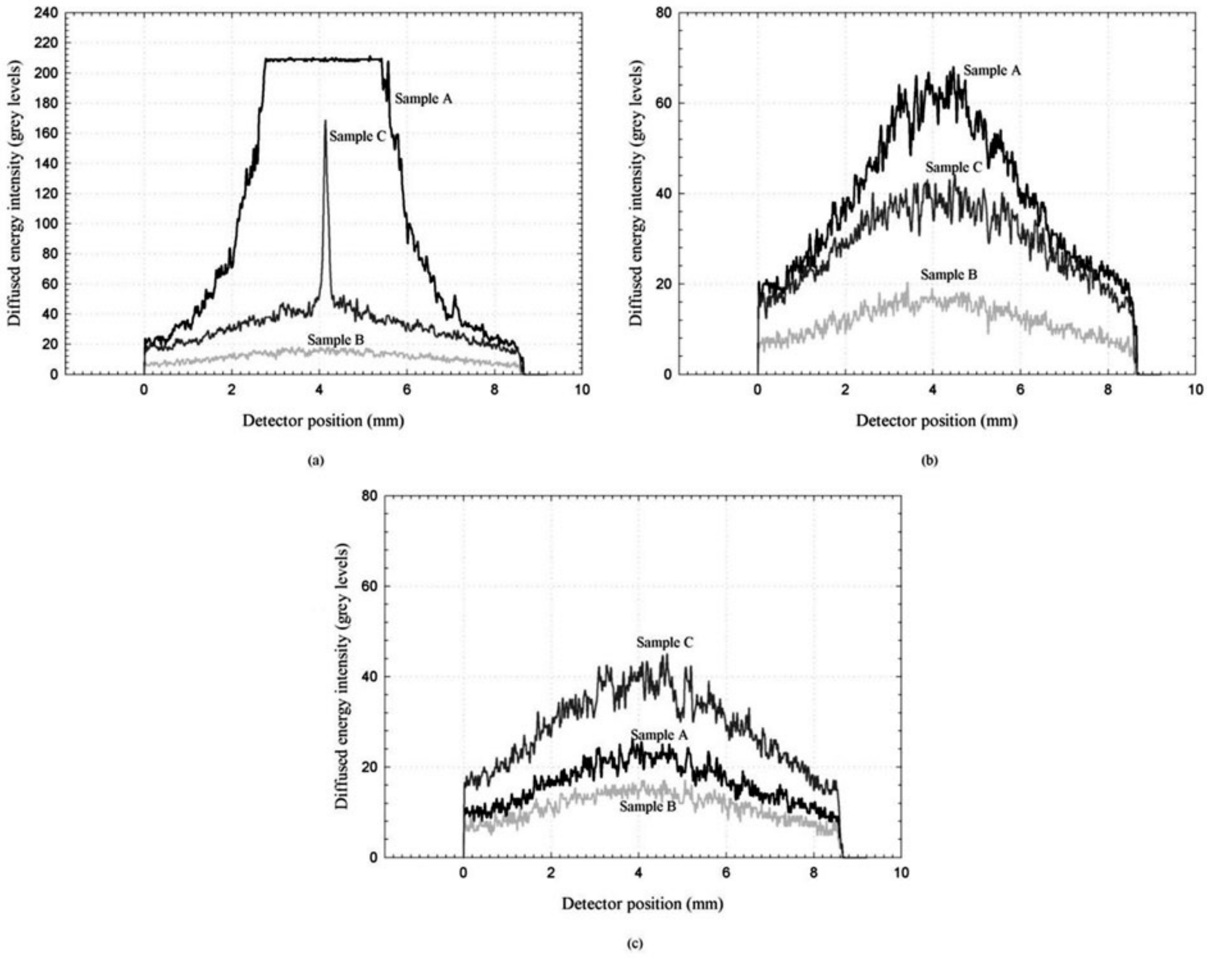


Figure 9. A cut of the diffused energy pattern for samples A, B and C. Incident energy angle: (a) normal or 0°; (b) 30°; (c) 60°.

This descriptor was chosen because it is among those most widely used to characterize the quality of an image-forming system. Among all the test targets available for evaluating and calibrating imaging systems in terms of contrast and resolution, we chose the test USAF 1951. This is to allow a bidirectional film analysis at high frequencies. The MTF (equation (11)) is equivalent to the ratio of the contrast of the assembly (thin film + USAF 1951 test) to the original contrast of the USAF 1951 test, for each frequency. Also, with a view to analysing the influence of the incidence direction, figure 10 shows the results for the illumination at normal incidence and tilted by 60° with respect to the assembly (thin film + USAF 1951 test).

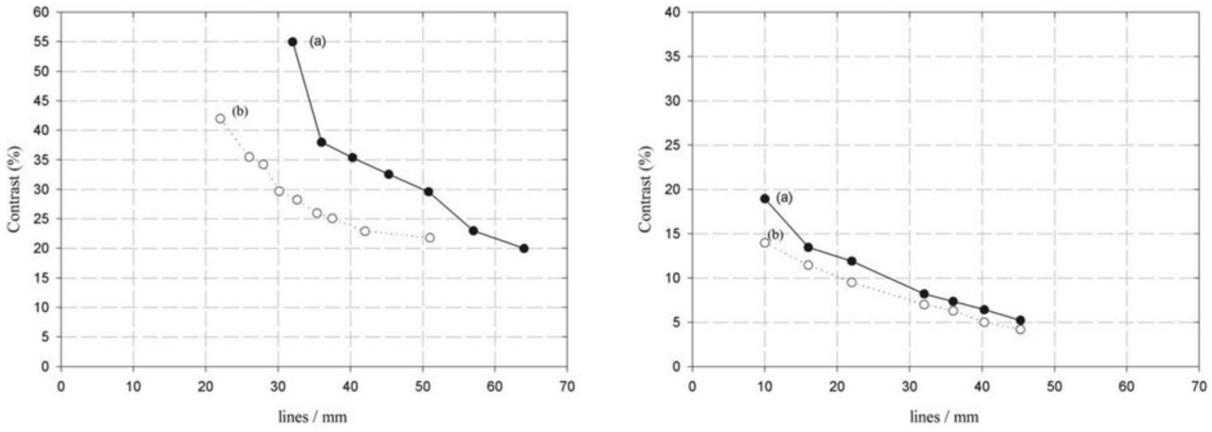
The contrast variation introduced in diffusing thin films is determined by the limit angle effect (figure 2). This effect, typical for thin films, depends of the physical parameters of the film and on the incident energy wavelength. The limit angle effect, if it is important, can limit the capabilities for transmitting details of a specific thin film. This effect contributes by causing greater contrast loss in this type of experiment. Two features that strengthen the limit angle effect are the optical path length increase inside the diffusing thin film and the enhancement of the reflectance when the medium changes. When the illumination is incident at an angle of 60° on the thin film, the energy augments the optical path length inside the film and increases the reflectance when the medium changes (with respect to the perpendicular incidence case). This strengthens the limit angle effect, leading to increased contrast loss when the incidence is tilted with respect to the perpendicular direction (figure 10).

In figure 10 one observes that for both incidence directions, sample A has a low contrast loss at high frequencies. When the energy incidence direction is perpendicular, a moderate contrast loss is detected—smoothed by frequency augmentation. In the tilted energy incidence case, the contrast loss for high frequency augmentation is somewhat strengthened by the limit angle effect.

Sample B causes a high contrast loss for both energy incidence angles; of all the samples evaluated, it is the one which gives the lowest MTF values.

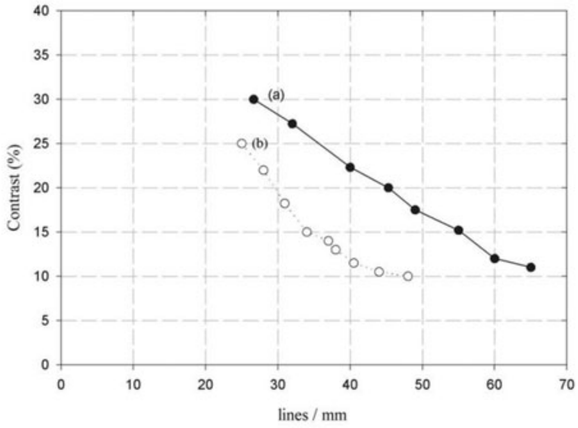
The contrast loss caused by sample C is of the same order of that caused by sample A. In the perpendicular incidence case, sample C introduces a regular contrast loss at high frequencies. As in previous cases, when the energy incidence direction is tilted, the contrast loss augments smoothly with respect to that for perpendicular incidence, due to the contribution of the limit angle effect.

These experiment results lead us to conclude that, for the diffusing thin films analysed, sample B is the one which causes the biggest contrast loss at high frequencies. This indicates that the small details detected through sample B have undergone a



Sample A

Sample B



Sample C

Figure 10. The MTF for the three samples evaluated. Incident energy angle: (a) normal or 0° (continuous curve); (b) 60° (dashed curve).

high contrast decrease. However, both sample A and sample C allow us to perceive small details (high frequencies) with a reasonable level of contrast reduction. The limit angle effect, in both cases, leads to the contrast loss with normal incidence being slightly less than that for tilted incidence.

6. Conclusions

The use of diffusing thin films is widespread in the field of optical imaging systems. These are employed as intermediate elements in systems that require the moving of an image.

A new method of characterization for diffusing thin films integrated in imaging optical systems has been proposed. The selected characterization parameters are those which allow one to evaluate the thin film as regards its performance in its application environment. The parameters evaluated are the proportion of energy transmitted by the film, the diffused energy distribution and the contrast change caused for different spatial frequencies. This has allowed us to reveal the sample whose performance provides good integration in the example application in this article.

Of the three diffusing thin films evaluated, sample B is the one which transmits the smallest proportion of the energy, sample A and sample C being the ones which show higher energy transference (experiment I). From this analysis, with perpendicular incidence sample A shows slightly higher transference, while with tilted incidence sample C is the one which shows the better transference.

The results from experiment II confirm that the diffusing thin films with higher unidirectional energy transmission have limited diffuser properties, with characteristics far from the Lambertian ones. This is the performance of sample A—which even saturates the image sensor. Likewise, the distribution of the low proportion of the energy transferred by sample B does not approximate a Lambertian distribution. However, the energy transmitted by sample C is diffused with a distribution close to the Lambertian one for perpendicular incidence. Moreover, the diffused distribution for incidence tilted with respect to the thin film is very near to a Lambertian distribution.

Experiment III reveals that the small details detected through sample B had undergone a high contrast decrease. However, both sample A and sample C allow one to perceive small details with only a moderate contrast reduction, for both incidence angles.

For the example application, it has been concluded that sample C best fulfils the requirements for the assembly: its energy transference is near to that of sample A and very superior to that of sample B, while its performance is the nearest to a Lambertian one. Likewise, sample C causes only moderate contrast decrease at high frequencies for both illumination angles for a range similar to that in which sample A causes only moderate contrast decrease.

In the methodology and information given, a certain relationship between the optical properties evaluated has been observed. A good diffusing thin film for image-forming applications would be one whose energy transference is high, with a highly Lambertian diffusion capability, and that introduces few contrast modifications. However, some of these properties are mutually incompatible, so a compromise, depending of the application, has to be reached. This may not need a perfect diffuser, but just one good enough not to excessively limit the system performance.

Acknowledgments

The authors are grateful to PPG IBÉRICA for preparation of the thin-film coatings. This research was financially supported by Institut Cartográphic de Catalunya (ICC).

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