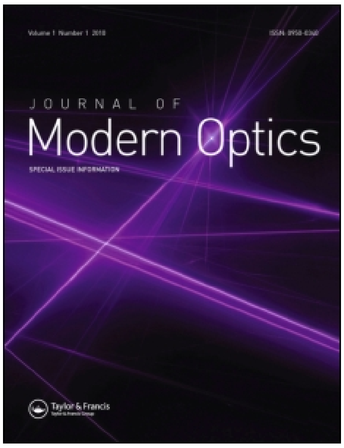

Journal of Modern Optics
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713191304

The Optical Properties of 'Moth Eye' Antireflection Surfaces

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To cite this Article Wilson, S. J. and Hutley, M. C.(1982) 'The Optical Properties of 'Moth Eye' Antireflection Surfaces', Journal of Modern Optics, 29: 7, 993 — 1009
To link to this Article: DOI: 10.1080/713820946
URL: http://dx.doi.org/10.1080/713820946

OPTICA ACTA, 1982, VOL. 29, NO. 7, 993–1009

The optical properties of 'moth eye' antireflection surfaces

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(*Received 3 December 1981; revision received 15 February 1982*)

Abstract. A 'moth eye' antireflection surface is a very fine array of protuberances which behaves as a gradation of refractive index, and which substantially reduces the reflectance. The reflection and transmission properties of such surfaces are described, and are shown to be equal to those of the best multilayer antireflection coatings.

1. Introduction

A 'moth eye' antireflection surface is one in which the reflection of radiation is reduced by the presence of a regular array of small protuberances covering the surface. The spacing of the array is less than the wavelength concerned, but the depth is a significant fraction of that wavelength. The principle has long been known and is commonly used in conjunction with microwaves, and in acoustics in the production of anechoic chambers. However, only comparatively recently has the phenomenon been demonstrated on the much finer scale required for optical wavelengths. It was first discovered by Bernhard [1] in 1967 as the means by which the reflection from the corneas of night-flying moths are reduced for the purpose of camouflage, and it is for this reason that the term 'moth eye' antireflection surface has been adopted.

Artificial moth eyes have been produced by recording in photoresist interference fringes generated at the intersection of two coherent laser beams, and these were described briefly by Clapham and Hutley [2]. The purpose of the present paper is to describe in more detail the optical properties of moth eye surfaces made in this way and to indicate the sort of applications for which they might be found suitable.

2. Theory

The operation of a moth eye surface may be understood most easily in terms of a surface layer in which the refractive index varies gradually from unity to that of the bulk material. Without such a layer the Fresnel reflection coefficient at an interface of two media is equal to $[(n_1-n_2)/(n_1+n_2)]^2$, where n_1 and n_2 are the refractive indices of the media. However, if there is a gradual change of index we can regard the nett reflectance as the resultant of an infinite series of reflections at each incremental change in index. Since each reflection comes from a different depth from the surface, each will have a different phase. If the transition takes place over an optical distance of $\lambda/2$, all phases are present, there will be destructive interference and the reflectance will fall to zero. The dependence of the reflectance on the effective thickness h and the wavelength λ was investigated by Lord Rayleigh [3], and similar results computed by representing the graded interface by many layers of equal thickness and progressively increasing refractive index are shown in figure 1. When

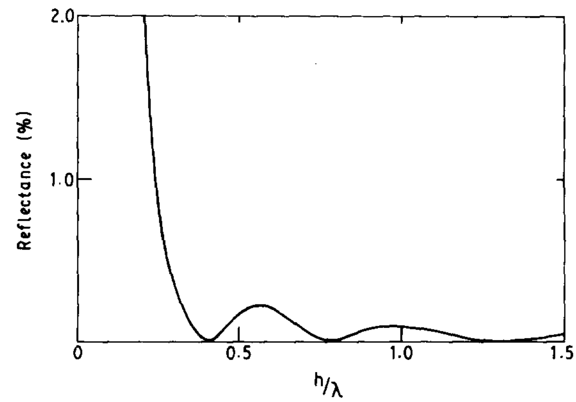


Figure 1. Computed dependence of reflectance on h/λ.

$h \ll \lambda$ the interface appears relatively sharp and the reflectance is essentially that of a discontinuous boundary. As h/λ increases, the reflectance falls to a minimum value at $h/\lambda = 0{\cdot}4$. Further increases in h/λ show a series of successive maxima and minima, but nowhere does the value approach that of a sharp interface. The details of the curve shown in figure 1 vary depending on the profile of the change of index [4], but the broad conclusions are the same; if the thickness is of the order of half a wavelength or more then the reflectance is considerably reduced.

In the case of the moth eye surface it is important that the spacing d of the protuberances is sufficiently small that the array cannot be resolved by the incident light. If this is not so the array will act as a diffraction grating and, although there may well be a reduction in the specular reflection (zero order), the light is simply redistributed into the diffracted orders. If this condition is fulfilled we assume that at any depth the effective index is the mean of that of air and the bulk material, weighted in proportion to the amount of material present at that depth. The condition that the array should not be resolved by the incident light is that the first diffracted order should be diffracted 'over the horizon' (i.e. at an angle greater than 90°). In other words, we require that $d < \lambda$ for normal incidence and $d < \lambda/2$ for oblique incidence if we consider only reflection, and that $d < \lambda/n$ and $d < \lambda/2n$ in the case of transmission where we must suppress orders diffracted inside the material.

For a given moth eye surface, where the height of the protuberances is h and the spacing is d, we might expect the reflectance to be very low for wavelengths less than about $2{\cdot}5h$ and greater than d at normal incidence, and for wavelengths greater than $2d$ for oblique incidence. For a transparent material one might expect an increase in transmission for wavelengths less than $2{\cdot}5\,h$ and greater for nd for normal incidence and for wavelengths greater than $2nd$ for oblique incidence. According to Bernhard [1], the protuberances on the cornea of the moth are about 220 nm deep and 220 nm apart. On the basis of these conditions one would expect a very low reflectance between wavelengths of 440 and 550 nm. In an ideal case we would like the spacing to be as fine as possible, and the depth as great as possible, in order to give the widest possible bandwidth.

This effect should not be confused with that of reducing the *specular* reflectance by roughening, as in the cruder forms of 'non-reflecting' picture glass. Roughness merely redistributes the reflected light as diffuse scattering and degrades the transmitted wavefront. In the case of the moth eye there is no increase in diffuse scattering, the transmitted wavefront is not degraded and the reduction in reflection gives rise to a corresponding increase in transmission.

More detailed and rigorous treatments of the theory have been put forward by Thornton [5], by Maystre and Nevière [6], and by McPhedran *et al.* [7]. Unfortunately, however, it is very difficult to measure the height and the shape of the protuberances with reasonable accuracy, so that it is not practical to attempt a detailed quantitative comparison of theory and experiment for visible wavelengths. Furthermore the calculations diverge for the depths required to give low reflectance. The simple theory that we have outlined above is therefore adequate to provide a qualitative understanding of the results we have obtained.

3. The manufacture of moth eyes

The pattern from which the moth eye array is recorded is generated as a staight line interference fringe pattern at the intersection of two coherent beams of light from a laser. This pattern is recorded twice in a thin layer of photoresist coated on the surface of a glass substrate, and between the two exposures the substrate is rotated by 90° in its own plane. When the resist is developed the surface is in the form of two orthogonal quasi-sinusoidal corrugations, as shown in figure 2, and this is a good approximation to the array of protuberances described by Bernhard [1].

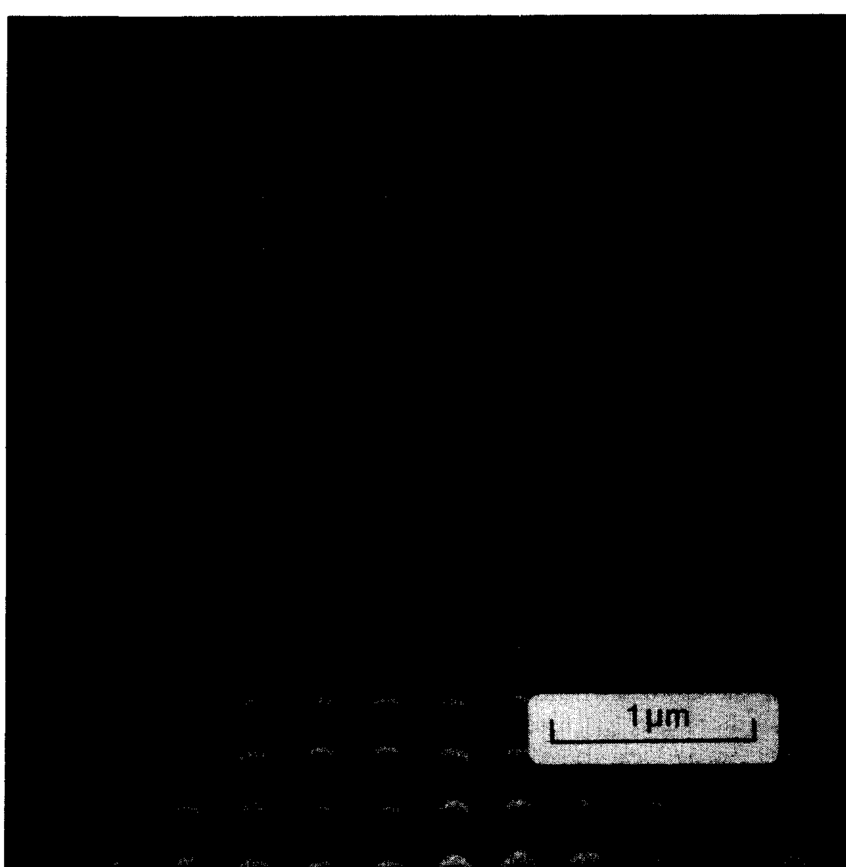


Figure 2. Moth eye surface generated by recording interference fringes.

The spacing of the array is determined by the fringe spacing, which is given by

$$d=\frac{\lambda_0}{2\sin\theta},$$

where λ_0 is the laser wavelength and θ is the semi-angle between the beams. In practice d has a minimum value of about $0{\cdot}6\lambda_0$. The two lasers that have been used for this work are an argon ion laser operating at 458 nm and a krypton ion laser operating at 351 nm. The minimum spacings are therefore 275 and 210 nm, respectively, which correspond to groove densitites of 3640 and 4750 grooves per millimetre. The argon laser was more powerful than the krypton one, but at the shorter wavelength the photoresist (Shipley AZ 1350) is more sensitive, so that exposure times were approximately the same. On this basis one would expect the krypton laser to be the most suitable since it provides for a greater range of spatial frequencies. In practice, however, it was found that moth eyes of a given pitch could be made better with the argon laser than with the krypton. Whether this was due to some instability in the laser such as mode hopping (which is difficult to detect in the ultraviolet), or to some property of the photoresist (such as higher internal scattering), we have been unable to determine. The krypton laser was therefore used only for those moth eyes which were too fine to be produced using the argon laser.

The spacing, as we have seen, is determined simply by the laser wavelength and by the geometry of the interferometer. The depth is controlled by the exposure and the development of the resist. Unfortunately, due to effects such as undercutting during development, there is a limit to the aspect ratio h/d that can be achieved in practice. This means that we are unable to vary the spacing and depth completely independently, particularly for the deeper grooves that we require.

4. Replication

In addition to moth eyes made in photoresist, it is also of interest to produce replicas made in other materials. This is important first because it permits the study of the optical properties of moth eyes made on, for example, a metallic surface, and second because if moth eyes are to find any widespread application they will almost certainly have to be produced as some form of replica in order to reduce the cost to an acceptable level.

Conventional techniques of casting in resin were found to be unsatisfactory. This was probably because the process entails the vacuum deposition of various parting layers and a layer of aluminium to separate the uncured resin from the resist. On a good moth eye the flanks of the protuberances are inclined very steeply with respect to the direction of evaporation, and under these conditions the quality of the film is very poor. No improvement was observed when the blank was inclined and rotated during the evaporation.

Chemical deposition, on the other hand, takes place in a more homogeneous manner and therefore provides a better coating of the master. Successful first-generation replicas were produced in nickel by first depositing a layer of electroless nickel, and then backing this with conventional electroplated nickel until it was sufficiently thick to be self-supporting. In this way foils up to 0·5 mm thick were produced, which were very much harder than the original photoresist and from which subsequent replicas could be produced in a number of ways.

Unfortunately the moth eye surface provides an excellent key between the master and the replica, and it is sometimes difficult to separate them without damage. In all cases the photoresist master was destroyed, but nickel replicas were usually able to withstand subsequent replication without damage. Several methods of second-generation replication were tried with varying degrees of success; these included hot and cold embossing into plastics or aluminium foil, casting acrylic plastics and electroforming in copper. The electroforming and casting were reasonably effective, but the embossing experiments were able at best only to demonstrate that the techniques might work given the appropriate equipment and expertise.

5. Measurements

Specular reflectance and transmission measurements were made at a series of discrete wavelengths betweem 450 and 750 nm. These were selected from a quartz iodine lamp by interference filters and detected by a selenium cell mounted in an integrating sphere. For the reflection measurements it was necessary to eliminate the reflection at the rear surface of the blank. This was reduced to a negligible level by roughening the surface to disperse the specular reflection, and by blackening with 'Ebonide' matt black lacquer. The reflection from the resist–glass interface was negligible because the refractive indices of the two materials were closely matched. The refractive index of the photoresist is 1·62 in visible light, and this was matched with blanks of dense flint glass.

The absolute value of the reflectance was calculated by comparing the intensity of the beam reflected from the sample with that reflected from a clean, silica surface for which the reflectance was known by calculation. This was considered to be more accurate than a direct comparison with the incident beam because it required the detector to work over a smaller dynamic range. The reflectances were measured at an angle of incidence of approximately 5° to an estimated uncertainty of $\pm 0{\cdot}1$ per cent. Transmission measurements were performed on pairs of samples cemented back to back with an index-matching cement, and in this case the uncertainty was estimated to be $\pm 0{\cdot}2$ per cent.

Surface profiles were measured with the aid of a scanning electron microscope in which the sample was mounted at an angle of between 40° and 70° to the electron beam. This enabled a qualitative assessment to be made of the shape of the top of the array, but it did not provide information about the bottom of the grooves, nor was it possible to evaluate the depth with any certainty. In some cases the samples from which the optical data were taken were made on substrates that could be mounted in the microscope so that they could be studied directly without the need of a replica.

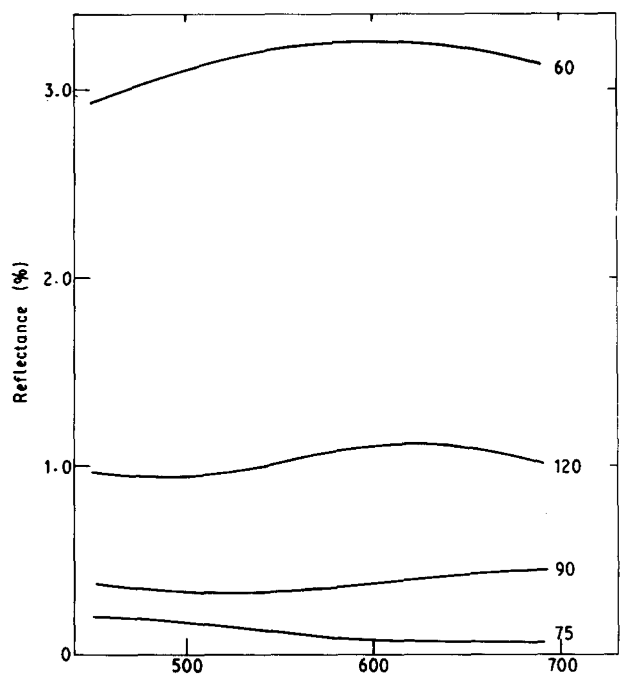
6. Results

Figure 3 shows the reflectance as a function of wavelength for a series of moth eyes made in photoresist. Curves are shown for a series of exposure values (for fixed development conditions) for four different spatial frequencies. It is evident in each case that there is an optimum value of exposure, and that overexposure leads to a deterioration in performance. However, as explained earlier, this does not necessarily imply an optimum depth but that, since during development material is removed perpendicular to the local normal, there is a point beyond which the profile is distorted. This is shown diagrammatically in figure 4, along with the corresponding index profile and typical electron micrographs. The optimum performance is expected when the mean slope of the index profile is a minimum.

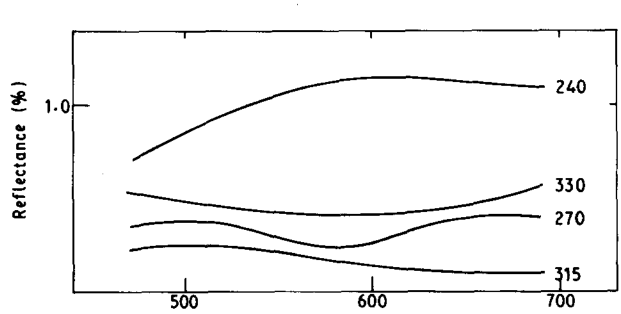
Figure 5 shows, for a spatial frequency of 3360 gratings per millimetre, the curves corresponding to a series of samples for which the groove depths have been estimated from electron micrographs. However, these figures are rather unreliable (because measurements at different orientations of the sample disagree) and really serve only to arrange the samples in order of depth. Furthermore, since the sample areas were rather small, reflectances had to be measured with a krypton laser and a silicon cell, and measurements taken in this way were rather less reliable than those taken with the conventional source. However, despite these reservations the data of figure 5 do indicate that, as we would expect, the reflectance is reduced as the depth increases.

Figure 6 shows the variation of reflectance with angle of incidence and polarization for a moth eye of 3300 grooves per millimetre measured at wavelengths of 647·1 and 514·5 nm. These curves indicate that the phenomenon is remarkably

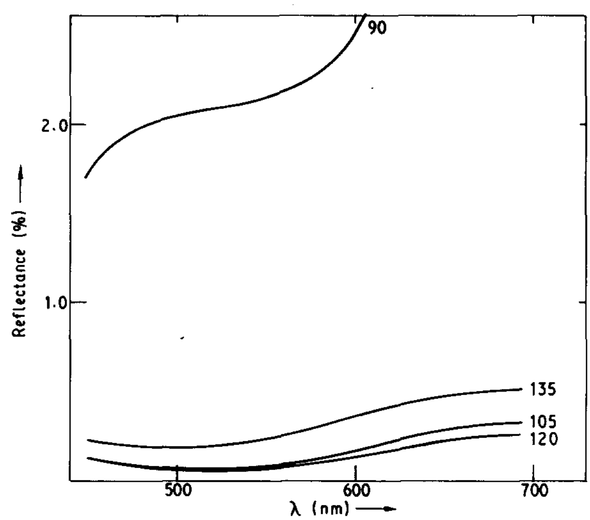
Figure 3.



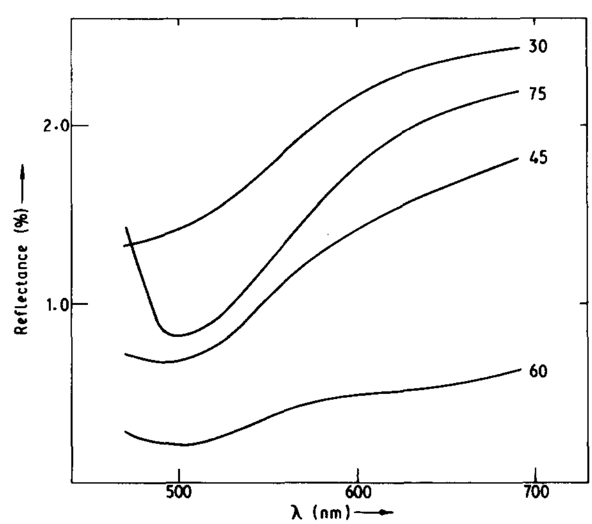
(a)



(b)



(*c*)



(*d*)

Figure 3. Reflectance of moth eye surfaces as a function of wavelength, period and exposure (n.b. exposure does not necessarily correlate with depth). (*a*) 2400, (*b*) 2700, (*c*) 3300 and (*d*) 4040 grooves per millimetre.

insensitive to the angle of incidence over a wide range. The discontinuities at 59·5° on the 514·5 nm curve correspond to the appearance of a diffracted order and are the same as Wood's anomalies on a diffraction grating.

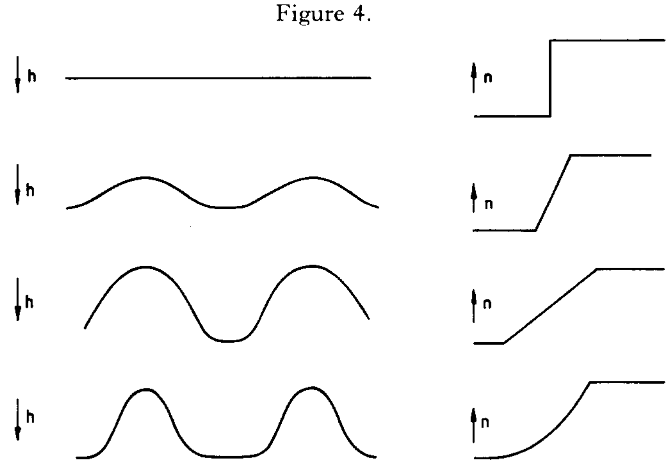
In order to put these results into perspective, figures 7 and 8 show the performance of some of the better moth eyes compared with that of other forms of antireflection coating. Figure 7 shows the reflectance at normal incidence for a moth eye, a single layer, a good commercially available broad-band multilayer and a commercially available graded index glass surface. Although it may be that these examples are not the very best that can be obtained, they are probably representative of antireflection coating technology. It seems fair to conclude that the moth eye compares very favourably with them, from the point of view of both minimum reflectance and bandwidth. The comparison is even more favourable if we take into account the angular dependence as shown in figure 8. Here, for simplicity, the means of the reflectances for both polarizations are shown for multilayer, graded index and moth eye, and the superiority of the moth eye is evident. The mean reflectance rises from 0·5 per cent at 55°, rather than 35° for the conventional coatings.

In figure 9 we show the measured transmission through pairs of photoresist moth eye samples on dense flint glass cemented back to back with index matching cement. This confirms that there is an increase in transmission due to the presence of the moth eye and that the reflectance is not merely being reduced by converting specular reflectance to diffuse reflectance. These results also show that the performance depends on the pitch of the array, as expected, and that at short wavelengths the specular transmittance is reduced because of the occurrence of diffracted orders within the bulk of the material.

So far we have been concerned only with moth eyes formed on dielectric materials with a real refractive index, but the principle applies just as well to materials such as metals which have a complex refractive index. In this case, however, the typical normal visible reflectance is higher, between 50 and 98 per cent rather than 4 or 5 per cent, and there is no transmission, so the radiation which would have been transmitted is absorbed by the material.

Figure 10 shows reflectance curves of various metal moth eye surfaces compared with those of the bare metal. In this case, however, the measurements have been extended to include the near infrared up to 15 μm. All the curves show that for visible radiation there is a very substantial fall in reflectance, but that for the infrared there is little measurable difference. This is as we would expect: at short wavelengths the depth is a sufficiently large fraction of the wavelength for the surface to appear to have a gradient of refractive index, whereas the same depth is a negligible fraction of the longer wavelengths so the surface appears as an abrupt boundary. The position of

Figure 4.



(a)

(*b*)

Figure 4. The distortion of a groove profile as the exposure is increased. (*a*) Diagrammatic representation of the effect on the gradient of refractive index. (*b*) Scanning electron micrographs of moth eyes of different depths.

the wavelength region over which the reflectance changes from low to high values will depend on the effective depth of the array. This is borne out to some extent by our measurements, but has not been verified completely. The difficulty is not only that of measuring the depth, but also that the reflectance between 0·8 and 1·5 μm is not covered by most commercial spectrophotometers.

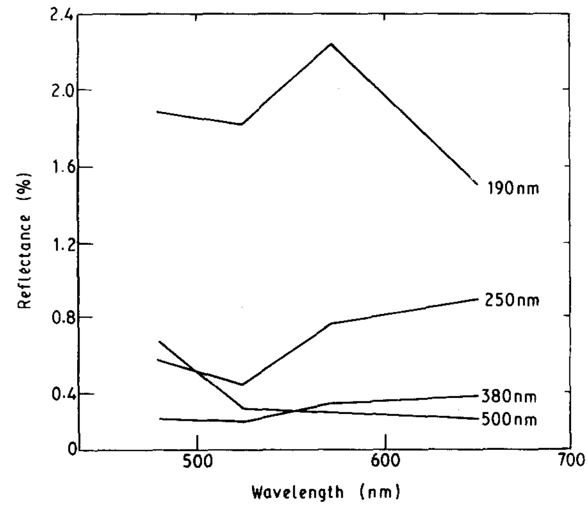


Figure 5. Reflectance as a function of groove depth for a moth eye of period 3660 grooves per millimetre.

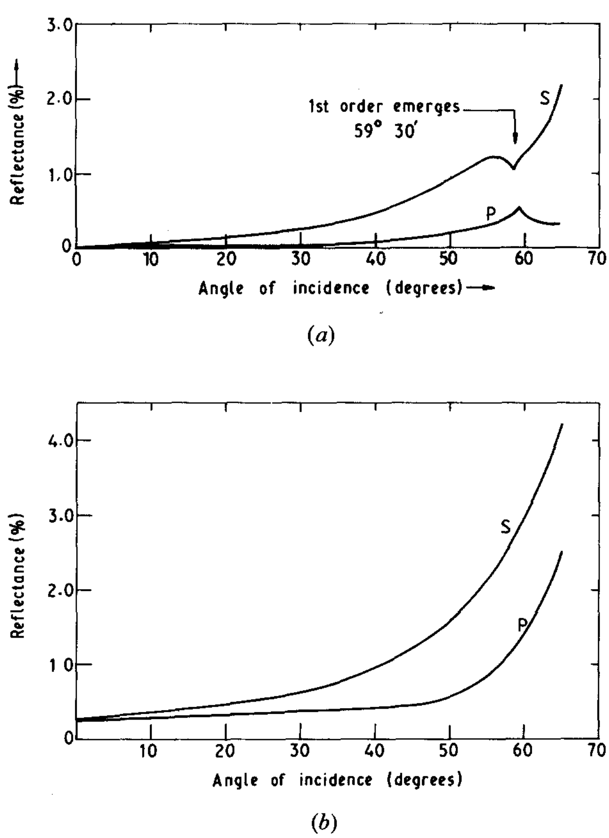


Figure 6. Reflectance as a function of angle of incidence and polarization for a moth eye with 3300 grooves per millimetre at (*a*) $\lambda = 514{\cdot}5$ nm and (*b*) $\lambda = 647{\cdot}1$ nm.

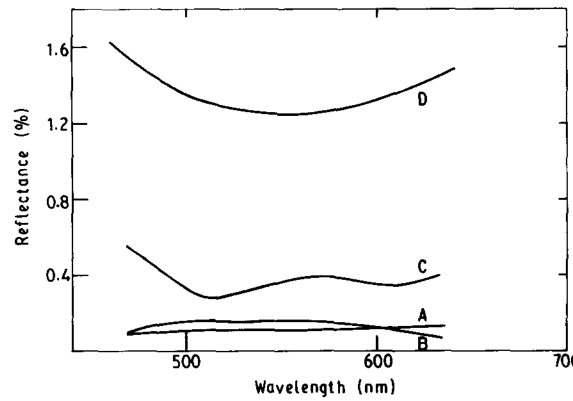


Figure 7. A comparison of the reflectance near normal incidence of a moth eye (curve A) and various other forms of antireflection coatings: curve B, good commerical multilayer; curve C, graded index glass; curve D, single layer of magnesium fluoride on a typical glass of index 1·52 (the reflectance would in fact be lower on a glass of higher index).

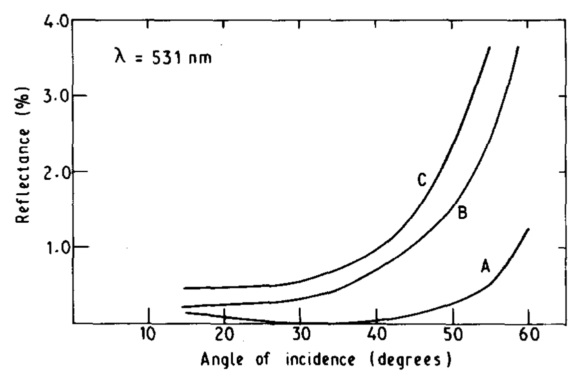


Figure 8. The reflectance as a function of angle of incidence for various anti-reflection coatings (mean of two polarizations). Curves A, B and C in figure 7.

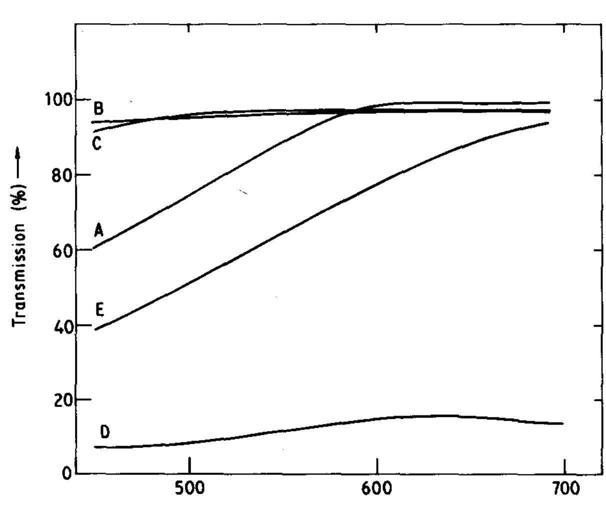
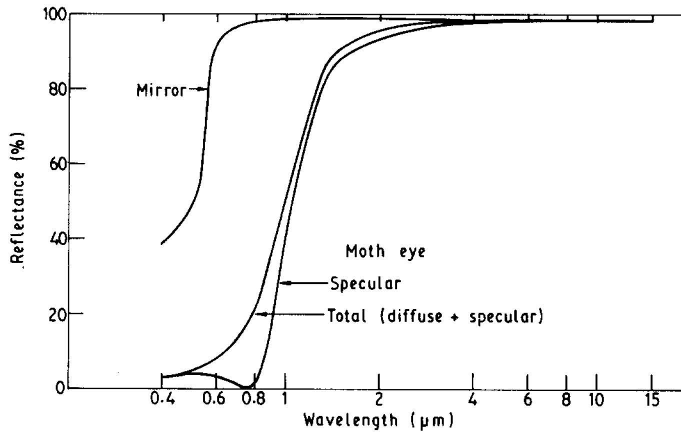
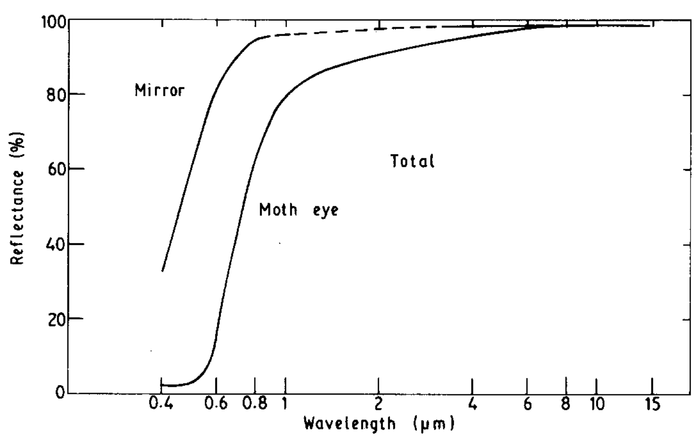


Figure 9. Transmission as a function of wavelength for dense flint blanks coated on both sides with moth eye surfaces of various pitches. Curve A, 2700; curve B, 4040; curve C, 3300; curve D, 1175; curve E, 2402 grooves per millimetre.



(a)



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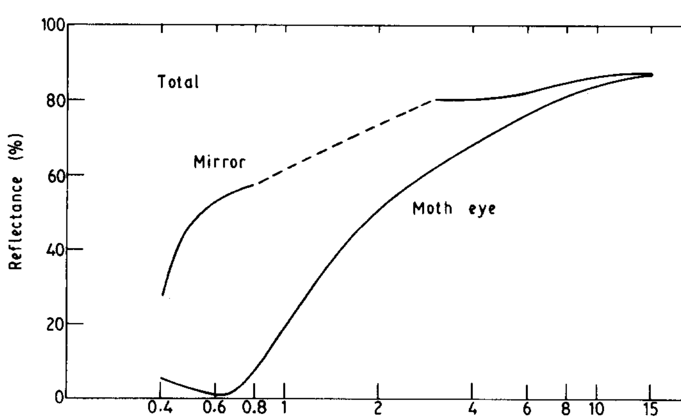

(c)

Figure 10. The reflectance in the visible and near infrared of metallic moth eye surfaces; also shown is the reflectance of the plain metal. (a) Gold, (b) copper and (c) nickel.

Figure 11 shows electron micrographs of a good photoresist moth eye, a first-generation replica in electroformed nickel and a second-generation one in electroformed copper. These indicate that in going from photoresist to copper there has been some reduction of depth, and they also bear out our suspicions that the bottoms of the grooves are flatter than the tops. The tops of the nipples of the nickel replica correspond to the bottoms of the photoresist array, whereas the copper electroform has the same orientation as the photoresist.

Figure 12 shows the angular dependence of the reflectance of a photoresist moth eye coated with gold. This curve is very similar to that of a dielectric, and is particularly interesting because for the p-polarization the reflectance falls practically to zero at a certain angle. If this were a dielectric, the angle at which this happens would be the Brewster angle θ_B, which is given by

$$\theta_B = \tan^{-1} n.$$

In the present case this angle is about 45° which would, if we were to pursue the analogy, correspond to an effective, refractive index of unity! It is not clear what

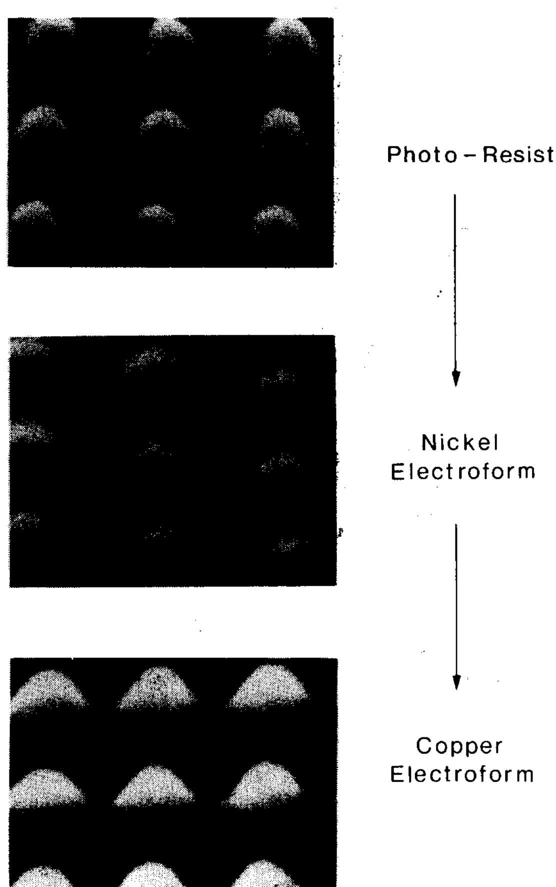

Figure 11. Scanning electron micrographs of a photoresist moth eye, and of first- and second-generation replicas.

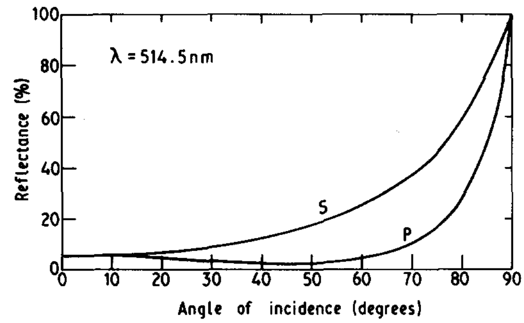

Figure 12. Reflectance of a gold-coated moth eye as a function of angle of incidence and polarization.

significance, if any, we should attach to this observation, but it is at least consistent with the fact that a refractive index of unity corresponds to a Fresnel reflection coefficient of zero, which is what we seek to achieve with a moth eye.

7. Applications

So far we have been concerned only with the optical properties of moth eyes, their reflection, transmission and absorption, and have presented data from samples prepared in the laboratory. We have not considered factors such as cost and durability, although these may well be crucial in determining the practicality of any possible application. We shall, however, continue to consider mainly the optical aspects, and we must accept that for many cases the technology will need to be developed far beyond the stage to which we have taken it. The purpose of the present section is to consider the advantages of moth eye surfaces which might justify this development. The applications fall, for the purposes of our discussion, into three categories: high-quality optical components, mass-produced plastic components and applications in solar energy.

If we consider first the case of an anti-reflection coating applied to a high-quality optical component operating over a wide range of wavelengths, then the moth eye offers much the same performance at normal incidence as conventional multilayer coating techniques. With the examples we have chosen the moth eye has in fact a lower reflectance over most of the working range, and it does not show the sudden increase in reflectance at the ends of the range. In practice, however, these advantages may not be particularly significant. On the other hand, at larger angles of incidence the performance of the moth eye is superior to that of the conventional coatings. It therefore merits serious consideration in applications where components have to work over a wide range of angles of incidence.

It should be borne in mind that our best examples have been chosen on the basis of lowest reflectance, not highest transmission. In some cases an antireflection coating is used to reduce glare and spurious images or interference effects in the optical system, and in these cases we would be justified in considering moth eyes with the lowest reflectance. On the other hand, in the case of complex compound lenses and other systems with large numbers of interfaces, the equally important function of antireflection coatings is to increase the transmission. In order to avoid diffracted orders inside the material a finer moth eye is required and, since this makes it difficult to produce very deep grooves, the performance at longer wavelenghts tends to deteriorate slightly.

On the whole it would appear that for the antireflection coating of high-quality optical components, any extra improvement in performance that might arise from using a moth eye would be unlikely to justify the adoption of a completely new technology. However, one possible exception may be in the case of components used with very-high-power densities where a moth eye structure etched into the surface of the component might well be more resistant to damage than a coating of different materials applied externally.

On the other hand, in the case of lower-quality optics, and particularly plastic optical components, the surfaces are usually left uncoated. The cost of antireflection coating is not usually justified and plastics are not as amenable as glass to multilayer coatings. There are, however, many applications where surface reflections are troublesome, and it would be a great advantage if they could be reduced. For example, a hand-held manifying glass for reading is usually used in levels of high ambient light which often produces glare. Similarly, instrument cover 'glasses' in both laboratory instruments and in cars and aircraft would benefit from some form of antireflection treatment. In most cases these components are moulded. So, if the moth eye structure is incoporated into the mould, an antireflection 'coating' would be produced automatically without the need for further processing. For components mass-produced in this way a significant improvement in performance could be achieved at negligible extra unit cost.

One possible application in which the increase in transmission could be used to advantage is in greenhouses where a thin plastic sheet, embossed on both sides with a motheye could be used for double glazing. Normally double glazing, even with plastic sheet, is not cost effective because reflection losses reduce the level of light available for photosynthesis early in the year. The crops are thus retarded and the grower misses the lucrative early markets. If plastic moth eyes are able to survive a greenhouse environment, they could lead to significant savings in energy.

In the field of solar energy, moth eye surfaces could be used in several ways on dielectric, semiconductor and metal surfaces. Flat plate collectors usually incorporate cover glasses in order to reduce convective heat loss, and the more covers that are used, the higher the equilibrium temperature that can be obtained. However, if each cover reflects a fraction of the incident energy this reduces the efficiency of the collector, and in practice only one or two cover glasses are used. If large areas of plastic sheet could be embossed on both sides with a moth eye structure, then this could be used for auxiliary cover glasses (protected by a conventional glass cover). In principle this could be done quite cheaply using techniques similar to those employed in the production of decorative diffracting plastic film. It may, for example, be possible to construct embossing rollers for the process using the flexible nickel foil replicas described above.

If a way could be found to generate semiconductor solar cells with a moth eye receiving surface, then this would significantly improve their efficiency. The refractive indices in the visible and near infrared of silicon and germanium are large and complex, so that surface reflection losses are between 20 and 50 per cent. This loss could be substantially reduced by the use of a suitable moth eye. It may be a rather expensive solution for terrestrial applications, but it may well be an attractive proposition for use in space where improvements in efficiency lead to useful reductions in weight.

Finally, we have seen that moth eyes made on metallic surfaces can have a spectral reflectance which makes them (from an optical point of view) ideal selective solar absorbers. In visible light the reflectance is low and the absorbance is high (e.g. 0·96 over the solar spectrum), whereas in the infrared the reflectance is high and the emittance is low (e.g. 4 per cent or less). There are, however, many other forms of solar selective surface and the development and study of such surfaces is at present the subject of considerable interest and effort [8]. Many of the alternatives are very much cheaper than the present cost of making moth eyes, so we must consider what advantages, if any, the moth eye has to offer.

We suggest that there are two features of the moth eye which may be used to advantage, and both result from the fact that the optical properties are determined largely by the topology of the surface. First, since a moth eye can be made in a solid material, it is intrinsically more stable than many coatings which are applied externally. There are no problems of poor adhesion or of the degradation of optical properties arising from the diffusion of one material into another.

The second point is that, for a moth eye made of a given material, it is to a large extent possible to control the optical properties by a suitable choice of the geometrical parameters. For example, the position of the cut-off in reflection depends on the height of the protuberances and can in principle be chosen at will. Since the optimum cut-off wavelength varies from one application to another, depending on operating temperature and the properties of the solar radiation, the ability to choose the cut-off wavelength may well lead to improvement in the efficiency of the system.

A further consequence of the ability to control the optical properties of materials in this way is that in principle one has the opportunity to choose the material for a solar collector mainly for its durability rather than its absorbance or selectivity, and then to increase its efficiency by creating upon it a moth eye surface. This is likely to be of greatest importance in high-temperature applications such as solar furnaces, where the main concern for the absorbing surface is durability, but where the extra efficiency may well justify the cost of producing the moth eye.

8. Conclusions

The moth eye effect is an interesting optical phenomenon. It has been known and applied for many years at longer wavelengths, but it is only comparatively recently that it has been discovered in nature and copied artificially at optical wavelengths. It provides an interesting alternative to the use of thin film as a means of reducing the reflectance of surfaces. The main purpose of this paper has been to record our measurements of the optical properties of moth eyes, and we have shown that optically the performance is equal to that of any alternative form of antireflection coating.

With the technology that we have developed so far the practical applications for such surfaces would appear to be rather limited. However, our experiments have indicated that it should be possible to develop techniques for producing such surfaces on a far larger scale and at a smaller cost, either by moulding or by embossing. If this is the case then we believe that there are applications for moth eye antireflection surfaces which would justify the effort of this development.

Une surface antiréflexion 'oeil de mouche' est un ensemble très fin de protubérances qui se comporte comme une gradation d'indice de réfraction et qui réduit d'une manière substantielle la réflectance. Les propriétés de réflexion et de transmission de telles surfaces sont décrites et sont équivalentes à celles des meilleures couches multiples anti-réfléchissantes.

Eine 'Mottenaugen'—('motheye')—Antireflexfläche ist eine Anordnung von sehr feinen Höckern auf der Oberfläche, die sich wie eine Brechzahlabstufung verhält und die Reflexion substantiell vermindert. Reflexions- und Transmissionseigenschaften solcher Oberflächen werden beschrieben; sie gleichen jenen der besten reflexionsmindernden Mehrfachschichten.

References

[1] Bernhard, C. G., 1967, *Endeavour*, **26,** 79.
[2] Clapham, P. B., and Hutley, M. C., 1973, *Nature, Lond.*, **244,** 281.
[3] Lord Rayleigh, 1880, *Proc. Lond. math. Soc.*, **11,** 51.
[4] Lowdermilk, H. W., and Milam, D., 1980, *Laser Focus*, Dec., p. 64.
[5] Thornton, B. S., 1975, *J. opt. Soc. Am.*, **65,** 267.
[6] Maystre, D., and Neviere, M., 1978, *J. Optics*, **9,** 301.
[7] McPhedran, R. C., Derrick, G. H., and Botton, L. C., 1980, *Electromagnetic Theory of Gratings*, edited by R. Petit (Berlin, Heidelberg, New York: Springer-Verlag), p. 227.
[8] Granqvist, C. G., 1981, *Appl. Optics.*, **20,** 206.