RECENT DEVELOPMENTS IN COATINGS, GRATINGS, AND REFLECTIVE COMPONENTS

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1. Introduction

The requirements on gratings and coatings for astronomical use differ from the general industrial requirements primarily in the scale of the components to be fabricated. Telescopes have large primary mirrors which require large coating plants to handle the components. Dispersive elements are driven by the requirement to be efficient in the presence of large working apertures, and usually optimize to large size in order to efficiently use the incoming radiation. Beyond this, there is a "new" technology of direct electronic sensors that places specific limits upon the image scale that can be used at the output of a telescope system, whether direct imagery or spectrally divided imagery is to be examined. This paper will examine the state of the art in these areas and suggest some actions and decisions that will be required in order to apply current technology to the predicted range of large new telescopes.

Perhaps the most important inhibition to progress in the construction of new telescopes is cost. Cost is a subtle driver to technology in that it requires that each large instrument be capable of being shared by a number of users for a number of different applications. An example is the need for all of the major components of a telescope, especially the primary mirror, to be adaptable to a wide range of wavelength bands from the ultraviolet cutoff at 0.3 micrometers, across the infrared bands, to wavelengths of several hundred micrometers, into the submillimeter region. Scattering and reflectivity must be as high as possible in the short wavelength regions. Reflectivity should be high and emissivity as low as possible for wavelengths that range toward the thermal infrared region from 5 micrometers to the submillimeter region.

An important requirement is that the large primary mirror retain its desirable characteristics under a variety of realistic environmental conditions and over a long period of time. These large mirror coatings must be capable of cleaning or renewal with minimum interruption to the observing schedule of the telescope, and with minimum dependence upon personnel skills that are ancillary to the primary mission of the observatory.

Auxiliary optics, including the secondary mirrors of a telescope, and those components following the first imaging step in a telescope, sometimes need to

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have similar characteristics to the primary optics. The size and location of such components usually permits an observatory to acquire a large number of components that are tailored to specific wavelength bands and experimental instrumentation arrangements on the telescope. The coating requirements for these mirrors then may be relegated to some established multilayer process or locally developed metallic coating. The environmental conditions experienced by these smaller specialized optics can usually be controlled to a more favorable set of conditions than the primary optics. These smaller components will not require the community wide attention that should be paid to the primary mirror coatings.

The dispersive elements that are used in telescope instrumentation are usually of classical form. Well known relations exist between the grating period, blazing of the ruling and the irradiance distribution that can be expected in the instrument. While these principles are taught in reasonable detail in many undergraduate courses, there are less well known limitations upon the aberrations produced in a grating instrument. The electromagnetic characteristics of diffraction gratings also produce a polarization dependence upon the grating dispersion. Today the theoretical tools to investigate and explain these instrumental characteristics exist, and can be applied to refine the quality of instrumentation. The concept of holographic gratings, produced on curved or aspheric surfaces permits additional freedom from the aberration limitations of classically ruled gratings. Such gratings are produced in interference from a small set of coherent point sources and captured in photoresist applied to an optical surface. Computer generated holographic gratings offer additional possibilities for the correction of aberrations using components that cannot reasonably be produced by "conventional" holographic construction means.

Modern fabrication techniques that have been applied to semiconductor mask and circuit fabrication offer possibilities for conversion of computer generated design information to actual gratings using electron beam machining techniques. There is thus the potential for an economically realistic capability for making individual gratings tailored to specific spectrometric requirements. The need for, and requirement for, such facility will require a substantial stimulus from the astronomical community. Where this development takes place is much less important than that it take place.

2. Coatings

The principal area for advantageous future development in coatings will be the enhancement of the reflectivity and durability of primary mirror coatings.

Before investigating this, we will consider the other requirements for coatings in telescopes.

An obvious first application is the reduction of the reflectivity of transmitting surfaces as may be encountered in field correctors or relay optics for a telescope. The size of such components will rarely exceed .5 to 1 meter diameter. Industrial multilayer coating capabilities exist for handling such components, and the technology is well established in terms of design and application. The technology is less well established in terms of environmental survivability of such coatings, but there are some new developments worth noting.

The damage mechanisms that are operative in a multilayer coating are primarily related to the mode of growth of the film as it is applied to the substrate. The evaporated material, usually from an e-beam source today, impacts the substrate, or outer portion of the film, with a thermal energy imparted by the source emission. The evaporated material will stick to the substrate in a form determined by the energy available from the source, by the microtopography of the substrate, and by the temperature of the substrate. Due to available, but restricted, mobility of the material impinging on the substrate, a partially ordered growth will take place. Most dielectric films demonstrate of columnar growth from the substrate. This growth lends a nonisotropic component to the properties of the film, and provides a defect path through the film which is aligned with the direction of the growth. It is this defect content that contributes to the difference between the properties of the bulk material and the film properties. Experience has shown that the effective index of refraction of the film can be varied by altering the water content of the porous defect laden film.

The environmental sensitivity of the coating can be traced to this approximately ordered defect. It can be shown that environmentally stable films can be produced by increasing the temperature of the substrate, which provides excess mobility of the molecular material upon reaching the substrate. At some point thermal damage to the substrate as well as the film will result, however. Modern techniques using ion assisted or laser assisted deposition of films have been used to provide densification of the film. Sputtering techniques have also been used for this purpose. The higher atmospheric pressure present in sputtering due to the presence of a transfer gas leads to additional surface roughness in deposited films. This is not desirable for an optical coating, but work in improving this situation is going on.

Design of coatings is not a major issue. Current microcomputer design programs have sufficient power and user friendliness that the limits of film behavior can easily be investigated. Materials and deposition techniques are still open to investigation, but require expensive analytic instrumentation to be pursued on a methodical basis. A rapid conclusion is that such coatings may be useful in specific applications, but not in wide spectrum applications such as telescope primaries.

There are some new techniques for coating that need to be considered. Chemical methods such as sol-gel coatings and etched surface coatings may be of importance. As of now, the principal interest in such coatings has been for coatings with a high laser damage threshold, rather than generally good optical properties. Since such "coatings" do not require a vacuum system, there may be some applicability to remote telescope sites that is not obvious.

High reflectivity coatings for large optics are an important issue for astronomy. The traditional approach to high reflectivity has been the deposition of a metallic coating of 500 to 1000 Angstroms thickness on the traditional glassy substrate. All of the metals have some undesirable properties. The reflectivity of silver is higher than aluminum, except in the short wavelength region. Silver, however, is extremely subject to environmental attack, especially if any sulphides are present in the atmosphere. Tarnished silver films degrade rapidly to a very low reflectivity. It is possible to protect the silver with a dielectric coating, but the activity of the silver and the porosity and defects of a dielectric coating convert the rapid tarnishing to a series of many local tarnished areas, and do not provide significant advantages.

Aluminum, as is well known, develops a thin aluminum oxide layer on the surface, but does not show the tarnishing activity characteristic of silver. Aluminum can be protected with a thin silicon dioxide overcoat, with substantial gain in the resistance of the coating to environmental damage, especially mechanical damage occurring in cleaning. However, the short wavelength reflectivity is reduced, and the coating still slowly degrades. Aluminum is easy to apply, and does not require an exotic vacuum tank for deposition. For this reason, the usual choice in telescopes has been to use bare unprotected aluminum as the primary mirror coating, and depend upon periodic recoating to keep the reflectivity of the primary in the acceptable range.

Recently an important development in this area has been made by the work of Macleod and his associates at the Optical Sciences Center. The substance of this work has been to develop a possible primary mirror coating that combines environmental stability with enhanced reflectivity in the visible and ultraviolet regions and reduced emissivity in the infrared region. This offers a significant possibility for improvement in astronomical instrumentation.

The basic work begins with the presumption that silver would be a better basic reflective material for all regions except the ultraviolet, if the tarnishing problem could be solved. Several approaches were used to improve this tarnishing characteristic, the most successful of which is the use of copper as a base layer of about 500 Angstroms thickness, with the silver layer of about 1000 Angstroms deposited on top of the copper layer. Accelerated damage tests have been made using a fuming sulfide material in a test chamber with coating samples of several materials. In all cases the copper based silver coatings showed less reflectivity loss with time than even the bare aluminum coatings. Especially significant is a plateau that appears at the beginning of the reflectivity degradation plot. This indicates that there appears to be at least two mechanism at work, and that these competing mechanisms appear to provide greater environmental protection to the surface.

Macleod and co-workers have looked in detail at these films and have concluded that the protection is likely due to an electrochemical action enhanced by the copper that provides a cathodic potential that discourages the formation of silver sulfides, at least until the available copper is used up as the reaction proceeds. They have discovered a peculiarity of the silver-copper film structure in that some copper appears at the top of the silver layer. This concentration has not been quantified but is certainly less than a .0001 fraction, since the silver reflectivity is not significantly modified by the presence of surface copper. There does not appear to be any copper content within the silver film as measured by Rutherford backscattering. How the copper ended up on the top is as yet open to speculation, but what is demonstrated is the presence of a film structure that is beneficial with regard to environmental properties.

The silver reflective layer accomplishes two things. The visible reflectivity is increased and the infrared emissivity is decreased with respect to bare aluminum. Environmental sensitivity has been decreased, as shown by accelerated tests. The ultraviolet reflectivity is still lower, but can be enhanced by application of a four layer multilayer dielectric stack optimized in the short wavelength region. One possible design uses a thin layer of Aluminum Oxide followed by quarter wave at .3 micrometer layers of tantalum oxide, silicon dioxide, and tantalum oxide. Such surfaces have been coated and tested and showed extremely good environmental resistance in accelerated testing. Some samples are in place at Kitt Peak for simulated application testing at the present time.

There is promise in such approaches. The use of copper rather than the traditional chromium underlayer for silver shows some advantages, and also may lead to the possibility of easier removal of the coating should a recoat be required. Successful application of the four-layer dielectric stack shows distinct environmental protection advantages. However, as mentioned above, the columnar growth present in multilayers is not desirable. Because of the possibility of damage to a substrate, the philosophy has been to apply the dielectric stack "cold," without substrate heating. Some method of densifying the dielectric stack, perhaps through controlled sputtering, may be required for large scale successful films.

The next step should be to give small samples of these films exposure tests in environments typical of an observatory, to see if the reflectivity and environmental characteristics of the films behave as predicted. A result will be to determine whether the major investment required to scale the process up to astronomical sizes is justified.

4. Exploitation of Coating Technology

The above section describes a program leading to some possible significant advances in telescope throughput. If the useful wavelength region can be extended, as well as the life of the primary mirror coatings, then the amount of data that can be gathered by a telescope can be increased. All this could be done, if two, or three, things happen.

The first is to prove the feasibility of the concept. So far, accelerated tests have shown some significant environmental advantages. Measurements of the reflectivity have shown advantages. Emissivity advantages can be shown theoretically, but have not yet been measured. Scale up appears possible. However, scale up would be into a complex facility operated by specialists. The cost of such a facility is high, but so is the potential payoff.

It is not likely that every large telescope would have such a facility. However, air transportation of large objects has reached a high degree of sophistication, and availability. A change of approach toward telescope maintenance where a large mirror is shipped to a central coating facility for a special enhanced coating is not out of the question. Such an approach to the logistics of coating might actually be cheaper in the long run than maintaining a local coating operation. Obviously a change in approach toward telescope operations is required, but tradition often dies hard.

Where such a central facility resides is not very important, as long as transportation is available, convenient, and economical. Perhaps it can best be run by an industrial organization, but would probably have to be capitalized by a consortium of observatories, including several national observatories.

Is it worth doing? The next step is to find out. The proposed next step in the program is to prepare a number of sample kits, including control surfaces, that would be sent to several observatories around the world. These would be given exposure tests, and possibly cleaning tests, over a one to two year period. The samples would be returned and measured, and the actual feasibility of the approach determined. At that time, sufficient information would be available to base a decision to build such an elegant coating facility.

If this is not done, what is the alternative? Probably all telescopes will continue to depend upon bare aluminum and periodic recoating. Putting off the investigation just defers the ability to make a rational decision about what could be a major operational advantage in telescope operation.

5. Gratings

Anyone who has had an undergraduate physics course knows what a grating is, and the general principles upon which it operates. These explanations are based upon scalar diffraction theory, and become erroneous when polarization is considered, or when the wavelength exceeds about one-fifth of the groove spacing, or when the shape or depth of the groove is modified. Under those conditions, the electromagnetic aspects of light become important and calculations of diffracted intensity must take the boundary conditions into account. The result is that the diffraction process becomes selectively polarizing. This gives rise to anomalies in grating behavior that must be considered in the design of spectroscopic systems and the analysis of data obtained from these systems. The purpose here is not to state that all spectroscopic systems are suspect, but to take note of modern results regarding diffraction gratings and to describe the numerical tools that are available for predicting and understanding these results. Whether the scalar description is sufficient for any given case depends upon the details of the situation and the accuracy required in the spectroscopic data to be analyzed.

The electromagnetic theory of gratings has developed over the past fifteen years in response to observations of polarization dependent efficiency that were made as good quality gratings with ever finer groove spacings were developed. At this stage, the theory has been successfully applied in detail only to plane gratings, and is quite complicated even in those cases. The modern approach to diffractive instruments using holographic gratings has only sketchily been examined in this regard, and it is only recently that tools have appeared which permit reasonably precise calculation of the aberrations from such gratings based upon scalar diffraction.

The electromagnetic theory of gratings is primarily a process of developing the boundary condition solutions to a periodic perfectly conducting surface. Realistic material properties can sometimes be dealt with as a perturbation to the perfect grating solution, as long as resistive losses are small in the surface being investigated. The problems that are easy to solve are those which fall naturally into certain coordinate sets. As the grating depth becomes competitive in dimension to the grating spacing, the local phase of the electromagnetic field must be solved for on a three dimensional periodic structure. The usual approximations that can be used to make the solution tractable can fail when the depth of the ruling exceeds the order of a tenth of the wavelength. Blazed gratings, and most holographic gratings, depend upon the depth modulation of the grating surface for their operation, and are especially difficult to deal with in this regard.

The details of the effect vary with depth of the grating, and presumably will vary with time if the conductivity and surface properties change due to environmental damage. In general there is fair to good agreement between the calculations and some experimental results. Some of the error is due to inaccuracies in the measurement of the precise groove profile and subsequent failure of the model to match the actual situation. Other errors are likely due to the inadequacy of conventional electromagnetic propagation theory to take into account solid state surface effects such as surface plasmon conductivity which is very sensitively dependent upon the microroughness of the surface of the coating on the grating, as well as the substrate surface roughness.

The preceding are presented to demonstrate the state of the art. The reader is referred to the references for details of the theory and the calculations. For the adventurous, descriptions of the analytic details are contained in the book edited by Petit. The future of such theory is probably limited by the practical capabilities of analytical applied mathematics. In the future, developments will likely come through the application of relaxation methods to numerical calculations of the boundary conditions in complex three dimensional structures.

6. Holographic Gratings

The most exciting area of grating technology is that labelled "Holographic Gratings." An appropriately located pair of coherent point sources generates a set of interference fringes on an optical surface that has been coated with a photoresist. Development of the exposed resist, and subsequent etching into the substrate can lead to a grating on the optical surface. The shape of the grating grooves depends upon the location and intensity of the point sources. This can be established to provide curved grating lines that produce local deviations in the diffracted wavefront that can correct intrinsic optical aberrations arising in the specific spectrographic arrangement. Some examples of this are given in the literature.

There are limitations upon the groove form, shape and depth that result from the interference construction of the holographic grating. Just as aspheric surfaces can be used to control aberrations in telescope optics, deviations from simple shapes of the lines in a holographic grating could be used to control aberrations in a spectrograph. The desired grating shapes can be determined by numerical calculation. Conversion of these to actual gratings might be accomplished by appropriate multiple locations of coherent courses and subsequent holographic exposure. There are some configurations of grating lines that are of interest but cannot be easily, if at all, generated by assemblies of point sources. These gratings can be fabricated by ruling using a programmed ruling machine, or by electron beam machining.

Electron beam generation of arbitrarily shaped grating grooves of arbitrary geometry is feasible using present day techniques. One can conceive of a facility in which a grating form on an optical spherical or aspheric surface is obtained by design optimization. Detailed analysis of the expected grating efficiency output can be obtained. The computer description of the grating can then be produced by numerically controlled electron beam machining of the surface. Subsequent coating of the surface can be optimized for the wavelength region of interest. In this way specialized spectrographic instrumentation could be developed with a minimum of optical surfaces, leading to an entire new class of analytical instruments.

Is the development of such a grating facility possible? Certainly it could be done. Is such a development desirable and economical? At this stage insufficient development work and research into the capabilities and limits of generalized dispersive instruments has been carried out to decide whether such a development will achieve a high payoff in the astronomical, or other fields. A program to examine the new type of instrument design that would be possible is of current interest, so that an intelligent decision on proceeding with such a facility can be made objectively. Unlike the large primary coating question, this type of facility has wider application than astronomy, and may be picked up by industry if feasibility is demonstrated, and a market for its product is shown to exist.

7. Predictions for the Future

First of all, nothing happens unless somebody tries something new. Nothing big occurs unless a community of interest is demonstrated. The suggested advances in coating efficiency and new types of grating instruments will probably not occur unless both actions take place.

The cost of each of the facilities of a scale of interest to astronomy is large, perhaps as much as $20,000,000. If this cost is spread over all of the observatories in the world it is affordable. The leverage that these developments would have upon telescope design could be substantial.

The next step that should be taken is a small one. Widespread testing of possible sample coatings should be carried out, and the results evaluated by a representative set of observers from the astronomical community. Possible changes in approach should be determined, and then the reasonableness of such a facility determined. The rest is possibly up to forces beyond the astronomical community. To not take the next step is a commitment to the use of bare aluminum on the next generation of telescope primaries.

The design of advanced dispersive instruments should be pursued, with a belief that an electron beam facility such as that described above is feasible and might be built. The resulting designs and analysis would then serve as the basis for an informed decision on whether to proceed with such a facility, and on what scale. The numerical design tools exist on high speed computers today. The application of human ingenuity and insight is the required next step.