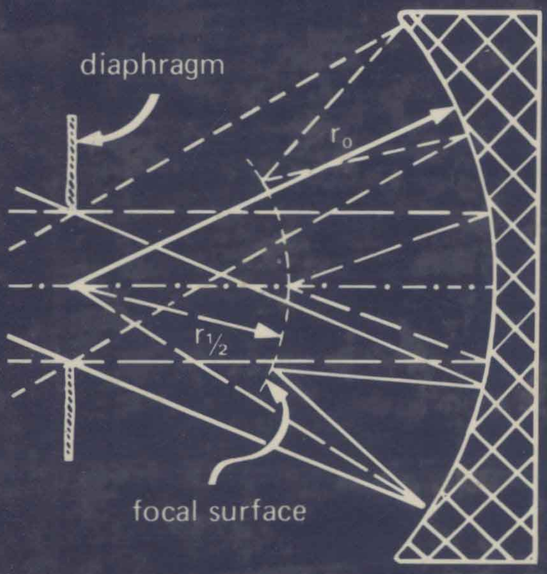
PROCEDURES IN APPLIED OPTICS



JOHN STRONG

Procedures in Applied Optics

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About the Series

Optical science, engineering, and technology have grown rapidly in the last decade so that today optical engineering has emerged as an important discipline in its own right. This series is devoted to discussing topics in optical engineering at a level that will be useful to those working in the field or attempting to design systems that are based on optical techniques or that have significant optical subsystems. The philosophy is not to provide detailed monographs on narrow subject areas but to deal with the material at a level that makes it immediately useful to the practicing scientist and engineer. These are not research monographs, although we expect that workers in optical research will find them extremely valuable.

Volumes in this series cover those topics that have been a part of the rapid expansion of optical engineering. The developments that have led to this expansion include the laser and its many commercial and industrial applications, the new optical materials, gradient index optics, electro- and acousto-optics, fiber optics and communications, optical computing and pattern recognition, optical data reading, recording and storage, biomedical instrumentation, industrial robotics, integrated optics, infrared and ultraviolet systems, etc. Since the optical industry is currently one of the major growth industries this list will surely become even more extensive.

Brian J. Thompson
University of Rochester
Rochester, New York

Foreword

Strong is back! It is a particular pleasure for me to write this Foreword to Professor John Strong's new book, a book that I am very proud to have in my series on Optical Engineering. Like very many other people I have enormous respect for John as a colleague, as an optical scientist, and as a human being. Also, like many others, I had the pleasure of learning from John Strong's writings. His *Procedures in Experimental Physics* (published by Prentice-Hall in 1938) was certainly a treasure house of information for me, made more realistic and personal because of the unique style of the figures drawn by architect Roger Hayward. In 1958, as a young faculty member teaching optics to optometrists, I eagerly awaited Professor Strong's then new book *Concepts of Classical Optics* (published by W.N. Freeman and Company). I was not disappointed and those unique illustrations by Roger Haywood were back.

I would like to use John Strong's words from his preface to the 1958 book since they are just as true today:

> Optics has been a mother of concepts to both experimental and theoretical science. On the side of appreciation, there are many beautiful patterns of color to be seen in optical experiments. On the other side, physical optics has moving mysteries in its theoretical structure. And a practical knowledge of geometrical optics is necessary for effectiveness in any applied science. In short, optics is the

most important background science—even if, currently, it appears to have yielded to particle physics in philosophic popularity.

Today, optics continues to be "the most important background science" but is also in the forefront of the applied sciences and is a dynamic field of engineering.

Professor Strong offers us a very practical book that covers a wide range of topics from radiometry to glass blowing. The Appendix on the production of thin films is contributed by H. K. Pulker and E. Ritter. Chapter 22 is a reprint of the first chapter of the 1938 book on fundamental operations in laboratory glass blowing. I could go on about the contents but I would not do justice to Strong's style. Read on and enjoy.

Brian J. Thompson

Acknowledgments

A book such as this one is never a solo effort. I wish to acknowledge and thank those people who contributed in some manner to the preparation of this book.

Some of the illustrations that the late Roger Hayward created for my previous two books have been used in this one since their art expresses the information intended "better than a thousand words."

I wish to acknowledge Nellie Bristol's uncomplaining typing of the all but illegible penmanship of my manuscript. When it came back from her typewriter it was clean and neat, just as I had imagined it.

I am especially grateful to Professor Fritz Stauffer (Department of Physics, Rhodes College, Memphis, Tennessee). He read the manuscript and corrected the page proofs. More importantly, he found and corrected substantive errors in the manuscript—thus reversing roles with me: a generation ago he was a student of mine.

I also wish to thank Stephan Goldstein (Reading, Massachusetts) for his help in reading the page proofs and providing corrections.

I am proud to be in Brian Thompson's series; and, I thank him for his generous Foreword.

Finally, I wish to acknowledge how easy it was to work with the staff of Marcel Dekker, especially with my production editor, Rosemarie Krist.

John Strong

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Artists in Optics

In this chapter, parallels are drawn between the work and worlds of artists and both theoretical and experimental physicists. Its title is drawn from Warner's *Alvan Clark and Sons—Artists in Optics* (1).

Poetry and musical composition are similar to theoretical physics in the respect that all three are expressed in languages: respectively, the language of words, scores, and mathematics. Sculpture and painting are similar to experimental physics in the respect of hands-on involvement: with a chisel, brush, or physical apparatus. The works are all parallel in the respect that they are renderings or executions of inspirations or conceptions that are expressed or embodied by means of their respective appropriate media. The response to the aesthetic appeal of one, or to the appreciation and understanding of the other, are, as subjective experiences, very similar. This similarity is especially close when the works have been executed without further improvement or at least so nearly perfect as to let criticism lie. However, the subjective appeal to the outsider is different in respect to the necessary background for appreciation: An aesthetic appreciation of art requires only general knowledge and general experience. In contrast, science requires a background of esoteric knowledge and specific experience for its full understanding. The conceptions to be rendered by means of the techniques of art, or in experimental physics to be executed or tested by means of the procedures of physics, come to those who are deeply committed. In this respect, the artist or physicist is an amateur—an amateur not in the sense of work without pay, ineptness, in-experience, but rather, in keeping with the etymological meaning of the word, as one who loves his work.

Apt examples of some of these parallels—especially, the quality of unimprovability—are provided by the poems of Emily Dickinson and experiments of Michael Faraday. In the poet's lifetime, she rejected editors' suggested improvements for her poems. After her poems were published, they were found to be unimprovable gems of perfection. On the other side, Michael Faraday in his experiments, aimed to confirm that the shock by the electric eel was the same in character as shocks produced by Benjamin Franklin's electricity, connected two wires to the body of the eel, one conducting to a carbon pencil that bore on a serrated, rotating metal disk, the other to the disk. When the eel's shock occurred at the same instant that the pencil point was breaking contact with one of the serrations, a tiny carbon arc was observed. Faraday is said to have repeated this demonstration over and over, not so much to confirm the observation as to repeat appreciation of it.

The advent of the experimental method is generally marked by Galileo's experiments with accelerated motion and Francis Bacon's philosophy. Science was stagnent until its acceleration began in the 1600s.

In the epoch when philosophy, logic, and mathematics emerged, ancient Greek philosophers based their concepts of reality on the happenings in nature that were general knowledge, without the benefit of the special knowledge that the experimental method is designed to provide. This special knowledge is provided by induced experiences that are contrived to bear on particular existing concepts, in order to confirm or deny them, and stimulate new ones. The contrivance is controlled to advance knowledge in any deliberately chosen direction.

If Greek citizens had not denied themselves the benefits of the method, they most certainly would have sorted out the concepts of mass and force, and the progress of science would have had over a millennium head start. There is no telling if indeed that event had occurred, at what advanced stage science would have reached now.

A Greek citizen with the necessary leisure time, talent, and philosophical urge to experiment would, by custom, have delegated the degrading hands-on involvement to a subordinate. Now, a belief of the experimental method is that the result of isolation from hands-on involvement is sterility: It is hands-on involvement that gives the experimental method its primacy. It is surprising that the Greeks did not recognize this, especially when we consider that it is man's hands together with his mind that differentiate him from the beasts.

There is good witness that ancient Greeks regarded such hands-on involvement as degrading, even as it applied to art. Homer said that although Greeks "admired and respected the artisan's work, they neither admired nor respected the artisan." Plato relegated craftsmen to the lowest social order in his Utopia. And Aristotle considered that "the best ordered state will not make an artisan a citizen." And, there remain today, among our academics, some with such snobbishness—a rare fault in those who accomplish seminal experiments. Indeed, experimentalists who have the command of engineers to design apparatus, craftsmen to construct it, and research assistants to take data with it, are themselves often found working over the drafting board, operating a machine tool in the shop, and taking down readings of data in the laboratory.

An incident involving Nobel Laureate Enrique Fermi illustrates this point. The incident was related by Professor Franco Rosetti. Fermi and a famous theoretician were professors at the University of Rome in the 1930s. The theoretician, looking for Fermi, was told he would find him in the shop. There he found Fermi bending up sheet aluminum to form the chassis for one of his electronic circuits. The theoretician remarked, "That is certainly very soft iron." This remark, repeated, prompted his students to formulate a rule: The theoretician does not need to know the difference between iron and aluminum any more than the experimentalist needs to understand his esoteric mathematical functions. The students then cited Fermi, who knew and understood both, as the exception to prove the rule.

Since the time of Benjamin Franklin, our country has participated increasingly in the developments of science. Today, we have a preeminence that can be attributed to our having distanced ourselves farthest from the unfortunate vanities of ancient Greece. The developments here in astronomical telescopes serve as a good example.

As telescopes developed, there occurred an oscillation of astronomers' favor between those with lens objectives and those with mirror objectives.

Early telescope lenses were flawed by chromatic aberration and small starlight gathering power. The Newtonian reflector telescope (slightly modified) used by Herschel for his discovery of the planet Uranus had considerably larger aperture and yielded brighter images that were achromatic. His parabolic, objective mirror was worked in speculum metal. This is a copper-tin alloy that can take a high polish. Its fresh reflectivity of 60% is slowly reduced by tarnishing. Because of this flaw, his mirror needed periodic buffing to remove the tarnish, a necessity that repeatedly put its parabolic figure at hazard. In addition, the heavy metal mirror made the telescope clumsy.

The refractor telescope quickly became favored by astronomers with the advent of achromatic lenses (of equal diameter) without a tarnish problem.

Warner's book summarizes the early participation of this country in that swing in favor to lens objectives.

> Alvan Clark and his sons . . . figured importantly in the great expansion of astronomical facilities which occurred during the second half of the 19th century. Almost every American observatory built during this period, and some observatories abroad, housed an equatorial refracting telescope, and often auxiliary apparatus as well, made by the Clarks. Five times the Clarks made the objectives for the largest refracting telescope in the world; and the fifth of their efforts, their 40-inch lens at the Yerkes Observatory, has never been surpassed. Their optical work, which was recognized as unexcelled anywhere in the world, was the first significant American contribution to astronomical instrument making.

Alvan Clark's works illustrate the kind of scientific glory the Greeks never achieved. After long labors in which he was intimately involved with glass, grinding grits, pitch, and rouge; alternating this with tedious testing as he executed his optical ideas, Alvan Clark "touched a star." He was the first to see the companion of Sirius, the brightest star in the heavens. A telescope he made with his own hands was the first perfect enough to show it. It was the first telescope that combined adequate resolving power with sufficient freedom from scattered light to show the companion—difficult to see because the primary star of the pair, Sirius A, is 10,000 times brighter than B, and its separation, varying over a period of 50 years, is never greater than 12 arc-sec.

When B was first seen in 1862, its existence had already been predicted for nearly a generation by Bessel, a conclusion drawn from observed variations of transit passage as compared with the transit times of neighboring stars.

Although the progression to larger and larger telescope lenses was approaching the limit set by the properties of available optical glasses and the weight of the lens (a limit reached in Alvan Clark's 40-in. lens for the Yerkes telescope), John A. Brashear constructed and introduced a prototype of the largest telescopes today. That prototype telescope used a glass primary mirror that was given a high reflectivity on its optical surface by a deposited reflecting film of silver.

This prototype influenced a second swing of astronomers' favor to reflector telescopes, a swing that was primarily due to Brashear's practical method of depositing silver on glass surfaces. His procedure was a development of Liebig's 1850 discovery that on reduction of the silver ion in a silver-salt solution, metallic silver is deposited as a mirror coating on the glass walls of a test tube. The reflectivity of the silver is half again greater than that of Herschel's speculum metal. Silver tarnishes also and requires occasional buffing. However, when the deposited film is worn out by buffing (after about six months of service atop Mt. Wilson), it can be removed with acid and the optical surface resilvered, at no hazard to its parabolic figure.

After the advent of Brashear's silvering method, the Lick Observatory's Crossley mirror, with a slightly smaller diameter than the Yerkes lens, was found to yield even brighter star images—images that were completely free from chromatic lens aberrations. Encouraged by this result, George Ellery Hale promoted the telescopes on Mt. Wilson: first, a 60-in. telescope and then a telescope with primary mirror of 100-in. diameter, followed by the plans for a 200-in. telescope.

In his *Autobiography* . . . (2), Brashear has left us with an account of the 100-in. silvering, the method that predicated further progression to telescopes of greater and greater star-light gathering power. He wrote

> Almost forty years later I stood in the laboratory of the Mount Wilson Observatory, admiring the beautiful silvered surface of the great one-hundred-inch reflecting telescope mirror, made by my old-time friend Professor Ritchey. Expressing my pleasure to him, he replied: "Well, it was silvered by Brashear's process." Many other methods have since been devised; but I know of none more certain and more easily applied.

In addition to this accomplishment in chemistry, he also accomplished much in optics: He was an artist in optics. Another quotation from (2) illustrates his preeminence in the generation of precision optical surfaces. In this instance, we consider flat surfaces generated on speculum-metal-grating blanks for diffraction-grating rulings, blanks that Brashear was supplying to Professor Rowland at Johns Hopkins University

> My relations with Professor Rowland lasted for many years, and never but once did we have any differences. . . . He had been testing some of our grating plates with one of the test plates or planes that were made for him by Steinheil of Munich and found they were uniformly depressed in the center. He wrote me at once about the trouble, and I was much worried, for our tests showed them to be as perfect as we could make them.
>
> I started at once for Baltimore and found Rowland at the laboratory when I reached the University. He immediately said to me,

"Those last plates you made are all bad." I told him that was what brought me to Baltimore. We . . . set up the testing apparatus, and sure enough, every plate showed a depression of half a wave length near the center. Professor Hastings who was present at the test remarked, "May not the error be in the test plane?" Professor Rowland said, "No. Steinheil makes the best planes in the world."

Fortunately, Hastings asked him if he did not have a mate to the plane made by Steinheil, and he remembered that he had. It was soon produced. The two test planes showed that the error was doubled.

Flat surfaces on test plates are more difficult to figure than spherical surfaces of equal precision. This is because the *radius of curvature* of the flat is tightly specified to be $r = \infty$ and an auxiliary spherical mirror of unimpeachable quality is required to test and guide the figuring of the flat. The figuring of a spherical surface, of course, needs no auxiliary mirror for testing.

Professor R. W. Wood added to this story information he had obtained from Rowland himself: Brashear had confirmed the truth of his own test plates by making three. When each one matched the other two to give straight interference fringes, then all three were assuredly flat.

Brashear also demonstrated a capacity to solve an optical-surface-generation problem. Professor S. P. Langley required an optical train consisting of two lenses and a prism, all fashioned from rock-salt crystals. He needed them for a spectrometer in connection with his program to determine the total solar flux-density that is incident at the top of our atmosphere, the solar constant. The following is Langley's account (3), telling of Brashear's help:

There arose a trouble . . . from the fact that glass is impermeable by . . . (infared) radiation and that rock-salt prisms had never been worked of a size or capacity to measure (the solar and lunar radiation). We were repeatedly assured by the best European optiçians that nothing better could be obtained in this way than the prisms they supplied us, which were incapable of showing a single Fraunhofer line, and we had to search long, both in Europe and North America, first for mines which could furnish the right material, and then for the right man to work it. Having found an artist, and previously the material, after a necessary apprenticeship to the use of the latter, this second obstacle was removed. . . . Brashear has worked for us optical trains (a prism and two lenses) of this substance of a size, and especially of a precision, heretofore unknown, a single rock-salt prism not only dividing the D lines, but showing the nickel line between. We have extensive salt beds in this country, but the material seems to be excavated with so little care and so injudiciously handled that we have been unable to procure specimens at once large and clear. What we now use is from the salt mines of Friederischsthal in Baden. As we have said, however, the chief difficulty lay less in finding the material than the artist.

The Brashear silvering method was superseded in the 1930s with the advent of thermal evaporation as a procedure to produce thin films on mirrors and lenses: aluminum on telescope mirrors to enhance the reflectivity of the glass mirror surface and films of MgF_2 on lens surfaces to reduce reflections of air-glass interfaces. In multiple-component lenses, like camera lenses, the transmission of the lens is increased by the same increment by which reflection is reduced. In addition, filming all the air-glass surfaces eliminates multiple reflections and the unsightly halos that they produce in photographs. The aluminizing of astronomical mirrors, rather than silvering, and the MgF_2 filming of all the air-glass interfaces in camera lenses are now universal practices.

The advantage of aluminizing over silvering, for astronomy, is indicated in Fig. 1. Two advantages not indicated are that the aluminum coating does not tarnish and, just after the aluminum coating is applied, the mirror is entirely free from the small-angle scattering that is a consequence of the necessary buffering of a silver coating applied by Brashear's method.

The transmission of a three-mirror, Cassegrain telescope is given by the cube of reflectivities indicated in Fig. 1. This explains why a three-mirror telescope gives very little ultraviolet spectrum, whereas one that is aluminized reaches the limit of transmission of the atmosphere, into the ultraviolet region at 3000 Å.

In practice, the limiting photographic magnitude, determined with blue-sensitive emulsions, was the same with the 60-in. Mt. Wilson telescope, when its mirrors were aluminized, as with the 100-in. telescope with its mirrors still silvered. This represented a 1 magnitude gain.

Scattering by the buffed silver coating was particularly troublesome in the determination of the spectrum of Sirius B, its spectrum being contaminated by scattered light from the 10,000 times brighter Sirius A.

The spectrum of B is particularly important. The flux of light from B is inferior because of the diameter of the star. It is a white dwarf star with a surface brightness even greater than that of our sun, or of A. Further, it is known, from the parameters of the orbits of the pair around their common center of mass, that the masses of B and A are comparable: that of B is 2/5 the mass of A. When we put all the facts together, it turns out that the average density of B is enormous: a boy's marble, if it had that density, would

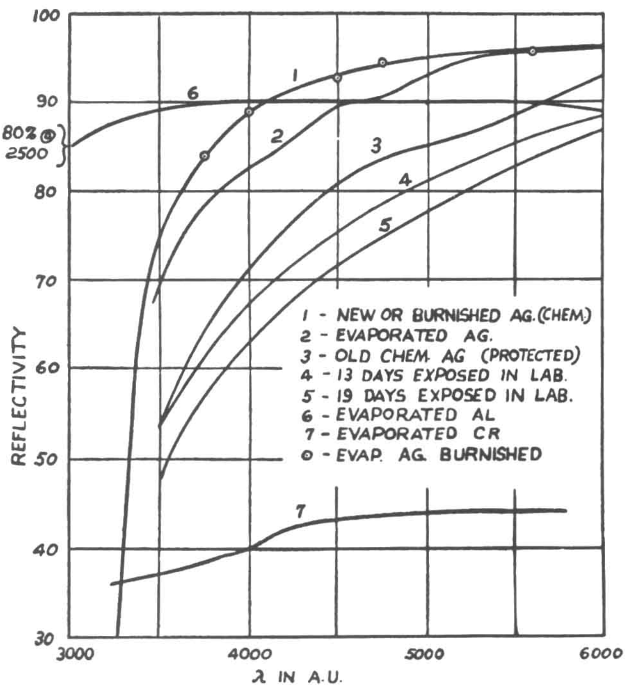

Figure 1 Comparison of reflectivities of aluminum and silver coatings.

weigh tons on the earth's surface. The high density of B makes the acceleration of gravity at its surface extremely high; and this, in turn, makes the spectrum of B important. Einstein's theory predicts a gravitational redshift and the spectrum of B is ideal to confirm this theory.

Dr. Walter Adams was using the silvered 100-in. mirror to this end when it was first aluminized in 1934. After aluminizing, he was freed from the difficult task of correcting the spectrum of B for scattered light.

The reflecting-reducing coatings of MgF_2 on the 14 lens and prism surfaces of the Lick Observatory's slitless spectrograph doubled its light transmission. With this slitless spectrograph, a photograph of the spectrum of planetary nebulae shows monochromatic images of the object for each of the spectrum wave lengths of its line emission.

Three full nights of exposure is the longest practicable, this owing to failure of the photographic reciprocity law. It was found, after the MgF_2 filming, that the faintest planetary nebulae previously observed by such an exposure produced the same photographic density in its monochromatic images after one full night of exposure. This three-fold gain in