Overview of specifications for laser optical components

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Abstract

The developments in the field of lasers and laser optics have placed increasingly demanding requirements on optical components designed for use in state of the art laser systems. Specifications for these components are often imposed without considering the requirements of the fabricator and can result in excessive costs and lengthened delivery times. The dichotomy of the specifying user and the component fabricator needs to be explored and resolved industry wide.

1. Introduction

A responsible review and control of specifications during the Laser Optical Component acquisition phase will assist the fabricator and manifest itself in reduced costs and delivery time to the component user. Key violators of this concept are the tolerances that are sometimes overspecified to obtain the "best" components, without regard for usefulness and purpose. This paper will highlight examples of practical experience specification problems, their resulting cost and schedule drivers, and trade off options to avoid them. The categories presented are:

Material specifications
Mechanical design specifications
Specification inconsistencies
Component surface quality specifications
Coating specifications

2. Material specifications

2a. Optical glasses

One of the most frequently specified glasses is BK-7, which is supplied in several grades relating to optical homogeneity. Grade A or H_1 (Homogeneity Group 1) is generally available from stock, has a maximum index variation of 2 x 10^{-5}, and costs $11.40 per pound. PH_4 (P-precision quality; H_4-Homogeneity Group 4), supplied in cut blanks only, has a maximum index variation of 1 x 10^{-6}, costs four times as much, and is not as readily available. Delivery times of 16 weeks are not uncommon. PH_4 characteristics are required only in those instances where a component is used simultaneously in transmission and reflection and tight wavefront tolerances are necessary for both beams. This requirement exists for interferometer beamsplitters. It becomes obvious therefore, that PH_4 should be specified only in those cases that truly demand it and when associated increased costs and delivery times can be tolerated.

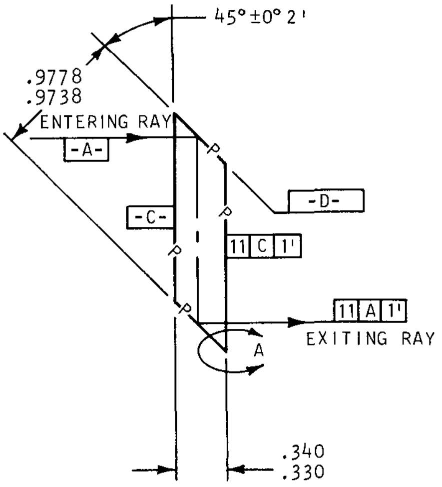


Figure 1.

1.MATERIAL SHALL CONFORM TO MIL-G-174 FUSED SILICA, TYPE ¶20, SUPRASIL 2, GRADE A STRIAE OR EQUIV.

A similar situation exists for fused quartz. Figure 1 is a transcribed portion of a specification drawing of a Rhomb Prism. The first note calls for Suprasil 2. Subsequent notes indicate that the prism is to be tested and used in the visible wavelength region. Figure 2 presents specifications for Suprasil 1 as compared to Homosil showing that the homogeneity of Suprasil 1 is 8 x 10^{-6} while that of Homosil is 1.5 x 10^{-6}, less than one-fifth as large. A two inch diameter, half inch thick blank of Suprasil 1 costs $115.50 and an equivalent blank of Homosil costs $77.40. Perhaps Suprasil was specified because it is more expensive and therefore considered to be better. The fact is that it is its ultraviolet transmission that is higher and it makes no sense to use it for components designed for use in the visible or near infrared wavelengths regions. Another point can be made about the homogeneity of fused quartz. The material is made in boules which are not homogeneous throughout, due to the manufacturing process, and it may not be possible to obtain an 8 inch diameter piece of specified homogeneity from even 16 to 24 inch diameter boules. The available sizes of a given quality depend on the manufacturer and his particular process. Specifying a particular manufacturer's material will not guarantee the desired quality for large pieces of quartz. Not long ago, we were asked to make an 8 inch diameter Fused-Silica Disc with twentieth-wave surfaces. When it was established that a twentieth-wave wavefront was actually required, it was found it was not possible to fabricate from the specified material and we actually had to use BK-7. There are alternative designs to avoid the need for homogeneity of large pieces of BK-7 or Fused Quartz. Figure 3 shows a Rhomb which performs the same function as that in Figure 1 but has a 14 inch offset and one arc-second parallelism between the entering and exiting beams. This would be extremely difficult to achieve in solid material. This alternative achieves the same result by using a hollow Pyrex tube with mirrors optically contacted on the ends. In other situations requiring tight angular and wavefront tolerances, adjustable wedges might be incorporated to compensate for wedge and power.

GRADE	*SIZE* ②	**STRIAE** ③ **Per MIL-G 174 through major faces**	**HOMOGENEITY Max index** ③ **variation (Δn) over any 70 mm dia aperture @ 546 nm**	**BIREFRINGENCE Max strain** ④ **in nm/cm path difference**
T22 Suprasil - W1	≦ 4"	A	10×10^{-6}	5
	≦ 8"	A	10×10^{-6}	8
T23 Suprasil - W2	≦ 8"	A	15×10^{-6}	8
T19 Suprasil 1	≦ 4"	A	8×10^{-6}	5
	≦ 10"	A	8×10^{-6}	8
T20 Suprasil 2	≦ 10"	A	10×10^{-6}	8
	> 10"	A to B	10×10^{-6}	10
T16 Ultrasil and T15 Homosil	≦ 10"	A	$1\ 5 \times 10^{-6}$	5
T17 Infrasil 1	≦ 10"	A	2×10^{-6}	5
T18 Infrasil2	≦ 10"	A	4×10^{-6}	5
	> 10"	A to B	4×10^{-6}	8
T12 Optosil 1	≦ 4"	A	3×10^{-6}	5
	≦ 10"	A	3×10^{-6}	5
	> 10"	A	3×10^{-6}	10

Figure 2.

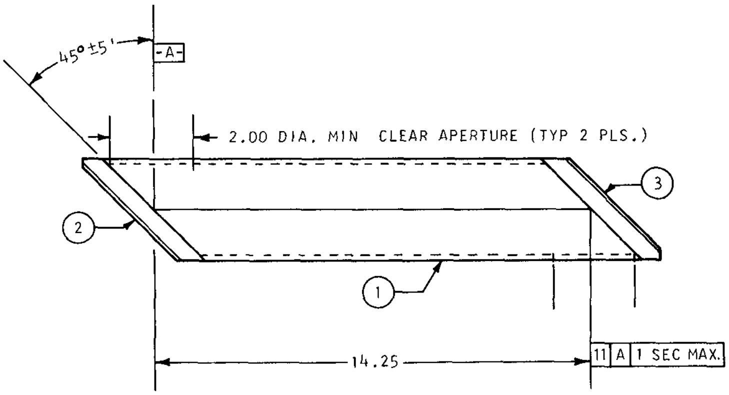


Figure 3.

Fabricators can also run into problems with single crystal synthetic materials in spite of advances in technology. Our design of a shearing interferometer that we call a Collimation Tester is used to determine laser beam quality and parallelism. We were called upon to make one to operate at 3 microns with a ten inch aperture and quarter wave performance. The material selected was calcium fluoride and it took us a year to obtain the blank. That blank, by the way, had a 10.25 inch diameter, was 1.5 inch thick, and cost $3700.00. The significant point is that when you scale up in size, the problems that may be encountered in addition to the weight of the material also rise on a steep curve.

There are other characteristics of optical glass that should be observed besides index, dispersion and homogeneity. Figure 4 shows a column from the Schott catalogue. This one is from SK-16 and I point out to you the line marked FR, which are stain characteristics. The use of glasses with numbers as high as 5 can result in serious problems. One of my horror tales involves some lenses we once made from SK-16 in production quantities. We found that the elements

SK16 - 620 603

Other Properties	
$\alpha_{-30/+70°C}$ [10^{-6}/K]	6.3
$\alpha_{20/300°C}$ [10^{-6}/K]	7.3
Tg [°C]	638
$T_{10^{7.6}}$ [°C]	750
c_p [J/g K]	0 578
λ [W/m K]	0 818
ρ [g/cm³]	3.58
E [10^3 N/mm²]	89
μ	0 267
HK	490
B	0-1
CR	4 (2 0)
FR	4
SR	52
AR	3.0

Figure 4.

stained rapidly after polishing and we had to repolish immediately before coating one side, then polish the second side before it was coated. This glass was so sensitive that some coating materials produced a reaction and further stain occurred during the coating process. It was necessary to redesign the coating with other materials before satisfactory results were obtained. The effects on delivery and cost should be obvious. I would also like to suggest that in addition to considering optical, mechanical, thermal and chemical properties of candidate glasses, the price and availabilty be examined. Glasses that are not stocked may have exasperatingly long delivery times. When selecting glasses, the possible candidates should be listed, paying particular attention to those characteristics which may present problems and trying to avoid them.

2b. Natural materials

Some designs call for the use of natural crystals. When you try to apply the same specifications used with glasses, it is found that Mother Nature does not always accomodate you and alternatives must be sought. In the use of calcite polarizers, for example, a wavefront distortion of eighth-wave in the visible is limited to apertures of less than 40mm. For larger apertures, thin film polarizers offer an alternative, with some sacrifice in performance. In applications requiring crystal quartz, retardation plates for example, we have been able to achieve tenth-wave performance for apertures up to 115mm. We are working larger apertures in the form of mosaic fabrication but obtaining and selecting large crystals is expensive both in material cost and in time. Large crystals in calcite or natural quartz are becoming scarcer each year.

The foregoing examples should indicate that soliciting the aid of and consulting with an experienced optical component manufacturer before material specifications are finalized can produce cost effective results.

3. Mechanical design specifications

The mechanical design requirements of optical components can also sometimes create problems. An example is illustrated in Figure 5 where a lens spacing is maintained by knife-edge contact of the elements. Knife edges are difficult to maintain through grinding and polishing. They chip easily, not only during these processes, but also, in centering and assembly. The chips, in addition to being unsightly, can propagate into the clear aperture and cause rejections. The rejection rate therefore is increased with similar effects on the cost. An alternative is to apply face bevels to negative elements and at the same time accurately hold the sag of the curve to the required face. This allows the use of mechanical spacers which are simple to make. Wherever possible, knife-edges should be avoided.

Unnecessary fanciness in bevels and edge finishing create another set of problems. Figure 6 shows the face view of the Rhomb illustrated in Figure 1. Note that the top end has the usual 45° chamfers while the bottom is to be ground to a full radius. This radius makes the part harder to produce without a clear reason for the requirement. If the reason is mounting, it should be remembered that it is much easier to machine metal than glass, and an alternative design should be considered.

Figure 7 is another example of a whimsical bevel design of a 90° prism which we made. Only the pertinent dimensions are shown of the design which may appeal to an engineer for the beauty of design but it is suggested that the cost of jigging and increased time to produce such bevels be considered.

Figure 8 illustrates a design that defies understanding. This 5 element assembly measures less than 0.75 inch in length. The specifications call for surface quality of one- fourtieth of a wave, tilt of less than one minute, centration of .0002 inch and spacings within .0002 inch. Rapid delivery of

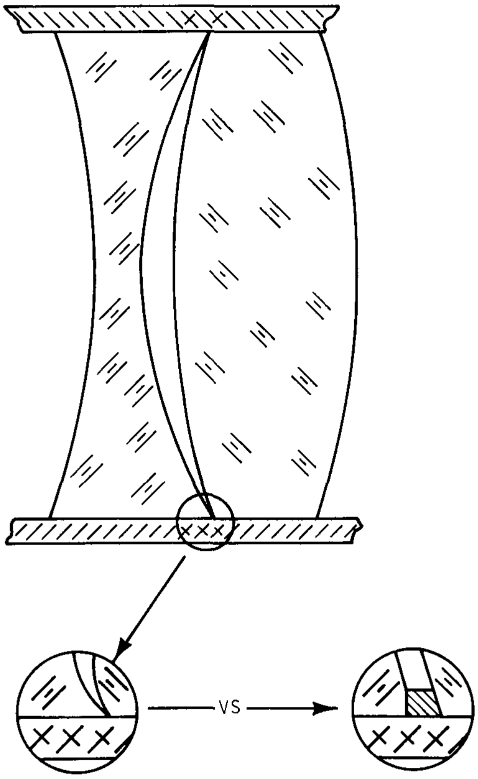


Figure 5.

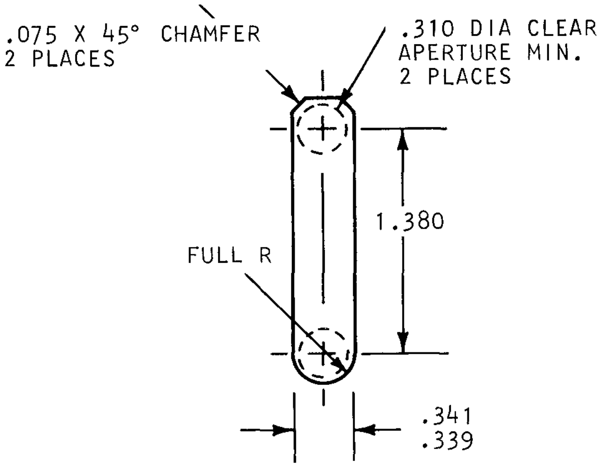


Figure 6.

100 pieces was requested. Note, in particular, the simplicity of the last two spacer rings. If there were a serious interest in maintaining such tolerances, the elements should have been specified to be mounted in metal, either by spinning or cementing. The metal should be machined and lapped to center the elements and provide spacing, assuming of course, that the thickness tolerances were within the realm of feasibility. Figure 9 shows another specification drawing we received. This is an interferometer assembly consisting of a beamsplitter cube with a cube corner on one face and a right angle prism on the other. The optical path lengths of the two beams were required to differ by a quarter wave plus or minus a tenth wave. Even if it were possible to produce the separate parts to the requisite tolerances, the assembly would require cementing, which must be done in a white light interferometer. Fabrication of such an assembly would be exceedingly expensive and surely alternatives should be considered.

4. Specification inconsistencies

4a. Components

Another ulcer producer for the poor suffering optical fabricator is inconsistency in specifications. Figure 10 illustrates a small prism to be manufactured to mechanical dimensions which turned out to have angular tolerances that range from 8 to 21 arc minutes. There was an additional specification on angular tolerance of the exiting ray with respect to the Datum planes of 1.5 milliradians or 5 arc minutes. The fact that the numbers are inconsistent may not become apparent until after fabrication and therefore necessitate full rework. In another example, a mirror flatness in one zone is specified as eighth-wave at .633nm and in another zone as less than 3 millidiopters spherical power when observed with a telescope of 40mm aperture. It is obvious that the latter specification is suitable only for final inspection requiring a special test setup. It is not useable by a polisher who has to use a testplate or an interferometer to check the surface. It would certainly seem possible to reduce this specification to interferometric terms to alleviate the fabrication process and preclude the requirement for special fixturing. In still another case, a roof prism of 10mm aperture was specified to have maximum deviation of entering and exiting beams of two arc seconds. Surface flatness of tenth-wave was also specified. Investigations disclosed that to limit the flatness to no more than two seconds deviation, the surfaces must be flat to less than one-twentieth wave and the tilt cannot exceed one fifth-wave--

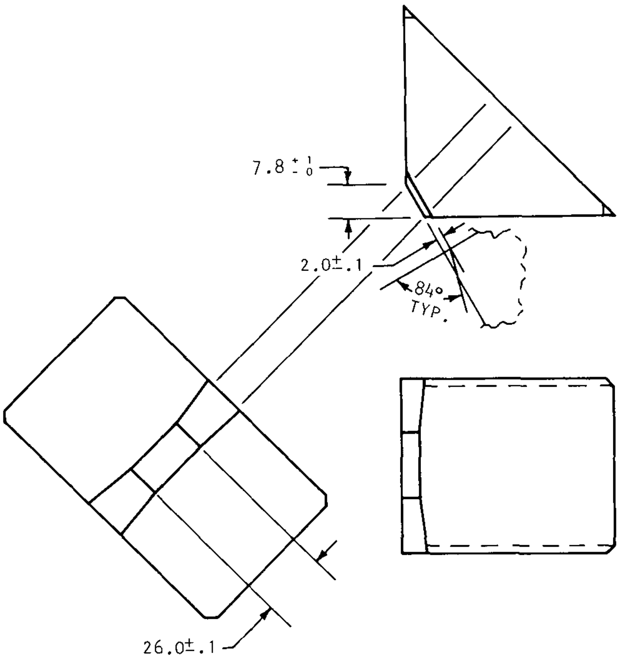


Figure 7.

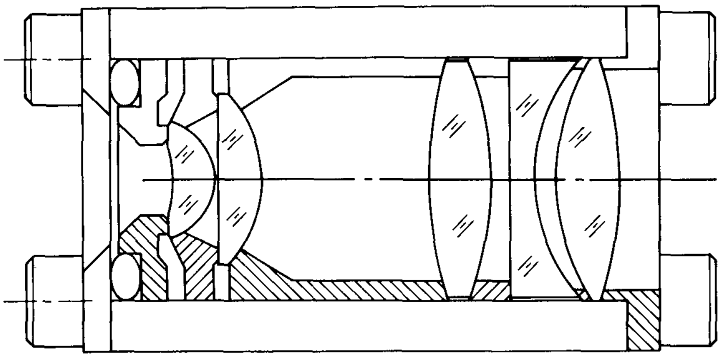


Figure 8.

Back to the polishing spindle.

In too many cases components are unnecessarily specified. In the case of thin windows, retardation plates and components to be used in transmission only, it is not necessary to specify surface flatness. In figure 11A, for example, a window is specified to have twentieth-wave surfaces to obtain a tenth-wave wavefront error. In reality, the surfaces could deviate considerably from flatness as long as they are parallel as shown in Figure 11B. In this instance wavefront was the important parameter and that is what should have been specified.

4b. Components in next higher assemblies.

For requirements when the component is to be bonded into an assembly, there should be a specification of performance on the assembly. In a recent case we had a specification on the flatness of a mirror that ultimately had to be bonded to a next higher assembly. There was no flatness requirement specified on the assembly. Because of bonding shrinkage, mechanical interferance and finally, a warped mirror, we found it necessary to alter the bonding material with the approval of the customer to avoid warpage. A mirror flatness specification after assembly would have alerted us to consider an alternate approach.

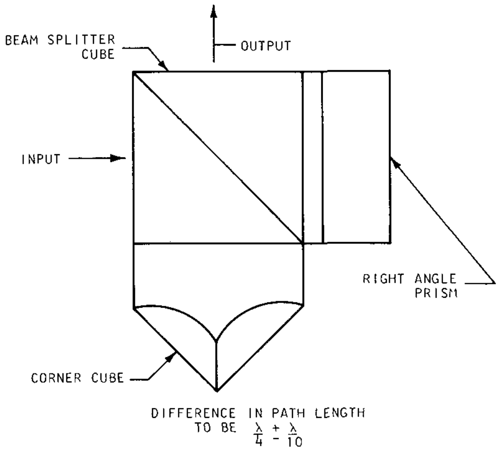


Figure 9.

Much has been said about angular tolerances on components. Users should be aware of where the time and cost breaks occur with respect to these tolerances. Prism angles and window parallelism of 5 minutes can be produced directly on machines. Tighter angles can be held by hand correcting in grinding, angles of 20 seconds being possible on larger parts, above 2 inches and angles of 2-3 minutes on parts with dimensions of 1 inch or smaller. This involves somewhat higher costs. Finer angles than these require polishing, then optical contacting, and then second grinding and polishing. This involves appreciably higher costs.

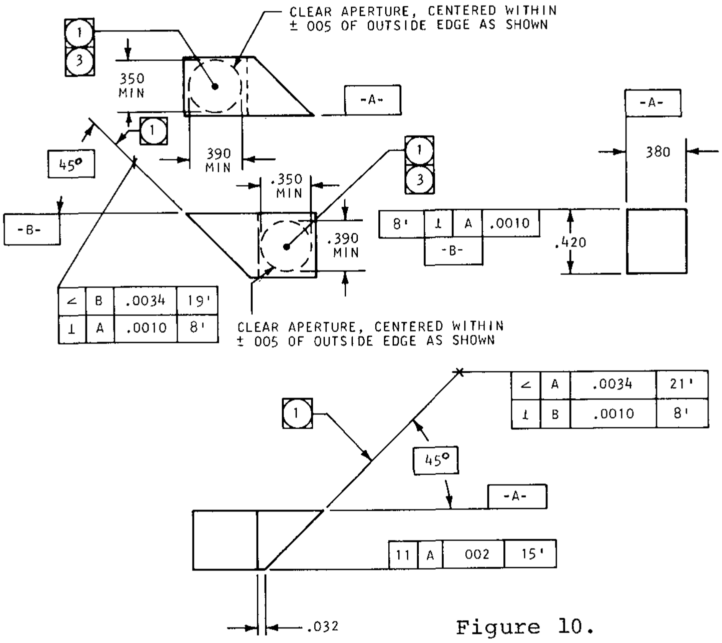
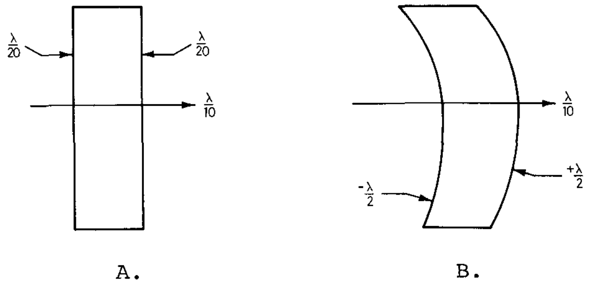


Figure 10.



A. B.

Figure 11.

5. Component surface quality specifications

5a.Mil-0-13830 scratch and dig specification.

The one area of specification that has caused a great deal of controversy and grief is the surface quality specification of Mil-0-13830, defining scratches and digs. These specifications are useful for checking surface quality of production runs by a visual comparison to a calibrated standard. This leads us to our first problem. Inspection is subjective since direct measurements are not allowed and are therefore open to interpretation, since the appearance of scratches is a function of width, depth, material and groove type. The full implication of these specifications are not generally appreciated in that dig specifications include not only surface quality but also internal quality. If a dig specification of 200 microns exists and you have a bubble larger than 200 microns, the specification has been exceeded. Anyone who has ever participated in any of the arguments and discussions involved in the subjective evaluation of the Mil-0-13830 specifications on scratches and digs will appreciate that a revision is warranted. This opinion is shared by other members of the optical fraternity. My personal preference is for a quantitative standard such as the DIN-3140 specifications where direct measurements can be made and costly arguments and unnecessary rework avoided.

The applicability of scratch and dig specifications to laser optics is also subject for discussion. There are reports that laser damage can occur at scratches and perhaps a specification might apply for high peak power conditions, if the relationship could be quantified. The presence of scratches, however, is primarily cosmetic in nature and usually has little effect on the optical performance in the visible and UV regions.The effect of scratches in laser optics only begins to be noticed as a source of scatter in the infrared and even here the effects may be overshadowed by scattering from particles and other microscopic artifacts.

5b. Surface roughness and scatter specifications.

The topic of scatter and the associated specifications of surface smoothness of microroughness should also be discussed. While the understanding of the field is still growing, it seems clear that the dominant source of scatter in the UV and visible region is due to microirregularities in the surface of components. This sometimes leads to a specification of surface roughness, usually in Årms, without an appreciation of what it means. The Total Integrated Scatter (TIS) can be related to the surface roughness, although it should be understood the optical constants of the surface and coatings can affect the simple theory. If there is a requirement for low scatter at given angles, then a specification of the distribution of surface irregularities, the surface autocovariance function, is needed. This is not something that an optical shop is prepared to measure. Even TIS measurements can only be made on small, nearly flat, surfaces and can be a tedious and costly procedure. In making scatter measurements it can sometimes be difficult to isolate single surface scatter from multiple surface scatter and multiple surface reflections as well as scatter from the measuring equipment itself. If, indeed, there is truly a requirement for low scatter, the specification should establish and define just how that measurement should be made. Until such times as there are standardized methods and equipment to perform scatter testing, the design engineer must be in a position to define exactly what is expected.

6. Coating specifications

6a. Spectral performance.

Coatings are another area where specifications must be carefully selected and clarified. For those coatings that must operate at high peak power levels, it is not sufficient to specify only the wave-length and the peak power. There must be some indication as to how they are used. There are different coating designs that are dependent upon whether the pulse durations are in picoseconds or nanoseconds. Other coating specifications that engineers sometimes ignore are the tolerances on the reflectivity and transmission, ie, what percent deviation is allowed. Design engineers should keep in mind that the tighter tolerances usually create higher cost. The angle of incidence must be specified along with an identification of any polarization problems created if non-normal incidence is employed. It should be noted that metallic coatings are less sensitive to polarization than dielectric coatings, however the price you pay is decreased efficiency. The importance of specifying the proper test equipment should become apparent after I relate to you another horror story that recently happened. We were asked to make a Beamsplitter with R:T = 50:50 coating, that was approximately flat from 0.8 to 1.0 microns for 45° and unpolarized light. We designed a coating whose measurements disclosed a steep rise with wavelength, Figure 12A. After several redesigns and retests we encountered the same phenomenon. We finally measured the coating in each polarization, "S and P" separately and computed the net effect, which was relatively flat, as illustrated in Figure 12B. It can be seen that the "S" polarization reflectivity is much lower than the "P". It was concluded therefore that the beam polarization in our grating spectrophotometer varied sharply with wavelength producing the apparent artifact.

An additional observation associated with coating specifications is that the bandwidth of the desired R or T should be specified. Problems are encountered in some high reflectivity coatings when they are measured in transmission. You can have both absorption and scatter which reduce the reflectivity. If this is an important consideration it should be dealt with and properly specified.

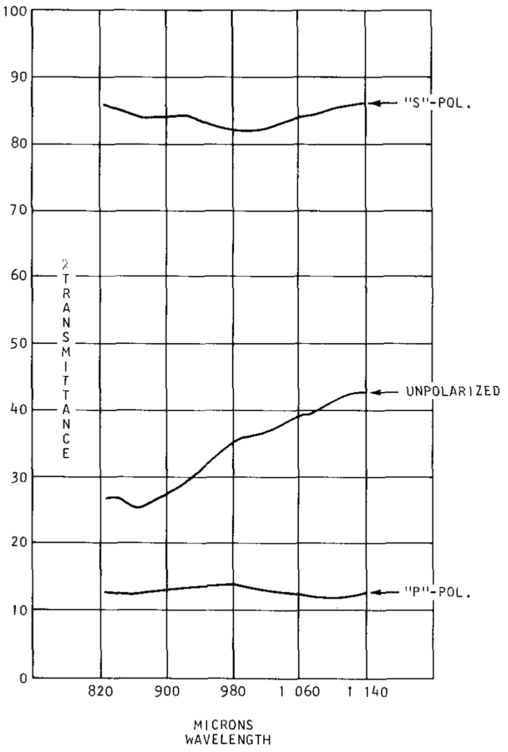


Figure 12A.

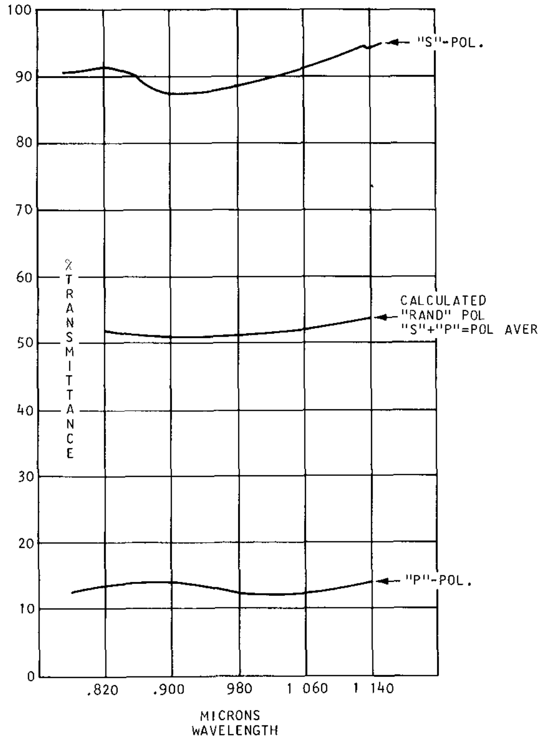


Figure 12B.

6b. Environmental requirement specification.

A final important specification consideration is the component's use environment. Components that are intended for laboratory use only should not be straddled with cost driving stringent environmental requirements. On the other hand there are many military applications that require external surfaces and coatings that can withstand exposure to salt spray, salt fog, high and low temperatures, humidity and various other environmental factors. In these applications, a careful evaluation to insure that the specified environmental testing tracks the actual required use may prove to be very cost effective.

7. Conclusions

It is an oversimplification to state that the synergism of uniting component users and manufacturers is long overdue. It would also be presumptuous to assume that any paper could address all the existing communicative problems among industry members. It is merely our hope that those that were addressed have stimulated interest and that the trade offs provided were worthy of consideration.

8. Acknowledgements

The author wishes to thank all of our many valued customers, with whom we have enjoyed many years of close working relationships. The references and excerpts cited in this paper were merely used as examples of situations that were selected at random. It was not our intention to defame nor embarass but rather assist where we can to effect a more cohesive industry relationship.