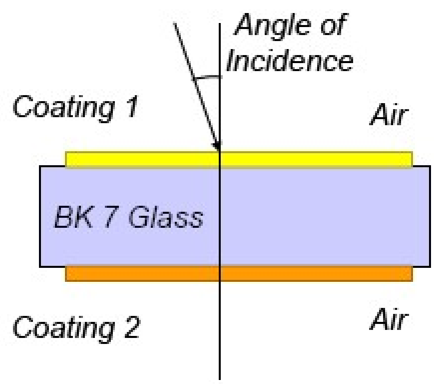
9. 양면 코팅(MULTICOAT)

1) Stack

양면에 코팅 필요한 경우 사용하는 기능

■ 설계 (예)



Coating 1: (HL)^15 H with λ_0 440nm

Coating 2: (HL)^15 H with λ_0 550nm

H is Ta2O5 and L is SiO2

1) 상기와 같은 조건으로 코팅 설계 파일을 Formula 기능(P.47)을 이용하여 각각 만든 후 파일 메뉴에서 “New”>”Stack”, 아래와 같이 해당 컬럼에 마우스로 클릭하여 작성 합니다.

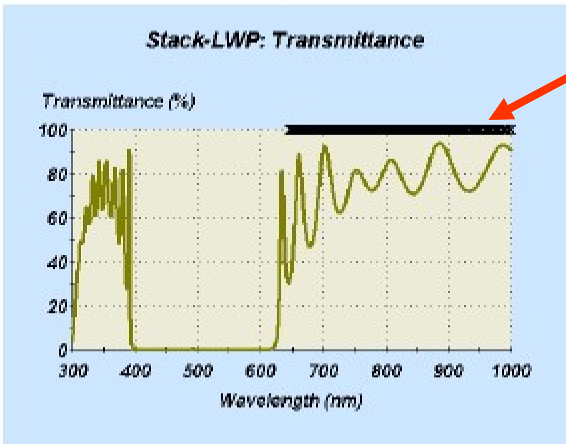
Stack-LWP

Stack | Notes

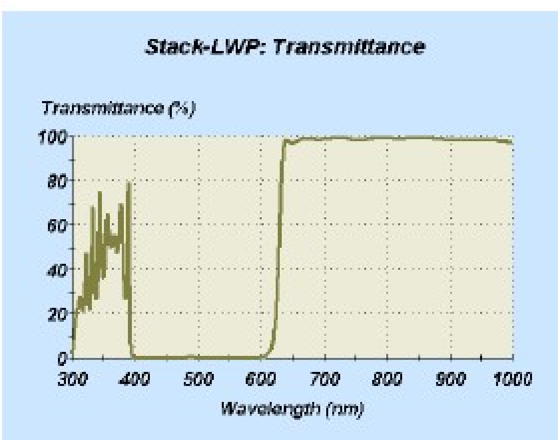
Medium Type	Medium Material	Medium Substrate	Medium Thickness (mm)	Coating File	Coating Direction	Coating Locked
Incident	Air					
Parallel	BK 7	BK 7	5.000	Coating 1	Forward	No
Emergent	Air			Coating 2	Reversed	No

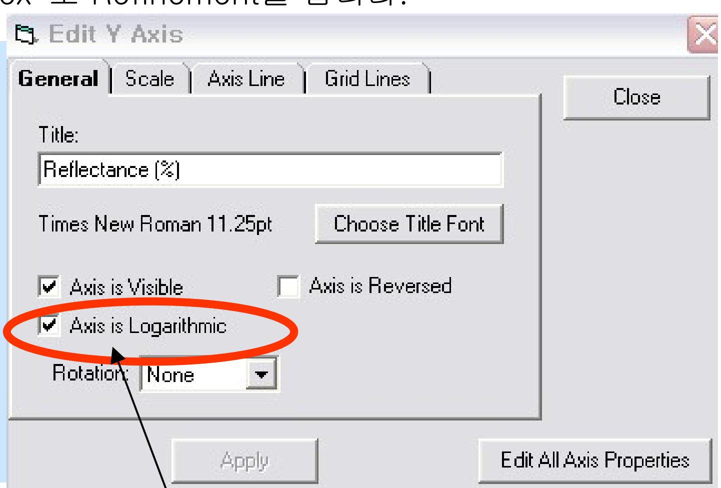
2) Plot 하면 다음과 같이 나타나면,

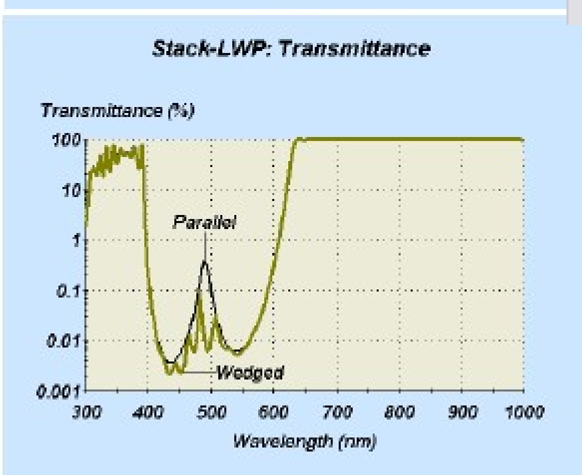
목표 값



3) Refinement > Target 에서 600~1000에 투과율 100% 하여 “Generate”한 후 “”Simplex”로 Refinement를 합니다.



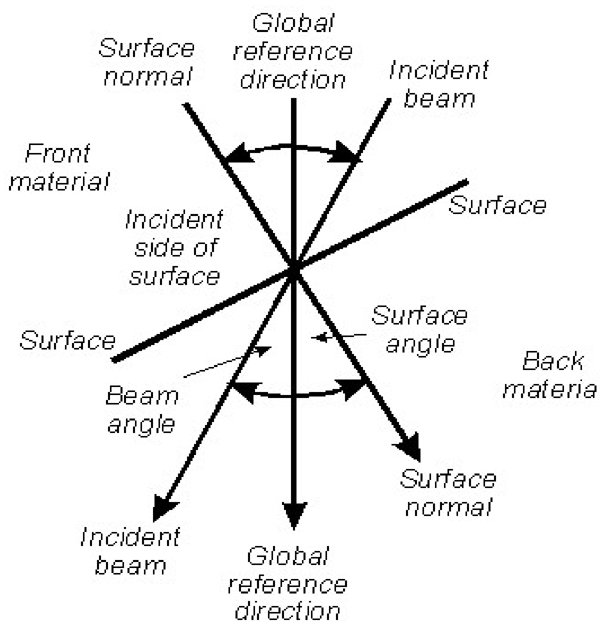




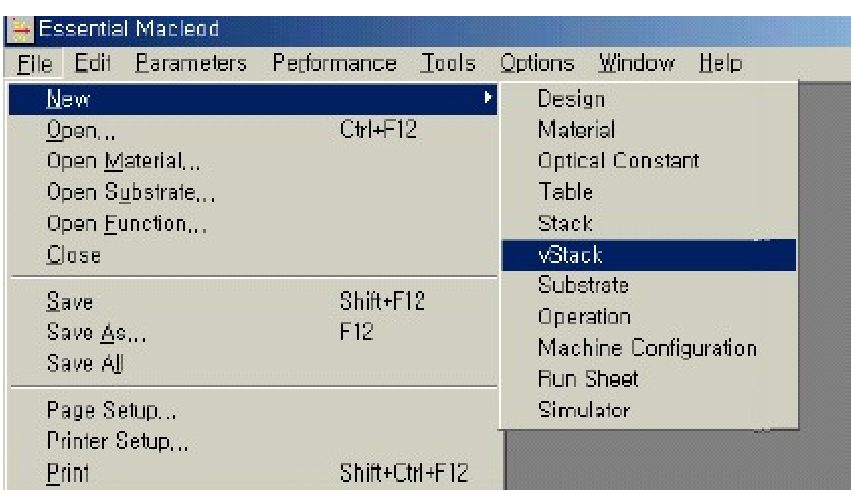
4)세로 축에 마우스 왼쪽 버튼을 더블 클릭 하여 Plot 모드를 변 하면 옆 그림으로 됩니다.

2) vStack

이종(2개 이상)의 필터로 Stack 구조와는 달리 경계 면에 입사 각(Angle)이 다르고 면이 평행 하지 않은 구조의 멀티 코팅에 대해 각각 계산하여 전체 시스템에서의 광 특성을 계산하며 특히, 프리즘이나 여러개의 경계면을 빛이 통과하는 경우, 그리고 수직입사가 아닌 경사 입사로 들어와서 여러 경계면을 반사 혹은 투과 하여 진행하는 빛에 대한 특성을 계산하는데 사용하는 Option 입니다.(Stack은 기본 제공)



메뉴 바에서 File ≫ New ≫vStack 선택



16.1 vStack Fundamentals

vStack is the tool that calculates the properties of assemblies of coatings and substrates where the substrates are not necessarily parallel-sided. The system of elements is known as a vStack and it consists of a series of *Surfaces*. Each surface may be uncoated or it may carry one optical coating. When there is only one surface then the system will appear exactly as a single coating on an infinite substrate but usually there will be a number of surfaces with associated coatings. vStack assumes that all beam directions and surface normals are coplanar.

The calculations performed by vStack apply to the path of a single beam through the assembly. This is in contrast to the Stack system where multiple reflections may be taken into account. The path of the beam is defined by the list of surfaces. The terms incident and emergent can be confusing since the surfaces may operate in transmission or reflection and the beams may not emerge in what has been called the emergent medium. We therefore use the terms *front material* and *back material* to refer to the two media on either side of each surface. The light is incident in the front material.

The beam is considered to pass from one surface to another without loss. No allowance is made for absorption in the media between surfaces. Thus the distance between surfaces is not specified. Absorption in the coatings is, of course, included.

First of all we need to define the conventions used in laying out the system.

In order to help in this there is a tool that draws a representation of the layout. This tool is activated by the *Draw Layout* item in the Tools menu.

The beam path in vStack is confined to a plane and all angles are defined in that plane. The *s*-direction for polarization-sensitive calculations is considered to be out of the plane towards the user. *p*, *s* and the beam direction are then defined as a right-handed set in that order.

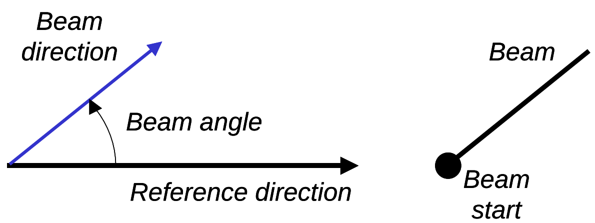


Figure 16-1. The Draw Layout tool uses the symbol on the right to indicate the initial beam direction. The Reference Direction is always horizontal and the beam angle is measured from it using the usual convention for positive and negative angles.

We start with a reference direction. This is the datum for all angular definitions. The reference direction is horizontal and pointing to the right, just like the *x*-axis of a normal coordinate system. All directions are defined in terms of the angle made with that reference. The angle is positive if rotated counter-clockwise. That is, the normal definition for positive angles is used. Figure 16-1 shows the definition of the *Beam Angle* together with, on the right, the representation of the beam used in the layout tool. When the beam angle is zero, the beam is along the reference direction. In the layout, the starting point for the beam is shown as a black dot. The user simply has to define the initial beam angle. All the subsequent beam angles are automatically calculated. To see the calculated angles select *Display Setup* in the File menu and check *Beam Angle Data*.

Surface orientation is defined with respect to the normal to the surface. The side of incidence is called *Front* and the other side, *Back*. The normal to the surface is considered to be drawn with direction into the surface. That is, the direction of the normal is from the incident, or front medium to the back medium. Figure 16-2 illustrates the definition of the *Surface Angle*. The symbol used for the surface in the layout is shown on the right-hand side. The normal is indicated by a line drawn into the surface. This line must be on the front or incident side in the layout, otherwise an error will occur because the light will not be able to reach the surface. The system is defined by the various surface angles. They should not subsequently be changed unless the system is changed.

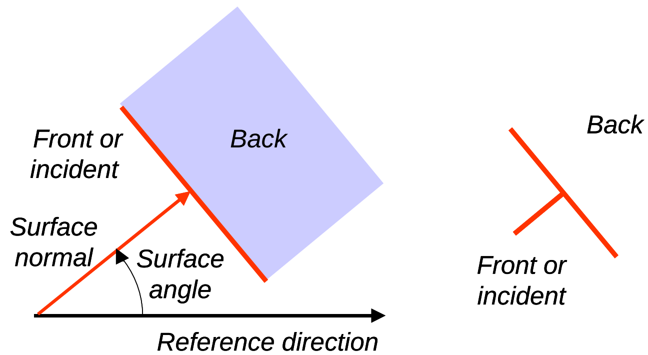


Figure 16-2. The definition of the Surface Angle with respect to the Reference Direction is illustrated on the left and the representation of the surface and its normal in the Draw Layout tool on the right.

The beam angle is then used to define the orientation of the input beam with respect to the system. Angles of incidence at the various surfaces will automatically be computed.

The materials on either side of the surface must be defined by the user. The material on the side of incidence is called the *Front Material*. The material on the back medium side is called the *Back Material*. If the light is reflected it will not actually enter the back material.

Each surface may carry an optical coating. The coating is considered to separate the front material from the back material. The coating is defined in a design document, but the incident medium for the vStack calculation becomes the front material defined in vStack and the substrate for the calculation becomes the back material in vStack. The design document will have its own incident material and substrate and the appropriate order of the defined layers. This layer order is important. If the layer order in the design document corresponds to the new vStack definitions of incident medium and substrate, then the coating will be labeled with the *Coating Direction* attribute *Forward*. However, should the order of layers in the design document correspond to an inversion of the vStack material order then the coating direction attribute should be *Reverse*.

The order of the surfaces in the vStack document must be the order in which the light reaches them. The user is responsible for ensuring that the order in the document is correct. Each surface is considered large enough to intercept the entire beam. The only error that will be detected by the software will be an orientation error so severe that the light is incident on the back medium side. The calculation will take each surface strictly in turn, even though in the actual system such a surface order might be impossible.

An attribute that must be defined for each surface is its *Transfer Mode*. The complete list of possibilities with their definitions is in the following table.

Transmit Reflect	These are the usual surface calculations. Transmit includes refraction and Reflect follows the law of reflection. Any calculations involving irradiances assume that the receiver is larger than the beam so that total beam power is measured.
Perfect Reflect	The surface has 100% reflectance with no influence on polarization except to introduce the usual parity shift. the direction of the reflected beam follows the normal law of reflection.
Rotate 0	This transfer mode has no effect on beam direction or on any other beam attributes. An important use is as a place holder for other Rotate modes avoiding having to delete a row when a rotation is removed.
Rotate 90	Rotates the polarization through 90°. The rotation is positive around the beam direction.
Rotate 180	Rotates the polarization through 180°.
Rotate –90	Rotates the polarization through -90°.
Perfect Retro	This reverses the direction of the beam so that it returns along the input path. It includes a parity change but otherwise has no effect on either power or polarization.

16.2 A Simple System – Right-Angle Prism

We illustrate the process by setting up a system consisting of a right-angled isosceles prism, Figure 16-3. The hypotenuse is uncoated and relies on total internal reflection. The entrance and exit surfaces of the prism have antireflection coatings. The first antireflection coating has air as incident medium and glass as substrate. This will usually be the way in which the coating is defined in the design document and so its attribute will usually be Forward. If the same coating is then used on the exit surface its attribute will need to be Reverse.

There are three surfaces and, therefore, three elements in the vStack document. The surface angles are shown in Figure 16-4.

These are then entered in the vStack document as shown and the antireflection coatings are added to the two surfaces. The second antireflection coating is flagged as Reverse. The Beam Angle is set, initially, as 0°.

The Draw Layout tool output is shown in Figure 16-5 and confirms that the layout in the document is what we require.

A quite useful feature is the display of the orientation angles in the vStack document. To activate this feature use Display Setup… in the File menu and check the Beam Angle Data box. This information is shown in Figure 16-6.

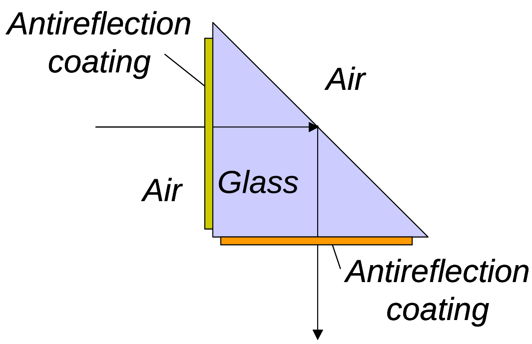


Figure 16-3. A right-angled isosceles prism with antireflection coatings on entrance and exit surfaces and total internal reflection at the hypotenuse.

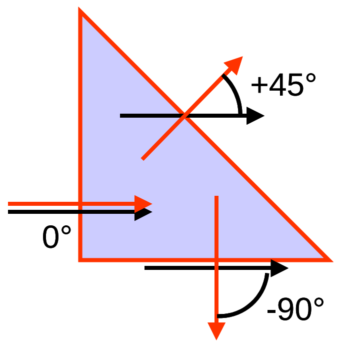


Figure 16-4. The various surface angles for the surfaces that will be entered in vStack.

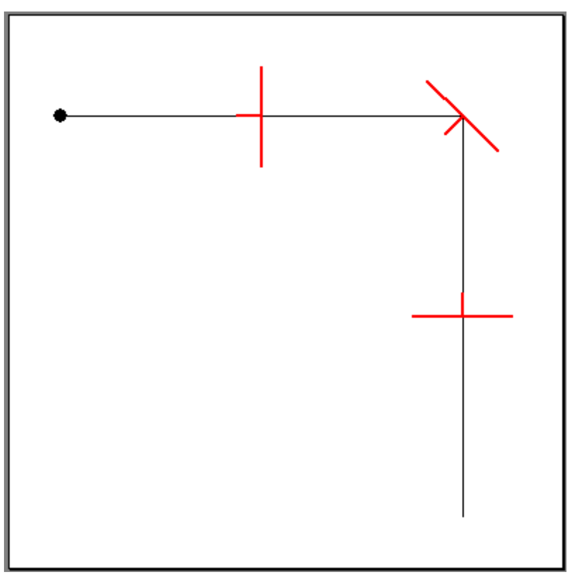
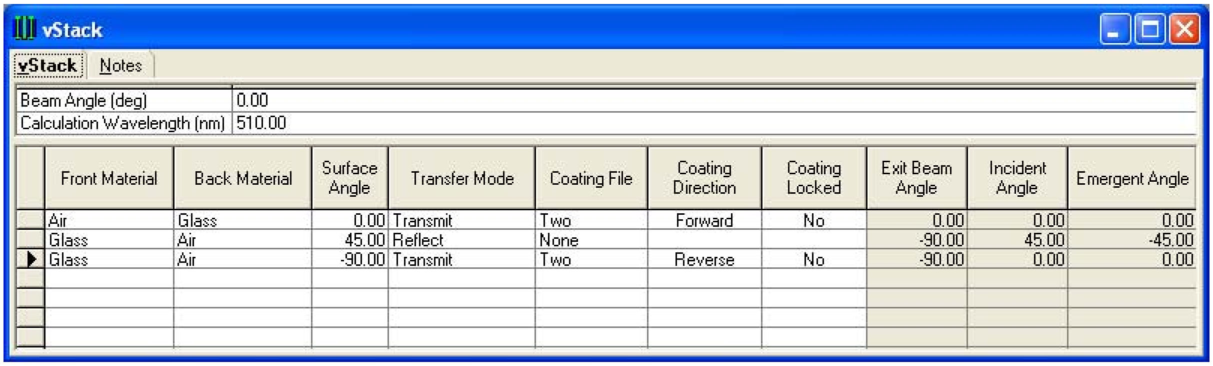


Figure 16-5. The various surfaces as they appear in the output from the Draw Layout tool. The direction of the light is from the black dot that indicates the beam start encountering the various surfaces in the order in which they are given in the vStack document.


vStack

vStack | Notes

Beam Angle (deg)	0.00
Calculation Wavelength (nm)	510.00

Front Material	Back Material	Surface Angle	Transfer Mode	Coating File	Coating Direction	Coating Locked	Exit Beam Angle	Incident Angle	Emergent Angle
Air	Glass	0.00	Transmit	Two	Forward	No	0.00	0.00	0.00
Glass	Air	45.00	Reflect	None			-90.00	45.00	-45.00
Glass	Air	-90.00	Transmit	Two	Reverse	No	-90.00	0.00	0.00

Figure 16-6. The vStack document containing the details of the reflecting prism. The antireflection coating is the three-layer quarter-half-quarter coating from the Tour of the Essential Macleod chapter.

The performance can now be calculated as a function of wavelength, frequency or beam angle. For increasing positive beam angles the total internal reflection condition will fail at a certain point because the incidence on the hypotenuse will no longer be beyond critical, Figure 16-7. This appears as a catastrophic drop in system throughput. The effect of a thick silver coating on the hypotenuse can be readily modeled by replacing the back material Air by Ag. It is not necessary, in this case, to add a coating design file.

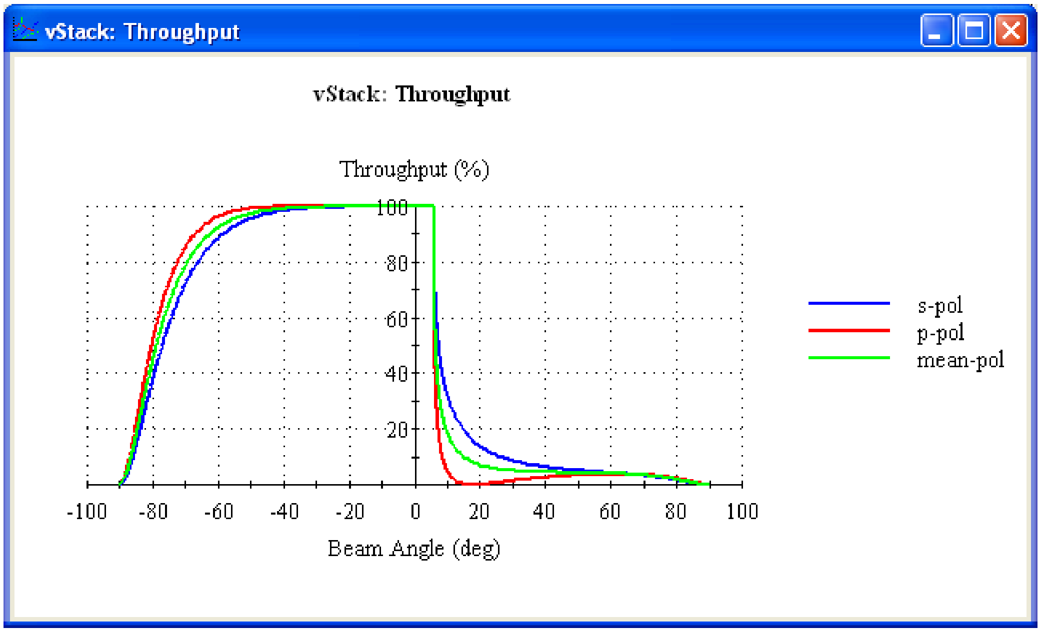


Figure 16-7. The throughput of the vStack as a function of beam angle at 510nm. The prism depends on total internal reflection and as the beam angle increases the incidence on the hypotenuse becomes less than critical and much of the light leaks through.

16.3 A Pentaprism

Now for a more complicated example we consider a pentaprism. This is a device for turning a light beam through 90° by a double reflection and, therefore, no change in parity. There are five surfaces on the prism but only four take part in the optical behavior. The fifth surface is normally left unpolished. Because the angles of incidence on the reflecting surfaces are below critical, they must be coated. this is usually a simple aluminum or silver coating, Figure 16-8

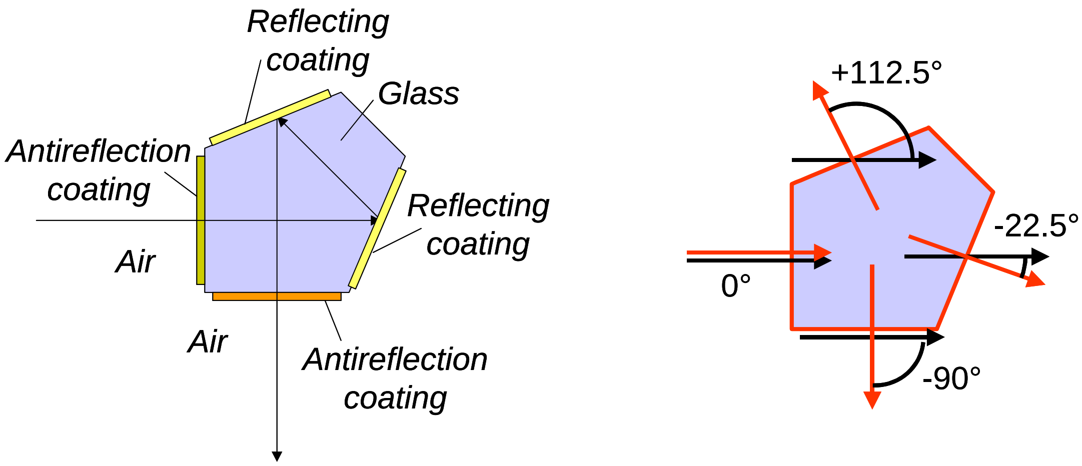
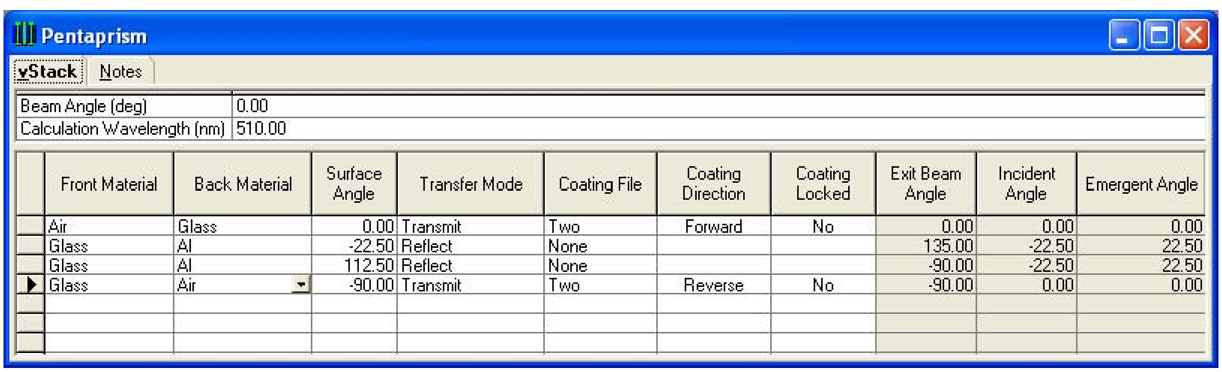


Figure 16-8. The pentaprism. Note the coatings on the reflecting surfaces, necessary because the angle of incidence is below critical. The drawing on the right shows the surface angles.

The calculated surface angles are shown in Figure 16-8. We use those to set up the four-element vStack.

Now we can enter the details into a vStack document,



Pentaprism

vStack | Notes

Beam Angle (deg)	0.00
Calculation Wavelength (nm)	510.00

Front Material	Back Material	Surface Angle	Transfer Mode	Coating File	Coating Direction	Coating Locked	Exit Beam Angle	Incident Angle	Emergent Angle
Air	Glass	0.00	Transmit	Two	Forward	No	0.00	0.00	0.00
Glass	Al	-22.50	Reflect	None			135.00	-22.50	22.50
Glass	Al	112.50	Reflect	None			-90.00	-22.50	22.50
Glass	Air	-90.00	Transmit	Two	Reverse	No	-90.00	0.00	0.00

Figure 16-9. The entries in the vStack document. Again we are using the antireflection coating designed in the Tour of the Essential Macleod chapter.

With a beam angle of 0° the layout, Figure 16-10, confirms that the entered angles are correct.

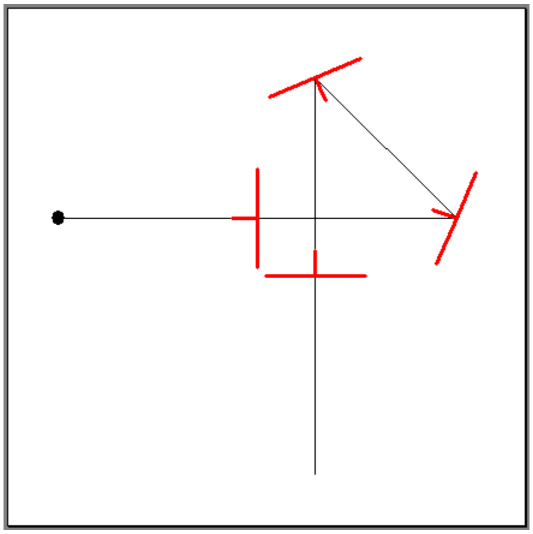


Figure 16-10. The Draw Layout tool confirms that the surface angles entered into vStack are correct.

The calculation of throughput, Figure 16-11, shows the difference between an aluminum and silver coating on the reflecting surfaces. Note the small degree of polarization sensitivity.

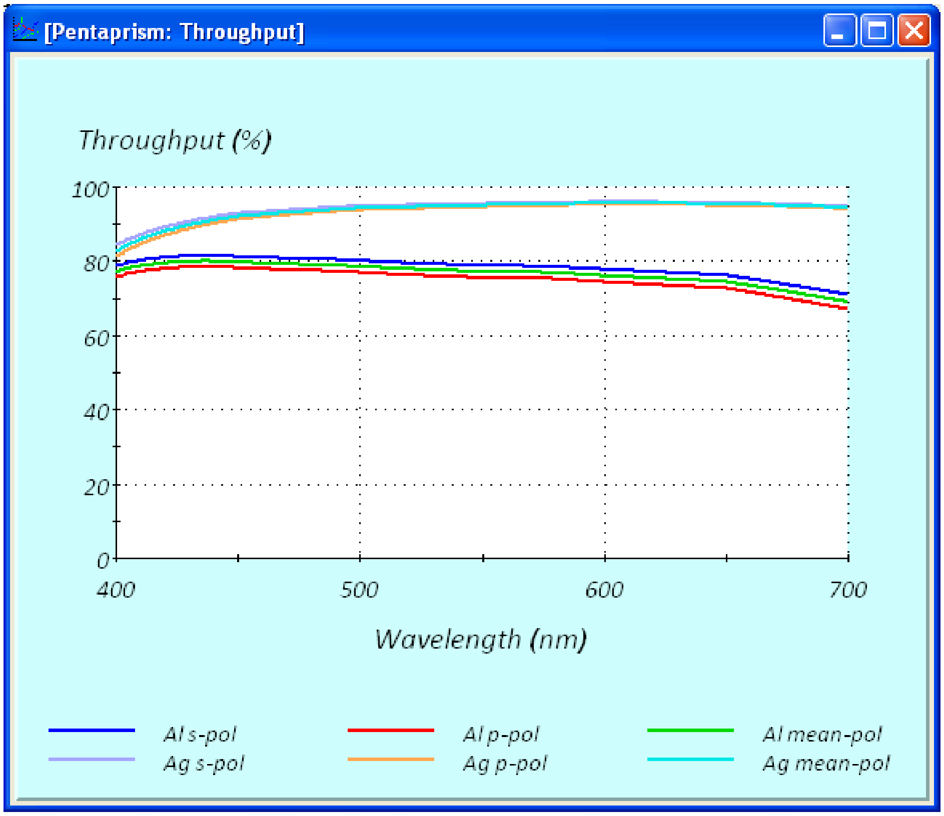


Figure 16-11. The throughput of the pentaprism with reflecting coatings consisting of silver and aluminum. There is some polarization sensitivity. By varying the beam angle we can confirm that the polarization sensitivity increases slightly with beam angle.

It is possible to examine the variation of throughput as a function of beam angle. The beam angle can be varied from -90° to 90° and an output curve will be drawn. However, the pentaprism is subject to quite severe vignetting as shown in Figure 16-12. This shows the unfolded prism and some of the ray paths through it. For a ray that enters the center of the input surface, the maximum allowable angle in the glass is 10.5° translating to around 16° in air.

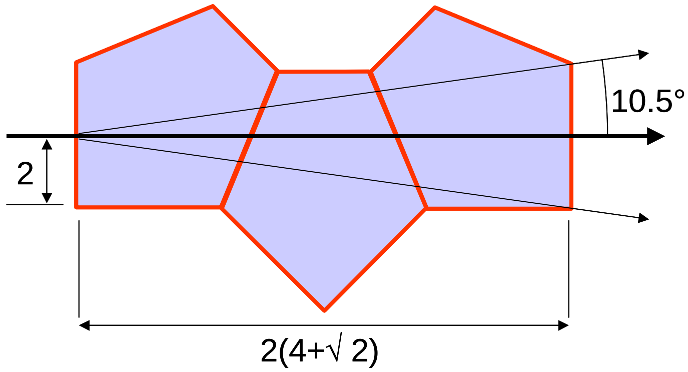


Figure 16-12. Vignetting in the pentaprism. If the beam is incident centrally on the input surface then the maximum semiangle that will be accepted by the system is 10.5°, measured inside the glass. This vignetting is not detected by vStack.

16.4 Dichroic Color-Separation Prism

Finally let us look at a dichroic color separating prism. This will split the visible region into red, green and blue light and we will need some preliminary designs for the coatings. These should be fairly good starting designs that we will refine in vStack. Although synthesis is available in vStack, the volume of calculation involved in any system of reasonable complexity makes the synthesis of coatings from scratch rather slow. If reasonable starting designs are known then it is much more efficient that they should be used.

The arrangement is illustrated in Figure 16-13. The first coating we will make a blue reflector and the second a green reflector. The red channel will be transmitted through both dichroic beam splitters. We shall also design the assembly purely for *s*-polarization. This is rather different from the various systems we have looked at because there are several different paths through the system and all must operate correctly and simultaneously. They are numbered from one to three in Figure 16-13. A vStack document defines a single path and so to describe this new system, we will need three vStack documents. We shall call them Path 1, corresponding to blue, Path 2, corresponding to green and Path 3, corresponding to red.

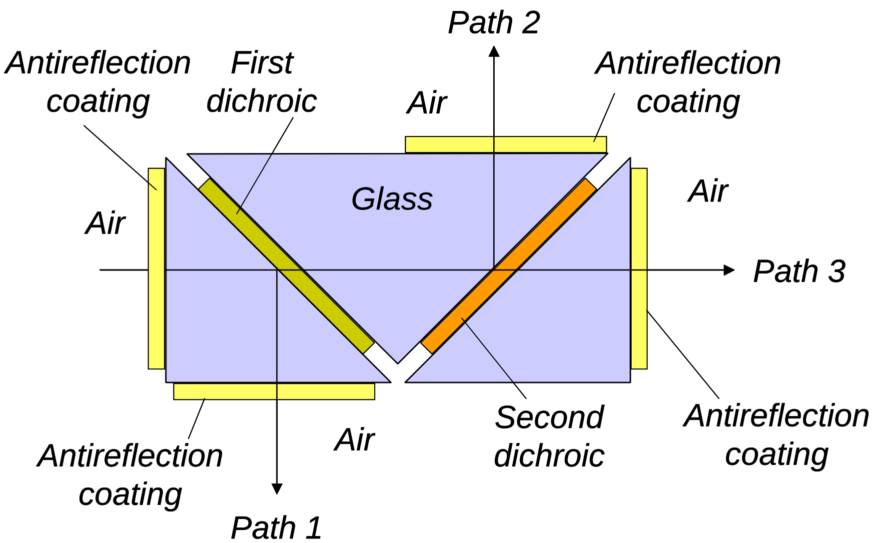


Figure 16-13. A simple dichroic beam splitting prism assembly separating the input into three different wavelength regions.

The surface angles are shown in Figure 16-14.

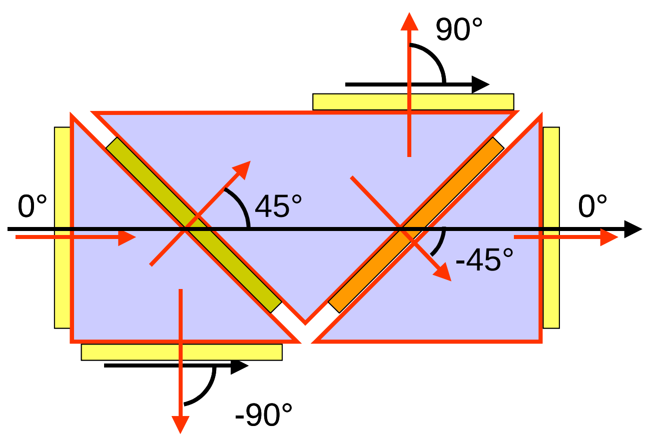


Figure 16-14. The various surface angles in the dichroic beam splitting prism assembly.

Now we need to consider the coatings. The performance of a simple 4-layer antireflection coating for the region 400 to 700nm is shown in Figure 16-15. This uses materials Ta2O5 and SiO2 and is a refined starting design of Air | *L HH* 0.1*L* 0.1*H* | Glass. For the dichroics, we will choose simple quarterwave stacks of 41 layers of Ta2O5 and SiO2: (*HL*)^20 *H*. For the blue-reflecting dichroic we choose a reference wavelength of 510nm and for the green-reflecting, 570nm. the three vStack documents are shown in Figure 16-16.

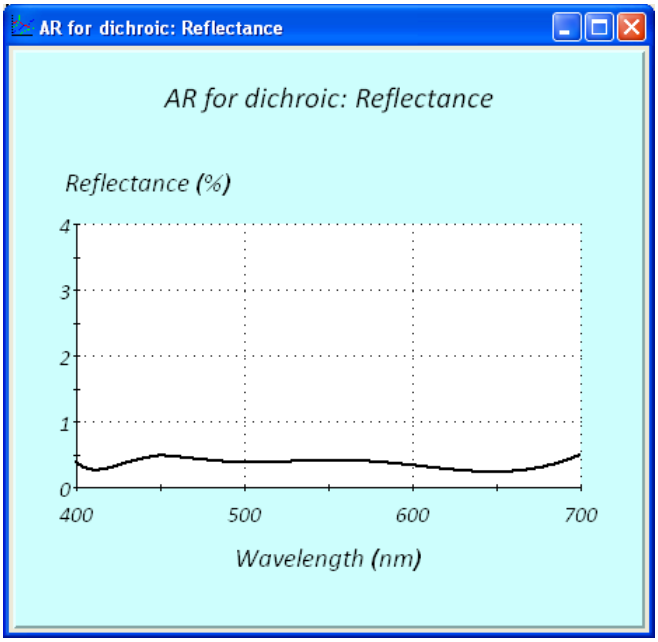


Figure 16-15. The performance of a simple 4-layer antireflection coating for the visible region. This will be used on the input and all output surfaces of the prism assembly.

Each vStack then requires a set of refinement targets. We can define the response regions as 405nm to 495nm for blue, 505nm to 595nm for green and 605nm to 695nm for red. Although for each channel we require a maximum response within the defined band and a minimum response outside it. If all channels exhibit their ideal maximum then the minimum requirements must also be satisfied automatically. Thus in the refinement targets we can simply require 100% throughput over the appropriate range. The appropriate targets then, are:

Path 1	405-495nm step 1nm, Beam angle 0° 100% Throughput, Weight 1, *s*-polarization
Path 2	505-595nm step 1nm, Beam angle 0° 100% Throughput, Weight 1, *s*-polarization
Path 3	605-695nm step 1nm, Beam angle 0° 100% Throughput, Weight 1, *s*-polarization

Note that even though the angle of incidence on the dichroics is 45° the setting of Beam Angle is zero and the polarization is set as *s*-polarization.

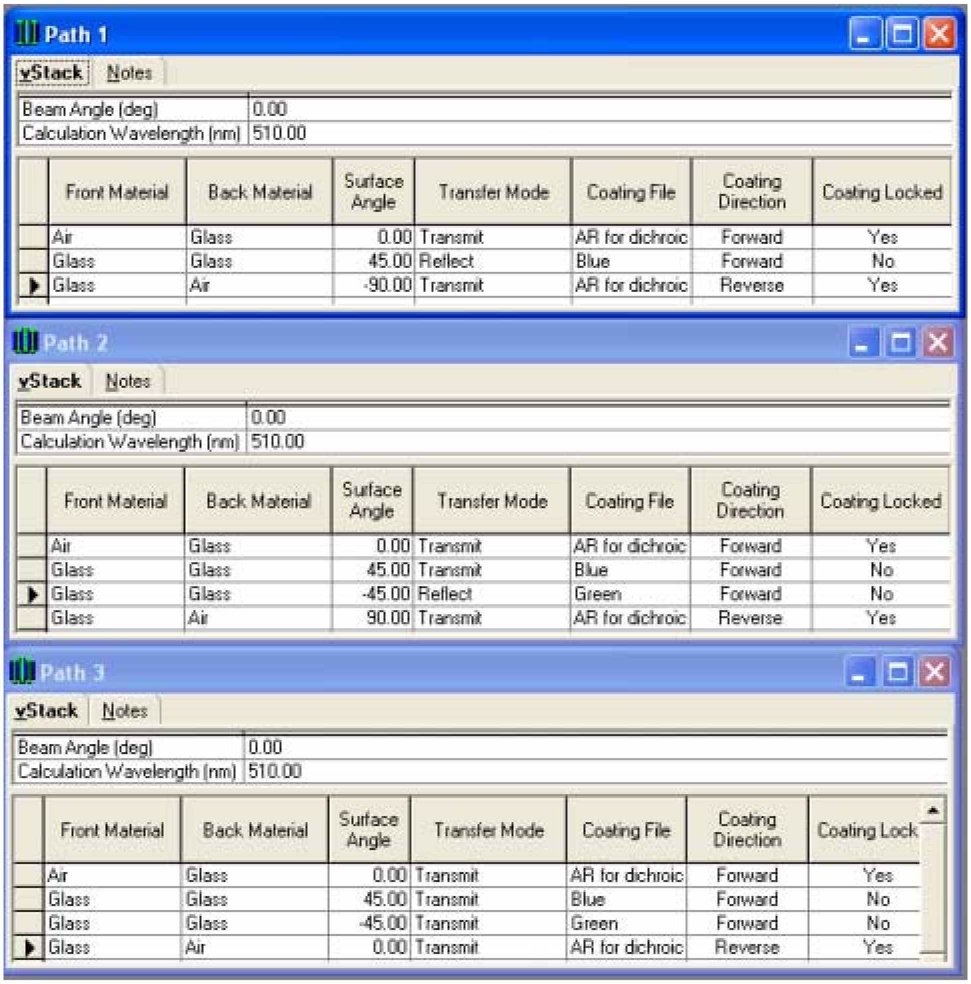


Figure 16-16. The three vStacks, Path 1, Path 2 and Path 3.

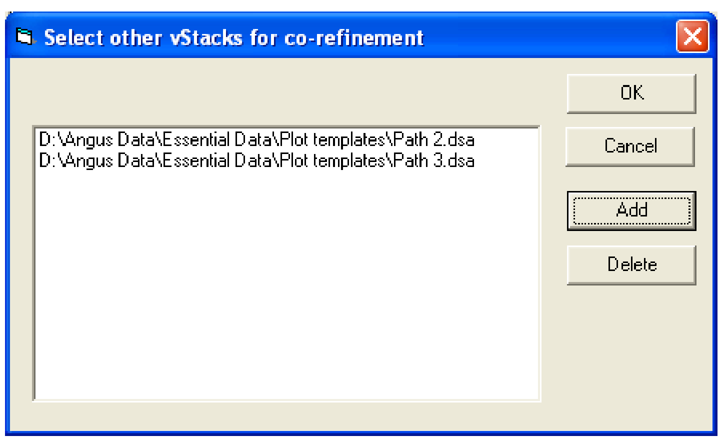


Figure 16-17. The Co-refinement dialog where the vStacks to be co-refined with the current one are defined.

These targets must be simultaneously satisfied and this involves all the coatings. To accommodate this type of condition, vStack has the ability of *Co-refinement*. Co-refinement is a technique that permits a number (any number) of vStacks to be simultaneously refined along with a principal one. The targets for the co-refinement process is the sum of all the individual targets. To activate co-refinement the vStacks to be co-refined are identified in the co-refinement dialog, Figure 16-17. This is opened in the Refinement Parameters submenu by choosing the Co-refinement item. The principal vStack is simply the one that will be used to launch the refinement. All progress plots will be of the principal performance, but the figure of merit that is reported and involved in the refinement will be calculated using all targets.

The starting performances of the various paths are shown together in Figure 16-18.

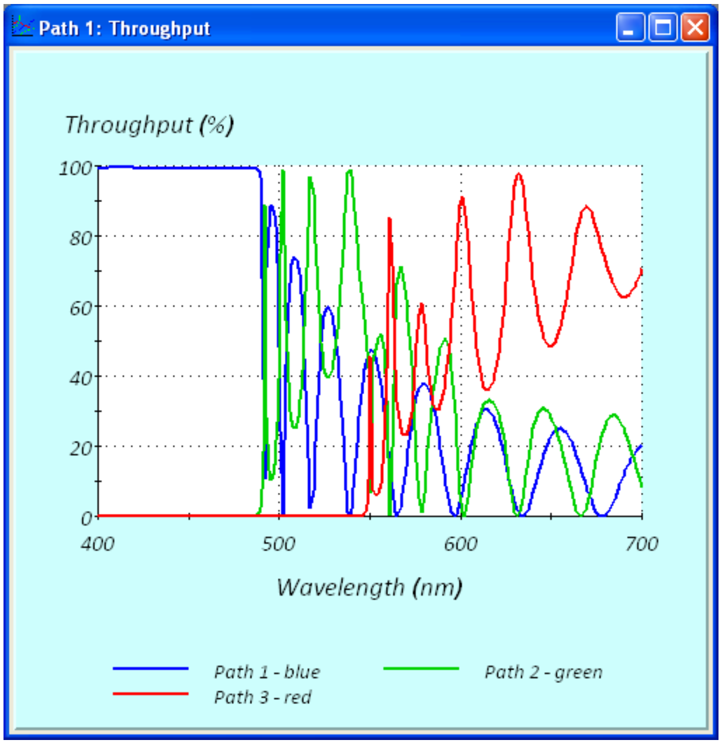


Figure 16-18. The unrefined performance of the three paths through the prism assembly. The large ripple complicates the figure enormously and makes it difficult to interpret.

In this particular case, where we have good starting designs, Simplex is the most efficient technique. The parameters we use are in Figure 16-19.

Refinement yields the performance shown in Figure 16-20.

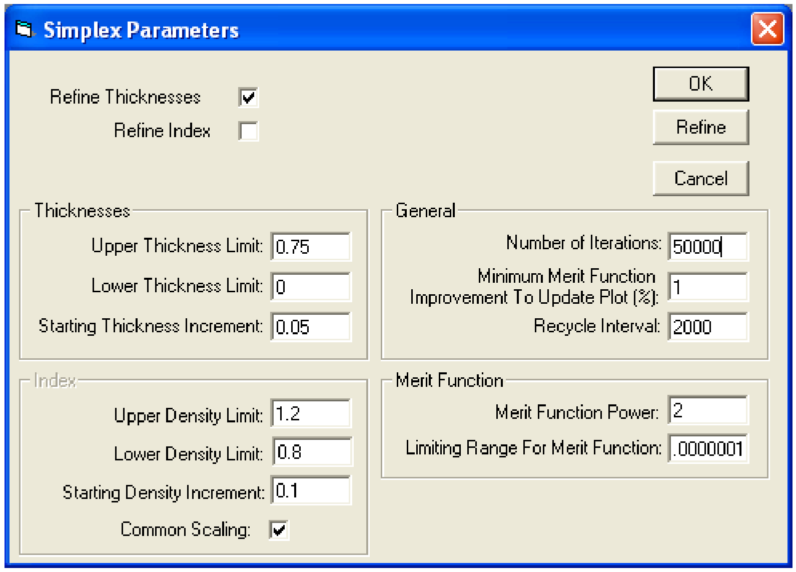


Figure 16-19. The parameters used in Simplex.

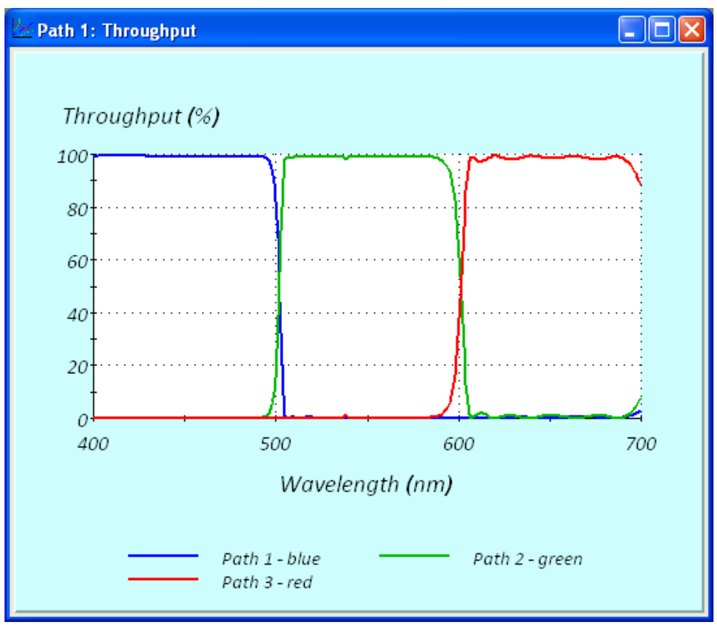


Figure 16-20. The final performance of the three channels after refinement.

16.5 Polarization Leakage

In many dichroic splitters and combiners, polarization preservation is important. The transport of energy demands apertures greater than zero, implying a collection of angles of incidence that can conveniently be thought of as a bundle of rays forming a cone around the direction of the principal ray. The polarization of the cone will be defined as either *p*-polarization or *s*-polarization with respect to the principal ray. But the *p*- and *s*-performance of the coating is tied to the local plane of incidence, and so those rays that are skewed with respect to the principal plane of incidence will exhibit what is termed *polarization leakage*. Some of the *s*-polarized light in the cone will leak into the *p*-direction and vice versa. For small skew angles, the leakage will be proportional to the square of the skew angle. Polarization leakage is therefore calculated in units of ppm/(degree)^2. Polarization leakage is particularly important in systems involving liquid crystal light valves that operate by altering the polarization state of the light. Image projectors are an important class of such instruments. There is nothing that can be done to alter the polarization leakage in a single tilted element. However, in some systems containing multiple elements, it is possible to arrange the design to reduce the extent of polarization leakage and so polarization leakage is a refinable parameter. Essentially the refinement process is actually altering the relative retardation through the system. This is normally neglected in a system where simple throughput is the design parameter.

To convert the polarization leakage coefficient into total leakage in a cone of semiangle Φ (degree) we use the expression:

$$\textit{Total leakage} = \frac{\gamma}{4}\Phi^2 \qquad (16.1)$$

where γ is the leakage coefficient. The result will be in parts per million and should be multiplies by 10000 to convert to per cent. In most cases this expression will be sufficiently accurate up to cone semi-angles of ten degree or so.

16.6 Wavefront Errors - Phase

To facilitate the calculation of wavefront errors, *Phase*, is included in the list of calculable parameters. This is the cumulative change in phase of the ray that can be attributed solely to the coatings. It does not include any phase change due to the traversal of the space between successive coatings. The change in phase can be associated with such as changes in beam angle or uniformity errors. A regular change in phase with angle indicates a tilted wavefront. One full wavelength is indicated by 360°. Such errors would be important only in very highly corrected systems. Errors in uniformity are more important. In order to assess the problems of uniformity errors we need two coating designs, one represents the perturbed coating and the other the ideal reference. Provided the order of layers in the design files are such that the substrate is the true coating substrate on which it is deposited, then the thinner of the two coatings should have sufficient front material added to its medium side to make the total physical thicknesses of the two coatings identical. Of course, if the coatings are used in the reverse mode, then back material should be added. This is to ensure that the path between the coatings in the system is identical in both cases. Comparison of the phases calculated with reference coating and with perturbed coating will yield an estimate of the wavefront error. Again, 360° represents one wavelength. Phase is wrapped to a principal range that is automatically -180° to +180° but can be manually altered.

16.7 Other Parameters

Other parameters that can be calculated include the dispersive terms, Group Delay, Group Delay Dispersion etc, the ellipsometric parameters psi and delta, and the exit beam angle