LIDAR SHORT COURSE  
NSF CEDAR MEETING  
BOULDER CO  
17-21 JUNE 1991

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CHAPTER 1
INTRODUCTION TO LIDAR

CHAPTER 2
OPTICAL SCATTERING

CHAPTER 3
ATMOSPHERE AND BACKGROUND RADIATION

CHAPTER 4
LASER TRANSMITTER

CHAPTER 5
TELESCOPE RECEIVER

CHAPTER 6
DETECTORS

CHAPTER 7
DATA SYSTEM

CHAPTER 8
SAFETY SYSTEM

CHAPTER 9
EXPERIMENT TECHNIQUE

CHAPTER 10
DATA FILTERS

CHAPTER 11
LIDAR SYSTEM PERFORMANCE

CHAPTER 12
LIDAR MEASUREMENTS

CHAPTER 13
REFERENCES
THE MEASUREMENT OF STRATOSPHERIC DENSITY DISTRIBUTION WITH THE SEARCHLIGHT TECHNIQUE

L. ELTERMAN

December 1951

Fig. 1. Receiver with photomultiplier at focus of mirror (impedance matching amplifier and input monitoring seen not included in instrumentation shown).

Fig. 1. Searchlight geometry.

The first rubin-laser configuration.

Rubin-laser energy levels.
ENERGY MONITOR

LOW ATM. TELESCOPE

TELESCOPE

DETECTOR BOX

BEAM EXPANDER

LASER (Nd-YAG)

ENERGY MONITOR

Above is a photograph of the Penn State Laser Atmospheric Measurement Program (LAMP). See Figure 8 for diagram labeling.
MAXWELL'S EQUATIONS

\[ \nabla \cdot E = \frac{q}{\varepsilon} \]  
\[ \nabla \cdot H = 0 \]  
\[ \nabla \times E = -\mu \frac{\partial H}{\partial t} \]  
\[ \nabla \times H = \varepsilon \frac{\partial E}{\partial t} + j \]

2.2. WAVE EQUATION AND PLANE-WAVE SOLUTIONS

\[ \nabla \times \nabla \times E = -\mu \frac{\partial (\nabla \times H)}{\partial t} \]  
\[ \nabla \times \nabla \times E = \nabla (\nabla \cdot E) - \nabla^2 E \]  
\[ \nabla^2 E = \mu \varepsilon \frac{\partial^2 E}{\partial t^2} \]  
\[ \nu \equiv (\varepsilon \mu)^{-1/2} \]  
\[ c = (\varepsilon_0 \mu_0)^{-1/2} = 2.9979 \times 10^8 \text{ m s}^{-1} \]
\[ r_\perp = \left( \frac{E_{r0}}{E_{i0}} \right)_\perp = -\frac{\sin(\theta_i - \theta_r)}{\sin(\theta_i + \theta_r)} \]  \hspace{1cm} (2.61)

\[ t_\perp = \left( \frac{E_{r0}}{E_{i0}} \right)_\perp = +\frac{2\sin \theta_r \cos \theta_i}{\sin(\theta_i + \theta_r)} \]  \hspace{1cm} (2.62)

\[ r_\parallel = \left( \frac{E_{r0}}{E_{i0}} \right)_\parallel = +\frac{\tan(\theta_i - \theta_r)}{\tan(\theta_i + \theta_r)} \]  \hspace{1cm} (2.63)

\[ t_\parallel = \left( \frac{E_{r0}}{E_{i0}} \right)_\parallel = +\frac{2\sin \theta_r \cos \theta_i}{\sin(\theta_i + \theta_r)\cos(\theta_i - \theta_r)} \]  \hspace{1cm} (2.64)

\[ R_\perp = r_\perp^2, \quad R_\parallel = r_\parallel^2 \]  \hspace{1cm} (2.65)

\[ T_\perp = \left( \frac{\tan \theta_i}{\tan \theta_r} \right) t_\perp^2 \quad \text{and} \quad T_\parallel = \left( \frac{\tan \theta_i}{\tan \theta_r} \right) t_\parallel^2 \]  \hspace{1cm} (2.66)

\[ R_\parallel + T_\parallel = 1 \quad \text{and} \quad R_\perp + T_\perp = 1 \]  \hspace{1cm} (2.67)

Fig. 2.9. Reflectance and transmittance versus incident angle for two perpendicular planes of polarization (Hecht and Zajac, 1974).
FRESNEL EQUATIONS

\[ n_1 = 1 \]
\[ n_2 = 1.5 \]

<table>
<thead>
<tr>
<th>( \theta_1 )</th>
<th>( n_2 )</th>
<th>( r_s )</th>
<th>( r_P )</th>
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<table>
<thead>
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<th>( \theta_2 )</th>
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<th>( R_P )</th>
<th>( T_s )</th>
<th>( T_P )</th>
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<td>0.700</td>
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<tr>
<td>90.000</td>
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<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

FRESNEL COEFFICIENTS

Graph showing \( r_s \), \( r_P \), \( t_s \), \( t_P \) as functions of \( \theta \).
INTERFERENCE FILTERS: REFLECTANCE

REFLECTION AT AN INTERFACE

When light strikes a smooth interface between two transparent media as in Fig. 1, some of the light enters the second medium and is refracted, and some is reflected at the interface. The relationship between the angle of incidence, \( i \), and the angle of refraction is given by Snell's Law:
\[
\text{Refraction at an Interface}
\]
\[
n_1 \sin i = n_2 \sin r
\]

Where:
- \( n_1 \) and \( n_2 \) are the indices of refraction of the media as shown.

Electromagnetic theory provides expressions for the fraction of incident radiation reflected. The reflectance depends on the indices of refraction, the angle of incidence and the polarization of the radiation.

\[
R = \frac{\tan^2 (i - r)}{\tan^2 (i + r)}
\]

\[
R = \frac{\sin^2 (i - r)}{\sin^2 (i + r)}
\]

Where:
- \( R_L \) = Reflectance for light polarized parallel to the plane of incidence.
- \( R_T \) = Reflectance for light polarized perpendicular to the plane of incidence.

For a glass slide the transmittance from two surfaces is \((1 - 0.4)(1 - 0.04) = 0.9216 = 0.92\). Since Fresnel derived equations similar to (4) using his elastic theory of light, the reflection at the interface is sometimes called F-radiation or Fresnel reflection.

The reflected wave also undergoes a phase change of \(180^\circ\) at the interface if \( n_2 > n_1 \). This is important in thin film design as discussed later.

Fig. 2 shows the variation of reflectance with angle \( i \) for an air-fused silica interface. The reflectance at normal incidence \((i = 0)\) is given by these equations and Snell's Law:
\[
R = R_L = R_T = \left[ \frac{(n_1 - n_2)}{(n_1 + n_2)} \right]^2
\]

From (4) you can see that the Fresnel loss becomes high for high index difference, \( n_2 - n_1 \). For a single air-xylene interface \((n_2 = 2.4)\), \( R = 0.17\).

Interface losses from sequential flat surfaces can be reduced by index matching. Water and many other liquids have refractive indices of about 1.3. If you fill the space between two plane glass surfaces with water, you reduce the total Fresnel loss from the two surfaces from 0.08 to 0.01. Index matching fluids are used in some assemblies, but interface loss reduction using thin film optical coatings is usually more practical.
FILTER THIN FILMS AND COATINGS

THIN FILMS AND INTERFERENCE

Fig. 3 shows monochromatic light incident on a surface coated with a thin film of index of refraction \( n_f \) and physical thickness \( t \). Light is reflected from each surface. The interference effect depends on the wavelength of the light. The film is not exactly a quarter wave thick for any wavelength except the design wavelength. The film is said to be a quarter wave thick and acts as an anti-reflection coating. The reflectance is increased, and the thin film makes the surface a partial reflector.

The reflectance of the coated interface depends on wavelength since the interference effect depends on the wavelength. The film is not exactly a quarter wave thick for any wavelength except the design wavelength. The film is said to be a quarter wave thick and acts as an anti-reflection coating. The reflectance is increased, and the thin film makes the surface a partial reflector.

Example

If light traveling through air \((n = 1)\) at 550 nm strikes a glass substrate \((n = 1.52)\) at normal incidence, then 4% is reflected. If we deposit a layer of magnesium fluoride \((n = 1.38)\) and the layer optical thickness is 1/4 wave at 550 nm, the reflectance drops to 1.3%.

When we use the simple Fresnel calculation, we find that the total loss is the sum of the Fresnel losses. The light reflected from the combined surfaces can interfere with each other. The intensity of this interference is described by the Fresnel equations. Both of these surfaces are simple interference filters: their reflectance, and therefore transmittance, is determined by the thickness of the thin film.

We describe optical coatings in more detail and list reflective and anti-reflective coatings on pages 10-2 to 10-9.

FILTER CAVITIES AND TYPES

WAVELENGTH DEPENDENCE

The reflectance of the coated interface depends on wavelength since the interference effect depends on the wavelength. The film is not exactly a quarter wave thick for any wavelength except the design wavelength. The film is said to be a quarter wave thick and acts as an anti-reflection coating. The reflectance is increased, and the thin film makes the surface a partial reflector.

Example

If light traveling through air \((n = 1)\) at 550 nm strikes a glass surface \((n = 1.52)\) at normal incidence, then 4% is reflected. If we deposit a layer of magnesium fluoride \((n = 1.38)\) and the layer optical thickness is 1/4 wave at 550 nm, the reflectance drops to 1.3%. If the light is reflected from the second surface, there is complete destructive interference. The light reflected from the second interface is completely out of phase with the light reflected from the first. The reflectance changes between 0% and 100% if the phase change mentioned on the previous page occurs. The two reflected beams interfere destructively to reduce the total reflectance. The result is that the bandwidth is approximately a logarithmic function of the number of layers in the reflector stacks. The reflectance in turn depends on the number of layers in the stack. Most filters are for isolation of a single pass band, and the unwanted pass bands must be blocked. Absorptance by the materials of the cavity and partially reflecting mirrors often blocks short wavelengths. Absorbing filter glasses may also be used for effective blocking.

Types of Filters

Multi-cavity Filters

In a Fabry-Perot of given spacing, the bandwidth decreases with increasing reflectance of the reflecting stacks. The reflectance in turn depends on the number of layers in the stack. The result is that the bandwidth is approximately a logarithmic function of the number of layers in the reflector stacks. Using several Fabry-Perot cavities (i.e. reflector spacer-reflector) in a single filter adds versatility in bandshaping and allows better control of transmittance at the wavelength of interest with improved rejection of other wavelengths. This type of filter is known as a multi-cavity filter. In a Fabry-Perot of given spacing, the bandwidth decreases with increasing reflectance of the reflecting stacks. The reflectance in turn depends on the number of layers in the stack. The result is that the bandwidth is approximately a logarithmic function of the number of layers in the reflector stacks.

Fig. 6 shows the construction of a multi-cavity filter. A typical 3 layer 10 nm bandwidth filter in the mid-visible has approximately 50 individual thin film layers. Multi-cavity filters have characteristic square tops with steeper sides than the simple Fabry-Perot. Multi-cavity filters still require additional blocking to suppress unwanted harmonics.
FILTER TYPES AND CHARACTERISTICS

Induced Transmission Filters
Induced transmission filters use dielectric layers on each side of the metal layers. The metal layer transmittance at the filter wavelength is increased dramatically by the dielectric layers. These filters, which have excellent blocking of long wavelengths, are particularly useful in the ultraviolet. These filters are sometimes bonded to sharp cut-on colored glass (to absorb the shorter wavelength harmonics), and used as completely blocking broadband filters.

The actual transmission can be up to 10% higher than the values indicated because cementing of the constituent filters with a match-curing cement eliminates the reflection losses from some surfaces.

In a finished filter, consisting of all dielectric filters, an induced transmission filter and a colored glass filter, it is the all dielectric filter which controls the band shape and central wavelength.

FILTER CHARACTERISTICS
Band Shape
As the number of cavities in the all dielectric filter increases, the shape of the band improves, i.e. the transition from maximum transmission to rejection becomes sharper.

Fig. 7 shows the shape of the pass band as a function of the number of cavities.

The Finished Filter
A finished filter should have:
• an accurate central wavelength
• good peak transmission
• good band shape
• good rejection on both sides of the pass band

For these, it is necessary to add additional filter devices to an all dielectric filter. The simplest is a colored glass filter.

Sometimes, an induced transmission filter is also appropriate.

The result is a combination of an all dielectric filter and dielectric/metal filters, and the induced transmission/cut-on colored glass filter. In a finished filter, the transmission is the product of the transmissions of each constituent filter component. Table 1 indicates the transmission at the central wavelength and at two wavelengths outside the pass band.

INDUCED TRANSMISSION FILTERS

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Dielectric Filter</th>
<th>Induced Filter</th>
<th>Colored Glass</th>
<th>Finished Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>0.05</td>
<td>0.20</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
<tr>
<td>550</td>
<td>0.90</td>
<td>0.70</td>
<td>0.92</td>
<td>0.64</td>
</tr>
<tr>
<td>750</td>
<td>0.91</td>
<td>0.91</td>
<td>0.92</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Environmental Factors
Temperature
All Oriel Band Pass Interference Filters are designed to operate from -50°C to +120°C. They may be operated intermittently to 150°C. The rate of temperature change should not exceed 10°C/minute. Above 120°C, all permanent changes and possible destruction can occur.

Apart from irreversible changes at high temperatures, the most noticeable temperature effect is the variation of central wavelength. At increased temperature the central wavelength increases. The temperature change is almost linear between 60°C and 120°C with values between 0.01 and 0.03 nm°C. Above 120°C the change in central wavelength becomes negligible. There are also small changes in bandwidth (about 0.001 nm°C) and peak transmittance (about 0.014%/°C) with increasing temperature.

Humidity
All Oriel ultraviolet, visible and infrared Band Pass Interference Filters are edge sealed as a barrier to environmental moisture. We test our filters to MIL-STD-810C method 507.4 procedure 1. This test consists of placing the filter in an environmental test chamber and cycling the temperature and humidity over a 24 hour period. Each 24 hour period is termed a cycle, and the number of cycles tested is specified for each filter type. After the completion of the test, the filter is inspected for spectral performance and physical damage.

Other Oriel multi-layer filter products such as long and short wavelength dielectric/metal filters, and colored glass filters, are affected by ambient humidity and are left exposed to the atmosphere. These coatings also meet the requirements of MIL-STD-810C method 507, procedure 1.

Filter Orientation
Most band pass interference filters are constructed using some type of auxiliary absorption blocking filters. Each side of the filter has a distinctly different appearance. One side will be highly mirrored while the other side will be colored (opaque or completely absorbent). Always orient the band pass filter so the highly mirrored side is facing the source of radiation. Most of the rejected radiation is reflected and does not heat the internal components of the filter.

Angle of Incidence
Filter specifications are usually given for collimated radiation normal to the filter surface. In many applications, collimation of radiation is not practical or even possible. You can, however, estimate the results of using off-normal incident radiation.

Induced transmission filters are composed of a series of layers of precisely controlled thicknesses of dielectrics and metals. Changing the angle of incidence increases the apparent thickness of these layers. However, the phase difference between the interfering waves decreases as angle increases. The effects of off-normal radiation are three fold. There is a decrease in the central wavelength; the transmittance decreases and the bandwidth increases. For off-normal angles less than 25°, the effect on transmittance and bandwidth are minimal. The shift in central wavelength with angle of incidence can be used to precisely tune a narrow band filter.

The decrease in central wavelength is a function of the angle of incidence. The actual transmission can be up to 10% higher than the values indicated because cementing of the constituent filters with a match-curing cement eliminates the reflection losses from some surfaces.

In a finished filter, consisting of all dielectric filters, an induced transmission filter and a colored glass filter, it is the all dielectric filter which controls the band shape and central wavelength.

Table 1: Transmittance of a Finished Interference Filter Designed for 550 nm

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Dielectric Filter</th>
<th>Induced Filter</th>
<th>Colored Glass</th>
<th>Finished Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>0.05</td>
<td>0.20</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
<tr>
<td>550</td>
<td>0.90</td>
<td>0.70</td>
<td>0.92</td>
<td>0.64</td>
</tr>
<tr>
<td>750</td>
<td>0.91</td>
<td>0.91</td>
<td>0.92</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Where:

\[ \lambda = \frac{1}{\sin(\theta)} \]

**Fig. 8: Transmittance of a Finished Interference Filter.**

Induced transmission filters used in interference filters must be accurate in central wavelength, have good peak transmission, good band shape, and good rejection on both sides of the pass band.
INTERFERENCE FILTERS: BLOCKING

FILTER CHARACTERISTICS

For typical visible and near infrared band pass interference filters (400 - 1100 nm) the experimental values of index spacer layers have been found to be 2.0 for high index spacer layers, and 1.45 for low index spacer layers.

When the angle of incidence is large, > 30°, the spectral pass band characteristics of the filter can be so degraded as to yield two distinct peaks and transmittance becomes dependent on polarization.

Table 3 lists multiplying factors for off-normal collimated incidence radiation. To find the new central wavelength at an off-normal angle, simply multiply the wavelength at normal incidence by the appropriate factor for that angle.

Table 3: Multiplying Factors for Off-normal Collimated Light

<table>
<thead>
<tr>
<th>Angle (degrees)</th>
<th>High Index Spacer Layer (n = 2)</th>
<th>Low Index Spacer Layer (n = 1.45)</th>
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<td>0.25</td>
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<td>1.0</td>
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<td>20.0</td>
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</tr>
<tr>
<td>25.0</td>
<td>0.966</td>
<td>0.958</td>
</tr>
<tr>
<td>30.0</td>
<td>0.957</td>
<td>0.938</td>
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</table>

Divergent or Convergent Incident Radiation

A diverging or converging beam incident on a filter means a spread of incident angles. The result is a broadening of the apparent band pass and a shift to lower wavelengths. Since the transmittance is angle dependent, the beam which passes the filter will have a slight angular wavelength dependence.

The change in center wavelength can be obtained by using the half cone angle in equation (6).

\[ \lambda = \lambda_0 \left(1 - \frac{n_0}{n^*} \cos \theta \right)^{0.5} \]

Where:

\[ \lambda_0 \] = Central wavelength at angle of incidence

\[ \lambda_0^* \] = Central wavelength at normal incidence (\( \theta = 0 \))

n_0 = Refractive index of the medium surrounding the filter

n^* = Effective refractive index for the filter

For solid cone angles to 20°, the change in wavelength can be about half that calculated. Band pass interference filters with bandwidths of less than 3 nm have negligible center wavelength changes with convergent or divergent beams with up to 5° full cone angle (F/11).

FILTERS AND MONOCHROMATORS

A Monochromator or an Interference Filter?

For maximum throughput efficiency with a monochromator, the F/8 of the input optics must match that of the monochromator. This puts a fundamental limit on the demagnification of a source to try to get as much light as possible through the slit. An interference filter, on the other hand, has a large acceptance aperture and can have transmission in the range of 50 - 60%. With extended (large) sources an interference filter can have up to 500 times greater throughput than a monochromator.

See our Volume 8 for an in-depth discussion.

A Monochromator Used With an Interference Filter

Interference filters are effective in reducing stray light accompanying the output from a fixed wavelength grating monochromator. If a high intensity continuous source is used, the filter should be placed between the exit slit and the detector to reduce the thermal load on the filter.

Fig. 10 530 nm central wavelength filter at normal incidence and at 20°.

INTERFERENCE FILTER TRANSMISSION/REJECTION

With an interference filter it is very common to think of the ratio of peak transmission to blocking as a system signal to noise ratio. This assumption can lead to very serious errors. In order to obtain a true system signal to noise ratio the spectral power distribution of the source and response of the detector must be considered as well as the peak transmission, bandwidth, and blocking of the interference filter.

For example, consider the use of an interference filter with a central wavelength of 400 nm. a bandwidth of 10 nm, a peak transmittance of 60%, and blocking of 99.9% from X-ray to infrared in a system which has a tungsten light source and a silicon photodetector. With a typical tungsten light source the intensity in the 1000 nm region can be up to 100 times that at 400 nm. Additionally, the silicon photodetector can have 3 - 5 times as much response in the 800 - 1000 nm region as at 400 nm. For this reason the interference filter, light source and detector described above were to be used in a 400 nm absorbance photometer, the result would probably be misleading.

To obtain a good indication of the real signal to noise ratio in such a system, make a signal measurement with the 400 nm interference filter, light source, and detector in place. Then place a sharp cut-on colored glass filter (such as Oriel Model 51484) in series with the interference filter and take a measurement. The colored glass filter will absorb the signal at 400 nm leaving most of the "noise" component.

A simple way to improve a system signal to noise ratio is to use two filters in series. The second filter could be a colored glass to eliminate most of the visible and near infrared, or the same type of interference filter.

A near worst case measurement with S3810 Filters (10 nm bandwidth at 420 nm), a tungsten halogen source (3200K) and a silicon photodetector gave the results below. A 470 nm long pass filter was used to block all the light coming through the filter bandwidth to record the leakage signal.

<table>
<thead>
<tr>
<th>Relative Signals</th>
<th>Single Filter</th>
<th>Two Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 - 1100 nm</td>
<td>100</td>
<td>47.5</td>
</tr>
<tr>
<td>Leakage Signal</td>
<td>3 x 10^-1</td>
<td>8 x 10^-1</td>
</tr>
</tbody>
</table>

* Most of this signal is in the 400 - 440 nm transmitting region of the filter.
ULTRAVIOLET INTERFERENCE FILTERS

***SPECIFICATIONS***

- **Sire tolerance:**
  - Thickness: ± 0.1 mm
  - Surface quality: 95 mm, max.
  - Useful aperture: ± 50 μm
  - Center wavelength tolerance: ± 0.5 mm
  - Bandwidth: ± 3 mm
  - Bandwidth tolerance: ± 5 mm
- **Band shape:** 
  - Band shape % of center wavelength
  - Center wavelength:
    - 390 nm: 0.01%
  - Band blocking factor (min.):
    - 400 nm to 700 nm: 0.01%
    - 780 nm to 900 nm: 0.01%

**ORDERING INFORMATION**

- **Center:**
  - Wavelength (nm):
    - 200 - 240 nm
    - 250 - 290 nm
    - 290 - 340 nm
    - 150 - 190 nm
    - 190 - 230 nm
- **Orders:**
  - (8) No. (*): 53970
  - (5) No. ($): 53900
  - Each filter set includes a hard shell protective case.
  - 18 filters listed above.

**FILTER SETS**

- **WAVELENGTH (nm):**
  - 250 - 350 nm
  - 350 - 450 nm
  - 450 - 550 nm
  - 550 - 650 nm
  - 650 - 750 nm
  - 750 - 850 nm
  - 850 - 950 nm
  - 950 - 1050 nm
  - 1050 - 1150 nm
  - 1150 - 1250 nm
  - 1250 - 1350 nm
  - 1350 - 1450 nm
  - 1450 - 1550 nm
  - 1550 - 1650 nm

**VIS-NIR INTERFERENCE FILTERS**

- **SPECIFICATIONS**
  - Sire tolerance:
    - 0.0 mm - 0.8 mm
  - Thickness:
    - 4 mm, max.
  - Useful aperture:
    - All but 1.6 mm outer rim
  - Center wavelength tolerance:
    - 1.2 mm
  - Bandwidth:
    - 10 mm
  - Bandwidth tolerance:
    - 2.5 mm
  - Band shape, # of cavities:
    - 3
  - Wavelength shift factor (max.):
    - See table
  - Blocking factor:
    - 0.01%
  - Blocking range:
    - X-ray to far IR
  - Max temperature:
    - 80°C
  - Environmental:
    - Per MIL STD 810C (method 567, procedure 1)

**ORDERING INFORMATION**

- **Center:**
  - Wavelength (nm):
    - 400 - 700 nm
    - 700 - 1000 nm
- **Orders:**
  - (8) No. (*): 53970
  - (5) No. ($): 53900
  - Each filter set includes a hard shell protective case.
  - 18 filters listed above.

**FILTER SETS**

- **WAVELENGTH (nm):**
  - 400 - 500 nm
  - 500 - 600 nm
  - 600 - 700 nm
  - 700 - 800 nm
  - 800 - 900 nm
  - 900 - 1000 nm
  - 1000 - 1100 nm
  - 1100 - 1200 nm
  - 1200 - 1300 nm
  - 1300 - 1400 nm
  - 1400 - 1500 nm
  - 1500 - 1600 nm
  - 1600 - 1700 nm
  - 1700 - 1800 nm
  - 1800 - 1900 nm
  - 1900 - 2000 nm

**FILTERS**

- **Ordering:**
  - 1 inch (25.4 mm)
  - 2 inch (50.8 mm)

**ORDERING INFORMATION**

- **Center:**
  - Wavelength (nm):
    - 250 - 350 nm
    - 350 - 450 nm
    - 450 - 550 nm
    - 550 - 650 nm
    - 650 - 750 nm
    - 750 - 850 nm
    - 850 - 950 nm
    - 950 - 1050 nm
    - 1050 - 1150 nm
    - 1150 - 1250 nm
    - 1250 - 1350 nm
    - 1350 - 1450 nm
    - 1450 - 1550 nm
    - 1550 - 1650 nm
    - 1650 - 1750 nm
    - 1750 - 1850 nm
    - 1850 - 1950 nm
    - 1950 - 2050 nm
  - **Orders:**
    - (8) No. (*): 53970
    - (5) No. ($): 53900
    - Each filter set includes a hard shell protective case.
    - 18 filters listed above.
**VIS - NIR LONG AND SHORT PASS FILTERS**

- Visible to near infrared models
- Allow separation of spectral bands
- Excellent monochromator order sorting filters
- High transmittance

Long pass filters transmit (or pass) a wide spectral band of long wavelength radiation while blocking short wavelength radiation. Short pass filters transmit a wide spectral band of short wavelength radiation and block long wave radiation. Both types are characterized by an extremely sharp transition from the region of maximum transmittance to maximum reflection. See Figs. 1 and 2 for typical curves shapes and terminology.

**SPECIFICATIONS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Long Pass Filters</th>
<th>Short Pass Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>0.0 mm - 0.8 mm</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>0.0 mm - 0.8 mm</td>
<td></td>
</tr>
<tr>
<td>Surface quality</td>
<td>All but a 1.6 mm outer rim</td>
<td></td>
</tr>
<tr>
<td>Useful aperture</td>
<td>All but a 1.6 mm outer rim</td>
<td></td>
</tr>
<tr>
<td>Transmittance</td>
<td>&gt; 50% avg</td>
<td>&gt; 60% avg</td>
</tr>
<tr>
<td>Blocking</td>
<td>0.0% avg</td>
<td></td>
</tr>
<tr>
<td>Blocking range</td>
<td>See table</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.03 mm</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>80 °C max continuous</td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>MIL STD 810C (truncated 0.1)</td>
<td></td>
</tr>
</tbody>
</table>

**TUNING A FILTER**

The transmittance of these filters moves to shorter wavelengths when they are tilted so you can essentially shift the cut-off. The change in wavelength can be predicted by using the cut-off. The change in wavelength can be predicted by using the cut-off. For example, letting the 57805 Long Pass Filter 15 degrees, the recommended maximum, moves the cut-off from 650 nm to 641 nm.

See pages 2-48 to 2-49 for filter holders.

**ORDERING INFORMATION**

<table>
<thead>
<tr>
<th>Cut-on Wavelength (nm)</th>
<th>Transmittance (%)</th>
<th>Blocking Model</th>
<th>Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>30</td>
<td>2.5</td>
<td>X-ray 145</td>
</tr>
<tr>
<td>2.5</td>
<td>100</td>
<td>5.0</td>
<td>X-ray 210</td>
</tr>
<tr>
<td>3.5</td>
<td>70</td>
<td>7.0</td>
<td>X-ray 320</td>
</tr>
<tr>
<td>5.25</td>
<td>150</td>
<td>7.5</td>
<td>X-ray 270</td>
</tr>
<tr>
<td>8.0</td>
<td>150</td>
<td>14.0</td>
<td>X-ray 77</td>
</tr>
<tr>
<td>10.0</td>
<td>300</td>
<td>20.0</td>
<td>X-ray 98</td>
</tr>
</tbody>
</table>

**Sharp cut-on or cut-off**

**Wide bandpass**

**Excellent transmittance**

These filters are excellent for isolating a wide spectral band in the infrared: they have low absorption so they can withstand incident high power density. Long and short pass filters are characterized by a sharp transition between transmittance and blocking. See Figs. 1 and 2 for typical curve shapes and terminology. You can combine a long and short pass filter to make a custom band pass filter.

**REFERENCE AND ABSORPTION**

The filters are a combination of absorbing glass and interference thin films. Part of the rejected spectrum is reflected back towards the source and part is attenuated. We tabulate the spectral region blocked by reflection. Filters can handle higher power densities (up to 100 W cm⁻²) if the blocked radiation is reflected rather than absorbed.

**Figs. 1 Typical Long Pass Filter.**

**Figs. 2 Typical Short Pass Filter.**
DICHROIC FILTERS

ULTRAVIOLET REFLECTING LONG PASS FILTERS
- Used at 45° or 0° angle of incidence
- Three spectral ranges available

These UV mirrors are used primarily for UV irradiation. Applications include photography, UV curing, material aging studies, and photobiology. They have an average of >90% reflectance over the specified wavelength range. See Figs. 1 and 2 for curves.

SPECIFICATIONS
- Size tolerance: ± 0.5 mm
- Thickness: 6.4 mm max.
- Material: Optical quality crown glass
- Surface quality: 80-50 at 2.5 mm outer dia.
- Temperature: 80°C max continuous
- Environmental: Per MIL-C-675A
- Abrasion: Per MIL-M-13508 C

HEAT CONTROL FILTERS (HOT AND COLD MIRRORS)
- Thermal borosilicate glass substrates withstand high temperatures
- Non-absorbing coating minimizes heat build-up
- May be used in high intensity applications

The following heat control mirrors act as long and short pass filters. They transmit one spectral region and reflect another.

0° Heat Reflecting Filter (Hot Mirror)
- Hot mirrors transmit the visible while reflecting much of the infrared. They are typically used at normal (0°) incidence to the source of radiation. In this position, the visible radiation is allowed to pass undeviated while the infrared (heat) is reflected back towards the light source.

When used at 45°, the transmission/reflection curve is shifted towards the shorter wavelengths. For higher rejection of infrared, use an infrared absorbing filter (page 2-5) after the hot mirror. The visible transmittance is the product of the visible transmittance of both filters.

45° Heat Transmitting Filters (Cold Mirrors)
- Cold mirrors are typically used at 45° to a beam of radiation from a source. In this configuration, the infrared is transmitted undeviated, while the visible is reflected at 90°. For many sources this is better than reflecting the infrared back towards the source.

At normal (0°) incidence the reflectance/transmittance curve is shifted towards longer wavelengths. We offer circular and rectangular cold mirrors. The rectangular sizes are large enough for 1.5 inch (38 mm) 2 inch (51 mm) and 3 inch (76 mm) diameter beams incident at 45°.

SPECIFICATIONS
- Size tolerance: ± 0.5 mm
- Thickness: 6.4 mm max.
- Substrate material: Polished thermal borosilicate glass
- Surface quality: 80-50 at 2.5 mm outer dia.
- Useful aperture: All but a 2.5 mm outer dia.
- Environmental: Per MIL-C-675A
- Abrasion: Per MIL-M-13508 C

ORDERING INFORMATION

<table>
<thead>
<tr>
<th>Size (in.)</th>
<th>Average Reflectance (%)</th>
<th>Reflectance Range (nm)</th>
<th>Average Transmittance (%)</th>
<th>Transmittance Range (nm)</th>
<th>Model No.</th>
<th>Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet Long Pass Filters</td>
<td>2.0 (50.8)</td>
<td>90</td>
<td>325 - 475</td>
<td>85</td>
<td>600 - 1000</td>
<td>59451</td>
</tr>
<tr>
<td></td>
<td>1.6 x 2.7 (41.7 x 69.0)</td>
<td>95</td>
<td>260 - 320</td>
<td>85</td>
<td>550 - 1000</td>
<td>66218</td>
</tr>
<tr>
<td></td>
<td>2.2 x 3.0 (55.9 x 76.2)</td>
<td>95</td>
<td>260 - 320</td>
<td>85</td>
<td>550 - 1200</td>
<td>66228</td>
</tr>
<tr>
<td></td>
<td>3.2 x 4.5 (81.3 x 114.3)</td>
<td>95</td>
<td>260 - 320</td>
<td>85</td>
<td>550 - 1200</td>
<td>66238</td>
</tr>
<tr>
<td>Heat Reflecting Filter (Hot Mirror)</td>
<td>2.0 (50.8)</td>
<td>90</td>
<td>750 - 1200</td>
<td>85</td>
<td>450 - 675</td>
<td>57401</td>
</tr>
<tr>
<td>Heat Transmitting Filters (Cold Mirrors)</td>
<td>2.0 (50.8)</td>
<td>90</td>
<td>420 - 630</td>
<td>85</td>
<td>750 - 1200</td>
<td>57431</td>
</tr>
<tr>
<td></td>
<td>1.6 x 2.7 (41.7 x 69.0)</td>
<td>95</td>
<td>420 - 630</td>
<td>85</td>
<td>750 - 1200</td>
<td>66219</td>
</tr>
<tr>
<td></td>
<td>2.2 x 3.0 (55.9 x 76.2)</td>
<td>95</td>
<td>420 - 630</td>
<td>85</td>
<td>750 - 1200</td>
<td>66229</td>
</tr>
<tr>
<td></td>
<td>3.2 x 4.5 (81.3 x 114.3)</td>
<td>95</td>
<td>420 - 630</td>
<td>85</td>
<td>750 - 1200</td>
<td>66239</td>
</tr>
</tbody>
</table>

The rectangular models are used at the output of our light source condensers to filter the UV or VIS. See Volume II, page 150 for more information, and holders.
Polarizing Optics Technical Discussion

Light travels as transverse electromagnetic waves. The electric and magnetic fields are perpendicular to the direction of propagation and each other (Fig. 1). Defining the direction of a ray and its electric field specifies the three vector directions: propagation, electric field and magnetic field. Most incident light sources consist of a large number of atomic or molecular emitters. The rays emitted from such sources have electric fields with no preferred orientation; these rays are unpolarized.

S and P Polarizations

The terms "s" and "p" polarization are convenient when linearly polarized light is incident on an optic. If the direction of polarization is parallel to the plane of incidence the ray is said to be "s" polarized. If the direction of polarization is perpendicular to the plane of incidence, the ray is "p" polarized. (The plane of incidence is the plane containing the ray, and the normal to the surface.)

Using vector resolution simplifies analysis

The polarization direction of a plane polarized light beam may not be parallel to the "x" or "y" axes of an optical system. Analysis of what happens to a light beam, polarized or unpolarized, in going through an optical system is simplified if the beam is broken into two components, one polarized along each axis. The system modifies the amplitude and phase of each component beam and the emergent "beams" are then recomposed to give the intensity and polarization state of the output beam.

Any ray that is linearly polarized can be resolved into its components polarized along any arbitrary orthogonal axes by normal vector sum rules. In Fig. 3, ray Z-Z is linearly polarized with the vibration direction making the angle $\theta$ with the X axis. The length of ray Z-Z represents the amplitude of the electric field. Ray Z-Z can be resolved into two rays: the horizontal polarized component with an amplitude of $E \cos \theta$, and the vertical polarized component with an amplitude of $E \sin \theta$.

CIRCULARLY AND ELLIPTICALLY POLARIZED LIGHT

The electric field (E vector) of linearly polarized light has a fixed direction perpendicular to the direction of propagation. The E vector of a circularly polarized light beam has constant amplitude and rotates about the direction of propagation at the frequency of the light.

If the E vector rotates clockwise as viewed by an observer receiving the beam, the circularly polarized light is said to be right-handed.

Many materials have different refractive indices for light polarized in orthogonal directions. Two equal rays passing through such a medium travel at different speeds and become out of phase. If the difference in index is an odd multiple of $\pi/2$, the two rays combine to give circularly polarized light. Our quarter wave retarders on page 3-30 convert linearly polarized light to circularly polarized or circularly polarized to linear.

If the E vector rotates at the frequency of the radiation but varies in amplitude then the light is elliptically polarized. This is the most general form of polarized light: linear and circular polarizations are special versions of elliptical polarization.

Production of Polarized Light

Light from natural and incoherent artificial sources is often slightly polarized; i.e. the degree of polarization is small, usually small enough to be negligible. Many lasers, on the other hand, emit polarized radiation.

We follow with a discussion of some of the ways to produce polarized light from unpolarized. Some of these are used deliberately, others are unavoidable and can cause serious error in radiometric measurements.

Polarization by Reflection

If an unpolarized beam of light is incident at an off-normal angle onto an optical surface, the reflected and transmitted beams become polarized to some degree. This is because the reflectance differs for a s and p polarized light. Any unpolarized beam is equivalent to equal s and p linearly polarized components. This effect is important for selection of beam splitters and in polarization sensitive radiometry.

Fig. 4 shows the reflectance for s and p polarized light against angle of incidence for a light incident from air on a fused silica interface ($n = 1.457$). P polarized light incident at Brewster's angle (55.6°) is completely transmitted by the surface. None is reflected. Only 6.9% of a p polarized light incident at Brewster's angle is transmitted. The remainder (93.1%) is reflected. This means that for an unpolarized beam incident at Brewster's angle, the reflected beam is linearly polarized (s) and the transmitted beam partially polarized.

Brewster's angle is given by:

$$\tan \theta = \frac{n_s}{n_p}$$

Where:

- $n_s$ = Refractive index of air
- $n_p$ = Refractive index of the optical material
- $\theta$ = Brewster's angle

For air ($n = 1.0$) and glass ($n = 1.5$), Brewster's Angle = 56.3°.

After an unpolarized beam (50% s and 50% p) passes through a stack of 20 fused silica plates at Brewster's angle, the transmitted beam has 99.7% p polarized light and 0.3% s polarized.

Instead of 20 stacked plates it is more practical to use a single surface with a multi-layer dielectric coating to produce highly polarized light. "Thin film polarizers" of this type are on pages 3-12 to 3-14.

The reflectance of light from metallic surfaces is also angle of incidence and polarization dependent. P polarized light goes through a reflectance minimum at an angle called the "principal angle."
POLARIZING OPTICS: TECHNICAL DISCUSSION

Polarization by Scattering

Light scattered at 90° by charged particles is polarized perpendicular to the plane of incidence (polarization). In the atmosphere, light from the sun is scattered by charged particles and molecules. The intensity of scatter increases with increasing frequency (increasing wavelength), which accounts for the blue appearance of the sky. Without a scattering atmosphere, there is no blue sky.

Polarization by Wire Grids

A series of fine parallel metal wires can function as a polarizer (Fig. 6). The component of the incident radiation which has its E vector parallel to the wire grid is absorbed and reflected so the transmitted component is largely polarized. The electric field along the grid drives the conduction electrons leading to Joule heating and re-radiation. For efficiency, the space between the wires must be small, compared to the wavelength, so these polarizers are more easily constructed for infrared radiation.

Polarization by Dichroism

Some materials absorb light polarized in one direction more strongly than light of the orthogonal polarization. Sheet polarizers such as those on page 3-12 exhibit this property called dichroism. The sheet polarizers are made from long chain polyvinyl alcohol. The sheets are stretched to orient and align the molecules. The stretched sheets are treated with iodine. Electrons can then move easily along the chain. This is equivalent to a fine grid polarizer. Light with the E vector in a plane perpendicular to the chain is transmitted; light with the E vector parallel to the chain is absorbed.

Dichroic sheet polarizers are ultraviolet, visible and near-infrared are moderately efficient and inexpensive. They do not withstand ultraviolet or high power beams and so are not recommended for use with intense sources. Dichroic sheet polarizers are relatively insensitive to angle of incidence, and are available in large sizes.

Polarization by Double Refraction (Birefringence)

Some transparent materials such as crystal quartz, sapphire, mica and calcite, do not have a single value for refractive index. This is due to structural anisotropy. These materials are crystals and many of their physical properties vary with crystal lattice orientation. The refractive index for a ray passing through these materials depends on the direction of the ray with respect to the crystalline structure, and on the direction of the E vector. Material characterized by two refractive indices is birefringent.

We use calcite for our polarizers because the difference in the two refractive indices is large. Light traveling parallel to the optic axis exhibits no double refraction. Light traveling perpendicular to the optic axis has one index of refraction 

\[ n_1 \] for light polarized in the plane of the optic axis (called the extraordinary or e-ray), and a different index of refraction 

\[ n_2 \] for light perpendicular to the optic axis (called the ordinary or o-ray).

At 550 nm, calcite has a refractive index of 1.65 for the o-ray, which is independent of the direction of travel. For the e-rays, the refractive indices are 1.68 for rays traveling parallel to the optic axis, and 1.49 for rays traveling perpendicular to the optic axis.

To follow the propagation of light rays through the calcite crystal, we resolve the rays into components parallel to the optic axis (e-rays), and perpendicular to the optic axis (o-rays). There are several possible conditions for light traveling through the calcite crystal:

1. If the rays travel parallel to the optic axis, then rays of any polarization have the same refractive index.
2. If the rays travel perpendicular to the optic axis, then the e-ray travels faster than the o-ray. Because of the lower index of refraction of the e-ray, it will be bent or refracted less than the o-ray on leaving the crystal at an angle.
3. The rays travel at some angle between 0° and 90° from the optic axis. The e-ray travels undeviated and is refracted according to Snell's Law. As it enters the crystal at an angle, the e-ray deviates from the o-ray due to the variation of the refractive index with direction; the direction of deviation will be away from the optic axis and generally out of the plane of incidence.

Fig. 1 shows an unpolarized beam incident on a calcite rhomb. The unpolarized ray is split into its o-ray and e-ray components at the entrance face and then both rays travel through the crystal at different speeds. They exit the crystal at different points and so are separated. The degree of separation is a function of the difference in index of refraction between the o-ray and e-ray and the thickness of the crystal. It is often more convenient to split a beam into orthogonally polarized beams by exploiting the large difference in \( n_2 \) and \( n_1 \) in calcite through total internal reflection. The birefringent crystal is cut so that the o and e rays leave the calcite crystal the o-ray is totally internally reflected. Most of the o-ray passes through the interface, and by use of a compensating prism continues parallel to its original direction (Fig. 8). This is the basis of operation of our Glan-Taylor polarizing prisms listed on page 3-18.

Fig. 6 Wire Grid Polarizer.

Fig. 7 A light beam travelling through a calcite rhomb is split into two orthogonally polarized beams. The e and o components emerge separated.

Fig. 8 With our Glan-Taylor Polarizers the e-ray extra parallel to its original direction.

EXTINCTION RATIOS OF POLARIZERS

When unpolarized light passes through a polarizer, the light which emerges is largely polarized with the E vector parallel to the transmission axis of the polarizer.

When a linearly polarized beam is incident on a polarizer and the polarizer rotated for maximum transmission, then k, the extinction ratio is the ratio of transmitted incident intensity, k, the minor principal transmittance, is the ratio when the polarizer is rotated for minimum transmittance. The extinction ratio is equal to k/k₀.

This ratio is typically 10⁴ for sheet polarizers, 10⁶ for thin film polarizers, and \( 10^8 \) for Orient Crystal Polarizers.

As the polarizer is rotated in a polarized beam the transmittance, k, varies as:

\[ k = (k_0 - k_1) \cos^2 \theta + k_1 \] (1)

Where:

- \( \theta \): Angle between the E vector of the light and the transmission axis of the polarizer.

Two Polarizers in Series

For unpolarized light passing through a pair of identical polarizers, the ratio of the intensity with the polarizers crossed, i.e. at extinction, to the intensity with the polarizers aligned is:

\[ \frac{k_0}{k_1} = \frac{2k_0}{k_1} \] (2)

Where:

- \( k \): Extinction ratio.
- \( k_0 \): Transmittance of the first polarizer.
- \( k_1 \): Transmittance of the second polarizer.

Note that from (2) the ratio of minimum and maximum intensity with two polarizers in unpolarized light is approximately twice the extinction ratio.
**POLARIZING MATERIALS**

**Birefringent Polarizing Materials**

The polarization behavior of a crystal is determined by the crystal structure and electron bonding. Isotropic crystals have a single index of refraction and are not birefringent. Cateite, crystalline quartz, sapphire and magnesium fluoride are birefringent with one optic axis. These uniaxial crystals have two principal refractive indices, \( n_o \) and \( n_e \). Still other materials such as mica have two optic axes and three principal refractive indices.

Cateite is widely used as a polarizing material because of its excellent transmission and large difference in the two index of refraction values. The large difference simplifies the separation of the two different polarizations. Table 1 lists the index of refraction values at 589 nm for the ordinary \( (n_o) \) and extraordinary \( (n_e) \) rays of several materials. Table 2 lists the variation of \( n_e - n_o \) with wavelength.

Table 1: Refractive Indices at 589 nm

<table>
<thead>
<tr>
<th>Material</th>
<th>( n_o )</th>
<th>( n_e )</th>
<th>( n_e - n_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cateite</td>
<td>1.656</td>
<td>1.486</td>
<td>0.172</td>
</tr>
<tr>
<td>Crystal Quartz</td>
<td>1.544</td>
<td>1.553</td>
<td>0.009</td>
</tr>
<tr>
<td>Mica</td>
<td>1.526</td>
<td>1.538</td>
<td>0.002</td>
</tr>
<tr>
<td>Sapphire (Al2O3)</td>
<td>1.760</td>
<td>1.760</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 2: Variation of \( n_e - n_o \) with Wavelength

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
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</table>

Sheet Polarizers

These polarizers are available for the ultraviolet to visible, visible, and near infrared. The low cost, wide acceptance angle, and large apertures make these the polarizers of choice for many applications. You should only select these polarizers for low power applications since they operate by absorbing the unwanted polarization and are easily bleached, particularly by ultraviolet light.

**Polarizer Overview**

The next three pages briefly summarize our family of polarizing optics. They are discussed in complete detail at the end of this section.

We offer the following types of polarizing optics:

- **Dichroic Polarizers**: 3-12
- **Crystal Polarizing Prisms**: 3-18
- **Polarizing Beam Splitting Cubes**: 3-24

**Dichroic Polarizers**

- High acceptance angle
- Large apertures

We offer three types:

- **Surface Film Polarizer**: 3-12
- **Silver in Glass Polarizers**: 3-15
- **Sheet Polarizers**: 3-14

**Surface Film Polarizer**

We offer one polarizer of this type; the 27220. It is made by depositing a proprietary coating on a specially prepared fumed silica substrate. This polarizer is notable for its large acceptance angle, 230 - 770 nm. Its high transmission and durability. It withstands prolonged exposure to ultraviolet and visible radiation much better than the sheet polarizers.

**Silver In Glass Polarizers**

Our new silver in glass polarizers have very high transmission, acceptance angles to 60° and higher power handling capability than our other dichroic polarizers. They are made by inserting tiny elongated silver particles in a borosilicate glass. The particles are aligned so the material works like a tiny wire grid, absorbing light with its E vector parallel to the long, conducting silver particles. The spectral range of these polarizers is limited, but we offer models for most popular near infrared regions.

---

**Fig. 1** Average Extinction vs. Wavelength range for our family of polarizers. Lower extinction is better. The chart does not highlight advantages such as power handling, transmittance, and local extinction. These make the Surface Film Polarizer and the Silver in Glass Polarizers much more attractive.
CRYSTAL POLARIZING PRISMS

- Broad usable wavelength range
- High power handling capability
- Highest Extinction Ratio

Our polarizing prisms are made from selected laser quality calcite to provide the purest polarized light available. These prisms have smaller apertures and acceptance angles than our dielectric polarizers. They are ideal for use with lasers, and for applications such as ellipsometry where high extinction is crucial.

We offer four types of crystal polarizers:

- Glan-Thompson Polarizers
- Glan-Taylor Polarizers
- Wollaston Polarizers
- Low Loss Prism Polarizers

Glan-Thompson and Glan-Taylor Polarizers

These similar polarizers operate by separating the two polarizations at an angled interface. The interface angle is such that the e-ray strikes it at more than the critical angle and is totally reflected. It is either absorbed at the exit face, or emerges from the models with exit windows. The e-ray passes through the angled interface, with some reflection loss, and then exits the prism slightly deviated laterally, but parallel to the input beam. If the input beam satisfies the acceptance condition, the transmitted beam has a high degree of polarization.

The transmitted e-ray contains typically less than 10^-3 to 10^-7 parts of the unwanted polarization. The beam that exits the side of the prism is mostly o-ray, contaminated with some of the e-ray component which was reflected from the angled interface. In the reflected beam the o-ray and the e-ray are not colinear, and therefore they can be easily separated.

Low Loss Prism Polarizers

Like our other crystal polarizers, these split an unpolared beam into two widely separated polarized components. Because of the Brewster's angle input and output, and close to Brewster's angle internal faces, the e-ray has a transmittance of 99% at 632.8 nm. These polarizers are usable with visible collimated beams up to 15 mm in diameter. The output beam is displaced from the input by 6 mm.

Wollaston Polarizers

Our Wollaston Polarizers split an unpolared beam into two orthogonally polarized components which exit the polarizer with high angular separation (~ 20° at 633 nm). The two orthogonally polarized rays travel co-linearly with different refractive indices through the first prism. At the interface the crystal orientation switches, so the o-ray beam is refracted away from the normal and the e-ray is refracted towards the normal. The rays are further separated on exiting the polarizer. The output rays are almost symmetrical about the input direction.

POLARIZER OVERVIEW

LOW PASS FILTERS

- Excellent extinction ratio
- High transmittance

When light strikes an angled interface between two dielectric media, the reflectance depends on the polarization state of the light. We describe this on page 3-3. These polarizers exploit this effect with thin film coatings designed for high reflectance for one polarization and high transmittance for the other.

The beam transmitted through our polarizing beam splitting cubes is almost pure p polarized (with respect to the cube reflecting face). The extinction ratio of 10^-7 is unmatched for this type of polarizer. The beam reflected at 90° to the incident beam is mostly s polarized. The cubes are usually designed for a specific wavelength, but sophisticated coating design has allowed us to offer broadband models with excellent transmitted beam extinction.

Polarizing beam splitters offer the convenience of orthogonal beam splitting. They are available in apertures up to 1 inch, have limited acceptance angles (typically a few degrees) and the power handling capability is limited by the construction.

RETARDERS: TECHNICAL DISCUSSION

Retarders change the state of polarization. They resolve an incident beam of light into two orthogonally polarized components and retard the phase of one component relative to the other. The emergent beam usually has a different polarization state from the incident beam.

The most common type of retarder is a slice of birefringent material in which the e-ray and o-ray travel at different velocities. Two rays which start in phase get out of phase with each other. For light of wavelength λ, the phase difference, φ, is given by:

\[ \phi = \frac{\pm 2 \pi d (n_e - n_o)}{\lambda} \]

and the path difference by:

\[ k \lambda = \pm d (n_e - n_o) \]

Where:

- d = Thickness of the plate
- \( n_e \) = Refractive index for the extraordinary ray
- \( n_o \) = Refractive index for the ordinary ray

k allows us to express the path difference in terms of λ, the wavelength.

When \( k = m/4 \) where \( m \) is any odd integer, the path difference is effectively a quarter wave, so the plate is called a quarter wave plate.

The action of this half wave plate is to rotate the E vector of the light through 2π, twice the angle between the E vector of the incident beam, and the optic axis.

Fig. 1 shows the operation of a half wave plate on a linearly polarized beam. The E vector of the input beam is at 90° to the optic axis. The input beam is effectively resolved into two orthogonally polarized component beams (page 3-28). one with the E vector parallel and the other with the E vector perpendicular to the optic axis.

Fig. 1 Rotation of polarization by a Half Wave Retarder.

The retarder delays one of these beams with respect to the other. After passing through the retarder, the phase of one vector component is delayed by ±(180°) with respect to the other; a path difference of one half wavelength. The sum of the two emergent beams is a beam with linear polarization but rotated by ±(90°) from the original input beam.

The action of this half wave plate is to rotate the E vector of the light through 2π, twice the angle between the E vector of the incident beam, and the optic axis.
GLAN-TAYLOR POLARIZERS

High power handling capacity
Transmittance from 400 to 2500 nm

These high extinction polarizers are specifically designed for use with high power lasers. They are extensively used for pulse extraction and feedback elimination. Because they use an angle rather than optical cement, they also have advantages over Glan-Thompson or Wollaston polarizers for any ultraviolet applications.

Two types are available:
- Standard models (without exit window). This type is intended to remove unwanted polarization from a substantially polarized beam.
- With exit window. The reflected beam exits the polarizer, so this type should be used in pulse extraction or any application where there is significant rejected power. They can also be used for beam combination.

POLARIZER DESIGN

Our Glan-Taylor polarizers are made from grade "A" natural calcite (CaCO₃). The material is carefully selected, optically oriented and then cleaved to size. The two calcite prisms are mechanically coupled at the hypotenuse. The hypotenuse faces are near the Brewster angle so there is minimal reflection loss for the transmitted component. The entrance and exit faces of the prism can be anti-reflection coated to increase the transmittance. See pages 10.6 to 10.7 for coatings. The polarizers come mounted in a black anodized aluminum housing.

STANDARD MODELS

The rejected beam is absorbed at the face of the crystal. This limits the application of these models to cases where the rejected component has low average or peak power.

MODELS WITH EXIT WINDOWS

The reflected beam escapes through two polished side windows and out through one of the two holes in the mount. See Fig. 1. Having two escape windows allows the polarizer to be used with high power cw or pulsed lasers traveling in either direction through the polarizer. This type is also used in intra-cavity gain switching applications. Be sure to terminate the rejected beam safely if it is not to be used. Our 14041 Beam Stop is a convenient beam terminator.

SPECIFICATIONS

- Dimension tolerance: ± 0.25 mm
- Material: Select grade calcite (CaCO₃)
- Wavelength range: 400 - 2500 nm
- e-ray transmittance: > 88%
- Extinction ratio*: < 10⁻⁶
- Field angle @ 632 nm: 8 (10 µrad)
- Wavefront distortion @ 632 nm: < 15 µm
- Maximum transmitted power**: 10 W/cm² CW
- 20 kW/cm² in 10 ns pulses
- Models with exit windows:
- None, faces may be AR coated to increase transmission

For lasers with wavelengths above 450 nm. Damage thresholds drop with wavelength.

MOUNTING

You can mount any 1.0 inch Glan-Taylor Polarizer in the 25010 Mini Rotator using the 25002 Adapter. See pages 3.35 to 3.38 for manual rotators and Volume I for a full listing of manual and motorized rotators.

ORDERING INFORMATION

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* The extinction ratio is somewhat dependent on beam collimation. The stated specification is for an input beam collimated to at least one half of the acceptance angle.

** For lasers with wavelengths above 450 nm. Damage thresholds drop with wavelength.

- Use the 25002 if your polarizer has a side exit window and you want to terminate the side exit beam.
Every surface reflects light. The reflected light is both diffuse and regular (or specular) and sometimes comes both from the surface and the bulk material. (Fig. 1) Regular and specular reflection are defined as “reflection in accordance with the laws of geometrical optics, without diffusion”. The reflectance of any surface is the ratio of the reflected radiant flux to the incident flux. For transmissive optics, the single surface reflectances range from 3% for calcium fluoride to 17% for zinc selenide, a high index material. Reflectivity is the reflectance of a layer of material of such a thickness that there is no change in reflectance with increase in thickness.

**Fig. 1** Om- and specular reflectivity. Only specular reflections will be important for any surface which is smooth (on the scale of a fraction of a wavelength).

**Fig. 2** With specular reflection, the angle of the reflected component is equal to the angle of the incident beam with respect to the normal.

**Fig. 3** Typical near normal reflectance of our metal reflector coatings. They are described on pages 10-8 to 10-9.

**Fig. 4** Reflectance of freshly deposited metal coatings.

**BARE SUBSTRATES**

The reflectivity of any uncoated surface depends on:
- The refractive index of the material which varies with the wavelength of the incident light
- The angle of incidence
- The polarization state of the incident light
- The smoothness or polish of the surface

For transmissive optics, the angle of incidence and polarization determine reflectance. The useful wavelength range of any dielectric reflector is limited. (See page 10-5.)

**METALLIC REFLECTORS**

Highly polished metal surfaces are good broadband specular reflectors. The best metallic reflectors are made by vacuum depositing a thin coating of the metal on a polished substrate. Aluminum adheres directly to glass but a chrome intermediary layer must be used for gold. A typical coating is less than 100 nm thick; thicker coatings have higher scatter from surface roughness. A freshly deposited aluminum coating has a reflectance of more than 98% from 200 nm to beyond 40,000 nm. Fig. 4 shows the reflectance of freshly deposited metallic reflector coatings.

Unfortunatly, the freshly deposited metals tarnish very quickly with the formation of oxides or other compounds. The reflectance drops dramatically. To prevent significant loss of reflectance we overcoat the metal films with thin dielectric films. See the following page.

**METALLIC OR DIELECTRIC REFLECTOR FOR HIGH REFLECTANCE?**

Dielectric coatings are more durable, and can be designed for a desired reflectance, including reflectances higher than available from a metallic coating. Any high reflectance dielectric coating however, is effective only over a narrow range of wavelengths. Most dielectric coatings are more sensitive to angle of incidence and polarization than metallic coatings. (Our maximum reflection mirrors on page 5-8 are exceptionally broad and insensitive to polarization or angle of incidence to 45°)

**CALCULATING REFLECTANCE**

**Bare Substrate**

If light hits a nominally transparent substrate surface the Fresnel reflectance from a single surface, for normal incidence, is given by:

\[
p = \left( \frac{n_i - n_0}{n_i + n_0} \right)^2
\]

Where:
- \( n_i \) = Refractive index of air (1.0)
- \( n_0 \) = Refractive index of the substrate

For an air (\( n_i = 1.0 \)) glass:
- \( n_o = 1.5 \) system, \( p = 4\% \) per surface.

(The spectral Fresnel reflectance \( p(\lambda) \) includes the wavelength dependence of \( p \) as the refractive indices vary with \( \lambda \)).

We list some bare substrates as “Beam splitters on pages 7-6 to 7-8. On page 12-2 we describe the dependence of the reflectance on angle of incidence and polarization.

**METALLIC COATINGS**

Metals are conductive and since optical radiation is electromagnetic in nature the conductivity leads to loss of energy through Joule heating. Metals are highly absorbing for EM radiation which “enters the metal”, but the absorption is accompanied by high reflectance. Conductivity, and therefore absorbance and reflectance, are wavelength dependent. The reflectivity from a metal surface is given by:

\[
p = \frac{n_1 + i \kappa}{n_1 + i \kappa + 1}
\]

Where:
- \( n_1 + i \kappa \) = Complex refractive index
- \( \kappa / n \) = Extinction coefficient

The complex refractive index includes the conductivity of the metal. The energy not reflected is absorbed in the metal. For aluminum at 594 nm, \( n = 1.44 \) and \( \kappa = 5.23 \). From these values \( p = 0.83 \). Strong absorbance (high values of \( \kappa \)) is accompanied by high reflectance. The absorption of the complex refractive index with wavelength leads to excellent broadband reflectance.
MIRRORS: TECHNICAL DISCUSSION

Angle of Incidence Effects

Unlike dielectric reflectors, metal reflectors are effective over a wide range of angles of incidence. There is a phase change on reflection and this differs for s and p polarized radiation (Fig. 5). A linearly polarized ray incident at high angle will be reflected partially elliptically polarized.

DIELECTRIC COATINGS ON TRANSPARENT SUBSTRATES

Dielectric coatings can be optimized for a single wavelength or a narrow (typically 250 nm) spectral range. The simplest coating is a single thin layer coating (page 10-8). To increase the reflectance from that of the bare substrate the refractive index of the coating must be higher than that of the substrate. The reflectance of a mirror with a single layer high index coating is shown in Fig. 6.

Overcoating Metal Reflectors

Aluminum or silver quickly tarnish and the reflectivity drops. We overcoat our metal reflectors with silicon monoxide or magnesium fluoride for protection. Fig. 3 on page 5-2 shows the reflectance of Al(MgF2) and Al(SiO). MgF2 is better in the ultraviolet but is more delicate than the SiO coating.

Any such coating must be a half wave thick or the reflectance will be reduced. This is feasible for ultraviolet or visible wavelengths, but not for the infrared as the layer stress increase with thickness. The half wave coating keeps the reflectance close to that of the bare metal over a spectral range of several hundred nm. We can also enhance the reflectance over a narrower spectral range by applying a multi-layer dielectric coating.

We list our metal and overcoated metal coatings on pages 10-8 to 10-9.

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FIBER OPTICS TECHNICAL DISCUSSION

All optical fibers operate by "total internal reflection" if a ray of light in a medium of refractive index \(n_1\) strikes the interface with another medium of refractive index \(n_2\) \((n_1 < n_2)\), at an angle \(\theta\), and if \(\theta\) is greater than \(\theta_c\), the ray is totally reflected back into the first medium, \(\theta_c = \sin^{-1}(n_2/n_1)\), and is called the critical angle. See Fig. 1.

![Fig. 1](image1)

**Fig. 1** Ray 1 is incident at an angle \(\theta_0\) (41.8° for glass) and is totally reflected. Ray 2, incident at an angle \(\theta_1\), is partially reflected into the glass and partially reflected.

An optical fiber exploits total internal reflection by having an inner region of low refractive index and a cladding of higher index. Light is confined by repeated reflections. Single strands of transparent material such as glass or fused silica can pipe trapped light over long distances with very low loss.

Figs. 2 and 3 show the simplest type of fiber, a cylindrical core of transparent material with an outer layer of lower index material. (The same effect can be obtained by grading the index from high in the center to lower values at the periphery.)

Light entering the fiber within the acceptance cone is totally reflected at the core cladding interface.

![Fig. 2](image2)

**Fig. 2** A single fiber accepts and guides light incident within the acceptance cone. Orient Fiber Bundles are comprised of a large number of fibers, each with a core and thin outer layer of cladding.

![Fig. 3](image3)

**Fig. 3** The light entering the fiber within the acceptance cone is totally reflected at the core cladding interface.

The acceptance angle, \(\alpha\), depends on the refractive indices of the core and cladding:

\[
\sin \alpha = \frac{1}{\sqrt{n_2^2 - n_1^2}}
\]

Note that the acceptance cone angle is \(2\alpha\), and \(n_2\) is usually \(1.0\).

Fiber input and output behavior is usually described in terms of numerical aperture (NA). If \(n_0 = 1\):

\[
\text{NA} = \sin \alpha = \sqrt{n_2^2 - n_1^2}
\]

This relates to F/\# through

\[
\text{F/\#} = \frac{1}{\sin \alpha} = \frac{1}{2\alpha}
\]

This is sometimes written as \(1/(2\alpha)\). We use \(\sin \alpha\) here because at high values of \(n_2\), \(\sin \alpha\) is more appropriate. At low values of \(n_2\), \(\sin \alpha\) is a tan of the fiber (i.e., \(\tan \alpha = \text{F/\#}\)).

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<tr>
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<td>Glass</td>
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</tr>
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</table>

Table 1 NA\#s and F/\#s for Orient Fibers
FIBER OPTICS: TECHNICAL DISCUSSION

Because of the small cross section required for flexibility, typically much less than a millimeter, single fibers are not efficient in collection of energy from larger incoherent (non laser) sources. Fibers packed in a bundle provide both the flexibility and large aperture. We supply bundles for illumination or energy transfer only. In these, the individual fibers are haphazardly located in the input and output of the bundle.

**Transmittance**

The transmittance of a single fiber, fiber bundle or liquid light guide varies with test conditions. A ray which passes down the axis travels a much shorter distance than a ray which enters at the limiting acceptance angle. The reflectance at the core-cladding interface is close to, but not exactly 1. A ray which enters at a high angle can have many thousands of reflections in going through a fiber and so experience more loss than an axial ray or one with few reflections. When a fiber is bent sharply, light leaks out and the transmittance drops. We show transmittance data for practical conditions of a large launch cone for a specified length of fiber which is loosely coiled. The transmittance is derived by ratioing the radiation through the fiber bundle to that through an aperture of the same size. This eliminates any loss from overfilling a fiber bundle. The data includes packing loss.

Light is reflected at the input and output faces and absorbed or scattered as it passes through the fiber. The absorption and scattering losses depend on the wavelength of the radiation.

Transmittance decreases with length. For light of one wavelength, the transmittance - length relationship for constant operating conditions is approximately:

\[
T = P \left(1 - A \right)^{RL/\alpha L}
\]

Where:

- \(P\) = Packing fraction
- \(R\) = Reflection loss
- \(\alpha\) = Absorption coefficient
- \(L\) = Length of the average light path through the fiber.

\(P\) is typically 0.04 for Oriel Fibers. \(P\) varies from 0.8 to 0.92 for fiber bundles and is 1 for single fibers and liquid light guides.

**Glass and Fused Silica Bundles**

We offer Glass Bundles and two grades of Fused Silica Bundles. The economical Glass Bundles transmit visible light and near infrared radiation (see Fig. 5). They have a very large acceptance angle (85°), and are therefore excellent for illumination of large areas or capture of radiation emitted from large sources.

Our Standard Grade Fused Silica Bundles use silica fibers with polymer cladding. They have excellent transmittance from the UV to 1200 nm and from 1500 - 1900 nm. Our High Grade Fused Silica Bundles use smaller silica fibers with a doped silica cladding. These have better overall transmittance and significantly lower UV transmittance than the Standard Grade. Fig. 5 shows the transmittance for the standard grade. We list both grades on page 8-12.

**Single Fibers**

We carry two types of single fibers in core sizes from 200 µm to 1 mm. Both have a single cylindrical core with a large acceptance angle (68°) and are therefore excellent for illumination or energy transfer only. In these, the individual fibers are haphazardly located in the input and output of the bundle.

**Liquid Light Guides**

Our Liquid Light Guides consist of a clear, non toxic anaerobic liquid in a flexible tube with polished silica windows on each end. They are available in 3 and 5 mm diameters, and have high transmittance from 270 to 750 nm (Fig. 8). They have no packing fraction loss and a large acceptance angle which makes them the most efficient type of large aperture flexible light guide in the 270 - 400 nm range.
CHOOSING THE FIBER OPTIC

The important considerations include:

- Spectral distribution of the light to be transmitted
- Size of the source and angular distribution of source radiation: size and acceptance angle of output target
- Cost

Spectral Considerations

See the transmittance curves on the previous page for the transmittance of the various fiber types. The curves have extended flat portions and sloping portions as shown in Fig. 5. The transmittance for light with a wavelength which lies on the flat portion of the curve will decrease gradually as the fiber length is increased. The transmittance for light on the sloping portions of the curve will decrease rapidly with fiber length.

Throughput/Collection Considerations

A large NA and bundle diameter are best for collection of radiation from large sources. Collection from a large area source varies as the square of the NA and the square of the diameter. If the light from the bundle is for illumination, a large source, or to be measured using an Integrating Sphere, then the larger the bundle and the higher the NA the better.

For a small source, the NA has to be reduced. A small NA and a small target will reduce the NA (beam angle) of the output of the fiber, i.e., it may be important to conserve "brightness." When using a laser, we effectively make a point source or an extended source, you might use a smaller NA and a smaller fiber system.

Cost and Availability

We provide both standard and custom fiber bundles and liquid light guides. Standard products are most economical, followed by liquid light guides and standard apertures.

Fused silica fiber bundles cost more than glass bundles. Our higher grade silica bundles use high performance silica. Because of the small diameter of these fibers, a high NA bundle requires many more fibers than a standard grade bundle. The increased performance is often worth the higher cost.

The liquid light guides have a better transmittance from 300 to 700 nm, so you should consider these if the wavelengths you work with are in this range. Liquid light guides are more expensive than glass, but standard grade fused silica bundles, by significantly less expensive than higher grade fused silica bundles.

If you need a very long length of fiber, then consider using a single fiber. You can select the length of a single fiber you need. The VIS-NIR fiber is more economical than the UV-VIS fiber, and has excellent transmission in the visible range.

NA AND WAVELENGTH

The index of refraction of fused silica varies rapidly with wavelength in the UV. Therefore the acceptance and output cones change with wavelength. Fig. 9 shows the significance of this for our standard grade fiber bundles. The higher grade silica bundles do not show this effect. The 254 and 546 nm scans are almost identical for the higher grade bundles.

EMERGENT CONE

The light cone pattern which emerges from the fiber will be determined by the input illumination, the fiber properties, and the lay of the fiber bundle.

For long fibers, the fiber properties dominate, while for short fibers (<1.2 m), the launch (or input) conditions dominate. For a short fiber (<1.2 m) or in a launch (or input) conditions dominate. Fig. 11 shows the outputs for various input conditions for the 7757B, 36 inch (914 mm) long, 3 mm diameter high grade fused silica bundle. The same broadband source was used.

The output from our liquid light guides is a little less sensitive to input conditions, but more sensitive to bending than the fiber bundle. The liquid light guides are smaller and less expensive.

The NA and bundle diameter are best for collection of radiation from large sources. Collection from a large area source varies as the square of the NA and the square of the diameter. If the light from the bundle is for illumination, a large source, or to be measured using an Integrating Sphere, then the larger the bundle and the higher the NA the better.

For a small source, the NA has to be reduced. A smaller NA and a smaller target are better with a low NA and small diameter fiber system.

Cost and Availability

We provide both standard and custom fiber bundles and liquid light guides. Standard products are most economical, followed by liquid light guides and standard apertures.

Fused silica fiber bundles cost more than glass bundles. Our higher grade silica bundles use high performance silica. Because of the small diameter of these fibers, a high NA bundle requires many more fibers than a standard grade bundle. The increased performance is often worth the higher cost.

The liquid light guides have a better transmittance from 300 to 700 nm, so you should consider these if the wavelengths you work with are in this range. Liquid light guides are more expensive than glass, but standard grade fused silica bundles, by significantly less expensive than higher grade fused silica bundles.

If you need a very long length of fiber, then consider using a single fiber. You can select the length of a single fiber you need. The VIS-NIR fiber is more economical than the UV-VIS fiber, and has excellent transmission in the visible range.

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LASER OPTICS AND CONVENTIONAL LIGHT SOURCES

LASER TO FIBER COUPLING

Nonimaging optics, such as those in our Photomax™, are useful for coupling a laser to a fiber. The key to getting the maximum output through a fiber optic is to use a bright (high radiance) source of appropriate size, and optimize the source to fiber coupling. Lamp brightness is sometimes described by color temperature. Our short arc lamps have color temperatures of more than 5000K while our tungsten halogen lamps have color temperatures as high as 3400K. Our Volume II catalog comprehensively describes the widest range of laboratory light sources available. It also discusses source to fiber coupling and has specific performance data. Here we give some general guidance.

Example

Couple a 100 W multimode cw Nd:YAG into a 77571 Fiber. The beam diameter for the laser is 6 mm and beam divergence is 11 mrad.
The fiber, listed on page 8-18 has a 400 μm core and NA of 0.22. S = F/6. 11 mrad, F/6 in mm, then S will be in μm.
The spot size is 11 μm x F6 μm. The 25 mm focal length lens (41220) gives a 275 μm spot size but the beam NA is less than 0.12, which matches well with the fiber NA of 0.22.

Single Mode Fibers

The number of modes which a fiber can guide drops as the fiber core diameter or NA is reduced. At small enough values of either, only one fiber mode exists. The fiber is then called single mode or monomode. Most single mode fibers have core diameters of 4 - 8 μm and NAs of about 0.2.

Optimizing the coupling of a laser into a monomode fiber requires mode matching theory. The focused laser spot should match the fiber mode diameter. This is in the range of 1 - 1.5 times the fiber core diameter. The converging beam must also be within the acceptance angle determined by the fiber NA.

Example

Select a lens to couple the 7862.0 mW HeNe to a 50 μm core fiber with 0.22 NA.
The beam diameter is about 0.7 mm at the laser output.
Since S = 1.27 x F6 x D6, then 0.7 = 1.27 x 0.633 x F6
S in μm and F6 in mm.
Where:
S is in μm and F6 is in mm.

For a spot size of less than 0.65 x 50 = 32.5 μm, the lens focal length must be less than 28 mm. The 13570 Microscope Objective has a focal length of 25.5 mm, and is well corrected so the spot size will be close to that calculated. The beam NA with this lens will be about 0.006, which is much less than the 0.22 of the fiber.

FIBER OPTICS AND CONVENTIONAL LIGHT SOURCES

1. Short arc lamps provide the maximum ultraviolet and visible light for fiber optic irradiation. Our xenon arc lamps have intense output from 250 nm to beyond 1000 nm. Our mercury arc lamps have more UV output and strong line outputs at 545 and 580 nm. See the spectra and source sizes in Volume II.

2. Use the dimensions of the fiber to select the size of the light source, arc or filament. Re-imaging optics will magnify the source by 1 for glass bundles and 2 for fused silica bundles. These numbers are based on collecting light at F/1 and re-imaging at F/2.

Using a larger size source eases alignment, but produces a lot of unwanted power which may have to be removed. A 500 watt arc lamp will give as much power through a single fiber of a 600 μm core as a kW arc lamp since these lamps have similar brightness. The ideal source has a very bright arc about the size of the fiber or fiber bundle.

3. Nonimaging optics, such as those in our Photomax™, the reflectors which are an integral part of the tungsten halogen lamps on page 48 of Volume II, or the conventional reflectors described on page 5-10 of this catalog are useful particularly with fiber bundles and Liquid Light Guides. We offer an F/2 reflector for Photomax™ to match the acceptance cone of fused silica fibers. With these broadband reflectors you do not need additional focusing optics, but do need spectral filtering to reduce the power density on the fiber input.
**LARGE CORE OPTICAL FIBERS for UV to NIR**

- Transmit from 200 nm to 2 um
- Core diameters from 200 to 1000 nm
- Available with SMA connectors
- Flexible nylon jacket protects fiber
- Ideal for laser or small bright sources

Single fibers are an economical and convenient method of transferring energy for long distance applications. They can be used for remote sensing or processing with high power lasers. We offer two types of fiber: UV-VIS and VIS-NIR.

**CONSTRUCTION**

Our single fibers are available with core diameters from 200 to 1000 nm. They consist of a silica core with cladding and a nylon jacket for protection. They may be ordered with bare ends or with SMA terminations.

**ADVANTAGES OVER FIBER BUNDLES**

Single fibers have several advantages over fiber bundles. These include:
- Lower transmission losses
- Higher damage threshold
- More economical in long lengths
- Require much smaller apertures and conduits

**LIGHT COLLECTION**

You cannot use a single fiber for efficient capture and transmission of radiation from large sources. The optical extent of the fibers is too small. Single fibers have major advantages for small sources including high transmission, over long lengths, flexibility, compactness and they are economical. You can mechanically hold several single fibers together for efficient capture of the output of a large arc source. This gives you the advantages of these fibers and efficient light transfer. Pages 8-9 to 8-10 discuss fiber to laser coupling. Page 8-25 describes our single fiber couplers.

**OPTICAL CHARACTERISTICS**

Available core sizes range from 200 to 1000 nm (1 mm). Transmittance for both fiber types is shown in Fig. 1. The numerical aperture is 0.22.

**UV-VIS FIBER**

This fiber has a high purity UV grade silica core and silica glass cladding. It is usable from 200 to 2000 nm (see Fig. 1 for transmittance curve), and suitable for high power laser beams. The damage threshold for a clean input surface is more than 10 J cm⁻² or 100 W cm⁻² for wavelengths above 360 nm.

**VIS-NIR FIBER**

This fiber has a water free silica core to reduce absorption in the IR, and depending on the size, is clad with silica or silicone. (See Fig. 1 for transmittance curve.) This is an economical alternative to the UV-VIS Fiber for any application where UV transmittance is not required.

**FIBER OUTPUT**

For short straight lengths (< 1 m) of fiber, the output retains many of the characteristics of the beam launched into the fiber. The spectral spatial distribution may change due to the attenuation of rays launched at an angle. These travel longer distances in the fiber.

For very long lengths of fiber, particularly where the fiber is coiled or bent, the output is determined by the fiber NA. The launch conditions are "forgotten." A central core, determined by the fiber NA, may be surrounded by a lower intensity high angle output. Fiber bend conditions also have an impact. Fig. 2 shows a scan of the output from the 77512 Fiber coupled to a mercury arc lamp. Fiber length was 5 m.

**SPECIFICATIONS**

- Numerical Aperture: 0.22
- Refractive Index of Core: 1.452 at 850 nm
- Refractive Index of Cladding: 1.438 at 850 nm
- Outer Jacket: Black Nylon

**ORDERING INFORMATION**

- Fiber only, without connectors
- Fiber only, with 2 SMA connectors

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Cladding Diameter (mm)</th>
<th>Minimum Bend Radius (mm)</th>
<th>Maximum Length (m)</th>
<th>Price/Meter ($)</th>
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**Fiber only, with 2 SMA connectors**

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</table>

Multiply length of fiber in meters by price/meter to get the price for fiber with bare unpolished ends. Minimum length is 1 meter.

Find the price for the fiber and add this price to the total price for fiber terminated with two SMA connectors.

- Order 5 meters of 77512 fiber at $0.80/meter, and a 77512 set of 2 SMA connectors at $165.00, for a total cost of $520.00.

See page 8-25 for Fiber Holders.
OPTICAL COATINGS: TECHNICAL DISCUSSION

OPTICAL COATING TECHNOLOGY

Optical coatings are used to alter the reflectance, transmittance, absorbance, or polarization properties of optical components. The optic being coated is usually referred to as the substrate. The coating is deposited in high vacuum (<10^-2 Torr) using the process of evaporation. Coating materials include metals, dielectrics or semiconductors. Oxides, fluorides, and sulfides are the most common dielectric materials. Tewdrides and salihides are used for specialized applications.

Reflection From Uncoated Optics

When light is incident to a smooth surface between two transparent media as in Fig. 1, some of the light enters the second medium and is reflected at the interface. The relationship between the angle of incidence (i), and the angle of reflection (r) is given by Snell's law:

\[ n_1 \sin i = n_2 \sin r \]  

(1)

Where:

- \( n_1 \) and \( n_2 \) = Indices of refraction of the media on both sides of the interface.

Evaporation

The coating material must be converted from a solid into a vapor, and then condensed on the optic surface. The most common methods of vaporization are Thermal Evaporation and Electron Beam Ion Bombardment.

Thermal Evaporation

In this process the coating material is resistance heated in a tungsten, molybdenum or platinum "boat" for metals and high temperature dielectrics. For some low temperature dielectrics, indirect heating with a refractory filament suffices.

Electron Beam Ion Bombardment

In this process the coating material is heated by direct electron bombardment. A variable voltage and current (5 - 15 kV at up to several amps) electron beam is concentrated in a very small movable spot in a multi-pocket water cooled copper crucible; different evaporation materials can be contained in the multi-pockets. This method of evaporation is versatile and reduces contamination resulting from interaction between the coating material and the crucible. The heating is localized and temperatures can be high enough to evaporate refractory materials.

Sputtering

Sputtering is another technique used for film deposition. It is particularly useful for large area substrates. The substrate and a target of the material to be deposited are held closed together in a plasma chamber. The substrate is cooled. Heavy ions from the plasma bombard the target and knock out small particles at target material. These "condense" on the cooled substrate. Sputtering can quickly produce uniform coatings over large areas, and uses the deposition material more efficiently than evaporation techniques.

Thickness Control

The control of layer thickness is crucial in optical coating. There are two principal methods used to control layer thickness, interference monitoring, and measuring the resonance of a crystal oscillator.

Interference Monitoring

Interference thickness monitoring is useful for deposition materials with a well defined refractive index. The technique is useful with dielectrics and some semiconductor materials. Either the transmitted or reflected beam can be monitored. In transmission mode, monochromatic light passes through the substrate being coated and the transmittance is monitored. The transmittance changes as the layer thickness builds up. If the index of the dielectric is higher than that of the substrate, the transmission gradually decreases. When the optical thickness reaches 1/4 of the monitoring wavelength, the change in transmission momentarily stops.

If evaporation is continued beyond the 1/4 wave thickness, the transmittance increases to the original value and then, again, momentarily stops. At the 1/2 wave monitoring thickness, this process could be continued, observing minimum transmissions at 1/4 wave multiples and maximum transmissions at 1/2 wave multiples of the monitoring wavelength. This evaporation process can be repeated many times using layers of different indices. As the number of layers increases each additional layer produces a smaller change in transmittance or reflectance. Measurements become more difficult and eventually monitoring is limited by the noise and stability of the monitoring instrument.

In a typical vacuum deposition system, light from a continuous source, a deuterium lamp, tungsten halogen lamp or infrared element is mechanically chopped, collimated and passed into the vacuum chamber. In the vacuum chamber, the collimated beam is transmitted through a monitoring test plate mounted on a rotating planetary wheel. A photodetector is placed in front of the plate. A lock-in amplifier selects the chopped signal from background. The lock-in output is then used to observe the transmission minima and maxima.

Crystal Deposition Rate Monitors

Crystalline oscillators monitoring is very often used to control the thickness of metals layers and for dielectric coatings with a few layers. A quartz crystal oscillator is placed on the same plane as the substrates to be coated. The resonant frequency of the crystal depends on its mass, size and the resonant frequency is determined by the deposited film thickness. As layers accumulate on the crystal the sensitivity to increasing thickness diminishes and the frequencies complex the relationship between resonant frequency and layer thickness. Because of this, the quartz crystal oscillator type of monitoring is usually limited to several layers.

Optical Coating Chamber with process monitoring and control.

HOW OPTICAL COATINGS WORK

Reflection From Uncoated Optics

When light is incident to a smooth surface between two transparent media as in Fig. 1, some of the light enters the second medium and is reflected. Some is reflected at the interface. The relationship between the angle of incidence (i), and the angle of reflection (r) is given by Snell's law:

\[ n_1 \sin i = n_2 \sin r \]  

(1)

Reflectance depends on the indices of refraction of the media involved: index of refraction of the substrate and the other media to be deposited.

\[ R = \frac{n_2 - n_1}{n_2 + n_1} \]  

(2)

At normal incidence, these equations reduce to:

\[ R = \left( \frac{n_2 - n_1}{n_2 + n_1} \right) \]  

(3)

Single Layer Anti-reflection Coatings

Fig. 2 shows a 1/4 wave optical coating of an air-dielectric material deposited on the surface of glass. At normal incidence there will be reflection from the air-dielectric and dielectric-glass boundaries. If the dielectric material has an index lower than the glass, the two reflections will be from a medium having an index greater than the one in which the light was traveling. Because of the 1/4 wave optical thickness of the dielectric layer, the two reflections will be 180° out of phase with each other, causing destructive interference. As shown in Fig. 3, the 1/4 wave optical thickness of dielectric reduces the total reflectance.

If the optical thickness of the layer is not an odd multiple of 1/4 wave, then the two reflections are not 180° out of phase and the interference is not totally destructive. The reflectance will be greater than the minimum (Fig. 3). For an optical thickness of a half wave, the phase change is 360°. This is equivalent to not having any layer, so the reflectance is the same as that of the bare substrate.

Fig. 1  Reflection and partial reflection of a ray incident at angle i on an interface between two media one of refractive index n_1 and the other n_2.

Fig. 2  Transparent thin film coating showing reflection from the air-dielectric-glass interfaces.

Fig. 3  1/4 wave thick AR coating on magnesium fluoride on a fused silica substrate reduces the reflection from 4% to < 2.0% at the design wavelength.

Reflection of light polarized parallel to the plane of incidence (p polarized)

\[ R_p = \frac{n_2 - n_1}{n_2 + n_1} \]  

(4)

Reflection of light polarized perpendicular to the plane of incidence (s polarized)

\[ R_s = \frac{n_2 + n_1}{n_2 - n_1} \]  

(5)
How much is the reflectance reduced?

The positions of the minima and maxima in Fig. 3 depend on the film optical thickness, i.e. thickness times refractive index. The reflectance, at normal incidence, for any 1/4 wave thick coating on a non-absorbing substrate is given by:

$$R = \frac{(n_2 - n_0)^2}{(n_2 + n_0)^2}$$ (5)

This is 0 for $n_2 = n_0$ (6).

For air $n = 1.0$, and glass ($n = 1.5$) the ideal value of $n_0$ would be 1.22. Unfortunately, a dielectric material having an index of refraction of 1.22 with desirable mechanical, environmental and optical properties does not exist. MgF$_2$ with an index of 1.38 is a good compromise as a relatively hard and durable anti-reflection coating.

For BK7 (n = 1.5167) and magnesium fluoride (n = 1.38), it is about 0.0128. A 1/4 wave coating of magnesium fluoride on a substrate of index $n_0 = 1.7$ reduces the reflectance from 0.067 to 0.003.

Further reduction in reflectance is possible by using a multi-layer V coating such as those on page 10-7.

Wavelength dependence

Since the optical thickness can only be 1/4 wave for one wavelength, the reflectance depends on the wavelength of the incident light. Fig. 3 shows the computed wavelength dependence at normal incidence for a 1/4 wave coating. Reflectance is reduced over a large part of the range of visible wavelengths. The reflectance increases in the red and blue, giving the surface a slight purple tinge when viewed in white light. This resembles the bloom on Lama plums and an application of this type of coating is sometimes called blooming.

Angle of Incidence

The change in reflectance which occurs with the application of a thin film coating is not only wavelength dependent. It is also angle of incidence dependent. At all normal incidence angles the expressions for calculating reflectance become more complicated and also differ for s and p polarized incident light. Angles of incidence of up to about 25° shift the reflectance curve to slightly shorter wavelengths. A single 1/4 wave thick (at 550 nm) layer of MgF$_2$ will provide an average reflectance of less than 2% reflection from 400 to 700 nm for angles of incidence up to 25° for unpolarized light.

Multi-layer Anti-Reflection Coatings

There are several ways of improving the efficiency and wavelength range of anti-reflection coatings. Most of these techniques involve the use of multi-layer coatings. One of the simplest is the double quarter layer. Two quarter wave layers of different materials are used. The reflectance from a two layer AR system at normal incidence is given by:

$$R_{nm} = \frac{(n_2 - n_{nm})^2}{(n_2 + n_{nm})^2}$$ (7)

where the layer indices are shown in Fig. 4.

This has a minimum at $n_0 = n_1/(n_2/n_0)$ (8).

DIELECTRIC REFLECTOR COATINGS

Equation 5 gives the reflectance at normal incidence for a 1/4 wave layer on a substrate. If the dielectric layer has a refractive index ($n_2 = 2.32$) higher than that of the glass substrate, the reflectance of the quarter wave layer is 0.314, much higher than the 0.042 from the bare substrate.

If a second layer having an index lower than the first layer is deposited, this second layer acts as an anti-reflection coating for the first layer, decreasing the reflectance. If a third layer is added with a material having an index higher than the second layer, this last layer acts as a reflector layer to the second layer, increasing total reflectance. This way the reflectance can be built up from the 0.042 from the glass surface to close to 1.

In the air - glass system, 13 layers of alternating high index material ($n_0 = 2.2$) and low index material ($n_0 = 1.33$) produces a 0.999 reflectance at the wavelength where the layers are 1/4 wave optically thick (Fig. 6). This reflector is now substantially wavelength dependent, at wavelengths above and below the 1/4 wavelength the reflectance decreases.

In the alternating high and low index reflector stacks, manipulation of the number of layers, layer thickness and materials can produce: long pass filters, short pass filters, cold and hot mirrors, maximum and partial reflectors and beam splitters.

As a custom service we can coat substrates with Dielectric Reflector Coatings. Contact us for a quote.

METAL REFLECTOR COATINGS

In metal reflector coatings the main considerations are: reflectance, durability, hardness, adhesion, uniformity and long term stability. Most metal reflector coatings are deposited under stringent clean high vacuum conditions. The optic to be coated is first cleaned in a series of ultrasonic baths (detergent, de-ionized distilled water, and reagent grade organic solvents). Then the optic is air dried in a dust-free environment. In the vacuum chamber, the optic is heated and further cleaned by ion bombardment glow discharge.

We offer the following metal coatings:
- Bare aluminum
- Aluminum with SiO$_2$ overcoat
- Aluminum with MgF$_2$ overcoat
- Graded Chrome
- Silver with overcoat

See pages 10-4 to 10-6.

BEAM SPLITTER COATINGS

These coatings are offered only for flat optics such as windows, lenses, etc. The following coatings are offered:
- Inconel metal in a thickness which gives a spectrally neutral coating with a 32/32 beam splitting ratio from 400 - 700 nm. (Absorption ~ 0.3% )
- All dielectric beam splitter coatings for 450 - 700 nm. Four R/T ratio coatings are available: 20/80, 30/70, 50/50 and 70/30.

See page 10-10 for a detailed listing.
ANTl-REFLECTiON COATINGS

SINGLE LAYER BROADBAND AR COATING FOR GLASS AND FUSED SILICA

Magnesium fluoride is an excellent, inexpensive anti-reflection coating for windows, lenses, and beam splitters. A layer of MgF₂ on a glass or fused silica substrate reduces surface reflectance to less than 1.5% per surface over a wide spectral band. See Fig. 1. We offer single layer MgF₂ anti-reflection coatings to cover five spectral ranges from the ultraviolet to the near infrared. The thickness of the MgF₂ layer is 1/4 wave at the mid point of the wavelength range, e.g. the 400 to 700 nm, 79710 coating is 1/4 wave thick at 550 nm.

SINGLE LAYER BROADBAND AR COATING FOR ZINC SELENIDE AND ZINC SULFIDE

Because of their high index of refraction, zinc selenide and zinc sulfide have high surface reflectance losses. ZnSe has an index of refraction of 2.4 at 10.6 μm, reflection losses are < 1% per surface. ZnS has an index of refraction of 2.2 at 10.6 μm, and reflection losses of < 14% per surface. A single 1/4 wave layer of Barium Fluoride can reduce the reflection loss to ≤ 2% per surface for ZnSe and ZnS. See Fig. 2.

V Coatings

Because of their high index of refraction, zinc selenide and zinc sulfide are designed for minimum reflection. Reflection losses are reduced to ≤ 0.5% per surface for the specified wavelength range. These coatings are extremely durable and withstand up to 2 J/cm² in 10 ns pulses. Because of the high number of layers, these coatings are more sensitive to incident angle than the single layer anti-reflection coatings. We offer these coatings for normal and 45° incidence. These coatings are for fused silica substrates and lenses.

SPECIFICATIONS

Material: MgF₂
Reflectance: < 0.5% per surface avg over the 632.8 nm. Other wavelengths are available on special request.
Reflective Index: 1.4 < 10.6 μm
Meets or exceeds Mil spec compliance: Abrasion. Mil-C-675A
Adhesion. Mil-M-13508C
Hardness. Mil-M-13508C
Incident angle: 0° to 20°

ORDERING INFORMATION

Wavelength Range (nm) Model No. Prices
250 to 400 79700 $100.00
400 to 700 79710 $100.00
700 to 1100 $100.00
1100 to 1700 $100.00
1700 to 2500 $100.00

* Cost for coating each surface.
** Cost for coating each optic.

These prices are for up to 2.0 inch (50.8 mm) diameter optics. For larger sizes contact Oriel for a quote.
METALLIC REFLECTOR COATINGS

Vacuum deposited thin films of several different metals make excellent reflectors. It is difficult to polish metal substrates to the smoothness required for specular reflectance in the visible and ultraviolet, so most metallic reflectors are made by applying a thin metal film to a highly polished glass substrate. We call these coatings metallic reflector coatings to distinguish them from dielectric reflector coatings.

Metallic reflector coatings are inexpensive, cover a broad spectral range, and have good reflectance (there is some loss due to absorption). Some metal coatings, such as aluminum and silver, tarnish rapidly, and reflectance drops significantly. Due to absorption, some metal coatings, such as aluminum and gold, are excellent reflectors in the visible and ultraviolet, so most metallic reflectors are made by applying a thin metal film to a highly polished glass substrate.

ALUMINUM WITH PROTECTIVE SI02 OVERCOAT

Overcoating aluminum with silicon monoxide (SiO2) produces an excellent general purpose, broadband reflector for the visible and infrared. The reflectivity of this coating is between 65% and 90% from 400 nm to 20 μm with a dip to ~75% at around 825 nm. This coating is much more durable than bare aluminum, but can still be easily scratched; care must be used in handling. The coated optic may be cleaned using a soft optical cloth. Table 1 shows a first surface and second surface reflector.

SPECIFICATIONS

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
<th>Mil spec compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum with Si02 overcoat</td>
<td>See curve (Fig. 2)</td>
<td>Meets or exceeds</td>
</tr>
<tr>
<td>Adhesion, MI-M 13508C</td>
<td>Hardness, MI-M 13508C</td>
<td></td>
</tr>
<tr>
<td>0° to 45°</td>
<td>** Cost for coating each optic.**</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 First surface reflector (a), and second surface reflector (b).

BARE ALUMINUM COATING

Freshly deposited aluminum has an average of 90% reflectivity between 200 and 1000 nm, with an absorption band (85%) at 820 nm. From 1.0 to 30 μm, reflectivity is 94% to 99%. An oxide coating forms quickly on aluminum exposed to air. UV reflectance falls due to the oxide coating, and determination of overall reflectance results from continued exposure to chemicals in the atmosphere. We recommend a bare aluminum coating only for second surface reflectors.

SPECIFICATIONS

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
<th>Mil spec compliance</th>
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<tr>
<td>Bare aluminum</td>
<td>See curve (Fig. 2)</td>
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<tr>
<td>Adhesion, MI-M 13508C</td>
<td>Hardness, MI-M 13508C</td>
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</tr>
<tr>
<td>0° to 45°</td>
<td>** Cost for coating each optic.**</td>
<td></td>
</tr>
</tbody>
</table>

These prices are for up to 2.0 inch (50.8 mm) diameter optics. For larger sizes contact Ortel for a quote.

UV ALUMINUM COATING

The aluminum coating has a protective layer of magnesium fluoride. The MgF2 overcoat prevents oxidation and enhances reflectance from the UV to the infrared. This coating is easily scratched, and must be cleaned carefully. See pages 11-1 to 11-3 for cleaning supplies.

SPECIFICATIONS

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
<th>Mil spec compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum with MgF2 overcoat</td>
<td>See curve (Fig. 2)</td>
<td>Meets or exceeds</td>
</tr>
<tr>
<td>Adhesion, MI-M 13508C</td>
<td>Hardness, MI-M 13508C</td>
<td></td>
</tr>
<tr>
<td>0° to 45°</td>
<td>** Cost for coating each optic.**</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 Typical rear normal incidence reflectance of our metallic reflector coatings. The reflectance of the aluminum coating falls rapidly in the ultraviolet when it is exposed to air.

GRADED CHROME - GOLD COATING

Gold is an excellent reflector from the near IR (800 nm) to the far IR (30 μm); in this region reflectivity exceeds 99%. Beyond 1.5 μm, reflectance is greater than 99%. Unlike aluminum, gold is resistant to surface oxidation, but it is extremely soft and care should be used in handling and cleaning. Clean a gold coated optic using a non-contact flow of water, organic solvent and dry air. Gold adheres poorly to most types of glasses. An intermediate layer of chromium, which adheres strongly to glass optics, is required. We apply a thin layer of chromium to the optic, and then deposit the gold. The result is a coating that is pure chrome, chrome with gold, and pure gold.

SPECIFICATIONS

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
<th>Mil spec compliance</th>
</tr>
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<tbody>
<tr>
<td>Graded Chromium - Gold</td>
<td>See curve</td>
<td>Meets or exceeds</td>
</tr>
<tr>
<td>Adhesion, MI-M 13508C</td>
<td>Hardness, MI-M 13508C</td>
<td></td>
</tr>
<tr>
<td>0° to 45°</td>
<td>** Cost for coating each optic.**</td>
<td></td>
</tr>
</tbody>
</table>

SILVER WITH DIELECTRIC OVERCOAT

As bare silver tarnishes rapidly in air and the reflectance falls quickly, we only recommend bare silver for internal or second surface reflectors. We offer an efficient dielectric protected silver coating as a first surface reflector. A layer of magnesium fluoride protects the silver from degradation. The 79938 has high visible and infrared reflectance and is durable. You can clean it with our 49122 Metallic Reflector Cleaning Fluid described on page 11-1.

These prices are for up to 2.0 inch (50.8 mm) diameter optics. For larger sizes contact Ortel for a quote.

SPECIFICATIONS

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
<th>Mil spec compliance</th>
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</thead>
<tbody>
<tr>
<td>Silver with Dielectric Overcoat</td>
<td>See curve</td>
<td>Meets or exceeds</td>
</tr>
<tr>
<td>Adhesion, MI-M 13508C</td>
<td>Hardness, MI-M 13508C</td>
<td></td>
</tr>
<tr>
<td>0° to 45°</td>
<td>** Cost for coating each optic.**</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 Typical rear normal incidence reflectance of our metallic reflector coatings. The reflectance of the aluminum coating falls rapidly in the ultraviolet when it is exposed to air.

These prices are for up to 2.0 inch (50.8 mm) diameter optics. For larger sizes contact Ortel for a quote.
Fig. 2.15. Angular configuration for scattering of electromagnetic radiation from a bound electron.

\[
\sigma_A(\lambda) = \frac{8\pi}{3} \left[ \frac{\pi^4(n^2 - 1)^4}{N^2\lambda^4} \right] \quad (2.132)
\]

\[
\sigma^R_\sigma = \frac{d\sigma_\sigma(\theta = \pi)}{d\Omega} = \frac{\pi^2(n^2 - 1)^2}{N^2\lambda^4} \quad (2.133)
\]

\[
\sigma^R(\lambda) = 5.45 \left[ \frac{550}{\lambda(\text{nm})} \right]^4 \times 10^{-28} \text{ cm}^2 \text{ sr}^{-1} \quad (2.134)
\]

\[
\beta^R_\sigma(\lambda) = N\sigma^R_\sigma(\lambda) = 1.39 \left[ \frac{550}{\lambda(\text{nm})} \right]^4 \times 10^{-8} \text{ cm}^{-1} \text{ sr}^{-1} \quad (2.135)
\]
**MOLECULAR RAYLEIGH SCATTERING**

**TABLE 2.3. RAYLEIGH BACKSCATTERING CROSS SECTION $\sigma^R_\pi$ AT 694.3 nm**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Formula</th>
<th>$\sigma^R_\pi$ (10$^{-28}$ cm$^2$ sr$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H$_2$</td>
<td>0.44</td>
<td>a, b</td>
</tr>
<tr>
<td>Deuterium</td>
<td>D$_2$</td>
<td>0.43</td>
<td>a</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>0.03</td>
<td>a, b</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O$_2$</td>
<td>1.80</td>
<td>b</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N$_2$</td>
<td>2.14</td>
<td>a, b</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO$_2$</td>
<td>6.36</td>
<td>b</td>
</tr>
<tr>
<td>Methane</td>
<td>CH$_4$</td>
<td>4.60</td>
<td>a, b</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N$_2$O</td>
<td>6.40</td>
<td>a</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>0.09</td>
<td>b</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>2.00</td>
<td>a, b</td>
</tr>
<tr>
<td>Xenon</td>
<td>Xe</td>
<td>11.60</td>
<td>a</td>
</tr>
</tbody>
</table>

Freons—important to stratospheric studies:

| Freon-12     | CCl$_2$F$_2$ | 36.08                   | b       |
| Freon-13B1   | CBrF$_3$     | 24.87                   | b       |
| Freon-14     | CB$_4$       | 4.91                     | b       |
| Freon-22     | CHClF$_2$    | 21.90                   | b       |

*a Rudder and Bach (1968).

Fig. 3.21. Theoretical distribution of vibrational-rotational Raman spectrum ($v = 0 \rightarrow 1$ vibrational transition) at 300 K, showing the $O$-, $Q$-, and $S$-branch structures and the differential Raman-scattering cross section for $N_2$ molecules (Inaba and Kobayasi, 1972).

Fig. 3.22. Theoretical distribution of Raman volume backscattering coefficient due to a molecular mixture contained in a typical oil smoke as a function of Raman-shifted frequency (Inaba and Kobayasi, 1972).

![Image of Fig. 3.21]

![Image of Fig. 3.22]

![Image of Table 3.3]

**Table 3.3.** RAMAN ($Q, O + S$ BRANCHES, AND TOTAL), PURE-ROTATION RAMAN, AND RAYLEIGH BACKSCATTERING CROSS SECTIONS

<table>
<thead>
<tr>
<th>Molecule</th>
<th>$\omega_0/2\pi$ (cm$^{-1}$)</th>
<th>$Q$-branch</th>
<th>$O + S$ Branches</th>
<th>Total</th>
<th>Rayleigh</th>
<th>Rotation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_2$</td>
<td>2329.66</td>
<td>2.9 x 10$^{-20}$</td>
<td>5.5 x 10$^{-21}$</td>
<td>3.5 x 10$^{-20}$</td>
<td>3.9 x 10$^{-27}$</td>
<td>1.1 x 10$^{-21}$</td>
<td>4.0 x 10$^{-27}$</td>
</tr>
<tr>
<td>$O_3$</td>
<td>1556.26</td>
<td>3.3 x 10$^{-20}$</td>
<td>1.3 x 10$^{-20}$</td>
<td>4.6 x 10$^{-20}$</td>
<td>3.3 x 10$^{-27}$</td>
<td>2.0 x 10$^{-21}$</td>
<td>15 x 10$^{-27}$</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>1388.15</td>
<td>3.4 x 10$^{-20}$</td>
<td>7.3 x 10$^{-21}$</td>
<td>4.2 x 10$^{-20}$</td>
<td>9.0 x 10$^{-27}$</td>
<td>8.3 x 10$^{-21}$</td>
<td>9.9 x 10$^{-27}$</td>
</tr>
<tr>
<td>$CH_4$</td>
<td>2914.2</td>
<td>2.1 x 10$^{-29}$</td>
<td>0</td>
<td>2.1 x 10$^{-29}$</td>
<td>8.6 x 10$^{-27}$</td>
<td>0</td>
<td>8.6 x 10$^{-27}$</td>
</tr>
</tbody>
</table>

* Based on the polarizability tensor theory of Placzek (1934); reproduced from Inaba (1976).
<table>
<thead>
<tr>
<th>Molecule</th>
<th>Raman Shift Wavelength (cm⁻¹)</th>
<th>Raman Shifted Wavelength (nm)</th>
<th>Raman Differential Cross Section (10⁻²⁰ cm² sr⁻¹)</th>
<th>Cross Section Relative to O-branch of N₂</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freon 114°</td>
<td>442</td>
<td>342.2</td>
<td>4.2(⁰)</td>
<td>1.4(P)</td>
<td>1</td>
</tr>
<tr>
<td>CCl₄</td>
<td>459</td>
<td>342.4</td>
<td>26.0</td>
<td>9.3(⁰)</td>
<td>2</td>
</tr>
<tr>
<td>Freon C-310°</td>
<td>699</td>
<td>345.2</td>
<td>7.8(⁰)</td>
<td>2.77(P)</td>
<td>1</td>
</tr>
<tr>
<td>NO₂(τ₁)</td>
<td>754</td>
<td>345.7</td>
<td>24.0</td>
<td>8.6</td>
<td>3</td>
</tr>
<tr>
<td>SF₆</td>
<td>775</td>
<td>346.1</td>
<td>12.0</td>
<td>4.3</td>
<td>2</td>
</tr>
<tr>
<td>Freon 116°</td>
<td>807</td>
<td>346.5</td>
<td>7.3(⁰)</td>
<td>2.6(P)</td>
<td>1</td>
</tr>
<tr>
<td>Freon 116°</td>
<td>908</td>
<td>347.7</td>
<td>5.3(⁰)</td>
<td>1.9(P)</td>
<td>1</td>
</tr>
<tr>
<td>C₆H₄(CH₃) (τ₁)</td>
<td>991</td>
<td>348.7</td>
<td>44.0</td>
<td>15.7</td>
<td>2.3</td>
</tr>
<tr>
<td>O₃</td>
<td>1103.3</td>
<td>350.2</td>
<td>6.4</td>
<td>2.3</td>
<td>4</td>
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<tr>
<td>SO₂</td>
<td>1151.5</td>
<td>350.8</td>
<td>17.0</td>
<td>6.1</td>
<td>3.5</td>
</tr>
<tr>
<td>CO₂(2τ₁)</td>
<td>1285</td>
<td>352.5</td>
<td>3.1</td>
<td>1.1</td>
<td>2.3</td>
</tr>
<tr>
<td>NO₂(τ₁)</td>
<td>1320</td>
<td>352.8</td>
<td>51.0</td>
<td>18.2</td>
<td>3</td>
</tr>
<tr>
<td>CO₂(τ₁)</td>
<td>1388</td>
<td>353.7</td>
<td>4.2</td>
<td>1.3</td>
<td>2.3</td>
</tr>
<tr>
<td>O₃</td>
<td>1556</td>
<td>355.9</td>
<td>4.6</td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>C₃H₆(CH₃) (τ₁)</td>
<td>1623</td>
<td>356.6</td>
<td>5.4(⁰)</td>
<td>1.2(Q)</td>
<td>2.3</td>
</tr>
<tr>
<td>NO</td>
<td>1877</td>
<td>360.0</td>
<td>1.5</td>
<td>0.54</td>
<td>3.5</td>
</tr>
<tr>
<td>CO</td>
<td>2145</td>
<td>363.5</td>
<td>3.6</td>
<td>1.3</td>
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<tr>
<td>N₂</td>
<td>2330.7</td>
<td>365.9</td>
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<td>1.3</td>
<td>2.6</td>
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<tr>
<td>H₂S</td>
<td>2611</td>
<td>369.7</td>
<td>19.0</td>
<td>6.8</td>
<td>2.5</td>
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<tr>
<td>CH₃OH(τ₁)</td>
<td>2846</td>
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<td>14.0</td>
<td>5.0</td>
<td>2.3</td>
</tr>
<tr>
<td>C₂H₄⁺</td>
<td>2885</td>
<td>373.4</td>
<td>124.0(C)</td>
<td>44.3(C)</td>
<td>1</td>
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<tr>
<td>C₂H₄⁻</td>
<td>2886</td>
<td>373.4</td>
<td>81.8(C)</td>
<td>29.2(C)</td>
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<tr>
<td>C₂H₄⁺</td>
<td>2886</td>
<td>373.4</td>
<td>124.0(C)</td>
<td>48.0(C)</td>
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<td>C₂H₄⁻</td>
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<td>373.8</td>
<td>93.5(C)</td>
<td>33.4(C)</td>
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</tr>
<tr>
<td>CH₃⁺</td>
<td>2914</td>
<td>373.8</td>
<td>32.3(C)</td>
<td>11.5(C)</td>
<td>1</td>
</tr>
<tr>
<td>C₂H₈(τ₁)</td>
<td>2941</td>
<td>374.2</td>
<td>21.0</td>
<td>7.3</td>
<td>2.3</td>
</tr>
<tr>
<td>C₂H₈⁺</td>
<td>2942</td>
<td>374.2</td>
<td>102.5(C)</td>
<td>36.6(C)</td>
<td>1</td>
</tr>
<tr>
<td>C₂H₈⁻</td>
<td>2943</td>
<td>374.2</td>
<td>65.6</td>
<td>22.7</td>
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</tr>
<tr>
<td>C₂H₄OH(2τ₁)</td>
<td>2955</td>
<td>374.4</td>
<td>19.0</td>
<td>6.8</td>
<td>2.3</td>
</tr>
<tr>
<td>C₂H₆⁺</td>
<td>3010</td>
<td>375.2</td>
<td>89.6(C)</td>
<td>32.0</td>
<td>2</td>
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<tr>
<td>C₂H₆⁻</td>
<td>3017</td>
<td>375.3</td>
<td>14.0</td>
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<td>C₂H₆⁺</td>
<td>3020</td>
<td>375.3</td>
<td>28.6</td>
<td>10.2</td>
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<tr>
<td>C₂H₈(τ₁)</td>
<td>3064</td>
<td>375.9</td>
<td>106(Q)</td>
<td>5.7(Q)</td>
<td>2</td>
</tr>
<tr>
<td>C₂H₈⁺</td>
<td>3070</td>
<td>376.0</td>
<td>87.7(C)</td>
<td>31.4(C)</td>
<td>1</td>
</tr>
<tr>
<td>C₂H₈⁻</td>
<td>3072</td>
<td>376.0</td>
<td>30.0</td>
<td>10.7</td>
<td>2.3</td>
</tr>
<tr>
<td>NH₃⁺</td>
<td>3334</td>
<td>379.8</td>
<td>11.0</td>
<td>3.9</td>
<td>2</td>
</tr>
<tr>
<td>C₂H₆⁻</td>
<td>3372</td>
<td>380.3</td>
<td>3.36</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>H₂O</td>
<td>3651.7</td>
<td>384.4</td>
<td>7.8(Q)</td>
<td>2.8(Q)</td>
<td>2.6</td>
</tr>
<tr>
<td>H₂</td>
<td>4140.2</td>
<td>392.2</td>
<td>8.7</td>
<td>3.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>

*Q indicates the value of the Q-branch vibrational Raman backscattering cross section: C indicates a broad multipeaked structure associated with the C—H stretch mode; P indicates a cross section based on a ratio of peak intensities rather than spectrally integrated signals.


'-1,2-Dichlorotetrafluoroethane.'

'Octafluorocyclobutane.'

'Hexafluorobenzene.'

'Tetrafluoromethane.'
### TABLE 6.1. OPTICAL INTERACTIONS OF RELEVANCE TO LASER ENVIRONMENTAL SENSING

<table>
<thead>
<tr>
<th>Technique</th>
<th>Physical description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh scattering</td>
<td>Laser radiation elastically scattered from atoms or molecules is observed with no change of frequency.</td>
</tr>
<tr>
<td>Mie scattering</td>
<td>Laser radiation elastically scattered from small particulates or aerosols (of size comparable to wavelength of radiation) is observed with no change in frequency.</td>
</tr>
<tr>
<td>Raman scattering</td>
<td>Laser radiation inelastically scattered from molecules is observed with a frequency shift characteristic of the molecule ((h\nu - h\nu^* = E)).</td>
</tr>
<tr>
<td>Resonance scattering</td>
<td>Laser radiation matched in frequency to that of a specific atomic transition is scattered by a large cross section and observed with no change in frequency.</td>
</tr>
<tr>
<td>Fluorescence</td>
<td>Laser radiation matched to a specific electronic transition of atom or molecule suffers absorption and subsequent emission at lower frequency; collision quenching can reduce effective cross section of this process; broadband emission is observed with molecules.</td>
</tr>
<tr>
<td>Absorption</td>
<td>Observe attenuation of laser beam when frequency matched to the absorption band of given molecule.</td>
</tr>
<tr>
<td>Differential absorption and scattering (DAS)</td>
<td>The differential attenuation of two laser beams is evaluated from their backscattered signals when the frequency of one beam is closely matched to a given molecular transition while the other's frequency is somewhat detuned from the transition.</td>
</tr>
</tbody>
</table>
Fig. 2.19. Representative diameters of common atmospheric particles (Johnson, 1969).

Fig. 2.27. Aerosol extinction coefficient as a function of wavelength (Wright et al., 197\ldots)
Transmittance spectra for a vertical path from ground to space from 0.25 to 4 μm, using the rural aerosol model, 23-km VIS and the U.S. Standard Model Atmosphere.

Fig. 51 Spectral distribution curves related to the sun; shaded areas indicate absorption at sea level due to the atmospheric constituents shown. [Valley (1965).]
Fig. 3.15. Lorentz dispersion line profile function.

Fig. 3.17. Doppler-broadened Gaussian line profile function.

Fig. 3.18. Convolution of Gaussian and dispersive profiles.

Background Sky Radiance, \( S_b(\lambda, T, \mu_m, \mu_s) \)
# Light Intensity Conversion Chart

<table>
<thead>
<tr>
<th>SCOTOPIC VISION</th>
<th>PHOTOPIC VISION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stellar Magnitude</strong></td>
<td><strong>Lumens per Square Foot (Foot-Candles)</strong></td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>$10^4$</td>
</tr>
<tr>
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<td>$10^3$</td>
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<tr>
<td>$10^{-6}$</td>
<td>$10^1$</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>$10$</td>
</tr>
<tr>
<td>$10^{-8}$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>$10^3$</td>
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<tr>
<td>$10^{-10}$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^{-11}$</td>
<td>$10^5$</td>
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<tr>
<td><strong>Lumens per Square Meter (Lux)</strong></td>
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</tr>
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<td>$10^1$</td>
<td>$10^6$</td>
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<tr>
<td>$10^2$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$10^4$</td>
</tr>
<tr>
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<td>$10^3$</td>
</tr>
<tr>
<td>$10^5$</td>
<td>$10^2$</td>
</tr>
<tr>
<td><strong>Photons/mm² (550 nm Band)</strong></td>
<td></td>
</tr>
<tr>
<td>$10^14$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$10^15$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td><strong>Watts/mm²</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Overcast Night Sky</strong></td>
<td><strong>Clear Night Sky</strong></td>
</tr>
</tbody>
</table>

**Intensifier**...plus **Auto-Iris**...plus **Auto-Gating**
Fig. 6.1. Optical interactions of relevance to laser environmental sensing.
**TRANSMITTER SYSTEM**

- **DETECTED VOLUME**
- **SURFACE AREA** $4\pi r^2$
- **REFLECTED LIGHT COLUMN**
- **RECEIVING MIRROR**
- **BEAM EXPANDER**

**LASER (Nd-YAG)**
The first ruby-laser configuration.

Ruby-laser energy levels.

Optical Schematic of the Model 899-LC Titanium Sapphire Laser

Typical Tuning Curve of the Model 899-LC Titanium Sapphire Laser
Figure 20-2. Energy levels in Nd-YAG (simplified).

Figure 14-1. Energy levels in neutral nitrogen molecules involved in 337.1-nm laser transition. The broad curves represent electronic energy levels, with the lines within the potential wells representing vibrational energy levels for molecules in those electronic states. The laser transition is a vibronic one in which both electronic and vibrational energy states change.

Figure 13-4. Typical output characteristics of a Raman-shifting cell for operation at 1-Hz repetition rate and optimum hydrogen pressure. S indicates Stokes-shifted line n; AS indicates anti-Stokes-shifted line n. The pumping laser is identified in the upper right corner of each small graph. (Courtesy of Lambda Physik.)
Figure 7-1 Energy levels in a helium-neon laser, with major laser transitions indicated. Collisions transfer energy from helium atoms to neon atoms, which drop through laser transitions on their way to the ground state. (Courtesy of Melles Griot.)

Figure 8-1 Relative intensities of major lines of argon and krypton for one laser model. Strengths of various lines may differ somewhat between models. (Courtesy of Spectra-Physics Inc.)

Figure 8-2 Energy levels of singly ionized argon, showing only the blue-green laser lines. Actual energy-level structure is considerably more complex, as indicated by the many possible emission lines.
Figure 10-1 Energy-level structure in the CO₂ laser, showing the relevant vibrational modes of the CO₂ molecule. Numbers in parentheses indicate the excitation levels of the symmetric stretching, bending, and asymmetric stretching vibrational modes, respectively, of the molecule.

Figure 12-2 Relative strengths of copper vapor lines as a function of temperature. (Courtesy of Oxford Lasers Ltd.)

Figure 12-3 Wavelengths and relative intensities of some major neutral metal vapor laser lines. (Courtesy of Quantron Optics Pty. Ltd.)
Figure 11-2. Basic elements of a commercial continuous-wave chemical laser include a gas supply, a discharge chamber that produces free fluorine, nozzles which mix the reactants, a mixing region, a laser resonator, and a vacuum pump to collect spent gas. Gas flow is from left to right; the laser beam is perpendicular to the gas flow.

Figure 11-3. Vibrational energy levels of HF and DF, shown with the energies remaining with the HF or DF molecules after certain reactions. (From Chester, 1976.)

Figure 11-4a. (a) HF and (b) DF emission lines from a continuous-wave chemical laser. (Courtesy of Helias Inc.)
Figure 14.27 Laser modes: (a) illustrates the nomenclature. (b) compares the broad atomic emission with the narrow cavity modes. (c) depicts three operation configurations for a cw gas laser, first showing several longitudinal modes under a roughly Gaussian envelope, then several longitudinal and transverse modes, and finally a single longitudinal mode.

Figure 14.28 Mode patterns (without the faint interference fringes this is what the beam looks like in cross section). (Photos courtesy Bell Telephone Laboratories.)
<table>
<thead>
<tr>
<th>NY82 Series</th>
<th>NY81-10</th>
<th>NY82-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition Rate</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Energy (mJ)</td>
<td>1400</td>
<td>1200</td>
</tr>
<tr>
<td>1064nm</td>
<td>750</td>
<td>600</td>
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<tr>
<td>532nm (Type II doubling)</td>
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<td>275</td>
</tr>
<tr>
<td>266nm</td>
<td>120</td>
<td>85</td>
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<td>Pulsedwidth (ns)</td>
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<tr>
<td>532nm</td>
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<tr>
<td>355nm</td>
<td>0.45</td>
<td>0.45</td>
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<tr>
<td>Beam passing stability (pW)</td>
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<td>9.5</td>
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<tr>
<td>Laser (A)</td>
<td>250</td>
<td>250</td>
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<tr>
<td>Energy stability (%)</td>
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<tr>
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<td>3.5</td>
<td>3.5</td>
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<tr>
<td>532nm</td>
<td>4.0</td>
<td>4.0</td>
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<tr>
<td>355nm</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Power drift (%)</td>
<td>3.0</td>
<td>3.0</td>
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<tr>
<td>1064nm</td>
<td>6.0</td>
<td>7.0</td>
</tr>
<tr>
<td>532nm</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Beam Spatial Profile (fit to Gaussian)</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>Near Field (cm)</td>
<td>0.95</td>
<td>0.90</td>
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<tr>
<td>Far Field (m)</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Service Requirements</td>
<td>Power</td>
<td>16A</td>
</tr>
<tr>
<td>220V, single</td>
<td>18A</td>
<td>4</td>
</tr>
<tr>
<td>208V, 30</td>
<td>380V PM 40-60PSI</td>
<td></td>
</tr>
</tbody>
</table>

(All specifications at 1064nm unless otherwise noted)

1. Full Width Half Maximum.
2. Full Width Half Maximum (1cm = 100 Hz).
3. 10% energy reduction.
4. Full angle for 80% energy.
5. Centered respect to external trigger; line with S1500.
6. shot-to-shot for 96% of pulsed.
7. from average for 8 hours.
8. A least squares fit to a Gaussian profile.
9. A perfect fit would have a coefficient of 1.

NY82 Series

Beam Spatial Profiles

Beam Temporal Profiles

Optical Layout NY82

Physical Layout NY82

Continuum, 3150 Central Expressway, Santa Clara, CA 95051 Tel: 408.727.3240, FAX: 408.727.3250
Beam Expanders
RECEIVER SYSTEM

RECEIVER

1) 24" optical flat: Reflectivity 90% @ 532nm  
    coating: AlSiO 84% @ 355nm  
    88% @ 607nm

2) Cassagrain telescope primary mirror:  
    Reflectivity 87% @ 532nm  
    coating: AlSiO₂ 89.5% @ 355nm  
    87% @ 607nm

3) Secondary mirror: Reflectivity 87% @ 532nm  
    89.5% @ 355nm  
    87% @ 607nm

4) 2", high reflective low power mirror:  
    Reflectivity 99.8% @ 532,355,and 607nm.

5) 1" fabry lens: Reflectivity .3% @  
    AR coated 532,355,607nm

6) 1" collimating lens: Reflectivity .3% @  
    AR coated 532,355,607nm

\[ R_{eff} = \begin{align*}  
67.4\% @ 532nm \\
66.8\% @ 355nm \\
66.1\% @ 607nm
\end{align*} \]
Fig. 6.4. Telescope configurations: (a) Newtonian; (b) Gregorian; (c) Cassegrainian (Ross, 1966).
Fig. 6 $D$ vs. $\lambda$ for selected detectors.
Voltage Divider Consideration

VOLTAGE DIVIDER CIRCUITS

To operate a photomultiplier tube, a high voltage of about 1000V is usually applied between the photocathode (K) and anode (P). To minimize noise generated by these Zener diodes, a high voltage current is used to separate the high positive voltage applied to the anode from the signal, making it impossible to obtain a DC signal output.

1) Anode Grounding and Cathode Grounding

In either the grounded anode or grounded cathode configuration, when the incident light on the photocathode is increased in level to increase the anode current, the relationship between the incident light level and the anode current deviates from the ideal linear relationship and the photomultiplier tube goes into saturation.

2) Voltage Divider Circuits and Output Linearity

In either the grounded anode or grounded cathode configuration, when the incident light on the photocathode is increased in level to increase the anode current, the relationship between the incident light level and the anode current deviates from the ideal linear relationship and the photomultiplier tube goes into saturation.

2-1) DC Operation Output Linearity

If we consider the case of deriving DC output using the voltage divider circuit shown in Figure 2 at (A), when the incident light level is increased, the current flowing through the Zener diode is insufficient. This decreases electron collection efficiency of the photocathode, leading to the danger of significant deterioration. For this reason, when designing the housing for a photomultiplier tube and when using an electrostatic or magnetic shield case, extreme care is required.

In addition, when using foam rubber or similar material to mount the tube in its housing, it is essential that material having sufficiently good insulation properties be used. This problem can be solved by applying a black conductive layer around the bulb and connecting to the cathode potential (called HA Coating). However, in scintillation counting, it is often impossible to use this technique, since the grounded scintillator is in intimate contact with the photomultiplier tube. In such cases, the cathode must be grounded, as shown in Figure 3, with a high positive voltage applied to the anode. Using this scheme, a coupling capacitor C is used between the last dynode and the anode as shown in Figure 2 at (B), and, if necessary, the previous stages as well.

However, using the former technique, the power which must be dissipated within the voltage divider circuit increases. This may raise the photomultiplier tube temperature, and subsequently results in an increase in dark current and possible variations in output. Using the latter described technique, also, if the current flowing in the Zener diode is insufficient, Zener diode noise can increase with the danger of reducing the output signal-to-noise ratio. To absorb possible noise capacitors should be connected across the Zener diodes. Note, also, that D1 and D2 of Figure 2 are used to establish a constant voltage on the electron focusing electrode regardless of variations in the applied voltage, and are thus not related to output linearity.

2-2) Pulse Operation Output Linearity

To use pulse operation with a photomultiplier tube, ceramic disk capacitors having good frequency characteristics are connected in parallel with the voltage divider in the last several stages as shown in Figure 5 (A). Those capacitors provide electric charge during the duration of the pulse and result in a significant increase in the maximum peak current.

Using this type of operation, to achieve good output linearity (better than 3%), the capacitor value connected between the last stage and the anode should be roughly selected as follows.

\[ C = \frac{100}{Q} \text{ (farads)} \]

where:
- \( Q \): Electric charge for one output pulse (coulombs)
- \( V \): Voltage between the last stage and the anode (volts)

When adding capacitors to the last few stages, the electric charges required by the preceding stage should be assumed to be 1/2 to 1/3.

When the pulse output increases further, even using this technique, it will result in saturated output by virtue of the space charge effect in the region of the anode. In such cases, the voltage divider resistance values from the central stages to the last stages should be changed so that the voltage gradually increases towards the last stage. This scheme is known as a tapered voltage divider circuit and is effective insofar as the interstage breakdown voltages will permit. In many cases.

Figure 1: Schematic Representation of PMT

Figure 2: Voltage Divider Circuit with Anode Grounded

(A) Using Resistors Only

(B) Using Resistors and Zener Diodes

Figure 3: Voltage Divider Circuit with Cathode Grounded

Figure 4: Output Linearity of PMT
however, since this is accompanied by a decrease in current amplification, it is necessary to increase the applied voltage. If the value of $R_i$ in Figure 5 is made unnecessarily high, the voltage drop $\Delta V$ across this resistance will reduce the voltage between the last stage and the anode. And the effect of the space charge and a reduction in secondary electron collection efficiency of the anode will cause a deterioration in output linearity. In addition, care is required since mismatching of impedances with the output cable and any external circuitry can cause ringing. Techniques used to obtain linear output using parallel capacitors or tapered voltage divider circuits apply as well to the grounded cathode circuit configuration and the anode positive voltage circuits.

Figure 5: Voltage Divider Circuits for Pulse Operation

(A) Using Parallel Capacitors

(B) Tapered Divider Circuit

TYPES OF SOCKET ASSEMBLIES
As discussed in the previous section, various cautions are required in making up the voltage divider circuit. To free the user from the necessity of designing voltage divider circuits and performing troublesome parts selection, Hamamatsu provides a variety of socket assemblies which enable sufficient performance to be derived from photomultiplier tubes by making simple connections only. Refer to the types of socket assemblies listed on page 5.

1. D Type Socket Assemblies (E717 Series, E990 Series etc.)

The D type socket assemblies have a built-in voltage divider in a metallic or plastic container, as shown in Figure 6. A selection guide is provided on page 7, enabling D type socket assemblies to be selected for individual application requirements. Note that this catalog includes only those types intended for general applications, and Hamamatsu is ready to produce special socket assemblies to individual user specifications.

Three types of D type socket assemblies are available with different circuit configurations. Figure 7 shows the general method used to make connection to an external circuit.

Figure 6: D Type Socket Assembly

2. DA Type Socket Assemblies (C1053 Series, C1556 Series)

The DA type socket assemblies have a built-in voltage divider and amplifier to convert the low-level, high-impedance current output of the photomultiplier tube to a low-impedance voltage output. Since the high-impedance output of the photomultiplier tube is connected to the amplifier circuit at a minimum possible distance, the problem of external noise induced in connecting cables is eliminated.

The DA type socket assemblies are available with a bandwidth of DC to 5 MHz for the C1053 series and DC to 10 kHz for the C1556 series. Either series is available for 1-1/8" (28 mm) diameter side-on and head-on photomultiplier tubes as standard products. In addition, variants having a BNC connector in place of the photomultiplier socket section are also available. This type enables use of other photomultiplier tubes in combination with an appropriate D type socket assembly.

PHOTOMULTIPLIER TUBE VOLTAGE DEPENDENCE

Photoelectrons emitted from the photocathode of a photomultiplier tube are directed by the electron lens system and collide with the first dynode where several times this number of electrons are emitted as secondary electrons. This multiplication process of secondary electrons is repeated at latter stage dynodes, so that when electrons finally reach the anode, the number of electrons is approximately $10^n$ times the original number emitted from the photocathode.

The relationship of the electron emission ratio $d$ for each dynode stage to the applied voltage is expressed as follows.

$$d = A \cdot e^{-E/n}$$

Where $A$ is a constant, $E$ is the interstage voltage, and $e$ is another constant determined by the dynode material and geometric structure. The value of $e$ is usually in the range 0.7 to 0.8. When a voltage $V$ is applied between the anode and photocathode of a photomultiplier tube having $n$ dynode stages, the overall current amplification $G$ is given as follows.

$$G = (A \cdot e^{-E/n})^n = A^n \cdot e^{-nE} = K \cdot V^n$$

(K is a constant)

(The usual type of photomultiplier tube uses 9 to 12 stages of dynodes and, as shown in Figure 1, the current amplification is proportional to the 6th to 10th power of the voltage applied between the cathode and anode. This essentially means that the output of the photomultiplier tube is extremely sensitive to variations in applied voltage. Thus the requirements in stability of the power supply must be at least 10 times as stable as the output stability required of the photomultiplier tube.)

Hamamatsu regulated high voltage power supplies are the products of many years of experience as a specialist in photomultiplier tube development and manufacture. Various models are provided, ranging from modular types to general-purpose bench-top types. All models are designed with requirements that arise in photomultiplier tube operations.

Figure 7: Current Amplification vs. Supply Voltage

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Parameters</th>
<th>Features</th>
<th>Output Voltage</th>
<th>Output Polarity</th>
<th>Output Current</th>
<th>Input Voltage</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>C655</td>
<td>High Stability</td>
<td>−200 to −1150 V</td>
<td>Neg. 5 mA</td>
<td>±15 Vdc</td>
<td>3.3 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3350</td>
<td>±5 kV Output, Large Current</td>
<td>0 to ±3000 V</td>
<td>Pos./Neg. 10 mA</td>
<td>±15 Vdc</td>
<td>8 kg</td>
<td></td>
<td></td>
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<td>C2533</td>
<td>Computer Compatible</td>
<td>±200 to ±3300 V</td>
<td>Pos./Neg. 5 mA</td>
<td>±15 Vdc</td>
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<td>C3360</td>
<td>−5 kV Output</td>
<td>0 to −500 V</td>
<td>Neg. 1 mA</td>
<td>±15 Vdc</td>
<td>3.5 kg</td>
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<tr>
<td>C309-01</td>
<td>Large Current Modular Type</td>
<td>−400 to −800 V</td>
<td>2 mA</td>
<td>+15 Vdc</td>
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<td>High Stability Modular Type</td>
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<td>0.7 mA</td>
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<td>120 g</td>
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<td>C309-04</td>
<td>−1.6 kV Output Modular Type</td>
<td>−400 to −1000 V</td>
<td>1 mA</td>
<td>+15 Vdc</td>
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<td>Small Modular Type</td>
<td>−190 to −1000 V</td>
<td>0.5 mA</td>
<td>+15 Vdc</td>
<td>100 g</td>
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</table>
COOLERS

Cooling Effect on Dark Current

FACTORS OF DARK CURRENT

The dark current of a photomultiplier tube is a slight output current which flows when a high voltage is applied to the tube and no light is entering the photocathode. Since dark current deteriorates the S/N ratio, it is a factor which establishes the minimum limit of detection when the output current is extremely low, when measuring extremely low-level light.

Factors which affect dark current can be classified into the seven described below. The degree to which each of these factors affects dark current will depend, however, on the type of photomultiplier tube and will vary from tube to tube and with respect to operation conditions.

1. Thermionic emission of electrons from the photocathode and dynode surfaces.
2. Leakage current between electrodes and pins. This is chiefly due to impurities on the electrode supporting materials, glass stem and plastic base surfaces and on the socket surfaces.
3. Ion current flowing as the result of ionization of residual gases inside the bulb.
4. Photoelectron emission as a result of collision of internal electrons and ions with electrode supporting materials and glass.
5. Photoelectron emission by glass scintillation as a result of gamma rays emitted from radioactive elements (chiefly *K) within the glass bulb.
6. Photoelectron emission caused by Cherenkov radiation due to cosmic rays passing through the glass.
7. Field emission of electron from the photocathode surface and dynode surfaces.

Figure 1 shows the relationship between the voltage applied between the cathode and anode of a photomultiplier tube and the anode dark current. This characteristic curve can be divided into three regions. In the low-voltage region A, the major cause of dark current is the leakage current 2) and in the high-voltage region C, 3), 4) and 7) become the governing factors which determine the dark current. In contrast to this, in the region B which approximates actual operation condition, thermal electron emission is the governing factor. From this behavior, it can be seen that cooling the photocathode surface and dynodes would be very effective in reducing dark current.

COOLING EFFECT

Figure 2 shows a comparison of the temperature characteristics of dark current for various photocathode materials in a photomultiplier tube of the same shape and dynode structure. From this figure, it can be seen that, as the work function becomes smaller (multialkali - S-1: silver oxide cesium), the influence of temperature in determining the dark current increases. Essentially, this means that the effectiveness of refrigeration in reducing dark current and improving the S/N ratio increases. In this figure, although the cooling effect decreases in the region below -20 to -30°C.

This is attributable to the fact that the contribution of factors other than thermionic emission becomes relatively large in this region. In photon counting applications since the leakage current can be ignored, it is possible to achieve greater effectiveness from cooling.

MAGNETIC SHIELD CASES

Influence of Magnetic Fields and Magnetic Shielding

The photomultiplier tube is a type of vacuum tube in which photoelectrons emitted from the photocathode repeatedly collide with dynodes and are multiplied before they reach the anode. The degree of multiplication varies significantly depending upon the position of the collision on the dynode. Therefore, external magnetic fields can cause electrons to be deflected from their normal paths, causing a loss in electron multiplication factors. Essentially, the photomultiplier tube output is extremely susceptible to the effects of magnetic fields. For example, since even the terrestrial magnetic field has quite an effect, merely rotating the position of a photomultiplier tube will result in a noticeable change. Because of this phenomenon, photomultiplier tubes which must be moved and those which must operate in proximity to the leakage flux from such devices as transformers must be mounted in magnetic shields.

MAGNETIC CHARACTERISTICS

The degree of change in output with respect to magnetic fields varies greatly depending upon the type of photomultiplier tube. Figure 1 shows the magnetic characteristics of typical photomultiplier tubes. The measurement was made by placing the photomultiplier tube and excitation coil inside a permalloy housing and degaussing the electrode before measurement. A uniform light intensity was applied to the photocathode and an output current of approximately 1µA was derived. The magnetic field direction is shown in Figure 2.

In general, photomultiplier tubes having a large distance between the photocathode and anode and, in particular, those having a large distance between the photocathode and the first dynode or a relatively small dynode opening in comparison with the photocathode area, will exhibit a large variation. Therefore, head-on types of photomultipliers which usually have a long distance between the photocathode and the first dynode are more susceptible to this effect than side-on types. And of these types which have a large photocathode area show particularly large variations.

Electrons chiefly receive the effects of a magnetic field in the region between the photocathode and the first dynode. This is because the distances between the following dynodes are relatively short and the dynodes themselves are made of nickel or other magnetic materials which provides a shielding effect with respect to electrons travelling through the dynodes.

Figure 2: Direction of Magnetic Fields

For data shown in Figure 1
**SHIELDING EFFECT**

Magnetic shield cases are metallic tubes fabricated from permalloy or other materials having high permeability. By positioning the photomultiplier tube within such a case, it is possible to reduce the influence of external magnetic fields on output levels. To express the effect of a magnetic shield case, the magnetic shielding factor may be used. It is determined by the permeability $\mu$, the thickness $t$ and inner radius $r$ of the shield case, as shown in Figure 3.

The magnetic shielding factor for two shield cases of different radii used one within the other is the product of the two shielding factors. This scheme is usable to obtain an extremely high shielding effect.

1) Substitution Characteristics

The B-H curve which expresses the relationship between the external magnetic field $H$ and flux density $B$ within a magnetic material indicates a saturation characteristic, as shown in Figure 4. Since the permeability $\mu$ is given by the B-H ratio, the relationship of $H$ to $\mu$, as shown in Figure 5, varies depending upon the external magnetic field intensity, with subsequent change in the shielding effect. Therefore, in extremely high-intensity magnetic fields, it is recommended that a soft-iron magnetic shield case having a thickness of approximately 3 to 10 $\mu$m be used as this material has a high saturation flux density.

2) Frequency Characteristics

The above described shield case characteristics are for DC magnetic fields. In contrast to this type of field, the leakage flux from a transformer creates an AC magnetic field effect which must be considered as well. The permeability of a magnetic material decreases with increasing frequency. This is particularly noticeable for thick materials, even at low frequencies. Hamamatsu E989 Series shield cases use a material of 0.8 mm thickness, yet providing sufficient effective permeability even at normal line power frequencies of 50 or 60 Hz, shown in Figure 6. If magnetic fields of high frequencies such as 1 to 10 kHz are applied, a thin shielding material (0.05 to 0.1 mm) having good frequency characteristic should be used in combination with the normal shielding.

3) Edge Effect

The shielding effect given by $3t/4$ applies in the case that the shield case is of sufficient length. Since actual shield cases have a finite length, however, there is a deterioration of the shielding effect at both ends which should be considered. For this reason, as shown in Figure 7, it is necessary to locate the photomultiplier tube so that its end is somewhat covered by the shielding tube. For head-on photomultiplier tubes, this depth should be approximately the case radius, if the magnetic field direction is parallel to that of the tube axis, however, the edge effect becomes extremely prominent, so that the photomultiplier tube should be kept to within at least the diameter depth from the end of the shield case.

---

**PRECAUTIONS FOR USE**

1. Magnetic shield cases should not be subjected to shocks. When deformed by shocks, permeability decreases. Also, whistling and dulling the case affect permeability, and therefore should be avoided.

2. Some shield cases have small holes near the edge. These holes should be used to mount the shield case on the chassis and not to cramp the tube in the shield case.

3. The E989-10 has a little flexibility in diameter as shown at the right. However, when the diameter exceeds the range from 14 to 17 mm, the shield case may be deformed and permeability lowered.

4. The PMT tends to increase in noise when a grounded object approaches the tube. Since the shield case is generally used at the ground potential, the PMT should be positioned in the center of the shield case by using, for example, elastic foam rubber with sufficient insulation wrapped around the tube.

5. The magnetic shielding effect decreases towards the edge of the shield case as shown at the right. It is suggested to cover the tube with a shield case longer than the length by at least half the tube diameter. See the Item "Edge Effect" on page 25.

6. Shield Case Mounting Method

In making precise photometric measurements, it is essential that the position of the photomultiplier tube be kept constant with respect to the other parts of the measuring system.

When using E989 Series shield cases, it is necessary to mount the photomultiplier tube securely to ensure that no looseness develops between the photomultiplier tube and the shield case or between the shield case and other parts of the system. When a photomultiplier tube which does not have an HA coating is used in a grounded anode circuit with a high negative voltage applied to the cathode, if the shield case is grounded, there is a danger of magnetic field being generated. This noise may be minimized by insulating the shield case from ground potential sufficiently and, even if the outside of the shield case is sufficiently insulated, by connecting the shield case to the cathode through a resistance of approximately 10 MΩ. This technique is particularly required when measuring extremely low light levels.

The following are typical shield case mounting methods.

- **E989-10 (For 1/2" Side-On Photomultiplier Tubes)**
  - The shield case can be positioned around the photomultiplier tube using an insulating material having good insulating properties between these two components. Then tighten the mounting fixtures.

- **E989: (For 1/16" Side-On Photomultiplier Tubes)**
  - Foam rubber or similar material having good insulating properties and elasticity can be used to hold the photomultiplier tube in the center of the shield case. By using the mounting holes in the shield case, mount the shield case to the mounting system. When doing this, use of L clamps or other mounting fixtures are suggested.

---

*Some Teflon and plastic materials may cause scintillation when illuminated with UV light. Care should be taken when selecting insulators.*
Photomultiplier Response to being Zonked

Lidar Signal
Hamamatsu R943-02 is a 2" diameter, head-on type photomultiplier tube having a GaAs(Cs) photocathode and a synthetic silica window. The combination of the GaAs photocathode and the synthetic silica window allows high sensitivity over a wide spectral range from UV to IR (160 - 930nm).

The R943-02 employs the linear focused dynode which is designed specifically for photon counting application. It features very low dark counts and excellent pulse height distribution (PHD) of single photoelectrons. (Fig. 2)

The R943-02 is equivalent type of RCA C31034 series photomultiplier tube, but basing diagram and voltage divider are somewhat different.

APPLICATIONS
- Raman Spectroscopy
- Fluorescent Spectroscopy
- Astrophysical Measurement
- Laser Detection

FEATURES
- Low Dark Counts 20 cps typ. (at -20°C)
- Wide Range Spectral Response 160 - 930nm
- Excellent Single Photoelectron Pulse Height Distribution
  - Peak to Valley Ratio = 1.8 (at -20°C)
- Fast Time Response Rise Time = 3.0ns (at 1500V)
- High Quantum Efficiency 14% (at 632.8nm)

GENERAL
- Spectral Response 160 to 930nm
- Wavelength of Maximum Response 300 to 800 nm
- Photocathode Material GaAs(Cs)
- Photocathode Minimum Useful Area 10mm x 10mm
- Mode Opaque
- Window Material Synthetic Silica
- Dynode Secondary Emitting Surface Cu-BeO
- Structure Linear Focused
- Number of Stages 10
- Direct Interelectrode Capacitances (Approx.)
  - Anode to Last Dynode 2pF
  - Anode to All Other Electrodes 3pF
  - Base 21-pin Glass Base
- Weight 93g
- Suitable Socket E678-21A (Supplied)

* See "Note D" on page 2 and "Cautions" on page 4
PHOTOMULTIPLIER TUBE R943-02

MAXIMUM RATINGS (Absolute Maximum Values at 25°C)

Supply Voltage Between Anode and Cathode 2200Vdc
Between Anode and Last Dynode 250Vdc
Average Anode Current A
Average Pulse Count Rate B
Average Cathode Current C
Ambient Temperature D

CHARACTERISTICS (at 25°C)

Table 1: Voltage Distribution Ratio

<table>
<thead>
<tr>
<th>Supply Voltage</th>
<th>1000 Vdc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution Ratio</td>
<td>1 1 1 1 1 1 1 1 1 1</td>
</tr>
</tbody>
</table>

Table 2: Average Anode Current vs. Supply Voltage

<table>
<thead>
<tr>
<th>Supply Voltage (V)</th>
<th>Average Anode Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>300</td>
<td>3</td>
</tr>
<tr>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 2: Typical Photoelectron Pulse Height Distribution

Figure 3: Typical Anode Sensitivity and Current Amplification

Cooling

As Figure 6 shows, the dark counts of the R943-02 decreases by cooling the tube. Therefore, when performing photon counting, it is recommended that the tube be cooled down to about -5°C. The cooler C2761 which features temperature control from -30°C to 0°C is available from HAMAMATSU.

Figure 4: Typical Time Response

Figure 5: Typical Temperature Coefficient of Quantum Efficiency

Figure 6: Typical Dark Counts vs. Temperature

NOTES
A. Averaged over any interval of 30 seconds maximum.
B. Measured at single photoelectron level. The drift in the dark current is set at 0.1%.
C. In practical operation is desired to be lower than 0.5% (5000 counts/s) to prevent the shortening of the photoelectrons. For example, if the cathode current is under 0.5 mA, the anode current should not get out of the region at B in the figure below.
D. At temperature of less than -50°C the tube may be damaged due to the difference in temperature coefficients between the glass stem and the socket. Don't use the socket below -50°C. However, the tube can be made possible by facilitating direct contact with the stem pin, using a socket contact (100-2520S) supplied by Winchester. For details, please contact your local HAMAMATSU representative.
E. Supply voltage is 150 volts between the cathode and all other electrodes.
F. The light source is a tungsten filament lamp operated at a temperature of 2500K.
G. The quantum efficiency of the cathode sensitivity measured with the light source same as Note E passing through a red filter (Toshiba R-88) divided by the cathode luminous sensitivity without the red filter.
H. Measured with the supply voltage and voltage distribution ratio in Table 1 after 30 minute storage in the darkness.
I. Measured with the supply voltage to provide the anode luminous sensitivity of 200 mA/W and the voltage distribution ratio in Table 1 after 30 minute storage in the darkness.
J. Measured with the supply voltage which gives 2 x 10^6 of current amplification and with the voltage distribution ratio shown in Table 1 after one hour storage in the cooler set at -20°C.
K. The dark counts are the dark counts of the anode kept at 37°C. The anode temperature is at 37°C at 0°C (5000 counts/s) to prevent the shortening of the photoelectrons.
L. The electron transit time is the interval between the arrival of a delta function light pulse at the entrance window of the tube and the time when the output pulse reaches the peak amplitude. In measurement the entire photo-cathode is illuminated.

Warning-Personal Safety Hazards

Electrical Shock - Operating voltages applied to this device present a shock hazard.
Ultra-low light level photon counting modules

PHOTONS IN...PULSES OUT

The SPCM-100 series of single photon counting modules, featuring a new generation of silicon avalanche photodiodes, are designed for applications such as photon correlation for particle sizing, fluorescence studies, etc.

These single-stage modules offer:
- Photon detection efficiencies up to 40% at 633 nm
- Up to 25% at 800 nm
- Dual voltage inputs: +5, -5 volts
- TTL output pulses
- Nothing to adjust

Ultra-low light level photon counting modules

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These single-stage modules offer:
- Photon detection efficiencies up to 40% at 633 nm
- Up to 25% at 800 nm
- Dual voltage inputs: +5, -5 volts
- TTL output pulses
- Nothing to adjust
This group of tubes is primarily intended for wide bandwidth, high gain photon counting applications although most types are equally suitable for dC measurements.

The parent type is the 520 response 9663 which is based on the Thorn EMI 14 stage fast linear focused dynode structure, with BeCu secondary emitting surfaces. However, the photocathode diameter is increased by internal focusing to 2.5 mm in the 9663/100 and 3 mm in the 9663/350. This results in negligible cathode dark count at room temperature while still preserving the wide spectral range of the 520 photocathode.

The 9863 is identical in construction to the bialkali-cathode 14 stage 9813 (page 36) but has a first dynode which is specially processed to give a high secondary emission coefficient (~10 at 600 eV). This results in an improved single electron response of typically 70% in m.

The 9814 is a 12 stage version of the 9863 for use where the higher gain is not necessary or where the slightly faster response time is an advantage.

All types are available with a quartz (fused silica) window option denoted by a Q suffix.

Note: These types are nominally supplied with glow discharge connected to cathode pins and black plastic sheath to eliminate all sources of noise. No sheath is provided for experimental purposes and should not be removed without consulting Thorn EMI.

Electrical Characteristics and Ratings

**Table: Electrical Characteristics and Ratings**

<table>
<thead>
<tr>
<th>Type</th>
<th>Response</th>
<th>cathode diameter</th>
<th>Effective quantum efficiency</th>
<th>μA/mT</th>
<th>Counting noise</th>
<th>S/N ratio</th>
<th>Yield</th>
<th>Voltage range</th>
<th>Cathode dark count @ 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>9863</td>
<td>14 stage</td>
<td>2.5</td>
<td>125</td>
<td>9.5</td>
<td>70</td>
<td>2.5</td>
<td>2.5</td>
<td>20</td>
<td>22 9000 2400 7500 27</td>
</tr>
<tr>
<td>9864</td>
<td>14 stage</td>
<td>2.5</td>
<td>125</td>
<td>9.5</td>
<td>70</td>
<td>2.5</td>
<td>2.5</td>
<td>20</td>
<td>22 9000 2400 7500 27</td>
</tr>
<tr>
<td>9865</td>
<td>14 stage</td>
<td>2.5</td>
<td>125</td>
<td>9.5</td>
<td>70</td>
<td>2.5</td>
<td>2.5</td>
<td>20</td>
<td>22 9000 2400 7500 27</td>
</tr>
<tr>
<td>9866</td>
<td>14 stage</td>
<td>2.5</td>
<td>125</td>
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<td>20</td>
<td>22 9000 2400 7500 27</td>
</tr>
<tr>
<td>9867</td>
<td>14 stage</td>
<td>2.5</td>
<td>125</td>
<td>9.5</td>
<td>70</td>
<td>2.5</td>
<td>2.5</td>
<td>20</td>
<td>22 9000 2400 7500 27</td>
</tr>
</tbody>
</table>

**Pin Connections** (viewed from below, counting clockwise from short pin as key)

- **Electrical characteristics:**
  - Vacuum connectors (solderable):
    - 1 J-J 2 T-3
    - 1 J-J 2 T-3
  - 3 lead connectors (solderable):
    - 1 J-J 2 T-3
    - 1 J-J 2 T-3
  - 4 lead connectors (solderable):
    - 1 J-J 2 T-3
    - 1 J-J 2 T-3

**Outline drawings** (dimensions are nominal unless otherwise stated and in mm with inches in brackets)
DETECTOR SECTION
GROUND BASED ATMOSPHERE
LIDAR SYSTEM

Two wavelengths (532 nm and 355 nm)
Shuttered for high and low altitudes
Fabry-Perot etalon.

$\delta = \delta_{\max} - \delta_{1/2}$

$\delta = \delta_{\max} + \delta_{1/2}$

$F = 200$

$R = 0.87$

Fabry-Perot fringes.
An Advanced Lidar Data Acquisition System
DATA ACQUISITION

Data acquisition systems and architectures should be matched to the intended application. With the variety in standards and interfaces currently available today, the system designer can choose among variables that include capacity (size), speed, data path width, expandability, flexibility, interconnection protocol and media, in-line preprocessing and control, and ease of replacement of faulty components.

LeCroy designs instrumentation that can be incorporated into several different types of architectures ranging from small scale (single channel or data source) to large-scale (500,000 channels) data acquisition systems that support speeds from 300 bits/sec to 5 megawords/sec (32-bit words). Both conventional TTL, ECL and fiber optic interconnections can be implemented.

GPIB

The GPIB (IEEE Std 488-1979) Bus is the most popular instrument bus today. This byte-serial system can connect up to 15 talkers (units such as a digital voltmeter able to transmit data), listeners (units such as a programmable power supply able to receive instructions and data) or talker/listeners to a master controller. All LeCroy standalone instruments are equipped with GPIB interfaces for data transfer rates up to 400 kbytes per second.

The strict serial limitations of the GPIB interfacing standard can be partially bypassed by using the IEEE-488 Bus to tie CAMAC crates together and connect to the host computer.

CAMAC

CAMAC is a modular data handling system used at every Nuclear Physics research laboratory and many industrial sites all over the world. It represents the Committees. The CAMAC Standard (IEEE 583) is the ideal system for a high speed, medium density acquisition system. High speed means at least 1 Mbyte/second. The 1 MHz, 24-bit wide data path on both the backplane of the crates and the interconnections between crates transfers data at rates that exceed the capabilities of Direct Memory Access (DMA) channels in many minicomputers. For a more detailed discussion, see LeCroy Application Note AN-33, Introduction To CAMAC, which can be found in the Appendix.

Its primary application is data acquisition, but CAMAC may also be used for remotely programmable trigger and logic applications (LeCroy ECLine family of programmable logic units).

Most LeCroy CAMAC data acquisition modules are multi-input. They contain between 1 and 16 inputs per single-width module (23 modules per crate). A simple seven-crate system is shown in Figure 1.

The CAMAC standard covers electrical and physical specifications for the modules, instrument housings or crates, and a crate backbone. Examples of crates with 25 positions include the LeCroy Model 143A and the high power version, Model 8025, and the Model 8013A with 13 positions.

Individual crates are controlled by slave or intelligent controllers such as the LeCroy Model 6010. The controllers are connected together with a parallel Branch Highway that ends in a Branch Driver. The Branch Driver is interfaced directly to a data acquisition computer. Alternatively, free or parallel data acquisition architectures may be created by connecting secondary CAMAC branches via Branch Driver Modules.

CAMAC crates may also be connected in a Local Area Fiber Optic Network via the LeCroy Model 5211 Fiber Optic Serial Link and serial crate controller. Up to 62 crates separated by a maximum of 500 meters can exchange data at transmission rates of 4 to 5 megabytes/sec. (See Figure 2.)

LeCroy also offers crate controllers that interface directly with the GPIB. Therefore, the entire CAMAC crate may appear as a single instrument on this very popular laboratory instrument bus. The Model 8901A is a GPIB/CAMAC slave interface that operates as a "Talker/Listener" while the Model 6010 may be programmed to do real time computations and data compaction.

Timing and protocol specifications permit up to one million 16 or 24-bit word transfers per second for both the DATAWAY and CAMAC Branch. GPIB speeds are usually limited by the host computer, but block transfer rates of up to 300 kibytes/sec are easily obtainable.

THE LECROY DATABUS AND DEDICATED CAMAC SYSTEM

The LeCroy DATABUS links a family of dedicated CAMAC data acquisition systems designed to fulfill the demanding requirements of large scale Drift Chamber (4290 Timing System) and Multiwire Proportional Chamber (PCOS III Latching Systems). Information from the data acquisition modules is read via the backplane of a CAMAC crate to a dedicated "executive* controller unit. The executive controllers can handle a variety of functions including data compacting, autotrimming, system testing, and control. The executive controllers are then daisy-chained together and transfer the data via DATABUS to an interface module located in a standard CAMAC crate (See Figure 3). Due to the dedicated CAMAC architecture and the bidirectional 16-bit wide DATABUS system, transfer rates may be three times faster than standard CAMAC rates for 16-bit words.

Camac Module 4299 DATABUS Interface downloads test and control commands back to the dedicated crates. It stores data and addresses of only pertinent data acquisition channels in its 4K x 16-bit memory. Rapid and simple CAMAC block transfers can be executed under control of an internal word count register or an automatic "end-of-data" monitor (CAMAC Q-Stop Mode).

FASTBUS

The FASTBUS Standard (ANSI/IEEE STD 960-1986) represents the fastest high density data acquisition available today. Designed for the next generation of High Energy Physics and Heavy-Ion experiments, it permits almost any architecture imaginable, transferring data at speeds up to 40 Mbytes/sec (See Figure 4).

LeCroy Application Note AN-26, An Introduction to FASTBUS, can be found in the Appendix.

FASTBUS was designed to keep features of older important standards while extending the capabilities of data acquisition systems. FASTBUS provides for a more densely packed system, reducing dramatically the per-input cost. This and other design goals have been achieved.
FASTBUS meets these requirements by incorporating several powerful features, including:

1. Modularity
2. 32-bit address and data fields
3. High speed, asynchronous ECL backplane with 32-bit wide Dataway
4. Multiple, parallel processor bus architecture with multiple bus segments that operate independently but link together for passing data
5. Asynchronous handshaking for compatibility with modules having different data transfer speeds operating on the same bus
6. Synchronous nonhandshake data transfer for maximum speed
7. Broadcast operations for initializing, clearing, etc., several modules in one operation
8. A polling structure for fast scanning of sparse data from a large number of modules

9. Easy links to computers for Host Intervention or Data Transfer

Essentially, the FASTBUS backplane is intended to be an extension of a computer backplane. By its nature, therefore, it is an expandable system. The backbone is called a "Segment". Connections between segments are made by a Segment Interface, called a Segment Interconnect (SI). An SI in one segment is connected to a SI in another segment by a Cable Segment. The Segment Interconnect can be either a Master or Slave, depending on the operation it is performing. Moreover, it can be a Master on the FASTBUS Segment and simultaneously a Slave on the Cable Segment. The designations Master and Slave here are dynamic, in that the designation is defined by the role played by the SI at some given time.

FASTBUS permits Multiple Masters to have access to the segment. The standard provides a protocol for arbitration when more than one master requests control of the segment. Once mastership is granted, the Master may then proceed to establish a communications "lock" with any other device on the segment which will act as a Slave. Alternatively, the Master may Broadcast a message to all Slaves in a segment, which respond to the Broadcast (e.g., Clear, Polling for Data Ready, etc.).

The role of VME systems has expanded from this first architecture to include complete data acquisition systems with front end modules all in the VME standard. While never being able to reach the high densities of FASTBUS (and the subsequent cost savings), these systems have become very attractive for monitoring and control applications. LeCroy has developed a line of medium density, high performance instrumentation ideally designed for these applications. Combining 8 or 16 channels of instrumentation in a single width VME module, permits several hundred channels of high fidelity TDC, ADC or scaler to be directly integrated into a VME system.

BUS COMPARISONS

FASTBUS, VME and CAMAC are all modern, standard buses that are used in data acquisition applications. While CAMAC is the oldest, FASTBUS the most sophisticated and VME the most well known because of its commercial applications, each has a role in physics research. In the chart below, these buses are briefly compared.
In order to assist with determining which data acquisition module will fulfill the experimental requirements, comparison matrices of ADCs and TDCs can be found below.

### Modular Analog-to-Digital Converters (ADCs)

<table>
<thead>
<tr>
<th>Model No.</th>
<th>No. of Channels</th>
<th>No. of Bits</th>
<th>Package</th>
<th>G in V</th>
<th>Full Scale</th>
<th>Min. Resolution</th>
<th>Date Format</th>
<th>Conversion Time</th>
<th>Fastest Test Time</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>11395</td>
<td>8</td>
<td>12</td>
<td>VME #1</td>
<td>12</td>
<td>700 mV</td>
<td>0.125 mV</td>
<td>50-100 nsec</td>
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<td>0.0 sec</td>
<td></td>
</tr>
<tr>
<td>1684P</td>
<td>16</td>
<td>12</td>
<td>FASTBUS #1</td>
<td>12</td>
<td>200 mV</td>
<td>0.5 mV</td>
<td>50-1000 nsec</td>
<td>3.75 sec</td>
<td>0.0 sec</td>
<td>Low range</td>
</tr>
<tr>
<td>1685P</td>
<td>16</td>
<td>12</td>
<td>FASTBUS #1</td>
<td>16</td>
<td>1000 mV</td>
<td>2.5 mV</td>
<td>50-1000 nsec</td>
<td>3.75 sec</td>
<td>0.0 sec</td>
<td>Dual-range</td>
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<td>224MA</td>
<td>12</td>
<td>10</td>
<td>CAMAC #1</td>
<td>12</td>
<td>1.0 mV</td>
<td>0.125 mV</td>
<td>10-3000 nsec</td>
<td>55 sec</td>
<td>3 sec</td>
<td>Research</td>
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<tr>
<td>2349AG</td>
<td>12</td>
<td>10</td>
<td>CAMAC #2</td>
<td>12</td>
<td>2.0 mV</td>
<td>0.25 mV</td>
<td>10-2000 nsec</td>
<td>55 sec</td>
<td>3 sec</td>
<td>Reference</td>
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<tr>
<td>234MM</td>
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<td>11</td>
<td>CAMAC #1</td>
<td>12</td>
<td>5.0 mV</td>
<td>0.25 mV</td>
<td>10-30000 nsec</td>
<td>110 sec</td>
<td>2 sec</td>
<td>Reference</td>
</tr>
<tr>
<td>225BB</td>
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<td>11</td>
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<td>12</td>
<td>3.0 mV</td>
<td>0.25 mV</td>
<td>10-30000 nsec</td>
<td>110 sec</td>
<td>2 sec</td>
<td>Reference</td>
</tr>
<tr>
<td>2523s</td>
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<td>Channel can be extended for higher noise</td>
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<td>1 mV</td>
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<td>N/A</td>
<td>1 ch. Buffer</td>
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<tr>
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<td>11</td>
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<td>20.0 mV</td>
<td>2.0 mV</td>
<td>50-3000 nsec</td>
<td>± 4-5-5 macc</td>
<td>± 1 macc</td>
<td>ECL Input</td>
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<td>50-3000 nsec</td>
<td>5 macc</td>
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<td>Loading or monitoring mode</td>
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### Amplifiers and Preamplifiers

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Package</th>
<th>No. of Channels</th>
<th>G in V</th>
<th>Full Scale</th>
<th>Max. Resolution</th>
<th>Min. Resolution</th>
<th>Conversion Time</th>
<th>Fastest Test Time</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>6072A</td>
<td>NIM #1</td>
<td>12</td>
<td>100</td>
<td>100 mV</td>
<td>10 macc</td>
<td>10 macc</td>
<td>10 macc</td>
<td>10 macc</td>
<td>N/A</td>
</tr>
<tr>
<td>6072M</td>
<td>NIM #1</td>
<td>8</td>
<td>5-8</td>
<td>500 mV</td>
<td>10 macc</td>
<td>10 macc</td>
<td>10 macc</td>
<td>10 macc</td>
<td>N/A</td>
</tr>
<tr>
<td>7276</td>
<td>Board</td>
<td>24</td>
<td>100 mV</td>
<td>1.5 mV</td>
<td>1.5 mV</td>
<td>1.5 mV</td>
<td>1.5 mV</td>
<td>1.5 mV</td>
<td>N/A</td>
</tr>
<tr>
<td>7280</td>
<td>Board</td>
<td>24</td>
<td>100 mV</td>
<td>2.0 mV</td>
<td>2.0 mV</td>
<td>2.0 mV</td>
<td>2.0 mV</td>
<td>2.0 mV</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Modular Time-to-Digital Converters

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Package</th>
<th>No. of Channels</th>
<th>G (V)</th>
<th>Full Scale at Maximum Resolution</th>
<th>Conversion Time</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>117/3D</td>
<td>VME #1</td>
<td>16</td>
<td>0</td>
<td>10 macc</td>
<td>10 macc</td>
<td>N/A</td>
</tr>
<tr>
<td>117/3G</td>
<td>VME #1</td>
<td>12</td>
<td>40 macc</td>
<td>25 macc</td>
<td>100 macc</td>
<td>Common Shop</td>
</tr>
<tr>
<td>117/34</td>
<td>Hybrid</td>
<td>16</td>
<td>40 macc</td>
<td>25 macc</td>
<td>100 macc</td>
<td>Mullard Shop</td>
</tr>
<tr>
<td>117/347</td>
<td>Hybrid</td>
<td>16</td>
<td>40 macc</td>
<td>25 macc</td>
<td>100 macc</td>
<td>Mullard Shop</td>
</tr>
<tr>
<td>117/348</td>
<td>Hybrid</td>
<td>16</td>
<td>40 macc</td>
<td>25 macc</td>
<td>100 macc</td>
<td>Mullard Shop</td>
</tr>
</tbody>
</table>

Notes:
1. Only models with 4-V base are listed.
2. Other models may be available by special order.
3. Fastest scan time for all models is 10 macc.
### Interfaces

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Package</th>
<th>Control Transfer Rate (Maximum)</th>
<th>Data Transfer Rate (Maximum)</th>
<th>Run</th>
<th>Instruments Supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>1131</td>
<td>UAdv #1</td>
<td>10 MHz/sec</td>
<td>10 MHz/sec</td>
<td>120</td>
<td>FASTBUS - 1931 9AD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HV - System 1400 (140AG)</td>
</tr>
<tr>
<td>1231A</td>
<td>PC Cond</td>
<td>2 MHz/sec</td>
<td>2 MHz/sec</td>
<td>120</td>
<td>FASTBUS - 1931 9AD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HV - System 1400 (140AG)</td>
</tr>
<tr>
<td>1202</td>
<td>FASTBUS #1</td>
<td>5 MHz/sec</td>
<td>30 MHz/sec</td>
<td>120</td>
<td>FASTBUS - 1931 ECL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MPVPC System - 2750</td>
</tr>
<tr>
<td>2232</td>
<td>CAMAC #1</td>
<td>10 MHz/sec</td>
<td>10 MHz/sec</td>
<td>05-312</td>
<td>HV - System 1400 (140AG)</td>
</tr>
<tr>
<td>22301</td>
<td>CAMAC #1</td>
<td>N/A</td>
<td>N/A</td>
<td>4eCry Bus</td>
<td>MCA - 3200 OVT</td>
</tr>
<tr>
<td>2191A</td>
<td>CAMAC #1</td>
<td>1 MHz/sec</td>
<td>1 MHz/sec</td>
<td>18</td>
<td>FASTBUS - 1931 9AD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HV - System 1400 (140AG)</td>
</tr>
<tr>
<td>4232</td>
<td>CAMAC #1</td>
<td>2 MHz/sec</td>
<td>2 MHz/sec</td>
<td>4eCry Bus</td>
<td>DATA BUS</td>
</tr>
<tr>
<td>42302</td>
<td>CAMAC #1</td>
<td>N/A</td>
<td>N/A</td>
<td>50 MHz/sec</td>
<td>ECLINE</td>
</tr>
<tr>
<td>6030C</td>
<td>PC Cond</td>
<td>125 kib/sec</td>
<td>600 kib/sec</td>
<td>GPRB</td>
<td>CAMAC - 9010</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CAMAC - 901A</td>
</tr>
</tbody>
</table>

### Modular Scalers/Counters

<table>
<thead>
<tr>
<th>Model #</th>
<th>Package</th>
<th>No. of Inputs</th>
<th>Input Signals</th>
<th>Count Rate (kHz)</th>
<th>Dynamic Range (mV)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1101E</td>
<td>UAdv #1</td>
<td>15</td>
<td>ECL</td>
<td>120</td>
<td>22</td>
<td>Bicllional Counting</td>
</tr>
<tr>
<td>1101F</td>
<td>UAdv #1</td>
<td>13</td>
<td>ECL</td>
<td>120</td>
<td>22</td>
<td>Bicllional Counting</td>
</tr>
<tr>
<td>2530</td>
<td>CAMAC #1</td>
<td>12</td>
<td>NM</td>
<td>100</td>
<td>22</td>
<td>Crasslide Channels</td>
</tr>
<tr>
<td>3331A</td>
<td>CAMAC #1</td>
<td>1</td>
<td>NM or ECL</td>
<td>100</td>
<td>22</td>
<td>MUR Clannel Scller with MURIDSA Memory</td>
</tr>
<tr>
<td>4401</td>
<td>CAMAC #1</td>
<td>20</td>
<td>ECL or TL</td>
<td>20</td>
<td>22</td>
<td>Latchlng Scller</td>
</tr>
</tbody>
</table>
SIGNAL AVERAGERS

HIGH FREQUENCY SIGNAL AVERAGERS

2102SA  8 Bit, 200 Megasamples/s
2103SA  8 Bit, 200 Megasamples/s  Dual Channel
2101ASA 8 Bit, 100 Megasamples/s
2130SA  8 Bit, 30 Megasamples/s
2112SA  12 Bit, 10 Megasamples/s
2112FSA 12 Bit, 20 Megasamples/s

REAL TIME SIGNAL AVERAGERS

2824SA  12 Bit, 2 Megasamples/s  Dual Channel
2860SA  12 Bit, 1 Megasamples/s
2812ASA 12 Bit, 100 Kilosamples/s  Four Channel
2814SA  14 Bit, 100 Kilosamples/s

FEATURES

- Fast repetition rate high frequency signal averagers (over 3000 sweeps/second for 1024 samples/sweep) with pre-trigger recording
- Real time signal averagers at conversion rates up to 2 Msamples/s
- Multiple channel real time averagers
- Complete hardware signal averaging; releases host computer from time-consuming averaging
- Programmable number of samples/sweep from 1 to 32,768
- Programmable number of sweeps from 1 to 65,538
- 24 bit per sample deep averaging memory
- Addition and subtraction modes, including algebraic sums
- Built in DAC for oscilloscope display of averaged signal during and after averaging

DESCRIPTION

Signal averaging greatly improves the signal-to-noise ratio for repetitive signals with synchronized triggers. DSP Technology signal averagers use summation averaging, the arithmetic addition and/or subtraction of digitized sweeps. If the associated noise is random, the summation procedure results in a signal-to-noise improvement proportional to the square root of the number of sweeps. For example, averaging 65,536 sweeps improves the signal-to-noise ratio by a factor of 256.

Many different types of signals lend themselves to signal averaging:

1) Signals which are inherently repeatable (for example, signals from rotating machinery scanning spectrometers).
2) Signals which can be repeated using an external stimulus such as kinetic reaction studies where the reaction is stimulated by an energy source such as a laser.
3) Repetitive signals which have no associated synchronization or trigger pulse but have an inherent dominant feature which can be used as such.

REAL TIME SIGNAL AVERAGERS:

These units use DSP TRAQ™ P ADC system modules to implement multi-channel, real time averaging. An external clock (not included) commands the analog to digital converters to sample, convert, and transfer data to the Model 4101. Up to 8 channels can be controlled by one Model 4101 with a maximum conversion and transfer rate of 500 nsec/sample. Record lengths are programmable from 1 to 256 sweeps/sample. All samples in these real time averagers are post-trigger.

GENERAL

Both addition and subtraction averaging modes are selectable via either a front panel input connector or by computer command. The mode can be changed from addition to subtraction, or vice-versa, without disturbing the sum already accumulated. This feature might be used, for example, to subtract a bias or background waveform from an experimental apparatus setup. The internal arithmetic is programmable as either offset binary (± 6,777,215) or 2's complement (± 3,388,607). Averaging can be automatically disabled on overflow or underflow.

The averaged waveform can be observed with a standard laboratory oscilloscope while the data is accumulating. The display from the internal 12 bit digital-to-analog converter can be adjusted via a front panel switch to scale over any 12 of the 24 bit data range. This display is generally useful only with single channel averager configurations.

[Diagram of signal averager setup]
MODELS 2012 & 2012F
10 & 20 MEGASAMPLES/S, 12 BIT, 8 KSAMPLE TRANSIENT RECORDERS

FEATURES
- 12 Bit Dynamic Range at up to 20 Megasamples/s
- Sampling Rate
- Switch Selectable, and Computer Readable Controls (digitizing rate, pre/post trigger samples, record length)

DESCRIPTION
The Models 2012 and 2012F combine the wide dynamic range (12 bits) needed to capture signals whose baselines are either dynamically changing or are single module transient recorders with ADC, control and storage functions self-contained.

The digitizers can be entirely controlled from the front panel of the instrument much like a normal scope. All switch positions are readable by the computer. Access by the computer and run status are indicated by front panel LED's.

Data conversion and storage can be initiated by front panel toggle switch or computer command. An external signal (TTL level), toggle switch or computer command stops the conversion after the programmed number of post-trigger samples have been recorded. An external clock can be used to accommodate any sampling rate from D.C. to full sampling speed or variable rate importance sampling.

Digitized data can be viewed by attaching a standard laboratory oscilloscope to the DAC display out connector and triggering with the sweep trigger generated by the unit. Computer driven display of multiple waveforms is especially suitable for multichannel data acquisition systems.

TECHNICAL SPECIFICATIONS - MODELS 2012 & 2012F

SIGNAL INPUTS
- Impedance: 50 Ω (1K Ω optional), 30 pf
- Voltage Range: 2.0 V full scale ± 1 % full scale per 10°C
- Overvoltage Recovery: 50 ns from 2X overdrive
- Overvoltage Protection: 7 Volt dc, 50 V for 1 ms, LED indicates input over full scale
- Bandwidth (3dB): Full scale: 10 MHz
  - ± 0.2 dB: DC - 5 MHz
- Offset: ± full scale. Continuous adjustment by potentiometer. Front panel test point for DVM, Drift 1 count per 10°C

STOP TRIGGER
- External: TTL level, positive edge sensitive, 50 µs min.
  - with 1 KO input impedance. Input protection 25 V dc, 250 V for 1 ms.
- Manual: Front panel switch
- Computer: F(25)A(0) command

ANALOG TO DIGITAL CONVERTER
- Resolution: 12 bits (one part in 4096)
- Dynamic Distribution:
  - - 70 dB down at 1 MHz input frequency
  - - 65 dB down at 2.5 MHz input frequency
- Aperture Uncertainty: 24 ps
- DC Linearity: ± 1/2 LSB, ± 0.05 %
- Continuity: Monotonic

SAMPLING CLOCK
- Internal: Crystal controlled clock
  - 20, 10, 5, 2, 1, 0.5, 0.2 MHz
- CLK IN: Edge triggered, TTL input, 20 MHz max for 2012F, 10 MHz max for 2012. No restrictions on frequency changes.
- CLK OUT: TTL output, drives 50 Ω load. Regenerated internal or external sampling clock

MEMORY
- Type: Static ram
- Size: 8192 samples

Organization: Reduction of record size is selectable by computer control. Reduction of record size is selectable by computer control. Cyclical data recording allows division of memory into pre-post trigger periods by computer control

DISPLAY
- Digital to analog reconstruction of memory contents drives 1 KΩ to ± 5.0 V. Scope trigger of TTL level is also provided at the beginning of each display sweep

DIGITAL OUTPUT
- Data Format: 16 bit 2's complement encoding (Offset binary encoding, strap selectable)
- Readout Protocol: IEEE #583 CAMAC, Full NAF encoding, LAM implementation and Q = 1 is returned for every executable NAF command. After the last memory word has been read, Q = 0 is returned.

COMPUTER COMMANDS
- F(0)A(0): Reads pre-trigger samples, record size, sampling period
- F(2)A(0): Stop waveform data. O = 0 returned after last data word
- F(3)A(0): Read module I.D. (2012 or 2012F)
- F(8)A(0): Test LAM, Q = 1 returned if LAM is on
- F(9)A(0): Initialize module and start sampling
- F(10)A(0): Reset LAM
- F(11)A(0): Computer single sample
- F(16)A(0): Write pre-trigger samples, record size, sampling period
- F(24)A(0): Disable LAM
- F(25)A(0): Computer stop trigger
- F(26)A(0): Enable LAM and computer readout
- F(27)A(0): Enable offset measurement. To read, issue F(25), wait for post-trigger samples, and read offset data with F(2)

POWER REQUIREMENTS
- ± 6 V 3 A
- ± 24 V 300 mA

PACKAGING
- #3 width CAMAC module
- 221 mm H, 50 mm W, 292 mm D (8 7/8" x 2" x 11 1/2")
- Depth from front to rear panel. Rear connector is 13 mm (0.5")
- In conformance with the CAMAC standard for RF shielded instrumentation modules (IEEE standard 583, European Esone Report #EUF4100e)

TEMPERATURE RANGE
- 0° to 40°C (32° F to 104° F) ambient to operate within specifications when installed in crate with enough air flow to hold maximum air exit temperature to 55°C (131°F)

MATING CONNECTORS
- Cable terminators: LCOB (LEMO-BNC) and LCOL (LEMO-LEMO) are compatible with all input and output connectors. Not included.
Table 5
MPE for Direct Ocular Exposure, Intrabeam Viewing, to a Laser Beam

<table>
<thead>
<tr>
<th>Wavelength, λ (nm)</th>
<th>Exposure Duration* (s)</th>
<th>Maximum Permissible Exposure (MPE)</th>
<th>Notes for Calculation and Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet</td>
<td>10^-8 to 3 x 10^-6</td>
<td>3 x 10^-4 J cm^-2</td>
<td>or 0.56 /μm²* cm^-2, whichever is lower.</td>
</tr>
<tr>
<td>0.200 to 0.302</td>
<td>10^-8 to 3 x 10^-6</td>
<td>4 x 10^-4 J cm^-2</td>
<td>1-mm limiting aperture</td>
</tr>
<tr>
<td>0.304</td>
<td>10^-8 to 3 x 10^-6</td>
<td>6 x 10^-4 J cm^-2</td>
<td>See Figs. 5 and 6 for graphical representation.</td>
</tr>
<tr>
<td>0.305</td>
<td>10^-8 to 3 x 10^-6</td>
<td>1 x 10^-3 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.306</td>
<td>10^-8 to 3 x 10^-6</td>
<td>1.6 x 10^-3 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.307</td>
<td>10^-8 to 3 x 10^-6</td>
<td>2.5 x 10^-3 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.308</td>
<td>10^-8 to 3 x 10^-6</td>
<td>4.0 x 10^-3 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.309</td>
<td>10^-8 to 3 x 10^-6</td>
<td>6.3 x 10^-3 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.310</td>
<td>10^-8 to 3 x 10^-6</td>
<td>1.0 x 10^-2 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.311</td>
<td>10^-8 to 3 x 10^-6</td>
<td>1.6 x 10^-2 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.312</td>
<td>10^-8 to 3 x 10^-6</td>
<td>2.5 x 10^-2 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.313</td>
<td>10^-8 to 3 x 10^-6</td>
<td>4.0 x 10^-2 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.314</td>
<td>10^-8 to 3 x 10^-6</td>
<td>6.3 x 10^-2 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.315 to 0.400</td>
<td>10^-7 to 10^-6</td>
<td>0.56 /μm²* cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.315 to 0.400</td>
<td>10^-7 to 10^-6</td>
<td>1 J cm^-2</td>
<td></td>
</tr>
</tbody>
</table>

Visible and Near Infrared**

| 0.400 to 0.700    | 10^-7 to 1.1 x 10^-5   | 5 x 10^-3 J cm^-2                | 7-mm limiting aperture. |
| 0.400 to 0.700    | 1.8 x 10^-10 to 10     | 1.8 x 10^-10 J cm^-2             | 7-mm limiting aperture. |
| 0.400 to 0.700    | 10 to 10^-9            | 10 x 10^-9 J cm^-2               | 7-mm limiting aperture. |
| 0.550 to 0.700    | 10 to 10^-8            | 10 x 10^-8 J cm^-2               | 7-mm limiting aperture. |
| 0.550 to 0.700    | 10^0 to 10^-7          | 10 x 10^-7 J cm^-2               | 7-mm limiting aperture. |
| 0.700 to 1.050    | 10^-6 to 10^-5         | 10 x 10^-5 J cm^-2               | 7-mm limiting aperture. |
| 0.700 to 1.050    | 10^-5 to 10^-4         | 10 x 10^-4 J cm^-2               | 7-mm limiting aperture. |
| 1.050 to 1.400    | 10^-4 to 10^-3         | 10 x 10^-3 J cm^-2               | 7-mm limiting aperture. |
| 1.050 to 1.400    | 10^-3 to 10^-2         | 10 x 10^-2 J cm^-2               | 7-mm limiting aperture. |
| 1.4 to 10^1       | 10^-2 to 10^-1         | 10^-1 J cm^-2                    | 7-mm limiting aperture. |
|                   | >10                    | 10^-1 J cm^-2                    | 7-mm limiting aperture. |
| 1.54 only         | 10^-1 to 10^-0         | 1.0 J cm^-2                      | 7-mm limiting aperture. |

* See Note in Section 8 for pulsewidths less than 1 ms.
**See Figs. 4, 5, and 6 for graphic representation.

NOTES:
C = 1 for λ = 0.400 to 0.700 μm,
C = 10^4/μm²* cm^-2 for λ = 0.700 to 1.05 μm (see Fig. 8),
C = 5 for λ = 1.05 to 1.40 μm,
C = 10^{10}/μm²* cm^-2 for λ = 1.4 to 1.54 μm (see Fig. 9).

Table 6
MPE for Viewing a Diffuse Reflection of a Laser Beam or an Extended-Source Laser

<table>
<thead>
<tr>
<th>Wavelength, λ (nm)</th>
<th>Exposure Duration* (s)</th>
<th>Maximum Permissible Exposure (MPE)</th>
<th>Notes for Calculation and Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet</td>
<td>10^-7 to 3 x 10^-5</td>
<td>3 x 10^-1 J cm^-2</td>
<td>or 0.56 /μm²* cm^-2, whichever is lower.</td>
</tr>
<tr>
<td>0.303</td>
<td>10^-7 to 3 x 10^-5</td>
<td>6 x 10^-1 J cm^-2</td>
<td>1-mm limiting aperture</td>
</tr>
<tr>
<td>0.304</td>
<td>10^-7 to 3 x 10^-5</td>
<td>1.0 x 10^-1 J cm^-2</td>
<td>See Figs. 5 and 6 for graphical representation.</td>
</tr>
<tr>
<td>0.305</td>
<td>10^-7 to 3 x 10^-5</td>
<td>1.6 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.306</td>
<td>10^-7 to 3 x 10^-5</td>
<td>2.5 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.307</td>
<td>10^-7 to 3 x 10^-5</td>
<td>4.0 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.308</td>
<td>10^-7 to 3 x 10^-5</td>
<td>6.3 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.309</td>
<td>10^-7 to 3 x 10^-5</td>
<td>1.0 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.310</td>
<td>10^-7 to 3 x 10^-5</td>
<td>1.6 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.311</td>
<td>10^-7 to 3 x 10^-5</td>
<td>2.5 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.312</td>
<td>10^-7 to 3 x 10^-5</td>
<td>4.0 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.313</td>
<td>10^-7 to 3 x 10^-5</td>
<td>6.3 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.314</td>
<td>10^-7 to 3 x 10^-5</td>
<td>1.0 x 10^-1 J cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.315 to 0.400</td>
<td>10^-6 to 10^-5</td>
<td>0.56 /μm²* cm^-2</td>
<td></td>
</tr>
<tr>
<td>0.315 to 0.400</td>
<td>10^-6 to 3 x 10^-5</td>
<td>1 J cm^-2</td>
<td></td>
</tr>
</tbody>
</table>

Visible**

| 0.400 to 0.700    | 10^-7 to 10^-5         | 10 x 10^-1 J cm^-2               | 1-mm limiting aperture or a_m, whichever is greater. |
| 0.400 to 0.700    | 10^-5 to 10^-4         | 2.1 x 10^-1 J cm^-2              | See Figs. 8, 9, and 11 for correction factors. |
| 0.550 to 0.700    | 10^-5 to 10^-4         | 2.1 x 10^-1 J cm^-2              | See Figs. 8, 9, and 11 for correction factors. |
| 0.700 to 1.050    | 10^-4 to 10^-3         | 2.1 x 10^-1 J cm^-2              | See Figs. 8, 9, and 11 for correction factors. |
| 1.050 to 1.400    | 10^-3 to 10^-2         | 2.1 x 10^-1 J cm^-2              | See Figs. 8, 9, and 11 for correction factors. |
| 1.4 to 10^1       | 10^-2 to 10^-1         | 2.1 x 10^-1 J cm^-2              | See Figs. 8, 9, and 11 for correction factors. |
|                   | >10                    | 2.1 x 10^-1 J cm^-2              | See Figs. 8, 9, and 11 for correction factors. |
| 1.54 only         | 10^-1 to 10^-0         | 1.0 J cm^-2                      | See Table 9 for apertures. |

* See Note in Section 8 for pulsewidths less than 1 ms.
**See Figs. 7 and Fig. A.3 of Appendix B for graphic representation.

NOTES:
C = 1 for λ = 0.400 to 0.700 μm,
C = 10^{10}/μm²* cm^-2 for λ = 0.700 to 1.05 μm (see Fig. 8),
C = 5 for λ = 1.05 to 1.40 μm,
C = 10^{10}/μm²* cm^-2 for λ = 1.4 to 1.54 μm (see Fig. 9).

See Table 9 for apertures.
See Figs. 8, 9, and 11 for correction factors.
NOTE: For correction factor information at wavelengths between 0.7 μm and 1.4 μm, see Table 5.

Fig. 4
MPE for Direct Ocular Exposure to Visible and Near Infrared Radiation (λ = 0.4 to 1.4 μm) Intrabeam Viewing
(Angular Subtense < α < 90° in Fig. 3), for Single Pulses or Exposures.
### Table 7

**MPE for Skin Exposure to a Laser Beam**

<table>
<thead>
<tr>
<th>Wavelength, Å</th>
<th>Exposure Duration</th>
<th>Maximum Permissible Exposure (MPE)</th>
<th>Notes for Calculation and Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3 x 10⁻⁹ J cm⁻²</td>
<td>or 0.56 x 10⁻⁸ J cm⁻², whichever is lower.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 mm limiting aperture.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>See Figs. 5 and 6 for graphic representation.</td>
</tr>
</tbody>
</table>

#### For Visible and Near Infrared

<table>
<thead>
<tr>
<th>Wavelength, Å</th>
<th>Exposure Duration</th>
<th>Maximum Permissible Exposure (MPE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10⁻² to 10⁻¹</td>
<td>2 x 10⁻⁹ J cm⁻²</td>
</tr>
<tr>
<td></td>
<td>10⁻¹ to 10</td>
<td>1.1 x 10⁻⁸ J cm⁻²</td>
</tr>
<tr>
<td></td>
<td>10 to 3 x 10⁶</td>
<td>0.2 J cm⁻²</td>
</tr>
</tbody>
</table>

#### For Near Infrared

<table>
<thead>
<tr>
<th>Wavelength, Å</th>
<th>Exposure Duration</th>
<th>Maximum Permissible Exposure (MPE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.4 to 10</td>
<td>10⁻⁴ J cm⁻²</td>
</tr>
<tr>
<td></td>
<td>10⁻¹ to 10</td>
<td>0.5 x 10⁻⁸ J cm⁻²</td>
</tr>
<tr>
<td></td>
<td>&gt; 10</td>
<td>0.1 J cm⁻²</td>
</tr>
</tbody>
</table>

#### For Far Infrared

<table>
<thead>
<tr>
<th>Wavelength, Å</th>
<th>Exposure Duration</th>
<th>Maximum Permissible Exposure (MPE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10⁻³ to 10⁶</td>
<td>1 x 10⁻⁸ J cm⁻²</td>
</tr>
</tbody>
</table>

*See 8.4.2 for large beam cross-sections.*
**FLAT SURFACE REFLECTION**

**CURVED SURFACE REFLECTION**

**NOTE:**
*TOTAL BEAM DISTANCE FROM LASER TO EYE (DIRECT PLUS SECONDARY)*

**Fig. B2**
Interscan viewing - Specularly Reflected (Secondary) Beam.

**APPENDIX**

**Fig. B3**
Extended Source Viewing - Normally Diffuse Reflection.

**Eq. B4**
Examples of Use of Laser Range Equation for Determining Nominal Hazard Distance.

**Fig. B5**
Nominal Hazard Zone for a Diffuse Reflection.
Reference Guide

Cleaning of any precision optic risks degrading the surface. The need for cleaning should be minimized by returning optics to their case or covering the optic and mount with a protective bag when not in use. If cleaning is required, we recommend one of the following procedures:

Cleaning Materials

Polyethylene lab gloves. Please wear them. Solvents are harsh to the skin.

Dust free tissue, Lens tissue or equivalent.

Acetone promotes rapid drying of the surface tension of a wet alcohol swab.

Blowing removes some dirt. The best bulb type blowers and brushes must be very clean to prevent redistribution of dirt.

Mild, neutral soap, 1% in water. Avoid perfumed, alkaline or colored products. Several drops of green soap (available in any pharmacy) per 100 cc of distilled water is acceptable.

Spectroscopic grade isopropyl alcohol and acetone.

Caution should be exercised when using rubbing alcohol or acetone that does not dissolve in alcohol or acetone.

Cleaning Procedures

Dust on optics can be very tightly bound by static electricity. Blowing removes some dirt; the remainder can be collected by the surface tension of a wet alcohol swab.

Acetone promotes rapid drying of the optic to eliminate streaks.

1) Blow off dust.
2) Repeat (2) with acetone soaked swabs.
3) Blow off dust.
4) Using a wet swab, wipe the optic gently in the same figure-eight motion.
5) Repeat (2) with distilled water only.
6) Repeat (2) with alcohol.
7) Repeat (2) with acetone.

Surface quality of an optical element ultimately determines the performance of a system. Even the highest quality material, if finished poorly, will cause distortion, loss of contrast, or loss of functionality of the optical system. In order to communicate optical surface quality, Newport has adopted the following standards:

A clear aperture is specified for all Newport optics. This indicates a minimum area over which specifications are guaranteed.

Although typical optics will meet or exceed their ratings in the edge of the component, a clear aperture specification allows sufficient area for safe handling of the optic during manufacture.

Scratch-dig ratings measure the visibility of scratches and digs (small pits). A “#” scratch-dig number indicates a surface free of visible defects. Numbers increase as the visibility of scratches increases.

Scratch numbers are linear with a #10 scratch appearing identical to a 0.01 mm diameter scratches. #10 scratch-dig number is specified above of dig. A #1 dig appears identical to a 0.001 mm diameter scratches. Please note that no absolute measurement of defect size is made or implied by the scratch-dig standard.

Components with small scratch-dig numbers will have increased damage thresholds, reduced scatter, and will eliminate unwanted diffraction effects. Newport recommends the following guidelines in selecting surface finishes:

Scratch-Dig Applications

- 60-40 Non-laser optics
- 60-40 Low-power
- 40-20 Unfocused beams
- 40-20 Collimated laser beams
- 40-20 High-energy, focused beams

Figure 1: A measure of how closely the surface of an optical element matches a reference surface. Since geometrical errors will cause distortion of a transmitted or reflected wave, deviations from the ideal are measured in terms of wavelengths of light.

Spherical Error comprises the majority of figure deviations. Optical polishing relies on circular strokes to finish a surface. For this reason, deviations from the ideal are usually spherical, either concave or convex. Newport computes spherical error as the maximum peak-to-valley deviation from a best fits surface. Mathematically, the spherical surface is halfway between the points of maximum deviation. Practically, this represents the point of best alignment. Figure errors are represented by a line with an error corresponding to the maximum peak-to-valley deviation from the reference surface.

Although less frequently used, the mean square error, E, and the average error, E, may also be defined.

Laser Damage

Certified Damage Threshold optics are available from Newport. Testing on a lot basis enables Newport to certify damage resistance to specified fluences. Please see the Certified Damage Threshold optics section on page 24-77 for more information.

Safe Energy Levels are listed for a majority of Newport optical components. Although these carry no certification, the levels published are conservative and derived from laboratory use tests.

Orders are shipped from our main plant in Fountain Valley, California. Unless otherwise noted, all optics are in stock and ready for delivery.

Unlisted (+) prices or starred (*) part numbers indicate high accuracy optics with very specific applications. They are stocked on a limited stock basis. Contact Newport for price and delivery.

Certified Damage Threshold

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The Discrete Prolate Spheroidal Filter as a Digital Signal Processing Tool

JOHN D. MATHEWS, SENIOR MEMBER, IEEE, J. K. BREAKALL, AND GEORG K. KARAWAS

II. MATHEMATICAL DERIVATIONS

A General Nonrecursive FIR Filter

In keeping with the tutorial nature of this paper we start with the simplest of statements concerning the FIR approach to filtering. Using the time and frequency domains, a tapped delay line representation of a nonrecursive FIR filter acting on analog signal \( x(t) \) is shown schematically in Fig. 1. The resultant output signal has the form

\[
y(t) = \sum_{m=-\infty}^{\infty} a_m x(t - mT) \tag{1}
\]

where the coefficients \( a_m \) are real and where the time reference is, for later convenience, at the center of the delay line. Assuming that the Fourier transform of \( x(t) = X(\omega) \) exists we Fourier transform (1) and find

\[
Y(\omega) = H(\omega) \cdot X(\omega)
\]

where

\[
H(\omega) = \sum_{m=-\infty}^{\infty} a_m e^{-j\omega m} \tag{2}
\]

is the "voltage" transfer function and \( j = \sqrt{-1} \). The corresponding "power" transfer function is

\[
S(\omega) = |H(\omega)|^2 = \sum_{m=-\infty}^{\infty} a_m a_n e^{-j\omega m} e^{j\omega n} \tag{3a}
\]

\[
= \sum_{m=-\infty}^{\infty} |a_m|^2 + 2 \sum_{m=-\infty}^{\infty} a_m a_n \cos(n - m)\omega \tag{3b}
\]

while the inverse Fourier transform of (3) is

\[
h(t) = \sum_{m=-\infty}^{\infty} a_m \delta(t - mT) \tag{4}
\]

the filter impulse response with \( \delta(t) \) the unit impulse. Note that \( h(t) \) convolved with \( x(t) \) yields (1).

The filter described by (3) or (4) becomes a digital filter if we uniformly and instantaneously sample \( y(t) \) at intervals of \( T \) time. Then (1) becomes

\[
y_i = \sum_{m=-\infty}^{\infty} a_m x(i - m) \tag{5}
\]

where the index \( i \) refers to consecutive members of the set of sampled signals. If we restrict \( \omega \) to be band limited to the Nyquist frequency \( (2\pi f_s/2) \) or less, then the sampling theorem process occurs without aliasing.

Choice of Coefficients

Equations (3) or (5) describe the effects of the filter on an input signal given a particular set of coefficients \( \{a_m\} \). These coefficients are often chosen such that the digital filter characteristics are similar to one of various common analog filters (e.g., the "ideal" filter). The process of synthesizing these filter characteristics often involves smoothing (windowing) of the resultant coefficient sequence to suppress ringing [14], [15].

As mentioned in the introduction, we propose to choose

\[
W(\omega) = \sum_{m=-\infty}^{\infty} \sin(n \omega T) \tag{6}
\]

\[
\omega_0 = \omega_0 \tag{7}
\]

\[
\epsilon = \omega_0/\omega \tag{8}
\]

and the windowing function \( W(\omega) \) is such that \( W(\omega) = 0 \) for \(|\omega| > K\) thus truncating the series so that the resultant transfer function becomes

\[
H_\epsilon(\omega) = \sum_{m=-\infty}^{\infty} W(n) C_n e^{j\omega m} \tag{9}
\]

The \( W(n) \) \( -K \leq n \leq K \) are chosen to minimize in some sense the ringing (Gibb's phenomena) which results from truncation of the series representation of the ideal low-pass filter [15, chap. 5].

Fig. 1. Block diagram of the nonrecursive FIR filter described by (1). This schematic form of the filter is valuable because of its visual simplicity.

Fig. 2. Filter frequency response (dB) plotted versus normalized frequency (Nyquist frequency \( f_s = 0.5 \)) and corresponding impulse response envelope plotted versus time in samples for rectangular, Kaiser, and Von Hann windows of length 31 (see Table I and Fig. 2). In all cases the normalized 3 dB frequency is approximately \( 0.05 \).
Fig. 1. Similar to Fig. 2, but for Dolph-Chebyshev and Hamming windows, and the prolate spheroid filter. The normalized cutoff frequency of the prolate spheroid filter is 0.7. The filters in Figs. 2 and 3 are ordered according to overall quality with, in our opinion, the rectangular window filter worst and prolate spheroid filter best.

Fig. 4. We compare the time domain effects of the various filters on a square wave plus Gaussian distributed noise. Note that all filters except the prolate spheroid filter "rag" and that the rectangular window filter rings most with the Kaiser window next while the Dolph-Chebyshev, Hamming, and Von Hann windows are similar in this case.
\[
N(Z) = \eta_{\text{eff}} T_A \times \frac{P_L}{hc/\lambda} \times \sigma_R n(Z) \Delta Z \times \frac{A_R}{4\pi z^2}
\]

PHOTOCOUNT = SYSTEM X PHOTONS X SCATTERING X RECEIVER
EFFICIENCY TRANSMITTED PROBABILITY PROBABILITY

=> Special care should be taken to maximize the efficiency of the lidar’s optical design by:
1) Maximizing transmission through lenses and filters.
2) Maximizing reflection off mirrored surfaces.
3) Minimizing the total number of surfaces in the system.
<table>
<thead>
<tr>
<th>Facility</th>
<th>Laser</th>
<th>λ(nm)</th>
<th>Laser Power $P_L$(W)</th>
<th>Telescope Area $A_R$(m²)</th>
<th>Performance Factor* $A_RP_L$(m²W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFGL (mobile)</td>
<td>Nd:YAG</td>
<td>532</td>
<td>3</td>
<td>0.07</td>
<td>0.2</td>
</tr>
<tr>
<td>Haute Provence</td>
<td>Nd:YAG</td>
<td>532</td>
<td>4</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Kyushu Univ.</td>
<td>Excimer</td>
<td>351</td>
<td>16</td>
<td>0.2</td>
<td>4.2</td>
</tr>
<tr>
<td>CEDAR</td>
<td>Dye</td>
<td>589</td>
<td>5</td>
<td>1.2</td>
<td>4</td>
</tr>
<tr>
<td>CEDAR+</td>
<td>Excimer</td>
<td>351</td>
<td>30</td>
<td>1.2</td>
<td>50</td>
</tr>
</tbody>
</table>

*Equivalent performance at 532 nm
*Not yet tested

**DETECTOR**

24) Fused silica plano-convex lens (1" dia. x 1" FL) AR coated, 99.7% trans. @ 532,355,607nm
14) Dichroic beamsplitter: reflects 99.5% @ 532nm transmits 82% @ 355nm transmits 86% @ 607nm
6) Narrow-band filter, BW = .29nm @ 532nm 55% transmission
7) Beamsplitter, transmits .5%, reflects 99.5%
27) Glass plano-convex lens (1" dia. x 1" FL) AR coated, 99.7% transmission @ 532nm.
13) highly reflective mirror @ 532nm,355nm reflects 99.8%
4) Glass plano-convex lens (1" dia. x 2" FL.) AR coated, 99.7% transmission.
19) Photon counting PMT, 20% quantum efficiency @ 532nm.
25) Dichroic beamsplitter: reflects 99.5% @ 607nm transmits 82% @ 355nm
22) Narrow-band filter, BW = 3.5nm @ 607nm 83% transmission.
23) Photon counting PMT, 7% quantum efficiency @ 607nm.
10) Narrow band filter, BW = 3.2nm @ 355.1nm. 24% transmission.
8) fused silica plano-convex lens (1"dia. x 2" FL) AR coated, 99.7 transmission.
20) Photon counting PMT, 24% quantum efficiency @ 355nm.

$D_{eff} = 10.71\% @ 532nm$
$4.93\% @ 607nm$
$3.78\% @ 355nm$
**SYSTEM EFFICIENCY**

\[ \eta_{\text{eff}} = T_{\text{eff}} \times R_{\text{eff}} \times D_{\text{eff}} \]

<table>
<thead>
<tr>
<th></th>
<th>532</th>
<th>355</th>
<th>607nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAMP</td>
<td>.0718</td>
<td>.0251</td>
<td>.0324</td>
</tr>
<tr>
<td>GLINT</td>
<td>.0481</td>
<td>.0218</td>
<td>--</td>
</tr>
</tbody>
</table>

**LASER POWER**

\[ P_L = \text{laser power in joules.} \]

<table>
<thead>
<tr>
<th></th>
<th>532</th>
<th>355nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAMP</td>
<td>.7J</td>
<td>.4J</td>
</tr>
<tr>
<td>GLINT</td>
<td>.5J</td>
<td>.18J</td>
</tr>
</tbody>
</table>

**NUMBER DENSITY**

\[ n(z) \text{ is read from table II in the U.S. Standard Atm. 76} \]

<table>
<thead>
<tr>
<th>Alt.</th>
<th>n(Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30Km</td>
<td>3.745E23 /m²</td>
</tr>
<tr>
<td>50Km</td>
<td>2.135E22 /m²</td>
</tr>
<tr>
<td>60Km</td>
<td>5.995e21 /m²</td>
</tr>
</tbody>
</table>

**TELESCOPE AREA**

\[ A_R = \pi R^2 \text{ where } R \text{ is the radius of the} \]

<table>
<thead>
<tr>
<th></th>
<th>A_R</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAMP</td>
<td>.13 m²</td>
</tr>
<tr>
<td>GLINT</td>
<td>.0804 m²</td>
</tr>
</tbody>
</table>

**RAYLEIGH BACKSCATTER CROSS SECTION**

\[ \sigma_R = 5.45 [550/\lambda(\text{nm})]^4 \times 10^{-32} \text{ m}^2\text{sr}^{-1} \]

<table>
<thead>
<tr>
<th></th>
<th>532</th>
<th>355nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>\sigma_R</td>
<td>62.26E-33</td>
<td>313.6E-33 m²</td>
</tr>
</tbody>
</table>

**ATMOSPHERIC TRANSMISSION**

\[ T_A = T_{\text{Up}} \times T_{\text{Back}} \]

\( T_U \text{ and } T_B \text{ are calculated from LOWTRAN 7} \)

<table>
<thead>
<tr>
<th>Alt.</th>
<th>( T_{U(532)} )</th>
<th>( T_{U(355)} )</th>
<th>( T_{B(607)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>30Km</td>
<td>.6249</td>
<td>.3337</td>
<td>.6768</td>
</tr>
<tr>
<td>50Km</td>
<td>.6215</td>
<td>.3313</td>
<td>.671</td>
</tr>
<tr>
<td>60Km</td>
<td>.6214</td>
<td>.3312</td>
<td>.6709</td>
</tr>
</tbody>
</table>

**PHOTON ENERGY**

\[ E = \frac{hc}{\lambda} \]

<table>
<thead>
<tr>
<th></th>
<th>532</th>
<th>355</th>
<th>607nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>373.9E-21</td>
<td>560.1E-21</td>
<td>327.5E-21J</td>
</tr>
</tbody>
</table>

**INTEGRATION HEIGHT**

\[ \Delta Z = c \tau_d/2 \text{ where } \tau_d = \text{integration time} \]

\[ \tau_d = 2\mu s \]

\[ \Delta Z = 300 \text{ m} \]

**ATMOSPHERIC HEIGHT**

\[ Z = \text{height of scattering volume} \]
Fig. 5. The density and temperature results obtained on 8 and 9 March 1986 at the same time by rocket instrument and lidar.

Fig. 4. The four datasonde rocket flights and the corresponding lidar results are shown for the density ratio to the USSA76 model and for the temperature.
Fig. 6. The data obtained on 14 February 1986 exhibits significant departures between the lidar and rocket data. Two major differences are observed in this data set, the large wave response associated with the strong wind field during this period and the additional optical scattering between 25 and 35 km.

Fig. 7. The simultaneous measurement of the UV (355 nm) and the visible (532 nm) backscatter clearly shows the aerosol signal because of the relative difference in backscatter cross-section at the two wavelengths.
Hydrostatic Equation

$$dP = -\rho gdz$$

Ideal Gas Law

$$P = \rho RT/M$$

By combining these two equations and integrating downward from a starting altitude $z_o$ and upper level temperature $T(z_0)$ we obtain

$$T(z) = \frac{T(z_o)p(z_o)}{\rho(z)} + \frac{M}{R} \int_z^{z_o} \frac{g(r)p(r)}{\rho(z)} \, dr$$

$P(z)$ = atmospheric pressure profile
$\rho(z)$ = atmospheric density profile
$T(z)$ = atmospheric temperature profile
$g(z)$ = gravitational acceleration
$M$ = mean molecular weight of atmosphere
$R$ = universal gas constant

Density perturbation profiles and power spectrum measured on February 24, 1986 using the AFGL Rayleigh lidar at Poker Flat, AK. The diagonal lines indicate the 0.3 m/s phase progression of the 7.7 km wave [Miller et al., 1987].
Temperature profiles obtained at Andoya, Norway on March 13, 1986 with the University of Bonn Na lidar. Integration period is 5 min. and vertical resolution is 500 m [von Zahn and Neuber, 1987].

Na temperature can be measured by scanning a narrowband laser through the D2 resonance line. Technique was first demonstrated by Thomas and co-workers [Gibson et al., 1979; Thomas and Bhattacharyya, 1980].

Resonance-fluorescence lidars are used to study metallic species in the mesosphere and thermosphere. Systems have been developed to measure Na, Li, K, Fe, Ca and Ca+.
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