

# Practical Aspects of Mirror Usage in Optical Systems for Biology

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# 1. Introduction

The newcomer to a biological optics laboratory browses to a website with a catalog of optical parts, intending to purchase a mirror, and is confronted by a large number of offerings. Each part description indicates it is to be used for a specific purpose, wavelength range, etc. The newcomer first wonders, “Why are there so many varieties of mirrors?” and shortly afterwards, “How do I know which mirror to use for my specific purpose?”

This paper seeks to answer that question, by providing practical, useful information on the specific topic of the now ubiquitous flat dielectric mirror. It also outlines some of the key design considerations and specifications one should consider when selecting the appropriate flat mirror for an optical system used in biology.

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## 2. Some Early History of the Mirror

The mirror’s essential and original purpose is reflection, in which an incident beam of light from one direction reflects in another direction, sometimes containing an image which is seen or projected. The history of fabricated mirrors, which can be traced back to 6000 BCE, started with polished volcanic glass and stones, followed by the metal mirror, in which a metal plate was polished to achieve suitable reflection [1]. Later versions employed a layer of metallic material such as a silver- or tin-mercury amalgam [2], coated onto a solid backing, among which glass began to be used because it could be readily produced with sufficient flatness, transparency and rigidity to produce an image of higher quality.

One unusual type of mirror, fabricated during the Han Dynasty in China (206 BCE to 220 CE), demonstrates a surprising effect, as pointed out in Needham’s monumental work on science in ancient China [3]. The mirror is cast of bronze and has a polished, reflective front surface, which functions as a normal mirror. The back side of the mirror is sculpted with ideograms or designs, and the unusual aspect is that when the front surface is illuminated brightly and positioned to reflect on a wall, the design on the back side is clearly visible in the reflected image. Since the mirror is of solid bronze, this behavior has seemed contradictory, as if the mirror were simultaneously reflective and partially transparent. Indeed the name 透光镜(*tòu guāng jìng*) literally means “light penetrating mirror” [4], though the Chinese scientist Shěn Kuò had correctly concluded by 1088 CE that the effect was in fact due to small distortions on the front surface [5].

The resolution of this paradox came eventually. Bragg concluded in 1932 that the pressure and materials used in the fabrication process resulted in minute distortions on the front surface, that matched the shapes on the back surface but were too small to see, and that these distortions are the origin of the image in the reflection [3]. Calculations by Berry in 2006 showed that the reproduction is the Laplacian transform image of the distortions on the front surface [6]; this transform is the second spatial derivative of the original, often used as an edge detection filter in image analysis. Berry’s calculations further suggest that the distortions are likely not more than about 400 nm high, supporting Needham’s comment that this mirror represents “the first step on the road to knowledge about the minute structure of metal surfaces” [3].

### 3. The Metal Mirror

Our hypothetical beginner in the optics lab might wonder if it is really necessary to purchase one of the very specialized mirrors in the catalog, given that metal mirrors seem to be flexible in their application and relatively inexpensive.

In fact, the metal mirror has several very useful features: the reflection can be obtained over a wide range of angles, is insensitive to angle

of incidence and polarization, and does not induce variable angle- and wavelength-dependent phase shifts. Besides, fabrication is often relatively straightforward and therefore usually less costly.

However, the metal mirror has several key disadvantages. The free electrons in the shiny metal surface, being mobile due to the conductivity of the metal, move in response to the

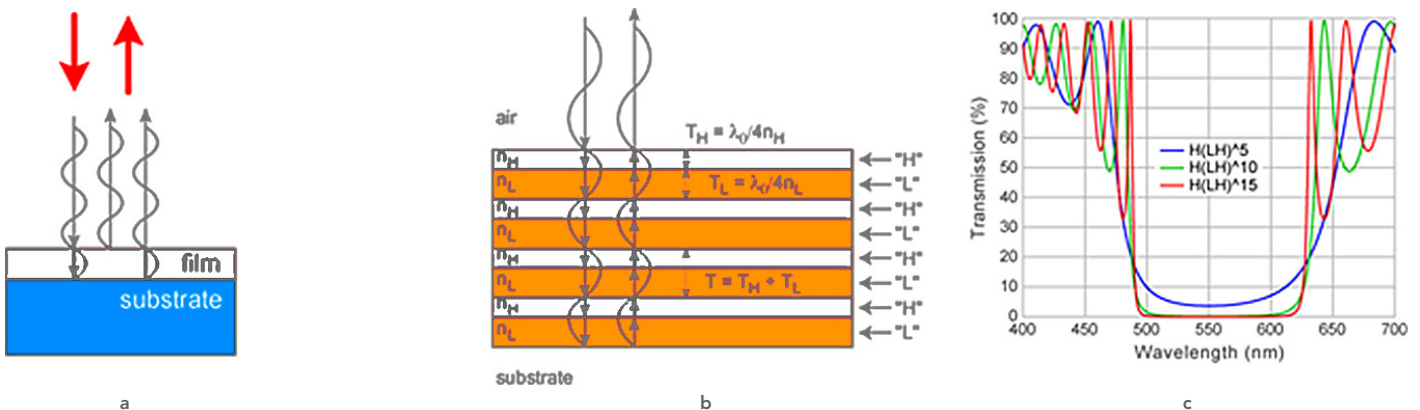
electromagnetic field of the incident light, and this mobility comes with a degree of loss of electron energy, which results in a lower reflection. This loss also results in a low threshold for heat-induced damage. Some metal mirror surfaces tend to oxidize, and though coatings can be used to prevent this, the mirror remains susceptible to scratches and mechanical damage during handling or cleaning.

### 4. The Dielectric Mirror

If the disadvantages summarized in the previous section had never been overcome, optical capabilities would be a far cry from what they are today, and our hypothetical newcomer would have much less choice in the mirror section of the website catalog. The technology enabler was the development of the dielectric mirror, which has replaced the metal mirror in many demanding applications, and whose innovation continues today.

The dielectric mirror is made up of many thin layers of dielectric material, coated on a glass substrate. The behavior of such a mirror is based on constructive interference between light reflected from the individual layers. Figure 1a illustrates this for the simple case of two layers with high and low indices of refraction, and shows constructive interference taking place between the reflected light from each layer interface. Figure 1b shows a quarter wave stack, a "building block" frequently used in filter design;

the alternating layers are composed of material with high and low index of refraction  $n_H$  and  $n_L$ , the thickness of each layer is one quarter of the optical wavelength ( $\lambda/4n_H$  or  $\lambda/4n_L$ ) in that medium, and the wavelength to be reflected is  $\lambda$ . As more layers with  $n_H$  and  $n_L$  are added, as in Figure 1c, the transmission is suppressed in the central region, called the "stop band", where reflection will therefore take place. For a fuller description of the design concepts and considerations, see [7].



**Figure 1.** Illustrations of design concepts of the dielectric mirror; (a) constructive interference between light reflected from adjacent layers; (b) a quarter-wave stack; and (c) development of a transmission stop band with increasing number of dielectric layers.

## 5. Key Parameters

The dielectric mirror can have very high reflection, to better than 99.99%. Also unlike the metal mirror, the dielectric mirror tends not to absorb energy from the incoming optical radiation, and tends to have a much higher threshold of damage. And finally, the dielectric coatings are robust, and can tolerate cleaning and other processes that would damage a metal mirror.

In analogy to the Han Dynasty mirror, one can say of the dielectric mirror that it takes advantage of the minute structure of thin films to achieve wavelength selectivity, and can now truly be called a “light penetrating mirror”.

The dielectric mirror has very important advantages, but it is not perfect either. Since the dielectric mirror takes advantage of the wave nature of light, mirror performance depends on wavelength, as well as on other optical parameters. Mirrors must therefore be designed and fabricated to the specific purpose intended, which accounts for the large number of mirror parts in the catalog being viewed by our hypothetical newcomer.

The next sections discuss this dependence on parameters of optical systems, and illustrate the use of recently innovated dielectric mirrors that can be used over a much wider range of these parameters.

This section describes the key parameters relevant to the usage of any mirror, including the dielectric models discussed in this article. A summary of the parameters is shown in Table 1. Some application-specific remarks are shown within boxes below each parameter description.

- ✓ Intensity, which refers to the power of a beam of light, for example in W or mW, divided by the area over which the power is measured, over a defined range of wavelengths.
- ✓ Wavelength, which for this article is understood to range between 300 and 1200 nm, the range that includes most biological applications of light.

In general, it can be fairly challenging to design a dielectric mirror with high reflection over a large wavelength range, and trade-offs or compromises may be necessary when specifying the two parameters.

- ✓ Reflection, the primary purpose of a mirror, also refers to the fraction of light intensity that is reflected specularly from the mirror upon which an incoming beam of light is incident, meaning that the reflection preserves the beam and any image contained in it.

A mirror with reflection > 95% is usually ample for optical setups used for biological applications with incoherent light from LEDs, lamps, etc. Mirrors

| Parameter Name                               | Abbreviation; Units    | Notes   |
|--|------------------------|---|
| Reflection                                   | R, $R_{avg}$ ; %       | See this section, below                                       |
| Transmission                                 | T, $T_{avg}$ ; %       | See this section, below                                       |
| Scatter                                      |                        | See this section, below, and Section 15                       |
| Absorption                                   | A                      | See this section, below                                       |
| Wavelength Range                             |                        | See Section 7   |
| Angle of Incidence                           | AOI; °                 | See Section 8   |
| Cone Half Angle                              | CHA; °                 | See Section 9   |
| Polarization                                 |                        | See Section 10  |
| Diameter or Dimensions                       | mm                     | See Section 13  |
| Thickness                                    | mm                     | See Section 13  |
| Clear Aperture                               | mm                     | See Section 14  |
| Radius of Curvature                          | m, mm                  | This white paper deals only with flat mirrors; see Section 12 |
| Optical Damage Rating                        |                        | See Section 16  |
| Surface Quality – Scratch-Dig and Scattering |                        | See Sections 14 and 15  |
| Wedge  | arc second             | See Section 12  |
| Substrate Material                           |                        | See Section 13  |
| Flatness                                     | Waves P-V per distance | See Section 12  |
| Transmitted Wavefront Error                  | TWE                    | See Section 12  |
| Group Delay Dispersion                       | fs <sup>2</sup>        | See Section 17  |

Table 1: Parameters that describe mirror performance.

used in laser setups usually require higher reflection, in the range of 99%, and mirrors used for cavities typically have reflection up to 99.999% or even higher. In general, the higher the reflection of a mirror, the narrower the range of wavelengths over which that reflection holds.

✓ The following processes remove light from the reflected beam, thereby reducing reflection; see Figure 2 for an illustrative cartoon.

- › Scatter refers to the reflection of light that does not preserve the beam. Scatter occurs from surface roughness, patterned surface structure left behind by glass polishing, defects in the glass, and from the glass atoms themselves, even with no defects, surface structure or roughness present. For the dielectric mirrors discussed here, the amount of light lost through scatter is in practice typically about 0.1%, and not more than a few tenths of one per cent.

Scatter is significantly impacted by the characteristics of the substrate. The quality of substrate polish affects the substrate texture, which in turn affects the scatter properties of a mirror. A good mirror not only minimizes light loss due to scatter, but also limits highly directional scatter, as if from diffraction gratings, when used with a coherent beam. More detailed information on scatter is to be provided in Part 2 of this article.

- › Absorption refers to the conversion of light energy into energy initially held in the structures that make up the coating layers and the mirror substrate. The amount of absorption is wavelength-dependent, but in the range 400 to

1200 nm absorbance (the fraction of light absorbed) is negligibly small. The absorbance between 300 and 400 nm can be significant, but depends on the specific type and thickness of the glass being used.

Absorption results in heating of the mirror, but this is usually negligible for the dielectric mirrors discussed here. However, please refer to the section on damage thresholds, to be described in Part 2 of this article. Light-absorbing mirrors, which are not dielectric, may need cooling to reduce thermal stress.

- › Transmission of light takes place if the light is not reflected, scattered, or absorbed. Transmitted light therefore emerges from the far surface of the mirror and continues in the same direction as the incident light. Conservation of energy requires

$$T + R + A + S = 1$$

where the four symbols refer to Transmission, Reflection, Absorption and Scatter, respectively.

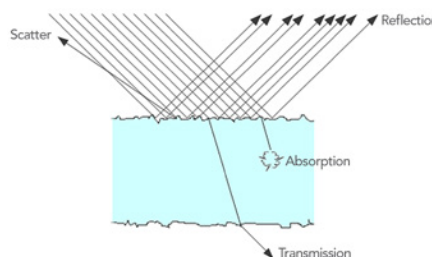


Figure 2: Cartoon illustrating interactions of light with a mirror.

- ✓ Angle of Incidence, or AOI, is the angle from the substrate surface normal made by the incoming or reflected beam of light; see Figure 3.

Though the AOI parameter is typically set by the geometry of the light path in the imaging system, the light path must take into account the anticipated mirror

performance at the planned AOI. The AOI is usually provided with a tolerance, e.g.  $5.0^\circ \pm 1.5^\circ$ ; see Section 6 for an example and discussion.

- ✓ Cone Half Angle, or CHA, refers to half the range of angles of rays in the beam of light, if the beam is not parallel. It is understood to always be a positive number if it is nonzero. AOI and CHA are sometimes confused, but bear in mind that they are independent. An optical system can have a nonzero AOI and zero CHA, or zero AOI and nonzero CHA, or both AOI and CHA nonzero. The simplest starting point, however, is the case of both AOI = CHA =  $0^\circ$ . Figure 3 shows situations with several combinations of AOI and CHA.

The CHA parameter, like AOI, is typically set by the geometry of the light path.

The best performance from a mirror is achieved when CHA =  $0^\circ$ , but the behavior of the mirror at nonzero CHA can be assessed to very good accuracy using simulations of mirror performance.

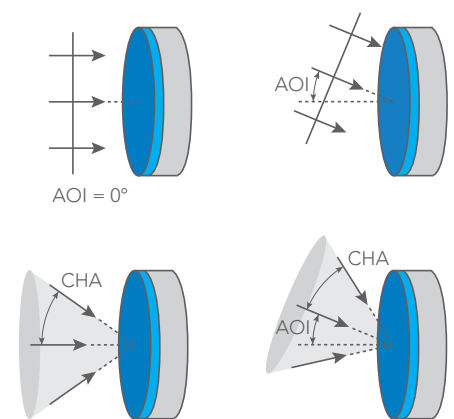
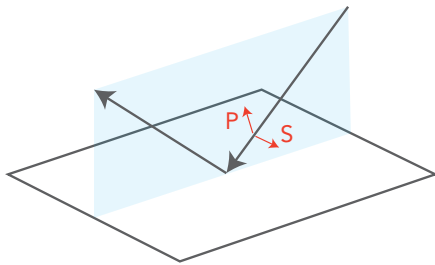


Figure 3: Combinations of AOI and CHA. From left to right: AOI = CHA =  $0^\circ$ ; AOI >  $0^\circ$  and CHA =  $0^\circ$ ; AOI =  $0^\circ$  and CHA >  $0^\circ$ ; AOI >  $0^\circ$  and CHA >  $0^\circ$ .

✓ Polarization refers to the direction of the electric field vector of a ray of light. If a light ray is incident on and reflected specularly from a mirror surface with  $\text{AOI} \neq 0^\circ$  (Figure 4), the plane (shown shaded) formed by the two rays allows us to define the polarization. If the electric field vector is oriented parallel to that plane, the ray is referred to as P-polarized; if perpendicular, as S-polarized; these are often abbreviated P-pol and S-pol respectively.



**Figure 4:** Diagram illustrating S-polarized and P-polarized electric field vectors for a ray of light reflected from a mirror surface. The vector *P* is parallel to the shaded plane formed by the incident and reflected rays, and *S* is perpendicular to that plane.

In a more general case, the field may be linearly polarized, meaning that the field vector points at a fixed angle with time in the plane perpendicular to the direction of propagation; or circularly polarized, when the tip of the vector traces a circular path with time in that plane; or, most generally of all, elliptically polarized, when the tip traces an elliptical path.

If the different rays making up a beam of light all have different polarizations, the light is referred to as being unpolarized. The term average polarization refers to the practice of taking an average of S- and P-polarized spectral behavior. For example, if the reflection is 97% for P-polarized light, and 99% for S-polarized light, then the average polarization is said to be 98%, the average of 97% and 99%.

The absence of polarization is sometimes termed random polarization.

There are subtle but practical differences between the terms average and random in this context.

For example, if a measurement is made under average polarization conditions, someone repeating this measurement is obliged to measure under both S- and P-polarized conditions and then to calculate the average. If random polarization is specified, only one measurement need be made, using an unpolarized light source, and without use of any polarizer elements in the beam. Thus the latter requires less effort, which can be of practical advantage to, for example, someone performing incoming quality control on a large number of received mirrors or filters.

Light from bulbs or lamps is unpolarized, as is light from LEDs, though some OLEDs can be manufactured to output polarized light from the assembly. Light from gas and solid state lasers is often polarized, and the state of polarization must be taken into account (S, P, or other) when choosing a mirror to be placed at non-normal beam incidence. If a beam is known to be polarized, it is important to know the degree of polarization; if a significant fraction of the light has the opposite polarization to the dominant one, one must take this into account when choosing a mirror, as the behavior of the unwanted polarization may interact with mirrors and other polarization-sensitive optical components in unanticipated ways.

Reflection from dielectric mirrors results in a relative phase shift between the S- and P-polarized components of the incident light. The mirror preserves the polarization state of pure S- or P-polarized incident light upon reflection, but mixed states, such as linear, circular, or elliptical polarization states are altered, so that for example a circularly polarized beam may become elliptically polarized after reflection. This is discussed further in Section 10.



## 6. Example Mirror Specifications

Performance characteristics will be examined in detail for two Semrock mirrors in following sections; their performance specifications are summarized here.

The general purpose mirror MGP01-350-700 has specifications shown in Table 2.

|                           |                            |
|---------------------------|----------------------------|
| Reflection Band 1         | Ravg > 98%, 350 – 700 nm   |
| Reflection Band 1 (S-pol) | Ravg > 99.5%, 350 – 700 nm |
| Reflection Band 1 (P-pol) | Ravg > 96%, 350 – 700 nm   |
| Angle of Incidence        | 45.0° ± 1.5°               |

Table 2: Specifications for Semrock MGP01-350-700 mirror.

The S-pol specification, for example, means the following: The reflection of S-polarized light, averaged over all measured wavelengths from 350 to 700 nm, is guaranteed to exceed 99.5% for  $43.5^\circ \leq \text{AOI} \leq 46.5^\circ$  and **CHA = 0°**. The bold text here emphasizes that a nonzero CHA would increase some of the rays' angles to beyond 1.5° tolerance around the central ray, and therefore outside the range in which the specification can be guaranteed.

The Semrock MaxMirror MM3-311-t6 is a higher performance and more versatile alternative to the MGP01 series. The MM3-311-t6 maintains very high reflection for both S- and P-polarized light, over a very wide wavelength range, and a large AOI range. Specifications are shown in Table 3.

|                           |                           |
|---------------------------|---------------------------|
| Reflection Band 1         | Ravg > 99%, 350 – 1100 nm |
| Reflection Band 1 (S-pol) | Ravg > 99%, 350 – 1100 nm |
| Reflection Band 1 (P-pol) | Ravg > 99%, 350 – 1100 nm |
| Angle of Incidence        | 0° – 50°                  |

Table 3: Specifications for Semrock MaxMirror MM3-311-t6.

## 7. Wavelength Dependence of Reflection

Wavelength dependence of reflection is employed to achieve the various special types of mirrors, such as the hot mirror (which reflects the longer wavelengths and is transparent at shorter wavelengths); the cold mirror (the converse of the hot mirror, i.e. which reflects the shorter wavelength and is transparent at longer wavelengths); and the beam splitter, which reflects a designed-for fraction of the light and transmits the rest, also as a function of wavelength.

Broadband light sources such as those from arc lamps, discharge tubes, halogen and projector lamps, and LEDs can take advantage of dielectric mirrors that have been designed for non-narrow band reflection, along with the often large CHA that these systems employ.

Laser light sources, on the other hand, are able to take advantage of the narrow-band dielectric mirror. If one has multiple laser wavelengths present in a system, obtaining a mirror that can reflect all wavelengths effectively may be nontrivial.

Figure 5 shows examples of wavelength dependence of reflection

in a mirror, for the Semrock general purpose mirrors MGP01-350-700 and MGP01-650-1300, for  $\text{AOI} = 45^\circ$ . Both mirrors have high reflection over their respective wavelength ranges. Note however that the user who wants a single mirror to reflect at  $45^\circ$  over the range 600 to 800 nm could not use these mirrors.

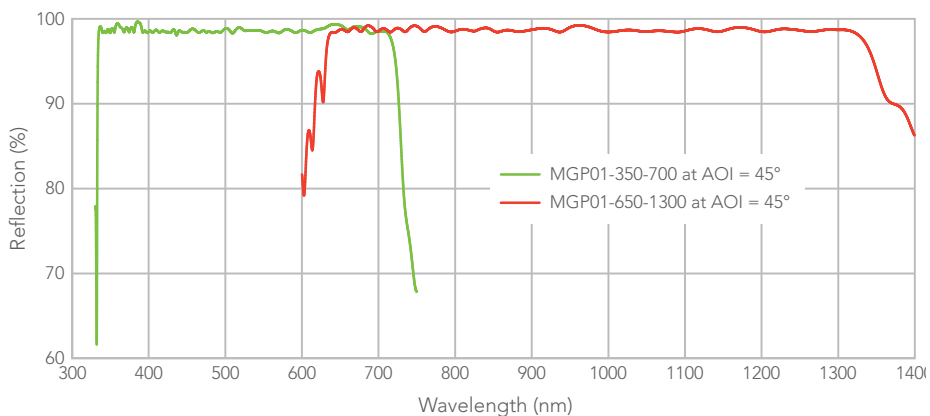


Figure 5: Plot of reflection versus wavelength for Semrock mirrors MGP01-350-700 and MGP01-650-1300.

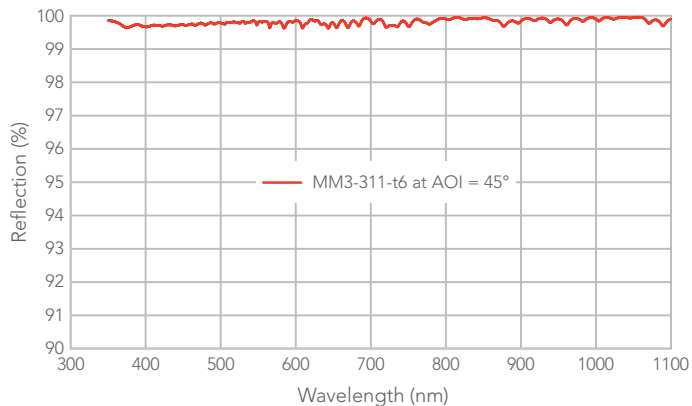


That user could instead use the MaxMirror MM3-311-t6, which has uniformly high reflection over a very broad range, even at an AOI of 45°, as shown in Figure 6.

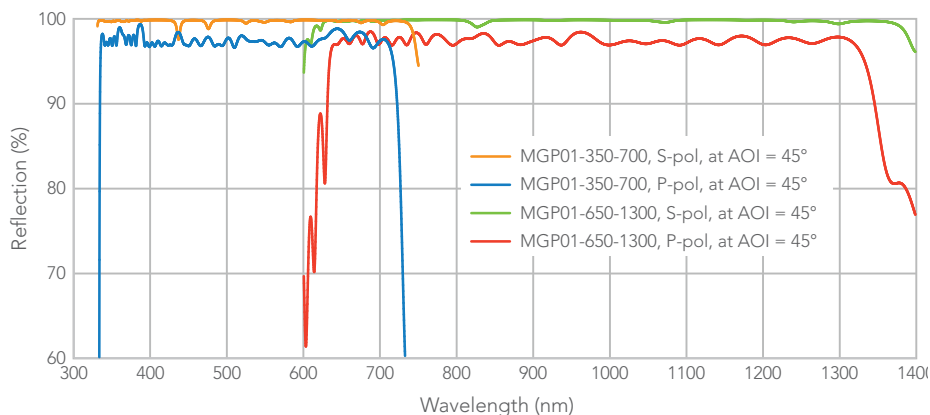
No distinction was made in Figure 5 between S- and P-polarization. Figure 7 shows data for the same mirrors as in Figure 5, and the same AOI, but with the two polarization states shown individually. This illustrates the general statement that S-polarized light is usually more reflective from a surface than is P-polarized light.

Suppose the MGP01-650-1300 mirror were to be used with a ruby laser at 628 nm in a P-polarized configuration. The expanded plot in Figure 8 shows that the reflection of the P-polarized light (green trace) is reduced to near 80% at that wavelength (red arrow). If greater reflection is required, one would therefore either use the laser in the S-polarized configuration (e.g. rotate the laser or the beam by 90°) – if the rest of the optical system could be adapted to this change – or choose a different mirror.

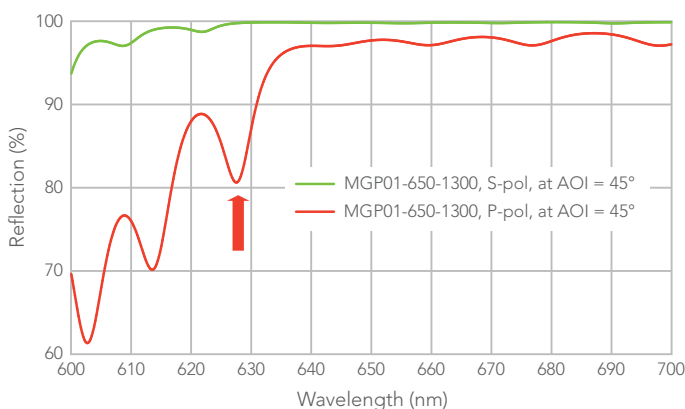
On the other hand, the MaxMirror shows very little difference between polarization states over its operating range; see Figure 9. If changing the polarization of the ruby laser is not an option, this mirror would be a good solution for that application.



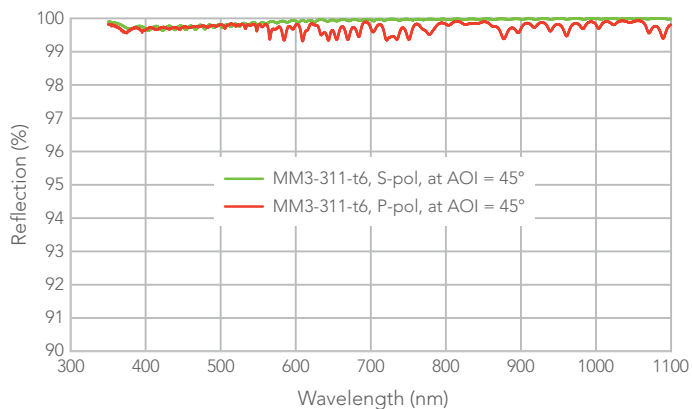
**Figure 6:** Plot of reflection versus wavelength for Semrock MaxMirror MM3-311-t6.



**Figure 7:** Plot of reflection versus wavelength for different polarization states for Semrock mirrors MGP01-350-700 and MGP01-650-1300.



**Figure 8:** Plot of reflection versus wavelength for different polarization states for Semrock mirror MGP01-650-1300, with expanded horizontal scale. The red arrow indicates the wavelength of 628 nm.



**Figure 9:** Plot of reflection versus wavelength for different polarization states for Semrock MaxMirror MM3-311-t6.

## 8. AOI Dependence of Reflection

This section shows some effects of AOI on mirror performance. As an example, we take again the general purpose mirror MGP01-350-700. This was optimized for use at AOI = 45°, as is appropriate for beam steering applications in which 90° reflections are used. It can however easily happen that the mirror is to be used in a setup where the AOI would be 30° or perhaps even 60°, though the latter is rather extreme. The reflection versus wavelength for the different AOI and polarizations is shown in Figure 10.

The following trends and issues can be identified in Fig. 10, and are typical of trends present in dielectric mirrors. Unsurprisingly, these are also found in band pass filters and dichroic mirrors based on layers of dielectric thin films.

- ✓ The performance of the mirror at smaller AOI is in general better than at larger AOI.
- ✓ The performance deficit of P-polarized reflection compared to S-polarized increases with AOI.
- ✓ At high AOI, the P-polarized reflection has relatively strong wavelength dependence.
- ✓ The overall reflection plot shifts towards the blue (i.e., towards shorter wavelengths) with increasing AOI. The absolute amount of shift is greater at the red edge than at the blue edge, though when normalized to the wavelength, the shift is relatively constant.

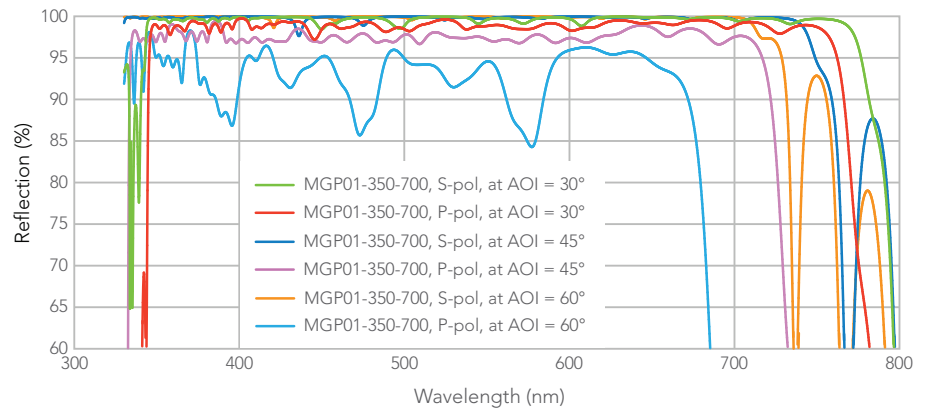


Figure 10: Reflection of Semrock mirror MGP01-350-700 for different AOI and polarization settings.

## 9. CHA Dependence of Reflection

Finally we examine the effect of CHA on the performance of the mirror MGP01-350-700, in this case keeping the AOI at the nominal value of 45°; see Figure 11.

In this case the mirror maintains very reasonable performance over the 350 to 700 nm range, except for

P-polarized light at the highest CHA, where as in Figure 8 the higher angles result in fall of reflection beyond 650 nm. The main effect of CHA is to smooth the wavelength dependence of reflection, for example at the ends of the useful range of the mirror.

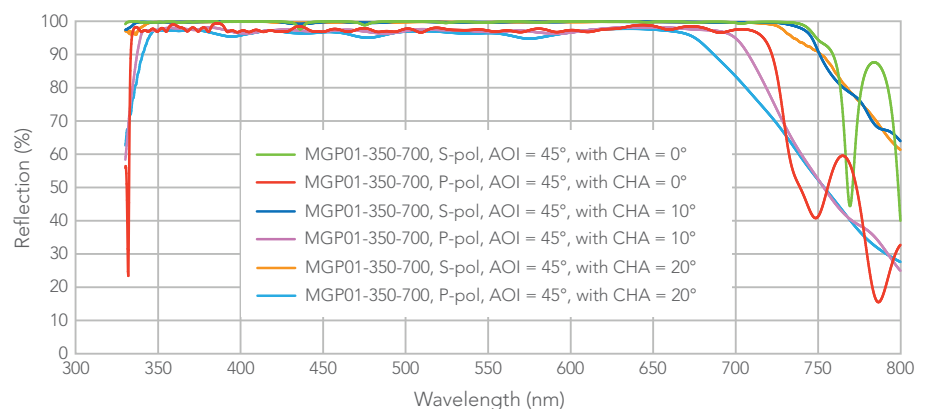


Figure 11: Reflection of Semrock mirror MGP01-350-700 for different CHA and polarization settings.

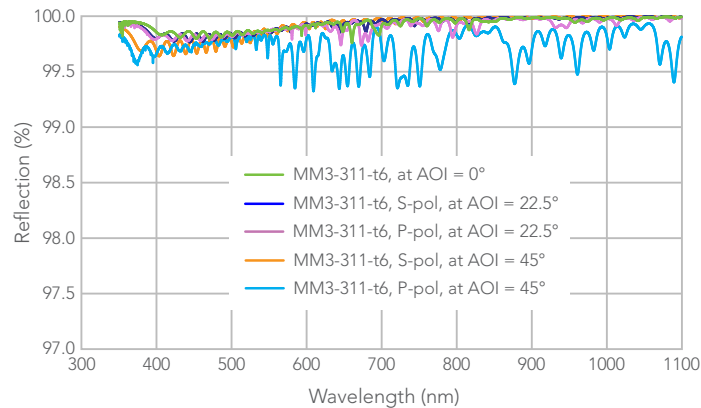
## 10. AOI Dependence of Polarization

In this section we examine the effects of AOI upon the polarization state of a reflected coherent beam. The example used here is the Semrock MaxMirror MM3-311-t6. The effects of AOI and polarization state upon spectral reflection performance is shown in Figure 12.

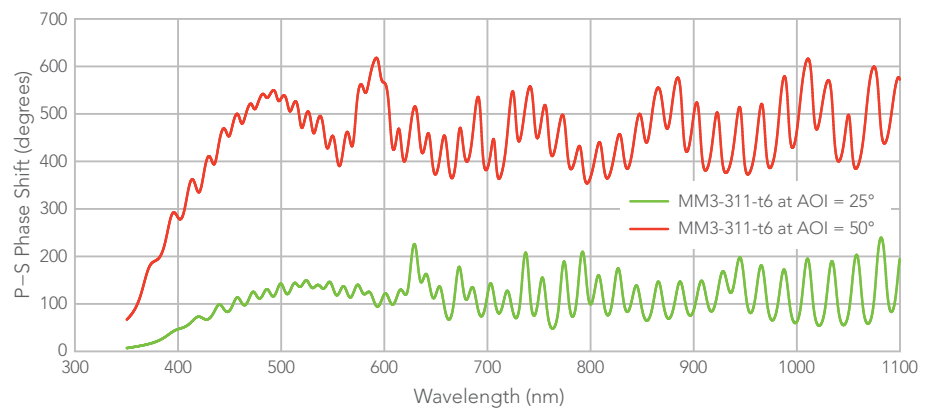
As claimed in the specifications in Section 6, the MaxMirror reflection remains very high over a wide wavelength and angle range for both S- and P-polarization components.

At the end of Section 5, it was mentioned that a dielectric mirror preserves the polarization state of pure S- or P-polarized incident light upon reflection, but that mixed states are usually altered. To get some insight into this, consider the difference in phase shifts induced by the mirror in the reflected beam between P- and S-polarized beams, shown in Figure 13.

The polarization state is irrelevant for  $\text{AOI} = 0^\circ$ , as at normal incidence no S and P designation is possible. For non-normal incidence, the phase shifts differ significantly for the two polarization components, both in size and in wavelength dependence. A pure S- or P-polarized beam will remain so after reflection, though the phase of the component present will be changed. However, light with both polarization components



**Figure 12:** Reflection of Semrock mirror MM3-311-t6 for different AOI and polarization settings.



**Figure 13:** Spectral and AOI dependence of the difference in polarization-specific phase shift ( $P - S$ ) induced in a coherent beam by Semrock mirror MM3-311-t6.

and a specific phase between them will suffer changes to that phase relationship. Plane and circularly polarized beams will in general become elliptically polarized, with the characteristics of the ellipse dependent on the AOI and wavelength. A quantitative description of the relation between phase and polarization state, in the context of reflection from a dielectric mirror, is given in [8]. The use of incompletely

polarized light with dielectric mirrors at incidence angle away from  $0^\circ$  can evidently result in complicated and unanticipated behavior. If this is an issue, consider the use of maintaining either S- or P-polarization. Alternatively, one can use metal mirrors, which have much less of this chromatic dispersion effect, though, as noted in Section 3, these tend to have lower reflection and lower damage threshold.

## 11. Reducing Dependence of Reflection on Wavelength, AOI and Polarization

On some occasions it is preferred to use a mirror with reduced sensitivity to parameters such as AOI, CHA and polarization. For example, the CHA or AOI might be relatively large, say 25° to 35°, which occurs not infrequently in modern optical designs designed for reduced lens count and LED-based illumination systems. These high angles exceed the limits of the range over which performance

can be guaranteed for standard or catalog parts. Alternatively, it might be important to minimize spectral shift with wavelength, especially given the amount of shift seen for the mirror in Section 8.

As a partial remedy, the availability of multiple coating materials with a range of indices of refraction makes it possible to design mirrors and filters

with reduced sensitivity to AOI and CHA, permitting a larger range of parameters over which performance can be guaranteed. As these designs usually require more layers of coating materials, the cost tends to be higher than for the standard designs. Please consult Semrock for more information on this subject.

## 12. Surface Flatness, RWE, TWE and Wedge

An ideal flat mirror is able to reflect a beam of incoming light without changing the optical characteristics of the beam itself. Because deviations from perfect surface Flatness result in changes to the wavefront of the reflected light, the degree of Flatness is a key parameter for a flat mirror.

The Flatness specification is given in terms of multiples of the wavelength of light at either 632.8 nm or 546.17 nm, depending on the optical standards system used to codify the specifications (ANSI or ISO, respectively), and is provided as either full range (PV, or peak to valley) or average (RMS, or root mean square) values, over one inch (25.4 mm).

Whether PV or RMS is more appropriate to a specific optical system in development will not be discussed here, but PV evidently describes the

worst-case anticipated deviation, and can include the effects of data outliers and other extraneous factors. Reference [10] discusses this issue and provides rules of thumb for converting between PV and RMS for low order aberrations. In any case, PV remains the most often used specification for Flatness.

A non-flat circular mirror will have deviations from perfect Flatness that vary over the surface, and these deviations over the surface can be described mathematically as a sum of a series of terms, each of which is associated with an aberration and can be assigned a numeric coefficient describing how much of that aberration is present. In practice, it is common to break down the deviation from Flatness into two components, Power and Irregularity.

Power corresponds to the aberration called defocusing, and is defined as the radius of curvature that best fits the surface profile, usually measured in meters. An infinite radius of curvature corresponds to a flat surface. Dielectric coatings impart a stress on the bulk substrate of the mirror material, and this stress causes the surface to take on a profile well characterized by a single radius of curvature, i.e. a well-defined Power. A section of a spherical surface then has a radius of curvature, which is equivalent to a center-to-edge height difference (i.e., the mirror depth in the center), also known as the sagitta or sag. The Power specification is sometimes not specified by the mirror manufacturer, as Power can be compensated for in many optical systems by changing the focusing behavior of lens-based elements.

In those cases, the Flatness is specified as Irregularity alone. By definition, Power is a PV value.

Irregularity is the lumped deviation from flatness, once the Power has been removed (i.e., the shape of the best-fit radius of curvature has been subtracted from the profile of the mirror, so that the remaining best-fit radius of curvature is infinite). Knowing a value of Irregularity does not provide specific information about the amount of each aberration expected. This value is specified as a multiple of a reference wavelength, either PV or RMS.

Semrock specifies mirror Flatness as a single number, i.e. the sum of Power plus Irregularity. Semrock mirror Flatness is specified for the surface, not for the wavefront, and is specified as multiples of 632.8 nm PV. For example, the MM3-311-t6-25 Flatness is given as  $\lambda/10$  PV per inch at 632.8 nm.

The wavefront distortion resulting from the mirror Flatness is referred to as the Reflected Wavefront Error. For information on this and other topics related to Flatness, consult Semrock's white papers on Flatness, references [11] and [12].

Transmitted Wavefront Error (TWE) refers to the wavefront distortion after passing through the mirror. Since light does not normally pass through a mirror, this parameter is usually neither needed nor specified.

Wedge is the maximum difference in parallelism between front and back sides of the mirror specified as an angle, typically as seconds or minutes of arc. Since light does not normally pass through a mirror, this parameter may be omitted. Mirrors designed to reflect high power levels may specify a wedge of a few degrees on the back side of the mirror, so that light that does reach the back surface and reflect from it will not interfere with the main beam reflecting from the front surface.

## 13. Material, Dimensions, Thickness and Tolerance

Mirrors are coated on a wide range of glasses, such as Pyrex<sup>®</sup>, Borofloat<sup>®</sup>, N-BK7<sup>®</sup>, fused silica, and ZERODUR<sup>®</sup>. The dielectric coatings can be of either soft or hard materials.

Semrock mirrors consist of dielectric coatings sputtered on fused silica (FS), which is chosen for its high quality. FS also has a low thermal expansion coefficient, quite high thermal conductivity, and low specific heat, all of which tend to better resist changes due to temperature and help

confer a higher laser induced damage threshold. Semrock dielectric coatings are optically refractive materials, which are as hard as the glass substrates, and are highly resistant to damage due to cleaning, environmental hazards, and normal use.

The lateral dimensions of a mirror are usually chosen to be as small as possible to minimize cost and to fit in restricted spaces. The Power of a mirror should not depend on the mirror size; for example, a 50 mm

mirror would be expected to have the same Power as its 25 mm counterpart. However, Irregularity cannot be reliably scaled with mirror diameter, so if one wants to estimate the Irregularity of a 12.5 or 50 mm mirror given this figure at 25 mm, one must make the required measurement to find out.

The dimensional tolerances must be consistent with the manufacturing tolerances of the mirror housing.

## 14. Surface Quality

The surface quality refers to localized imperfections on the mirror surface, which include scratches, digs and edge chips. Scratches and digs affect the beam reflected from a mirror due to the scattering of light that in turn can increase background signal at the detector and decrease optical image contrast. A large enough Dig can in case of high power levels result in local heat buildup leading to mirror damage, as described in Section 15.

The definition and specifications of these at present fall under one of several standards: ANSI/OEOSC OP1.002-2009, ISO 10110-7:2008, or MIL-PRF-13830B (which is itself closely related to the ANSI standard). Understanding the specification requires some familiarity with one or more of these. Semrock can specify surface quality using either the ANSI or the ISO standards.

Both standards consider Scratches and Digs only within the Clear Aperture, a region of the mirror surface, smaller than the overall mirror size, over which all specifications such as Flatness are also to hold. For a circular mirror, the Clear Aperture can typically have a radius of up to 80% to 90% of the mirror radius.

A Scratch is defined as a marking or tearing of the optical surface that is significantly longer than it is wide. The ANSI standard specifies that the grade of a Scratch be based on its brightness when compared to the brightness of a standard Scratch, when using a standard workstation with no more than 4x magnification. A Scratch is assigned a value of 10, 20, 40, 60 or 80 on the basis of the comparison, though this assignment process has elements of subjectivity. The ISO standard allows a less subjective measurement of the width of a Scratch, optionally with use of a microscope. Both standards specify how to determine if a surface passes or fails the Scratch specification if more than one Scratch is present.

A Dig is defined as a round or irregularly shaped hole or void, opened entrapped bubble, or mechanical damage on the surface of the mirror. In the ANSI system, unlike the Scratch, the Dig grade is defined by measurement as the average of the length and width of the Dig in  $\mu\text{m}$ , divided by 10, and rounded up to 5, 10, 20, 40 or 50. In the ISO system, the size is specified in terms of the square root of the dig area, in mm. Both standards specify how to determine if a surface passes or fails the Dig specification if more than one Dig is present.

Edge chips are defined similarly in both ANSI and ISO standards, and may not intrude into the Clear Aperture.

This paper does not discuss the process of determining an acceptable Scratch and Dig specification for a particular application but, in general, a mirror placed away from an intermediate focal plane might be able to use ANSI Scratch/Dig values of 60/40 in life science applications that use incoherent or lower power lasers as light sources. Semrock's MM3-311S-t6 with Scratch/Dig of 60/40 is an ideal solution for such mirror for generic life sciences applications. For maximum flexibility in mirror placement, however, mirrors can have much better specifications. For example, the Semrock MM3-311-t6 specifies ANSI Scratch/Dig of 20/10. High power laser systems may even require 10/5, and 5/2 is available for very precise systems, though these two specifications are never needed in the great majority of life science optical systems.

## 15. Laser Induced Damage Threshold (LIDT)

Laser-induced damage to a dielectric mirror is strongly application-dependent and can arise from a number of factors. This Section only summarizes the relevant causes, and refers the reader to Semrock's more complete source material [14] and to the very useful Semrock LIDT Calculator [15].

Laser induced damage can result from dielectric breakdown in the mirror, usually at locations of surface or volume imperfections that result in nearby irregular electric field properties. So-called long-pulse lasers can cause dielectric breakdown, in which high electric fields in the laser pulse free electrons from their bound states. The laser pulse energy is then absorbed by the electron cloud, resulting in more electrons being accelerated and freeing yet more electrons. This avalanche process permits high levels of electrical conduction in the normally insulating material, and the associated heat causes permanent damage.

To estimate an LIDT value, one scales the experimentally determined long-pulse laser damage threshold reference value  $LIDT_{LP}$  by wavelength, beam diameter and pulse length [15].

Laser induced damage can also result from absorption effects in the thin films and the substrate. This is the case for continuous (CW) laser sources, where thermal relaxation does not occur once the laser is turned on. The presence of defects (e.g. Digs) in the substrate can increase light scattering and contribute to damage. The same damage mechanism can apply to quasi-continuous lasers, in which the pulse duration and repetition rates result in inter-pulse times too short to allow thermal relaxation. The relevant parameters in this case include the material's optical absorption coefficient, specific heat, thermal conductivity, and melting point. A simple, reliable calculation of the threshold  $LIDT_{CW}$  is therefore not possible, but one can use an experimentally based rule of thumb, that  $LIDT_{CW}$  in  $W/cm^2$  is at least 10,000 times the  $LIDT_{LP}$  in  $J/cm^2$ . Note however that this is not a guaranteed specification.

## 16. Dispersion Phenomena

In systems with an ultrafast laser, with pulse length  $> 1$  ps, the mirror coating can distort the pulse shape, resulting in pulse broadening, which reduces performance. Additional constraints on the mirror design must be considered for these short pulse widths, including management of Group Delay (GD), Group Delay Dispersion (GDD) and Third-order Dispersion (TOD). As additional coating layers and coating thickness can result in poorer dispersion performance, optimizing for dispersion can limit the bandwidth and reflectivity levels of the mirror. For detailed consideration of this issue, consult the Semrock white paper [16].

## 17. Mounting

A discussion of mounting methods for mirrors is beyond the scope of this paper, but it is worth pointing out that incorrect mounting techniques and/or use of standard mounts can result in physical distortion of the mirror, degraded Flatness, etc.



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