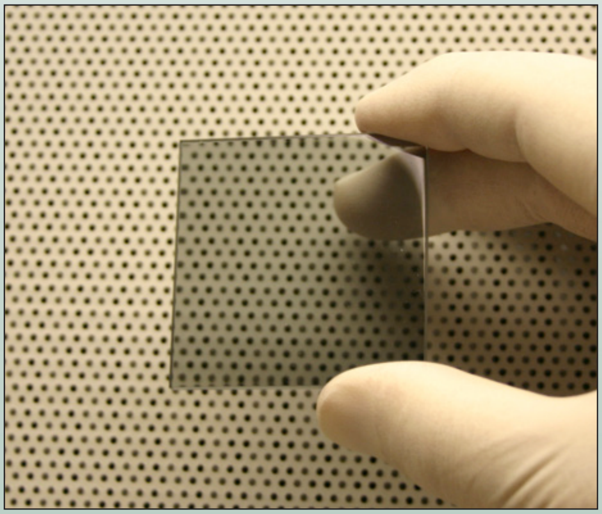
Colored Glass as a Versatile and Economical Means for Optical Filtering

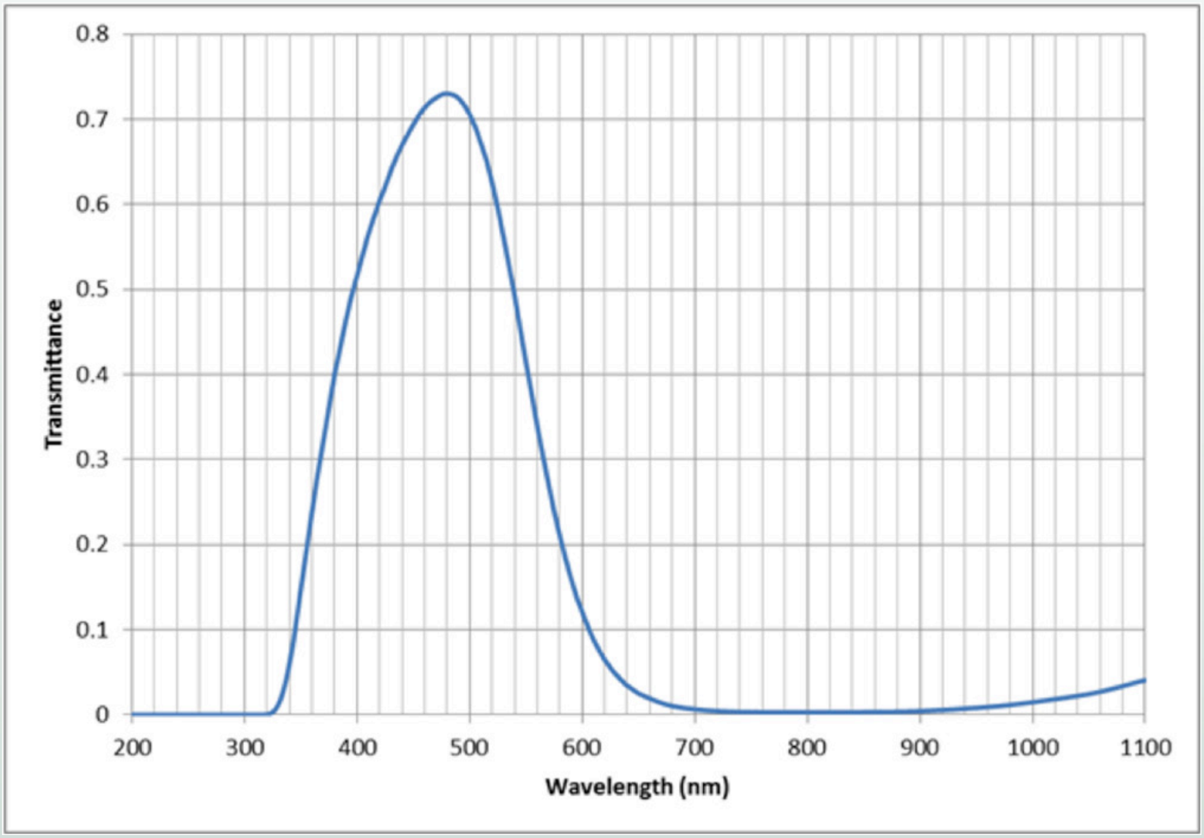
Opticology designs and fabricates custom optical systems and components. *One such component we offer is our Colored Glass Filters, for which we've found innovative applications for production and OEM customers during our 20 years as a supplier and contract engineering firm. In this white paper, we describe our novel applications of colored glass filters and techniques to overcome shortcomings of the raw material.*

Optical filtering is an important aspect of most optical systems. As designers and fabricators of optical systems, we often specify an optical filter for either attenuation or pass filters (including short, long, or band).



Attenuation of an optical signal is generally needed to avoid saturating a detector when the amount of incident light exceeds the dynamic range of the detector. An attenuator or *density filter* is inserted into the beam path to reduce the optical power striking the detector. In visible light, these filters can be varying shades of gray which give equal attenuation throughout the visible spectrum in which case they are referred to as ***neutral density filters***. Commonly used in photography, neutral density filters are extensively used in many types of optical systems, from lasers to imaging systems. Density filters can be used across a spectrum (ultraviolet, visible, or infrared) or at a specific wavelength.

A ***bandpass filter*** serves to limit the incoming radiation to a detector within a particular wavelength range or band. In some cases the bandpass filter will be used to attenuate the optical signal as well, but in general the signal will be reduced whether desired or not. As an example, a fluorescent system will employ a bandpass filter to strip out the excitation beam and any other wavelength not of interest, sending only the fluorescent signal to the detector. A ***shortpass filter*** will pass shorter wavelengths and attenuate longer ones, while a ***longpass*** filter will do just the opposite. A colored glass bandpass filter is shown below.



Both attenuators and pass filters can be made from thin-film coated glass or from colored filter glass, the latter being much less expensive to produce, as well as easier to clean and handle. Colored glass can be polished by conventional means and is therefore inexpensive to produce in large quantities with no secondary operations, making it an ideal production component. Even though colored glass filters work on the principle of absorption, where the light energy is absorbed into the material, they are able to withstand high-power laser pulses without fracture or damage within limitations.

Optical filtering is one of the more mundane aspects of our system designs, however over the years we have fabricated filter systems from colored glass that are novel and very useful, at a fraction of the cost of the thin-film coated counterpart. Due to the simplicity and durability of colored glass, we try to specify it whenever possible, especially in production systems, to reduce costs.

COLORED GLASS FILTERING

The attenuation of an optical signal is achieved optically by using a filter characterized by its *optical density* (OD), which is related to transmission by the following:

$$OD = \log(1/T) \text{ and } T = 10^{-OD}$$

The term "neutral density" describes filters that attenuate equally for all wavelengths over a given band and is usually reserved for the visible portion of the spectrum.

The simplest and most frequently used means of neutral density attenuation involves a thin-film deposition of metal on glass. In high power laser systems, where metallic coatings would break down, dielectric thin-film coatings are employed which are also used for long, short, and band pass filtering at a much higher cost than metal films.

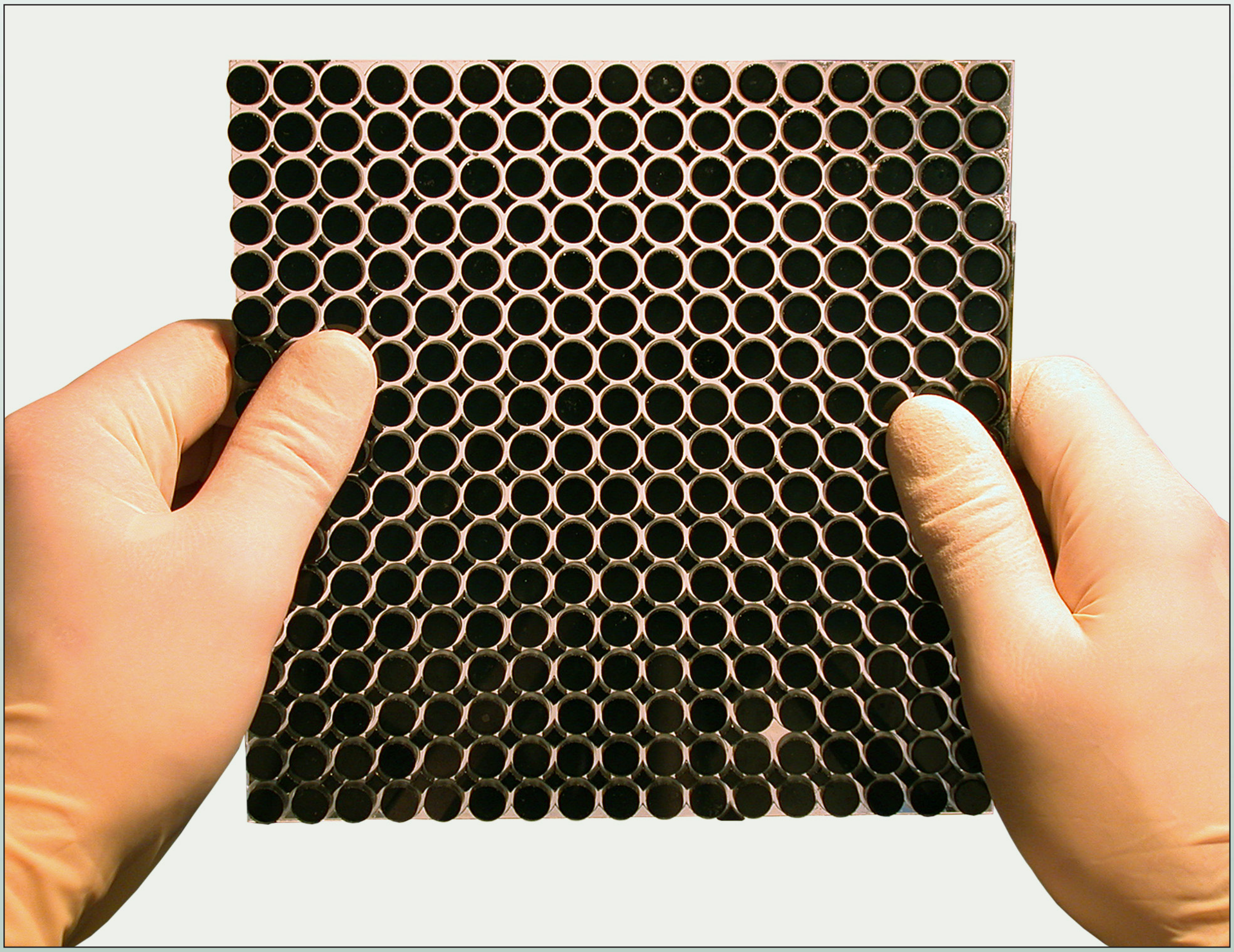
Density filters fabricated from *colored filter glass*, is glass ionically or colloidally colored during the production process where materials are mixed in molten glass. There are over 40 types of colored glasses available primarily from three raw material suppliers (Germany, Japan, China) each offering identical products (cross referenced). The colored filters range from longpass from the UV to the IR and to bandpass, to neutral density. These are absorptive-type filters – the energy is absorbed into the material, and attenuation is a function of filter thickness. Colored glass is used for pass filters at particular wavelength bands while gray glass is used for neutral density, where the density relatively flat over the visible spectrum.

ECONOMICS

A colored filter glass is simply a polished substrate and requires no thin-film coating to function. This is significant especially when used as a production part. Thin-film coated filters also require a polished substrate but thin-film process quickly introduces costs: coating chambers hold a finite number of parts and the cost of the coating run is amortized over the number of parts; each part has to be cleaned and loaded/unloaded from the chamber (a per part charge is typically added to the run charge); production time is nearly doubled; finished coated parts can be difficult to clean and handle.

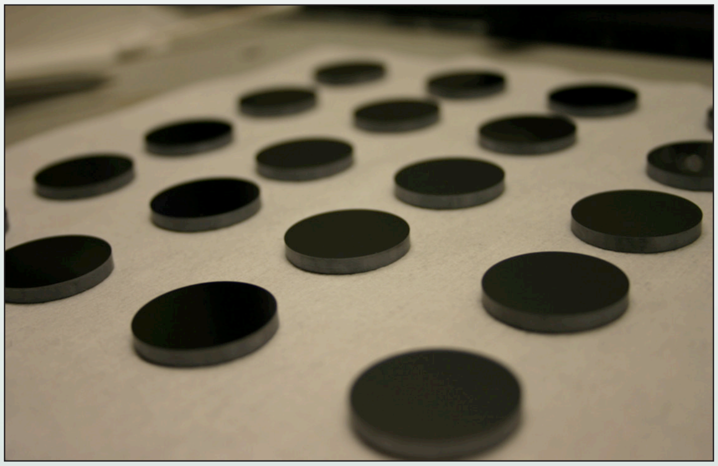
Despite the usefulness of colored glass filters they do have limitations. Since there is a discrete number of glasses that are manufactured, one is not always able to find the ideal solution to the need of the application. Also, there are variations in production lots or 'melts' which sometimes need to be addressed.

There are several services we offer at Opticology with regard to filter glass as to address the limitations.



POLISH – TO – TRANSMISSION

Transmission of a particular filter glass is based entirely on thickness of the material (surface reflections contribute to attenuation but this is a constant). Problems arise for customers needing exact density or transmission values. Filter glass raw material manufacturers publish data sheets on each glass produced. One parameter is the transmission of the glass at a reference thickness. For example, for Schott NG5 glass at 1mm thick the transmission will be ~50%. However this data is nominal, and due to variations in the manufacturing and melting process of the glass, the transmission value can vary as much as 10% to 20% from nominal. This is unacceptable in some applications.

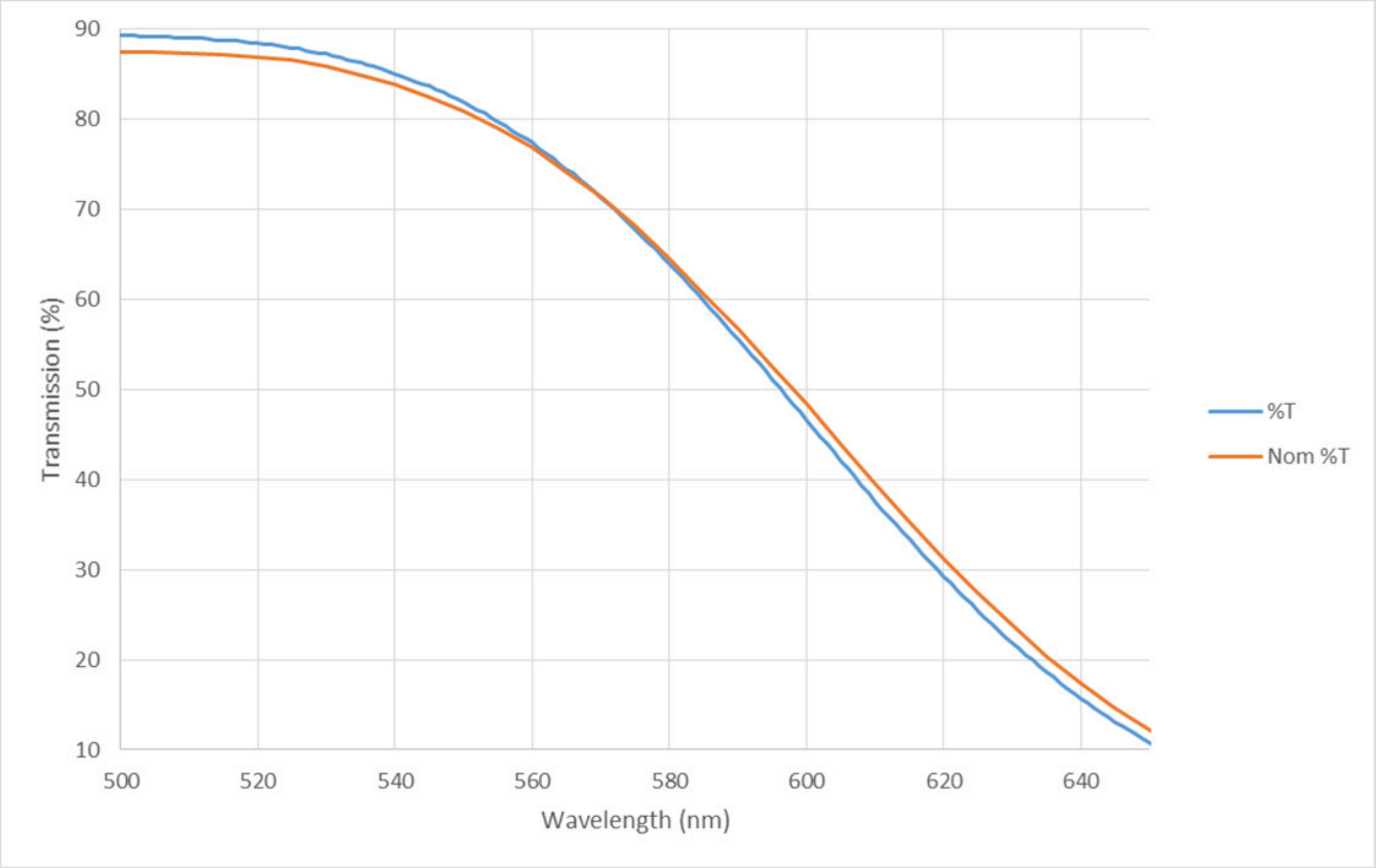


To address this issue, Opticology will characterize a manufacturing lot of material or melt. To do so we first polish a sample from the melt to an arbitrary known thickness and measure transmission. From this transmission value and thickness we calculate the parameter known as the *internal transmission* T_i of the material which is the transmission minus the contribution of surface reflections.Once the internal transmission of a melt is known then any value of transmission can be produced with precision. Since the only variable is thickness, how well the shop can hold thickness tolerance is directly related to transmission tolerance. Most optical shops can hold thickness to +/-0.05mm without issue. To hold to +/-0.02mm and less requires a bit more precision during the manufacturing process, for example optically contacting the parts prior to polishing which is done routinely.

To put the thickness tolerances in perspective, for the 1mm thick NG5 filter example above at +/-0.02mm tolerance in thickness would correspond to a +/-0.6% variation in transmission. Since each glass has its own transmission sensitivity to thickness, these differences need to be carefully considered when designing a filter for a critical application.

Not only have we found variation in transmission from melt to melt, but we also find variation in the spectral response of the filter glass. In other words, the nominal transmission values given in data sheets can vary at more than one wavelength thereby changing the shape of the expected transmission curve. The variation is usually small, however in precise applications it is necessary to be aware of differences. We show below two transmission curves from 500-650nm of blue colored filter glass.

The nominal data is superimposed on data gathered by our spectrophotometer on a sample filter of the same thickness as the data. Note the separation of the two curves which ideally would be identical. For most applications, this deviation of the measured curve from the nominal is acceptable. In other instances it would be necessary to quantify the deviation and compensate in the final data.

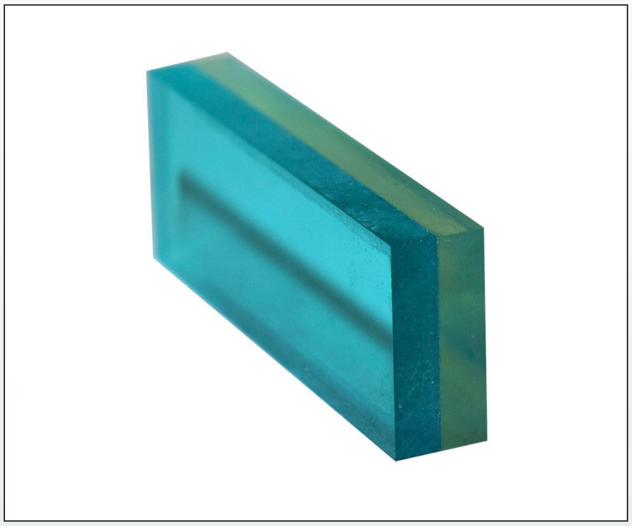


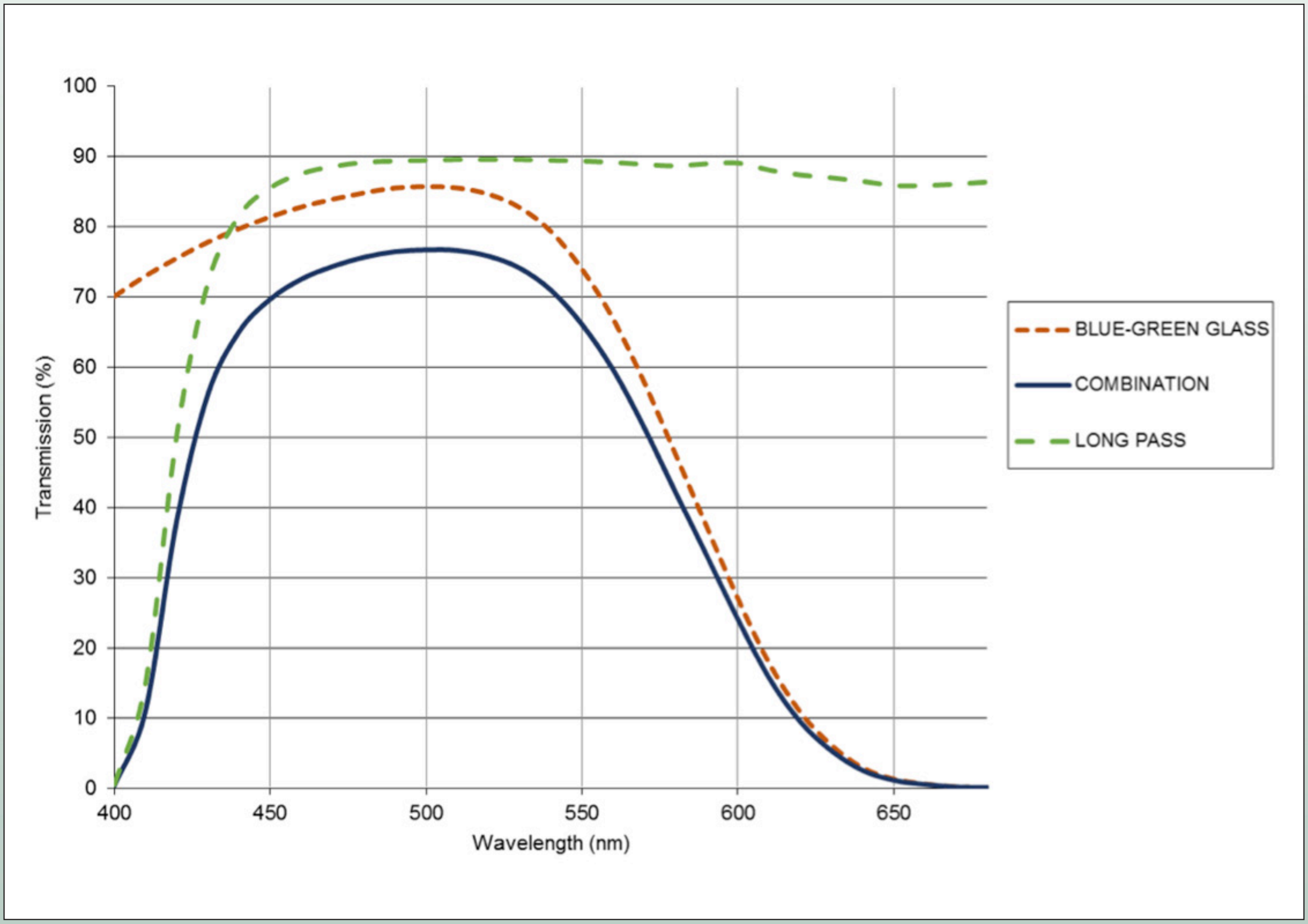
Since melts are produced by raw material manufacturers in large volumes, we can typically buy enough material of one melt to satisfy our customer's production needs within a given timeframe without needing to remeasure and recalculate. While not a difficult task, it takes time and resources of production and engineering staff, the cost of which can be spread over the entire production run. If the run of parts is moderate in size, this cost is usually minimal making filter glass an excellent choice for production systems.

Opticology fabricates custom filter glass for OEMs. **Learn more here.**

COMBINATIONS

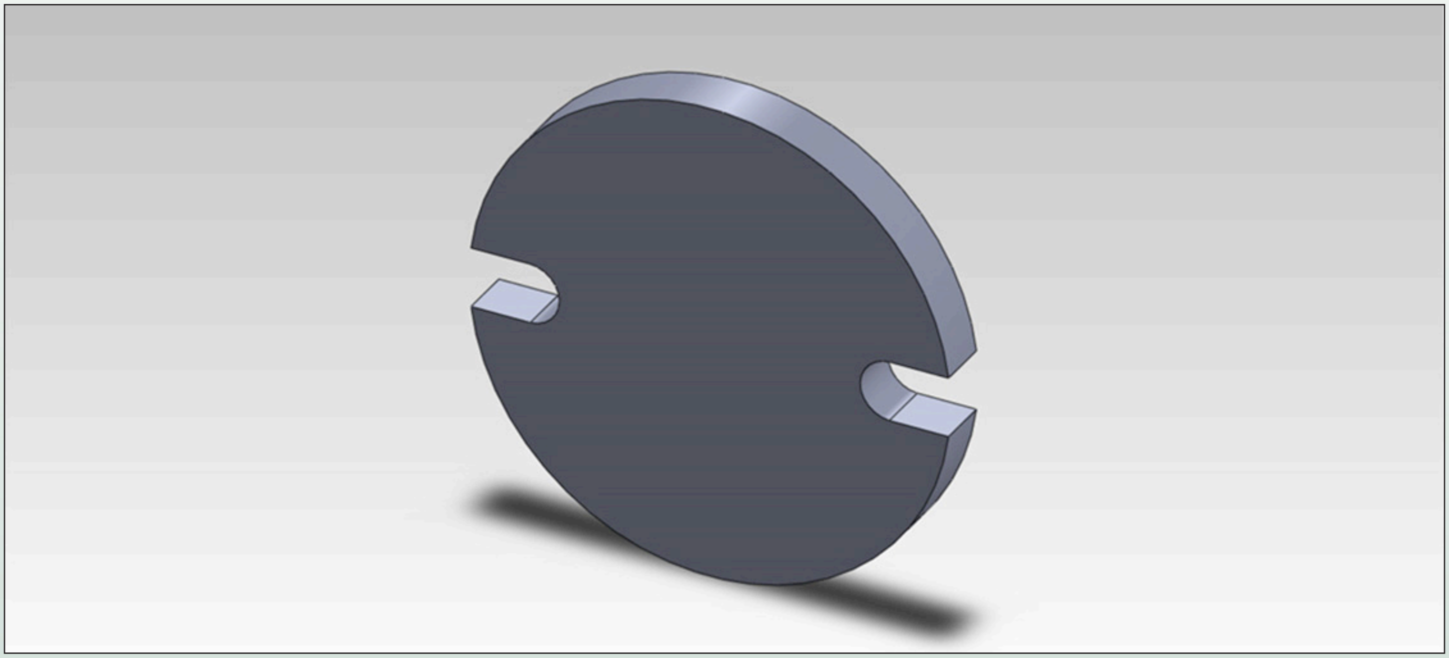
Since there is a finite set of glasses produced, there are limitations on the filtering capability of one particular glass. Fortunately it is possible to combine two (or more) different filter glasses together. One example is given on the right where a filter was created from two glasses to produce a UV and IR blocking filter. The two glasses were polished to a designated thickness, then joined together with optical cement. This customer had a specific requirement on the wavelength range transmission and Opticology was able to narrow the passband by the combination of the two glasses.

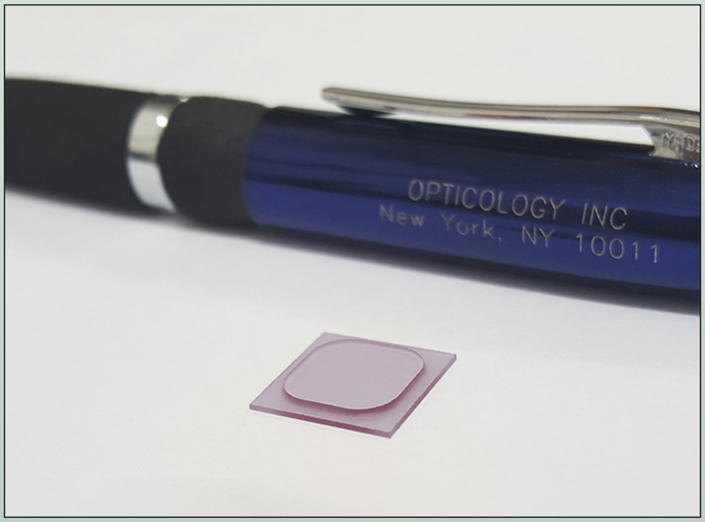


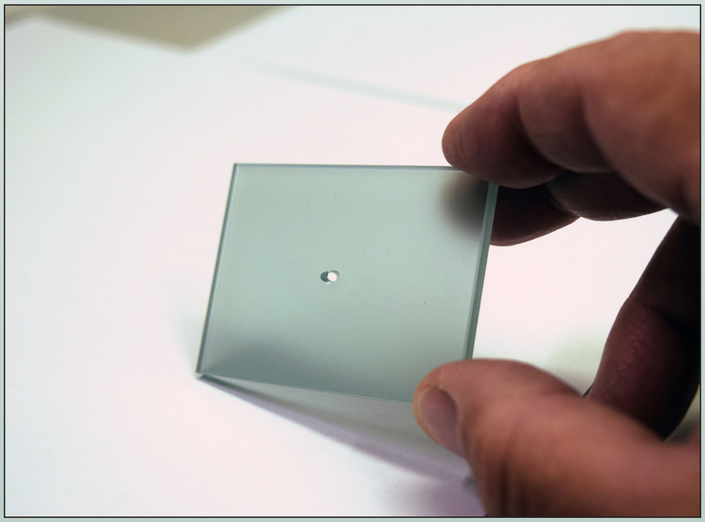


GEOMETRIC FEATURES

Since glass can be machined, Opticology has been able to create features in filter glass to exactly fulfill our customers' requests. Since filter glass is inexpensive, features machined in the glass add marginal cost especially in a production environment. Examples of machined filter glass are shown below. The part below is a circular filter with mounting notches; the lower right shows a part where a small hole was drilled at 45 degrees to allow a guide beam to pass unfiltered. *With CNC machinery any shape can be created in filter glass.* The filter glass part on the lower left had a ledge machined around the edge for mounting purposes.







ADDING THIN-FILM COATINGS / PRECISION OPTICS

Opticology often produces filter glass to a high degree of precision and add to them thin-film coatings. These filters have been used for military applications, space flight systems, and astronomy. Since the material behaves much like standard optical glass, we are able to produce precision surfaces characterized by λ/20 flatness, arc second parallel, and cosmetic quality of 10/5 scratch/dig. We will typically coat these filters with multilayer antireflection coatings to substantially reduce reflection in systems where back reflections are problematic. When antireflection coated, reduction in surface reflections must be taken into account calculating density or transmission.

For a given thickness, the transmission through a neutral gray glass like Schott NG5 in the example above, is given by its *internal transmittance* (T_i) times its *reflection factor* (P). Both of these values are given in raw material manufacturers' catalogs. Internal transmittance T_i can also be measured as described above, which is the transmission of the material minus the surface reflections. Manufacturers provide internal transmittance T_i typically for a sample thickness 1mm. Reflection factor P takes into account the Fresnel reflection from each surface which is dependent upon index of refraction. Most filter glass has an index n=1.5 which causes a reflection of ~4% from each surface. The transmittance T therefore is:

$$T = T_i \times P$$

As an example, a neutral gray glass NG5 has an internal transmittance at 550nm of 0.577 (for each 1mm of thickness), and a reflection factor P = 0.92 (100% - 4% per surface = 92%). For a 1mm thick piece the transmittance would be:

$$T = 0.577 \times 0.92 = 0.531 \text{ or } 53.1\% \text{ transmission}$$

For parts that are antireflection coated a new reflection factor has to be used. For a good narrowband dielectric antireflection coating the residual reflectivity would be 0.25% per surface down from 4% per surface uncoated. The new reflection factor therefore would be 0.995 and in the case above the transmittance would be:

$$T = .577 \times .995 = .574 \text{ or } 57.4\% \text{ transmission}$$

If a filter requirement is complex, colored glass filter can be used as the base substrate to simplify the thin-film coating. Having the colored glass do some of the filtering work drastically reduces the price of the finished component.

EQUAL THICKNESS NEUTRAL DENSITY

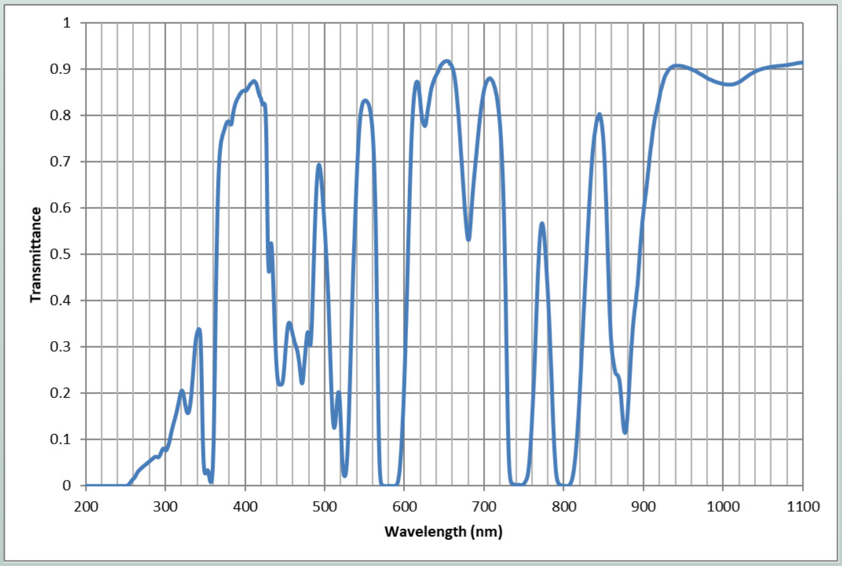
Opticology produces neutral density filters using different gray glasses of the *same* thickness to produce a neutral density filter set. This is useful if flipping a density filter into a beam path to adjust to changing ambient conditions where different thickness filters would cause a different optical path and the need to refocus. An example would be in a telescope system where the filter is located within a convergent bundle of rays and different thickness filters would cause an inconvenient need to refocus each time a different density filter is required. We produce neutral density filter sets of equal thickness of 5 different densities for the visible, UV, and infrared.

***Our equal thickness neutral density filter sets can be purchased from our website* here.**

CALIBRATION FILTERS

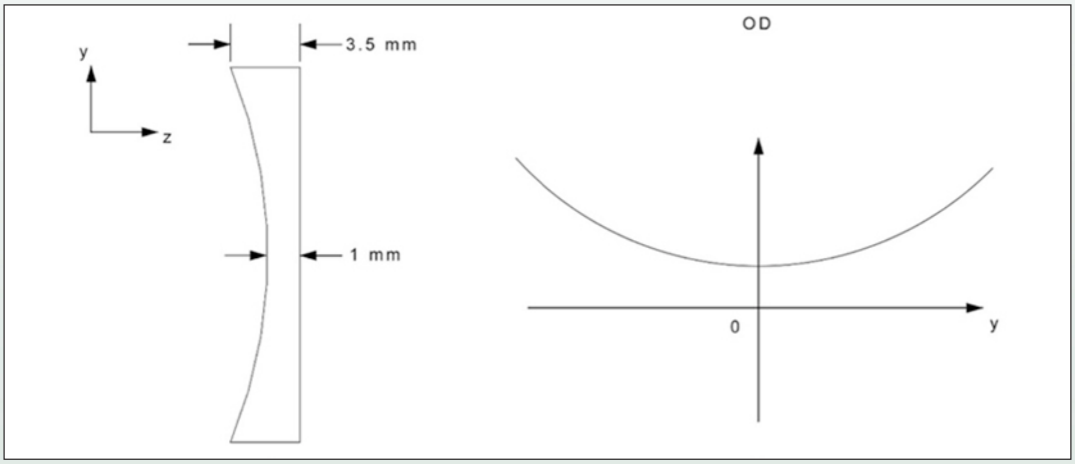
Colored glass filters can serve as a calibration point in a system. Since they can be precisely made to a particular density by the polish-to-transmission technique described above, they are routinely used when exact attenuation is required. Calibrated neutral density filters are produced to specified density values within a given tolerance and we routinely supplies transmission curves along with the parts.

Filter glass also can be used in spectroscopic instrument calibration. Multiband filter glass has a distinct transmission signature as a function of wavelength. This transmission spectrum can be used to calibrate wavelength position on the spectrometer detector. This is an old technique that was done with a neon lamp (or some other optical source emitting discrete lines) though the filter glass means is more convenient. Though a modern laboratory spectrometer may not need calibration of this sort, miniature and micro spectrometers being produced in production quantities may benefit from a reliable calibration source.

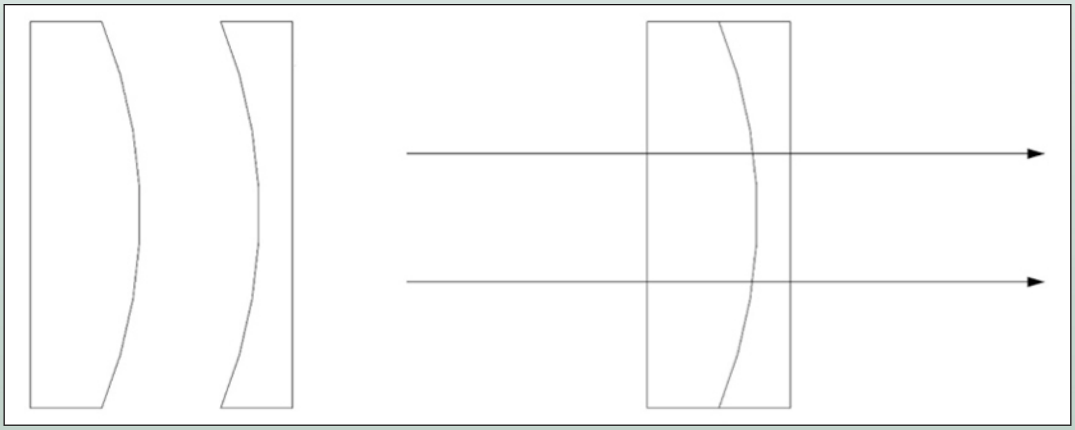


BEAM SHAPING

Since optical density is a function of thickness in colored glass filters, varying thickness of a surface as a function of part diameter can create variable filters. If a filter-glass material (e.g. neutral gray) is polished with one concave spherical surface and one flat surface as in a plano-concave lens, the OD varies from the least at the center of the lens (thinnest part) to a maximum at the edge of the lens. The figure below shows the plano-concave filter glass and the plot of optical density (OD) vs radial position on the filter. Note that the surface shape is spherical but the OD plot is exponential.



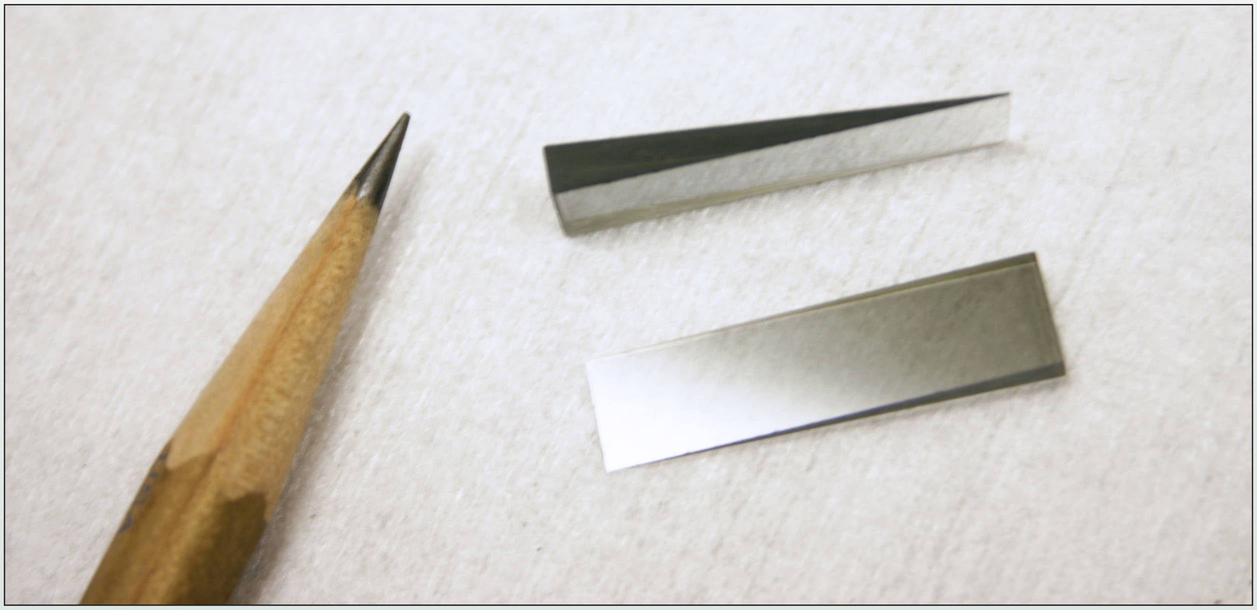
The plano-convex filter glass introduces optical power into a traversing beam of light and can have a dual function as a lens and filter combination. If this is undesirable, optical power can be eliminated by using a clear glass lens of equal but opposite power adhered to the filter glass lens with optical cement as shown in the figure below.

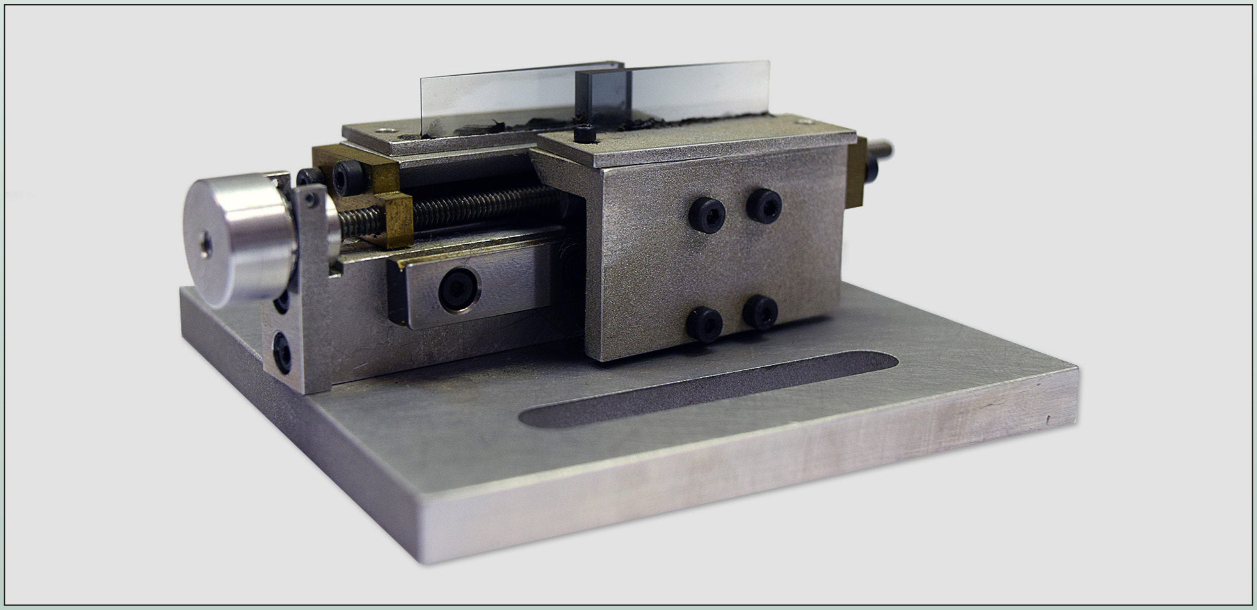


This configuration creates a Gaussian Compensator or Apodizer – a filter that changes the Gaussian distributed intensity profile to a flat top distribution.

VARIABLE COLORED GLASS

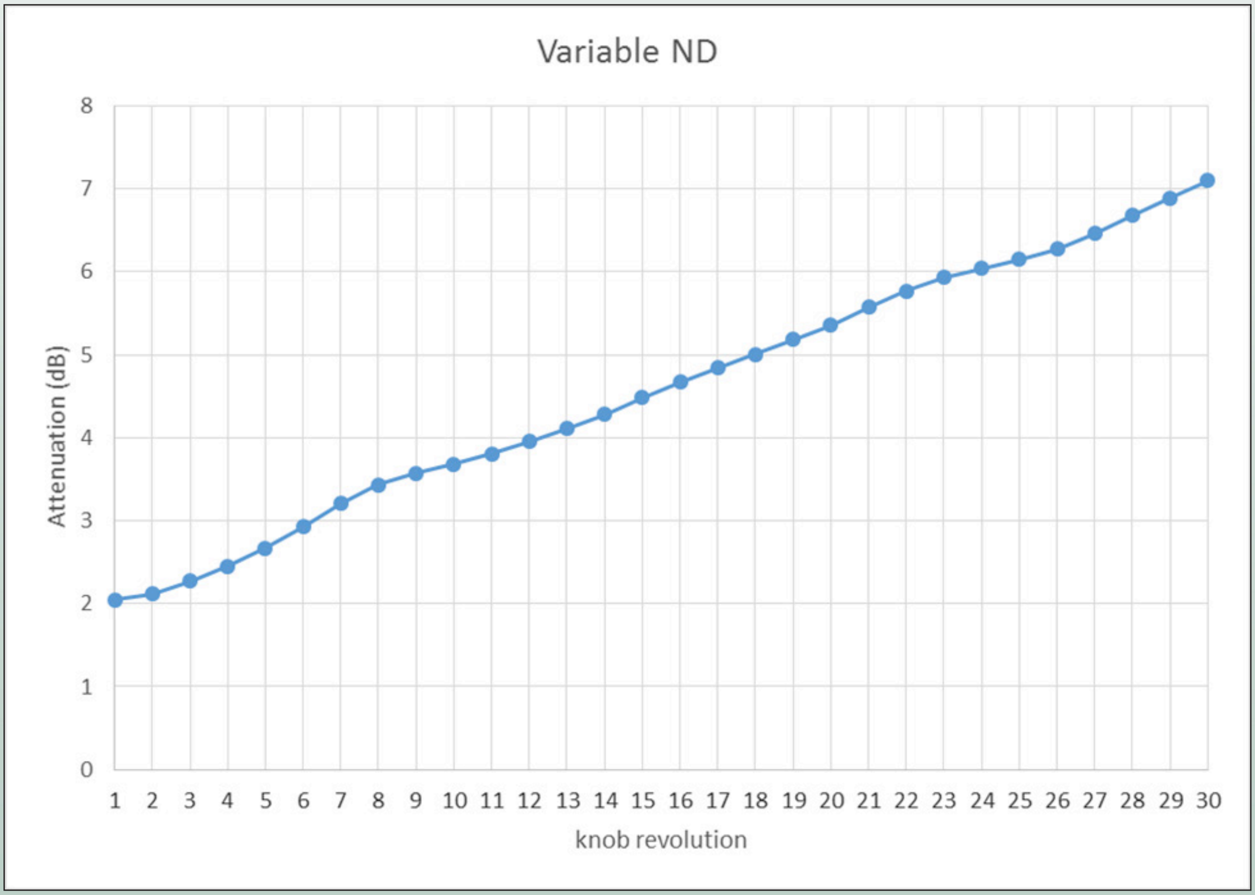
Other variable filters are possible. Opticology offers a Linear Variable Attenuating Filter which works by a wedge of filter glass opposed by an identical wedge of with apex in the opposite direction of each other. One of the filter glass wedges is shown below and the internal works of the system are shown at the bottom. Turning the knob translates the wedges in opposite directions and adjusts the density. Any filter glass material can be used for the wedge and these systems can be customized and made to order.





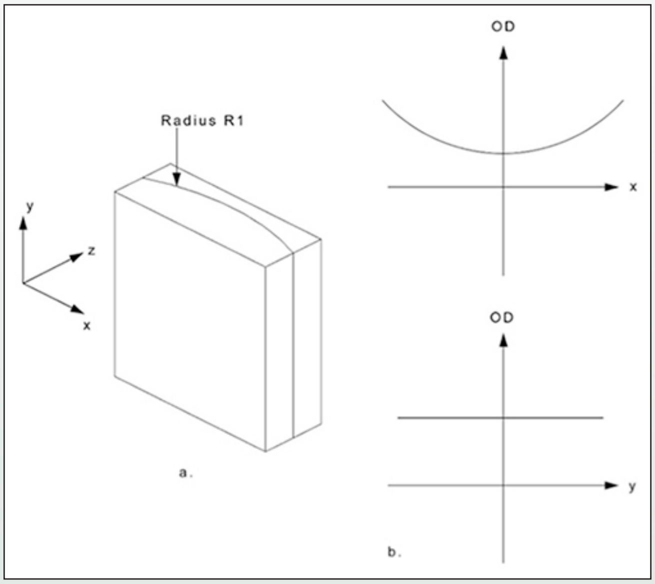
Complimentary circular wedges that opose each other creates a Circular Variable Attenuator. Here, two portions of each wedge overlap and each wedge rotates on its own axis. A compact ½" optical post mounted version isavailable for sale from Opticology. These are customizable for optical density range or filter type and are therefore built to order.

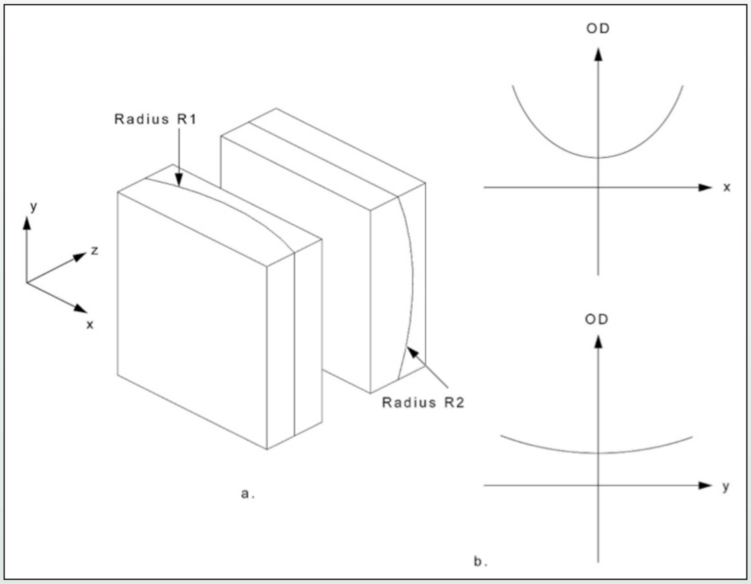
The unit is shown on the right with more details on our website. **Learn more here.**



Any geometric shape can be imposed on filter glass giving a variable intensity profile of transmitting beams. If the shape is cylindrical, OD would vary in only one axis as shown in the figure below on left.

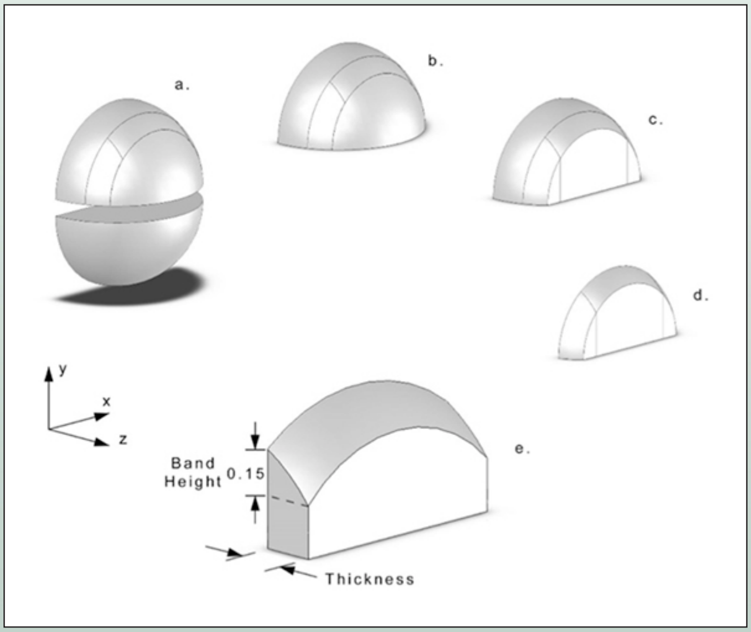
Two crossed cylinders of different radii would generate different OD as a function of axis. This is shown in the figure below on right.





In preliminary work for a military application we were given a very specific optical density profile. We designed (but never built) a filter that matched the OD profile using a section of a sphere, the fabrication process shown devised in the figure to the right.

With optical machinery now readily available to fabricate aspheric or free form geometry in glass, many other possibilities lie ahead.



Colored filter glass remains an economic alternative to thin-film coated filters and are an excellent choice for production systems as they can produced in high volumes with no secondary operations. Materal lot characterization is a means to produce calibrated filters for demanding applications. Many type of material is produced such that bandpass short-or longpass filters can be tailored to the application. The filters are produced in attenuation steps used as neutral density filter sets, or variable density filters are created by shaping the filter glass material.

Opticology produces finished colored filter glass parts in any shape or size from commercial to precision quality. We provide in-process testing to calibrated filters or filter sets. Antireflection coatings, thermal strengthening, and CNC machining are available options. We offer free design assistance or can build parts to print.

Please see our website for more details. **Learn more here.**