Custom Thin-Film Filters

TECH NOTE

Filter considerations for the miniaturization of your optical system

The world is getting smaller. Not only are people able to communicate over thousands of miles and fly from here to there in a matter of hours, but computing power that filled a room 60 years ago can fit into a watch today. The miniaturization trend is continuing into the design of optical instruments. From spectrometers that clip onto your phone to hand-held, point-of-care diagnostic devices, science is being brought to the masses in miniature.

There are many advantages to going “mini” including portability, cost, durability, and quicker results. However, there are several considerations that have to be made when designing a miniature optical system including control of scattered light and angle-of-incidence (AOI).

Free Space Optics

A typical optical system contains a light source (lamp, laser or LED), lenses, a sample, a monochromator or optical filters (for wavelength selection of the light source or detected photons), and a detector (PMT, photodiode, camera, etc). Miniaturization dictates that these components are very close together in space. The process of translating a large table-top prototype into a small (sometimes handheld) device introduces a number of challenges and trade-offs including altering the angles-of-incidence (AOI) and f/#s of system components. Further, a table-top prototype typically doesn’t have an enclosure, so stray light effectively leaves the system and is not detected. The differences in AOI and stray light can lead to altered filter performance and must be considered in the miniaturization process.

Optical filters are typically designed to sit in a collimated beam at a single AOI. Wavelength landmarks (center wavelength or cut-on/cut-off wavelengths) shift to lower values when the light hitting the filter is strongly convergent or divergent (more than about 10°, depending on the design). This makes it difficult (and expensive) to design a filter with very steep edges or with a very narrow spectral width that will give consistent performance over a wide angle. Figure 1 shows a filter’s response in a collimated beam and in an f/1.37 beam, both with AOI= 0. The center wavelength shifts to the blue and the edge steepness suffers. [1,2]

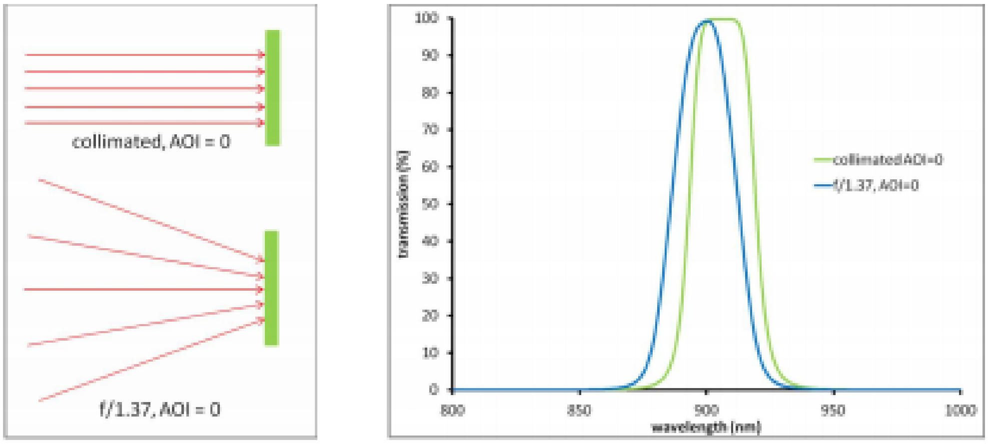

Figure 1. Left: A filter in a collimated beam (top) and convergent beam (bottom) with an f/1.37 (+/- 20o cone angle). Right: Spectral response of a filter in both types of beams. The center wavelength shifts ~6 nm lower in the convergent beam.

Control of reflected and scattered light in the system

Perhaps the biggest obstacle to miniaturization is optical scatter and stray light control. Some issues only become apparent after the fact, such as the choice of mounting materials. Since the optical components are so close together, absorbing materials for mounts and enclosure surfaces are important to reduce unwanted reflections and the corresponding reduction in signal-to-noise. Most miniature systems start life as larger, breadboarded prototypes with plenty of space between optical components and without enclosures for light to bounce off of.

Typically, interference filters do not absorb light. Any light that is not transmitted is reflected back into the optical system. For high OD filters, the majority of the light is reflected. In miniature systems, the reflected light can bounce off other elements in the system (such as mechanical mounts, sides of enclosures, etc). In the example below, a 20 mm diameter laser-blocking filter was placed in the beam. An adjustable aperture was placed between the filter and the detector and two sets of measurements were made. One was with a mask between the laser and the filter - such that any specular back reflection passes through the mask, but the bulk of the scattered light is blocked. The other measurement was performed without a mask. On the right we plot optical density (OD - a measure of how much light goes through the filter (2-log%T)) versus the diameter of the variable aperture. The higher the OD, the better the blocking and the higher the signal-to-noise ratio.

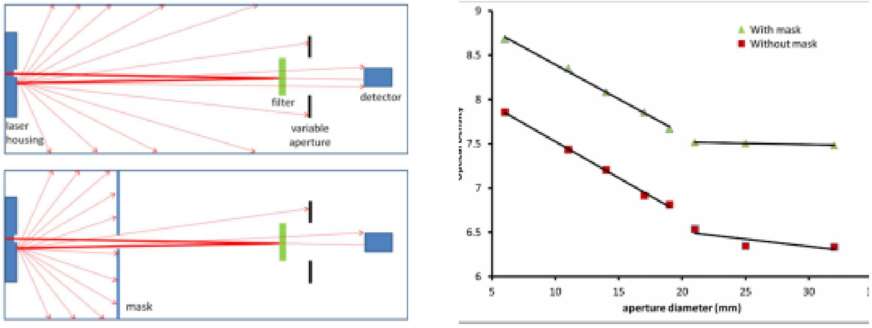

Figure 2. Top left: No mask in the system (4.6 cm between the filter and detector). Bottom left: With a mask to control back reflections and scatter. Right: Adding a mask increases the OD and signal to noise. The breaks in the line fits indicate the point at which the aperture surpasses the diameter of the part.

In this example, the setup is quite large (4.6 cm between the filter and detector), but when the mask is included in the system, the OD increases by almost a full unit, which corresponds to a factor of 10 reduction in “noise”. Further, as illustrated in the top left, stray light within the system is not controlled. Only the first two reflections are outlined here (from the filter and laser housing). If additional bounces are modeled (using Zemax or similar optical design software), it becomes apparent that the entire chamber is bathed in unwanted light. This can also be observed in the traces on the right (red squares). As the aperture exceeds the diameter of the part (20 mm in this example, break in the line fits), the OD is still decreasing significantly without a baffle in the system (red squares), whereas, with a mask in place (green), the OD flattens out considerably at larger apertures. In a miniature system, this effect is amplified because light intensity from a scattering center decreases with the square of the distance. It is crucial to capture reflected beams in beam dumps or behind masks in these miniature systems to maximize signal to noise.

Optical Scatter

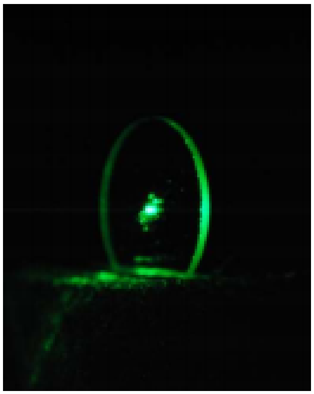

Figure 3. Edge scatter from a reflective filter in a laser beam.

High quality optical glass scatters roughly 1 part in 10^6 in all directions. The light can scatter through the glass, increasing background light levels or it can be totally-internally propagated to the edge of the optic (effectively amplifying it). This is why the edges of lenses and filters glow when a collimated beam hits the surface (Figure 3, Figure 4 middle). Edge scatter can be well-controlled with proper masking. The proper use of rings and holders can eliminate direct scatter from the edges into the detector (Figure 4, right). It will not solve the problem of light being reflected back through the optic after hitting the edge. To reduce this internal backscatter, light should be propagated through the edge and into an absorbing medium; such as potting with index matched epoxy that allows the light to reach an absorptive mount, or with a black index-matched epoxy that absorbs the light directly.

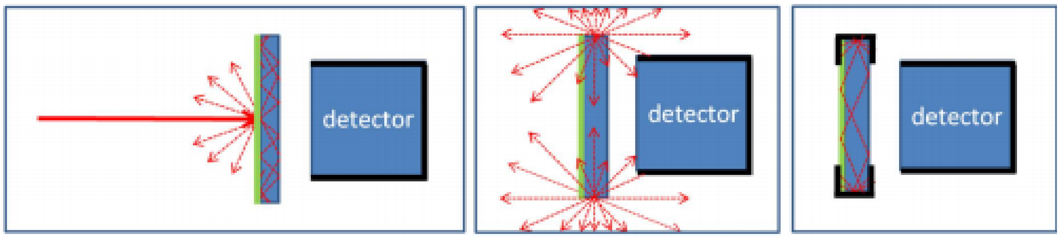

Figure 4. Left: A beam hitting the surface of an optic undergoes specular reflection (backward- not pictured), refraction (through the optic, not pictured) and scatter. Some of the light is scattered into the optic and propagates to the edges by total internal reflection. Middle: When the light reaches the edge, it is again scattered in all directions like a point source. Right: When the edges are masked, light is absorbed instead of entering the detector.

After adding rings to control edge-scatter and masks to control stray light, the final source of scattered light is within the glass itself. As mentioned above, high quality glass scatters light at roughly one photon in 10^6. Again, in a tabletop prototype, this scatter is too weak and far away from the detector to cause problems, but if the filter is within a few mm of the detector, this can limit the measurable OD that can be achieved.

Fiber Optics

A novel way to reduce stray light in the system is to translate the free-space optical layout into a fiber-optic based system. Omega has mastered the application of filters onto the tips of optical fibers. Fiber connectors are light-tight and obviate the need for masks. As described above, the f/# and AOI distribution in the fiber come into play when designing filters for this application. Other parameters such as whether the filter will be immersed (inside a fiber connector) or coupled to air, as well as whether the fiber is multi-mode or single mode, are also important when using fiber optics. Many light sources and detectors can be ordered from the manufacturer with a fiber-coupled output (or input). Converting an instrument to a fiber-optic design is also useful for mechanical stability (vibrations, shock, etc). [4-7]

Conclusions

System miniaturization has significant challenges in terms of light management, but with careful thought as to layout and masking, high signal-to-noise ratios can be achieved. Filters are typically measured for spectral compliance in a standard spectrophotometer where the filter is far (over 10 cm) from the detector and scatter is controlled. Performance in an integrated miniature system may differ significantly from the measured values if the effects of AOI and scatter are not accounted for in the design process.

References

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5. “High-speed multispectral confocal biomedical imaging” J. Biomed. Opt. 19(3), 036016 (Mar 21, 2014).; http://dx.doi.org/10.1117/1.JBO.19.3.036016
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