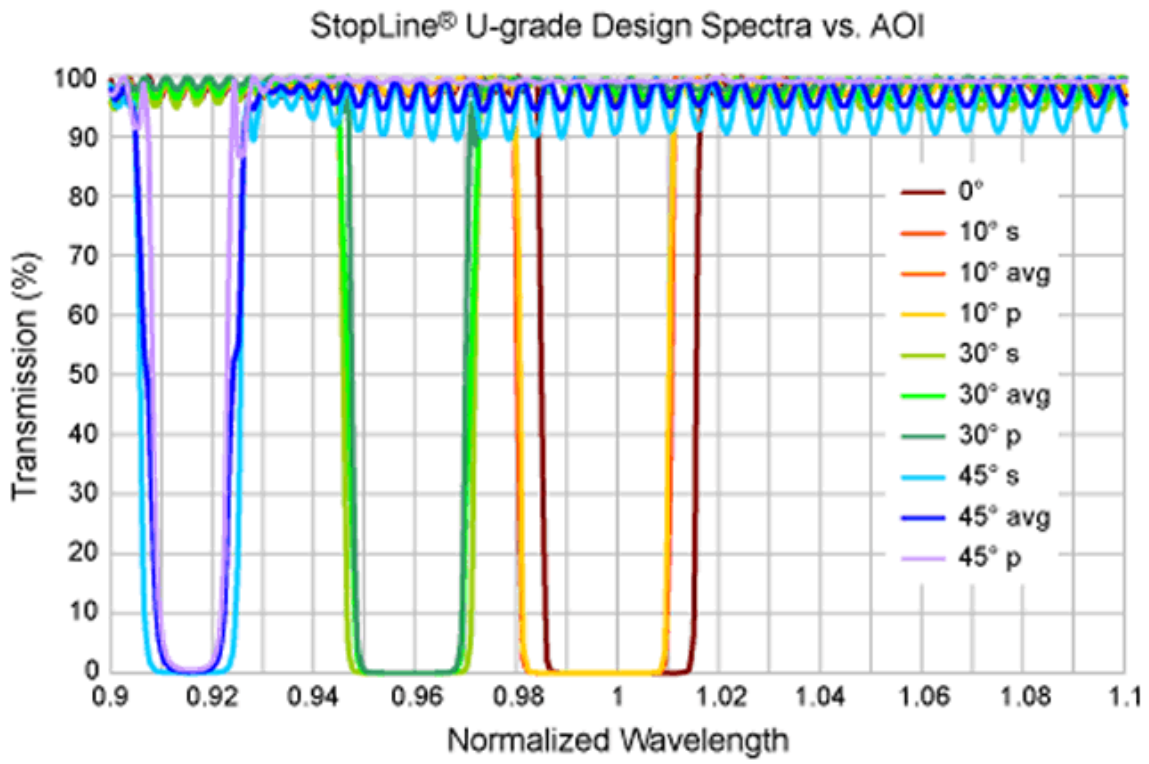
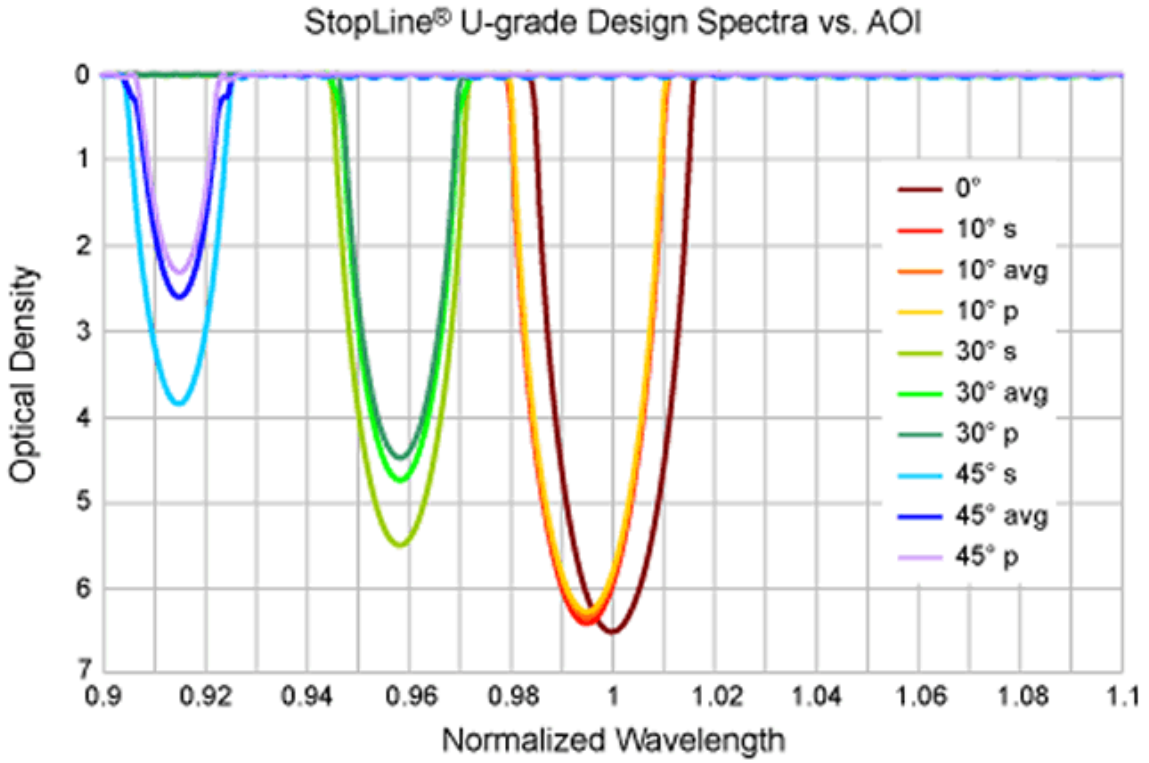
Notch Filter Spectra vs. Angle of Incidence

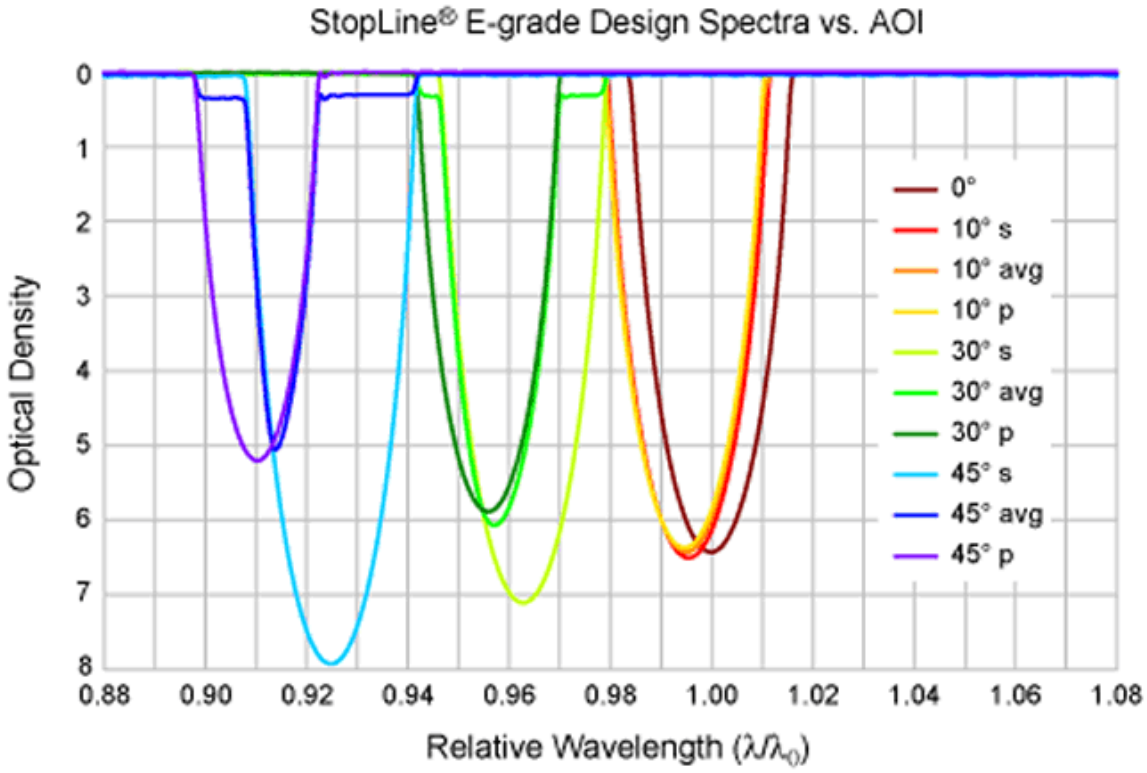
Semrock's deep StopLine® Notch filters have been optimized for use with light at or near normal incidence. However, for many applications it is desirable to understand how the spectral properties change for larger angles of incidence.

There are three main effects exhibited by the spectrum as the angle is increased from normal: (1) the notch center wavelength shifts toward shorter wavelengths; (2) the notch depth changes; and (3), the notch bandwidth changes. For Semrock's U-grade (as well as S-grade) notch filters, the notch center wavelength shifts with increasing angle of incidence identically for s- and p-polarized light, the notch depth decreases for both s- and p-polarized light, and the notch bandwidth decreases for both s- and p-polarized light (the decrease is greater for p-polarized light than it is for s-polarized light). Because of this third effect, the spectrum for unpolarized light demonstrates a "shelf" near 50% transmission when the difference in bandwidth between s- and p-polarized light exceeds the edge steepness. These effects are demonstrated in the two graphs immediately below, which show spectra derived from a typical design curve for Semrock's StopLine U-grade notch filters. Because the designs are so similar for all of the StopLine filters in the series (with the exception of the notch bandwidth, which is proportionally narrower for shorter-wavelength filters), the sets of curves in the graphs can be applied approximately to any of the U- or S-grade notch filters. Therefore, the spectra are plotted as a function of "normalized wavelength" λ / λ_0, where λ is the wavelength of light associated with a particular feature on the spectral curve and λ_0 is the wavelength of that feature when light is normally incident on the filter.





Semrock's unique, ultrawide passband E-grade notch filters are based on a fundamentally different design for thin-film notch filters, and as a result the angle of incidence dependence is different from the more standard U-grade (as well as S-grade) notch filters. For the wide-passband E-grade notch filters, as the angle of incidence is increased from normal incidence, the notch center wavelength shifts to shorter wavelengths, but the shift is greater for p-polarized light than it is for s-polarized light. Further, whereas the notch depth and bandwidth both decrease as the angle of incidence is increased for p-polarized light, as with the U-grade filters, in fact the notch depth and bandwidth increase for s-polarized light.

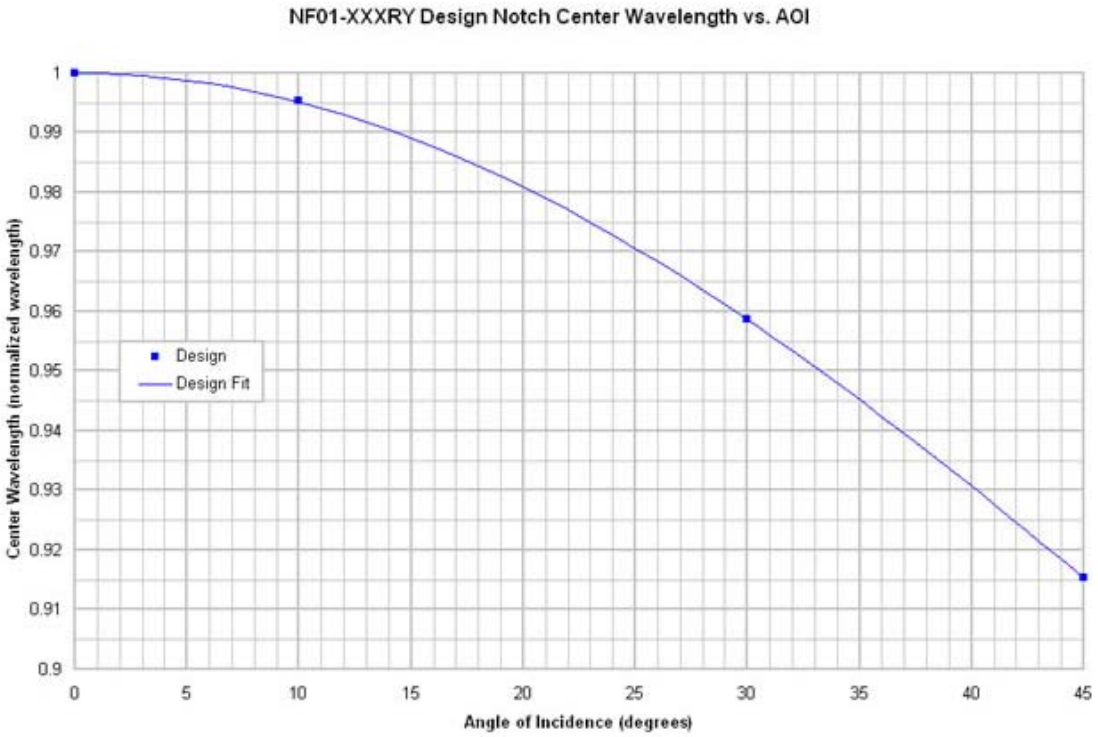


Note that whereas these curves demonstrate the behavior of filters optimized for light at normal incidence, they do not represent the best performance that can be achieved at higher angles of incidence for filters specifically designed to operate at such high angles. In fact, deep, narrow notch filters can be optimized for operation even at 45 degrees.

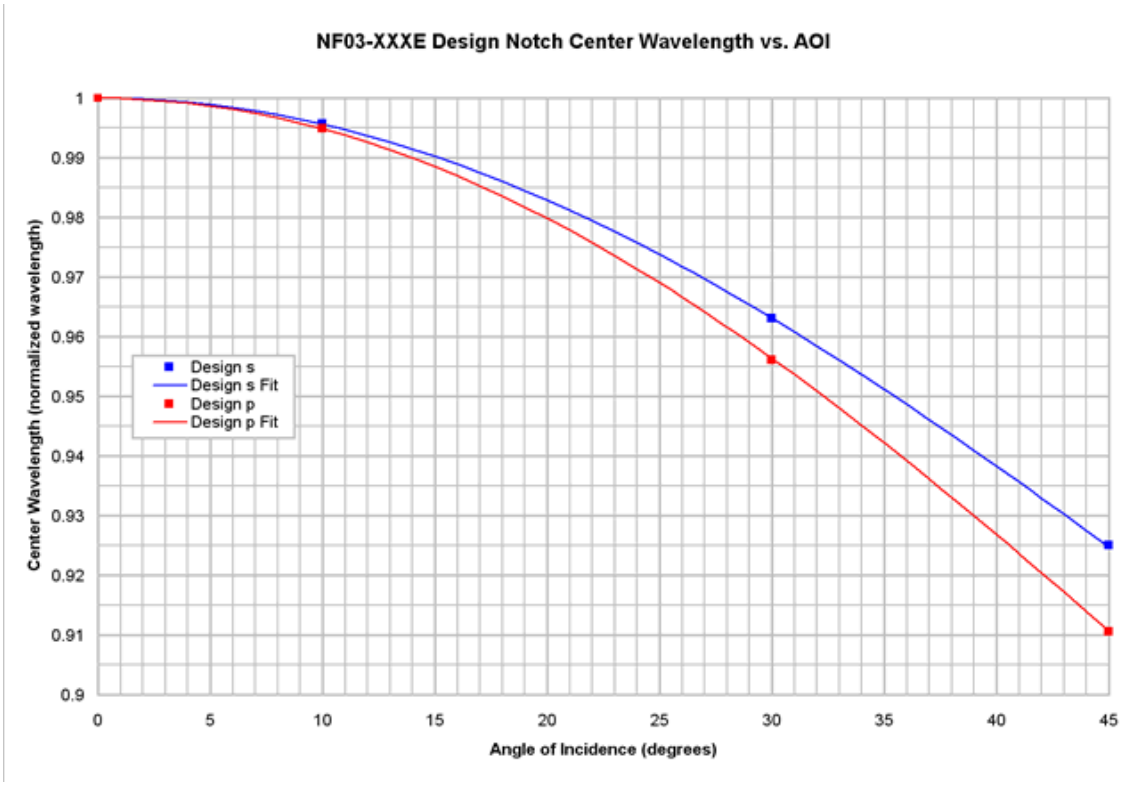
The shift of the center wavelength can be accurately quantified by a simple model of the center wavelength λ vs. angle of incidence θ . The following expression accurately describes this dependence:

$$\lambda(\theta) = \lambda_0 \sqrt{1 - (\sin\theta / n_{eff})^2}$$

where n_{eff} is called the "effective index of refraction," and λ_0 is the wavelength of the spectral feature of interest at normal incidence. A curve fit of this equation to data taken from the spectra above for the U- and S-grade notch filters is shown in the graph below. Again, because the designs for all StopLine filters of a given grade are similar, the graphs below apply approximately to any of the filters of that grade.



For comparison, a curve fit of the above equation to data taken from the spectra above for E-grade notch filters is shown in the graph below. Two curves are shown: one for s-polarized light (blue curve) and one for p-polarized light (red curve). The parameters used for the curve fits in the above and below graphs are listed in the table below.



Filter / Polarization	λ_0	n_{eff}
U-grade / s- & p-polarizations	1.0000	1.7567
E-grade / s-polarization	1.0000	1.8582
E-grade / p-polarization	1.0000	1.7115