IRIDIAN
SPECTRAL TECHNOLOGIES

Edge Filters for Raman Spectroscopy

Raman Spectroscopy

Raman spectroscopy probes the molecular vibrational and rotational modes of a material in order to detect and identify the material. Laser light is incident upon the material and the scattered light is measured.

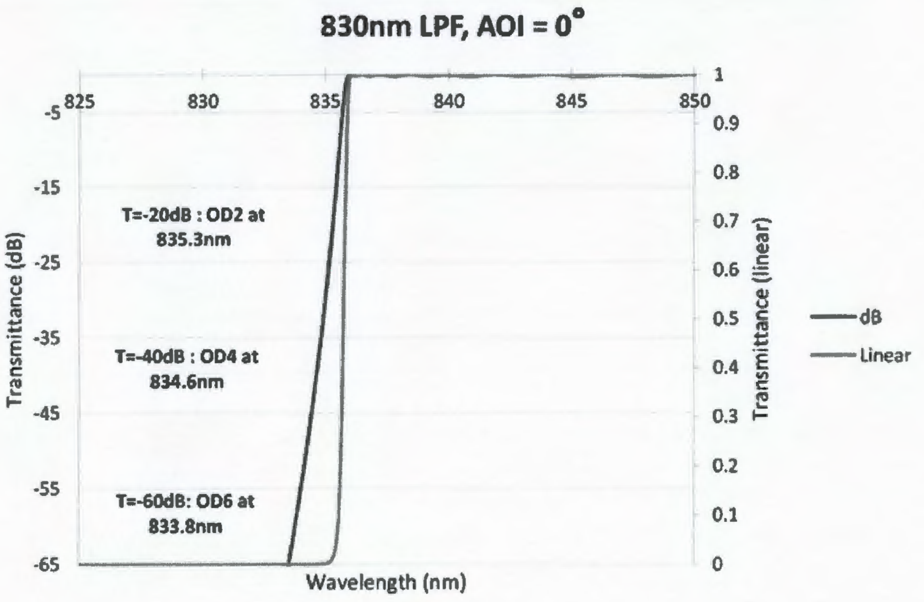
The excitation source laser intensity is often 6 to 8 orders of magnitude greater than the Raman scattered signal. Therefore, edge pass (or notch) filters are required to block the Rayleigh scattered laser light while transmitting the wavelength shifted (red-shifted, Stokes and blue-shifted,Anti-Stokes) Raman scattered signal.

Optical Density

Optical Density (OD) is a measure of the blocking ability of an optical filter. As light passes through the filter, some of the light is transmitted, while some is reflected, scattered, or absorbed. Optical density takes into account all forms of light attenuation, including absorption, reflection, and scattering. Optical density is defined as

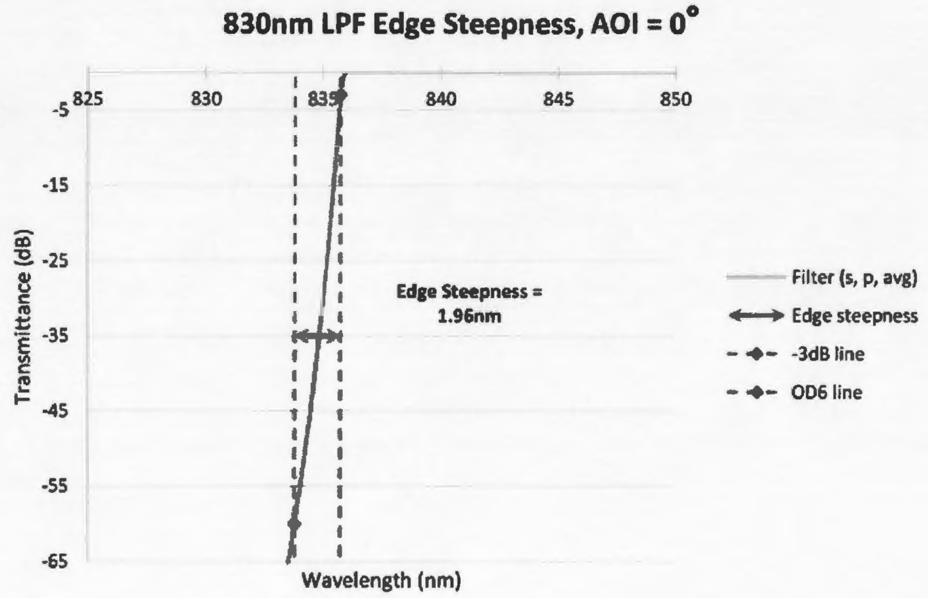
$$\mathbf{OD = -log_{10}T}$$

The OD value is numerically equivalent to -1/10 of the transmittance value in dB.



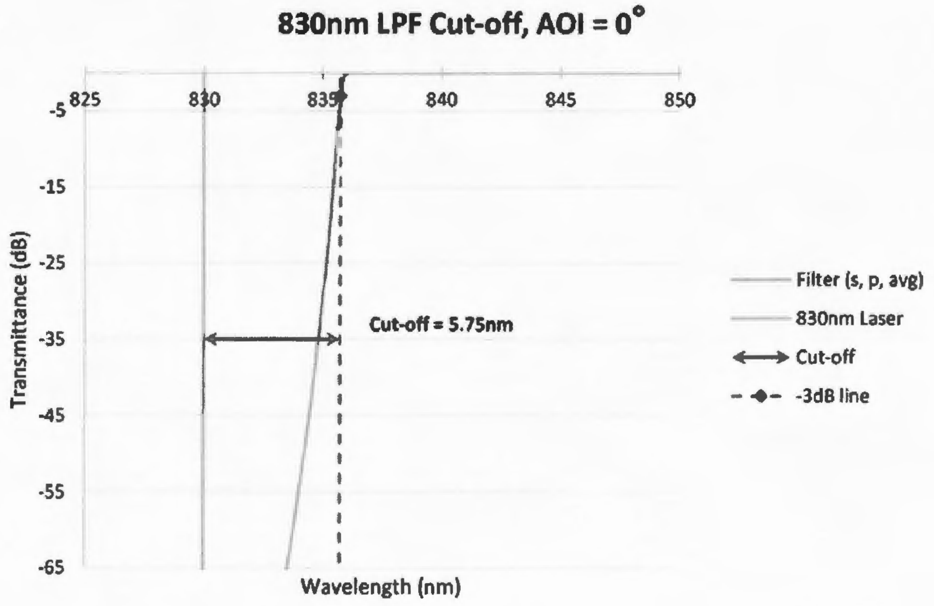
Edge Steepness

The edge steepness of an edge pass filter is defined as the spectral width between two points on the transmittance spectrum of the edge pass filter.The smaller the edge steepness value of the filter (the sharper the transition), the more challenging it is to fabricate the filter.



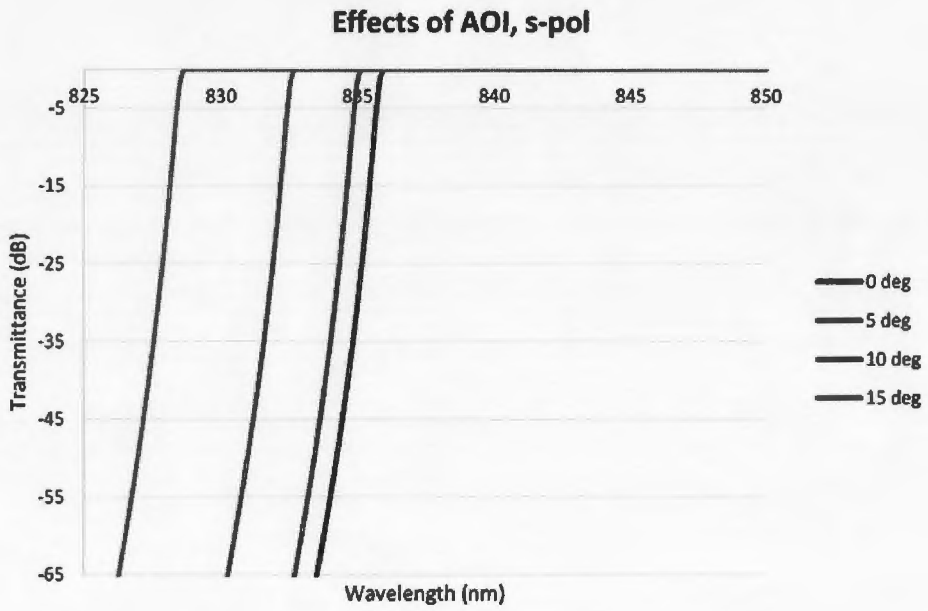
Cut-Off

The cut-off of an edge pass filter is defined as the spectral width between the laser line and the 50% transmittance (-3dB) point on the transmittance spectrum of the edge pass filter. Generally speaking, for a given laser the smaller the cut-off value, the "sharper" the filter, and the more challenging it is to fabricate such a filter.Although both the cut-off and edge steepness describe the spectral steepness of the filter, the cut-off value is relative to the laser line of the excitation source whereas the edge steepness is an inherent property of the filter. Achieving a specified cut-off value requires both achieving the steepness of the filter and positioning this edge relative to the laser line. As such, cut-off is a more demanding spec, and is also more relevant to the application.



Effects of AOI

Angle of incidence (AOI) is the angle between the incident beam and the normal of the surface of the filter. An AOI of 0°is also denoted as "normal incidence". For any non-zero AOI (non-normal incidence), the spectral edge of the filter will shift towards shorter wavelengths.

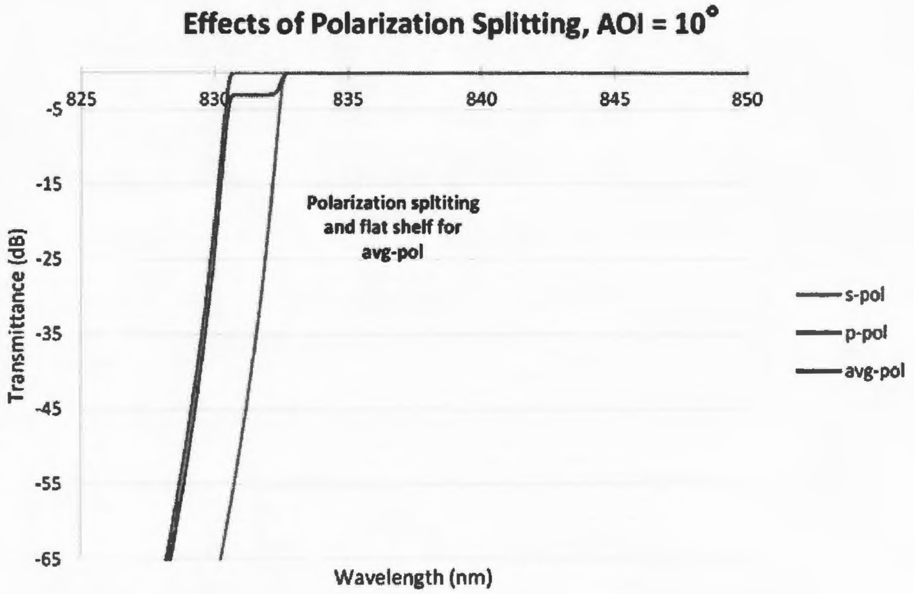


The wavelength downshift for non-zero AOI is design dependant, and is different for each polarization which leads to polarization splitting.

Polarization Splitting

As the AOI increases from normal incidence, the filter edges shift to shorter wavelengths ("blue-shift"). The edges for s and p polarizations shift different amounts leading to polarization splitting. For a long-pass filter (LPF), the p-polarized spectral edge is blue-shifted more than the s-polarized edge. For a short-pass filter (SPF), the s-polarized spectral edgeis blue-shifted more than the p-polarized edge.

Polarization splitting results in a flat "shelf" in the spectral response of unpolarized light (the average of s and p polarized edges).This reduces the effective edge steepness, and therefore cut-off, of the filter.



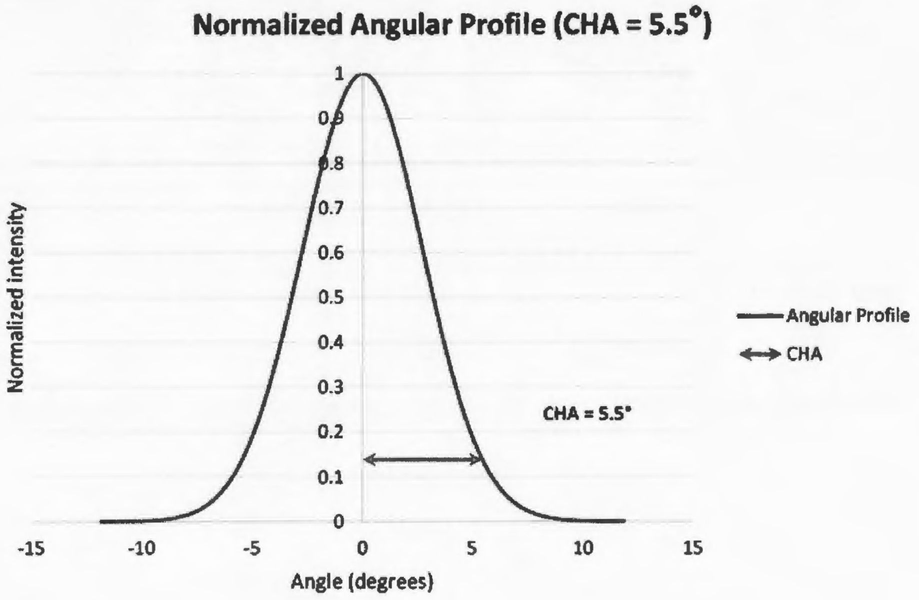
Effects of Laser Wavelength

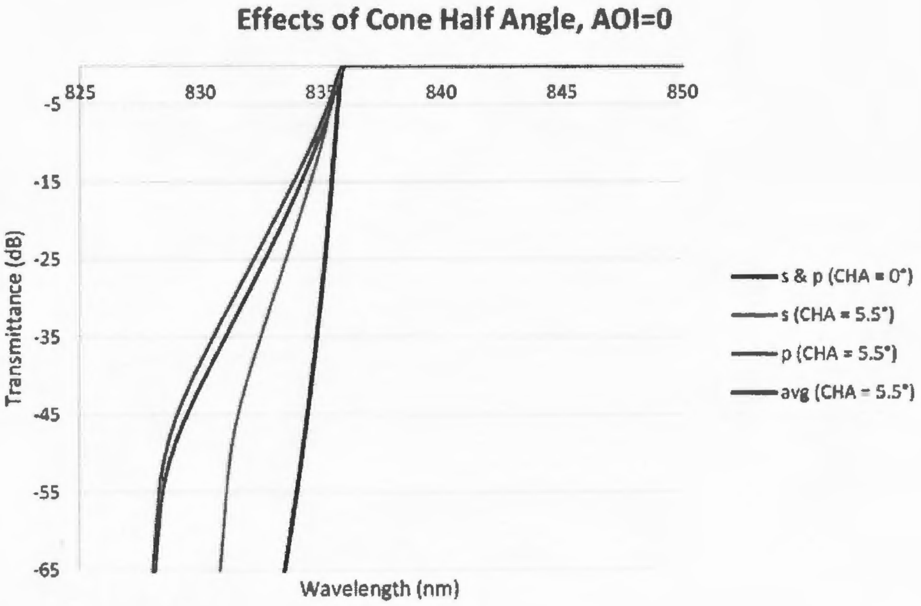
By definition, the filter cut-off is the wavelength difference between the laser line and defined transmittance point (typically T=50% point) on the filter spectrum.Variations in laser wavelength will affect the filter cut-off. It is, therefore, very important to consider both the cut-on wavelength (typically the T=50% wavelength) of the edge filter along withthe wavelength, spectral width and uncertainty of the laser line when selecting or defining the needs of a Raman edge filter.

The edge steepness is an inherent property of the edge pass filter. It is defined as the wavelength difference between two transmittance point (for example at OD6 and at 50%) and, therefore, will not be affected by variations in the excitation laser wavelengths.

Effects of Cone Half Angle (CHA)

The Cone Half Angle (CHA) defines the angular spread of the light for a non-collimated light source, such as an LED. The angular spread can be modelled, for example, as a Gaussian profile with a CHA defined as the angle at which the normalized light intensity is $1/e^2$ of the maximum intensity. The following graph shows a Gaussian profile light source with cone half angle of 5.5 degrees.

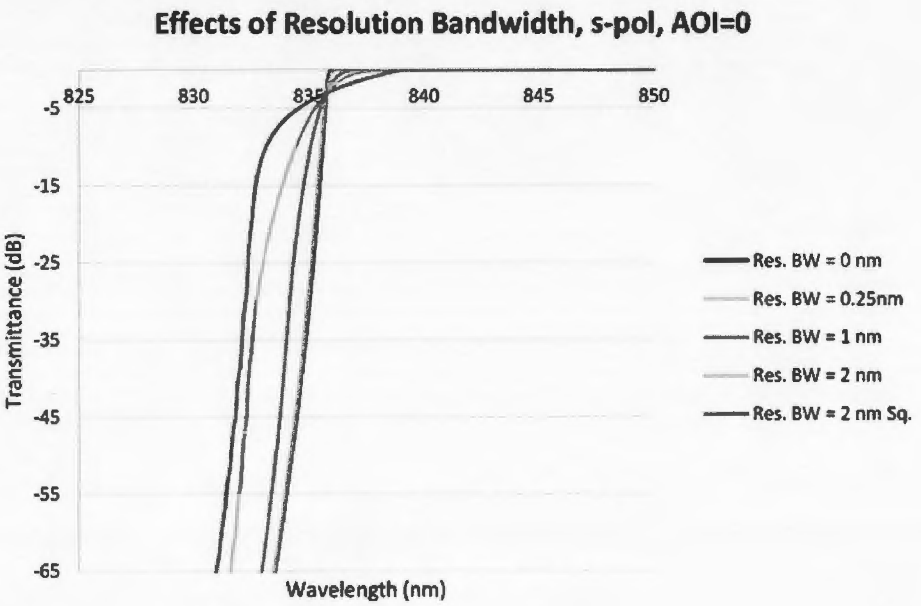




The un-collimated content in the beam (angular spread), is effectively a continuous distribution of AOIs in the beam. The effect of this angular spread is to broaden the characteristics of the spectrum.This increases the cut-off,reduces the edge steepness of the filter, and also decreases the OD at any given wavelength and AOI.

Effects of T-Bandwidth (Detector resolution bandwidth)

The theoretical transmission curves of these filters are based on 0nm spectral resolution. Optical metrology instruments typically use a resolution between 0.1 nmand 2 nm. Often when measuring OD, the spectral bandwidth of a measurement is increased to maximize the amount of light received by the detector and improve the signal to noise (S/N) ratio. The effect of finite resolution bandwidth is that the spectral edges are "rounded". The amount of rounding is proportional to the resolution bandwidth that is used, with higher bandwidth corresponding to increased rounding.

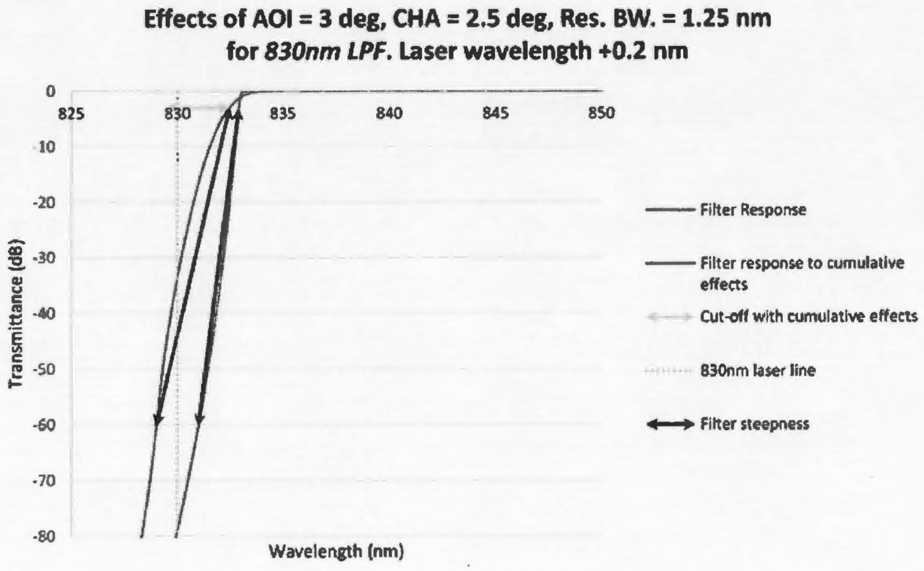


For the example above, when measured with a resolution bandwidth of 2 nm, the transmittance curve is very different compared to the 0nm curve, including degraded edge steepness and reduced OD at all wavelengths. However, this is not due to manufacturing defects in the filter, but rather an artifact of the measurement.

Cumulative Effects

The cumulative effects of AOI, cone angle, polarization, laser wavelength uncertainty are less intuitive, and small changes in individual parameters can impart large overall change in the filter spectral performance. In general, with one or more combinations of the above effects, the measured edge steepness will decrease, the cut-off of the filter will increase, the spectral edge will be more rounded and shift towards shorter wavelengths, and OD decreases. This occurs without any change in the filter performance.

For a fairly realistic condition of AOI = 5 degrees, CHA = 2.5 degrees, resolution bandwidth of 1.25 nm, the measured spectral performance of the same 830nm LPF filter is affected as shown in the figure below:



In the example above two filter response curves are shown for the same filter, but will yield different performance values:

Parameter	Filter Performance	Filter performance with incompatible beam
Blocking	7.8 OD	4.5 OD
Cut-Off	2.9nm	3nm relative to 829.5nm or 2.5 nm relative to 830nm
OD6 - 50% Steepness	1.9nm	3.5nm