

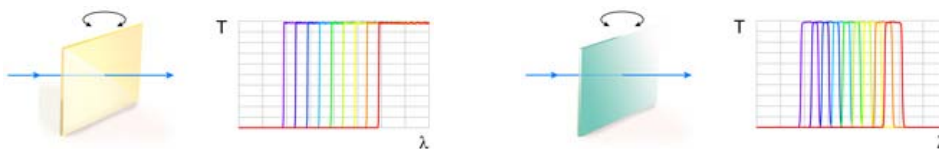


Tunable Bandpass Filters

Thin-film filters are the ideal solution for wavelength selection in most optical systems due to exceptionally high transmission at passband wavelengths (close to 100%), very steep spectral edges, and blocking of optical density 6 or higher over wide spectral regions for maximum noise suppression. However, thin-film filters are considered to be "fixed" filters only, such that changing the spectral characteristics requires swapping filters, thus constraining system size, speed, and flexibility for systems that require dynamic filtering. Diffraction gratings are often used when wavelength tuning is required, but gratings exhibit inadequate spectral discrimination, have limited transmission, are polarization dependent, and are not capable of transmitting a beam carrying a two-dimensional image since one spatial dimension carries spectral information.

Fluorescence microscopy and other fluorescence imaging and quantitation applications, hyperspectral imaging, high-throughput spectroscopy, and fiber-optic telecommunications systems can all benefit from tunable optical filters with the spectral and two-dimensional imaging performance characteristics of thin-film filters and the center wavelength tuning flexibility of a diffraction grating. There exist several technologies that combine some of these characteristics, including liquid-crystal tunable filters, acousto-optic tunable filters, and linear-variable filters, but none are ideal and all have significant additional limitations.

Semrock has now developed a revolutionary new optical filter technology: thin-film filters that are tunable over a wide range of wavelengths by adjusting the angle of incidence with essentially no change in spectral performance. As the diagrams below indicate, both edge filters (left) and bandpass filters (right) with wide tunability are possible.



It is well-known that the spectrum of any thin-film filter shifts toward shorter wavelengths when the angle of incidence of light upon the filter is increased from 0° (normal incidence) to larger angles. In general, however, the filter spectrum becomes highly distorted at larger angles, and the shift can be significantly different for s- and p-polarized light, also leading to a strong polarization dependence at higher angles. The graph below on the left shows the spectrum of a typical fluorescence filter at six different angles of incidence ranging from 0° to 60° . Note that for angles greater than about 30° transmission for s-polarized light is approximately 0% and the ripple for p-polarized light is intolerably high.

In contrast, the spectrum of a Semrock VersaChrome™ bandpass filter (below right) maintains high transmission, steep edges, and excellent out-of-band blocking over the full range of angles from 0 to 60° . At the heart of this invention is Semrock's discovery of a way to make very steep edge filters (both long-wave-pass, or "cut-on," and short-wave-pass, or "cut-off," type filters) at very high angles of incidence with essentially no polarization splitting and nearly equal edge steepnesses for both polarizations of light. An equally significant and related property is that the high edge steepness values for both polarizations and the lack of polarization splitting apply at all angles of incidence from normal incidence (0°) to very high angles. As a consequence, it is possible to angle tune the edge filter, or a combination of edge filters, over this full range of angles with little to no change in the properties of the edges regardless of the state of polarization of the light passing through the filter. And thus it is now possible to make tunable thin-film filters which operate over a very wide range of wavelengths – Semrock's VersaChrome series of filters are specified with a tuning range of at least 12% of the filter edge or center wavelength at normal incidence.

