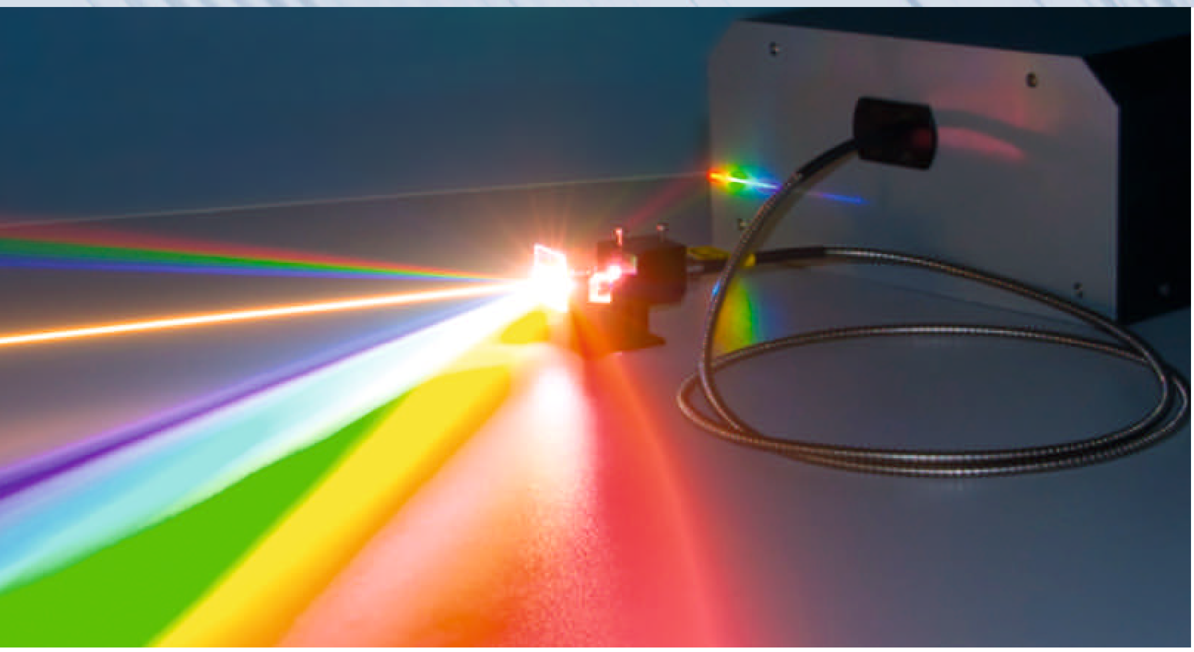
New tunable filters for supercontinuum fiber lasers

TUNABLE FILTERS CONVERT SUPERCONTINUUM SYSTEMS INTO FLEXIBLE LASER SYSTEMS. High power Supercontinuum ›white-light lasers‹ have proven to be popular and versatile light sources for research and industry. In many applications only a single wavelength from the full spectrum is used at any one time and therefore the choice of filter is critical. There are many options for filtering and new technologies can offer improved performance and features.



1 Fianium SC400-4 supercontinuum fiber laser in operation with the beam dispersed with transmission grating

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Supercontinuum generation, the ultra-wide non-linear spectral broadening of a laser source, was discovered in the 1970s using solid-state lasers and bulk non-linear materials. With advances in fiber lasers and novel microstructured optical fiber technology in the 1990s it became possible to generate supercontinuum light from a compact, efficient all-fiber laser system. Fianium released the first commercial high power supercontinuum source in 2004 and has since supplied over 900 ›WhiteLase‹ systems to the leading universities and research institutions around the world (**Figure 1**).

While the full supercontinuum spectrum is sometimes used simultaneously, typically extending from 400 to 2500 nm, in many applications only a single wavelength, or narrow wavelength range, is required at any one time and the rest of the spectrum needs to be blocked. For this reason, the choice of filter can be critical as various filter technologies have different strengths and weaknesses. There is not one ›perfect‹ filter for all applications. The main considerations are usually the combination of the bandwidth and transmission efficiency as this determines the average optical power that will be available after the filter. The other performance parameters that vary between different filter technologies are the ability to block unwanted light (or out-of-band suppression), the wavelength tuning range, the tuning speed and whether the filter is polarizing or not.

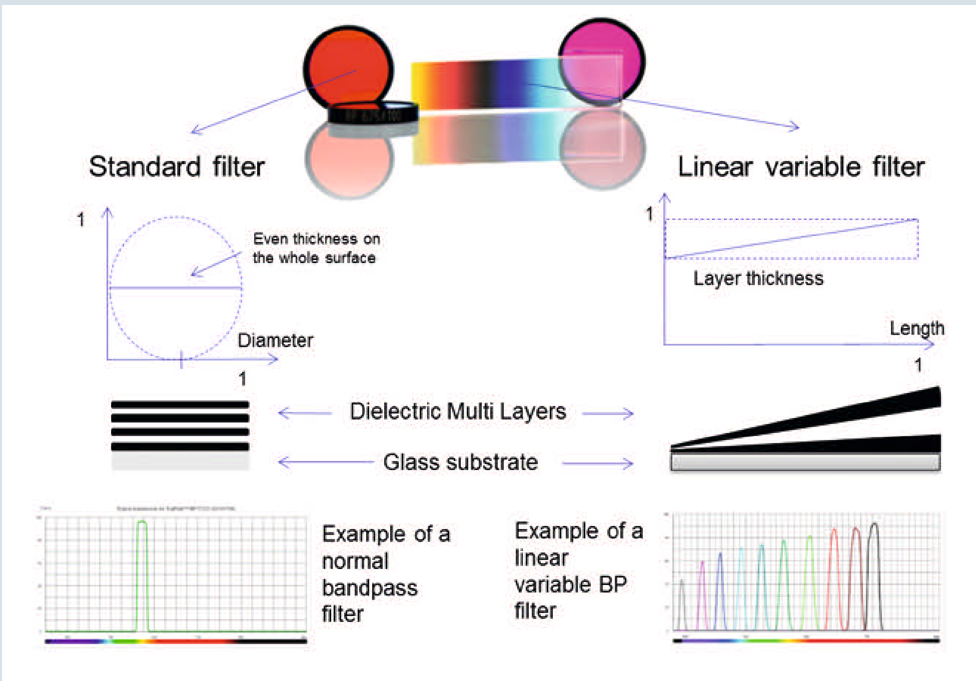
Existing filtering technology

The simplest method of filtering the supercontinuum light is to use fixed bandpass filters which transmit the desired wavelength and block the unwanted light. This solution is relatively low cost and transmission efficiency and out-of-band blocking are generally very good but there are also major drawbacks. The main factor, of course, is that these filters are not tunable and so a different optic is required for each desired wavelength. To achieve tunability, the most commonly used existing filter technology is the Acousto-Optic Tunable Filter (AOTF) which exploits the acousto-optic interaction inside an anisotropic medium. When an RF signal is applied to the acousto-optic crystal, a single wavelength corresponding to the frequency of the applied signal is diffracted out of the supercontinuum beam at a fixed angle. AOTFs have two unique properties; they can output multiple discrete wavelengths simultaneously in the same beam path and can switch each wavelength on microsecond timescales. The out-of band suppression is typically relatively low, however, with the spectral output suffering from prominent ›side bands‹ separated both spectrally and spatially from the selected wavelength. Because of this feature, and the somewhat limited tuning range of any given AOTF crystal, other new filter technologies have proven to be very useful.

4 Plug-and-play LLTF contrast tunable filter from Fianium based on holographic volume gratings

Linear variable filters

A linear variable filter (LVF) is an optical interference filter whose spectral functionality varies along one direction of the filter, compared to a traditional optical filter whose spectral functionality is intended to be identical at any location of the filter. The term linear relates to the goal of making the wavelength variation a linear function of the position on the filter. The wavelength variation is achieved by an interference coating that is intentionally wedged in one direction, creating a linear shift of the center or edge wavelength along the same direction of the filter (**Figure 2**). The linear variable filters made by Delta, for example, are rectangular types where the wavelength characteristic changes along the longitudinal direction. Other manufactures have made circular variable filters where the variation is obtained by rotating the filters. In other designs, tunability can also be obtained by changing the angle of incidence.



2 Design principal of standard and linear variable filters

The highest optical power provided by a commercial supercontinuum source is up to 10 W (Fianium ›WhiteLase SC480-10‹ system) so it is important that any filter can withstand very high intensity light. Absorptive or induced transmission filters and soft coated filters are susceptible to damage when used with high power sources so a hard-coating non-absorbing technology, such as all-dielectric metal-oxides and quartz constructions utilized by Delta, is essential for this application. The other benefit of high precision multi-layer coatings is that the edge steepness of the filter can be very high along with around 90 percent transmission efficiency and typically better than 40 dB out-of-band suppression (**Figure 3**).

The simplest implementation of LVFs is a single tunable bandpass filter where the output wavelength is selected simply by the spatial position on the filter. A more flexible filter can be designed however by combining two edge-pass LVFs, one long wave-pass and one short wave-pass, to create a tunable bandpass. By moving both filters together, the central wavelength can be continuously adjusted and by moving them relative to one another the bandwidth of the filter can also be tuned. In applications such as fluorescence imaging this allows the user to optimize the filter perfectly to maximize the efficiency of the imaging. Using two of these fully tunable bandpass filters together with a linear variable dichroic (LVD) makes it possible to design measurement systems that work after the epi-fluorescence principle. Because the LVFs have intrinsically high transmission efficiency this technology allows maximum tunable power from a supercontinuum source with in excess of 100 mW of tunable light possible with the highest power supercontinuum lasers.

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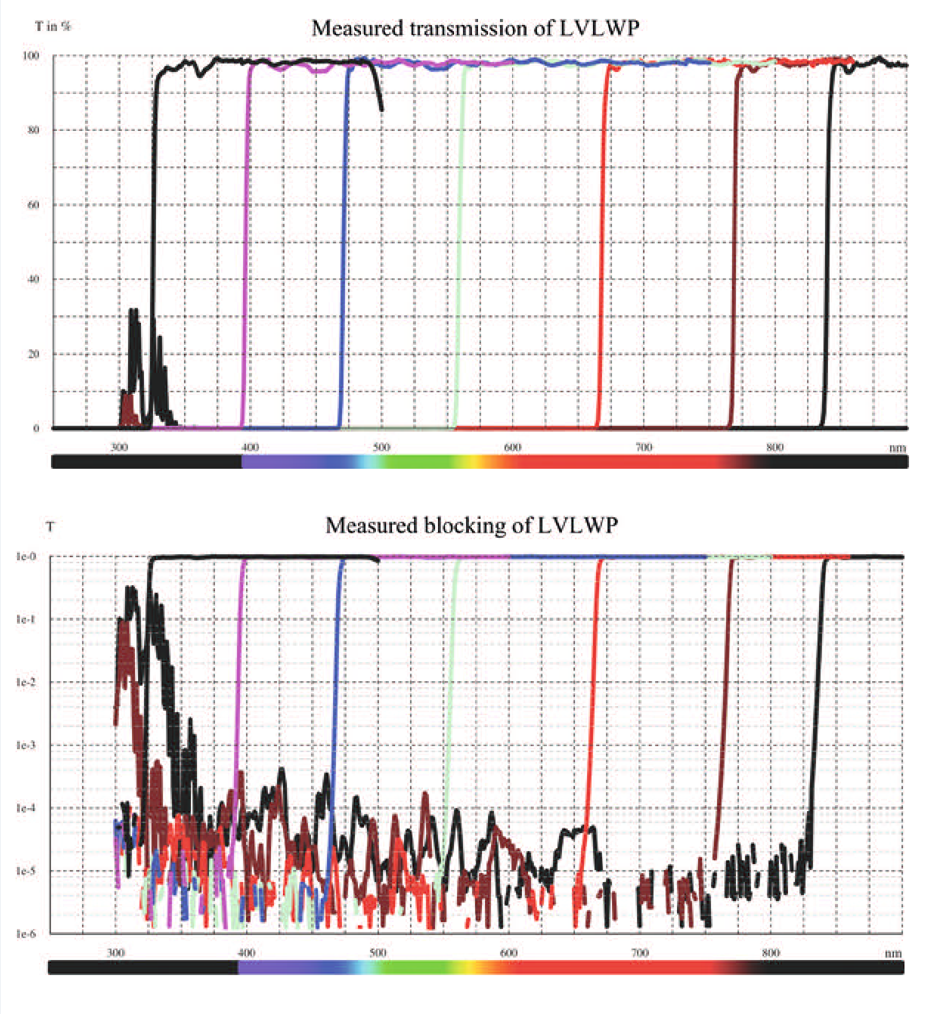
Grating-based ›Laser Line‹ tunable filters

Grating based filters are also used with supercontinuum because of the exceptional-



3 Measured transmission and out-of-band suppression spectrum of a Linear Variable Long Wave Pass filter from Delta

ly high out-of-band suppression that can be achieved. Traditional monochromator designs have the problem that they degrade the near perfect beam quality of the supercontinuum laser. This problem can be overcome with the use of holographic volume Bragg gratings which can match the out-of-band blocking of dispersive gratings, at >60 dB, while maintaining the spatially single-mode output. The use of this technology in a high performance ›laser line‹ tunable filter (LLTF) was developed by Photon Etc and is now available as a compact plug-and play accessory from Fianium for any of their supercontinuum fiber lasers (**Figure 4**).

Another benefit of this type of filter is an extended tuning range compared to other technologies with just two LLTF filter modules able to cover almost the complete supercontinuum spectrum. In addition, the narrow filter bandwidth of approximately 2 nm and high transmission of up to 60 percent make this an ideal tool for spectroscopic applications.

Summary

Supercontinuum white light fiber lasers are versatile light sources where the potential range of applications can be defined as much by the performance of a tunable filter as by the light sources itself. There are a range of tuning options available and the best one will depend on the desired characteristics of the output. Some existing filter technologies, like acousto-optic tunable filters, bandpass filters and monochromators have been used successfully but they have their intrinsic limitations. New filter technologies have now emerged, such as high quality linear variable filters and volume grating based filters, which offer enhanced performance and extend the versatility of the supercontinuum light source.

As filter technology improves, new applications will become possible although it is unlikely that one filter technology will be suitable for every use. In the future, it may be possible to arbitrarily shape the supercontinuum with high efficiency allowing any output spectrum to be programmed at will but until then , the choice of filter will remain of critical importance. ■

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