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Laser Characterization with Etalon-Based Cross-Dispersion Spectrometers

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Introduction

The use of spectrometers to characterize laser behaviour is becoming more and more prevalent as laser applications expand. Laser manufacturers and laser users often need to measure the spectra of continuous and pulsed lasers to determine properties such as linewidth, exact wavelength and wavelength drift, the occurrence of mode hopping, the presence and relative intensity of side-lobes, etc. Often these measurements must be completed in a timescale of a few milliseconds to allow fast transient behaviour to be captured.

A variety of spectrometers can be purchased to measure some or all these laser characteristics. These instruments range from scanning instruments such as Fourier Transform spectrometers and wavemeters, through conventional grating spectrometers and OSAs, to cross-dispersion spectrometers such as echelle- and etalon-based instruments. While each specific type of spectrometer has its advantages and disadvantages, we show in this article that cross-dispersion spectrometers are particularly well-suited to measuring a wide range of laser parameters. In contrast to scanning spectrometers, a cross-dispersion spectrometer can measure the entire spectrum in a "single shot", allowing the recording of the spectra of pulsed lasers, or fast repetitive measurements on continuous lasers. In addition, the use of a Fabry-Perot etalon as the main dispersing element in the spectrometer ensures high spectral resolution can be achieved in a much more compact instrument than with competing technologies.

The technology behind etalon-based cross-dispersion spectrometers

At the heart of all non-scanning spectrometers is a dispersive element that separates light into different wavelength components. The higher the dispersion of this component, the better the ability of the spectrometer to distinguish closely-spaced wavelengths in the light source. Typical dispersive elements (ranked approximately in increasing order of dispersion) are prims, conventional diffraction gratings, echelle gratings and Fabry-Perot etalons. As laser characterization almost always involves the need to examine closely-spaced wavelengths, an etalon-based spectrometer would seem to be the obvious choice for this application. Unfortunately, the high dispersion of an etalon comes with the drawback of overlapping interference orders. While an etalon can easily separate wavelengths spaced a few picometers (pm) apart, wavelengths separated by the free spectral range (FSR) of the etalon overlap after passing through the etalon. Cross-dispersion spectrometers are used to solve this problem, as illustrated in Figure 1 below. After passing through beam-shaping optics, the light input is first dispersed *vertically* by an etalon, which provides the dispersive power to distinguish wavelengths separated by a few picometers. The output of the etalon is then cross-dispersed *horizontally* by a conventional diffraction grating to separate overlapping FSR orders and thus

provide a large unambiguous spectral range in the instrument. Finally, an imaging lens focuses the different spectral components onto a megapixel 2D sensor. It is worth pointing out that the commercial availability of megapixel 2D sensors made a major contribution to the development of cross-dispersion spectrometers.

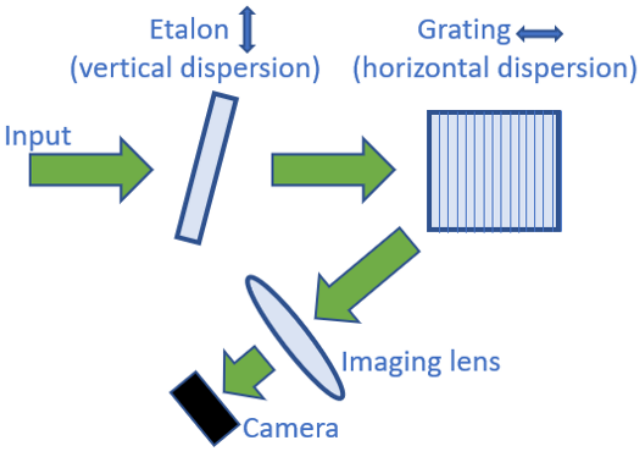

Figure 1 - Schematic of the optical layout of an etalon-based cross-dispersion spectrometer

Principles of operation of an etalon-based cross dispersion spectrometer

Thanks to the 2D dispersion scheme shown in Figure 1, many spectral elements can be acquired in a single shot. The optical layout disperses the light in such a way that the spectrum is effectively "folded" into hundreds of sections - largely overlapping - imaged onto the camera. Figure 2 below illustrates how these sections arise by visualizing how the camera image changes as a single-frequency laser is tuned from 550.000 nm to 550.600 nm - a total of 10 FSRs

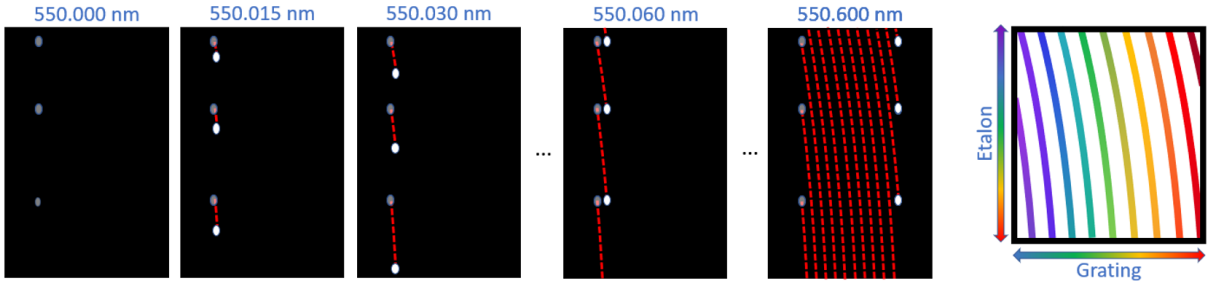

Figure 2 - Schematic representation of the image on the camera sensor as a single-frequency laser is tuned.

On the left of Figure 2 we see three white blobs of light hitting the sensor, corresponding to three different etalon orders. Each blob corresponds to a different angle of transmission through the etalon and hence a different optical path difference for successive reflections within the etalon. Each of the three path differences corresponds to a different *integral* number of wavelengths - the condition for constructive interference in transmission through the etalon. As the wavelength is tuned slightly, the large etalon dispersion results in significant vertical motion of each blob.

The smaller grating dispersion results in a smaller horizontal motion. However, after tuning the wavelength by a full etalon FSR (60 pm here) to 500.060 nm, we can see that the cumulative horizontal shift caused by the grating prevents the overlapping of successive etalon orders on the sensor. As the wavelength is tuned further, we can see tilted stripes being traced, each corresponding effectively to small sections of the spectrum. The schematic on the right summarizes the dispersion and wavelength map, with blue representing shorter wavelengths and red representing longer wavelengths. A corresponding image, as recorded by the camera sensor, is shown in Figure 3.

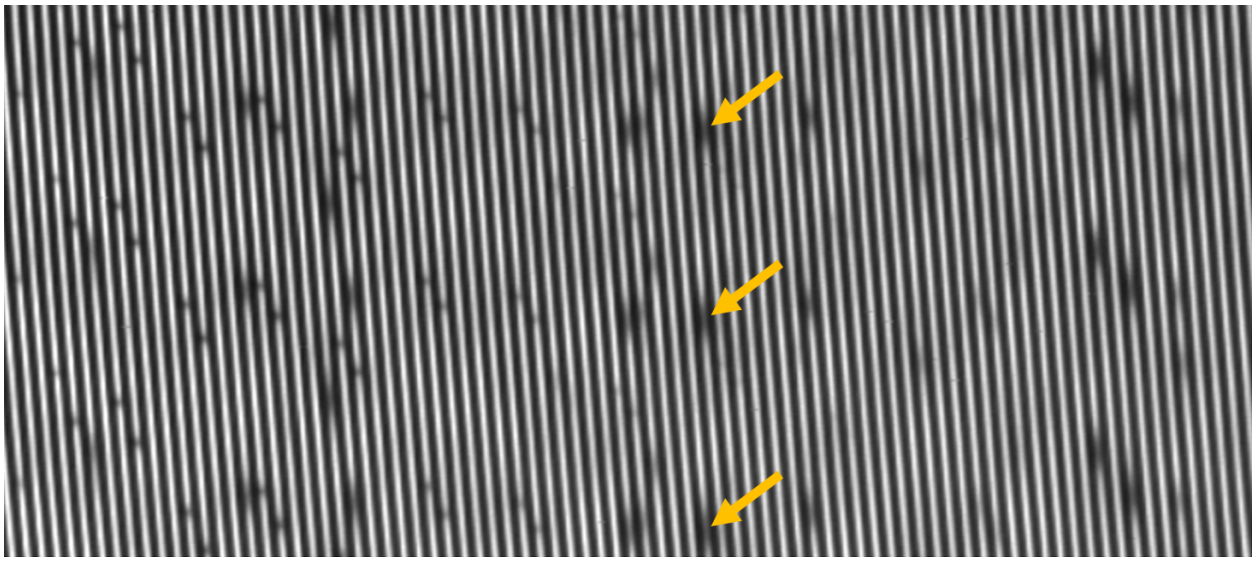

Figure 3 - Sensor image recorded by an etalon-based cross-dispersion spectrometer illuminated by sunlight. Typically, hundreds of white light "stripes" are generated by the cross dispersion, with the dark regions corresponding to Fraunhofer absorption lines in the Sun's spectrum. Successive stripes contain overlapping sections of the spectrum, as illustrated by the orange arrows.

Before the full spectrum can be displayed, the sensor image must be converted into a standard intensity-versus-wavelength spectrum by stitching together the overlapping spectra from the individual stripes. This conversion can be carried out in real time (as fast as the successive images are captured) by dedicated software. The dedicated software is also designed to deal with the challenges that are inherent to all cross-dispersion configurations, both etalon- and echelle-based. When stitching together overlapping spectra from successive stripes, it is essential to ensure *exact* overlap of the wavelengths from each stripe. Any mismatch in wavelength can easily broaden a narrow spectral feature and reduce the resolution of the instrument. Similarly, the intensities from top to bottom of each stripe must be normalized to ensure an accurate intensity scale when the intensities of multiple stripes are summed at a given wavelength.

<u>Resolution limits of etalon-based cross-dispersion spectrometers</u>

Spectral resolution is classically described in terms of the ability of a spectrometer to distinguish between two closely-spaced spectral lines. If the spectrometer can *just* separate two lines with wavelengths of λ and $\lambda+\Delta\lambda$, then the resolution is defined as $\Delta\lambda$. The closely related resolving power is given by

$$\text{Resolving Power} = R = \lambda/\Delta\lambda$$

Figure 4 shows an example of two closely-spaced laser modes separated by 1.4 picometers. In this case, the spectrometer resolution is 0.85 picometers and hence the two modes are clearly resolved. (The resolving power is 750,000).

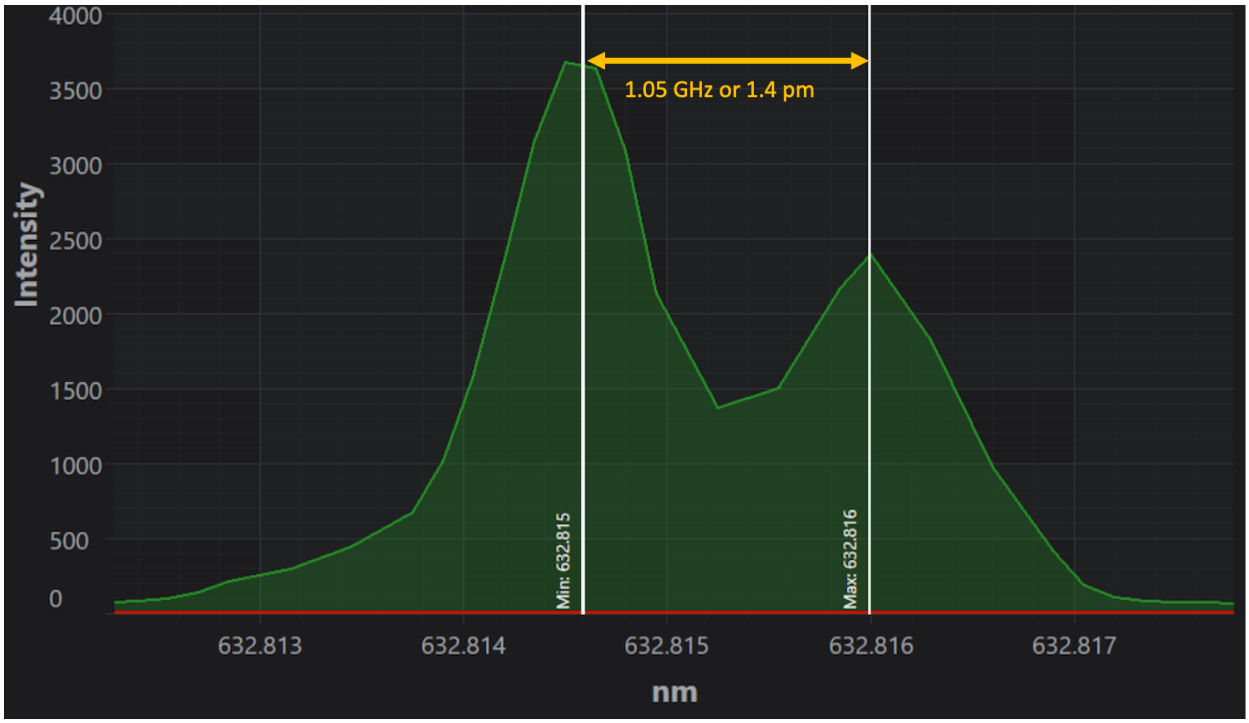

Figure 4 - Spectrum of a red He-Ne laser operating at 632.8 nm as measured with a LightMachinery HN-8989 spectrometer. Although the He-Ne laser operates in a pure TEM00 mode, it tends to alternate between one and two longitudinal modes. The spectrum was taken when the laser emitted two longitudinal modes of almost equal intensity, spaced in wavelength by 1.4 picometers (1.05 GHz). As the two wavelengths can clearly be separated by the spectrometer, we can estimate the resolution as better than 1 picometer.

In terms of laser characterization, the classical definition of resolution is not very practical, as for measurement purposes this definition requires two spectral lines of appropriate spacing at every wavelength of interest. As a result, the resolution of modern spectrometers is usually defined as the full-width, half-maximum, FWHM, of the instrument response when illuminated by a narrowband source of light, as shown in Figure 5.

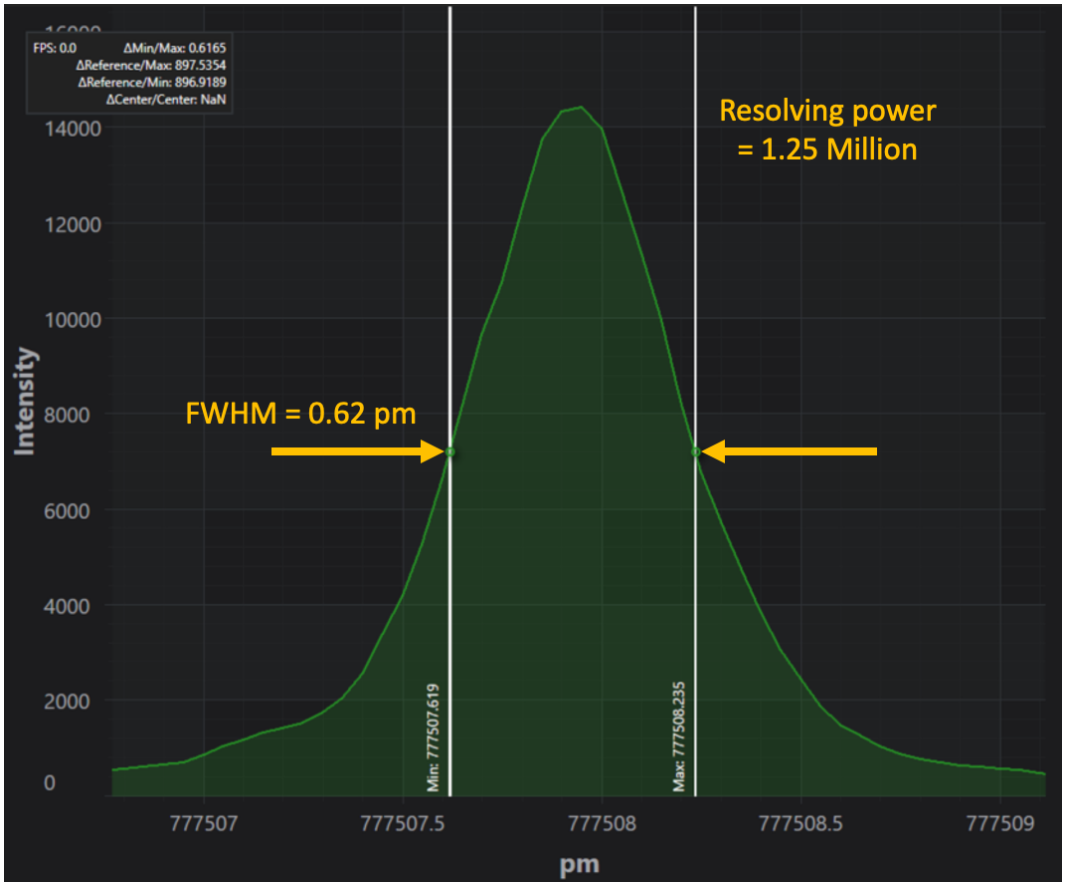

Figure 5 - Spectrum of a single-longitudinal-mode laser operating near 780 nm as measured with a LightMachinery HN-8995-1-UHR spectrometer. The observed linewidth is dominated by the instrument response function of the spectrometer, as the laser itself has a negligible linewidth.

In the case of high-resolution spectrometers, care must be taken to ensure that the light source used for resolution measurements has a linewidth much smaller than the instrument resolution. Typical gas-discharge calibration lamps, which are often used to characterize standard spectrometers, do not have sufficiently narrow linewidths to characterize etalon-based cross-dispersion spectrometers, as shown in Figure 6 below.

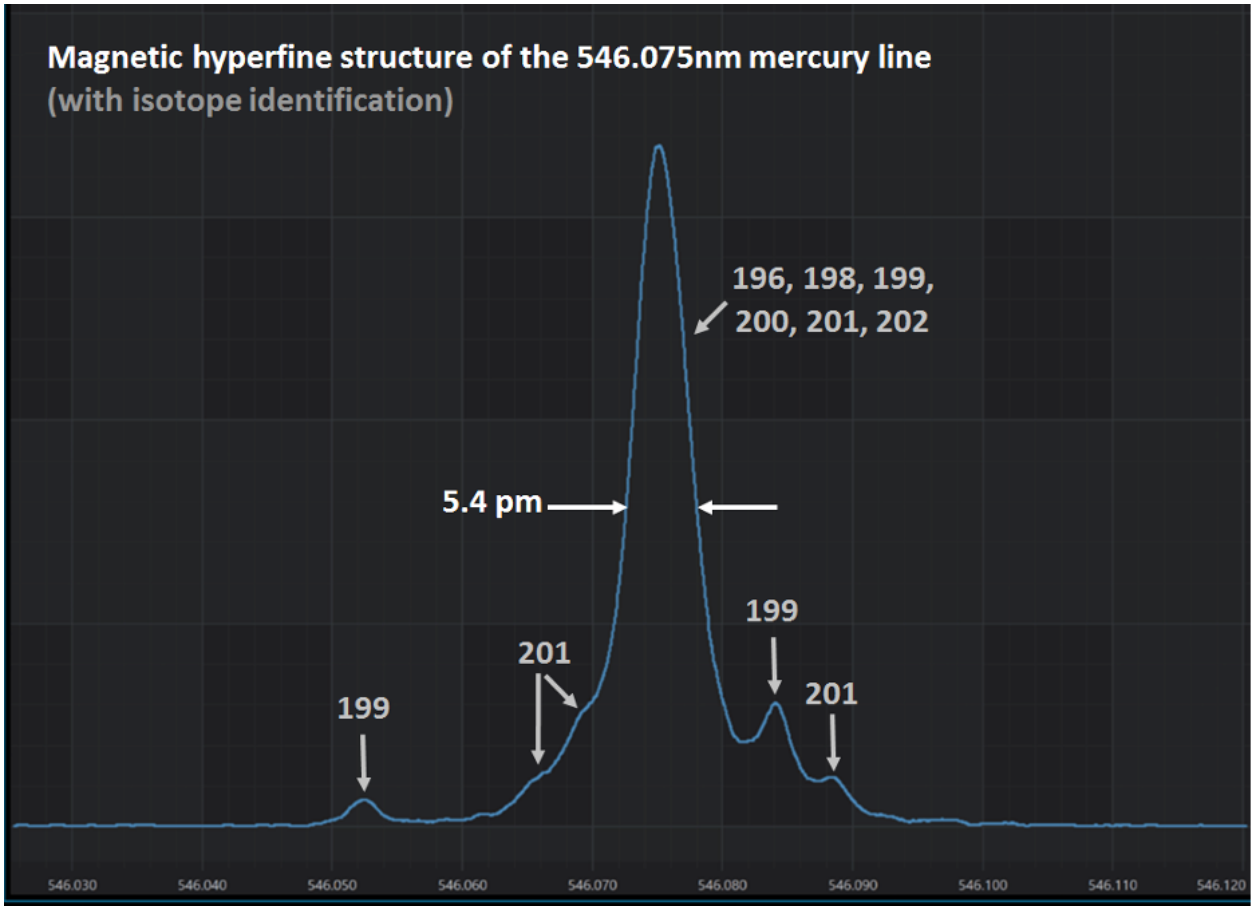

Figure 6 - Spectrum of a conventional Hg calibration lamp line at 546 nm taken with a LightMachinery HF-8989-2 spectrometer. The resolution of this spectrometer is 1 picometer, and the observed linewidth of the main spectral peak (5.4 pm) can be almost entirely attributed to the linewidth of the light source. Note that the 546 nm line in the Hg spectrum is composed of several hyperfine contributions from each of the naturally occurring Hg isotopes.

Having discussed both the definition and measurement of resolution, let us now examine the factors that limit the achievable spectral resolution in practical spectrometers. All spectrometers operate on the principle of using multiple interfering beams to distinguish between light of different wavelengths. The number of beams can vary from two in the case of Fourier Transform instruments, through hundreds or thousands of beams for cross-dispersion instruments (etalon- or echelle-based) to thousands or tens of thousands of beams in the case of a conventional diffraction grating. However, in all cases, the resolution is determined by the maximum path difference between the extreme beams in the instrument. There is a linear relationship between maximum path difference and resolving power, and thus instruments with larger path differences have better resolution. If we take a conventional diffraction grating spectrometer as an example, better and better resolution can only be attained with bigger and bigger gratings (and hence larger diameter optical beams and larger instruments). For Fourier Transform instruments, the scanning path length must increase to obtain better resolution. Instruments based on Fabry-Perot etalons must use etalons with larger and larger mirror spacings, but resolving powers of >1,000,000 are easy to achieve in a compact package using mirror spacings of less than 1 cm.

Figure 7 illustrates how two different technologies for generating multiple interfering beams in spectrometers result in very different instrument sizes.

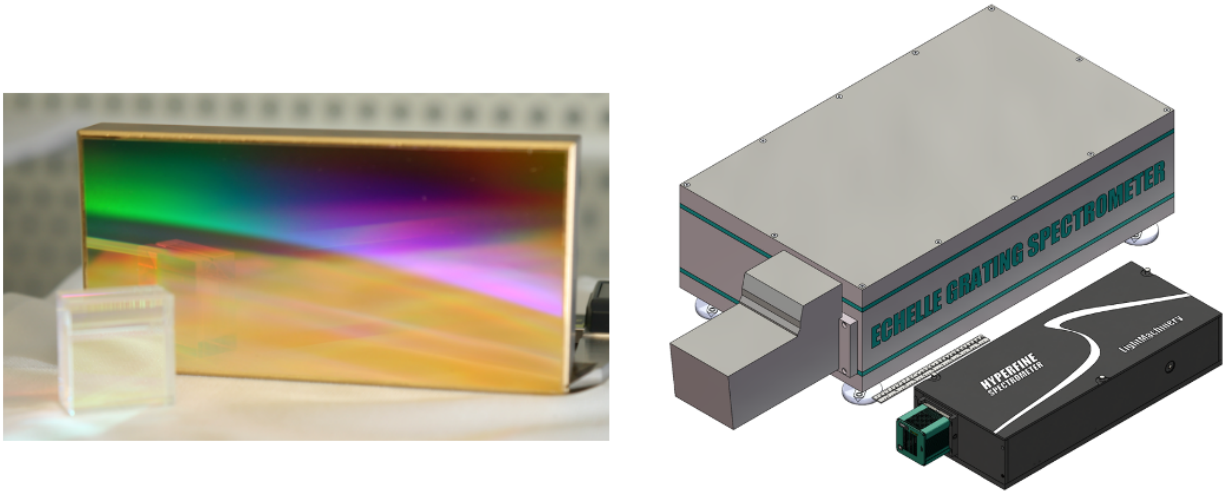

Figure 7 - Comparison of etalon-based and echelle-based cross-dispersion spectrometers with resolving powers of 500,000 and 200,000, respectively.

The left side of Figure 7 compares the size of a Fabry-Perot etalon (2.5 cm square) and an echelle grating (10 cm long) that deliver resolving powers of 500,000 and ~200,000, while the right side of the Figure shows the relative sizes of two commercial spectrometers incorporating the respective technologies. (Note the 12-inch ruler between the two spectrometers). The echelle-based spectrometer has >8X the volume, 3X the weight, and yet delivers less than half the resolving power.

Before discussing the application of high-resolution spectrometers to laser characterization, one challenge that is unique to cross-dispersion spectrometers (both etalon- and echelle-based) should be discussed. This challenge is the occurrence of crosstalk due to the “bleeding” of intensity from an intense narrowband source in one stripe into adjacent stripes. This is illustrated in Figure 8.

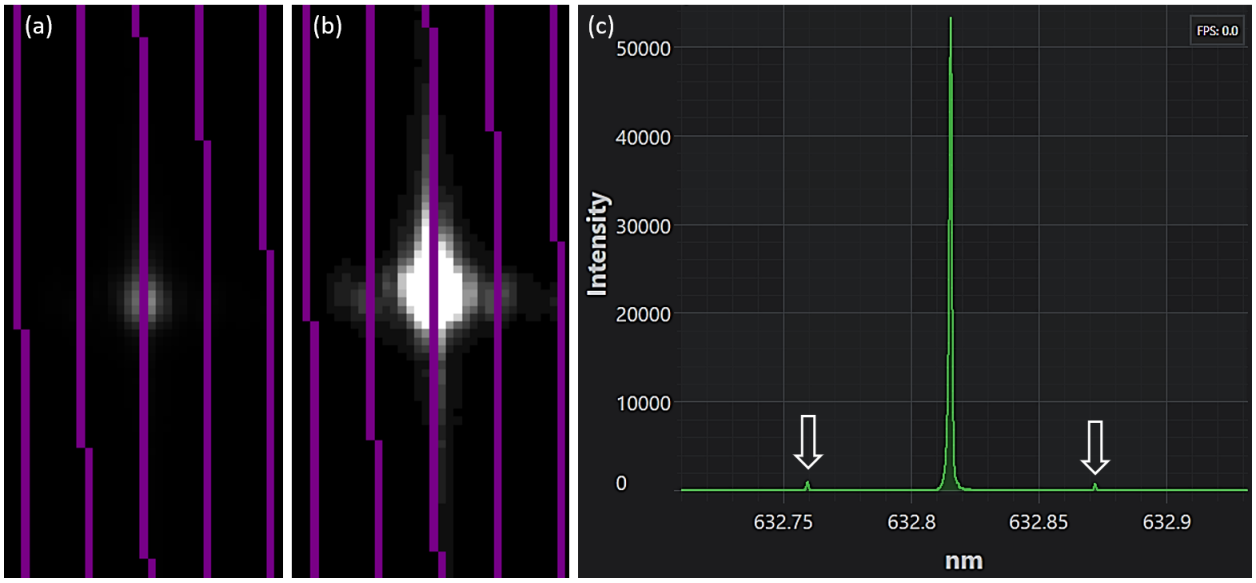

Figure 8 - Illustration of the origin of crosstalk in cross-dispersion spectrometers. The crosstalk peaks are shown by the white arrows. While cross-talk is typically ~ 0.5 % (customizable to ~ 0.05 %), the spectrum in (c) presents a large cross-talk of 2 % to ease visualization.

In Figure 8(a), a Helium-Neon laser illuminates the sensor at 632.816 nm - a single blob is shown on the sensor and the stripe positions are represented by purple lines. In Figure 8(b), the software gain is significantly increased to show the faint wings of the blob. Note that some intensity "bleeds" onto the left and right stripes, which are at a longer and shorter wavelength, respectively. Figure 8(c) shows the spectrum as unwrapped by the dedicated software. The faint blob wings appear as crosstalk at 632.872 nm and 632.760 nm, or ± 56 pm on either side of the main peak, corresponding to +/- one FSR of the etalon.

The hardware in LightMachinery HN spectrometers is designed to minimize crosstalk, as is the dedicated software. Typically, crosstalk is ~ 0.5% of the intensity of the nearby spectral peak, but it can be made significantly lower if required by the application (see Figure 9 for instance). Also, the crosstalk feature duplicates the shape of the main peak and is always separated from the main peak by exactly one FSR, allowing for subtraction techniques to be applied to further reduce crosstalk, if required.

<u>High resolution applied to laser characterization.</u>

By their very nature, most continuous-wave lasers have extremely narrow linewidths. These narrow linewidths are often used to determine the resolution of a spectrometer, but a spectrometer can rarely be used to determine the linewidth of a continuous-wave laser operating at a single wavelength. However, lasers often operate at multiple wavelengths and high-resolution spectrometers are usually required to detect and measure the additional wavelengths (sidelobes) caused by multiple longitudinal and transverse modes, for example. As the sidelobes become closer and closer spaced, higher and higher resolution is required to detect them. Roughly speaking, an instrument resolution of 20% to 50% of the minimum sidelobe separation is required to *detect* a sidelobe with *significant* intensity.. (See Figure 2 of the red

He-Ne modes for an example). Even more challenging than simple sidelobe detection is the common requirement in laser characterization for accurately *measuring* the intensity of *weak* sidelobes that are spectrally close to the strong laser signal. In these cases, key spectrometer parameters are the dynamic range and contrast. Dynamic range refers to the ratio between the largest measurable unsaturated laser intensity and the smallest measurable sidelobe intensity. To a first approximation, the dynamic range of cross-dispersion spectrometers is similar to that of the camera employed. The *single-exposure* dynamic range is typically on the order of 25-35 dB (~300:1 – 3000:1). However, by utilizing the range of exposure times available from the camera, the dynamic range of the spectrometer can typically be increased to >60 dB. In other words, measuring *simultaneously in a single exposure* two wavelength peaks which differ in intensity by ~100 is not a problem. If the two peaks differ by a factor of 10,000, and the contrast is not a limiting factor (see below), two spectra will need to be acquired with different exposures and subsequently analyzed.

The other key parameter that comes into play is contrast. A direct representation of contrast is the spectral response of an isolated instrument-limited spectral line (typically a single longitudinal mode laser) displayed in log scale. Contrast is then defined as the ratio between the magnitude of the peak and that of its tail at a given separation. An example is shown in Figure 9 below. Typically, the contrast of an etalon-based cross-dispersion spectrometer ranges from >30 dB (1000:1) to >45 dB (30,000:1) approximately 10 FWHM away from a given peak.

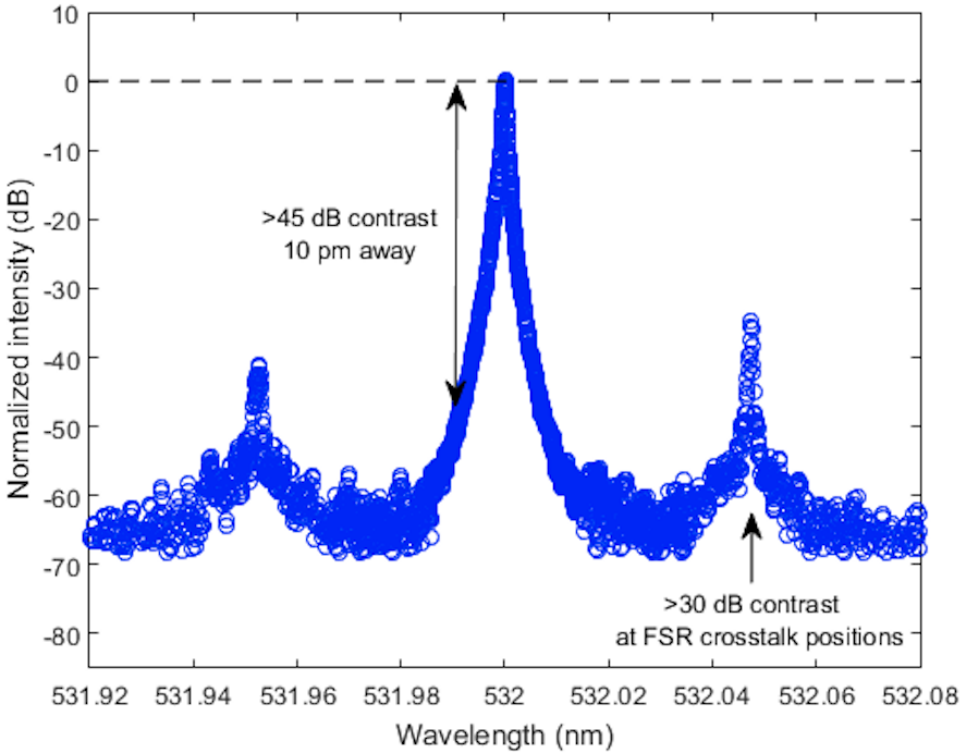

Figure 9 - Instrument-limited spectral response of the LightMachinery HF-7888-532 spectrometer displayed on a log scale when illuminated by single-longitudinal-mode 532 nm laser. The high resolution of the spectrometers (1 pm FWHM) ensures excellent contrast 10 pm away from the laser wavelength. Contrast increases even further away from the laser

wavelength, except at those predictable wavelengths where crosstalk appears. The data is a composite of several exposure times.

A very demanding application of spectrometers is to measure the spectral purity of a nominal single-frequency laser source. For these measurements, even the high-contrast performance shown in Figure 9 may not be sufficient. To meet this requirement, LightMachinery offers cross-dispersion spectrometers which contain two etalons in series - resulting in a further improvement in contrast to ~60 dB (1 million : 1) approximately 10 FWHM away from the laser frequency. If more than 60 dB contrast is required, LightMachinery offers a “Pump Killer" module that attenuates the laser wavelength by ~65 dB while allowing the nearby wavelengths to pass with minimum attenuation. In combination with an etalon-based cross-dispersion spectrometer, an effective contrast greater than 100 dB can be achieved. Hence, measurement of very weak spectral features with <80 dB intensity near the nominal single-frequency laser peak are now possible, as presented in Figure 10.

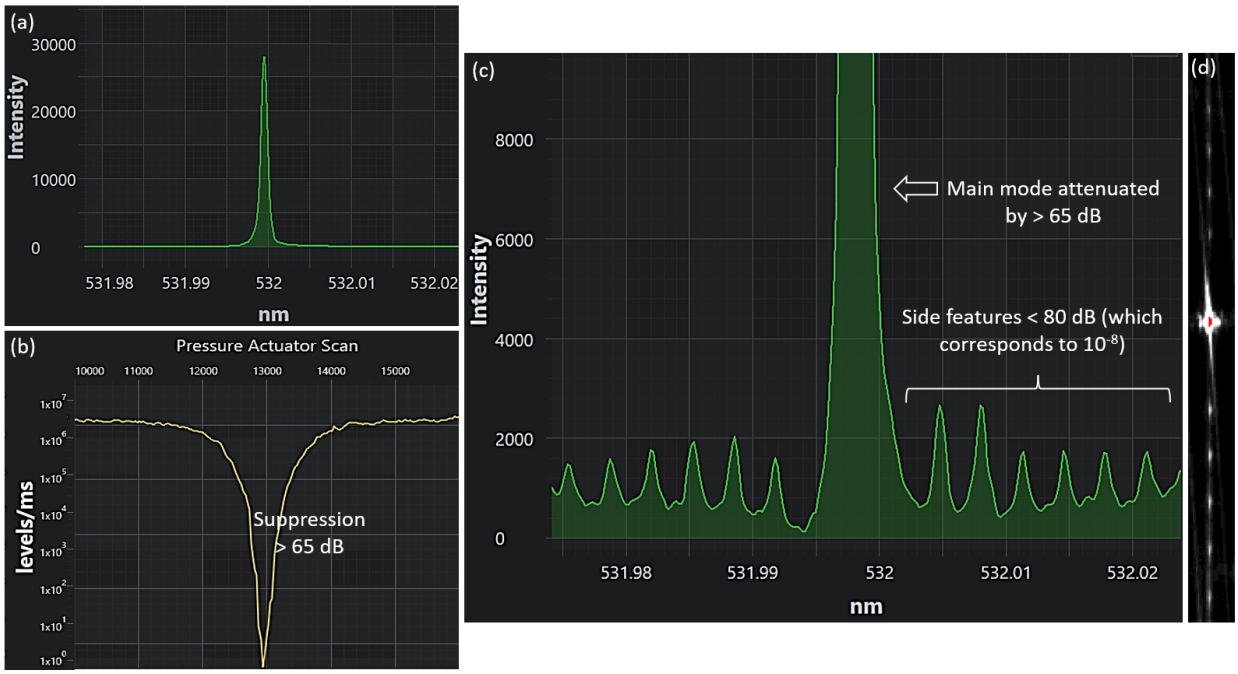

Figure 10: Measurement of the spectral purity of a nominally single longitudinal mode laser. Spectrum (a) displays a conventional scan of a single longitudinal mode laser. The manufacturer’s datasheet specifies a spectral purity greater than 60 dB, which is well below the noise and contrast floors. Such low amplitude features in the immediate vicinity of the main laser mode cannot be measured under normal circumstances. To display any laser side features, the laser line must be attenuated with an ultra-narrow tunable notch filter. The suppression curve in (b) is ~ 65 dB deep (3 000 000:1) and has a FWHM of ~ 12 pm. The resulting spectrum (c) and camera image (d) show the laser side features surrounding the highly attenuated central mode. Our measurement indicates a spectral purity higher than 80 dB. This measurement was achieved by using a Hyperfine spectrometer with a resolution of 1 pm and a pm-wide notch filter (LightMachinery’s Pump Killer). Note that the laser power was significantly increased for (c).

The suppression curve in (b) is plotted on a log scale (Y-axis) while the X-axis is significantly expanded compared to (a).

Short exposure times and fast acquisition rates applied to laser characterization

In many cases, laser characterization involves the detection of transient phenomena such as mode hopping, fast wavelength drifts, and the transient appearance and disappearance of weak sidelobes. Short exposure times and fast acquisition rates are essential for such applications. Fortunately, cross-dispersion spectrometers have no moving parts, and do not require the use of scanning. Hence the time taken to acquire a spectrum is only limited by the exposure time of the camera and the processing time of the software that converts the sensor image into a spectrum. The minimum real-time acquisition speed achievable with most LightMachinery cross-dispersion spectrometers is greater than 10 frames per second (>10 Hz). 10 Hz is ideal for applications involving real-time optimization since the resulting display of the spectrum appears like a continuous video to the eye. For certain applications however, higher acquisition speed is desired. For such cases, faster acquisition modes have been developed that do not display every acquired spectrum in real time. These modes can be used with either internal or external triggering. The rate at which the full spectrum can be acquired and saved varies with the spectrometer model and the camera option, but typically it is ~50 Hz. Figure 11 illustrates the use of an etalon-based cross-dispersion spectrometer to capture transient laser phenomena.

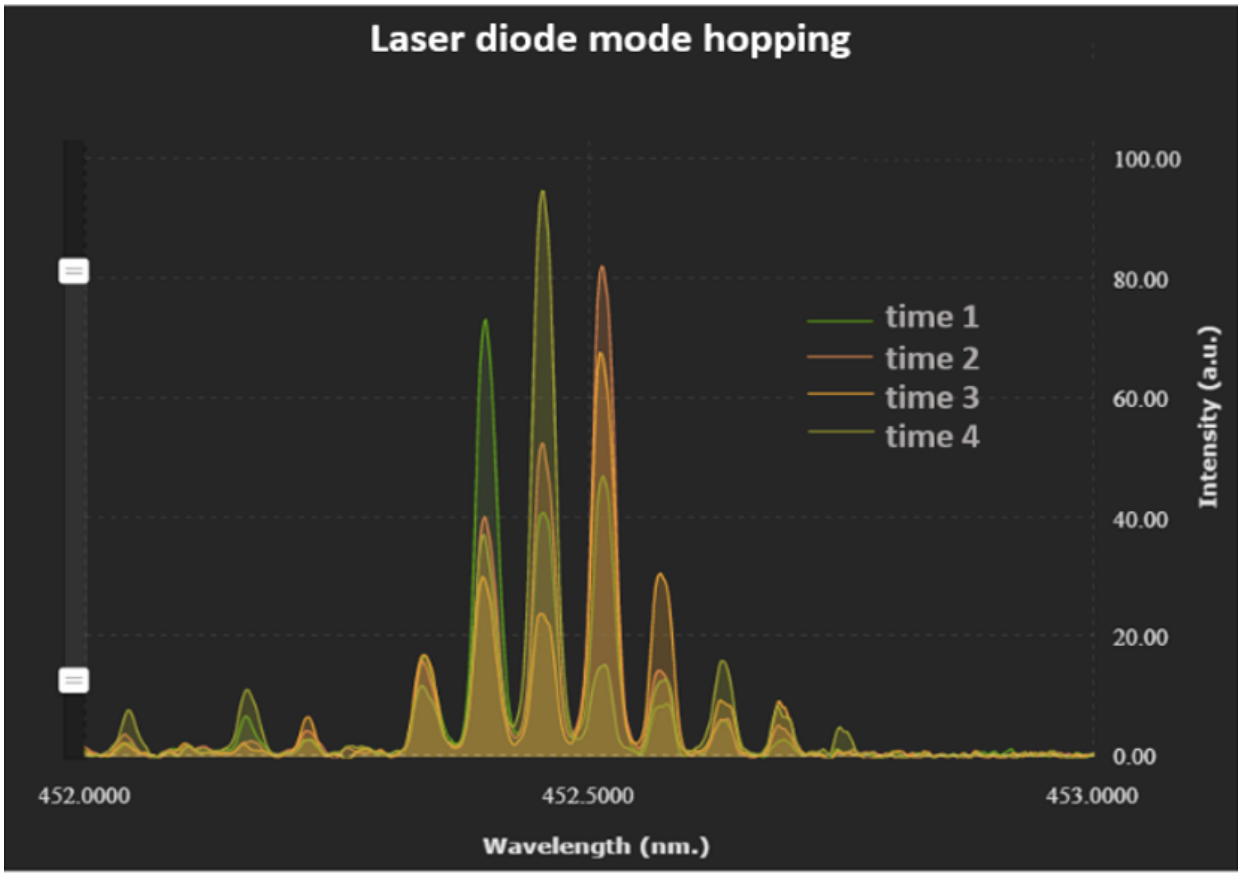

Figure 11 - Spectra taken with a LightMachinery HN-9332 spectrometer (simultaneous range = 425-700 nm) illuminated by a 452 nm laser diode. The diode emits several different modes at different wavelengths, and the relative mode intensities "hop" on a timescale of milliseconds. The time between the acquisition of successive spectra is 20 milliseconds.

For even more demanding applications, acquisition speeds of ~50 Hz may still be far from sufficient. Spectrometer models are available from LightMachinery that can capture spectra at an acquisition rate of 1000 Hz (one millisecond exposure time) - ideal for capturing fast transient behaviour of laser sources that otherwise might be missed by more conventional spectrometers.

Cross-dispersion spectrometers and pulsed laser sources

Cross-dispersion spectrometers are equally suited to pulsed lasers, continuous lasers, and lasers emitting trains of femtosecond pulses. Fast exposure times coupled with the absence of moving parts allows the spectrometer to capture the spectra of all types of laser sources. Examples are shown in the Figures below.

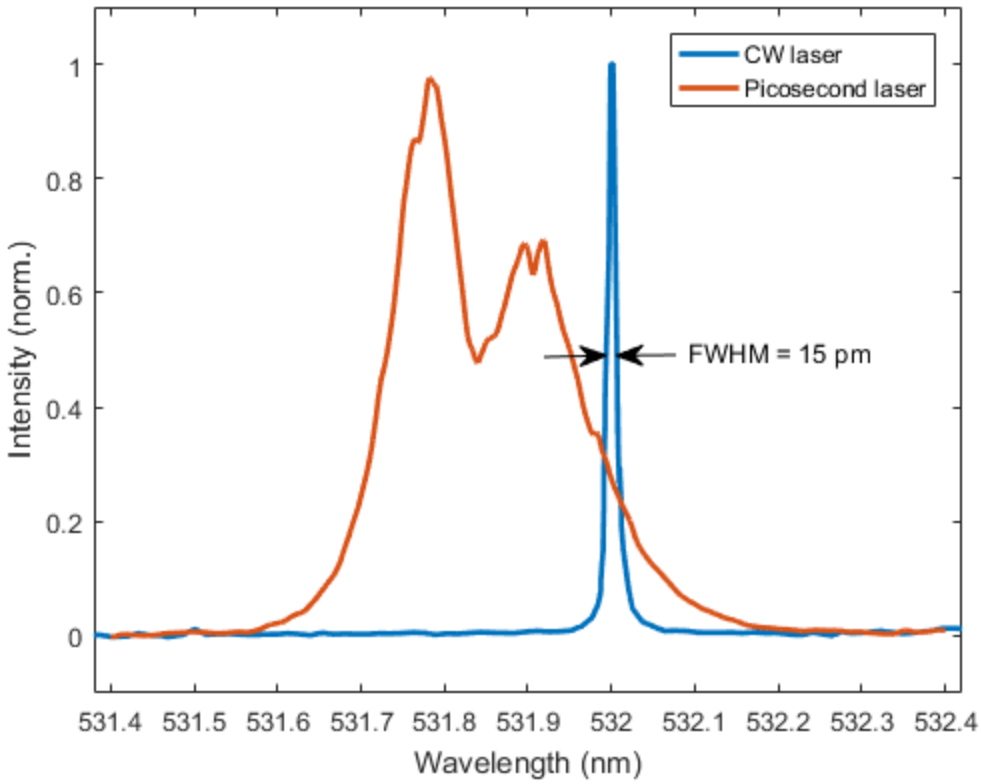

Figure 12 - Spectrum of a single pulse from a picosecond laser (red) recorded with a compact LightMachinery HN-9332 spectrometer (simultaneous range = 425-700 nm) with a resolution equal to 15 pm in the 500 nm region (as demonstrated by the instrument-limited spectrum of a CW laser).

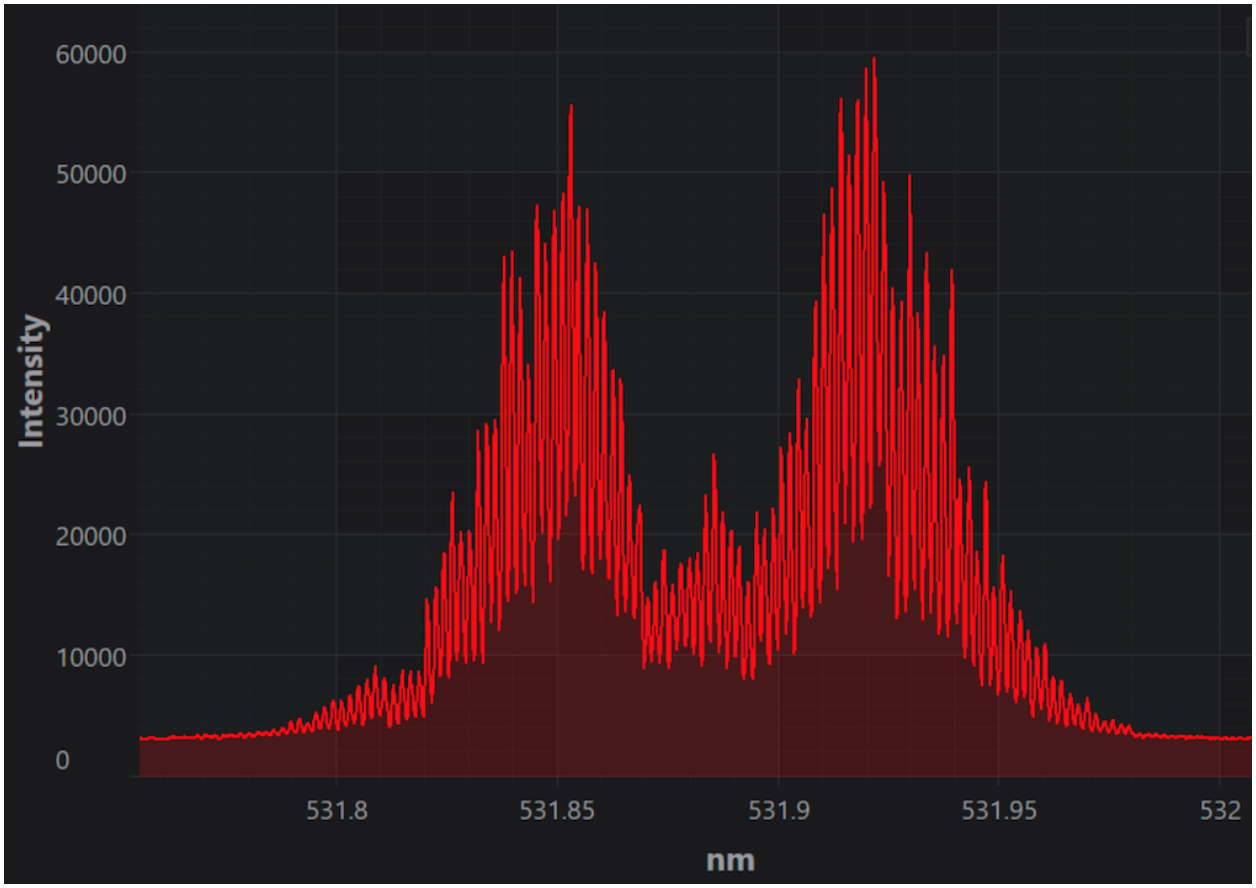

Figure 13 - Spectrum of a laser emitting a continuous train of femtosecond pulses (a frequency comb) as recorded by a LightMachinery HF-8989-2 spectrometer.

Wide wavelength range of cross-dispersion spectrometers

Thanks to their cross-dispersion configuration, LightMachinery spectrometers can utilize the millions of distinct pixels in modern 2D sensors to acquire ~50,000 data points simultaneously. Each data point is a distinct wavelength/intensity pair (λ, I), and generally there are ~5 data points in each resolution element. Thus, a spectrometer with a 1 pm resolution (the width of a spectral element) can display a full 10 nm of wavelength range, with data points every 0.2 pm, from a single exposure captured by the sensor. Some spectrometer models have a grating that can be rotated to change the wavelength range that falls on the sensor. Typically, this extends the wavelength coverage by an order of magnitude. Thus, a spectrometer that captures a 10 nm range with a resolution of 1 pm in a single exposure can be configured to measure spectra over a total range of 100 nm in 10 nm intervals. This versatility allows lasers with a wide range of wavelengths to be characterised at high resolution with the same instrument. Spectrometers are available for wavelengths from the UV to the NIR (200 nm to 1700 nm). Cross-dispersion spectrometers can also cover a range of ~300 nm with a single shot capture at medium resolution (~25 pm), if required for specific laser characterization applications.

Spectrometer Throughput

When characterizing lasers, there are often so many photons available that one needs to attenuate the laser beam by orders of magnitude to prevent detector saturation. In this case, there is no advantage to maximizing the spectrometer throughput (the fraction of input photons reaching the detector). Hence, there is no drawback in using a conventional Fabry Perot etalon as the main dispersing element, even though such etalons generally transmit <1% of the incident light through to the camera sensor. In those special cases where high spectrometer throughput is crucial (such as the investigation of very weak laser sidelobes), LightMachinery has developed the HF line of HyperFine Spectrometers. These spectrometers are based on a special type of etalon called a Virtually Imaged Phased Array (VIPA). The throughput of these VIPAs can reach >90%, providing maximum throughput to the HF line of spectrometers.

Conclusions

The variety of technologies employed in modern spectrometers can result in a bewildering choice of specifications for potential customers. If the spectrometer application is to measure the characteristics of a laser light source, and high resolving power is a key specification, then etalon-based cross-dispersion spectrometers often provide the best solution in terms of performance, size and cost.