

Introduction to the operating principles of the HyperFine spectrometer

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A spectrometer is an optical instrument designed to split light into separate colors, or wavelengths. Thus, white light directed into a spectrometer will be separated into red, green, yellow, and blue light at the exit of the spectrometer.

Inside a spectrometer, a variety of optical components can be used to separate the wavelengths. The choice of component depends primarily on the required resolving power, R^1 . A glass prism is sometimes used for low-resolution ($R < 1000$) instruments, but the most common optical component used in modern spectrometers is a diffraction grating². Diffraction gratings are used in either transmission or reflection, and generally provide resolving powers in the range of 1000 to 100,000. However, to use diffraction gratings at higher resolutions, requires the use of increasingly larger gratings.

To illuminate large diffraction gratings, optics with large diameters and long focal lengths (large f-numbers³) are required to minimize aberrations. A large entrance focal length (together with a narrow slit) is also required to achieve high resolution due to imaging considerations. Hence, diffraction grating instruments with $R > 50,000$ are generally expensive ($> \$50,000$) and large (> 1 meter in length).

For high-resolution spectrometers, Fabry-Perot (F-P) etalons provide a compact and cost-effective method to separate closely-spaced wavelengths. Figure 1 explains the principle of the F-P interferometer⁴.

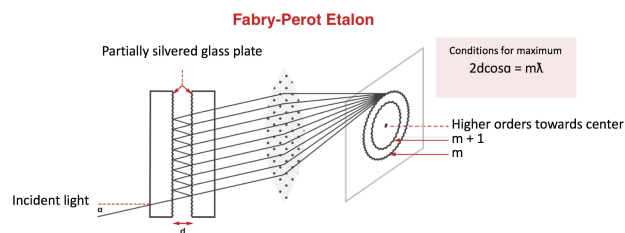


Figure 1: Principle of operation of an F-P interferometer, with the condition for the transmission maximum of the interference pattern⁵.

Note that the condition for maximum transmission of a particular wavelength, λ , is that a round-trip between the etalon plates must be exactly an integral number (m) of wavelengths. When the illumination source for the etalon provides a range of incident angles, circular fringes are formed at the focus of the lens. If the plate separation, d , is 0.25 mm, then a round trip is equal to $1,000\lambda$ at 500 nm, and it is easy to show⁴ that it is possible to achieve $R \sim 50,000$ with a high-quality etalon with a 0.25 mm plate separation using sufficiently reflective coatings.

While F-P etalons with circular fringes provide high resolution, they suffer two significant drawbacks. Firstly, only a small fraction of the incident wavelength is transmitted through the etalon; the majority of the incident light is reflected and lost to the measurement system. Typically, $> 95\%$ of the light incident on the F-P etalon is wasted. The second drawback with an F-P etalon is the problem of overlapping orders. In the example above, light of wavelength 500 nm is transmitted through the 0.25 mm etalon because **exactly 1000** wavelengths fit into a round-trip in the etalon. However, light with a wavelength of 500.5 nm will also be transmitted through the etalon, this time with **exactly 999** wavelengths in a round-trip. The measurement system cannot distinguish between these two wavelengths, which are termed overlapping orders (order #999 and #1000, in this case).

A special type of etalon, called a VIPA (Virtually Imaged Phased-Array), can be used in combination with a grating to overcome the two drawbacks of the Fabry-Perot etalon, while still retaining its high resolution. The HyperFine Series of spectrometers is based on LightMachinery's VIPA⁶ technology. Figure 2 shows the principle of operation of a VIPA.

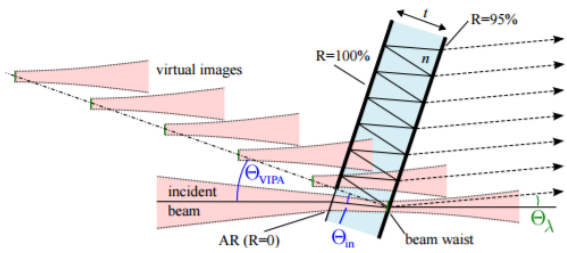


Figure 2: Principle of operation of a VIPA, which consists of two parallel reflecting surfaces (one ~100% reflective, one ~95% reflective). A cylindrical lens is used to focus the light into the VIPA through an anti-reflection coated slot in the R = 100% coating⁷.

Once light is focused into the tilted VIPA, it can only exit in the forward direction – through the 95% R surface (the 100% R surface does not allow any light to be reflected backwards). Hence, in principle, the VIPA allows all the incident light coupled into the VIPA to be imaged into the measurement system – a significant advantage over a conventional F-P etalon that typically reflects and wastes over 95% of the incident light.

In other respects, VIPAs and F-P etalons behave in a similar fashion, as illustrated in Figure 3.

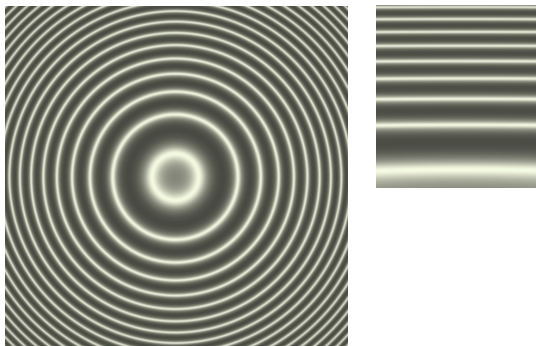


Figure 3: Typical light patterns for FP-etalons and VIPAs illuminated by a single wavelength of light. On the left is the pattern of light transmitted by an F-P etalon illuminated by the cone of light from a spherical lens. On the right is the light pattern transmitted by a VIPA illuminated by the same source and focused by a cylindrical lens.

In many respects, the light pattern transmitted by a VIPA is equivalent to a thin “slice” of the light pattern transmitted by the F-P etalon. Hence, a spectrometer based on a VIPA still faces the issue of overlapping orders as illustrated in Figure 4.

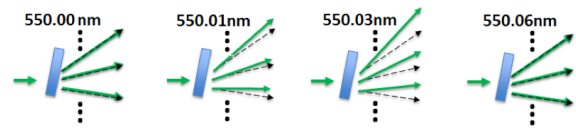


Figure 4: Three adjacent orders transmitted by a VIPA as the wavelength of the incident light is tuned in steps from 550.00 nm to 550.06 nm. Note that the VIPA cannot distinguish between light at 550.00 nm and 550.06 nm. The separation of these two wavelengths, 0.06 nm or 60 pm, is termed the Free Spectral Range (FSR) of the VIPA, and corresponds to a glass VIPA with a thickness of 1.68 mm⁶

Fortunately, for a VIPA illuminated using a cylindrical lens –as shown in Figure 2– the various orders and wavelengths are dispersed⁸ only in the vertical direction (unlike the F-P etalon, as illustrated in Figure 3). Hence, adding a cross-dispersing element that provides dispersion in the horizontal direction can separate the overlapping orders. The resolution in the horizontal direction needs only be sufficient enough to separate the adjacent orders. In the HyperFine spectrometer, the cross dispersion is provided by a reflective diffraction grating, as illustrated in Figure 5.

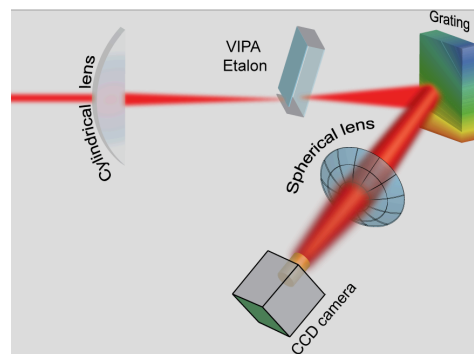


Figure 5: Schematic layout of the optical components in a HyperFine spectrometer⁹. The VIPA disperses the incident light in the vertical direction, providing a high resolution, but also overlapping orders. The grating separates the overlapping orders in the horizontal direction.

With the VIPA and grating providing dispersion in the vertical and horizontal directions respectively, a lens can be used to focus the different wavelengths onto the surface of a CMOS camera. The lens converts angles (in vertical and horizontal directions) into position on the CMOS array at the focus of the lens. Figure 6 illustrates the cross-dispersed spectrum as seen by the camera.

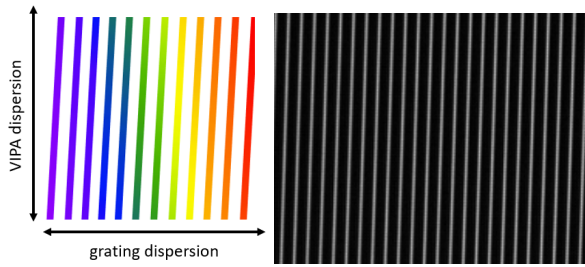


Figure 6: Schematic of the display expected at the CMOS camera when the crossed VIPA and grating are illuminated with broadband (“white”) light. In the vertical direction, the VIPA provides high resolution, but only for a range of one FSR. In the horizontal direction, the grating separates the overlapping orders to allow the entire high-resolution spectrum to be “unwrapped”. Thus, the vertical stripes are spaced by one FSR in the horizontal direction. In the chart, red represents longer wavelengths; blue shorter wavelengths. A typical screen shot from the camera is shown on the right. Only a small portion of the full CMOS sensor is shown, covering 23 FSRs of the VIPA horizontally, and 0.5 FSR vertically.

The LightMachinery HyperFine spectrometer combines high resolution (provided by the VIPA) with an extended measurement range (provided by the grating)¹⁰, and utilizes modern megapixel camera arrays together with custom software to provide unprecedented performance from a spectrometer of modest size and cost.

Recording and calibrating spectra with the HyperFine Spectrometer

Each HyperFine spectrometer ships with custom software that allows the user extensive control over the display, recording, and calibration of the spectra. At the most elementary level, the user has access to the raw output from the CMOS sensor, and can write their own software to analyze specific spectral records. Figure 7 shows examples of the raw sensor display for both broadband light and a monochromatic light source.

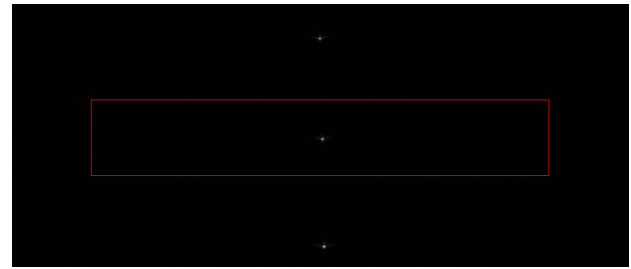
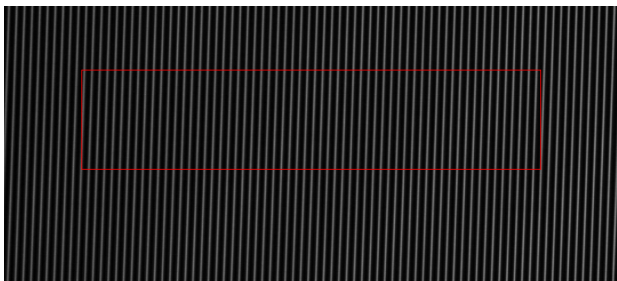


Figure 7: Typical CMOS sensor display when the HyperFine spectrometer is illuminated with broadband light (upper), and a narrow-line-width monochromatic laser (lower). The full spectrum can be extracted by “unwrapping” the information in the regions marked with a box.

Figure 7 (upper) is the same image as Figure 6, only zoomed out slightly. In the horizontal direction, the “stripes” of light are separated by one FSR of the VIPA. Figure 7 (lower) shows 3 separate intense spots of light in the vertical direction. Each spot represents a separate VIPA order, but each spot is formed by light of exactly the same wavelength (the wavelength of the monochromatic laser)¹¹. Thus, there is generally redundant spectral information in the vertical direction as the spectral features repeat in each spectral order. The full spectra can be extracted by “unwrapping” the information contained in the sensor region indicated by the boxes in Figure 7. The HyperFine software takes the information from images similar to Figure 7 and calibrates the entire CMOS sensor in both the horizontal and vertical directions in units of the VIPA FSR. The software then determines the range of “useful” pixels, and the procedure to be used in the “unwrapping” process.

In principle, if both the wavelength of the laser used to record Figure 7 (lower), and the *exact* FSR of the VIPA are known, the “unwrapped” spectrum can be calibrated in absolute wavelength. However, in general, it is more accurate to input a second known wavelength into the HyperFine spectrometer, and to use the positions of the two known wavelengths to calibrate the entire spectrum. The HyperFine software can utilize either approach, resulting in a spectrum that is calibrated to better than 5 pm over the entire wavelength range.

Sunlight is an ideal light source for demonstrating the performance of the HyperFine spectrometer. Sunlight is the original “white light” source, is inexpensive, and provides intense blackbody radiation from the UV to the IR. More than 40,000

discrete absorption lines (Fraunhofer lines)¹² are superimposed on the black-body background, and several of these lines have line widths of less than 10 pm^{13} . The Fraunhofer lines are distributed throughout the wavelength region from 270 nm to 1600 nm, and the spectral positions of the vast majority of the lines are accurately known. Figure 8 shows two raw CMOS images taken of dispersed sunlight in the HyperFine spectrometer.

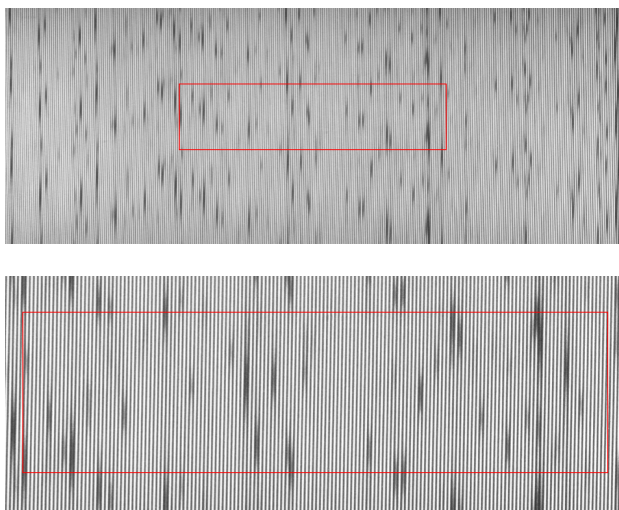


Figure 8: CMOS sensor images of sunlight taken with a HyperFine spectrometer. (The upper image covers the region from 527 to 547 nm, while the lower image covers a smaller spectral region from 532 to 541 nm). Multiple dark regions – each of which represents a Fraunhofer absorption line – interrupt the white light background of the sunlight. The red box in each image indicates one VIPA FSR in the vertical direction. The images were overexposed (i.e. highly saturated) for increased visibility.

The HyperFine software takes these images, unwraps the spectrum, calibrates the wavelength scale and produces output such as that shown in Figure 9.

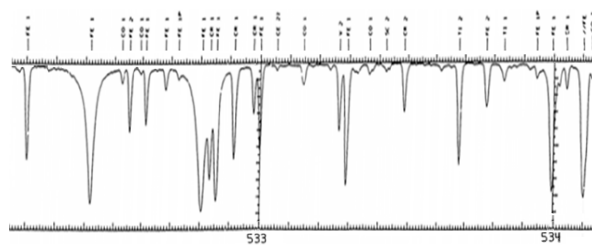
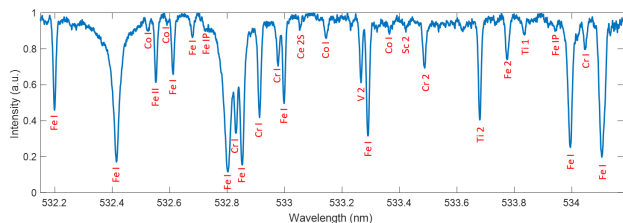


Figure 9: The upper trace shows the output from the HyperFine software once it has analyzed images such as those shown in Figure 8. The labels in red are the ionic species responsible for the individual absorption lines in the solar background, and the labels were added once the HyperFine spectrum was compared with a spectrum from the literature¹⁴.

Figures 8 and 9 illustrate the performance of the HyperFine spectrometer when it is illuminated with broadband light containing many spectral features. At the other extreme, many applications involve the investigation of light sources that are almost monochromatic, but require extremely high resolution (Brillouin and Raman spectroscopy, measurement of diode laser modes, etc.).

To demonstrate the performance of the HyperFine spectrometer with this type of light source, the input to the HyperFine spectrometer was illuminated with the output of a green He-Ne laser. This laser operates near 544 nm, and the narrow line-width of the gain medium is expected to support two or three longitudinal modes with a spacing of only 0.5 pm (corresponding to a 30-cm long laser). Figure 10 shows the extracted spectrum.

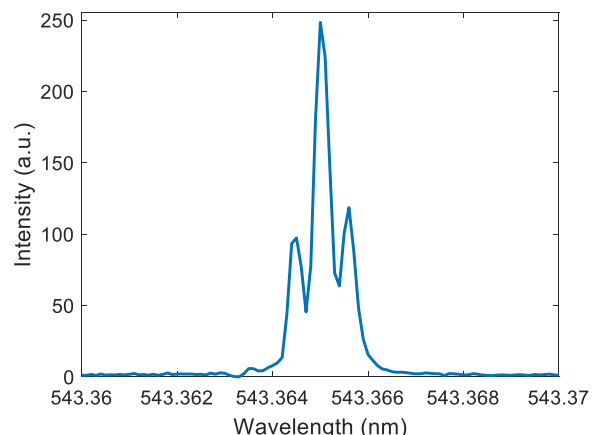


Figure 10: The extracted spectrum shows that the spectrometer can resolve longitudinal laser modes separated by only 0.5 pm (500 MHz or 0.17 cm^{-1}).

It is worth pointing out that the spectral resolution demonstrated in Figure 10 is equivalent to a resolving power of ~ 0.5 pm at a wavelength of 500 nm, or $R = \text{one million}$. Spectrometers with a resolving power this high are generally very large (>2 meters) and very expensive instruments ($> \$100,000$).

Additional information

This document is meant to provide an introduction to the principles of operation (and the software implementation) of the new line of LightMachinery high-resolution spectrometers. More detailed information on the operation of the spectrometers can be found in the manuals provided with the instruments, and additional examples of measured spectra can be found in companion documents¹⁵.

References and footnotes

1) If two wavelengths λ , and $\lambda + \Delta\lambda$, can just be separated (or resolved) by a spectrometer, the resolving power of the spectrometer, R is defined by:

$$R = \lambda / \Delta\lambda$$

Hence, a spectrometer operating at 500 nm with $R = 10,000$ can just separate two wavelengths that are spaced by 0.05 nm or 50 pm.

2) The link below provides a description of diffraction gratings:
<https://lightmachinery.com/optical-design-center/library/users-guides/grating-designer-users-guide/>

A calculator for diffraction gratings can be found at:
<https://lightmachinery.com/optical-design-center/more-optical-design-tools/grating-spectrometer-designer/>

3) The **f-number** of an optical system such as a lens is the ratio of the system's focal length to the diameter of the entrance pupil. It is a dimensionless **number** that is a quantitative measure of lens speed, and an important concept in photography and spectrometer design.

4) The link below provides an introduction to Fabry-Perot etalons:
https://en.wikipedia.org/wiki/Fabry-Pérot_interferometer

A calculator for F-P etalons can be found at the link below:
<https://lightmachinery.com/optical-design-center/etalon-designer/>

5) Reprinted from:
<http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/fabry.html>

6) A detailed description of VIPAs can be found at the link below:
<https://lightmachinery.com/optical-design-center/library/users-guides/vipa-designer-users-guide/>

A VIPA calculator can be found at the following link:
<https://lightmachinery.com/optical-design-center/more-optical-design-tools/vipa-designer/>

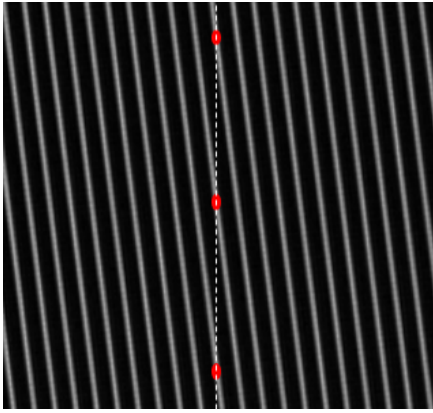
7) Reprinted from:
Metz, Philipp, et al. *Optics express* 21.3 (2013): 3324-3335

8) Prisms, gratings, and etalons all separate the incident light into its components by ensuring that different wavelengths emerge at different angles – this variation in angle with wavelength is called dispersion.

9) Reprinted from:
Van den Berg, Steven A., et al. *Scientific reports* 5 (2015): 14661.

10) The crossed-dispersion feature of the HF spectrometer is similar to that used in spectrometers based on echelle gratings. However, echelle-grating instruments with resolving powers comparable to the HF spectrometer are generally much larger and more expensive.

11) Each VIPA order is centered on a different “stripe”, as shown schematically below:



12) An introduction to the Fraunhofer lines can be found in the Wikipedia article:

https://en.wikipedia.org/wiki/Fraunhofer_lines

A more detailed description of the solar spectrum is given in a NASA presentation:

http://mark4sun.jpl.nasa.gov/report/UT_seminar_Solar_Spectrum_Toon.pdf

13) Line-widths of several of the stronger Fraunhofer lines are listed at:

<http://www.coseti.org/9006-025.htm>

14) Beckers, Jacques M., Charles A. Bridges, and Lou B. Gilliam. A High Resolution Spectral Atlas of the Solar Irradiance from 380 to 700 Nanometers. Volume 2. Graphical Form. No. AFGL-TR-76-0126 (II). AIR FORCE GEOPHYSICS LAB HANSCOM AFB MA, 1976.

15) Additional documents available from LightMachinery describe high-resolution spectra of Hg calibration lamps, solar radiation, picosecond lasers, and Brillouin scattering.