Resolving the magnetic hyperfine structure of Hg Isotopes using a VIPA grating spectrometer

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Introduction

LightMachinery's new series of high-resolution spectrometer – the HyperFine spectrometer – is its first to be built around a Virtual Imaged Phased-Array (VIPA) (1). To test the capabilities of the HyperFine spectrometer, we chose to measure the hyperfine magnetic structure of the Hg isotopes in mercury. The rationale behind our choice was threefold: 1) Mercury lamps are a common calibration source in most optical labs, allowing the experiment to be easily verified. 2) Traditional grating spectrometers capable of resolving the hyperfine lines of Hg isotopes are typically large (> 1 m in length) and expensive. 3) Spectra measurements of the resolved hyperfine structures of mercury lamps are readily available in literature.

Mercury has six naturally occurring isotopes (2), two of which show hyperfine splitting in their atomic emission lines (3; 4). Only by utilizing a spectrometer with a resolution greater than 1 picometer can the individual hyperfine peaks of these atomic emission lines be resolved.

Experiment

The experiment was performed in two parts. In the first, the hyperfine magnetic structure of the 546.1 nm line of the Hg source was measured with the HyperFine spectrometer. These measurements were then compared with two verified sources from literature to confirm their accuracy on the basis of wavelength position and relative intensity. The experiment also proved a good opportunity to determine how the HyperFine spectrometer's capabilities matched up against the complex and expensive laboratory-based spectroscopy setups (4; 5) used in the reference experiments.

In part two, measurements of the 577/579.1 nm doublet lines were taken with the HyperFine spectrometer and two traditional diffraction grating spectrometers classified as high resolution (Oriel model 260i, Ocean Optics HR 2000). Results from the spectrometers were compared with one another in terms of their spectral accuracy and ability to resolve individual isotope hyperfine peaks.

LightMachinery's HyperFine spectrometer was equipped with a 1.68 mm thick VIPA etalon paired with a diffraction grating. It obtained a typical resolution of 1 pm at 530 nm with a simultaneous measurement over a wavelength range of 15 nm (the range can be increased to 100 nm with grating rotation). A multimode fiber (MMF) optic port supplied the light input to the spectrometer's internal components.

Prior to the measurements, the HyperFine spectrometer was calibrated using a 532 nm monochromatic laser of precisely known wavelength. Measurements made with the monochromatic laser at 532 nm produced a FWHM of 1.0 pm (Figure 1), and a VIPA finesse of ~55.

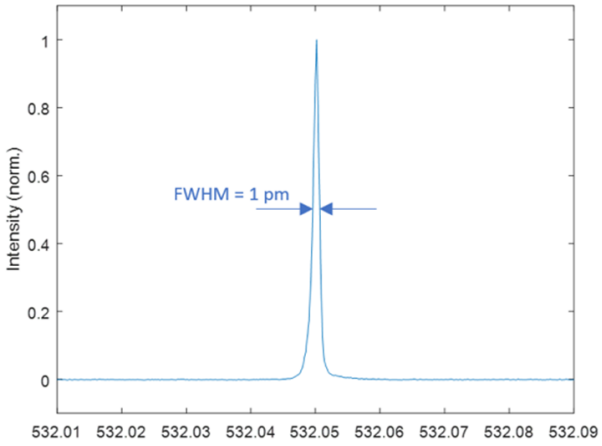

Figure 1: Second harmonic of a narrow-linewidth ytterbium-doped fiber laser demonstrating the resolution of the Hyperfine spectrometer. The 1 pm width is instrument-limited.

The Oriel spectrometer uses a traditional diffraction grating arrangement to achieve an optimum resolution of ~0.2 nm. The entrance collimating optics of F/3.9 (focal length of 220 mm) guide the light source into the 50 x 50 mm grating (1200 l/m). An adjustable entrance slit allows for fine tuning of the resolution down to a minimum of approximately 0.2 nm. The Ocean Optics spectrometer is considered a state-of-the-art fixed grating spectrometer with sub-nm resolution.

The Hg source was provided by an Ocean Optics spectral calibration lamp (5). The lamp was imaged directly onto the entrance slit of the Oriel spectrometer, while the HyperFine spectrometer and Ocean Optics HR2000 were supplied with a 125 μm fiber optic cable.

Results

When overlaid with measurements of the hyperfine structure of mercury – extracted from Doppler-free saturated absorption and frequency modulated spectroscopy measurements in ultralow pressure mercury cells – the HyperFine spectrometer's measurements show excellent agreement in both relative intensity and wavelength position (Figure 2). In addition, the satellite peaks of the Hg isotopes are clearly resolved and align precisely with the measurements from literature.

It is important to note that the wavelength calibration was carried out independently, and was not adjusted to match the hyperfine structure. We must also emphasize that the observed central line width of 5 pm is not instrument-limited; it is the true linewidth of the Hg-lamp source (this linewidth is due to Doppler broadening in the lamp).

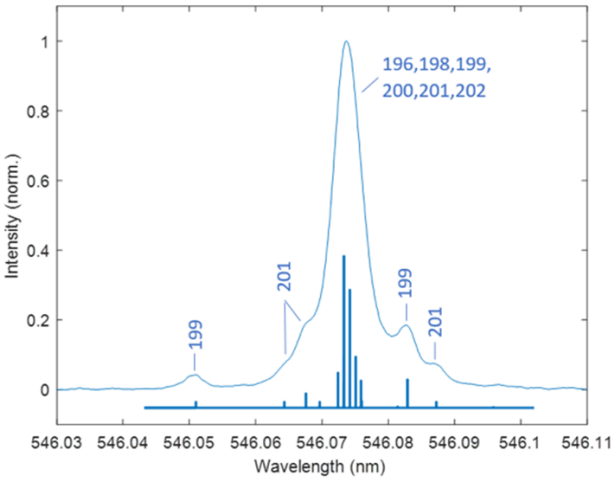

Figure 2: Hyperfine structure of the 546.1 nm line of mercury. The spectral width of the observed features is limited by the pressure of the mercury lamp. The dark blue lines underneath the spectrum measurement display the known hyperfine magnetic structure of mercury (4; 6). It should also be noted that the known hyperfine structure displayed underneath the HyperFine's spectrum is not an experimental curve; it is the set of extracted lines.

The 577/579.1 nm doublet line of mercury was measured with the Oriel spectrometer at several different slit sizes. From the spectra results (Figure 3), we can see that the stated resolution of 0.2 nm was achieved once the input slit was adjusted to the optimum width. While the 0.2 nm resolution is sufficient to resolve the 577/579.1 nm doublet line, the spectrometer's maximum resolution falls far short of that required to differentiate the individual hyperfine structures of the Hg isotopes.

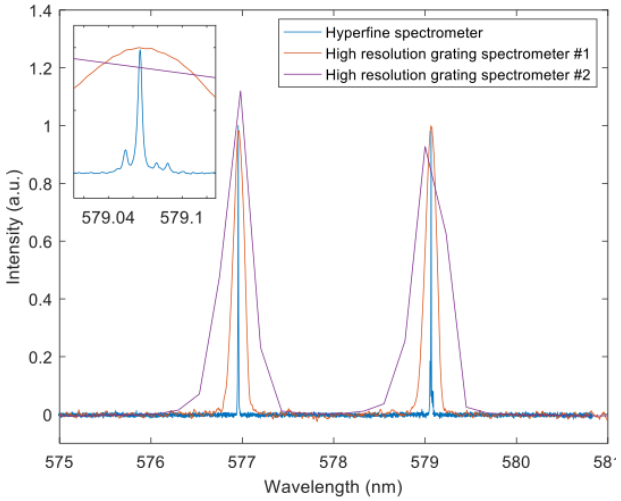

Figure 3: Comparison of the 577/579 nm mercury doublet measured using the HyperFine spectrometer and two standard grating spectrometers categorized as high-resolution. The slit and grating settings of high-resolution grating spectrometer #1 (Oriel, 260i) were adjusted to provide the optimal resolution specified for that model, namely ~0.2 nm (we obtained 0.15 nm here). The settings of high-resolution grating spectrometer #2 (Ocean Optics, HR2000) were fixed by the manufacturer and its resolution was found to be ~0.7 nm.

Despite the natural linewidth of the mercury lamp, which is ~5 times broader than the HyperFine's resolution, the difference between the spectrometers measurements is striking. The HyperFine spectrometer was able to obtain much narrower lines, with the resolution difference becoming most apparent in the magnified view of the of the 579 nm line (Figure 3 inset). The HyperFine spectrometer was the only instrument capable of rendering any definable hyperfine structures.

Conclusions

The HyperFine spectrometer clearly defined the individual hyperfine structures of the Hg lamp at the 546.1 nm line and 577/579 nm doublet; confirming its ability to obtain 1 pm resolution with an accuracy greater than 2 pm.

References

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