Improved Monochromatic Imaging Spectrometer

MICHAEL R. WEBB and GARY M. HIEFTJE*

Department of Chemistry, Indiana University, Bloomington, Indiana 47405

Distortion inherent to a previously described system for acquisition of two-dimensional monochromatic spatial images is described. A solution is offered in the form of an improved instrument. The system uses a Czerny–Turner monochromator for spectral discrimination and a charge-coupled device (CCD) as the detector. A second Czerny–Turner monochromator, with identical dimensions, is added to correct the distortion, albeit with a slight loss in spatial resolution. With the earlier uncorrected arrangement, spatial resolution was on the order of 0.1 mm vertically and 0.3 mm horizontally, with a magnification of 0.52. With the same magnification, the new, corrected system offers spatial resolution of 0.1 mm vertically and 0.4 mm horizontally.

Index Headings: **Monochromatic imaging; Imaging spectroscopy; Image correction.**

INTRODUCTION

Spatial resolution in optical spectroscopic measurements can be valuable in the observation and characterization of heterogeneous samples and sources. For example, it has long been known that sources for atomic spectroscopy—including flames, inductively coupled plasmas, microwave plasmas, and glow discharges—exhibit such heterogeneity.[1–18]

A number of approaches have been used to obtain spatial resolution with optical probes. Point-by-point measurements can be made with relatively simple, sensitive, and inexpensive instrumentation. However, the time required to complete such a process is long when a large number of points must be investigated. For example, interrogating an array of 100 × 100 points with a 1-s integration time would require 2.8 h if done in this fashion, not including the time taken to move from point to point. Long acquisition times prohibit the measurement of transient phenomena. Systems using interference filters in conjunction with two-dimensional imaging detectors are another approach to acquire data in two dimensions, and with greatly reduced acquisition times, but this requires different filters for each spectral line or band and is limited by the spectral bandpass in some applications. Other techniques are available for spatial resolution, each with its own advantages and disadvantages.

The monochromatic imaging spectrometer (MIS) introduced by Olesik and Hieftje[19] uses a monochromator for spectral discrimination and a two-dimensional vidicon for detection, giving a monochromatic two-dimensional image. A later version of this instrument uses a charge-coupled device (CCD) for detection. It has been used to examine inductively coupled plasmas (ICP)[8–12,14–18] and glow discharges.[13] It has been used both to study the fundamental properties and processes of plasmas[8,10,11,13,14,16–18] and to optimize the performance of plasmas.[9,12,15]

In the MIS described by Olesik and Hieftje,[19] displayed schematically in Fig. 1, the image of the source is spatially scrambled at the entrance slit of the monochromator and is reconstructed after passing through the exit slit. This is accomplished by placing the source at the focal length f_{L1} of a lens L1 placed as close as practicable to the entrance slit S1, making that slit serve as an aperture stop. Light from the source is therefore collimated before passing through the slit. This has the effect of performing a spatial Fourier transform on the image. This scrambled image is then reformed within the monochromator. In the simplest situation, the distance from M1 (usually the collimating mirror of the monochromator) to the grating is equal to the focal length of M1. In this case, an image of the source is formed on the grating. The image is re-collimated by M2 (the focusing mirror of the monochromator) before passing through the exit slit. Outside the monochromator, a second lens L2 reforms the image of the source at its focal point, where the detector is placed. This refocusing process has the effect of performing an inverse spatial Fourier transform.

The spectral bandpass of this system is controlled by the widths of the entrance and exit slits, by the grating angle and groove spacing, and by the focal length of the monochromator. Because the image exists in Fourier space while passing through the entrance and exit slits of the monochromator, the image size is not restricted by the slit widths. Instead, narrowing the slits has an effect analogous to the degraded spectral resolution caused by shortening the distance the mirror travels in a Michelson interferometer. In the case of the MIS, it is the spatial resolution that is degraded, but only in the direction of the slit width (i.e. the horizontal direction in a typical arrangement). The spatial resolution is also determined by the optics outside the monochromator, the detector, and the fidelity of the entire optical system.

Olesik and Hieftje[19] discussed several effects that must be considered in the design of the MIS. Care must be taken to identify limiting apertures. For example, the intermediate image on the grating cannot be larger than the grating itself. The effective width of the grating perpendicular to the optical path will vary with grating angle. In the system used in the present study, the distance between M1 and the grating is approximately 34 cm, slightly shorter than the 35-cm focal length of mirror M1. As a result, the light exiting the monochromator is not truly collimated. When the light is not collimated at the slits of the monochromator, vignetting effects can occur. Vignetting by the slits can be minimized by placing the external lenses as close to the slits as is practicable. Also, a field-limiting effect can occur if the aperture of L1 is imaged near the intermediate or final source image. This effect is minimized by placing L1 as close as possible to the entrance slit. Aberrations due to the monochromator and external optics must also be considered. Most notably, the distances between the source and the collimating lens and the focusing lens and the detector must be adjusted for each significant change in wavelength to compensate for chromatic aberration (the wavelength dependence of f_{L1} and f_{L2}). Ideally, this is done

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* Author to whom correspondence should be sent. E-mail: hieftje@indiana.edu.

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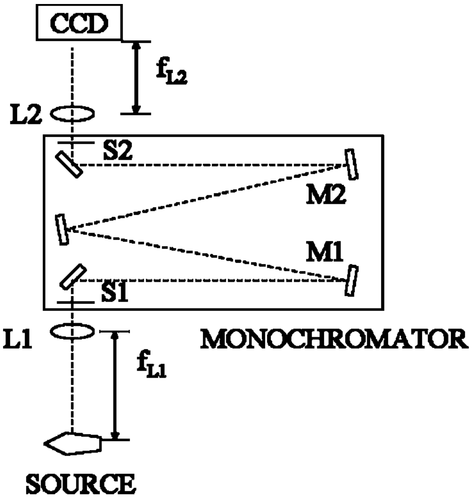

FIG. 1. Monochromatic imaging spectrometer of Olesik and Hieftje:[19] L1, collimating lens; f_{L1}, focal length of lens L1; S1, entrance slit; M1, M2, concave mirrors; G, grating; S2, exit slit; L2 focusing lens; f_{L2}, focal length of lens L2.

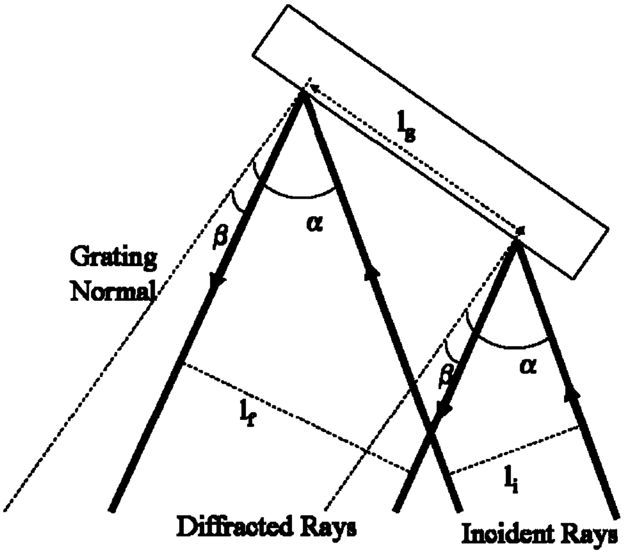

FIG. 2. Two parallel rays diffracting from a grating: α, incident angle; l_i, initial separation of rays; l_g, separation of rays on the grating surface; β, angle of diffraction; l_f, final separation of rays.

by moving the source and detector rather than the lenses so that the aforementioned field-limiting effect can be avoided.

A drawback of the MIS that has not been fully considered is that the final reconstructed image width varies with wavelength. In fact, to our knowledge, the reason for this effect has not been described in the literature. It is a consequence of the fact that the angle of incidence on the grating is different from the angle of diffraction (shown in Fig. 2). Analogously, a circular light projected onto a wall at a 45-degree angle would appear stretched out into an ellipse if it were viewed by someone at an angle perpendicular to the wall. Light forming a line of horizontal length l_i strikes the grating at an angle α, relative to the grating normal. It will cover a length l_g on the grating. The length l_g can be calculated from α and l_i by trigonometry:

$$l_g = l_i \cos\alpha \tag{1}$$

The light then diffracts from the grating at an angle β, resulting in a line reduced to a length l_f. From trigonometry, it is found that

$$l_f = l_g/\cos\beta \tag{2}$$

Combining these equations produces the result

$$l_f = l_i \cos\alpha/\cos\beta \tag{3}$$

This demonstrates that the horizontal dimension varies with the angles of incidence and diffraction.

This distortion can be corrected mathematically; however, the wavelength dependence of the effect complicates this option. Another option is to use an instrumental approach. This approach uses a second monochromator (shown in Fig. 3). If the subscript 1 is used to refer to the first monochromator and the subscript 2 is used to refer to the second, we have the following two equations:

$$l_{f,1} = l_{i,1} \cos\alpha_1/\cos\beta_1 \tag{4}$$

$$l_{f,2} = l_{i,2} \cos\alpha_2/\cos\beta_2 \tag{5}$$

Because the light exiting the first monochromator is the same as the light entering the second monochromator, $l_{f,1} = l_{i,2}$. Using this equivalence to combine the equations, we find:

$$l_{f,2} = l_{i,1}(\cos\alpha_1/\cos\beta_1)(\cos\alpha_2/\cos\beta_2) \tag{6}$$

In the case where $\alpha_1 = \beta_2$ and $\alpha_2 = \beta_1$, the equation reduces to:

$$l_{f,2} = l_{i,1} \tag{7}$$

The grating formula[20]

$$d(\sin\alpha + \sin\beta) = m\lambda \tag{8}$$

shows that doing this does not change the wavelength selected by the monochromator.

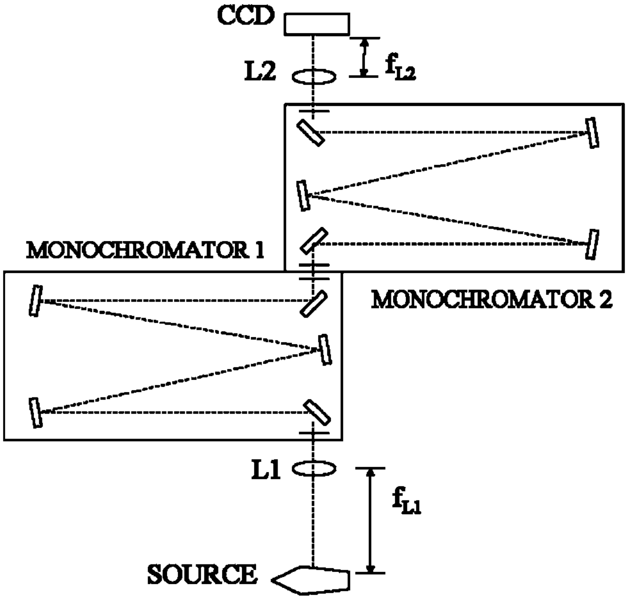

FIG. 3. Corrected monochromatic imaging spectrometer: L1, collimating lens; f_{L1}, focal length of lens L1; L2, focusing lens; f_{L2}, focal length of lens L2.

EXPERIMENTAL

For spectral resolution, a McPherson (Model 270) 0.35-m Czerny–Turner monochromator was used with a 1200 grooves/mm grating. For spatial correction, a Heath (Model EU-700) 0.35-m Czerny–Turner monochromator was used with a 1200 grooves/mm grating. These two units are nominally the same, although purchased at different times. Light from the source was collimated by a 25-cm focal length, plano-convex, fused-silica lens. Light passing through the monochromator was re-imaged by a 15-cm focal length, plano-convex, fused-silica lens onto the detector. A Photometrics CH315/A CCD was used as the detector. The acquisition time was adjusted depending on the desired sensitivity. A 1951 USAF glass-slide resolution target (Edmund Optics), backlit by a tungsten lamp, was used to characterize the system. The target was positioned at a distance from L1 approximately equal to the focal length of L1. L2 was positioned at a distance from the CCD approximately equal to the focal length of L2. The positions of the target and L2 were both then adjusted for best spatial resolution. The slit widths of the first monochromator were set depending on the desired spectral resolution. The slit heights were 12 mm. The slits of the second monochromator were removed, resulting in a circular aperture 12 mm in diameter.

RESULTS AND DISCUSSION

As would be expected, care must be taken in positioning the second monochromator. In the system used here, the exit slit of the first monochromator could not be placed exactly at the entrance slit to the second monochromator because both slits were recessed. Instead, the entrance slit to the second monochromator had to be placed approximately 5 centimeters further along the light path. The combination of slits from the monochromators resulted in a field stop. The field stop was widened when the slits of either monochromator were opened, so it was decided to remove the slits of the second monochromator altogether. This procedure effectively made the field stop larger than the field stop created by the grating. Further, when the two monochromators are not on the same horizontal plane, ghost images arise, placing an additional constraint on spatial resolution. Resolution is also adversely affected if the grating angles are not equal. Given the extremely large size of the slits in the second monochromator, the most significant light loss should be due to incomplete transmission by the second monochromator's optics and particularly the grating.

The magnification of the system is controlled by the collimating and imaging optics. For this system, the magnification was experimentally measured to be approximately 0.52. The spatial resolution of the instrument was derived from measurements obtained using the 1951 USAF target. The target test pattern consisted of groupings of three equal lines spaced by a distance equal to their width. Resolution was judged based on the smallest-width lines that could be resolved with valley intensities of 50% or less peak intensity. The precision in this measurement is limited by the available sizes of line pairs. The detector-limited resolution is the case where the line width is the same as the pixel width (and a line pair width is equal to two pixels). At this magnification, given that the pixels are 24 μm wide, the detector-limited resolution is 10.9 line pairs/mm. For the single-monochromator system with 1-mm slit widths, 8.00 line pairs/mm were resolved vertically and 3.17 line pairs/mm were resolved horizontally. For the single-monochromator system with 2 mm slit widths, 8.00 line pairs/mm were resolved vertically, and 4.00 line pairs/mm were resolved horizontally at the same wavelength. For the system using a second monochromator for correction, the resolution was degraded somewhat. With 1 mm slit widths, 8.00 line pairs/mm were resolved vertically but only 2.52 line pairs/mm were resolved horizontally. With 2 mm slit widths, 8.00 line pairs/mm were resolved vertically and 2.83 line pairs/mm were resolved horizontally. Although the reason for the loss of resolution is not entirely clear, it is likely from a cumulative effect of slight misalignments, the occurrence of which is likely to be increased with additional components. In particular, there is an inherent mismatch between the focusing and collimating mirrors' focal lengths and the distances between those mirrors and the gratings. Adding a second monochromator likely compounds any problems.

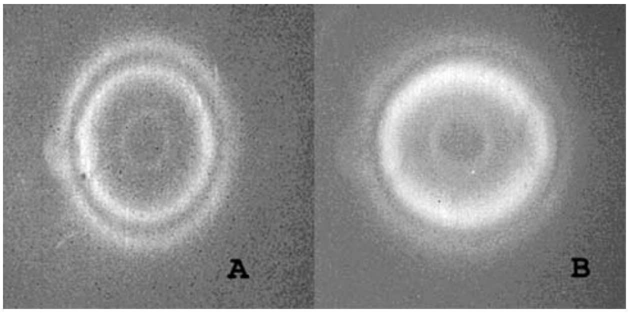

FIG. 4. Images of a circular hollow cathode lamp acquired with (**A**) the single-monochromator MIS and (**B**) the double-monochromator MIS.

The distortion caused by the grating can be seen in Fig. 4. The distortion caused by the grating angle was also determined from the target images. The distance between the centers of the first and third lines in the 1 line pair/mm grouping was measured in both the horizontal and vertical directions. The ratio of horizontal to vertical distance was then calculated. For the single-monochromator system, at a wavelength of 400 nm, the ratio was 1.17. At 500 nm, it was 1.23. At 600 nm, it was 1.29. At 700 nm, it was 1.36. The precision of these measurements was on the order of 0.02 (limited by the finite size of the pixels). The same procedure was performed to determine the effect of adding the second monochromator. For all wavelengths, the ratio was between 1.00 and 1.01, indicating that the distortion was corrected. These distortions provide an opportunity to check the theorized origin of the distortion. Realizing that the angle between the light striking the grating and the light leaving the grating is fixed (it must equal the angle formed by the two mirrors and the grating), it can be surmised that the difference between α and β must also be fixed. For this to be true, it is important that one of the angles be represented as negative and the other as positive when they are on opposite sides of the grating normal but that they both be given the same sign when on the same side of the angle. Using the grating formula (Eq. 8), Eq. 3, and certain parameters of the monochromator (for the monochromators used in this work, the fixed angle was approximately 35.4° and the groove spacing (d) is 833.3 nm/groove), the distortion of the horizontal direction could be predicted. The agreement between the results of this calculation and the measured skew was excellent. The ratio l_f/l_i was predicted to be 1.18 at 400 nm, 1.24 at 500 nm, 1.30 at 600 nm, and 1.37 at 700 nm.

The spectral resolution of the system was verified using the Ca 422.7 nm line from a hollow cathode lamp. The manufacturer's stated reciprocal dispersion is 2.0 nm per mm at the exit slit. With 1-mm slit widths, the full-width at half-maximum of the line was measured as 2.0 nm, in good agreement with the manufacturer's specifications.

CONCLUSION

The MIS can provide high quality spectrally resolved two-dimensional images. However, it introduces a grating-angle-dependent distortion. This distortion results in a change in the width of an image with wavelength. A simple arrangement that adds a second monochromator corrects for this effect, although some spatial resolution is lost. The residual resolution is sufficient for many tasks. Presumably, a similar arrangement would compensate for any similar effect in the slitless spectrograph of the type used by Olesik and Hieftje.[19]

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