A modified Seya–Namioka monochromator with improved light intensity transfer

Anthony M. Maletta and Philip M. Johnson

Department of Chemistry, State University of New York, Stony Brook, New York 11794

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A monochromator with improved focusing properties has been designed and constructed using a novel optical geometry based on the Seya–Namioka concept. The only optical elements used are a spherical grating and a cylindrical mirror mounted in the exit arm (within the Rowland circle), retaining the Seya–Namioka scanning simplicity while minimizing reflections. This optical system compensates for the astigmatism associated with spherical optics at large incidence angles (as in the Seya–Namioka geometry) shortening the effective vertical focal length and providing a single, tight focus. A method of constructing a similar apparatus for any given spherical grating is presented. Experiments involving constructing coherent vacuum ultraviolet generation from harmonic mixing demonstrate the utility of the new design. © 2000 American Institute of Physics.

INTRODUCTION

The Seya–Namioka monochromator has been employed in vacuum ultraviolet (VUV) research because of its simple design.1 Due to the small reflectance of optics in the VUV it is usually best to minimize the number of reflections. In the case of the Seya–Namioka design, using one spherical grating in a fixed 70.25° geometry, wavelength tuning is achieved by simply rotating the grating about an axis perpendicular to the plane of incidence. The geometry is fixed so there is no translation of the grating or telescoping of entrance and exit arms while scanning wavelengths.2-3 It is a very convenient design mechanically, and it provides moderately high wavelength resolution using linear entrance and exit slits. However, due to the off-axis reflection from the spherical grating, the vertical and horizontal foci do not appear in the same place, and a point source at the entrance slit is imaged to a line at the exit slit. This is not a disadvantage for an extended light source and a large area detector. However, for a light beam with high brightness such as from a laser or synchrotron, the loss of focus is significant in reducing the transfer of the light intensity. In the past, the astigmatism has been corrected by nonspherical optics or multiple cylindrical optics before and after the slits.4-6 Instruments have been constructed using pre- and postfocusing mirrors of toroidal,5,7 cylindrical,4-6 spherical,8 and ellipsoidal8 shapes to control aberration and create optimized spectral images. Alternately, a toroidal grating can be used to force the foci to be coincident.9,10 Pre- and postfocusing mirrors present various disadvantages, and toroidal gratings are expensive, so a new scheme was developed to enable a compact but efficient design using a spherical grating. This new design places a cylindrical mirror inside the Rowland circle, in the exit arm, and provides for a very efficient intensity transfer while minimizing the expense and the number of reflections. An additional benefit is that it allows flexibility in the overall deviation angle of the monochromator, an important consideration when joining the monochromator to other bulky vacuum systems.

In our particular application, the focus of a laser generating VUV via four wave mixing serves as the entrance aperture, while the experimental sample occupies the exit focus. By design, the Seya–Namioka monochromator gives an image that will not move as the grating is rotated synchronously with the changing input wavelength. In a harmonic generation application, wavelengths to be rejected (the laser fundamentals) are very far from the VUV of interest, so resolution is not a primary concern. However, the output focus size must be at a minimum in order to enhance overlap when using techniques which require other coincident laser beams. The present design, where all the optics are compactly contained and provide a tight focus, is very convenient. It is also advantageous to have the ability to cause the light to be deviated at the 90° angle typical of most laser optical elements, and to have the large amount of working room provided by that angle.

MONOCHROMATOR DESIGN

The present monochromator has been designed around a spherical grating and a plano-concave cylindrical lens (coated to act as a cylindrical mirror). The 1 m radius grating has a blaze wavelength of 123.5 nm at 35.13° and a blaze angle of 2.58°. The cylindrical lens (Melles Griot, f = 300 mm, r = 155 mm) was coated by Acton Research Corporation with aluminum and protected by magnesium fluoride (ARC coating No. 1200).

The grating is fixed to a turntable inside a stainless steel vacuum chamber. Wavelength scanning is accomplished via a sine-bar drive with a stepper motor-driven precision screw mounted below the chamber. The entrance arm is capped with a stainless steel butterfly valve that acts as a 12 mm aperture when fully opened. The VUV generation cell (static gas cell) is mounted below the butterfly valve, and a focus of the laser light entering the monochromator acts as the en-
trance aperture. The exit arm is attached in sections to allow for the custom aluminum cylindrical mirror housing. The mirror housing and a butterfly valve are mounted about midway between the grating and the exit focus. The mirror is attached to a commercial mount, which has been modified to allow adjustment from outside of the vacuum. A 10 mm exit aperture is mounted 50.8 mm before the exit focus to provide rough blocking of unwanted dispersed wavelengths. For higher resolution work this would be smaller and placed at the exit focus. The monochromator chamber, with arms attached, is kept at a pressure of $3.3 \times 10^{-6}$ Pa with a turbo-molecular pump (Balzers model TMU 520). All optical elements are mounted in the same horizontal plane. The monochromator, attached to the molecular beam apparatus, is shown in Fig. 1.

In the Seya–Namioka (SN) geometry, the astigmatism caused by the 70° reflection from the spherical grating causes the vertical and horizontal exit foci to be very far apart. Using simple first-order optical calculations, a cylindrical mirror was introduced into a standard Seya–Namioka geometry to pull in the vertical focus of the spherical grating while leaving the horizontal focus at the standard location, see Fig. 2. The mirror resides approximately midway in the exit arm of the monochromator, making the foci coincide, such that using a point entrance source, a single, round, tight focus is created at the Seya–Namioka distance.

Since the horizontal focus of the spherical grating is not affected by the cylindrical mirror, the analysis of the optics can be restricted to the vertical coordinate. The effective focal length of a spherical (or cylindrical) mirror changes with the angle of incidence according to the formula:

$$f_{\text{eff}} = \frac{R}{2 \cos \Phi},$$

where $R$ is the radius of the spherical optic and $\Phi$ is the angle of incidence. The input Seya–Namioka aperture (located at 0.817$R$, where $R$ is the radius of the grating) is not at a vertical focus symmetry point of the grating. If one uses that as an input focus, the vertical focus appears [using Eq. (1) and the SN angle] at 2.447$R$ on the exit side. When a cylindrical mirror is placed in the exit arm, its focusing properties are determined by its focal length, its angle of incidence, and its longitudinal position in the arm. Since the former two properties are determined by the commercial availability of appropriate optical elements (cylindrical lens or mirror) and experimental design, the vertical and horizontal foci, are made to coincide by adjusting the longitudinal position.

The location of the cylindrical mirror in the exit arm is established by using Eq. (1) and applying the thin lens formula twice, first to determine the effective focal length of the grating’s vertical focus and then to determine the grating to mirror distance for a given exit focal point. Assuming a 35.13° incidence angle at the grating (the Seya–Namioka geometry) and equal arm lengths, a general formula can be derived which can be solved for the grating to mirror distance $d_m$:

$$d_m^2 - 3.2631Rd_m + 1.6315R(R/0.8166 - r_m/2 \cos \varphi) = 0. \quad (2)$$

Here, $R$ is the radius of the grating element, $r_m$ is the radius of the cylindrical mirror, and $\varphi$ is the incident angle of the light on the cylindrical mirror. The optical geometry is shown in Fig. 2. It should be noted that since the arm lengths were assumed to be fixed and equivalent, Eq. (2) will only work for a 70.25° angle. Other angles require motion of the arms or grating to stay consistent with the Rowland circle while tuning the wavelength.

We chose to have the total deviation angle of the monochromator to be 90° in order to allow the insertion and removal of the monochromator without reorienting our lasers. Most laser optical elements are designed for a 90° angle, so modularity encourages this angle. An additional advantage of this geometry is that the low-angle 20° reflection from the cylindrical mirror allows for higher reflectivity.
The monochromator optics were bench tested for intensity transfer using a helium–neon laser (632.8 nm). On the entrance side, the laser was focused through a 100 μm aperture placed at the Seya–Namioka distance. On the exit side the light again passed through a 100 μm aperture mounted in an xyz stage and was recorded on a detector. By moving the exit aperture, the overall size of the approximately circular exit focus was determined to be 240 μm. However, much of the intensity is at the center, and by comparing the light intensity with and without the aperture, it was determined that 80% of the light reflected in zero order passed through the 100 μm aperture at its optimum position. Since the grating is blazed at 123.5 nm, a meaningful absolute efficiency could not be measured at the HeNe wavelength. While we have not performed detailed testing of the wavelength resolution of this design, this apparatus produces an image with a shape and intensity distribution comparable to that obtained by Chang et al. for a Seya–Namioka system with spherical pre- and postfocusing mirrors designed for the Synchrotron Radiation Research Center (Taipei, Taiwan).8

This design has some elements in common with that of Rehfeld et al.,5 who used two cylindrical mirrors symmetrically placed outside of the normal Seya–Namioka slits. The first of these takes light at 1.224R and refocuses it horizontally at the input slit. The second horizontally refocuses the exit light onto the natural vertical focus at the same exit distance. This also allows a flexible geometry, and has been used in several synchrotron applications.5,6,8 However, it uses one more mirror than the present design and the input mirror is a disadvantage in high power laser experiments, since it can be easily damaged by the radiation intensity.

An alternative design, which would have only a single cylindrical mirror outside the Rowland circle, could place the cylindrical mirror after the normal exit slit position to refocus the light horizontally to the natural vertical focus of 2.424R (when the input focus is at 0.817R). This could be a cumbersome distance when large radius gratings are used, but may be the desired method for a short radius grating (when there may be little room to place a mirror inside the Rowland circle) or when it is desired to use an existing Seya–Namioka monochromator without substantial modification. We have not tested this alternative.

RESULTS

The experimental apparatus used to demonstrate the utility of the new design in harmonic generation experiments, as shown in Fig. 1, employs two Quantel Nd:yttrium–aluminum–garnet (YAG) lasers pumping Quantel TDL50 dye lasers (synchronously pulsed at 10 Hz) to produce scannable VUV in an inert gas cell filled with krypton (77 Torr). The output of the first dye laser is mixed with the Nd:YAG fundamental (1064 nm) and doubled to produce 216.666 nm light which excites a two photon resonance in krypton. This light is brought together with the output of the second dye laser (the "difference photon") in the VUV cell. The second dye laser can then be scanned to produce VUV light over a range of wavelengths (for Fig. 3, only 135 nm was generated). The VUV light is then separated from the laser input wavelengths by the modified Seya–Namioka monochromator and finally interacts with the sample. The details of the rest of the instrument, which is essentially a standard time-of-flight (TOF) mass spectrometer, are reported elsewhere.12

In addition to the obvious function of separating out fundamental laser wavelengths, the monochromator also serves to refocus the VUV light into the sample. The focus size is important for two reasons: (a) The mass resolution of a TOF mass spectrometer is sensitive to the spread in initial ion positions, and (b) other laser beams are often overlapped with the VUV beam in the sample. Minimal astigmatism is therefore a necessity.

Molecules in Rydberg states are created and analyzed with this system using VUV light, carefully timed ionizing electric fields, and pulsed lasers. This new design will allow the application of VUV light generated by resonant four wave mixing13 and resonant third order frequency conversion13 to the spectroscopy of molecular and atomic species, which are very sensitive to the fundamental laser wavelengths used for VUV generation. We are currently investigating the spectroscopy and Rydberg physics of molecules and clusters using the mass analyzed threshold ionization14 and photoinduced Rydberg ionization15 techniques. Some previous attempts at such experiments proved very difficult, if not impossible, in the presence of the "extra" photons admitted via VUV generation, which may cause interfering dissociation or ionization.

As a test gas, trans-butene was admitted into the ionization region via a pulsed nozzle at 10 Hz from a backing pressure of 35 psi (He carrier gas). Our butene sample, as acquired from Matheson, is 95% trans-2-butene. The remaining 5% (impurities) consists of an unknown mixture of cis-2-butene [ionization potential (I.P. = 9.11 eV), butane (10.53 eV), propane (10.94 eV), and propylene (9.73 eV)].

In the past, VUV light (135 nm, 9.18 eV) as well as considerable residual light at 433.3, 216.66, and 534.9 nm was focused through a 64 mm MgF2 lens into the sample molecular beam. The VUV light was tunable with this setup but the light interacting with the sample was far from monochromatic. The effects of the residual photons focused on the sample are unpredictable, causing considerable wavelength independent multiphoton ionization, among other processes.

The TOF traces from the apparatus are shown in Fig. 3. Comparing Figs. 3(a) and 3(b), the interfering effects of the unwanted, collinear photons are revealed. Figure 3(a) shows the TOF mass trace of t-butene acquired without the monochromator. The main effect of the stray light appears as a continuous background signal from residual gases in the vacuum ionized by the laser fundamentals. Here, the signal from our target molecule (the monomer and multiple van der Waals clusters) is much larger than the baseline noise, but some of this is not due to the VUV. If one inspects the baseline, peaks appears that may be assigned to the fragmented contaminants in our sample or from ambient pump oil. The stray light focused into the sample region is of the right frequency to cause absorption, ionization, and fragmentation of these contaminants. Since many experiments involve searching for additional small peaks, the presence of these additional fragment peaks is a great disadvantage.
Close examination reveals that the width of the largest sample peak full width at half maximum averages about four TOF channels.

The advantages of using the monochromator are clear when one examines the TOF mass trace shown in Fig. 3(b). In this trace the baseline is essentially flat. The experiment employs only light just higher in energy than the ionization threshold of trans-butene (9.127 eV). Species of higher I.P. are not ionized, and those of lower potential are not fragmented, resulting in a cleaner trace. The fragmentation peaks are gone and only the peaks that correspond to the target molecule remain. The width of the sample peak here is about 2 TOF channels.

These TOF traces clearly show that the monochromator provides both a reduction in background signal and better mass resolution. The latter indicates that the focusing properties of the monochromator are better than those of the previously used lens. This is probably because of the difficulty in keeping the lens positioned, due to the chromaticity of the lens.

The relatively compact nature of the new optical system, coupled with the fixed geometry of the Seya-Namioka design, enables the monochromator to serve as an easily detachable module in the molecular beam apparatus. One could envision modifications based on our design to make this geometry useful in surface studies and spectroscopy in the laboratory as well as at synchrotron facilities. The right angle geometry allows the chamber and lasers to remain in the same orientation when switching from one experimental arrangement to the next. The valve system allows removal of the monochromator system while leaving it under high vacuum ($2.5 \times 10^{-8}$ Torr, $3.3 \times 10^{-6}$ Pa). Inserting a cylindrical mirror in the exit arm of the Seya-Namioka monochromator thus improves the quality of the exit focus while allowing a convenient geometrical relationship in a relatively simple, modular, and inexpensive design. Experimental results were improved while maintaining the ability to adapt our system to a variety of useful spectroscopic techniques.

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