COMPUTATIONAL AND EXPERIMENTAL INVESTIGATIONS ON A TUNEABLE SPATIAL HETERODYNE SPECTROMETER

Dávid Jenő Palásti[1,2], **Miklós Veres**[3], **Miklós Füle**[4,5], **Zsolt Geretovszky**[2,6], **Gábor Galbács**[1,2*]

[1]Department of Inorganic and Analytical Chemistry, University of Szeged, H-6720 Szeged, Dóm tér 7, Hungary
[2]Department of Materials Science, Interdisciplinary Excellence Centre, University of Szeged, 6720 Szeged, Dugonics sq. 13, Hungary
[3]Department of Applied and Nonlinear Optics, Wigner Research Institute for Physics, H-1121 Budapest, Konkoly-Thege Miklós út 29-33, Hungary
[4]Faculty of Engineering, University of Szeged, H-6724 Szeged, Mars square 7, Hungary
[5]ELI-ALPS Laser Research Institute, H-6728 Szeged, Wolfgang Sandner street 3, Hungary
[6]Department of Optics and Quantum Electronics, University of Szeged, H-6720 Szeged, Dóm tér 9, Hungary
e-mail: galbx@chem.u-szeged.hu

Abstract

Spatial heterodyne spectrometers (SHS) are interference based instruments for obtaining spectroscopic information in the UV and visible ranges. In this current study we are representing our experimental and computational findings about a tuneable SHS instrument.

Introduction

Although SHS concept was first described in the 1960s and 1970s [1], but the practical applications of this type of spectrometers only came in the early 1990s, when Harlender et al. demonstrated its potential in high resolution spectroscopic observation of faint, distant objects in astronomy [2]. Recently we built and used an SHS spectrometer for qualitative and quantitative Raman spectroscopy [3].

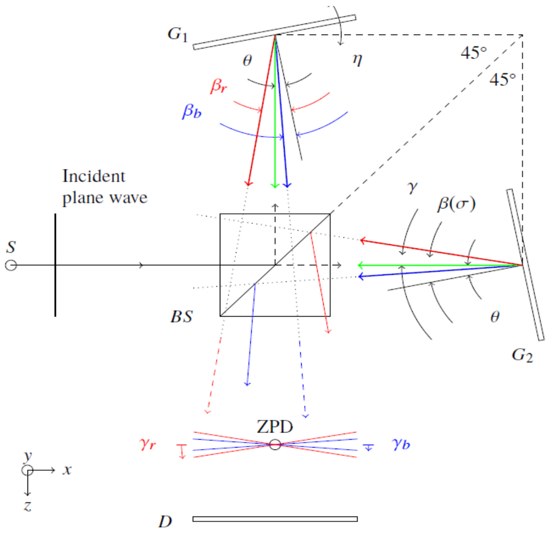

Figure 1. The schematic and working principle of spatial heterodyne spectrometers

Fig. 1. shows the basic arrangement and working principle of SH spectrometers. The collimated incident wave is split by the beamsplitter (BS) and illuminates two gratings (G_1, G_2), where the spectral components are diffracted at different β angles. The combination of these diffracted wavefronts creates an interference pattern. Each spectral components create its own Fizeau fringes with a spatial frequency characteristic of the γ angle between the two wavefronts. The superposition of the individual fringes may create a very complex pattern. All lines of this pattern contains spectral information, which can be extracted by Fourier-transformation.

SHS has many unique features, which can be advantageously utilized in atomic spectroscopy. It has high light throughput, which improves the sensitivity and robustness of the instrument. It is easy to achieve high resolution in any wavelength region. It is a “one shot” technique, that is the whole covered spectral range can be extracted from a single interference pattern.

As it is obvious from the drawing, γ can be changed by the rotation of the gratings, thus the observed spectral range can be shifted which provides a tuning feature. It creates a possibility to record very high resolution spectra in a wider spectral range by splicing adjacent spectrum segments. Our final goal with this project is the construction of an automatic, self-tuning SHS, capable of providing high resolution and a wide spectral coverage at the same time. To achieve our goal, it is essential to understand the tuning characteristics and the instrumental function of the setup, thus we carried out a thorough computational and experimental analysis.

Experimental

The optical model of the double greating SHS arrangement (Fig 2.) was constructed in Comsol Multiphysics, using the geometrical optics interface and the ray tracing module. During the modeling of the sensitivity, and free spectral range of the setup, parametric sweeps of non-sequential ray tracings were performed using hexapolarly arranged, unpolarized, monochromatic and collimated input light beam consisting of 331 individual rays, with plane wave approximation. The fundamental experimental variables of the SHS setup were the groove density of the gratings, the grating arm lengths (distance of the grating surface from the active plane of the beamsplitter), grating rotation angle (around an axis oriented along the *z* direction and placed at the grating surface), input beam wavelength, and input beam diameter.

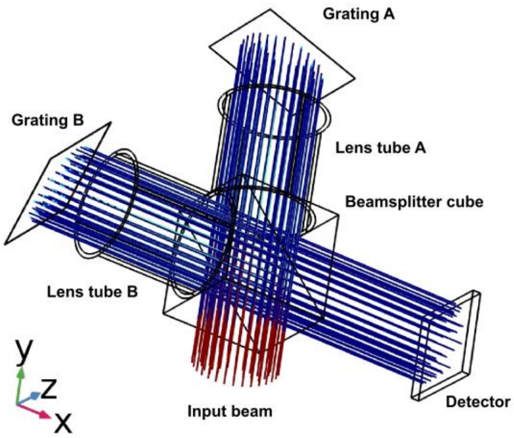

Figure 2. Conceptual ray tracing model of the SHS setup in Comsol. Please note that the number of rays plotted here is much smaller than the number of rays used in the modeling.

In our experimental setup (Fig. 3.), the light from the source (Hg-Ar spectral calibration lamp) was led by a fiber optics into a reflective collimator, which feeds the light into a bandpass filter (this eliminates some spectral interferences) towards the 50:50 beamsplitter. The splitted light beams go through irises then reach the diffractive ruled gratings sitting in grating holders.

One of the gratings were placed on the top of a motorized rotation stage, able to provide sub-minute precision rotation. The gratings were oriented in such a way that the first order of diffraction was sent back towards the camera. The gratings were also slightly tilted in order to make the interpretation of the Fourier transform easier. Further spectral filters were also applied in the beam path for the purpose of eliminating order overlap. Spectral calibration was achieved by a mercury-argon calibration lamp (Ocean Optics Hg1).

The camera objective and some additional lens image the plane of the gratings onto the an Andor iSTAR iCCD camera. Lens tubes were also employed to protecting the lightpath from scattered ambient light.

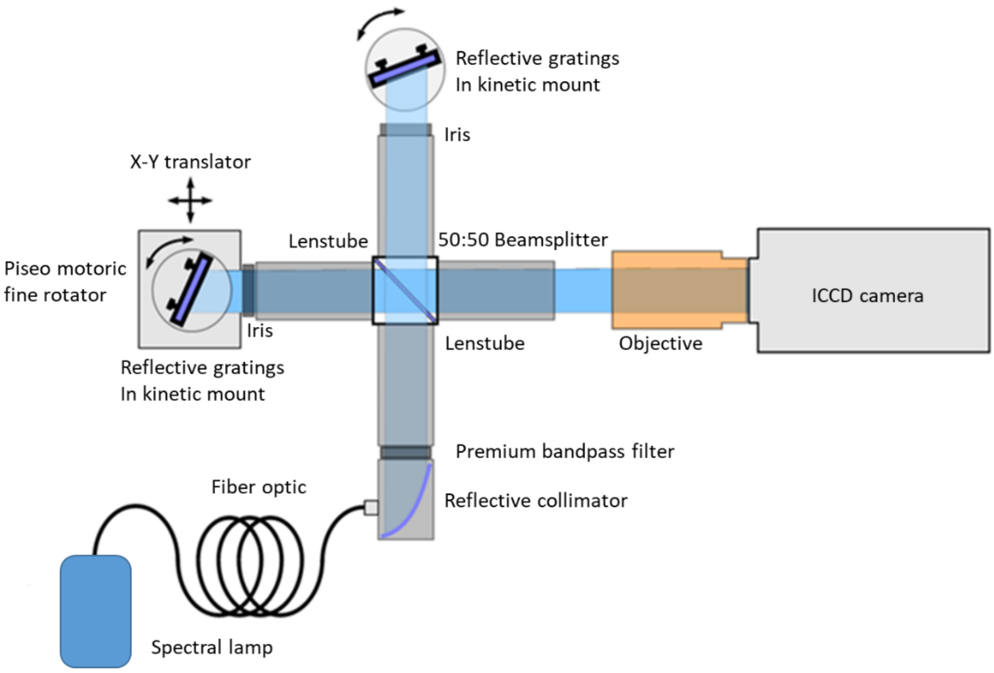

Figure 3. Schematic of our experimental setup

Results and discussion

The ray tracing simulations revealed, not entirely surprisingly, that the sensitivity of the recorded spectral lines depend on how far they are from the blaze wavelength of the grating. Since the setup is constructed in such a way that it uses the first order reflection, therefore for maximum sensitivity the rotation angle has to be adjusted to coincide with the blaze angle. The relative sensitivity decreases rapidly, if the gratings are rotated concertedly; a few degree rotation results in a sensitivity drop of about 50%. We simulated the sensitivity surves for three different gratings (with different grating density) and the results can be seen in Fig 4.

A similar parameter sweep was executed to estimate the spectral coverage of the spectrometer. This time, the rotation angle was fixed, and the wavelength of the incident light was changed between 400 and 700 nm in the geometrical optics simulation. The simulations showed that with 50 mm armlength, it is possible to achieve at least 150 nm free spectral ranges. The calculations also revealed the possibility for an overlap between the first and second order diffracted beams, which emphasized the importance of adequate filtering.

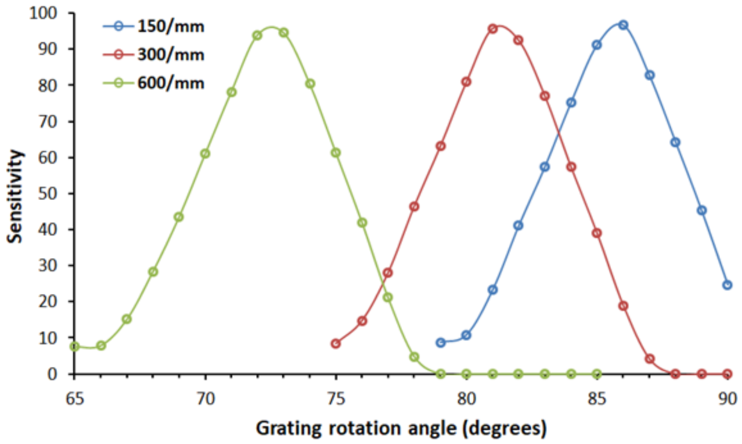

Figure 4. Effect of concerted grating rotation on the relative sensitivity of the SHS arrangement, at the 500 nm blaze wavelength. Arm length is 50 mm.

We experimentally assessed the spectral resolution of our SHS for a set of 300 mm^{-1} and 600 mm^{-1} gratings and values of 0.03 and 0.015 nm/pixel were achieved. These values are excellent considering the compact size of the instrument. Similar resolutions can only be obtained with regular, dispersion monochromators if the arm length (focal length) is on the order of 750-1000 mm and by using a holographic grating (1800 or higher grooves/mm)

The tuneability of the system was also investigated experimentally. One of the gratings was rotated by the piezo rotation stage, while the other was fixed. According to our observations, the spectral lines emitted by the calibrating Hg-Ar light source shifted linerally with the angle of rotation as it is demonstrated in the Fig 5. The effect of the rotation was found to be similar in case of both applied grating sets.To move a spectral peak with a certain amount of pixels into one direction the same rotation is needed, thus the rotation angle needed to move the observed range with a certain value is double in case of the 600 mm^{-1} compared to the 300 mm^{-1} one. It was found that the system is very sensitive for the rotation angle, a sub-degree rotation shifts the recorded spectral range with 20-40 nm.

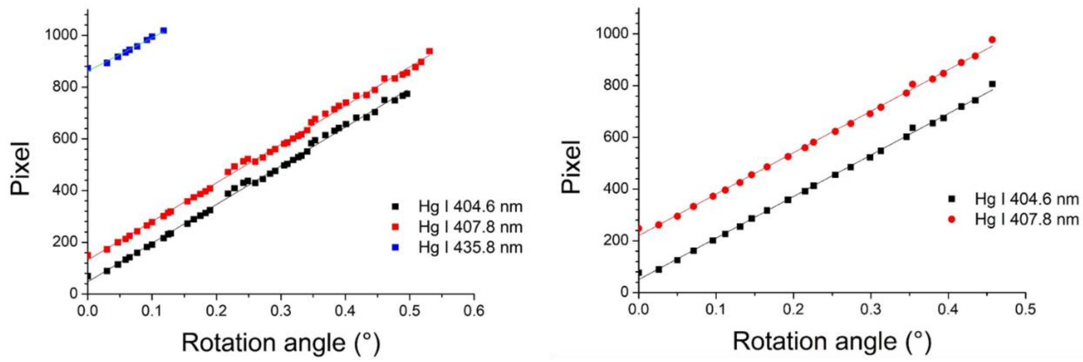

Figure 5. The shift of the observed pixel position of spectral lines as a function of the rotation angle. Left graph: 300 mm^{-1} gratings, right graph: 600 mm^{-1} gratings.

Conclusions

A capable geometrical optics model of an SHS was constructed using the Comsol Multiphysics software package. Using this model, a wavelength dependence of the spectrometer sensitivity as well as the spectral coverage was investigated. Experiments were carried out to assess the spectral resolution which resulted in 0.03 and 0.015 nm/pixel values, which are remarkable for such a compact spectrometer. We also studied the tuning characteristics of the SHS and it was found that the system is very sensitive for the rotation angle, a sub-degree rotation shifts the recorded spectral range with 20-40 nm.

Acknowledgements
The financial support received from various sources including the Ministry of Innovation and Technology (through project No. TUDFO/47138-1/2019-ITM FIKP) and the National Research, Development and Innovation Office (through projects No. K_129063, EFOP-3.6.2-16-2017-00005, TKP 2020 Thematic Excellence Programme 2020) of Hungary is kindly acknowledged. It was also supported by the ÚNKP-20-3 - New National Excellence Program of The Ministry for Innovation and Technology from the source of The National Research, Development and Innovation Fund.

References

[1] G. W. Stroke, A. T. Funkhouser, Physics Letters, 16 (1965) 272-274.
[2] J. Harlender, R.J. Reynolds, F.L. Roesler, The Astrophysical Journal, 396 (1992) 730-740.
[3] A.B Gojani, D.J. Palásti, A. Paul, G. Galbács, I.B. Gornushkin, Applied Spectroscopy, 73 (2019) 1409-1419.