PERFORMANCE OF A RAPID-SCAN VACUUM MICHELSON INTERFEROMETER AT THE NSLS

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Abstract

A commercial Nicolet Magna series rapid-scan Michelson Fourier Transform Infrared (FTIR) was installed in a vacuum housing and integrated into the U4IR beamline at the National Synchrotron Light Source, at Brookhaven National Laboratory. The frequency reference laser was mounted outside vacuum, but the moving mirror mechanism and the dynamic alignment system for the fixed mirror were in vacuum. The performance of the instrument was measured in the usual way by measuring the repeatability of data collected under specific conditions of aperture, resolution and mirror scanning velocity. We briefly discuss the beamline design, to put the interferometer in context, then present signal to noise data which we discuss in terms of both instrument performance and also storage ring beam stability. Under optimal conditions, the instrument has a reproducibility of 0.01% in 1 minute of measuring time at a resolution of 2 cm^{-1}, over a range from 100 - 3000 cm^{-1}.

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1. Introduction

Infrared synchrotron radiation (IRSR)[1-5] is significantly brighter than a thermal "globar" source but requires large extraction angles. In fact 1mA of stored beam current in a storage ring has about the same brightness as a 2000K black body. IRSR is also an absolute source, the brightness being determined by the stored beam current and the easy to calculate physics of the particular source.

In the infrared one is confronted with the same issues as with other spectral ranges, namely spectral range and resolution, the mechanical manifestation, and the instrument performance. Since synchrotron radiation is broadband and since beamsplitting is straightforward, one naturally looks towards interferometers. These instruments have significant advantages over dispersive spectrometers, the differences being illustrated in Fig. 1 and listed in Table 1. The anticipated performance of an interferometer is far superior to its dispersive counterpart.

The multiplexing advantage is only realized, however, if detector noise is the limiting factor, and one must therefore look at this issue carefully. In principle synchrotron radiation is light emitted by the same electron bunches over and over again as they orbit the storage ring. The change in the number of particles is extremely small, and with up to 10^{12} particles per bunch, the shot noise is negligible. However, orbit instability is the major factor in generating effective noise in synchrotron radiation sources, and this usually defines the ultimate performance limit.

2. Beamline

In previous papers we have presented calculations of the brightness of synchrotron radiation and compared it with thermal sources. We have also described the U4IR beamline on which the present spectrometer was installed, but we summarize the essential characteristics here. The beamline extracts 90 × 90 milliradians of light from a 1.9 meter bending radius dipole on the 800 MeV NSLS VUV storage ring. The light is reflected by a side-cooled plane mirror, and eventually brought to a 1:1 focus with an ellipsoidal mirror onto a wedged diamond window with a 10mm clear aperture. After the diamond window, the diverging beam is collimated by a 430 mm focal length paraboloid, 5 degrees off axis. The collimated beam is then approximately 38 × 38 mm with a diagonal of 53 mm, and therefore slightly overfills the 40mm optics of the Michelson interferometer. The emerging collimated beam from the Michelson was focused onto a detector using a 150mm focal length, 90^0 off-axis paraboloid for the measurements reported here. The liquid-helium cooled boron-doped 2mm × 2mm silicon bolometer detector from Infrared Laboratories was placed at the end of a 12mm diameter Winston cone with an angular acceptance of *f*/4. A 600 cm^{-1} low frequency pass filter cooled to 77K was placed between the polyethylene window and the cone entrance. Note that the detector acceptance is much higher than the beam emittance. For example in the diffraction limit the beam emittance is λ^2, and at 100 cm^{-1} the emittance is .01 mm^2, whereas the detector has an acceptance or etendue of $(\pi \times 6^2 \div \pi \times 1.5^2) = 16\ mm^2$. For other experiments the beam is focused to the sample using appropriate demagnifications prior to being refocused at the detector.

The beamline vacuum is as follows. Machine vacuum is preserved up to the diamond window. The collimating mirror and interferometer share a 50 mTorr vacuum, while a wedged polyethylene window separated this vacuum from the $<10^{-6}$ thermal vacuum of the detector. For some experiments additional windows were added between the spectrometer and the detector to allow samples to be contained at lower pressures.

Thus in the present configuration the Michelson was operated at a pressure of 50 mTorr, although we did pump the interferometer chamber to 10^{-5} Torr with a turbo pump with no problems, and it seems likely that it could be used at this pressure. Going down to pressures of $< 10^{-6}$ (thermal vacuum) would likely require the heat-sinking of several components, but would not be too difficult.

3. The Vacuum Michelson Interferometer.

We preface this section by remarking that the motivation for the development of this instrument was the lack of availability of a commercial product with appropriate specifications. The commercially available instruments were either not true vacuum benches by virtue of using an air bearing, and/or contained instrumentation that was not necessary, such as sample compartments and detector optics. We were seeking a beamline "component" only. The specifications were as follows: ability to work in 50 mTorr pressure; 0.125 cm^{-1} best resolution; range from 10 – 5000 cm^{-1}, with the range 10 – 2500 cm^{-1} covered by a single beamsplitter; rapid-scan type instrument with scanning speed variable from 10 kHz to 100 kHz HeNe laser scan frequency; 40mm optics.

The principle of operation of this rapid-scan type of instrument is shown in Fig. 2. The beam is amplitude divided into 2 beams, one of which traverses a fixed path length, while the other traverses a path length which varies. In the normal mode of operation of such an instrument the signal is measured for different and measured positions of the moving mirror. This is called step-scanning. In order to be able to detect a signal, the incoming beam is modulated using a chopper, and a lock-in amplifier is used to detect the synchronous signal from the detector. In a rapid-scan instrument, the moving mirror is moved at a constant velocity. This causes each input wavelength to be modulated at a specific frequency and has the advantage that no chopper is required so that one is looking at the signal all the time. Typically one adjusts scanning speeds so that wavelengths being modulated are in the few 100 to few 1000 Hz region. The top frequencies depend on the detector response, while the lower frequencies should be high enough to be above laboratory noise whose main component is 60 Hz. For accurate calibration purposes most such benches simultaneously modulate a laser beam as shown in Fig. 3. The speed of the moving mirror is often specified by the modulation frequency of the HeNe laser. Since this laser has a wavelength of 632.8nm, if the mirror moves by 0.5 cm/sec, so that the optical path difference is changing by 1 cm/sec, then the laser modulation frequency will be 15803 Hz. In addition, the resolution of the scan is proportional to the maximum path difference, while the highest frequency in the spectrum is proportional to the frequency of data taking during the scan.

The philosophy of the present application was to try to use commercial products if possible, and we selected the Nicolet Magna (now Nexus) series of instruments. We purchased the Michelson interferometer, the power supply, reference laser and electronics and re-packaged them into a welded aluminum vacuum chamber that we designed ourselves. This instrument uses a graphite-in-glass bearing for the moving mirror, and previous tests showed that such a bearing works well in vacuum. We also previously showed that the remainder of the electronics would function in vacuum. The result of the packaging of the instrument in vacuum is shown in Figs. 4 and 5. The incorporation into the beamline is shown in Fig. 6.

After installation we tested the performance of the instrument by placing a detector directly after the instrument. Since the primary purpose of this beamline is low frequency surface science, which is brightness limited, the region from 50 – 800 cm^{-1} is of primary interest. In the performance tests we ran the bench at laser modulation frequencies from 10 kHz to 120 kHz and at various resolutions. There were no surprises. Clearly at the faster speeds the mirror turnaround time represented a larger percentage of the total data gathering time, particularly at low resolution. At slower speeds we observed laboratory noise. The spectrum shown was selected to be under near optimum conditions.

4. Conclusions

The performance of the vacuum Michelson interferometer meets the requirements for the experiments. One can think of many improvements to the quality of life of the beamline, and we mention 3 of them here. First it would be highly desirable to have a white-light source to be able to detect zero path difference (when the 2 optical path lengths are identical) for calibration purposes. This can easily be done with the synchrotron beam, but since the beam is not always available it would be desirable to be able to do this independently of the synchrotron. The Nicolet interferometer does have such a white-light detector already mounted, and the implementation would not be difficult. Secondly it would be useful if the mirror could collect data in both directions to minimize the loss of measuring time due to turnaround, a feature that is indeed becoming available in newer instruments.

Acknowledgements

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High Resolution
High Throughput (Jaquinot advantage)
Multiplex Advantage (Fellgett advantage)
No Diffraction Losses
Higher Order Rejection
No Resolution determining Focusing Elements
No Heat Load Problem

Table 1. Advantages of an interferometer over a spectrometer, particularly for use with infra-red synchrotron radiation.

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Figure Captions

Fig. 1. Schematic of spectrometer and interferometer illustrating the fundamental differences between the 2 instruments and pointing out the practical advantages of the interferometer.

Fig. 2. Schematic of the operation of the rapid-scan Michelson interferometer. The elimination of a chopper means that one is always measuring all the light.

Fig. 3. Schematic operation of the laser calibration system for the Michelson interferometer.

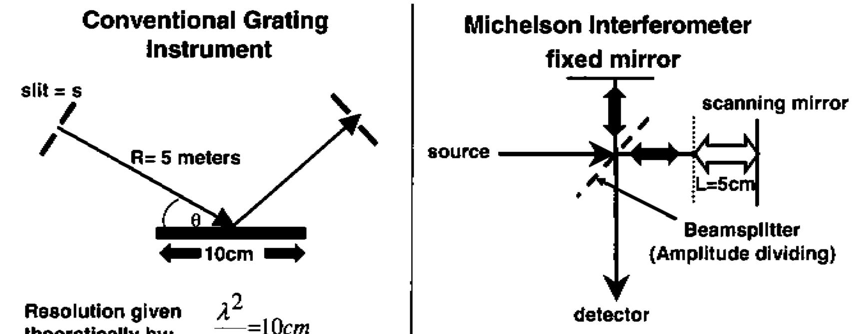
Fig. 4. Plan view and photograph of the vacuum Michelson interferometer.

Fig. 5. Side view of the vacuum Michelson interferometer showing the electronics and reference laser.

Fig. 6. Schematic of the beamline U4IR at the NSLS, showing the location of the vacuum Michelson interferometer.

Fig. 7. Spectrum obtained using infrared synchrotron radiation and the Nicolet solid substrate beamsplitter. The low energy cut-off is believed to be due to diffraction, while the slow cut-off to higher frequencies is due to the black polyethylene filter in the detector.

Fig. 8. Reproducibility of the vacuum Michelson interferometer in the range 0-700 cm-1 and showing that in the range 150-250 cm-1 rms deviations of only 3 parts in 10^5 are obtained. Such values can be obtained elsewhere with suitable filtering.



Resolution given theoretically by: $\frac{\lambda^2}{\Delta\lambda}=10cm$

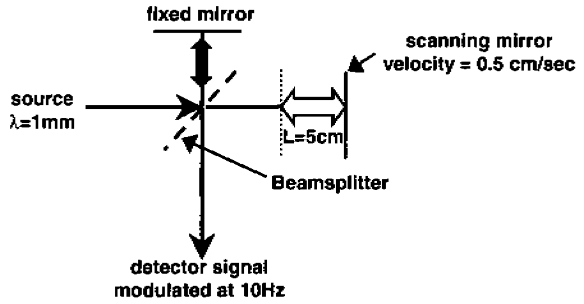
So, if λ=50Å, $\lambda/\Delta\lambda$=2X10^7

But, practically, if θ=2°, and if s=10 microns
# of resolution elements is R θ/10 =2X10^4

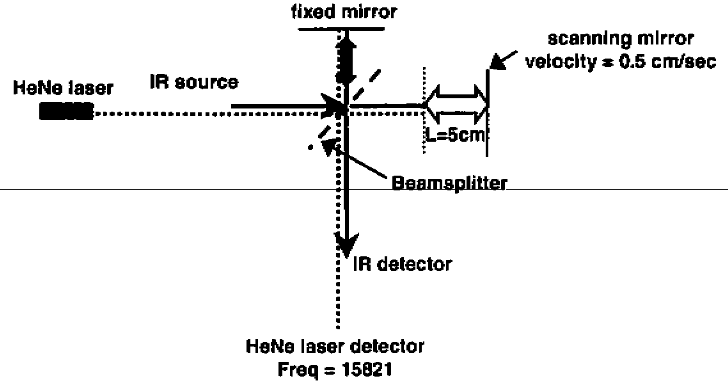
Resolution given theoretically AND practically by: $\frac{\lambda^2}{\Delta\lambda}=10cm$

Since λ is in the range 1 - 1000 microns,
$\lambda/\Delta\lambda$ is in the range 10^2-10^5

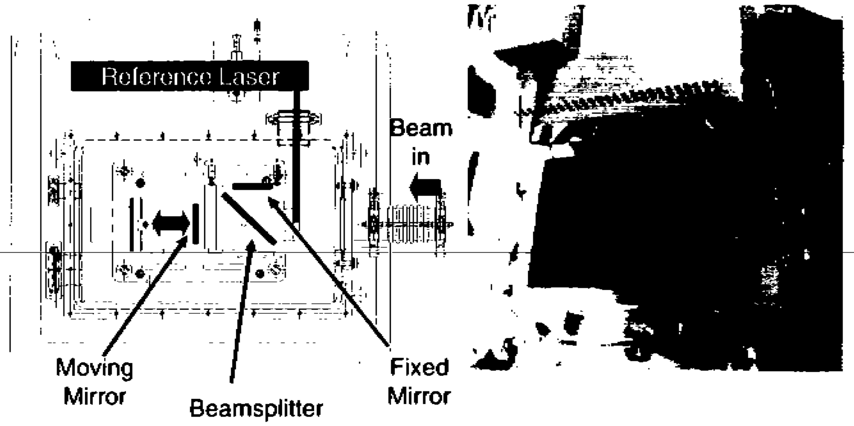
Dumas, Brierley, Smith and Williams Fig. 1



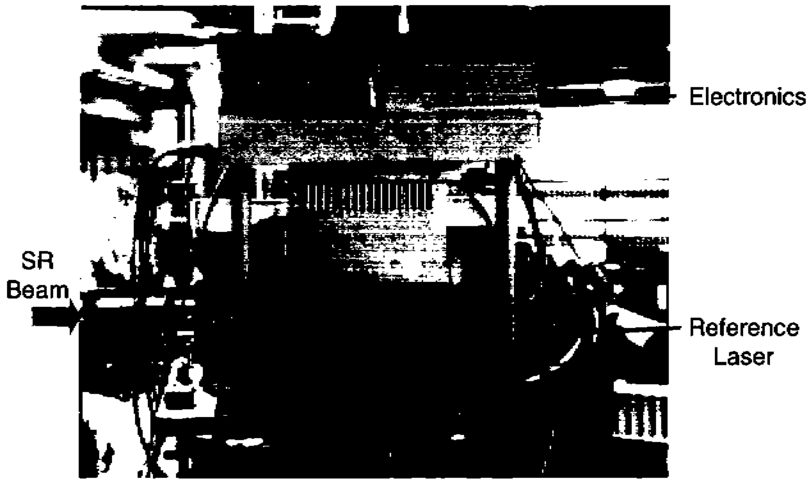
Dumas, Brierley, Smith and Williams Fig. 2



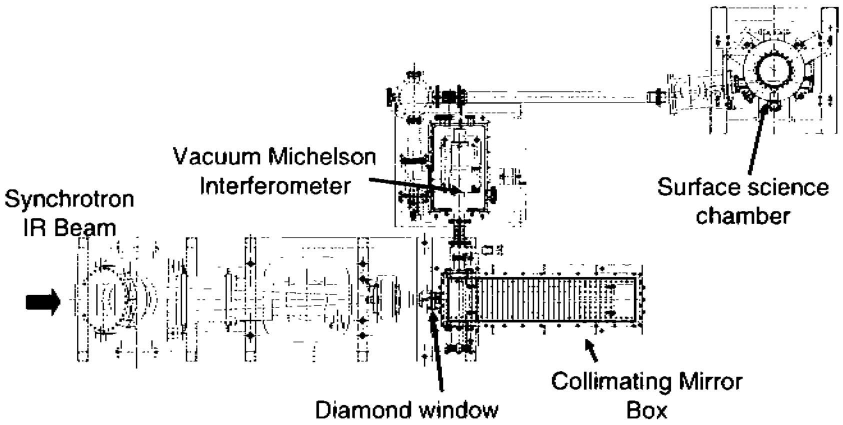
Dumas, Brierley, Smith and Williams Fig. 3



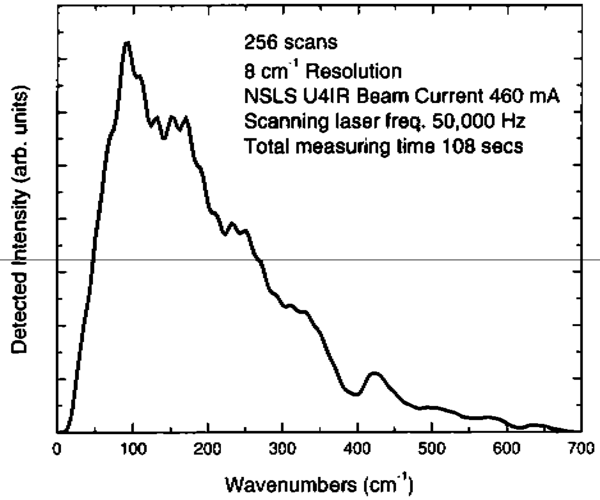
Dumas, Brierley, Smith and Williams Fig. 4



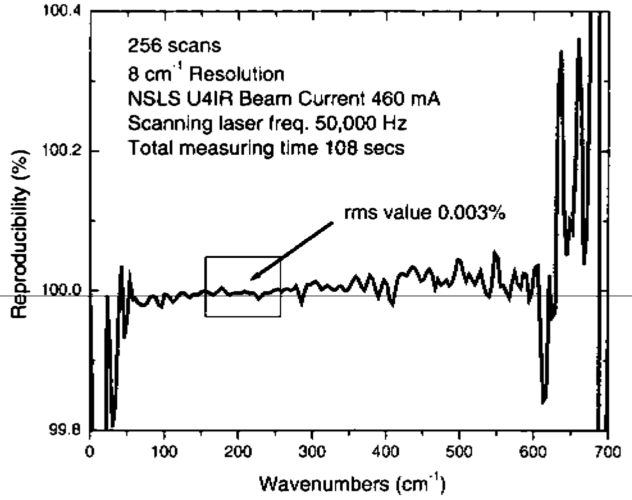
Dumas, Brierley, Smith and Williams Fig. 5



Dumas, Brierley, Smith and Williams Fig. 6



Dumas, Brierley, Smith and Williams Fig. 7



Dumas, Brierley, Smith and Williams Fig. 8