First light results from a novel cryogenic Fabry-Perot interferometer

David Naylor[1], Ian. Veenendaal[1], Trevor Fulton[1], Brad Gom[1], Adam Christiansen[1], Willem Jellema[2,3], Carolin Feenstra[2], Martin Eggens[3] and Peter Ade[4]
[1]University of Lethbridge, Lethbridge, Alberta, Canada
[2]Kapteyn Astronomical Institute, University of Groningen, Groningen, Netherlands
[3]SRON Netherlands Institute for Space Research, Groningen, Netherlands
[4]Cardiff University, United Kingdom

***Abstract*—The sensitivity of state-of-the-art superconducting far-infrared detectors is such that astronomical observations at these wavelengths are limited by photon noise from the astronomical source unless a method of restricting the spectral bandpass is employed. One such method is to use a high resolution Fabry-Perot interferometer (FPI) in conjunction with a lower resolution, post-dispersing system, such as a grating spectrometer. The resonant wavelength of an FPI is typically tuned by changing the spacing or medium between the parallel reflecting plates of the etalon. We previously reported on a novel design in which the wavelength is tuned by scanning the angle of incidence, which simplifies the cryo-mechanical design, actuation and metrology. Here we present first light results from the realized instrument.**

I. INTRODUCTION

SPICA is an ESA-JAXA observatory class mission [1] that will provide imaging and spectroscopic capabilities in the 5 to 230 µm wavelength range with a 2.5 m telescope cooled to a temperature less than 8 K. In combination with a new generation of ultra-sensitive detectors (NEP ~10^{-19} W/√Hz), the cold telescope will allow astronomers, for the first time, to achieve sky-limited sensitivity over this wavelength range. To realize this goal, however, a dispersive spectrometer based upon a diffraction grating is required so that each detector observes a limited spectral band chosen such that the photon noise from the astronomical source in this band falls below the detector noise level. Since a diffraction grating spectrometer provides only low resolution spectroscopy, a complementary high resolution component is required to resolve narrower astronomical spectral features. A Fabry-Pérot interferometer (FPI) is one solution that is being explored. The design we present has a volume envelop that will not only fit within our recently commissioned test facility cryostat [2], but is also compatible in size with the space that would be required to mount four such units that would be necessary to cover the wavelength range proposed for the SPICA SAFARI instrument.

In the case of an ideal, plane parallel FPI, the transmitted intensity can be expressed as [3]:

$$I_T = \frac{I_0}{1 + \left[\frac{4R}{(1-R)^2}\right] sin^2\left(\frac{\delta}{2}\right)}$$

Where I_0 is the incident intensity, R is the surface reflectivity and δ is the phase difference between consecutive interfering beams, where $\delta = \frac{2\pi}{\lambda} 2\mu d \cos\theta$. The resonant wavelength of the FPI can be scanned by varying d, μ *or* θ; by far the most common approach is to vary the etalon spacing, d.

II. FPI DESIGN

The cryogenic FPI design (Figure 1) is based on scanning the angle of incidence (AoI), θ. A monolithic pendulum scanning mechanism, which incorporates two precision, diamond turned plane mirrors, with an internal angle of 90°, directs light through the etalon, which is mounted at a pupil image and at an offset angle to allow single sided scans of a fixed gap etalon.

The principal advantages of this design are that motion is only required around one axis, which simplifies both the actuation (voice coils) and metrology (fibre-fed laser interferometer) and that the etalon itself can be fabricated plane and parallel by design, obviating the need to maintain parallelism of the etalon plates if the gap, d, were to be scanned [4]. This is an important consideration for an instrument operating at cryogenic temperatures (~4 K).

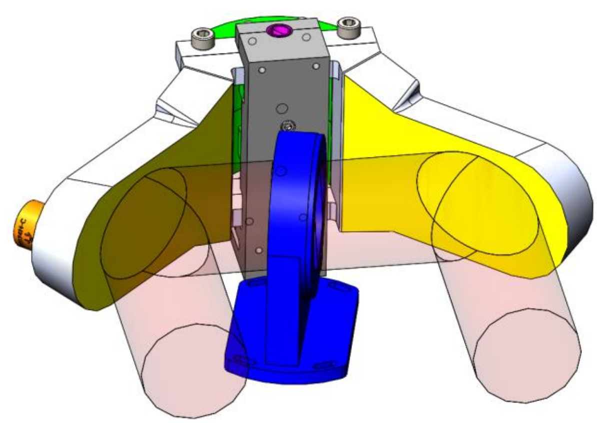

Figure 1. FPI schematic in which the angle of incidence on the offset mounted etalon (blue) is scanned as the pendulum, actuated by opposing rotary voice coil drivers (green), rotates about the pivot (purple). A corner cube retro reflector (orange) mounted to the rear of the pendulum arm forms part of a cryogenic laser metrology system to determine θ.

The principal disadvantage is that the multiply reflected beams suffer increasing *walk-off* of the finite etalon aperture as the angle of incidence increases. The effect of *walk-off* is to change the spectral response as a function of angle, or effectively wavelength, as the number of interfering beams decreases with increasing θ. In the case of n interfering beams the above equation is modified to [5]:

$$I_T = \frac{I_0\,(1-R^n)^2}{1 + \left[\frac{4R}{(1-R)^2}\right] sin^2\left(\frac{\delta}{2}\right)} \left\{1 + \left[\frac{4R^n}{(1-R^n)^2}\right] sin^2\left(\frac{n\delta}{2}\right)\right\}$$

The situation is further complicated by the fact that n varies depending on where the incident beam strikes the etalon, as shown in Figure 2, which requires an integration over the pupil. For these reasons, historically, Fabry-Pérot interferometers have been operated at normal incidence. However, with modern computing power the challenges of calibrating an angle-scanned etalon, which requires a unique correction for each angle of incidence, are considered manageable.

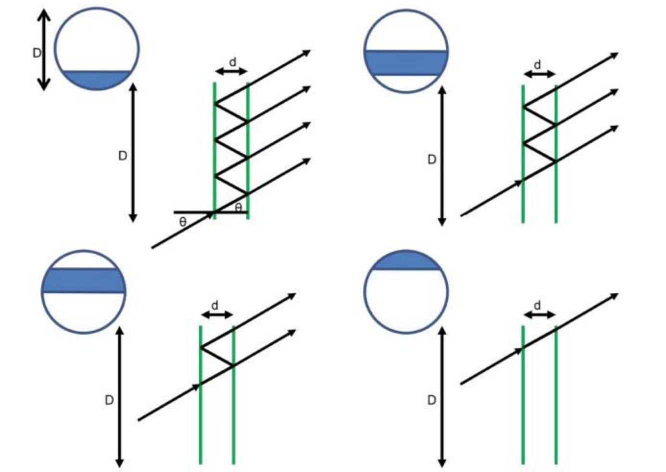

Figure 2. Schematic of the impact of *walk-off* as a function of the location of the incident beam on the etalon. A beam incident at the bottom of the etalon (upper left) results in the greatest number of multiply reflected beams; a beam incident at the top of the etalon (lower right) produces no multiply reflected beams; the case shown in the lower left corresponds to two beam interference similar to that observed in the classical Michelson interferometer.

III. RESULTS

Figure 3 presents the first light results obtained from the angle-scanned Fabry-Pérot interferometer discussed above. The measured spectral line profile (circles) has been compared with the theoretical prediction (line) for a monochromatic line source having a wavelength, λ, of 302.4 µm. There is seen to be excellent agree between the measured and modelled spectra.

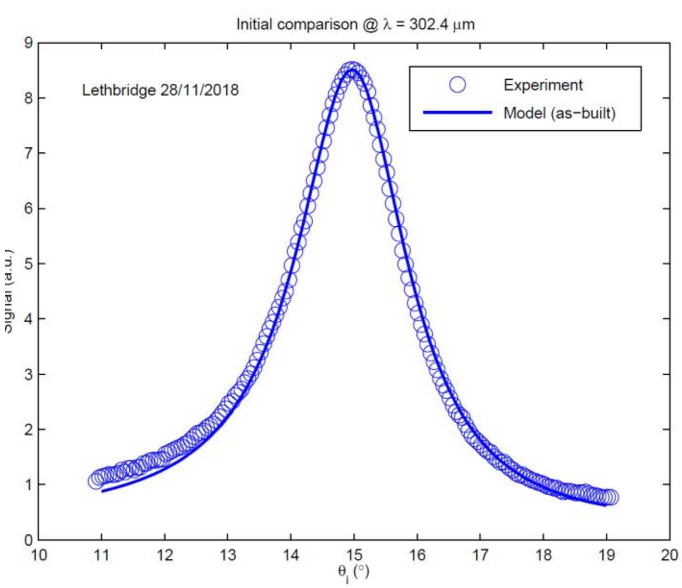

Figure 3. First light measurements of the realized FPI.

Spectra were subsequently obtained over the wavelength range from 280 – 320 µm. While the etalon was designed to provide optimum performance at wavelengths between 220 and 300 µm, the available power from the photomixer, which varies as λ^4, quickly became the limiting factor in obtaining the high signal-to-noise measurements necessary to study the line profile in detail. Despite this limitation, by carefully tuning the wavelengths of the individual (~1.55 µm) DFB lasers that illuminate the photomixer, and thus the resulting difference frequency of radiation produced by the photomixer, we were able to compare the measured and theoretically predicted resolving power over the wavelength range 280 – 320 µm.

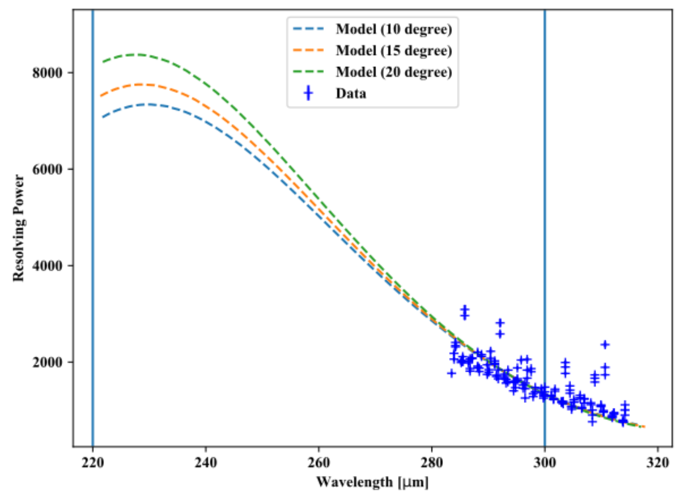

Figure 4. Comparison of the measured resolving power (blue crosses) with theoretical models corresponding to different initial offset angles (Figure 1).

The resolving power was determined by fitting the raw data to the second equation given above. The fitting parameters were the effective thickness, refractive index and loss tangent of the custom HRFZ-Si etalon, and the variation of these parameters with temperature, and the angle of incidence. Of these the angle of incidence carried the most uncertainty. The results are shown in Figure 4 for three different initial offset angles of incidence. While there exists limited data in the optimal operating region of the etalon, indicated by the blue vertical lines in Figure 4, the data are consistent with the design goals for the angle-scanned Fabry-Pérot interferometer of achieving mean resolving powers of 3000.

In summary, these first results from a novel cryogenic angle-scanned Fabry-Pérot interferometer show that the effects of *walk-off* and potential absorption losses have not compromised the performance of the custom design etalon at the target resolving powers.

REFERENCES

[1]. B. Swinyard, et al. “The space infrared telescope for cosmology and astrophysics: SPICA A joint mission between JAXA and ESA”, *Experimental Astronomy*. 23: 193-219, 2009.

[2] I. Veenendaal, et al., Performance of a cryogenic test facility for 4 K interferometer delay line investigations, Proc. SPIE 9904, 99045E, 2016.

[3]. M Vaughan, “The Fabry-Perot Interferometer”, *Taylor and Francis*, 1989

[4]. P. Clegg et al., “The ISO Long-Wavelength Spectrometer” *Astronomy and Astrophysics*, 315, L38 1996.

[5] J. Green, "The ‘walk-off’ effect in Fabry-Perot etalons", *J. Phys. E: Sci. Instrum.*, 13: 1302 – 1304, 1980.