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Published in:
2017 42nd International Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz 2017

DOI:
10.1109/IRMMW-THz.2017.8066903

A novel design for a cryogenic Fabry-Pérot interferometer

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***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-Pérot 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 present a novel design in which the wavelength is tuned by scanning the angle of incidence, which simplifies the cryo-mechanical design, actuation and metrology. The effects on the spectral response as a function of incident angle have been simulated and shown to be manageable.**

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 CONCEPT

In this paper, we present the design of a cryogenic FPI (Figure 1) based on scanning the angle of incidence, 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 the etalon.

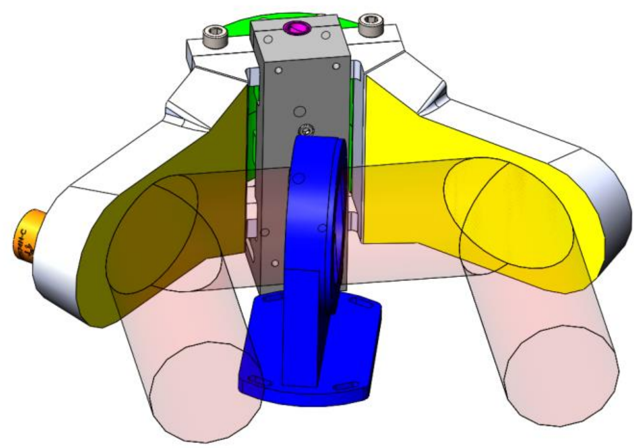

Figure 1. FPI schematic in which the angle of incidence on the offset mounted etalon (blue) is scanned as the pendulum, actuated by opposing rotary voice coil drivers (green), rotates about the pivot (purple). A corner cube retro reflector (orange) mounted to the rear of the pendulum arm forms part of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

The principal advantages of this design are that motion is only required around one axis, which simplifies both the actuation and metrology, 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 below ~10K.

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.

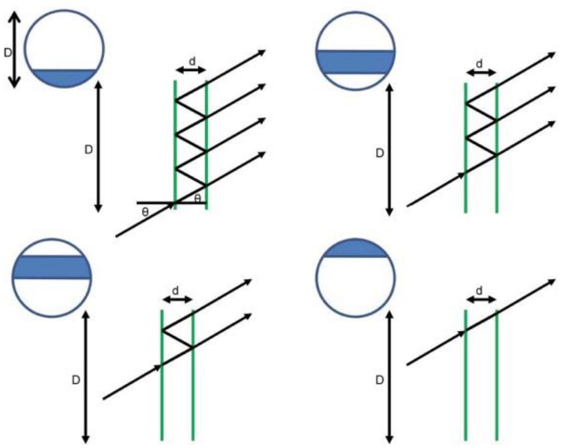

Figure 2. Schematic of the impact of *walk-off* as a function of the location of the incident beam on the etalon. A beam incident at the bottom of the etalon (upper left) results in the greatest number of multiply reflected beams; a beam incident at the top of the etalon (lower right) produces no multiply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

Figure 3 shows the simulated effect of *walk-off* for an angle scanned, airgap etalon designed to provide a Finesse of ~10 at a wavelength of 260 µm. The etalon is formed using inductive metal mesh grids [6]. To achieve the desired Finesse requires a gap of 34 mm. The analysis assumes that the reflecting surfaces are parallel to 10 arcseconds. The change in the spectral response as a function of wavelength is clearly apparent.

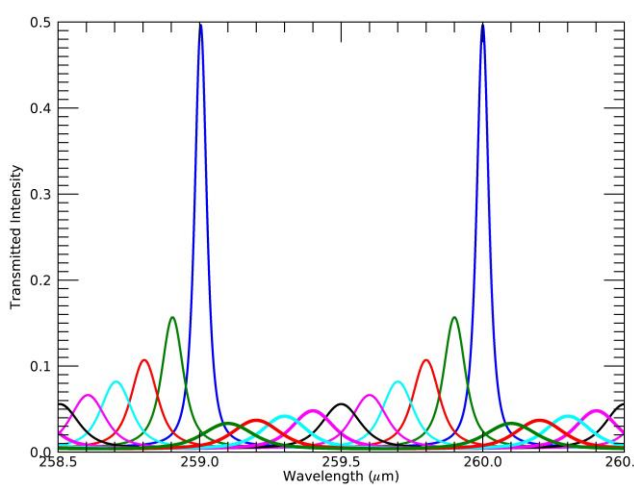

Figure 3. Simulated transmission as a function of wavelength for an air gap (34 mm) etalon employing inductive metal mesh reflectors, with an internal wedge angle of 10″. The etalon has a clear aperture of 40 mm at normal incidence and the scan range is 0 to 4.8 degrees. The effect of *walk-off* is evident.

Figure 4 shows the simulated effect of *walk-off* for an angle scanned etalon formed by mounting the same inductive meshes of Figure 3 on either side of a high resistivity silicon substrate of thickness 7 mm, with small airgaps of 10 µm. Again, a parallelism of 10 arcseconds has been assumed. While the high refractive index of the substrate partly mitigates the effects of *walk-off*, the angle scan required to achieve the target finesse increases. For the example shown, the range is between 10 and 22.2 degrees. The resulting variation in spectral response as a function of wavelength is significantly improved. However, the effect of absorption within the silicon substrate, not present in the airgap etalon has not been included in this analysis.

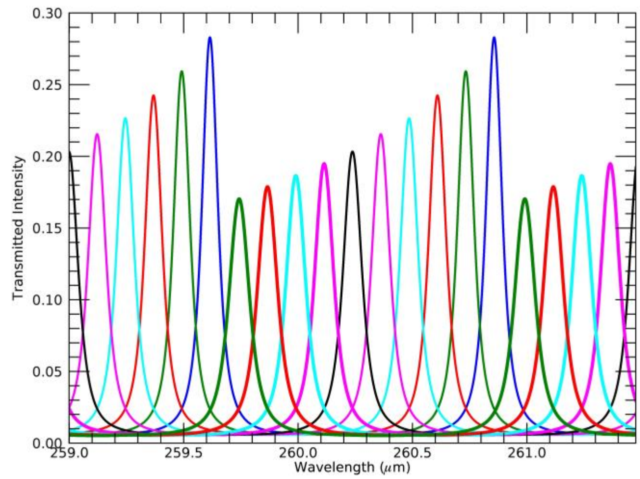

Figure 4. Simulated transmission as a function of wavelength for an etalon made from a high resistivity silicon slab (7 mm) sandwiched between the inductive metal mesh reflectors of Figure 3. The effect of *walk-off* is seen to be less severe, however, absorption within the Silicon have not been included in this analysis.

The loss tangent of silicon is not well characterized at cryogenic temperatures. We are in the process of procuring high resistivity HRFZ silicon samples to measure absorption at cryogenic temperatures. These measurements will be included in our model to optimize the design of the angle scanned Fabry-Pérot interferometer.

Once complete, the performance of the system will be analyzed using a tunable photomixer THz source, based on the difference frequency between two tunable 1.55 µm lasers and, in absorption, using a gas cell incorporating HCl and DCl at equal partial pressures of around 10 Torr.

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