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T. Tollet, L. Rodriguez, V. Revéret, A. Poglitsch, L. Dussot, A. Aliane, C.
Delisle, V. Goudon, G. Lasfargues

► **To cite this version:**

T. Tollet, L. Rodriguez, V. Revéret, A. Poglitsch, L. Dussot, et al.. Tuneable Spectrometer for Submillimeter Astronomy Based on Silicon Fabry–Perot, Preliminary Results. *Journal of Low Temperature Physics*, 2024, 216 (1-2), pp.165-174. 10.1007/s10909-024-03120-2 . cea-04769916

HAL Id: cea-04769916

<https://cea.hal.science/cea-04769916v1>

Submitted on 1 Dec 2024

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Tuneable spectrometer for submillimeter astronomy based on silicon Fabry-Perot, preliminary results

Timothée Tollet

`timothee.tollet@cea.fr`

CEA Saclay

Louis Rodriguez

CEA Saclay

Vincent Revéret

CEA Saclay

Albrecht Poglitsch

Max Planck Institute for Extraterrestrial Physics

Laurent Dussopt

CEA LETI

Abdelkader Aliane

CEA LETI

Cyrille Delisle

CEA Saclay

Valérie Goudon

CEA LETI

Gilles Lasfargues

CEA LETI

Research Article

Keywords: Fabry-Perot, tuneable spectrometer, sub-mm astronomy, Bragg stack

Posted Date: November 8th, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-3552487/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Journal of Low Temperature Physics on May 12th, 2024. See the published version at <https://doi.org/10.1007/s10909-024-03120-2>.

Abstract

We are studying and developing high performance spectroscopy solutions in silicon technology in the framework of the instrumental developments around the B-BOP bolometer arrays [1] and in the continuity of the former developments of the Herschel space telescope instruments and in particular its PACS instrument [2]. The integration of multi-wavelength spectroscopic capabilities close to the array of a cooled bolometer would make it possible to detect the interstellar medium (ISM) continuum by scanning and to trace its evolution in particular by the detection of characteristic lines such as the cooling line [CII] at $158\mu\text{m}$.

In this paper, we present the first concept under development and the preliminary results obtained in our cryogenic optical test bench. This solution is a tunable cavity Fabry-Perot (FP) with silicon mirrors driven by a cryogenic piezoelectric mechanism with a nanometric step. Each mirror is a dielectric Bragg structure, a stack of quarter-wave layers of silicon and air providing a high reflectivity without metal losses. This solution allows extremely accurate scanning around a targeted wavelength. The first prototype is a relatively bulky proof of concept and future optimizations will allow it to be adapted to a focal plane array.

1 Introduction

The long-term project is to design a spectrometer integrated into the focal plane of a detector. For this reason, we have chosen to focus on silicon technology that is easily compatible with different detector technologies, and we decided to focus on the simplest type of interferometer, the Fabry-Perot. This kind of interferometer has no influence on the polarization of the light and retains the spatial information as long as the beam is collimated. A Fabry-Perot interferometer is composed of two parallel mirrors perpendicularly positioned to the propagation direction of the incident wave. The light travels back and forth in the cavity and interferes constructively in transmission at the output of the cavity for selected wavelengths. This optical system transmits a comb of wavenumber in which all orders are directly dependent on the cavity size, and whose fundamental wavelength is equal to twice the cavity.

The efficiency and the resolution of this kind of interferometers depend directly on the mirror properties. The higher the reflectivity of the mirrors, the better the transmission of the FP peaks.

Furthermore, in practice, any degradation of parallelism between the two mirrors, of flatness or of surface of each mirror degrade the resolution of the transmitted peaks. Our objective is to build a mid-resolution compact FP interferometer with the least possible absorption that is capable of transmitting several wavelengths close to each other. To develop a tunable Fabry-Perot, we choose for this concept to modify the cavity size by scanning one of the mirrors.

2 The concept of Bragg-mirror Fabry-Perot

Most of the common Fabry-Perot interferometers for space applications are made of thin-sheet metal or metallic mesh mirrors. This introduces metal losses and a loss in efficiency.

The concept we propose here is a Fabry-Perot with no losses in the mirrors and has been realized by S. Bounissou during her thesis work [3]. Each mirror is made of a Bragg stack of dielectric layers, here silicon and vacuum. The mirrors used here is a three layers stack silicon-vacuum-silicon. The big advantage of such mirrors is the use of dielectric materials that do not absorb the light wave. They also reflect light very efficiently over a wide band of wavelengths.

For feasibility reasons, we are targeting transmitted wavelength around $320\mu\text{m}$. In fact, the layers composing our device are made of pure crystalline silicon and this is technically difficult to manufacture and handle thinned-layers with a thickness of less than $50\mu\text{m}$. However, the principle we demonstrate in this paper for wavelengths around $320\mu\text{m}$ remains identical to the one we would implement for a Fabry-Perot transmitting at $158\mu\text{m}$. The layers used here are $70.2\mu\text{m}$ thick ($3\lambda/4$) for the silicon and $80\mu\text{m}$ thick ($\lambda/4$) for the vacuum. In order to scan the wavelengths around $320\mu\text{m}$ with the best resolution, we decided to scan the first order, which means a cavity size around $\lambda/2$.

As mentioned previously, to reach a good finesse, the surface of the mirrors must be as flat and smooth as possible. That is why we have had the thinned silicon manufactured with high precision tools at the CEA/LETI and we built a mechanical mount to assemble the Fabry-Perot with minimum deformation of the individual sheet.

In 2019, the high performance of this concept has been proved with a Bragg mirror FP with a fixed cavity. This first sample reached more than 98% of efficiency for a resolution of over 180. Our objective is now to be able to scan the cavity between the two mirrors to transmit several wavelengths close to each other with the same interferometer.

3 The prototype of scanning Bragg Fabry-Perot

The prototype we developed is made of a three piezoelectric actuators mechanism that allows one to adjust the parallelism of the Fabry-Perot and to scan the cavity. We designed this whole setup to operate under cryogenic vacuum conditions.

On Fig. 2 above, we fixed the mobile mirror on the blue part connected to the piezo mechanism and the other mirror on the bracket in front of the first one. The challenge of this experiment is to reach a good parallelism of the mirrors before the vacuum and cold operations, and then, under those harsh conditions find back the initial parallelism and adjusting it by varying the tip and tilt of the mechanism. Many calibrations and characterization, optically and thermally are thus necessary before taking the spectral measurement of the Fabry-Perot.

4 Results

The measurements are performed with a cryogenic Martin-Pupplet Fourier Transform Spectrometer (FTS) with a 10cm travel. The signal is acquired by a bolometer cooled down to 300mK allowing us to get high resolution and low signal interferograms. Our optical samples are placed in the optical path between the FTS and the bolometer. For each spectrum showed below, many interferograms have been acquired with the sample in the path and another batch of measurements has been made without the sample, for reference. Therefore, we can eliminate the spectral signature of the test bench environment and retrieve the absolute spectral efficiency of our sample.

Thanks to a measurement of the single silicon sheet we use for the Bragg mirrors, we have been able to know precisely its thickness and thus feed the theoretical model with the spectral response of the two Bragg mirrors that we measured on the FTS at 77K Fig. 3.

The measured spectra of those mirrors are really close to the simulation, they have high reflectivity (more than 95%) on a wavelength range wider than 100 μ m. The numerical simulation plotted in this article are calculated on the model basics of the thin-films theory developed by Abelès [4].

We then measured the response of the scanning FP with those two Bragg mirrors and saved the spectra for four different sizes of cavity in order to get four different peaks of transmission at 310 μ m, 320 μ m, 330 μ m and 340 μ m. To begin with, this first series of measurements was carried out with the Fabry-Perot kept at room temperature in order to simplify mirror-parallelism operations. The rest of the optical bench was kept at cryogenic temperature. Figure 4 below shows the four spectra obtained with the scanning FP. By changing the cavity size of a known distance, we shift the position of the transmitted peak in accordance with the model.

With the same model used for the Bragg mirrors, we can compare the performance of our interferometer with the theoretical simulation. We see on the Fig. 5 that the experimental measurements fit perfectly with the theory for the four positions.

Therefore, we clearly see that the efficiencies of the transmitted wavelengths are lower than the ones simulated. We summarize the efficiency and the resolution of each peak of FP in the table below, and compare them with the expected performance:

As shown on Fig. 6, the performance of the transmitted peaks are lower than expected. This can be explained by several factors. The most probable here, in addition to the possible small parallelism defects, is that the Bragg stack are a little bit deformed by the way they are assembled on their mounts (some microns of wedge). Even those small deformations have a big impact on the shape of the peak. Here, we cannot precisely fit those peaks with Lorentzian curves, which confirms our hypothesis. Their shape are closer to the case of FP peak with a non-zero angle of incidence.

The next step is to optimize the assembly of the Bragg mirrors in order to reduce the deformations down to less than 1 μ m of wedge and for the next cold measurements of this Fabry-Perot, the parallelism procedure should be fine-tuned.

Declarations

Acknowledgements:

This work has been partially supported by the LabEx Focus ANR-11-LABX-0013.

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Figures

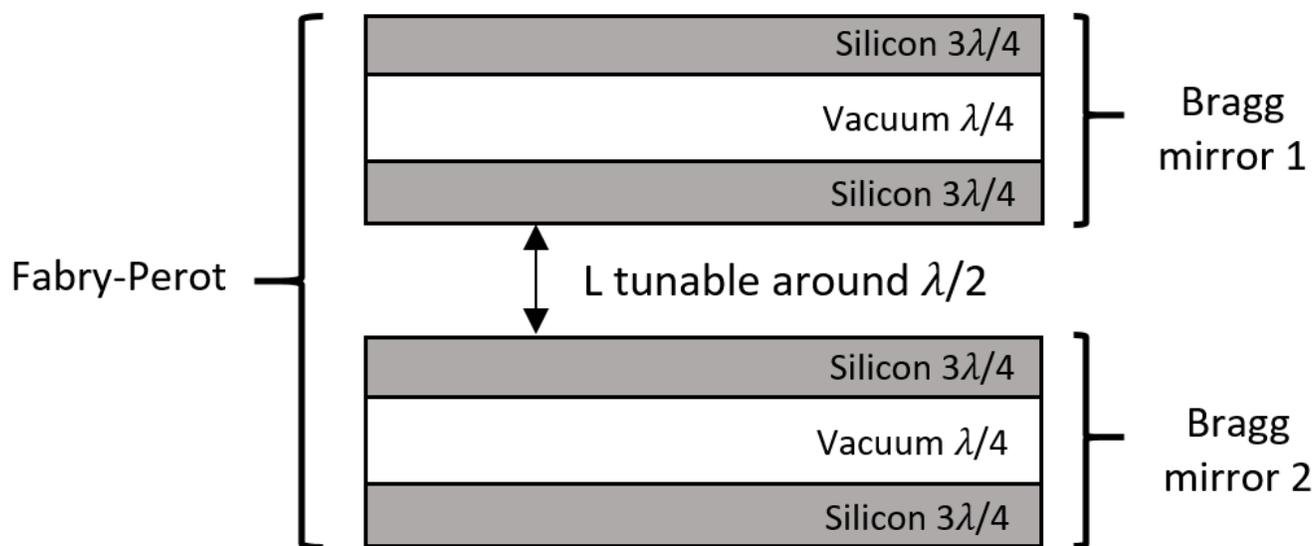


Figure 1

Scheme of the scanning Bragg mirror Fabry-Perot concept

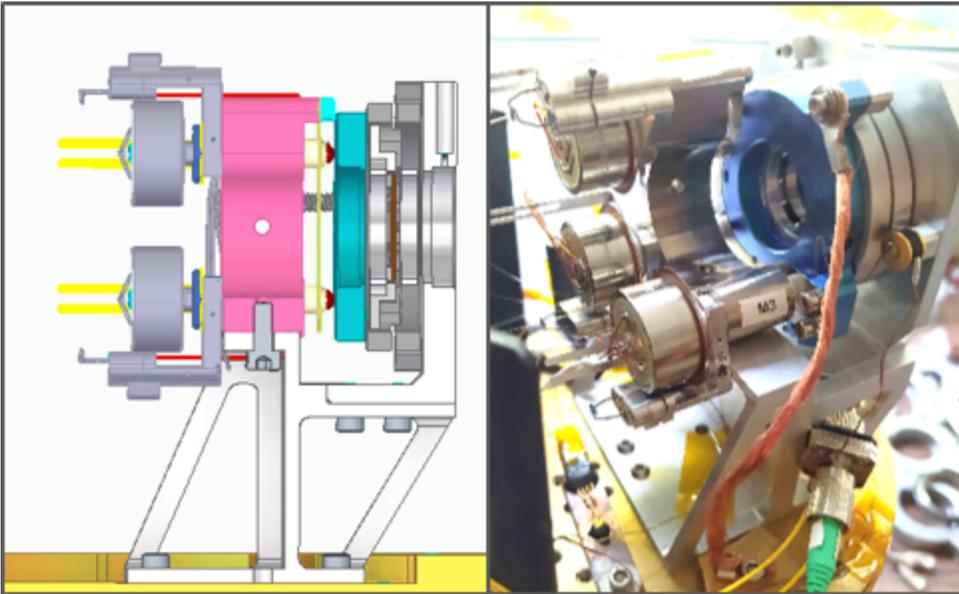


Figure 2

3D cut of the assembly of the scanning Bragg mirror prototype (left) and picture of the full setup of scanning FP on the plate of the cryostat (right).

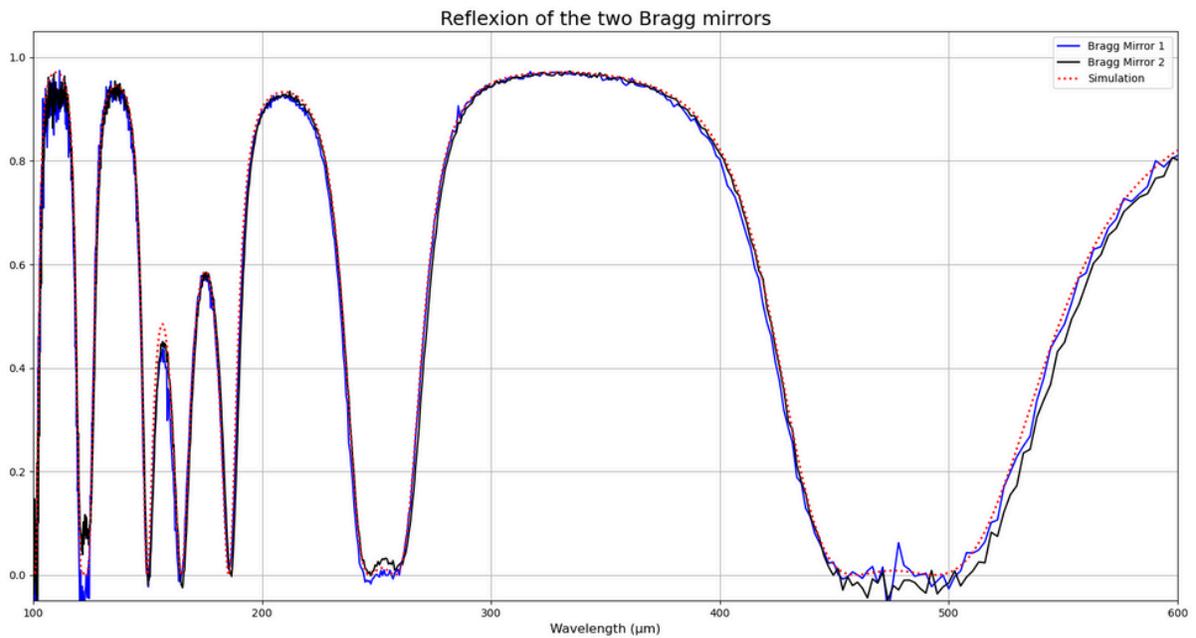


Figure 3

Spectral reflection of the two Bragg mirrors used for the scanning FP measured in the FTS, in black and blue, compared to the theoretical response in red.

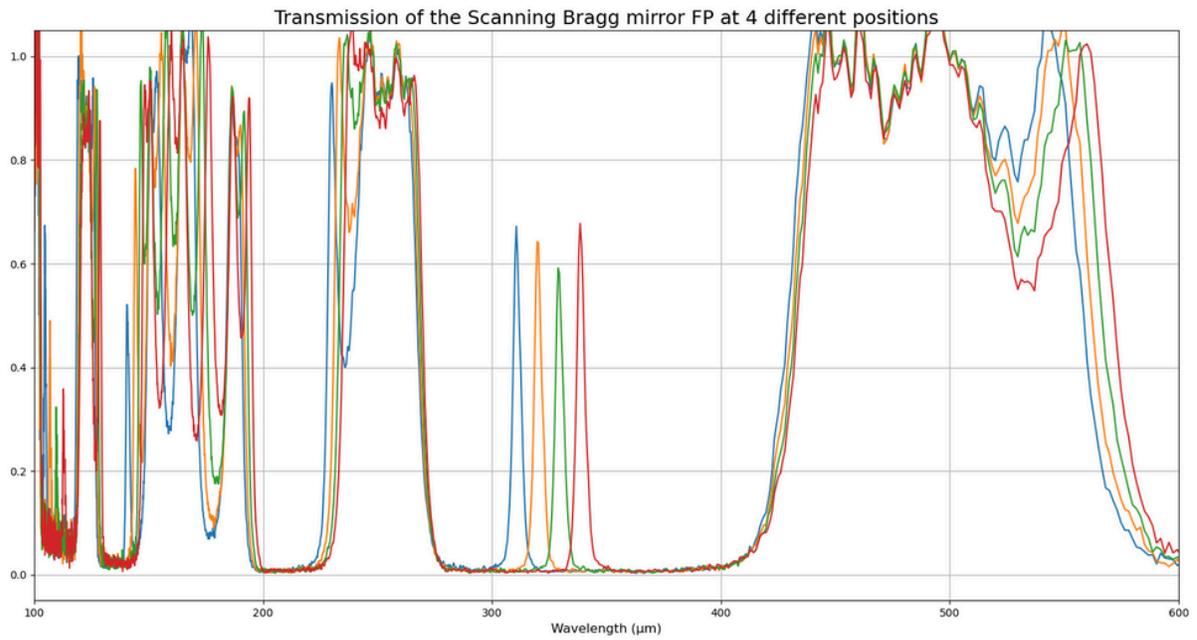


Figure 4

Transmission spectra of the scanning FP for the four sizes of cavity

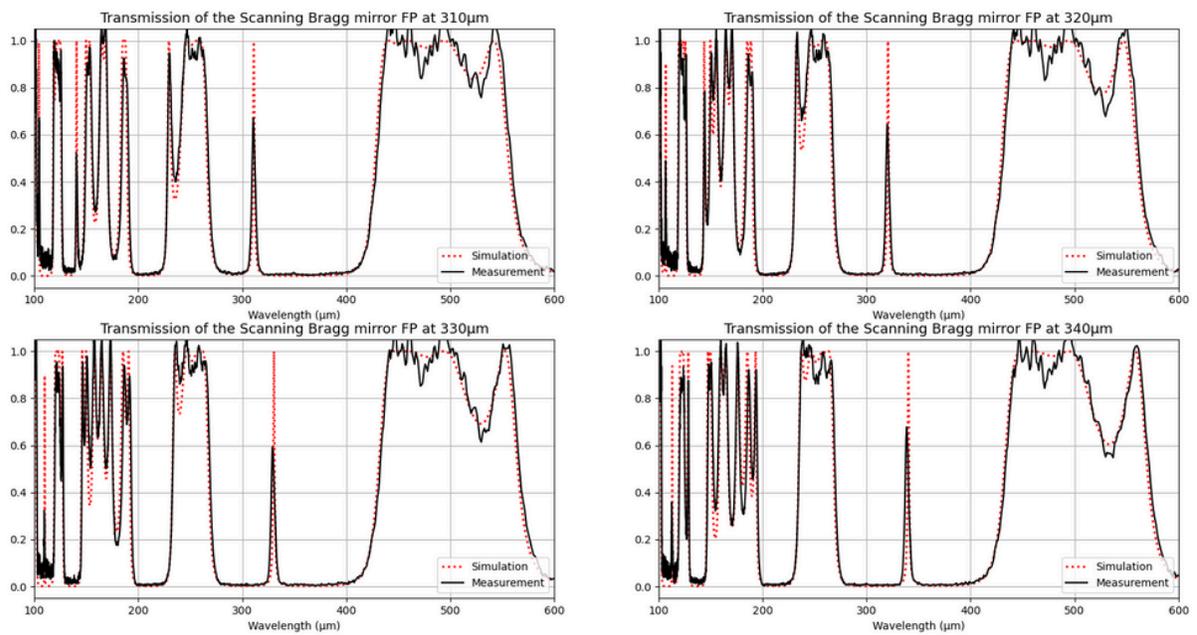


Figure 5

Superposition of the measured spectra (black) with the simulation for the for spectra (red)

Wavelength	Measured resolution	Expected resolution	Efficiency
310.8 μm	79	180	68 %
320.1 μm	84	210	66 %
329.3 μm	80	216	60 %
338.7 μm	86	211	69 %

Figure 6

Table of the performance of the four transmitted peak of FP. We calculated the expected resolutions from the theoretical model for a perfect Bragg mirror FP, plotted in red on Fig. 5.