Prototype-testbed for infrared optics and coronagraph (PINOCO)

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ABSTRACT

We present the Prototype-testbed for Infrared Optics and Coronagraphs (PINOCO) which is a large, multi-purpose cryogenic chamber. At present, the priority for PINOCO is to evaluate binary pupil mask coronagraphs in the mid-infrared wavelength region, which are planned to be adopted for the SPICA coronagraph instrument. In addition, various other experiments are possible using PINOCO: testing diverse high dynamic-range techniques, mirrors, active optics, infrared detectors, filters and spectral dispersion devices, the mechanics of the instruments, measurement of material properties, and so on. PINOCO provides a work space of 1m × 1m × 0.3m, of which inside is cooled to <5K. Flexible access to the work surface is possible by removing detachable plates at the four sides and on the top of the chamber. At the interface to the exterior, PINOCO is currently equipped with an optical window, electric connectors, and an interferometer stage. PINOCO is cooled by two GM-cycle cryo-coolers, so no cryogen is needed. A cooling test of PINOCO was successfully completed.

Keywords: coronagraph, testbed, infrared, cryogenic, exoplanet, SPICA

1. INTRODUCTION

The direct, spatially resolved observation of exoplanets is expected to be important to understand how planetary systems were born, how they evolve, and how diverse they are. For the spatially resolved observation of exoplanets, the enormous contrast in luminosity between the central star and the planet is a critical difficulty. Indeed, the contrast between the sun and the earth is $\sim 10^{-10}$ at visible light wavelengths and $\sim 10^{-6}$ in the mid-infrared wavelength region[1]. Therefore, there is an advantage for observations in the mid-infrared wavelength region from the point of view of contrast. Considering this advantage, a coronagraph has been proposed[2] for the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission[3].

Experimental demonstrations of various coronagraphs have been made in many laboratories, mainly in the visible wavelength region. On the other hand, laboratory demonstrations of mid-infrared coronagraphs have not been dedicated so much. One of the reasons for the difficulty in demonstrating high contrast with a mid-infrared coronagraph is the need for a cryogenic system to reduce the background caused by thermal radiation. Even for laboratory demonstrations of coronagraphs targeting SPICA, the experiments done so far have been limited to those using light sources in the visible wavelength region; Using a visible laser, high contrast sufficient for the detection of exoplanets in the mid-infrared region has been demonstrated using binary shaped pupil masks manufactured on glass substrates[4][5][6]. Recently, free-standing binary pupil masks have also been presented, and tests of their coronagraphic performance have been carried out using a visible laser[7][8]. Such free-standing masks are expected to be applicable in the mid-infrared wavelength region in the future.

Considering this background, we have developed a large multi-purpose cryogenic chamber(Fig.1-Fig.4) which we have named the Prototype-testbed for Infrared Optics and Coronagraphs (PINOCO).

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Fig. 1. PINOCO in a clean room (the external stages shown in Fig.2 are not attached).

2. PINOCO

2.1 Aims

The aims to develop PINOCO are following.

1. Pioneer the development of and build a cryogenic infrared multi-purpose testbed.
2. Carry out experiments which require a cryogenic environment and/or operate at mid-infrared wavelengths, e.g., mid-infrared coronagraphs, mirrors and optical structures, active optics, cryogenic mechanics, properties of materials, and so on.
3. Use the techniques and experience of us to manufacture similar testbeds.
4. Conduct guest experiments using the testbed on a 'best efforts' basis
5. Use the testbed for the education of students

2.2 Design

PINOCO provides a 1m x 1m cryogenic copper work surface with M4 screw taps on a pitch of 50mm. The work space is defined by the cold work surface and the inner radiation shields. The height of the work space above the work surface is 0.3m (partially 0.25m). The temperature of the work surface and the work space are required to be 5K or less. A window with a effective aperture of 50mm in diameter is needed to enable various optical measurements to be done, for example, testing the thermal deformation of optical devices using an interferometer. An electrical interface to operate infrared array detectors and for other purposes is required. Flexible access to the work space is also needed. We also require cryogen-free system, i.e., cooling is done by electrical power only.

Fig. 2. Left: An external stage with an optical window to one side of PINOCO. An interferometer, ZYGO GPI-XP, is set on the stage. Right: an external stage with weights for balancing on the opposite side to the optical window.

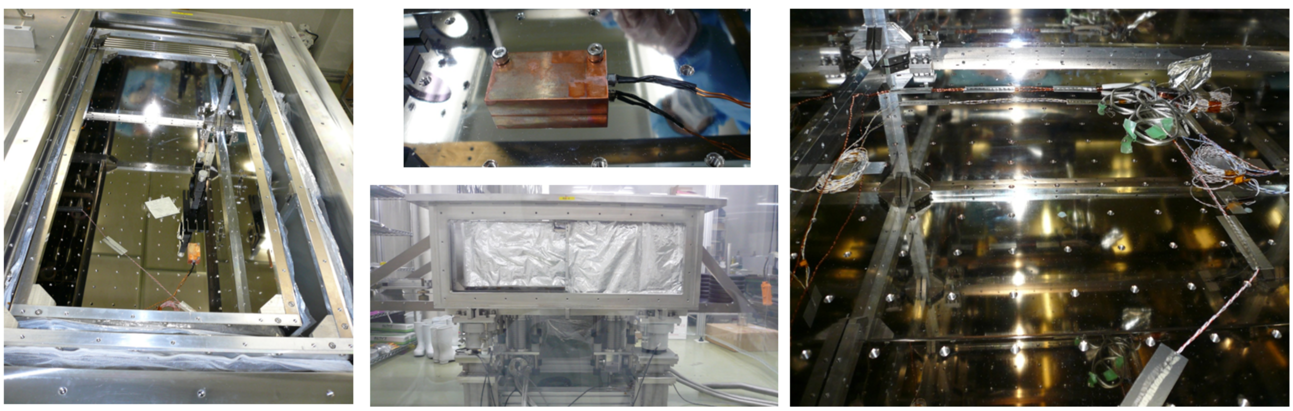

Fig. 3. Left: Half the top plate, outer shield, and inner shield have been removed, revealing the work surface. Middle-top: The heater block installed on the work surface. Middle-bottom: A side plate and the left-half of the outer shield have been removed, revealing the inner shield on the left side. Right: Inside the work space.

Fig. 4. Two GM-cycle mechanical coolers, RDK-415(left) and a helium compressor, CSA-71A(right), made by Sumitomo Heavy Industry. Co. The coolers are supported by dampers and bellows to reduce the vibration they cause to the chamber.

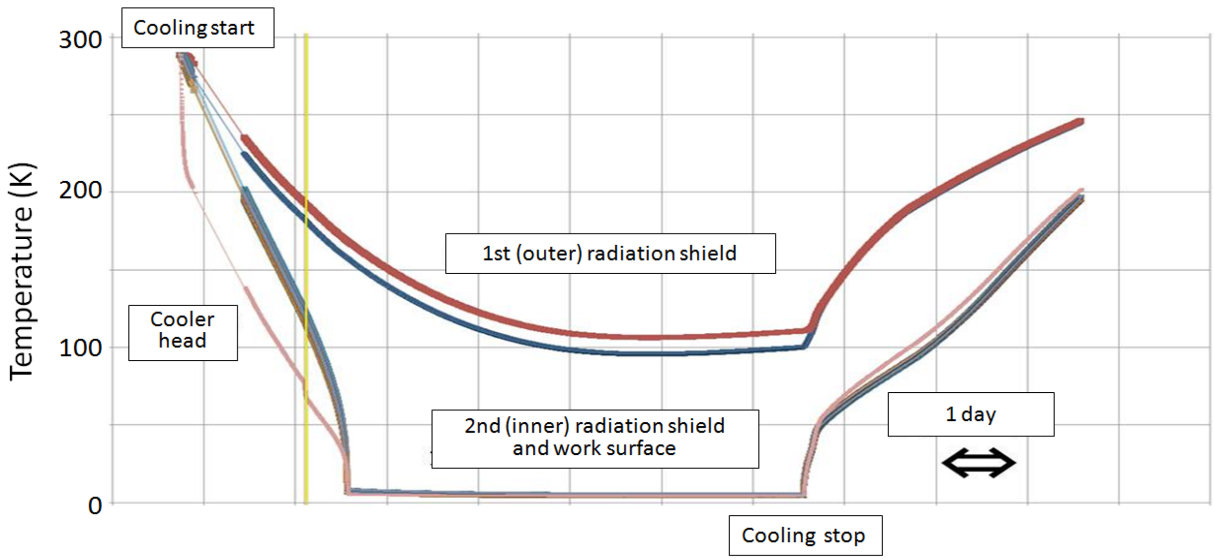

Fig. 5. Temperature curves for the first cooling test of PINOCO. The temperatures of the outer and inner radiation shields, the work surface, and the cooler head were monitored. The heater shown in Fig. 2 was not used in this test.

To realize these requirements, the vacuum chamber for PINOCO was designed as a rectangular box(Fig.1). Double radiation shields made of aluminum, the inner and outer shields, are installed in PINOCO(Fig2, Fig3). Multi layer insulation is placed outside both radiation shields. Two GM-cycle mechanical cryo-coolers, RDK415, made by Sumitom Heavy Industry. Co., are adopted(Fig.4). The helium compressor units of this system, CSA-71A, are cooled by an air fan only(Fig.4). The cooler heads are set at the bottom of the chamber with bellows and a damper to reduce vibration of the work surface by the cooler heads. The cooler heads have two stages. The first stage cools the outer radiation shields, and the second stage cools the inner radiation shields and the work surface. The PINOCO chamber is set on four supports with air suspension, and the temperature is monitored using sensors of silicon diode. A heater is installed on the work surface to accelerate the warming up process(Fig.3). The heater consists of a copper block and a resistance molded in the block.

On all four sides of the chamber, the vacuum shield plates, the outer radiation shields, and the inner radiation shields are detachable. The top of the chamber has two detachable vacuum shield plates. The top outer and inner radiation shields are also detachable. This design provides flexible access to the work space from five sides of the chamber.

BK7 glass windows were prepared for the optical interface. It is possible to install glass windows on the vacuum shield plate, the outer radiation shields, and the inner radiation shields. Blank aluminum plates can also be installed instead of the glass windows. A stage for the interferometer was manufactured and is attached in front of the optical window. Another stage was also prepared at the opposite side of the chamber to set balance weight of the interferometer.

For the electrical interface, hermetic connectors are installed in the vacuum shield plate and manganin wires link the connectors and the work space. The number of wires at present is ~100, and further installation is possible.

2.3 Cooling test

The first cooling test of PINOCO was successfully carried out May 2011. Vacuum pumping was applied for 24 hours at room temperature before cooling. Next, the two cryo-coolers were switched on. The temperature on the outer and inner radiation shields, the work surface, and the cooler head were monitored using silicon diode temperature sensors. The temperature curves obtained are shown in Fig. 5. The heater shown in Fig. 2 was not used in this test. The work surface and the inner radiation shield were cooled rapidly to 10K in the first 2 days of cooling. After that, the temperatures of the

Fig. 6. Masks manufactured for a comparative study of coronagraphic performance[8]. Masks on BK7 glass, Si, and Ge substrates, and free-standing masks made of Cu and Ni are shown. An identical checkerboard design of the same size was adopted for all masks.

work surface and the inner and outer radiation shields decreased gradually. Finally the temperature of the work surface and the inner radiation shield reached 4.5-4.9K. Then, the coolers were switched off and the chamber warmed up. Fig.5 shows the natural increase in temperature without the use of the heater. If the heater were to be used, the warm up time is expected to be shorter. Optimizing operation of the heater is planned for future work.

2.4 Experiments that can utilize PINOCO

PINOCO is potentially useful for experiments which need a cryogenic environment. For instance, the following are considered to be major issues.

Infrared coronagraphs and high dynamic-range techniques:
Recently we presented binary pupil coronagraph masks with identical designs but which were made by various manufacturing methods(Fig.6). Tests for the masks on BK7 substrates and the free-standing masks were completed in visible wavelength region(Fig.7, Fig.8). Demonstration and comparison of the coronagraphic performance of the masks in the mid-infrared region should be carried out soon. This is important for the SPCIA coronagraph and using PINOCO to do this has high priority. On the other hand, in basic research, there are various interesting high dynamic-range optical techniques: PIAA, phase masks, aperture masking, interferometric techniques, and so on. PINOCO has the potential to pioneer the application of these methods for the mid-infrared wavelength region.

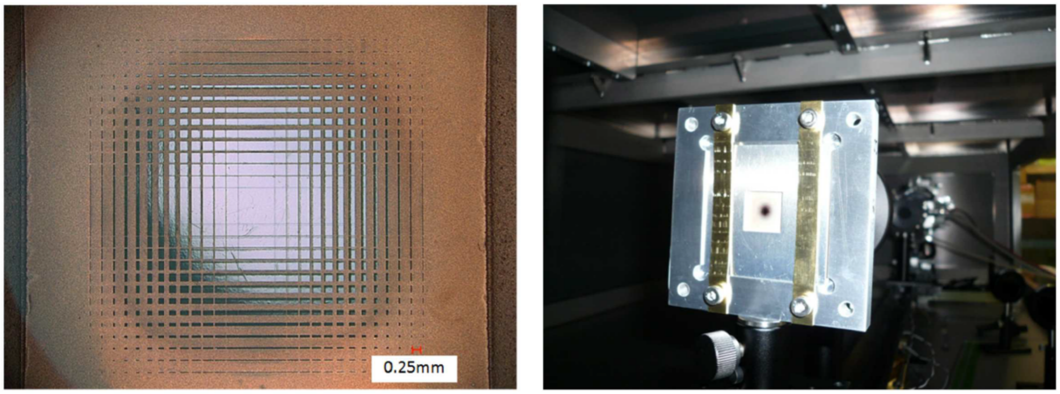

Fig. 7. Left: microscope image of a free-standing mask of Cu. Right: mask installed in the holder.

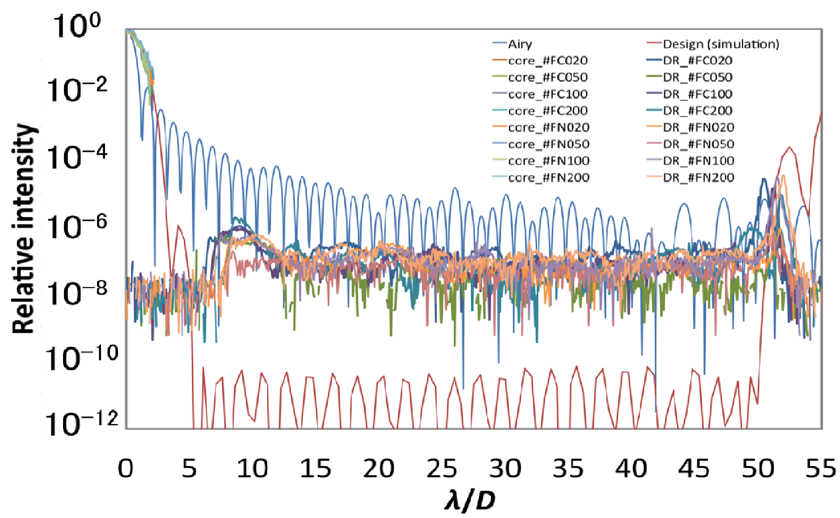

Fig. 8. Diagonal profiles of coronagraphic images obtained with free-standing masks using a visible laser (λ= 632.8nm)

Mirror optics:
Thermal deformation of mirrors and their alignment are important issues for cryogenic infrared instruments. The combination of PINOCO and an interferometer can be beneficial in addressing these issues. Infrared scattering due to the surface roughness of mirrors is also an important issue.

Active optics:
The revival of the use of a tip-tilt mirror system is being considered for SPICA-SCI. PINOCO is useful for tests of a tip-tilt mirror system. Development of a cryogenic deformable mirror is another important target of active optics for space infrared instruments.

Infrared detectors
In general, a cryogenic environment is indispensable for testing infrared detectors, e.g., Si:As, InSb, and Si:Sb. Especially for infrared coronagraphs, it is important to evaluate well internal reflection, scattering by the surface, and the stability of detectors.

Filters and spectral dispersion devices:
The evaluation of filters, gratings(including immersion grating), grisms, etc., are possible with PINOCO.

Measurement of properties of materials at low temperature
It is essential for the development of space infrared telescopes to have highly accurate cryogenic data for the materials, e.g., the coefficient of thermal expansion, thermal conductivity, Young's modulus, etc. PINOCO can provide the cryogenic environment required to measure these properties of the materials.

Cooling tests of the mechanics:
The large work space of PINOCO is suitable for testing the mechanics of cryogenic instruments, e.g., filter wheels, mask changer, and so on.

3. FINAL REMARK

We have developed a large, multi-purpose cryogenic chamber, called PINOCO. The experiments with the highest priority using PINOCO are laboratory demonstrations of binary pupil mask coronagraphs in the mid-infrared wavelength region, since this type of coronagraph is planned to be adopted for the SPICA mission. Also there are various interesting experiments which need a cryogenic environment that can be carried out using PINOCO. Officially, PINOCO is not guaranteed to be public use, and for the time being, we need to concentrate on our own engineering development. However, we are considering making it available for guest experiments, and we would welcome you contacting us for this.

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