An IR Spectrometer for Mars Drill operations

William Smythe
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
Marc Foote
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
Edward Johnson
ICX Photonics
4 Federal Street
Billerica, MA 01821
James Daly
ICX Photonics
4 Federal Street
Billerica, MA 01821
Peter Loges
ICX Photonics
4 Federal Street
Billerica, MA 01821
Irena Puscasu
ICX Photonics
4 Federal Street
Billerica, MA 01821
Steven Gorevan
Honeybee Robotics
460 W. 34th Street
New York, NY 10001
Philip Chu
Honeybee Robotics
460 W. 34th Street
New York, NY 10001
J. Granahan
SAIC
4501 Daly Drive Suite 400
Chantilly, VA 20151

Abstract - **An infrared spectrometer suited for use during drilling has been implemented by integrating an Ion-Optics solid-state IR spectrometer, a Pulse-IR blackbody source and a microthermopile detector array developed by Marc Foote at JPL into a package to fit within a Honeybee Mars Drill design. The borehole IR spectrometer is used to monitor subsurface stratigraphy encountered throughout the drilling process. The spectrometer/IR combination is used in reflectance spectrometer mode to monitor H_2O and CO_2 content, as well as iron and carbonate mineralogies.**

The solid state spectrometer uses the index of refraction of silicon to achieve the required dispersion in a small footprint. The package has low mass, with minimal requirements for a supporting structure and has most components are bonded into alignment to withstand launch and drilling loads. The original Ebert solid state spectrometer has been modified to fit within the spatial constraint of the drill segment diameter. Changes include using a Littrow layout (more compact) and stacking the grating and detector on planar part of the optical bench to conform better to the cylindrical geometry.

The illuminator is built a standard Ion Optics (Pulse-IR) infrared source with off-axis paraboloid concentrators. Illumination is a critical element for the borehole spectrometer, with the illumination and reflected signal sharing the same (small) window.

The spectrometer window is situated between fluting on the drill thus sampling cuttings near drill tip. This spectrometer will both speed operations and reduce risk in

remote drilling operations by reducing the number of times the drill string must be extracted from the borehole.

I. INTRODUCTION

The Mars Borehole Spectrometer (MBS) is a spectrometer operates in the near-infrared. It is designed to fit within the footprint of a typical Mars drill to allow monitoring compositional stratigraphy throughout the drill process – mitigating requirements to remove the drill to understand the mineralogy at various intervals during the drill process.

The motivations for drilling on Mars include understanding subsurface stratigraphy and looking for materials that are either unstable at surface conditions (e.g. water ice) or are unstable with respect to the weathering conditions at Mars surface (e.g. the intense UV irradiation, together with large temperature swings and arid conditions make the predicted lifetime for many organic molecules extremely brief.)

A. *Stratigraphy*

As the resolution of images obtained from orbit has increased, the perception that Mars subsurface stratigraphy is very complex has grown dramatically. HiRise typically achieves 30 centimeter resolution The examples from the MRO HiRise instrument, one from the north Polar Layered Deposits (PLD) and one from Valles Marineris, allows one to obtain "road cut geology" views of Mars' subsurface stratigraphy, illustrate the complexity of layering and provide evidence for mineral alteration – probably due to the presence of water. These high resolution pictures still have characteristics scale length that is more than an order of magnitude greater than for the drills: one to ten meters drill stem length, sample intervals about one to ten centimeters in separation , and imaging scales at 10-100 microns. However, these images give a feel for the stratigraphic complexity that will be encountered.

B. *Drill monitoring*

An infrared instrument located within a drill provides opportunity to monitor cuttings, and the drill wall, without removing the drill. A typical drilling sequence involves periodic removal of the drill to acquire samples for analysis. This removal and re-emplacement requires a significant amount of time that can exceed the time required for drilling, and carries significant risk with respect to backfilling the hole, cross contamination, and even sticking the drill. The spectrometer enables analyzing the cutting and wall for mineralogy without removal, speeding drill operations and enabling sample selection based on composition. It helps to limit the scale lengths for cross contamination between stratigraphic layers. It is anticipated that the compositional measurements of stratigraphy will provide high contrast between some layers that would be overlooked based on variations of visible albedo.

Figure 1 Mars Polar Layer deposits imaged by HiRise (PIA09097) show the complexity of layering of dust, sand, and ice.

II. INSTRUMENT DESCRIPTION

A. Instrument summary

The MBS is a near-infrared spectrometer in a Littrow configuration. The spectrometer uses a solid state waveguide both to achieve sufficient dispersion in a small footprint and to improve the throughput. The MBS subsystems include a silicon waveguide, a grating, a focal plane assembly, an illumination source, a Figure 2 window, a drill mount and a controller. This particular instance of the instrument operates in the 3-5 micron range with 64 discrete wavelengths. The waveguide material, silicon, constrains the wavelength range to the silicon transparency region, essentially 1-6 microns. Other waveguide materials can be used to extend this range. To date it has not proved practical to add order-sorting filters to the focal plane, so the waveguide range must span a single octave (eg 1-2, 2-4 microns). The spectrometers can be ganged to cover the entire silicon transparency wavelength region.

B. Silicon waveguide

The silicon waveguide is used to increase dispersion, to increase throughput, and to maintain alignment in for the spectrometer, The high index of refraction for silicon increases the dispersion by about a factor of three, allowing MBS to achieve the desired spectral resolution within the nominal drill diameter, The silicon wafer, 1 mm thick, also serves as a waveguide. Light diffracted off the grating at an angle reflects off the parallel planes of the waveguide and adds constructively at the detector.

A preliminary version of a solid state spectrometer was developed under Small Business Innovative Research by Ion Optics, Inc., and later as a joint effort under NASA's Planetary Instrument Definition and Development (PIDDP) programs. At the heart of this breadboard is a D-shaped silicon waveguide 1 mm thick and roughly 5 cm by 3 cm across. The unit uses a conventional Ebert layout, with the optical elements on the edges of the silicon waveguide. Infrared radiation is focused by an external lens onto an entrance slit defined by gold coatings on the silicon edge. Radiation traverses the silicon to a curved mirror on the opposite face, and then the light is dispersed by an ion-milled diffraction grating and focused by a second concave mirror. After exiting the silicon waveguide on the flat edge, the spectrum is detected by a linear array of thermopile infrared detectors. Each component of the spectrometer: the slab waveguide, the fold mirror, and the reflective diffraction grating, is made of silicon and fabricated into a seamless, permanently aligned unit with no moving parts. The components themselves incorporate a number of advanced design features. The slab waveguide is formed to include the other components (stops, mirrors, and grating), including A/R coated beam dump facets to remove unwanted diffraction orders. Because silicon is opaque to photons above its band gap, the slab excludes visible light from the detector. Silicon's high refractive index provides lossless reflections at the polished top and bottom faces of the device, acting as a waveguide to keep the radiation in the plane of the slab. Because of the high index of silicon, the cone of incident illumination is dramatically reduced upon entering the waveguide. This effect provides better optical throughput than can be achieved with an open-air spectrometer and overcomes many of the astigmatism issues associated with conventional designs. This waveguide, with its f/1 input lens, was tested independently of the thermopile detector array by mounting an infrared imaging camera at its output port. Initial tests with a broadband source were very promising. The zero order diffraction spot is roughly the size of the 80 μm input slit, showing that the imaging components of the spectrometer are optimized. Very little stray light is seen between the zero order spot and the first order diffraction spectrum. Comparison of total light in the first order spectrum to the zero order spot yields a 47% grating efficiency. The total throughput of the silicon waveguide with input lens is estimated to be 15%.

Development challenges for this prior version of the waveguide included tuning the zero order beam dumps and developing a process that permitted polishing the waveguide and applying gratings in a batch process having reasonable yield. This earlier spectrometer was in an Ebert configuration, and had a footprint too large to fit within the drill. Additionally, both the grating and the detector were mounted on the (one millimeter) edges, further increasing the footprint size. These size issues were resolved both by converting the spectrometer to a Littrow configuration and by moving the focal plane array off the edge through use of a 45 degree mirror polished into the silicon wafer.

The MBS has modifications of the prototype wavegude that include conversion to the Littrow configuration and focal plane placement mentioned above and direct writing of the grating onto the waveguide to improve blazing and throughput.

C. Grating

Several processes for applying gratings to the waveguide were tested including bonding replicated gratings to the waveguide, forming a grating out of the photo-resist, and ruling the gratings directly onto the waveguide. The latter process, though preferable, was early believed to be too technically challenging due to the difficulty of ruling silicon, and the very tight dimensional control required. A test ruling in silicon has recently been achieved by D. Wilson (JPL) and will be used on the borehole instrument – significantly improving throughput.

D. Focal plane assembly

Thermopiles are broad band, uncooled infrared detectors in the same class as bolometers and pyroelectric detectors. A thermopile consists of several series-connected thermocouples running from the substrate to a thermally isolated infrared absorbing structure. Incident infrared radiation creates a temperature difference between the absorber and the substrate, which is measured as a voltage across the thermocouples. Thermopiles offer a simplicity of system requirements that make them ideal for some applications. Thermopiles typically operate over a broad temperature range and are insensitive to drifts in substrate temperature, so require no temperature stabilization. They are passive devices, generating a voltage output without bias. Thus, for some applications thermopile detectors can be supported by more simple, lower power, more reliable systems than either bolometers, pyroelectric or ferroelectric detectors. If thermopiles are read out with high input impedance amplifiers they exhibit negligible *1/f* noise since there is no current flow. They typically have high linearity over many orders of magnitude in incident infrared power.

A NASA funded development effort at JPL has produced 64 element linear arrays of thermopile detectors on silicon substrates. These detectors are 1.5 mm long with a pixel pitch of 75 µm, matching the geometry of the current Ion Optics spectrometer. Each micromachined detector consists of a 0.6 µm thick suspended silicon nitride membrane with 11 thermocouples composed of Bi-Te and Bi-Sb-Te. A schematic diagram of a single pixel is shown in Fig. 6, while a photograph of the complete array is shown in Fig. 7. At room temperature these devices exhibit D* values of 1.4×10^9 over the full range of wavelengths proposed for this instrument (3-12 µm). This performance is significantly better than that reported for other thermopile arrays. Detector responsivity is typically 1100 V/W at dc, and thermal response times are 100 ms. The detector noise has been measured at frequencies as low as 20 mHz, and the only noise source is Johnson noise from the 40 kΩ detector resistance. The responsivity and response time have been measured as a function of temperature from room temperature down to 100 K. The total change in these quantities over the entire temperature range is roughly 20%, indicating that these detectors perform well over the entire range of Martian temperatures.

Figure 6. Schematic diagram of a single thermopile detector pixel. The detector is a 0.6 µm membrane composed of silicon nitride and metal lines and connected to the substrate at the left and right side of the figure. Infrared radiation heats the thermally isolated membrane structure. The temperature difference between the membrane and substrate generates a voltage in the 11 series connected Bi-Te / Bi-Sb-Te thermocouples.

E. Illumination source

The illuminator utilizes an Ion Optics *puls***IR**® radiator, an extremely thin metal ribbon with a proprietary surface treatment to improve the conversion efficiency of radiator thermal energy to in-band radiation. The *puls***IR**® sources, with efficient, low thermal mass radiators and appropriate infrared windows (or windowless) convert significantly more electrical energy into useful, in band radiation than standard tungsten filament bulbs.

Shot-to-shot repeatability will govern measurement resolution. Experimental data of thermal stabilization of Ion Optics IR sources is shown in Figure 7. Time in seconds is displayed on the x-axis, source power voltage (square wave signal) is on the left, and thermal signal voltage (triangular signal wave) is on the right. In this experiment, the standard deviation was about 2 mV on the power supply, and on the infrared detector signal. This would be the equivalent calibration error – 2mV out of a 3V signal. Improved electronics has reduced the standard deviation of drive voltage for Ion Optics new MEMS chip filaments by more than a factor of ten (Figure 8) below 0.2mV.

F. Window and drill

The drill is a fluted cylinder with a 25 millimeter clear ID. It has so far proved impractical to place the windows in the fluting itself, because of the small dimension. The windows are currently placed between the fluting, and routinely monitor the cuttings. Several window materials, together with two bonding approaches were tested. Results showed that both traditional metallic bonding and epoxy bonding provided satisfactory performance with respect to durability. Both sapphire and diamond windows remained scratch-free during tests drilling into representative materials.