MICROSPECTROMETER FOR INTERPLANETARY MISSIONS AND ROVERS, 4th international Planetary Probe Workshop, 27 June- 30 June, 2006, Pasadena, California, USA

Dipl. Ing. Kruselburger Andreas

Department for Astronautics
Technische Universität München
Boltzmannstrasse 15
85748 Garching
Germany
Email: andi.krusel@t-online.de

ABSTRACT

Developments in micro technology over the last years offer the possibility for new instrument designs. These instruments could provide scientists with a complete new family of mission scenarios. This paper contains a summary of flying instruments and their main parameters, as well as a summary of new methods, technologies and elements for sensor development. This leads to new instrument designs. The present study analyzes the case for micro spectrometers.
In this presentation a couple of different micro spectrometer designs for potential interplanetary missions are presented. All of them have been realized as prototypes through the use of MEMS Technologies.
This new class of instruments provides opportunities for new mission concepts or improvements for existing mission scenarios. All space missions are strictly limited in mass, size, power and cost. The use of MEMS technologies provides the opportunity to dramatically decrease all of these factors. Instrument miniaturization also leads to mass reduction and power consumption minimization. Through the use of inexpensive reproduction methods, the fabrication cost for these instruments could be minimized.
One potential new mission concept is the use of a large group of miniaturized instruments connected to each other by means of a radio linked network. Small and simple mechanisms within each sensor element provide the ability to move around collecting data from different spots. Through this kind of mission it would be possible to explore caves and very rough terrains. Instead of sending one spacecraft with a selection of a few expensive, conventional experiments, these new instruments offer the possibility to send hundreds of small sensor packages to a planetary surface. A similar approach could be used to perform Aerobot missions, where instrument packages are dropped during flight through an atmosphere. For such missions to be successful, new miniaturized payloads are necessary. A novel micro spectrometer that combines the advantages of the waveguide and the programmable grating technology is described in this paper.

1. MEMS/ MOEMS

Through the use of MEMS technologies, new types of instrument design are possible. Mechanisms of the smallest dimensions and minimum power consumption are now feasible.
The main advantages of this relatively new type of technology are as follows:
- Production in large numbers at low cost
- Small size
- Low weight
- Extreme accuracy
- Complex mechanisms feasible

However, some disadvantages are connected with MEMS technologies. The basis for most of the process steps applied in this area is the use of masks. The layout and production of these masks is quite expensive which makes the production of a few units comparatively expensive. Therefore, applications where larger amounts of units are used could be of interest.

2. MISSION CONCEPTS

All previous space missions were one of the following types of main mission scenarios:

Flyby
Flyby missions have the advantage of smaller propulsion requirements. However, the shorter pass-over time limits the ability to observe the target in comparison to orbiters. An orbiter goes into orbit around a celestial body which allows long term observation of a target.

Lander
Landers touch the surface of a moon and/or a planet. Therefore, they offer much better ground resolution. These probes can apply in situ research methods rather than using remote sensing methods.

Rover
To improve the surface mobility, mobile rover systems like the Mars Exploration Rovers are applied.

Sample return
A sample return mission from moons, planets, or comets is of great interest for the interplanetary science community. Such a mission has only been completed a few times due to the propellant requirements and the mission complexity. One mission has been completed from the moon with interplanetary dust, and an unsuccessful attempt at a sample return from a comet has also taken place.

New concepts with improved capabilities are now a realistic alternative through the use of miniaturized elements and payloads. The concepts listed below will briefly be described in the following section.

Aerobots
Aerobots are simple probes that could be dropped from a balloon. Through this type of mission, atmospheric profiles could easily be realized. Potential targets for their use could be the atmospheres of Mars, Venus or Titan.

Balloons
Deeply connected to the Aeroprobes are potential balloons. Mars, Venus or Titan are interesting targets for this type of mission. Humankind has had both successful and unsuccessful experiences with orbiters and landers especially on Mars, and balloons could possess great potential for exploration. Balloons may provide the best opportunity to climb to different heights, which would allow for the collection of different measurements from varying altitudes and at the same time travel greater distances over the planet to obtain an overall picture. By decreasing the altitude during the night it would be possible to do in-situ surface science.
A further possibility would be the use of a blimp to further improve previous mission concepts through improved maneuverability.

Air vehicles
Aside from balloons, aerobots and blimps, there are other possibilities for atmospheric exploration missions. These could include other potential "Unmanned aerial vehicles". NASA is investigating this option with the ARES Airplanes. There are also various papers available on the use of micro helicopters.

Penetrators
A penetration system is a device that is driven through its own kinetic energy into the soil of a moon's or planet's surface. MEMS or MOEMS payload devices are, therefore, highly recommended because they can withstand enormous acceleration loads that would appear during such missions.

Surface vehicles
There are a large variety of mission concepts available that could be used for in-situ surface missions. The rovers used in the past had restricted movement and needed a relatively flat surface to land. New concepts could therefore offer great advantages.
An example of a surface vehicle could be a spider like robot that is able to climb very steep hills or walk through rough terrains.

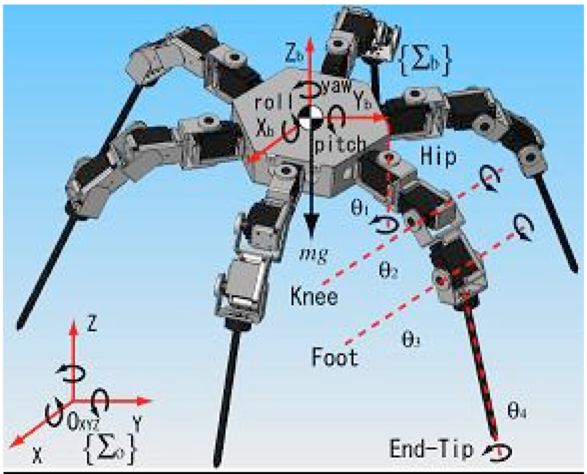

Fig. 1: Bio inspired surface vehicle developed at the Tohoku University [1].

Also, other types and designs of surface vehicles could be found on the drawing boards of universities and space agencies all over the world [2],[3].

Subsurface systems

The material of the top surface layers erode over billions of years due to wind, meteorites and other environmental influences.
Therefore, it is planned to send a small probe deep into the surface to collect data.
A "mole" is a tool that was developed for the Beagle 2 lander by DLR that would dig itself into the ground and transmit data.

Network-, Swarm- or Micro probes

Another new application is the use of groups of small spacecrafts. The idea behind this kind of mission is the use of hundreds of identical instruments that are all connected to each other via a radio linked network which allows communication between the spacecrafts. If single elements of the overall system fail, redundancy of the communication link is in place through the other elements of this network.
A potential application would be the use of small balls between the size of a ping pong and a tennis ball that has a spring inside. MEMS or piezo actuators contract this spring and release the mechanism which leads to a small jump of the device.
With such a mission approach it would be feasible to send a "Mars cave explorer" to the red planet. This mission could land near one of the great volcanoes where potential lava tunnels are expected. After finding a potential access to these caves, single hopper units can jump into the caves to collect data. Many astrobiologists think these specific places may be where life exists on Mars if it does.

Even if 40% of the total instrument packages were lost during such a mission, the overall mission is not endangered at all through the high redundancy within such a network.

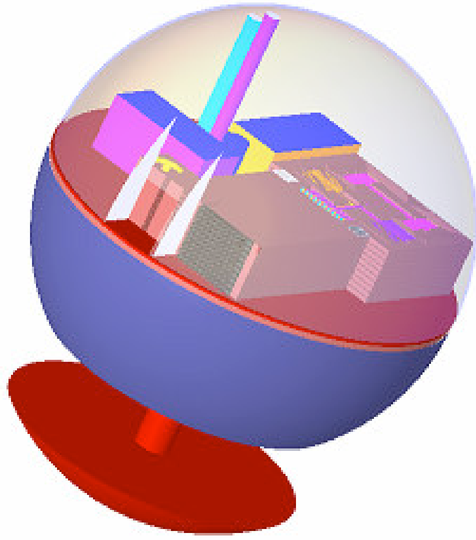

Fig. 2: Hopping micro probe for swarm applications for various targets [4].

3. ANALYSIS INSTRUMENT PARAMETER

To start the process of designing a new type of micro spectrometer the first step was to define the main instrument parameters required.
An analysis was made of various interplanetary instruments flown on different missions. This analysis covered the spectral range of the instrument and the possible spectral resolution. The overview led to average values for both numbers. These average values were targeted in this analysis as a required minimum performance for the new instrument.
Additionally, an overview of different studies on requirements for future instrument parameters was performed. These studies were done by the "Mars Exploration Programme Analysis Group" (MEPAG) and the "Astrogeology Programme Group". Furthermore, different papers on conferences regarding future science missions were considered. This includes the "Mars Infrared Workshop", "Spectroscopy on Mars" and a paper with recommendations on a Neptune mission.
The results of the survey of the different papers and the statistical analysis is summarized in the following table.
This overview led to a spectral "target" range of 0,4 - 2,5 µm and a desired spectral resolution of at least 10 nm.

	λ [μm]	Δλ[μm]	R=λ/Δλ
Analysis missions	0,4 - 2,1	18,3	3904
MEPAG	1,0 - 5,0	2,5	---
MARS IR Workshop	0,4 - 2,5	<15	---
Spectroscopy on Mars	0,4 - 2,5	<10	---
	2,5 - 5,0	---	250
Astrogeology program	1,2 - 4,8	---	---
Recommendat. Neptune	1,0- 5,0	---	300

Table 1: Overview Instrument requirements

4. INSTRUMENT CONCEPTS

During the research for this new concept, various other micro spectrometer concepts were found. These will briefly be described in the following section.

Micro Fourier- Transform- Spectrometer

A Fourier Transform Spectrometer uses a beamsplitter to divide the incoming radiation into separate rays. These rays travel different variable distances and are then recombined where they interfere. This interference is detected with the movement of the mirror that is responsible for the travel distance of one of the rays. A Fourier transformation of the detected signal then delivers the spectrum of the target. The following picture shows a prototype miniaturized Fourier-transform-spectrometer.

However, work on this type of a micro-Fourier-transform-spectrometer was canceled. The design and the production of a beamsplitter in this scale is quite a challenge, and this challenge caused the system to become obsolete which lead to the end of the project.

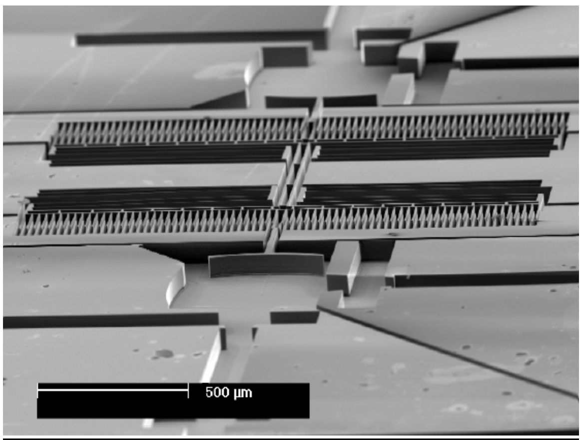

Fig. 3: Prototype of a micro Fourier transform spectrometer without beamsplitter [5].

Fourier lamellar grating

A similar approach is the use of lamellar grating. Instead of having two mirrors that are in a rectangular position to each other, the two mirror planes are parallel. Therefore, the beamsplitter could skipped. To avoid unplanned interference the two mirrors are split up into small pieces of mirrors that are overlayed as displayed in figure 4.

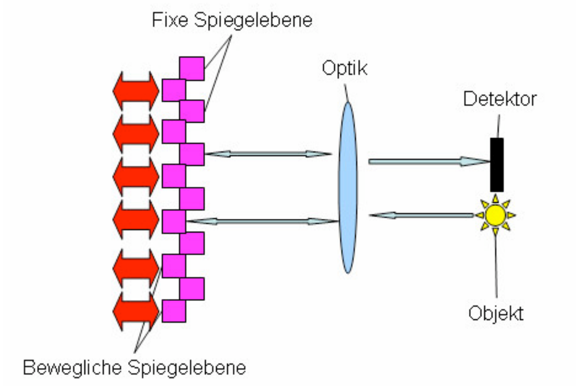

Fig. 4: Lamellar grating micro-spectrometer concept [2].

The purple rectangles display the two different mirror planes. The left row is the variable mirror plane. Through the movement of this plane it is possible to detect an interference signal similar to the Fourier transform spectrometer in a simplified instrument. Unfortunately, because of optical properties it is mandatory to use a relatively expensive optical system which makes the whole system less interesting in comparison to other options described in the following chapters.

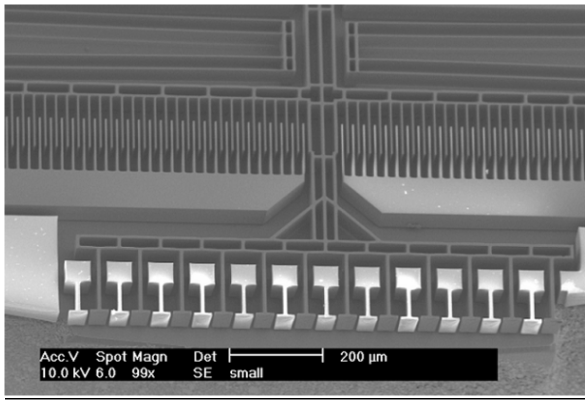

Fig. 5: Prototype of a lamellar grating micro-spectrometer [6].

Figure 5 shows a prototype of a lamellar grating for a micro spcetrometer. The light elements along the bottom are the fixed mirror plane, the dark elements in between are the variable mirror. All of the dark elements are connected with the electrostatically driven actuator in the upper part of the figure.

"Standing wave" spectrometer

A "standing wave" spectrometer is also a very specific form of a Fourier-transform-spectrometer. Here the sensor is combined with the beamsplittter, and one fixed mirror is used. The radiation first enters the partially transmissive sensor element. About half of the radiation is absorbed or detected. The rest of the radiation passes the detector and is reflected from a mirror behind the detector and falls again on the backside of the detector. The difference in the travel distance is measured through the movement of the mirror.

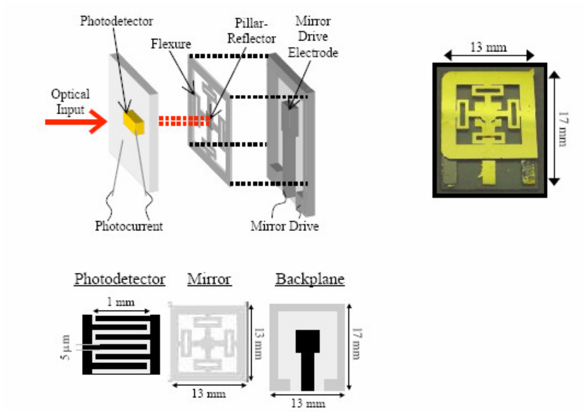

Fig. 6: "Standing wave" micro-spectrometer concept [7].

On the left side, Figure 6 shows the overall configuration of the device with the main dimensions of the parts. On the right the mirror element's mechanical structure is illustrated.
This is a very compact design for a spectrometer, and the technical requirements for the partially transmissive detector are quite high. Furthermore, the material properties of the sensor elements are highly dependent on the wavelength. Therefore, an application for a spectrometer that should work within a bigger wavelength range as required here is not viable.

Programmable grating
A very promising new technology is the use of a programmable grating. This is a normal grating spectrometer. Rather than a fixed grating, a micro mechanical device that can change its shape will be used. With such a device it would be possible to emphasize specific parts of the spectrum to get better information within this spectral area.
Another idea would be a completely new approach in spectroscopy. Through the change of the shape of the grating, very specific spectral ranges could be emphasized as mentioned above. Furthermore, the spectrometer has a database of different chemicals. Depending on the chemical of interest, the shape of the grating is adapted. The detector simply detects the main peaks within the spectrum. As opposed to detecting the whole spectrum, a "Yes-No" question is answered. Depending on the complexity of the grating and the size of the database, such a device would be able to answer the question of which specific chemicals are available. This type of system could dramatically reduce the amount of data to be transmitted back to Earth.

Waveguide spectrometer
The waveguide technology is also very promising for an application as a micro spectrometer. Similar to an optical fiber, a wave guide keeps radiation coupled into the core layer. A specific optical layout of the device allows very flexible designs. A specific structure along the sidewalls or a reflective surface establishes gratings or mirrors within this device.
With this simple technology, miniaturized and monolithic spectrometers can be produced.

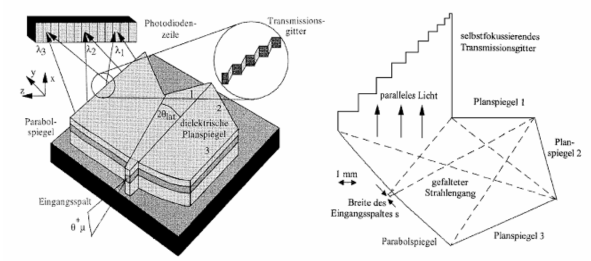

Fig. 7: "Standing wave" micro-spectrometer concept [4].

Figure 7 shows a potential design that includes three plain mirrors and one focusing mirror. On the upper left side of the device, there is a self focusing, transmissive grating. This technology offers great degrees of freedom to design the optical layout. This makes it very promising for an application for a new spectrometer.

Borehole spectrometer
This is not a specific concept for a spectrometer. However, because of its importance for future missions it will be mentioned briefly. Subsurface material is of great interest for the scientist. Surface material from radiation, erosion, weather, etc. was influenced over the millennia. Subsurface material, however, could provide clues about the original material. To obtain this data, new concepts on how to get there must be developed.
Common to all these concepts is the need for a miniaturized spectrometer in the diameter of a driller. Such an instrument could also be used for a mole mission similar to the DLR-payload for Beagle 2.

5. DEVELOPMENT PLAN

None of the technologies alone is sufficient enough to handle the requirements. The lamellar grating technology seems very promising. However, through the combination of a programmable grating and the waveguide technology a very interesting instrument can be designed. A potential stepwise development process will be described briefly.

The first step could be the design of a monolithic waveguide block with a reflective grating on one of the sidewalls. In Figure 8 this is illustrated in grey on the right side.

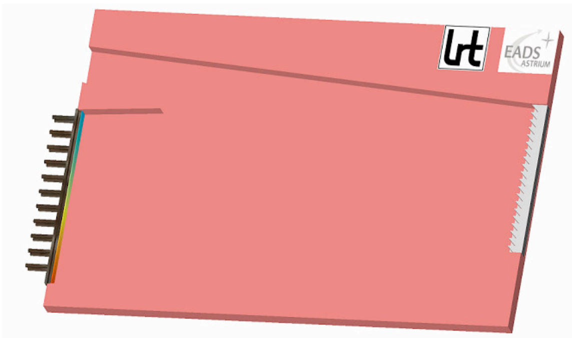

Fig. 8: Micro-spectrometer with fixed diffraction grating [4].

The input slit is on the left side next to the sensor element. After diffraction on the grating, the spectrum is on the detector on the left side in black.

The same layout could be used for an improved version where the grating is replaced through a programmable grating as described above. Figure 9 illustrates a simplified, variable, programmable grating. To use this technology a more detailed study must be performed on the various possible options to realize such a device.

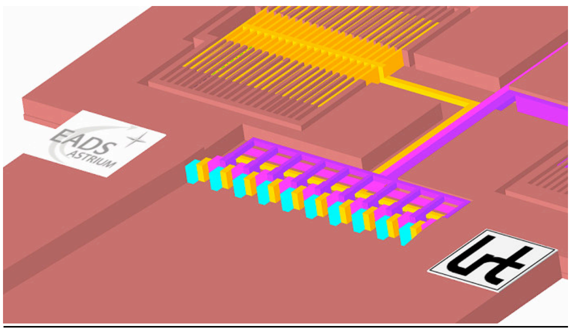

Fig. 9: Simplified programmable grating [4].

A further improvement could be the use of a light source to provide the opportunity to gather scientific data including data from the subsurface or in areas without sufficient sunlight. Such light sources could also be included in the substrate and, therefore, be part of the monolithic block which simplifies production. Missions as described under the chapter network/swarm missions would clearly benefit from such an instrument.

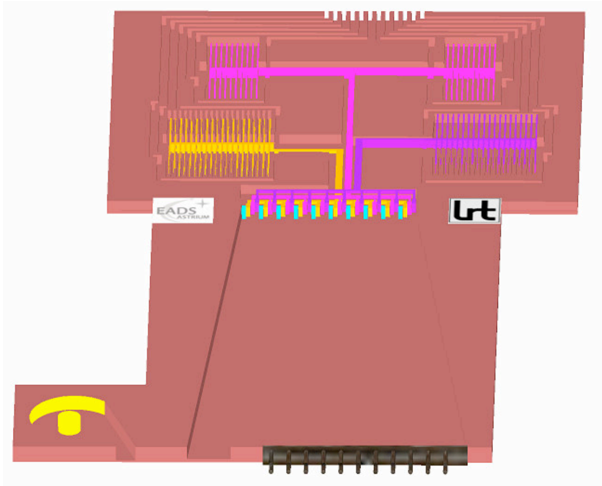

Fig. 10: Micro-spectrometer with programmable grating and integrated light source; approximate size 30mm by 10mm [4].

The basic layout with a single input fiber is able to observe one specific point. Therefore, no spatial information could be gained. MEMS elements like a small rotating micro mirror could provide the option to gain a line scan instead of a point observation. A two dimensional, moveable mirror could scan a two dimensional scene. However, the amount of data that has to be transmitted back to Earth increases dramatically.

Through the very thin design of the whole instrument the third dimension is almost not used at all. Therefore, a couple of instruments can be put on top of each other to provide mapping functions. Different types of spectrometers can be used together in the case of fixed gratings.

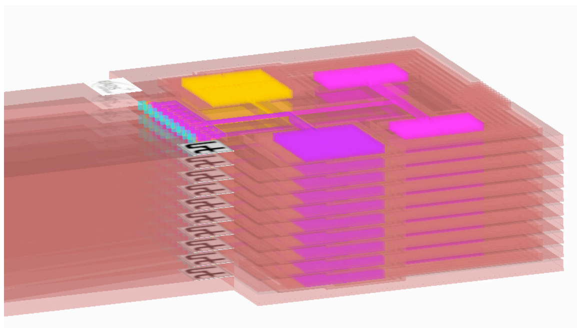

Fig. 11: Stack of micro- spectrometers [4].

6. CONCLUSION

This study showed the great potential for new miniaturized spectrometers and the possibilities such instruments provide. Different types of potential micro spectrometers were introduced, and as a result, a development process for a multifunctional miniaturized spectrometer was described. The main technologies used were the promising waveguide technology, programmable gratings and micro-electro-mechanical-system.

7. ACKNOWLEDGEMENT

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