Miniature, Low-Power, Waveguide Based Infrared Fourier Transform Spectrometer for Spacecraft Remote Sensing

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Abstract. Fourier transform spectrometers have a venerable heritage as flight instruments. However, obtaining an accurate spectrum exacts a penalty in instrument mass and power requirements. Recent advances in a broad class of non-scanning Fourier transform spectrometer (FTS) devices, generally called spatial heterodyne spectrometers, offer distinct advantages as flight optimized systems. We are developing a miniaturized system that employs photonics lightwave circuit principles and functions as an FTS operating in the 7-14 μm spectral region. The inteferogram is constructed from an ensemble of Mach-Zehnder interferometers with path length differences calibrated to mimic scan mirror sample positions of a classic Michelson type FTS. One potential long-term application of this technology in low cost planetary missions is the concept of a self-contained sensor system. We are developing a systems architecture concept for wide area in-situ and remote monitoring of characteristic properties that are of scientific interest. The system will be based on wavelength- and resolution-independent spectroscopic sensors for studying atmospheric and surface chemistry, physics, and mineralogy. The self-contained sensor network is based on our concept of an Addressable Photonics Cube (APC) which has real-time flexibility and broad science applications. It is envisaged that a spatially distributed autonomous sensor web concept that integrates multiple APCs will be reactive and dynamically driven. The network is designed to respond in an event- or model-driven manner or reconfigured as needed.

Keywords: Spectrometers, waveguides, planetary missions, autonomous systems, planetary spectroscopy, distributed systems.

1. Introduction

The 2010 Planetary Decadal Survey recommends a high priority be placed on remote sensing technology, with a focus on developing and maturing novel, cross-cutting, low-mass/power sensors integrated into robust, low-cost system architectures. The NASA Space Technology Grand Challenge report notes *"In part, our learning has been limited by the lack of sophistication of our technology to observe, probe, collect, distribute and analyze information about the geology, weather, climate, environment, and natural and man- made phenomena affecting the Earth and other elements in the universe."* High priorities for Earth science and planetary science include the Global Atmospheric Composition Mission (GACM) and New Frontiers 4, respectively, as their long-term mission goals with clear directives to *"foster innovative space-based concepts."*

Thus, we envision the need for continuous monitoring of atmospheric-gas-species composition and thermal changes at various sample positions on planetary surfaces. Driven by this goal, we are investigating a system for in-situ global mapping and monitoring of properties such as atmospheric species and surface mineralogy using near-infrared (NIR) and mid-infrared (MIR) spectral signatures. The system architecture will be comprised of heterogeneous network-centric sensors for automated acquisition of spectra and relayed to base for synthesis into global maps [1][2]. The system will be initially optimized for designated inner solar system bodies such as Mars, Earth, Moon, and near earth orbit asteroids. The system is certainly extensible

to outer planet missions. The primary goals of an idealized system involves a remote sensing architecture concept (i) that can be deployed on the surface or in orbit, for monitoring atmospheric species, surface emissions, and mineralogy over global scales on Earth, Mars, Venus, Moon, and other solar system bodies and (ii) be based on sensors that are reconfigurable in real time to address science investigations pertaining to a changing local environment.

1.1 A Potential Application

The changes in the Discovery mission program offer an enticing possibility for Mars missions. We vision deploying a large numbers of heterogeneous sensors communicating across an intelligent network to monitor local environmental properties. For example, an autonomous Mars rover or other delivery system (e.g., balloon for broader distribution) can drop these devices at various strategic locations for continuous monitoring of atmospheric species of interest such as gaseous water and CH_4. The sensor module must be self-contained and not require additional intervention in terms of alignment or power delivery. The sensor monitors environmental parameters such as dust abundance (Fig. 1), and sends data to command and control habitats and/or base stations on the planetary surface with an option for routing to Earth. As environmental changes are noted, real-time commands can set different operational states like wavelength and spectral resolution to optimize signal-to-noise; an example use case scenario is shown in Fig. 2.

1.2 The Concept of an Addressable Photonics Cube (APC)

Our APC concept is shown Fig. 3. Each face has a collecting area on the periphery to capture incident solar energy. The single optic focuses light from a broad field-of-view to the integral spectrometer-on-a-chip. The observed spectrum is relayed to a control station. The energy derived from the solar insolation is the sole source of power for instrument operation. The heart of the spectrometer includes a revolutionary development in spectrometer technology – Photonics Light-wave Circuit (PLC) waveguides – as the basis of the interference phenomenon.

Recent literature surveys indicate that three groups are developing NIR PLC spectrometers in a Fourier-Transform Spectrometer (FTS) configuration. The operational theory for NIR dielectric waveguides that employ total internal reflection as the waveguide principle has been developed[3][4][5][6][7]. A NIR spectral measurement using a modified dielectric design is also reported[8][9]. Both designs are based on the Mach-Zehnder approach from optical communications theory. These devices are inherently stable and robust. We are currently developing an FTS spectrometer using similar principles for MIR operation through a funded IRAD. Coupling of into sub-wavelength apertures has also explored[10][11][9]. Our purpose is to investigate and establish operational parameters in a manner as to guide future engineering design to produce plug-and-play waveguide spectrometer-on-chip devices. Such guidelines will establish a framework for mass-production, reducing unit cost and facilitating production. The APC will integrate stacks of spectrometer-on-chip units (Fig. 3). The APC is able to observe different directions in the sky with each direction being mapped to a spectrometer-on-chip unit. Each unit will be manufactured with a PLC-based FTS or grating design. They are fabricated from silicon chips using standard photolithographic etching processes. Fabrication of these units is convenient, repeatable, inexpensive, and will have predictable optical characteristics and sensor performance. High signal-to-noise spectra can be obtained for directions directly illuminated by sunlight. Advantages of PLC waveguides:

- miniaturization of free-space spectrometer concepts;
- spectrometer-on-chip design;
- FTS spectrometers based PLC Mach-Zehnder interferometers;
- grating spectrometers based on PLC arrayed waveguides;
- none scanning, excludes moving parts;
- free of internal vibrations;
- simultaneous interferogram (FTS case) – spectrum not modified by temporal variations;

- low power;
- small volume, small mass;
- shock resistant;
- low noise COTS ROIC's;
- radiation hard.

1.3 The Global Sensing System Architecture

The system architecture design is shown conceptually in Fig.1. A trade-off study will be performed to define the essential characteristics of the sensing system architecture such as the number of sensor nodes, node locations, science data, physical-layer interfaces, e.g. Ka-band, S-band, Kband and UHF, and link-layer interfaces like CCDS proximity, CFDF, WinMAX, WIFI or DVB. The sensing infrastructure would be self-supporting in terms of power. For example, the top-of-the-atmosphere solar insolation at Mars is ~590 W/m^2, and a 10×10 cm^2 cell area will capture only about 1W of usable energy. Thus, a system infrastructure based on solar energy will need sensor technologies that can operate within this stringent power consumption level, i.e., at low power. An autonomously operated rover or other delivery system will have inherently limited support in terms of sensor positioning and alignment. To resolve this limitation, we envision a self-standing cube with each side populated by sensors with a common, shared focusing optic. This design ensures as many as five sets of passive sensors can be interrogated for science investigations. The sensor's spectrometer components must be robust, reliable, and low cost. The spectrometer design should lend itself to reconfiguration in an operational state. The spectrometer component characteristics will impose a fundamental constraint on the scope and operational limits of the surface-network-sensing system.

2. Spectrometer Design

Recent decades have seen the advent of a number of compact spectroscopic devices for targeted science applications including the Spatial Heterodyne Spectrometer (SHS). The PLC-based spectrometers are an evolution in this effort for miniaturization and include the arrayed waveguide spectrometer (where the facet in a traditional grating are replaced by waveguides). A comparison the salient propertied of two techniques (Fig. 5) guided us to the WG based FTS design. We also evaluated the type of medium (Fi.g 6) for supporting the infrared radiation. The dielectric WG has distinct advantages in terms of light loss and relative path difference control. However, an ensemble of hollow WG based MZI strands can be micromachined with 1 μm precision and coated with a gold layer to construct a WG based FTS. We are in the fabrication process, and will be testing and evaluating these devices in the laboratory in the next few months.

3. Discussion

PLC-based spectrometers have been scientifically established. The principles of heterogeneous sensor-web concept are also well established. We are examining the limits of an APC architecture integrated in a sensor-web network that responds in a manner that is dynamic and reactive. The ideal system would feature innovative technologies that are inherently cross-cutting. It is deployable in broad mission areas spanning Earth, Moon, Mars, and near Earth orbit asteroids, thus decreasing technical risks. A significant impact is to promote "cost reduction across multiple missions" as directed by Decadal Survey of the Earth Sciences and Applications from Space (2010). Potential NASA applications for such a APC network would be in planetary science, astrophysics and Earth science. Applications of the APC modules are also envisaged in the commercial manufacturing sector and in the biomedical fields. These concepts will enable the development of a more cohesive, autonomous spectral-signature global mapping system based on heterogeneous APCs. The crosscutting nature of a technology development concept such as this will generate expertise in photonics technologies, and will also result in a paradigm shift in the way that spectral data are measured, collected and synthesized.

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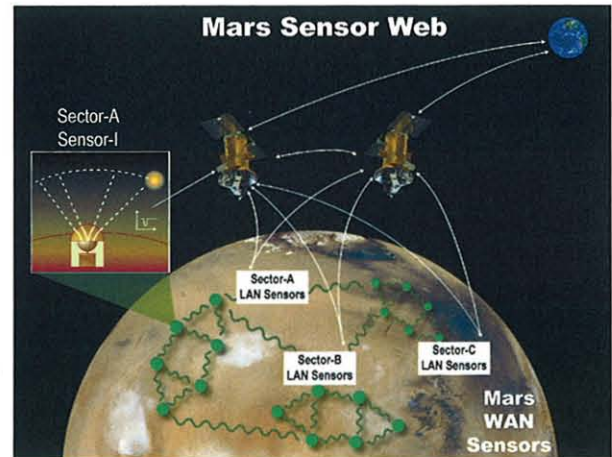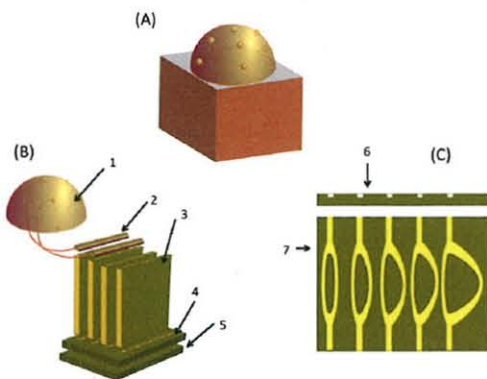[15] Robinson, L.C., 1973.

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Figure 1. Shows the Mars Sensor Web concept that integrates sensor ensembles organized as a network that is reactive and dynamically driven. The network is designed to respond in an event- or model-driven manner, or reconfigured as needed.

Figure 2. Table shows an example responses of the APC Sensor web concept for hazard warning notification for human-robot team exploration. In a more near term unmanned network system, the sensors may respond to an approaching dust storm and switch to monitoring modes such as observing frequency. The APCs network will be governed by two way communications: event driven notifications and targeted measurements. An APC node could respond with an alert for other vulnerable nodes in the storms path to shutdown state.

directly mate to a 2-D detector array and electronics. The ensemble generates the inteferogram that is the observable in a Fourier transform spectrometer. Other chips can implement a waveguide grating tuned to a particular spectral band. These spectra are the basis of observable quantities such as species abundance. Antenna and communication electronics are not shown here.
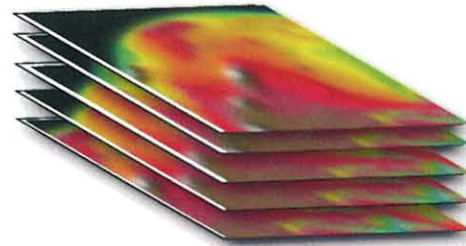
Figure 4. Schematic representation of data products from the Mars-Sensor-Web example discussed hereing. *Maps of abundance (e.g., water vapor) or temperature spanning the sensor field for sunrise, mid-morning, noon, afternoon, and sunset are constructed from sectors. Potential targets of interest to NASA include, but are not limited to, Earth, Mars, NEO, and Moon.*

Figure 3. (A) Schematic view of the APC; (B) APC elements including (1) dome with integrated solar cells and fiber optical couplings, (2) fiber-optic-light-pipe couplers, (3) spectrometer-on-chip modules, (4) 2-D detector array and (5) ASIC, FPGA and microprocessor with signal conditioning boards; (C) Spectrometer on a chip showing (6) top view cross-section and (7) side view cross-section with the ensemble of Mach-Zehder-interferometer strands that constitute the phase-delay lightwave circuits for various phase delays. Each aperture on the dome represents a line-of-sight and maps to a spectrometer-on-chip unit via a fiber light pipe. The stack of spectrometer chips

Property	Grating	FTS
Interference phenomenon	Multi-beam	Two-beam
Observable	Spectrum	Inteferogram
Multiplex advantage condition	Source noise limited	Detector noise limited
Time	Simultaneous	Simultaneous
Constraints	Controlling a uniform path difference increase across the ensemble. **For a given resolution, fabrications tolerances are tighter**	Controlling an increasing relative path difference between waveguide pairs. **Relaxes fabrication tolerance requirements.**

Figure 5.   Design choice for PLC waveguide
spectrometer type: grating vs. FTS.

	IR fiber	Dielectric WG	Hollow metallic WG
Medium	Silver Halides/ Chalcogenide for core and cladding	Si wafer substrate, core, and cladding needs developm ent	Si wafer substrate with conducti ve metallic coating
Cost	High cost of fibers $1K/m	Unknown	Nominal
Fabricat ion	Length control is cumbersome. Each pair needs a splitter/recom biner. Manual assembly. External cradle	Wafer etching is well establishe d. Substanti al effort for core/clad ding material.	Wafer etching is well establish ed. Assembl y toleranc es are well within current technical capabilit ies.
Volume , mass	High volume for 100 fibers with 100 μm core and 1 mm jacket; ~500-1000 gm	1 mm Si wafer chip 40 mm X 60 mm; ~15 gm	1 mm Si wafer chip 40 mm X 60 mm; ~10 gm

Figure 6.   PLC FTS design comparison.