*Thirteenth International Symposium on Space Terahertz Technology, Harvard University, March 2002.*

# Optical Modulation Spectrometer: A Concept Study

Volker Tolls[1] and Rudolf Schieder[2]

[1] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, U.S.A.
[2] 1. Physikalisches Institut, Universität zu Köln, 50937 Köln, Germany

## 1 Abstract

The Optical Modulation Spectrometer (OMS) is a new type of spectrometer backend for heterodyne receivers with large bandwidth. It utilizes the high spectroscopic power of Fabry-Perot etalons for the analysis of IF signal from, e.g., a heterodyne receiver. This paper describes the underlying principle of an OMS and then presents the preliminary results of a concept study for an ultra-wideband (>10 GHz) OMS. The main advantages of the OMS are that it can provide the large bandwidth while being of small size, low weight, and low power consumption. These attributes make it a good candidate for future air-borne, balloon-borne, or space-borne applications where multiple spectrometers will be required for multi-frequency or array receiver systems.

## 2 Introduction

Broadband spectrometers will be required when heterodyne receiver systems operating from 1 to 3 THz go online. Large bandwidths are required to observe broad emission or absorption lines from extra-galactic objects at high redshifts, to perform spectral line surveys, and to observe planetary atmospheres. Many of these lines are pressure or velocity broadened with either large half-widths or line wings extending over several GHz. Current backend systems can cover the needed bandwidth only by combining the output of several spectrometers, each with typically up to 1 GHz bandwidth, or by combining several frequency shifted spectra taken with a single spectrometer. The ultra-wideband optical modulation spectrometer with at least 10 GHz bandwidth will enable broadband observations without the limitations and disadvantages of hybrid spectrometers.

The most commonly used backends for heterodyne detections systems are: (1) the Filterbank Spectrometer (FBS), (2) the Acousto-Optical Spectrometer (AOS), (3) the analog or digital Auto-Correlation Spectrometer (AACS or DACS), and (4) the Chirp Transform Spectrometer (CTS). The spectrometer application plot (Figure 1) shows the current state-of-the-art in bandwidth and resolution of single band spectrometers at 2 THz. To increase the bandwidth, hybrid spectrometers, the simultaneous parallel use of multiple spectrometers, can be used. However, in application where there are restrictions on power, size, or weight, like space borne or balloon borne observatories, single band spectrometers offer many advantages. An ultra-wideband OMS shows clear advantages where large frequency coverage and medium resolution are required.

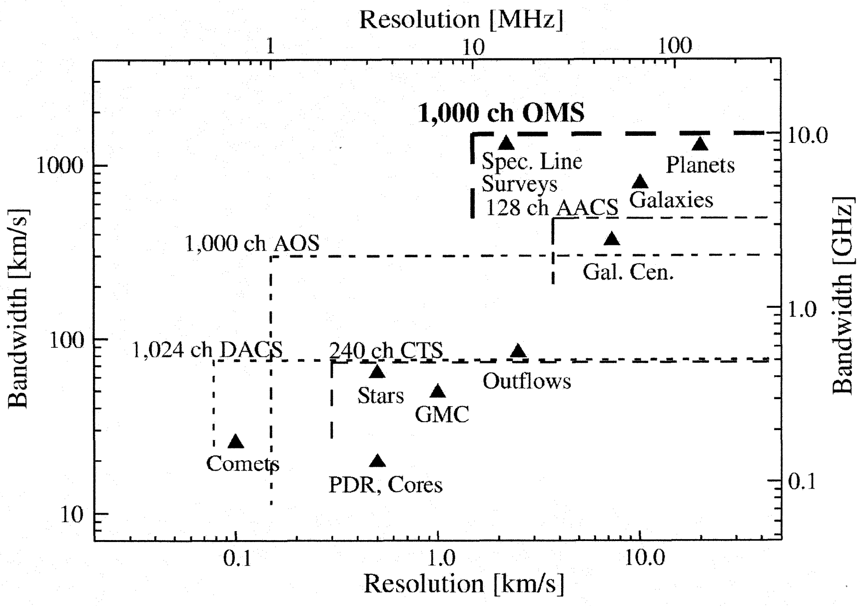

Figure 1: The spectrometer application plot shows the current state of the art in bandwidth and resolution of single band spectrometers. Also shown are the typical bandwidths and resolutions required at 2 THz (150$\mu m$) for a broad range of astronomical objects. The proposed 1000 channel OMS will offer both broad wavelength coverage and medium resolution. [adapted from Harris 1998]

## 3 Operational Principle

The OMS uses the high resolving power of Fabry-Perot etalons. Illuminated with divergent light with frequency $f_0$, the typical fringe system of bright rings of the Fabry-Perot etalon (see Figure 2, [Born 1989]) is converted into a linear system of bright lines by means of the illumination of the etalon and matching optics. The plotin Figure 2 shows the relative intensity $I/I_0$ as a function of the phase for two adjacent interference orders m and m+1. In the OMS (see Figure 3), laser light of frequency $f_0$ is modulated in an electro-optical modulator with a signal $\Delta f$ (e.g., from a heterodyne receiver). The modulated light, $f_0 \pm \Delta f$, is fed into a Fabry-Perot etalon. The free spectral range (FSR) of the etalon needs to be FSR $> 2\ \Delta f$ in order to separate the upper ($f_0 + \Delta f$) modulation sideband of the interference order m from the lower ($f_0 - \Delta f$) modulation sideband of the order m+1. Now, through means of the illumination of the etalon, only the phase range corresponding to $\Delta f$ is imaged onto a line detector array (effectively converting the phase or the corresponding frequency range into a space range). The intensities measured by the detectors are proportional to the input intensities to the modulator for a particular frequency interval within the input band. The detector read-out, A/D conversion and other spectrometer electronics are similar to the electronics of existing AOS's [Tolls 1992].

## 4 Design Goals

The design goals for the optical modulation spectrometer are summarized in Table 1. A first OMS

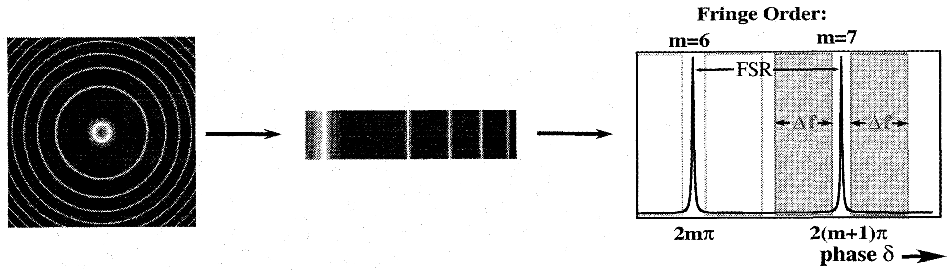

Figure 2: Schematic Fabry-Perot interference pattern for a divergent beam (left) and for a horizontally divergent and vertically parallel beam (center). When the beam is horizontally divergent and vertically parallel, the frequency is dispersed over many orders in the horizontal direction (center). In the proposed OMS (right), only a fraction of a single order (e.g., m = 7), denoted by the gray region with $f_0 + \Delta f$, is projected onto a linear CCD array.

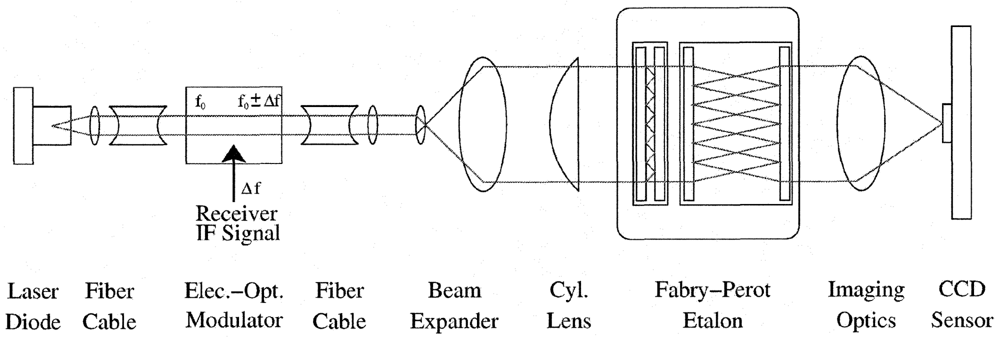

Figure 3: Optical schematic for an Optical Modulation Spectrometer: laser light is modulated by the IF signal from a heterodyne receiver and then spectrally analyzed in a double etalon and measured with a linear detector array.

instrument would have a bandwidth of 10 GHz (larger bandwidths are possible) with 10 MHz resolution. The mass, size, and power consumption are estimates (marked with *) derived from existing AOS spectrometers since the OMS incorporates similar optics and electronics (further improvement is possible but is undesirable for a first generation OMS). The specifications for the components will be refined once the design is complete and the components are selected. E.g., the modulator is listed with 10 GHz bandwidth, but modulators with 20 GHz bandwidth or more can be used as well since the final bandwidth is limited by the input signal (thus, by the currently available bandwidth of heterodyne receiver systems) and the etalon specification. The current design uses a Fabry-Perot etalon system with two matching solid glass etalons. The detector can be a linear CCD array or any other line detector depending on the laser wavelength and should have at least 1000 pixels.

## 5 Summary

The optical modulation spectrometer is a new kind of backend for applications which demand large bandwidth with moderate resolution, low power consumption, small size, and small weight. The last three design goals make the OMS a possible candidate for a single backend or array backends for future air-borne, balloon-borne, or space-borne heterodyne receiver systems.

Table 1: Specifications and key parameters of the proposed Optical Modulation Spectrometer. The values denoted with asterisks are estimates for a possible space flight configuration derived from the final specification of the SWAS AOS [Klumb 1994]. These values can be improved by further miniaturizing, making the mechanical setup as light as possible, and using highly integrated low power electronics.

| Parameter | Design Specification |
|---|---|
| Bandwidth: | 10 GHz |
| Resolution: | 10 MHz |
| Resolving Power: | 2 $10^5$ (in 2 THz heterodyne receiver system) |
| Spectroscopic Stability: | $>$ 60 seconds for ON-OFF measurements |
| Mass*: | $<$ 8 kg (optics, electronics, and RF components) |
| Size of Optics*: | 5 x 5 x 30 $cm^3$ |
| Size of Electronics*: | 10 x 10 x 30 $cm^3$ |
| Power Consumption*: | $<$ 10 Watts |

| Component | Specification |
|---|---|
| Laser: | diode laser |
| Laser Wavelength: | 1550 nm |
| Modulator: | electro-optical modulator |
| Modulator Bandwidth: | $>$ 10 GHz |
| Fabry-Perot<br>Finesse:<br>Free Spectral Range: | Fabry-Perot Etalon system<br>$>$2500<br>$>$22 GHz |
| Detector: | InGaAs IR line detector with 1024 pixel |

Acknowledgment: This work was supported by NASA grant NAG5-10476.

## 6 References

M. Born and E. Wolf, "Principles of Optics", $6^{th}$ Ed., Pergamon Press, Oxford (1989)

A. Harris, K. Isaak, J. Zmuidzinas, "WASP: Wideband Spectrometer for Heterodyne Spectroscopy", Proc. SPIE Vol. 3357, 384 (1998)

M. Klumb et al., "Acousto-optical spectrometer for spaceborne application", Proc. SPIE Vol. 2583, 420 (1995)

V. Tolls, PhD. Thesis, University of Cologne (1992)