A TUNABLE FABRY-PEROT FILTER FOR IMAGING SPECTROSCOPY IN THE INFRARED

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ABSTRACT

We present a new hyperspectral imaging system for the long wave infrared (LWIR) based on a tunable first-order Fabry-Perot Scanning Spectrometer (FPSS). The FPSS operates over 8 – 12 μm with a spectral resolution of 1% of the wavelength. The FPSS has a 22 degree field of view and a spatial resolution of 0.11 degrees. The key components of the FPSS system are the collection optics, a tunable Fabry-Perot etalon, optical position sensors, a closed-loop positioning system, an uncooled microbolometer focal plane array, a digital frame grabber card, and a user-friendly Graphical User Interface (GUI).

1. INTRODUCTION

OPTRA is in the midst of developing a hyperspectral imaging system based on a tunable, 1st order Fabry-Perot filter. The use of a Fabry-Perot filter coupled with a focal plane array (FPA) imaging system allows for the capture of spectral information over a large field of view at high spatial resolution. The result is a system ideally suited for a number of applications in environmental sensing and monitoring, such as chemical leak detection from refineries and oil, gas, or chemical processing plants. In this case, the benefit is the ability of the system to quickly detect small chemical plumes at large standoff distances and allow for a quick response to bring the situation under control before harming the environment or creating a safety concern. The system we are developing aims to combine the key attributes of imaging capability, good discrimination, large spectral bandwidth, and adequate resolving power in a low-cost package that would achieve an ideal solution for environmental monitoring applications.

A particular benefit of the tunable wavelength filtering capability of the Fabry-Perot based system is that it allows one to observe only those spectral elements of interest, which is unlike a Michelson FTS type system which necessarily observes all wavelengths over the operating spectral range. This is because the Fabry-Perot interferometer based sensor is effectively a spatial multiplexing device whereas the Michelson FTS is effectively a spectral multiplexing sensor. This is evidenced by the means with which each sensor obtains the hyperspectral cube of data. The Fabry-Perot system obtains a wavelength-
filtered image of the whole field of view and builds up the cube by scanning through the spectral
elements. For a Michelson FTS, the hyperspectral data is generally obtained one of two ways, either by
obtaining an interferogram at each intermediate field of view and scanning over the whole field or view,
or by imaging the whole field of view on an FPA while step scanning the interferometer to obtain the
interferogram. In either case, the Michelson FTS necessarily generates all the spectra. In general, it can
be shown that under similar conditions (e.g. equivalent detector D*, spectral elements, diffraction limited
resolution, etendue, etc.) the performance between the tunable filter and Michelson FTS is effectively the
same (the Signal-to-Noise ratios are within a factor of 2). However, under situations where only certain
spectral elements are needed, the tunable wavelength filtering capability of the Fabry-Perot based system
begins to hold an advantage over other techniques. An example of this is when the presence of single
chemical is being monitored and only a small number of spectral elements are required for detection (e.g.
on/off band scanning). In this case, the Fabry-Perot based system can scan on and off a feature and then
perform a differencing technique between the two hyperspectral image slices to obtain a resultant image
that shows the spatial location of a chemical cloud. The advantage then arises due to the fact that the
Fabry-Perot system only needs to obtain data at those wavelengths of interest, which is unlike a
Michelson FTS where by nature it observes all wavelengths. This results in the Fabry-Perot system
effectively increasing its integration time in comparison to the FTIR system, which leads to better
performance. This improvement in performance can be capitalized on through use of low-cost uncooled
microbolometer focal plane arrays, which ultimately achieve good performance at a very competitive
price.

The format of this paper is as follows. We first give a system overview in order to provide a basic
understanding of the operating principles of the system, with particular emphasis on the role of phase
dispersion in the high reflectance dielectric coatings and the resulting effects on achievable free spectral
range and resolution. This will then be followed up by detailed descriptions of the key components of the
system. Next, we will show performance data obtained from the system testing and then a sensitivity
analysis that provides a performance prediction. Finally, we will summarize with conclusions.

2. SYSTEM OVERVIEW

The specifications for the FPSS system are shown in Table 1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Target Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
<td>8 – 12 μm</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>1% (e.g. 100 nm FWHM at 10 μm)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>0.11 degrees</td>
</tr>
<tr>
<td>Field of View</td>
<td>22 degrees diagonal across the FPA</td>
</tr>
<tr>
<td>Intermediate field of view</td>
<td>0.11 degrees per pixel</td>
</tr>
<tr>
<td>Frame rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>FPA size</td>
<td>160 × 120 pixels, 50 μm square</td>
</tr>
<tr>
<td>Entrance Aperture</td>
<td>1 inch diameter</td>
</tr>
<tr>
<td>NESR per pixel per frame</td>
<td>1.4 × 10^-6 W/cm^2sr cm^-1</td>
</tr>
<tr>
<td>Size</td>
<td>12” × 6” × 7.5”</td>
</tr>
<tr>
<td>Weight</td>
<td>10 lbs</td>
</tr>
</tbody>
</table>

The basis for our system is the Fabry-Perot interferometer\(^2\), whose governing equations are given by
the well-known Airy formulas,

\[
\frac{I}{I_0} = \frac{4R \sin^2 \left( \frac{\delta}{2} \right)}{(1 - R)^2 + 4R \sin^2 \left( \frac{\delta}{2} \right)}, \quad \text{Reflection},
\]

(1a)
\[ \frac{I_t}{I_0} = \frac{(1 - R)^2}{(1 - R)^2 + 4R \sin^2 \left( \frac{\delta}{2} \right)}; \quad \text{Transmission,} \quad (1b) \]

where \( R \) is the reflection coefficient and the phase term, \( \delta \), is given by,

\[ \frac{\delta}{2} = \frac{2\pi nl \cos \Theta}{\lambda} - \phi(\lambda), \]

(2)

where \( n \) is the refractive index of the medium between the plates, \( l \) is the plate separation, \( \Theta \) is the angle of incidence of the incoming light, \( \lambda \) is the wavelength of the light, and \( \phi(\lambda) \) is the combined wavelength dependent phase shift upon reflection of the coatings for both mirrors. By noting that maximum transmission occurs when \( \frac{\delta}{2} = m\pi \), where \( m \) is the order number, Equation 2 can be solved to obtain the maximum transmission wavelength for a given plate separation and order number,

\[ \lambda_{\text{max}} = \frac{2nl \cos \Theta}{m + \phi(\lambda)/\pi} \]

(3)

From this set of equations the system performance parameters Free Spectral Range (FSR), resolution, and finesse are obtained as:

\[ \Delta \lambda_{\text{FSR}} = \frac{\lambda}{m + 1 + \phi(\lambda)/2\pi + \lambda/2\pi \frac{d\phi(\lambda)}{d\lambda}} \]

(4)

\[ \Delta \lambda_{\text{FWHM}} = \frac{\lambda(1 - R)}{\pi R^{\frac{1}{2}} \left( m + 1 + \phi(\lambda)/2\pi + \lambda/2\pi \frac{d\phi(\lambda)}{d\lambda} \right)^{\frac{1}{2}}} \]

(5)

\[ F = \frac{\pi R^{\frac{1}{2}}}{1 - R} \]

(6)

In order to obtain our spectral range of 8 – 12 µm, Eq. 4 indicates that with no phase dispersion our system needs to work in either the 1st or 2nd order. In the case of 2nd order operation, the FSR would exactly equal the 4 µm spectral bandwidth. However, all dielectric coatings have phase dispersion, which effectively requires our system to work in the 1st order in order to obtain the desired FSR. In fact, one still needs to be careful even in 1st order operation as standard high-reflectance multiplayer dielectric coatings can have enough phase dispersion to decrease the FSR below our requirement. This can be seen in figure 1, which shows results obtained from a model using the above equations and the original Phase I coating design of the system.

Thus, in order to achieve the required FSR the system was designed to work in the 1st order with coatings that had low phase dispersion. However, one consequence of working in the 1st order is that the plate separation is smaller, which requires a higher reflectance coating to increase the Finesse and achieve a given spectral resolution. In general, increasing the number of high/low index quarterwave stacks increases the overall reflectivity of multilayer dielectric coatings. Unfortunately, this is necessarily accompanied by an increased phase dispersion. The optimal solution is reached by maximizing the refractive index difference between the materials comprising the quarterwave stack, which leads to the minimum number of total layers required to achieve a given reflectivity.
3. SYSTEM COMPONENTS

Figure 1 shows a layout of the FPSS system. The key components are the Fabry-Perot etalon, collection optics, infrared FPA camera, servo controller that uses piezo actuators and NanoGage™ optical position sensors, and the command and control software, which includes data acquisition.

Table 2 shows the etalon mirror design, which was optimized for high reflection coefficient and low phase dispersion. In general, the finesse of the system is limited by the reflection coefficient, mirror flatness and roughness, cavity parallelism, and field of view (obliquity limit). The goal of our design was to limit the finesse by the mirror reflection coefficient, which was accomplished by designing all the other factors to achieve a finesse value greater than the reflection finesse, as shown in Table 3. Note that the individual finesse values add similar to capacitors in parallel, which results in a design finesse of approximately 46. Given the target free spectral range of 416 cm\(^{-1}\), this results in a maximum resolution of about 9 cm\(^{-1}\). Also note that each mirror has a slight wedge angle to mitigate internal etalon effects.

Table 2. Etalon mirror design

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear aperture</td>
<td>1 inch</td>
</tr>
<tr>
<td>Diameter to thickness ratio</td>
<td>4 to 1</td>
</tr>
<tr>
<td>Roughness</td>
<td>≤ 20 nm</td>
</tr>
<tr>
<td>Mirror side</td>
<td></td>
</tr>
<tr>
<td>Flatness</td>
<td>≤ 1/200 wave at 10 μm</td>
</tr>
<tr>
<td>Reflectance</td>
<td>≥ 96%</td>
</tr>
<tr>
<td>Wedged side</td>
<td></td>
</tr>
<tr>
<td>Flatness</td>
<td>≤ 1/2 wave at 633 nm</td>
</tr>
<tr>
<td>Reflectance</td>
<td>≤ 1 %</td>
</tr>
<tr>
<td>Wedge angle</td>
<td>8 arc-min</td>
</tr>
</tbody>
</table>
An f/1 germanium doublet was designed and fabricated for the Fabry-Perot. The set is composed of a positive aspheric meniscus lens followed by a plano-convex aspheric lens. The doublet was spaced and bent for minimum aberration over the entire field. The corresponding field of view is $13.68^\circ \times 18.18^\circ$ full-angle across the array dimensions. Figure 2 shows the layout of the lens system preceded by the etalon pair. Note that the lens diameters are set such that the etalons are the limiting aperture (at the gap). The lens assembly was designed to keep the point-spread-function below the 50 µm pixel size.

The FPA infrared camera is made by Infrared Solutions Inc. (ISI) and is based on uncooled microbolometer technology. The detector contains $160 \times 120$ 50 µm square elements and has a NETD of 0.1 deg K at 30 deg C. The FPA data is obtained with the ISI imaging engine, which operates at 15 Hz frame rate and provides both a standard NTSC composite video output and a 14-bit parallel digital output. This digital output was specifically designed for OPTRA to be compatible with a Coreco Imaging, Inc. PC-DIG frame grabber card, which is used by the FPSS system to obtain real-time data. Note also that the system contains a visible video system comprised of a CCD camera and small LCD monitor that is co-aligned with the infrared channel.

The key components of the servo control system are a flexure for scanning the etalon plate separation, a NanoGage optical position sensor for monitoring the plate separation, and piezo actuators. The system is designed for closed-loop operation, which is a necessity when using piezo actuators, as they tend to exhibit nonlinearities such as hysteresis and are also prone to drift. A flexure was chosen over a spring assembly because it provides high off-axis stiffness to prevent sag due to gravity. The servo loop is analog design with integral compensation. Good performance can be achieved with this simple design due to the high stiffness of the piezo actuators, which places the fundamental resonance of the system beyond a kHz. The system was designed to achieve a bandwidth that allows the filter to be scanned across the entire wavelength range in less than 30 ms. The reason for this is that a typical FPA camera has a 30 Hz update rate, so moving the system in a time less than a single frame minimizes the data lost while tuning the filter.

NanoGage proximity sensors are used to monitor the separation between the etalon plates comprising the Fabry-Perot cavity. The NanoGage is an optical triangulation sensor with a large linear range of up to 100 µm and a signal resolution down to the nanometer level. In order to maintain the finesse achieved by

<table>
<thead>
<tr>
<th>Finesse component</th>
<th>Value</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectivity</td>
<td>≥ 75</td>
<td>$\mathrm{R} \geq 0.96$</td>
</tr>
<tr>
<td>Flatness</td>
<td>≥ 100</td>
<td>$\leq \lambda/200 \text{ at } 10 \mu m$</td>
</tr>
<tr>
<td>Roughness</td>
<td>≥ 100</td>
<td>$\leq 20 \text{ nm at } 10 \mu m$</td>
</tr>
<tr>
<td>Parallelism</td>
<td>≥ 100</td>
<td>$\leq 60 \text{ nm at } 10 \mu m$</td>
</tr>
<tr>
<td>Obliquity (per IFOV)</td>
<td>≥ 200</td>
<td>$\leq 5 \text{ deg per pixel}$</td>
</tr>
</tbody>
</table>
the high reflectance coatings, the etalon plates must maintain a parallelism of 60 nm or better over the operating range. In the case of first order operation this roughly translates to plate separations from 3 – 7 \( \mu \)m. The FPSS system uses NanoGage sensors that have been designed to operate over a 30 \( \mu \)m linear range with a noise equivalent displacement of 2 nm rms. The additional range of the NanoGage sensors is used to tune the system into the first order and peak the alignment of the Fabry-Perot interferometer. Figure 3 shows a NanoGage proximity sensor, which Optra also offers as a standard product.

The goal of the software is to provide a user-friendly and interactive means to control the FPSS. The system has been designed to allow the user to select between four different operating modes:

1. Initialization
2. Single wavelength collection
3. Multiple wavelength scanning
4. Calibration

The initialization mode happens automatically upon power-up and places the system software and hardware in a default state ready to begin data collection. In the single wavelength mode, the user can provide a wavelength command and an integration time; upon command the system performs the requested task and then returns to the default state and awaits the next command. The multiple wavelength mode allows the user to supply a wavelength range and wavelength sampling increment, as well as the integration time per wavelength step. The calibration mode provides two calibration options: factory and field calibration. The factory calibration mode is used to determine the relationship between plate separation and transmission wavelength of the Fabry-Perot filter. In general, this relationship is nonlinear as a result of the phase dispersion in the coatings. The field calibration mode allows the system to be checked in the field against a known, portable standard to verify system alignment and order. The user can save the hyperspectral data in a number of formats compatible with industry standard data processing packages. Figure 4 shows the Graphical User Interface for operating the FPSS system.

![FPSS control panel](image-url)
4. MEASURED SYSTEM DATA

Figure 5 shows measured system data. The coating reflection coefficient was obtained by first placing an etalon mirror in front of a FTIR spectrometer and measuring the transmission coefficient as a function of optical frequency. The reflection coefficient was then obtained by subtracting out the loss associated with the AR coating on the other surface and the absorption in the coating design. For comparison, this data is plotted against the predicted data for the coating design in the top graph of Figure 5 and shows good agreement.

The measured first order FSR is shown in the middle graph, which was obtained by placing the etalon cavity in front of an FTIR spectrometer and tuning to the first order separation that passed light at the longest operating wavelength. The FSR is then given by the frequency separation between the first order peak at about 12-µm and the second order peak around 7.5-µm, which is 506 cm\(^{-1}\). The predicted FSR for this coating design is about 548 cm\(^{-1}\), which is a little larger than the measured amount. This would indicate that the actual phase dispersion for the coatings is a little worse than the coating design predicted, but clearly still well above the free spectral range requirement of 417 cm\(^{-1}\).

The bottom graph shows the system closed loop response to step change input. The data was obtained by commanding filter to tune across its operation range and then measuring the Nanogage voltage. The measured rise time is on the order of 3 ms and the system settles within 5 ms, well below the 30 ms requirement.
5. SENSITIVITY

The Noise Equivalent Spectral Radiance gives the sensitivity,

$$\text{NESR} = \sqrt{a_d} \sqrt{\frac{1}{\tau}} \frac{\text{Watts}}{\text{cm}^2 \text{sr} \text{cm}^{-1}}. \quad (7)$$

where \(a_d\) is the detector area, \(\tau\) is the integration time, \(\eta\) is the optical efficiency, \(D^*\) is the specific detectivity of the detector, \(a_c\) is the area of the collection optics, \(\Omega_c\) is the solid angle, and \(\Delta \sigma\) is the spectral resolution.

Table 4 shows the predicted sensitivity of the FPSS system using the design parameters. The detector \(D^*\) was obtained for the Infrared Solutions uncooled detector based on a NETD of 0.1 K (67 ms integration time, f/0.8 collection lens) using the relationship²,

$$D^* = \left( \frac{4f^2}{f^2 + 1} \right)^{1/2} \left( \frac{1}{\tau} \right)^{1/2} \left( \frac{\Delta P}{\Delta T} \right)_{\lambda_1-\lambda_2} \text{NETD}, \quad (8)$$

where \(f/#\) is the f-number of the collection optics and \(\left( \Delta P/\Delta T \right)_{\lambda_1-\lambda_2}\) is the change in power per unit area radiated by a blackbody at temperature \(T\) with respect to \(T\), measured within the spectral band from \(\lambda_1\) to \(\lambda_2\).

Table 4. FPSS sensitivity analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_d)</td>
<td>Single detector element area, 50 (\mu)m square pixel</td>
<td>(2.5\times10^{-5}) cm(^2)</td>
</tr>
<tr>
<td>(\tau)</td>
<td>Frame integration time</td>
<td>0.033 sec</td>
</tr>
<tr>
<td>(\eta)</td>
<td>Optical efficiency</td>
<td>0.75</td>
</tr>
<tr>
<td>(D^*)</td>
<td>ISI uncooled detector</td>
<td>(1.3\times10^9) cm(^2)Hz/W</td>
</tr>
<tr>
<td>(a_c)</td>
<td>Collector area for 1-inch diameter aperture</td>
<td>5.067 cm(^2)</td>
</tr>
<tr>
<td>(\Omega_c)</td>
<td>Solid angle per element for 0.11 degree IFOV</td>
<td>(3.87\times10^{-6}) sr</td>
</tr>
<tr>
<td>(\Delta \sigma)</td>
<td>System resolution</td>
<td>10 cm(^1)</td>
</tr>
<tr>
<td>NESR</td>
<td>Noise Equivalent Spectral Radiance per pixel, per frame</td>
<td>(1.43\times10^6) W/cm(^2)sr cm(^{-1})</td>
</tr>
<tr>
<td>NESR</td>
<td>Noise Equivalent Spectral Radiance, 1.1 deg superpixel, 5 sec (\tau)</td>
<td>(1.17\times10^8) W/cm(^2)sr cm(^{-1})</td>
</tr>
</tbody>
</table>

It is worth noting that the state of the art in uncooled microbolometer detectors has shown \(D^*\) values approaching \(D^*\sim1\times10^7\) cmHz\(^{1/2}\)/W\(^6\), which would further improve the per pixel, per frame sensitivity by a factor of 10. Summing adjacent pixels and increasing the integration time also obtains further improvement in the sensitivity. Table 3 also shows the NESR for the case of a 10 \(\times\) 10 superpixel (e.g. a 1.1 degree IFOV) and a 150 frame summation (e.g. a 5 second integration time). For the case of on/off band scanning, this shows it is conceivable to obtain very good sensitivity that can result in relatively quick detection of low concentration species of interest.

6. CONCLUSIONS

We have developed a first-order tunable Fabry-Perot hyperspectral imaging system. Preliminary results indicate that we have successfully obtained an operating spectral range of 8 – 12 \(\mu\)m with a spectral bandwidth of 1% through use of high reflectance coatings with low phase dispersion. The use of a low-cost uncooled microbolometer results in an affordable system with reasonable per pixel, per frame
sensitivity of $1.4 \times 10^{-6}$ W/cm$^2$srcm$^{-1}$. The imaging capability and fine spatial resolution make the system an ideal candidate for stand-off detection in environmental monitoring applications such as chemical leak detection from refineries and chemical processing plants.

7. ACKNOWLEDGEMENTS

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8. REFERENCES