MOEMS – based Fabry Perot array for SWIR-MWIR imaging spectroscopy

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ABSTRACT

The concept for a hyperspectral imaging system using a Fabry-Perot tunable filter (FPTF) array that is fabricated using "miniature optical electrical mechanical system" (MOEMS) technology. [1] Using an array of FPTF as an approach to hyperspectral imaging relaxes wavelength tuning requirements considerably because of the reduced portion of the spectrum that is covered by each element in the array.

In this paper, Pacific Advanced Technology and ARL present the results of a concept design and performed analysis of a MOEMS based tunable Fabry-Perot array (FPTF) to perform simultaneous multispectral and hyperspectral imaging with relatively high spatial resolution. The concept design was developed with support of an Army SBIR Phase I program The Fabry-Perot tunable MOEMS filter array was combined with a miniature optics array and a focal plane array of 1024 x 1024 pixels to produce 16 colors every frame of the camera. Each color image has a spatial resolution of 256 x 256 pixels with an IFOV of 1.7 mrads and FOV of 25 degrees.

The spectral images are collected simultaneously allowing high resolution spectral-spatial-temporal information in each frame of the camera, thus enabling the implementation of spectral-temporal-spatial algorithms in real-time to provide high sensitivity for the detection of weak signals in a high clutter background environment with low sensitivity to camera motion. The challenge in the design was the independent actuation of each Fabry Perot element in the array allowing for individual tuning. An additional challenge was the need to maximize the fill factor to improve the spatial coverage with minimal dead space. This paper will only address the concept design and analysis of the Fabry-Perot tunable filter array. A previous paper presented at SPIE DSS in 2012 explained the design of the optical array. [2]

Keywords: Simultaneous multispectral imaging, hyperspectral imaging, Fabry-Perot arrays, single frame spectral image processing, MOEMS, IED's, chemical/biological agents, ammonia nitrite, TICs, IMSS, cellular and molecular spectral imaging

1. INTRODUCTION

A Fabry-Perot Tunable Filter (FPTF) requires high reflectivity of the mirror surfaces to obtain high finesse which means that the material and thickness are carefully considered to insure maximum transmission. The objective is to use thin films of the reflective metal because of potential for no adhesive material and thus reducing the surface phase shift affecting the finesse and thus the transmission of the tuned wavelength. Gold (Au) was selected as the material of choice which has reasonable performance in the SWIR-MWIR spectral region.

The final system when integrated with the miniature lens array will cover the wavelength region from 1 to 4 microns with 16 simultaneous bands in each frame of the camera. There are several major advantages of using an array of FPTF with 16 elements for hyperspectral imaging.

1. When covering the region from 1 to 4 microns, wavelength tuning requirements are considerably reduced because of the reduced portion of the spectrum that is covered by each FPTF and thus only needs to be adjusted over a nominal mechanical range of 50 nm. The small displacement of the moving mirror reduces the electro-static actuation requirements considerably as opposed to the need to move through the entire 1 to 4 microns range with a single FPTF.
2. In electro-static actuation there is always a concern of reaching a voltage that causes pull-down. The pull-down effect will limit the allowed displacement of the distance between the moving and fixed mirrors of less than 1/3 of the original distance between the two mirrors. Very small required displacements in the FPTF array adjustment can stay well within the parameters needed to ensure pull-down does not occur.
3. The smaller displacement of the FPTF moving mirror also reduces mirror bowing found with larger displacements.

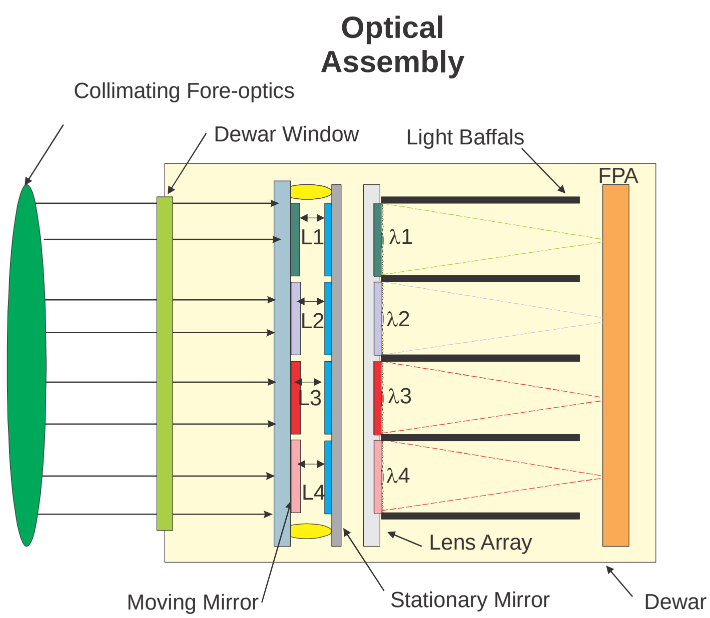


Figure 1. Schematic of the optical components in the test fixture for the FPTF.

After evaluating several approaches for a concept design the following was selected. A cross section of the optical system is shown in figure 1. The FPTF will be coupled with micro lenses to image and collimating optics to form multiple images on the focal plane array of the same scene each with a unique spectral response. The FPTF array will be made up of circular or octagonal mirrors configured in a 4 x 4 array as shown in figure 2. The bottom mirror will be fixed and the top mirror will be held by cantilevered serpentine springs attached to four posts. Actuation of the mirror will be performed electrostatically. The initial quiescent gap for each of the 16 FPTF will be determined by the thickness of the bottom mirror's base above the substrate as shown in figure 3.

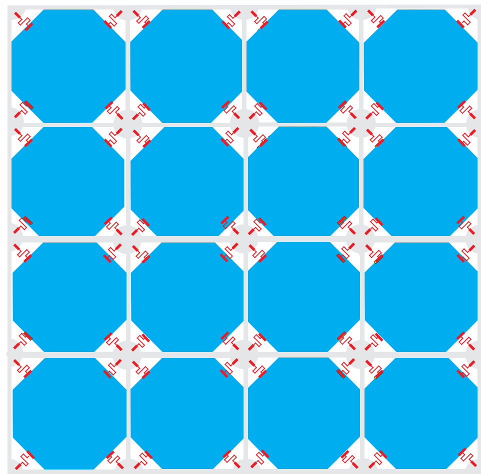


Figure 2. Schematic of the 4 x 4 Fabry-Perot tunable filter array.

The basic objective and the uniqueness of the MOEMS Fabry-Perot tunable filter (MOEM-FPTF) array approach to simultaneous multi-spec imaging over other approaches is the combination of the FP array and an array of lenses (either refractive or diffractive lenses). If the lens array is a diffractive optic as used in Image Multi-spectral sensing (IMSS) then the spectral tuning will be the combined function of the FP and the IMSS. The marriage of these two technologies brings unique capabilities that enhance each. The combined MOEMS device will give high resolution simultaneous multispectral imaging in a small package leading to lower cost systems.

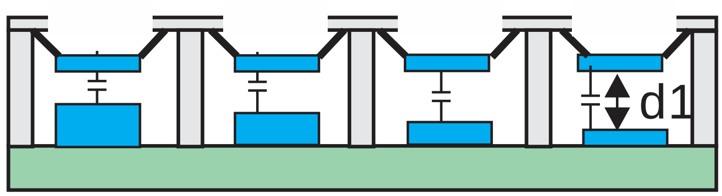


Figure 3. Schematic diagram of the cross section of the FP array showing the quiescent gap determined by the thickness of the stationary mirror on the bottom.

The lenslet array performs the spectral focusing but has a small amount of spectral crosstalk that introduces a blur to the image and added photon noise. Using the MOEMS-FPTF array prior to the lenslet array will reduce spectral crosstalk and thus reduce image blur and photon noise. The MOEMS-FPTF array needs lenses to create an image and the lenslet array will perform this function.

Figure 4 shows the quiescent position of the mirrors as d1 and the tuning range as Δd1. The gap will be tuned using cantilevered springs.

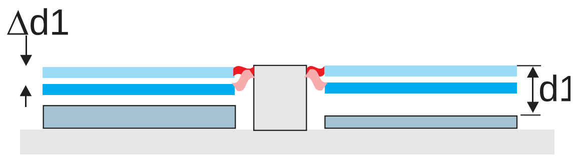


Figure 4. Schematic diagram of the cross section of two mirror elements in the FP array showing the quiescent gap between the top and bottom mirrors d1 and the tuning range Δd1

Since the mirrors will be metal (Au) they will act as the electrodes for the electrostatic actuation. The top movable mirrors will all be held at ground potential through the plating on the cantilevered springs. The bottom fixed mirrors will have variable voltage applied to control the gap spacing and thus potential tilt affecting parallelism.

Table 1 show the design wavelength for each of the 16 mirrors and the expected gap dimensions along with the tuning dimensions for each. Table 1 shows the center wavelength of each FPTF and the necessary displacement required to fill the gap in the spectral coverage.

Table 1. Lenslet array wavelength, gap spacing and tuning range.

Center Wavelength (Microns)	**d1 (microns)**	**Δd1 (nm)**
1.4	0.70	25.00
1.45	0.73	50.00
1.55	0.78	50.00
1.65	0.83	50.00
2.00	1.00	75.00
2.15	1.08	65.00
2.28	1.14	60.00
3.10	1.55	50.00
3.20	1.60	50.00
3.30	1.65	50.00
3.40	1.70	50.00
3.50	1.75	50.00
3.60	1.80	50.00
3.70	1.85	50.00
3.80	1.90	50.00
3.90	1.95	

2. DESIGNS PERFORMANCE ANALYSIS AND MODELING

To understand the performance both the optical and mechanical parameters were analyzed and modeled.

2.1 Optical Modeling Results

The modeling focused on metal mirrors (Al, Au, and Ag), since they are simple, low cost and low stress. Thermal analysis was not performed at this stage. Anti-reflection coatings were briefly looked at and will be very important in the final performance. To keep the optical model focused on the achievable results we concentrated on the Etalon affects in the gap between the mirrors and then looked at the Etalon affects in the silicon. The model structure is shown in Figure 5.

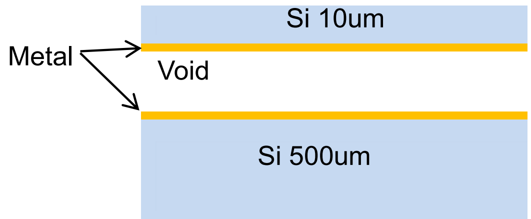


Figure 5. Schematic structure of the Fabry Perot cavity.

Au (gold) provides the highest finesse whereas very thin Al (aluminum) films are required to get reasonable (85%) transmission. The thickness of the films chosen was to normalize the transmission for comparison. Gold will give the narrowest spectral response with the FWHM considerably narrower than that for Ag and Al as shown in figure 6. Table 2 summarizes the results of this analysis comparing the three metals. Au was selected as the metal of choice.

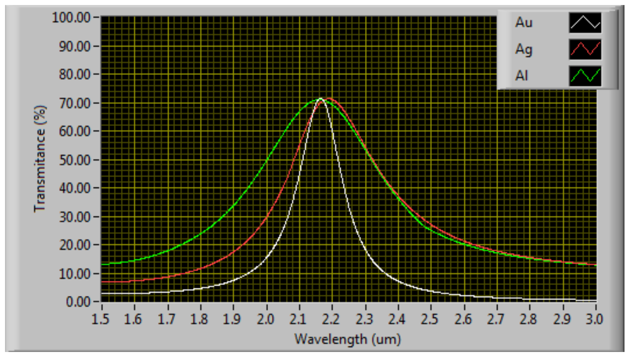


Figure 6. Shows the transmission peaks for Au, Ag, and Al at 2.15 microns.

The effect of the gold thickness on spectral performance was looked at. Four different thicknesses were evaluated 50, 100, 150 and 200 A. It appears that reasonable performance can be obtained for Au thicknesses of 100 to 200 A.

Table 2 – Thickness of the metals to normalize to 71% transmission giving equitable spectral resolution

	t(A)	**%T**	**HWHM(cm^{-1})**
Au	105	71	186
Ag	70	71	356
Al	20	71	598

If finer spectral resolution is the primary criterion then throughput will need to be sacrificed as shown in Table 3. Figure 7 shows the quiescent spectral response for the 16 Fabry-Perot filters. It is apparent that the transmission drops off going to longer wavelengths. There are alternatives to improve the longer wavelength response, such as using a dielectric stack. However, this will require more photolithographic masks and will significantly increase the initial cost to manufacture.

Figure 8 shows the modeling for a 4 layer A/R coating stack at the surface of the Si/Air interface that can be fabricated at wafer-scale using high reliability materials. The Si/Air Etalon effect is attenuated with this A/R coating. Further refinements can be implemented using a more complex stack. To mitigate the Si/Air Etalon effect the A/R coating will be applied at both surfaces of the Si and Air.

Table 3. Transmission and spectral resolution as a function of wavelength.

		λ	d	%T	HWHM (cm^{-1})
		1.40	.7	82	422
		1.45	.725	81	387
		1.55	.775	79	334
		1.65	.825	78	290
		2.00	1.00	71	186
		2.15	1.075	69	159
		2.28	1.14	66	139
		3.20	1.60	49	63
		3.30	1.65	47	59
		3.40	1.70	45	56
		3.50	1.75	44	52
		3.60	1.80	42	49
		3.70	1.85	41	46
		3.80	1.90	40	44
		3.90	1.95	38	41

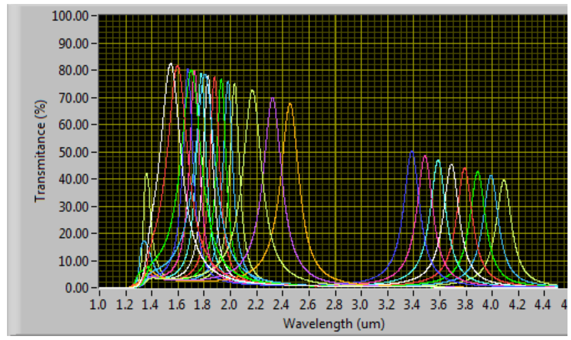


Figure 7. Transmittance summary for the 16 FP tunable filters, transmission through the Au film is falling as the wavelength increases. Higher order show up at lower wavelengths

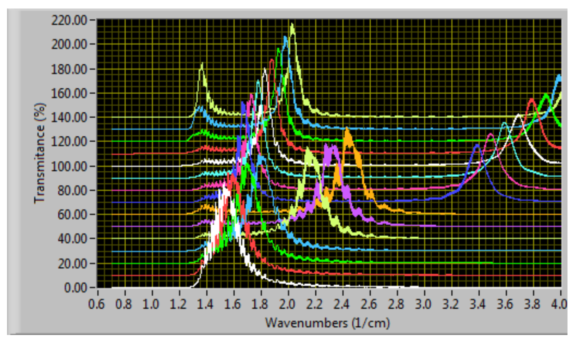


Figure 8. Shows the damping of the Si-Air effect by using an A/R coating.

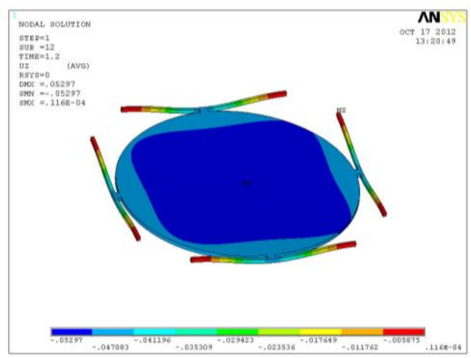
2.2 Mechanical Modeling Results

In the mechanical design of the FPTF array the objectives are to maximize the fill factor, and to minimize the mirror deflection to keep planarity across the mirror surface. Using a hexagonal or circle structure for the mirror will maximize the fill factor when interfacing with circular lenses. This gives an area at each corner of the FPTF for the actuation springs.

In analyzing the mechanical performance of FPTF array several approaches for the spring mounting were looked at. First analysis was for a 3 mm diameter mirror fully constrained at all the circumference. For this case the mirror showed a 4 nm curvature with a 5 volt potential difference and a 1 microns gap. Then several partially constrained mirrors using a simple beam model were evaluated to determine the ratio of mirror stiffness to restoration forces in spring. First a partially constrained case with a mirror constrained at 4 points and the deflection was 5 nm for a 4 voltage potential difference The next case analyzed was for 8 points of constraint with a 4 voltage potential the deflection is lower than the previous case at about 4 nm. When all factors were considered a baseline conceptual design with 4 point constrained dual serpentine spring structure was determined to be the best to meet the specifications as shown in figure 9.

A 3 mm diameter mirror with four retention springs can achieve a 50 um vertical movement with less than 10 nm of curvature and will require 2 - 4 volt actuation. This dual serpentine spring design can achieve needed retention force and fit within space constraints for the FPTF array.

When evaluating how much affect this deflection will have on the optical performance it was determined that a 4 point constrained mirror will not significantly affect the spectral resolution of the FPTF. The 4 or 5 nm mirror bow shouldn't be a problem. The gap variation is only λ/150. This will increase the FWHM ~10%. Lensing of the curved surface won't be a problem since both the front and the back surface of the Si are equally curved.



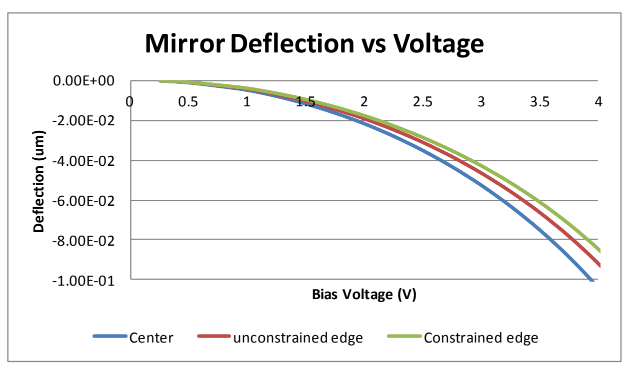


Figure 9. Shows the results for a 4 position constrained mirror with a weaker spring.

3. SUMMARY

The analysis indicates that the design for the Fabry-Perot Tunable Filter array will have reasonable performance and can be built for a concept definition demonstration. It was determined that the resolution and the spectral region in the SWIR and MWIR would cover a majority of the hyperspectral imaging applications of interest to the Army. The processing constraints are well understood and working with those constraints a proof of concept prototype can be built.

This approach can be used for handheld multispectral imaging for applications such as; IED detection where disturbed earth is an indicator of a buried device, the detection of HME manufacturing, detection of Toxic Industrial Chemicals (TIC's) such as petroleum products, detection of chemical and biological warfare agents and many more.

4. ACKNOWLEDGEMENTS

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