MEMS Programmable Spectral Imaging System for Remote Sensing

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ABSTRACT

ITT Industries Space Systems Division and Eastman Kodak Company have developed a scalable, data- and power-efficient imaging spectrometer system with a digitally tunable optical filter capability, which enables the rapid selection of high-quality user-defined optical spectral band(s) of interest. The system utilizes a custom-designed, high-contrast diffractive MEMS device with 50 independent spectral switches at the image plane of a double-pass dispersive/de-dispersive spectrometer. The custom MEMS device is based on grating electromechanical system (GEMS) display technology, which provides very high image contrast (2000:1), fast optical switching speeds (< 100 ns), and a large active area with a very high fill factor. The system enables the selection of arbitrary, narrow or wide spectral bands of interest across the visible spectrum with a sampling resolution of 5 nm, without any moving mechanical parts. The resulting optical filter quality and performance is comparable to conventional fixed-band dichroic filters used in current remote sensing systems. The brassboard systems are designed for rapid transition to space-based, electro-optical (EO) remote sensing missions that utilize large format linear TDI scanning sensors and large format area staring arrays in the visible band. This technology addresses numerous capabilities to meet future EO system requirements for rapidly selecting and utilizing a high quality imaging optical bandpass of interest. The system concept provides capability for a >20X scan rate advantage over conventional hyperspectral imagers as a result of the compatibility with TDI scanning. The image quality is comparable to current MSI and HSI systems.

Keywords: Imaging Spectrometer, Hyperspectral, Multispectral, MEMS

1. INTRODUCTION

1.1 Spectral Imaging Systems

Current scanning MSI (multispectral imaging) sensors use fixed optical filters that are attached to or in front of the focal plane. Staring sensors use a filter wheel or other mechanism that can be commanded to insert one of a limited number of filters into the optical path. In both cases, the optical filter characteristics *cannot* be changed after deployment. To overcome such limitations, reconfigurable systems with a filter that can be electrically modified at will have been proposed using light modulators in two fundamentally different configurations: 1) tunable transmissive filters based on liquid crystal devices, acousto-optic devices, or tunable Fabry-Perot cavities and 2) programmable dispersion-based systems with spatial light modulators. The dispersion-based approach provides significant flexibility for remote sensing missions because the pass band can be almost any shape. In this approach, input light is sent through a prism or grating to separate the various wavelengths onto a spatial light modulator, which then selects those of interest. Such systems have been proposed using a variety of spatial light modulators, including liquid crystal display panels and, more recently, micro-electromechanical mirror arrays such as the Texas Instruments DMD [1,2]. However, successful demonstrations of these programmable dispersion-based filter systems have been non-imaging or point imaging.

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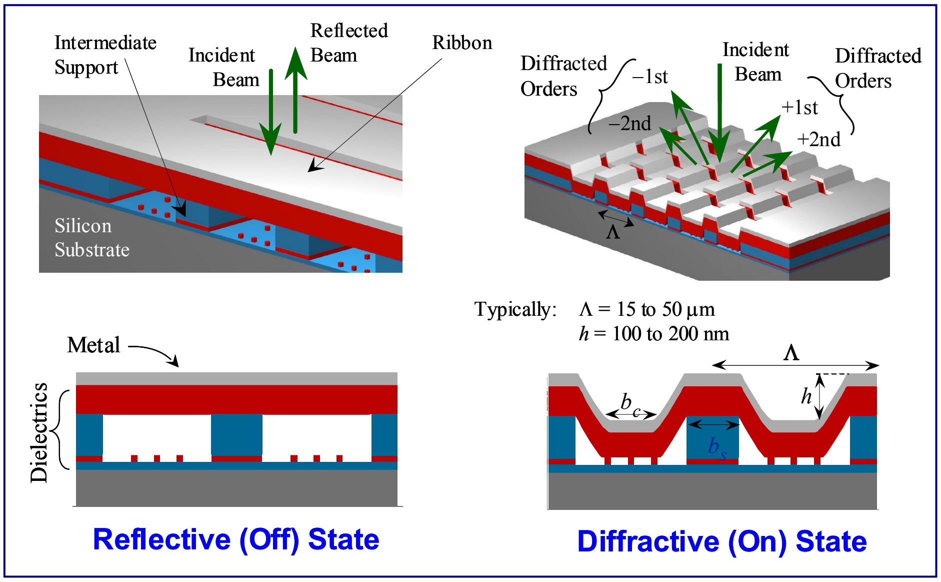

Figure 1: The GEMS device operates by diffraction of an incident beam on the grating surface that is formed when electrostatic forces pull down the metallized ribbons around the support structure.

1.2 Background on MPSI Technology

Our approach uses GEMS (grating electromechanical system) light modulation technology originally conceived and developed [3] at Eastman Kodak Company for use in the high-end commercial display market (see Figure 1). The development of custom GEMS devices for generic MSI and HSI (hyperspectral imaging) applications is currently being investigated under an ongoing ITT Space Systems IR&D activity. The MEMS programmable spectral imaging (MPSI) IR&D brassboards are highly scalable, low-power systems with very high image contrast (2000:1 goal) and fast switching speeds (< 100 ns goal) with no moving mechanical parts. The brassboard systems described in this paper are capable of supporting space qualified, large-format linear TDI scanning sensors in the visible band. The linear MPSI architecture offers the capability to program, from the ground, any combination of bands, any time, for any situation in increments as small 1 nm or less over a spectral range of 100 nm or more. Imaging performance that is comparable with today's fixed dichroic filter MSI sensors and dispersive HSI sensors is achievable with this technology. The history of MPSI development and potential for rapid transition is depicted in the innovation flowchart of Figure 2.

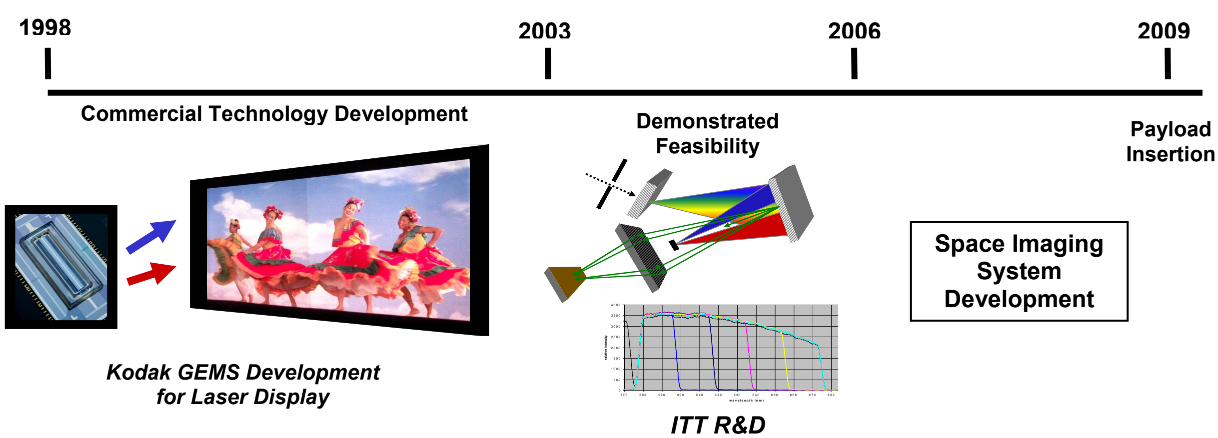

Figure 2: Technology innovation flowchart.

ITT's 2005 IR&D activities demonstrated the extensibility of the MPSI approach to a programmable "filter wheel" for large-format area staring arrays. The extremely fast switching speeds of GEMS devices allows for full 33ms integration times on an area video sensor operating at 30 frames/s. The area MPSI architecture provides a significant sensitivity and reliability improvement over mechanical "filter wheel" systems, which have integration times that are limited by vibrational settling times.

2. SYSTEM IMPLEMENTATION

The MPSI system is built upon many years of effort at Kodak to develop GEMS technology [3-6]. A large body of technical know-how and patented intellectual property has been developed relating to the GEMS device design, fabrication, and integration into systems. The current system application is an extension of the GEMS device's unique ability to act as a digital light switch. The GEMS device, being a sub-class of MEMS devices that are fabricated out of conventional CMOS materials, shares technology development with significant worldwide industrial and government investments in device design, fabrication technology and application concepts.

The basic operation of the GEMS device is shown in Figure 1. It is a diffractive-MEMS spatial light modulator that contains a linear array of actuators capable of high-speed operation, high optical contrast and good efficiency. The device operation is based on the deflection of electro-mechanical ribbons suspended over a silicon substrate by a series of intermediate supports, as shown in Figure 1. When electrostatically actuated, the ribbons conform to the support structure to produce a surface relief phase grating over a wide region. The device therefore operates on the principle of a hidden grating and is designed to be binary switching between a reflective mirror state and a diffractive state having ribbons in contact with substrate features. The diffractive state produces a number of high-contrast orders that are collected by the optical system. This multi-order collection provides high optical efficiency. Furthermore, the large actuation forces, low ribbon mass and small displacements of a GEMS device result in very fast switching times. As an example, Figure 2 shows that optical rise and fall times well below 100 nsec are possible.

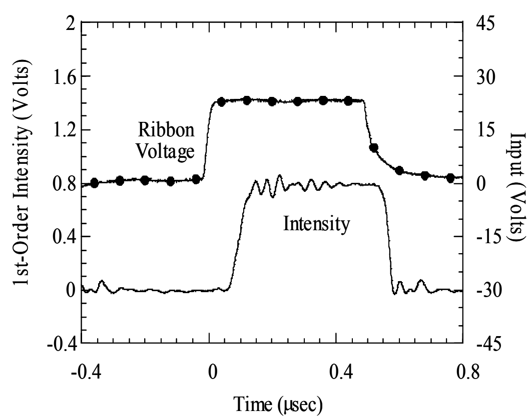

Figure 3: Measured optical response for a GEMS device structure driven by 500 nsec voltage pulse, showing rise and fall times of 30-50 nsec for this particular design.

A MPSI system designed for a linear scan imaging system is depicted in Figure 4. The system is configured as a double-pass spectrometer and targets a pushbroom architecture with a TDI image sensor. Compatibility with TDI scanning provides a >20X scan rate advantage over conventional hyperspectral imagers. The three lens groups are arranged in a one-to-one-to-one imaging configuration, with a patterned mirror and transmission volume phase grating placed near the common focus of all three lenses. In a remote sensing system, fore optics (not shown) would collect light to form an image at the entrance slit. Following the light path through the system, the input light passes through the clear portion of the patterned mirror, is diffracted and dispersed by the grating, and then reimaged onto the GEMS device. The device plane therefore contains a spectrally dispersed image of the input, similar to that in a typical imaging spectrometer. As described below, the GEMS device for a MPSI system is configured as a linearly addressed area array to have many parallel modulator channels that are long and narrow. The spectral components of interest are selected by turning on the corresponding GEMS modulator channels, i.e., by applying a voltage to switch to the diffractive state. The diffracted orders (-2nd, -1st, 1st, 2nd, …) associated with selected channels pass back through the transmission grating, which de-disperses the various wavelengths, and are reflected by the mirrored portion of the patterned mirror into the arm that contains the image sensor. The lens in that arm re-images the input image using only the selected spectra. Unwanted components, i.e., those corresponding to modulator channels in the reflective state, pass back through the clear portion of the patterned mirror and are not imaged. The GEMS device thus acts a spectral switch for the MPSI system. i.e., those corresponding to modulator channels in the reflective state, pass back through the clear portion of the patterned mirror and are not imaged. The modulator channels of the GEMS device thus act as spectral switches for the MPSI system.

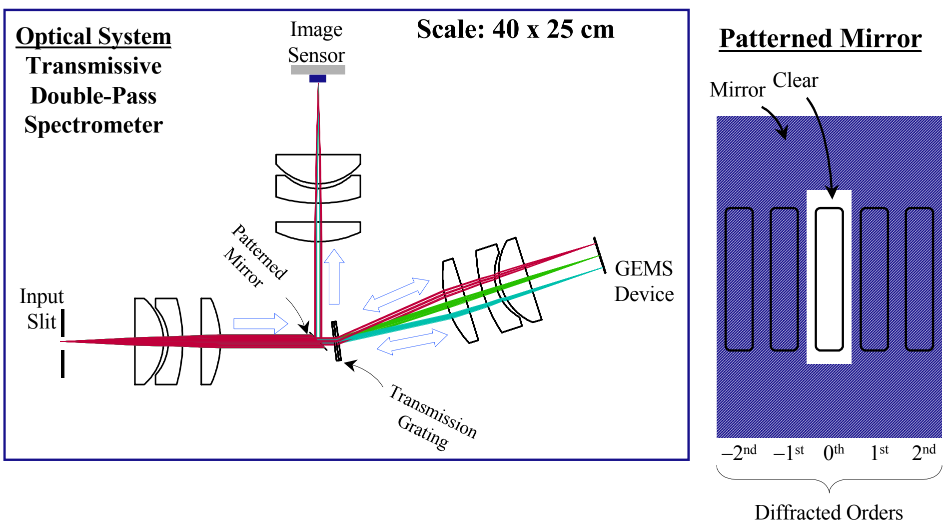

Figure 4: The MPSI system design is shown along side a view of the pattern mirror that acts as a selective optical stop to pass only the bands chosen by the GEMS device.

At the heart of the MPSI system is a custom GEMS device fabricated at Eastman Kodak Company on 6” silicon wafers (Figure 5a). The prototype device shown in Figure 5b has 50 parallel narrow modulator channels, each channel being 216 μm wide by 19.44 mm long and containing over 15,000 moving elements that operate in unison. The GEMS structure enables a very high fill factor within this large active area, unlike most other diffractive MEMS modulators. The total active area is 10.8 mm along the spectral axis of the MPSI system by 19.44 mm along the linear imaging axis,

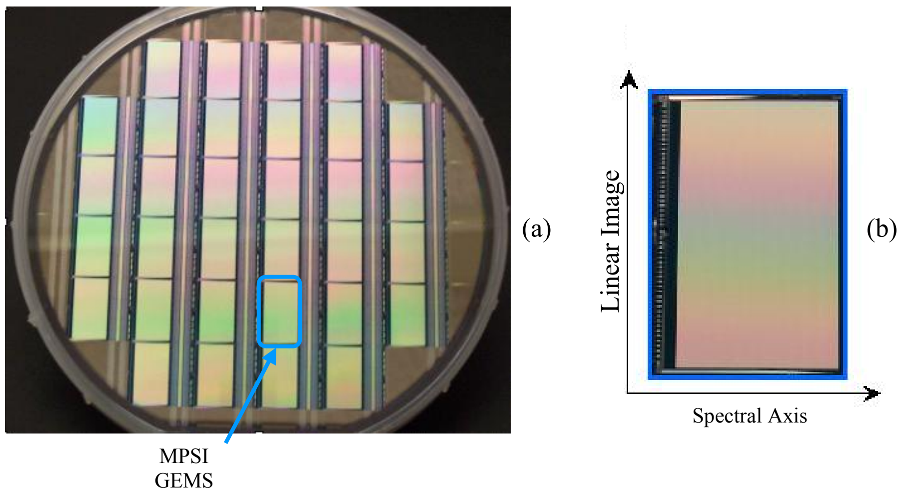

Figure 5: Photo-micrograph of (a) a 6” GEMS device wafer and (b) a custom 50-channel device.

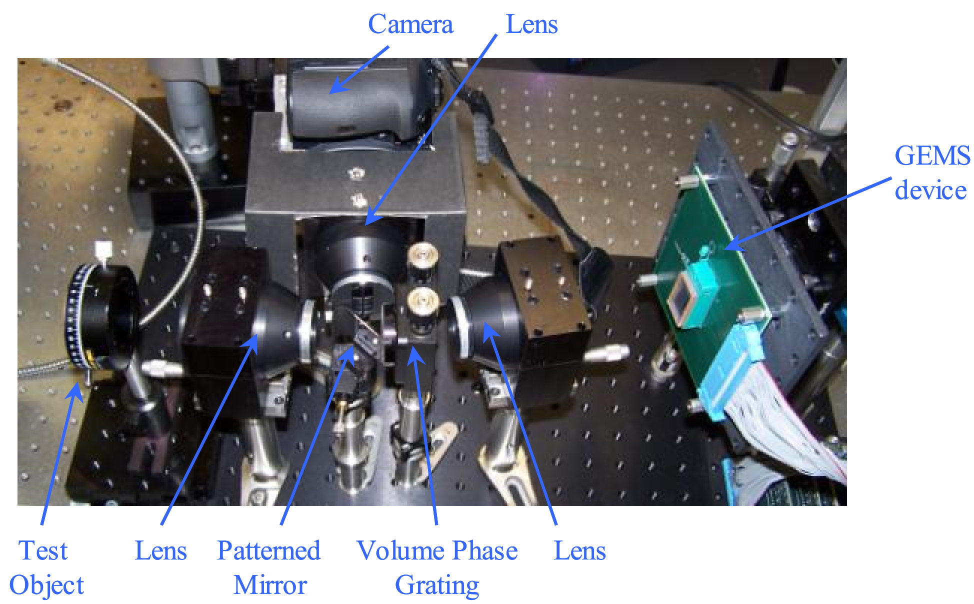

Figure 6: A laboratory demonstration with 11 spectral channels that shows the feasibility of a TDI-compatible programmable imaging spectrometer.

MPSI Brassboard

To demonstrate the imaging and spectral selection capabilities of the MPSI system, a laboratory brassboard (see Figure 6) was built using the 50-channel GEMS device, commercial off-the-shelf (COTS) lenses, and a custom volume phase grating. For initial evaluation, the system was configured with a COTS color digital camera. The system could then be tested for integration into a scanned Time Delay Integration (TDI) linear imaging system without having to implement a full TDI architecture. Only a narrow section of the camera’s area sensor, equal to the width of the entrance slit, is used to capture scene imagery. The system currently operates up to 32 independent channels, limited by the present drive electronics, not the GEMS device itself. Detailed characterization of the brassboard performance has confirmed the operation of the system and has provided key results, generating interest in flight-compatible design and optimization.

3. SYSTEM PERFORMANCE

The band-pass characteristics of the upgraded MPSI system are shown in Figure 7a. As currently configured, the 32-channel system has a range from approximately 450 nm to 700 nm with fourteen narrow 5 nm bands near the center of the spectral range and eighteen wider 10 nm bands near the edges. The bandwidth of each one of the bands is determined by the diffraction optics (grating pitch and lens focal length), the width of each GEMS modulator channel and the number of modulator channels being driven at the same time. It should be noted that a significant portion of the roll off towards blue and red wavelengths is due to the illumination light source itself, as evident from Figure 7b. As an example of the system's spectral selection and imaging capability, Figure 8 shows sample spectral separation images for a studio scene obtained by scanning a color slide film at the input of the system. As a TDI-like hardware simulation, separate slices of the scene were captured using the color digital camera and stitched together to generate these images.

A fundamental feature of the dispersive / de-dispersive system architecture is the capability to produce more complex spectral transmission functions. The Figure 8 images labeled "All Bands" and "Red & Blue Bands" illustrate advanced band-pass capabilities for panchromatic or dual-band capture. The MPSI system also provides variable bandwidth selection by turning on adjacent modulator channels. Figure 9a shows bandwidths from 5 nm to 40 nm wide in 5 nm increments. It should be noticed that, even when the bandwidth is changed, the top of the band pass remains nearly free of ripple and the band edges retain constant slope. More complex filter shapes are also possible, such as a filter with dual pass bands (see Figure 9b).

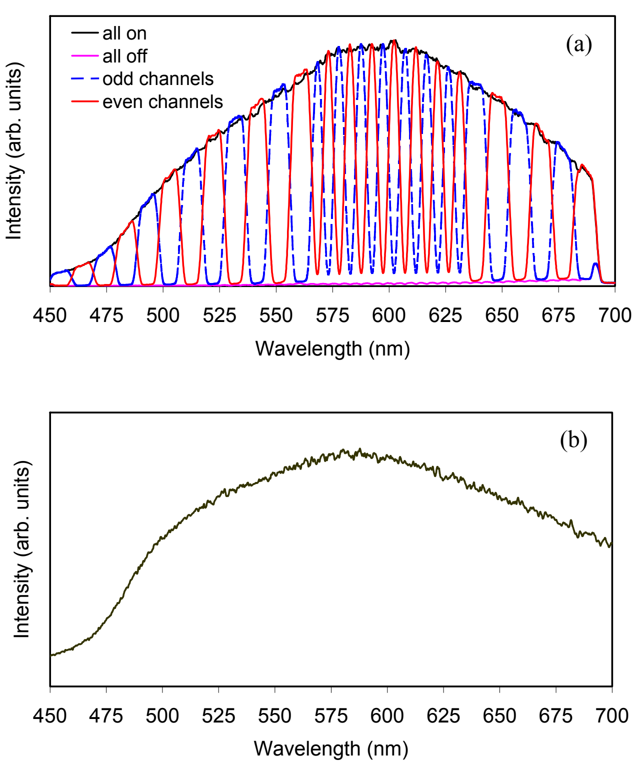

Figure 7: Spectral measurements of (a) MPSI band-pass characteristics and (b) the illumination lamp.

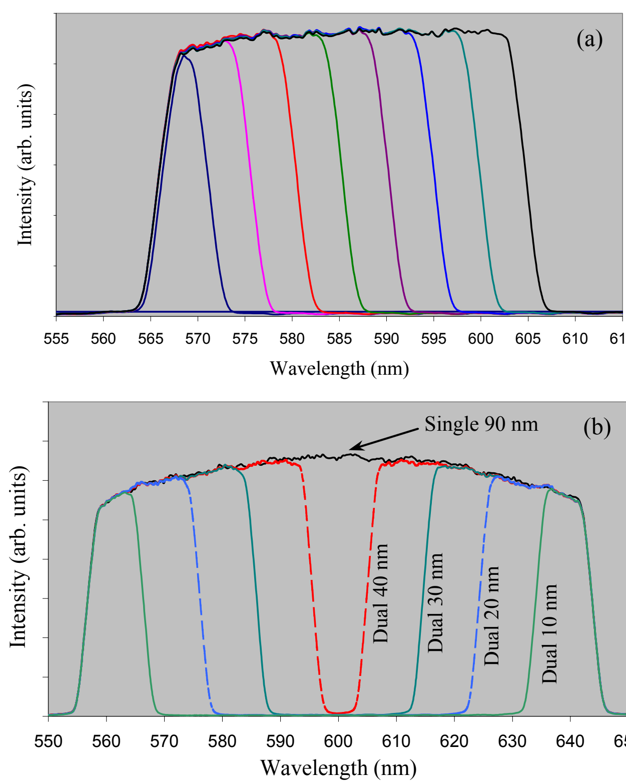

Figure 9: Measured spectra showing the capability (a) to select bandwidth and (b) to generate more complex filter shapes.

Figure 8. Sample spectral separation images of a color-saturated studio scene on a slide.

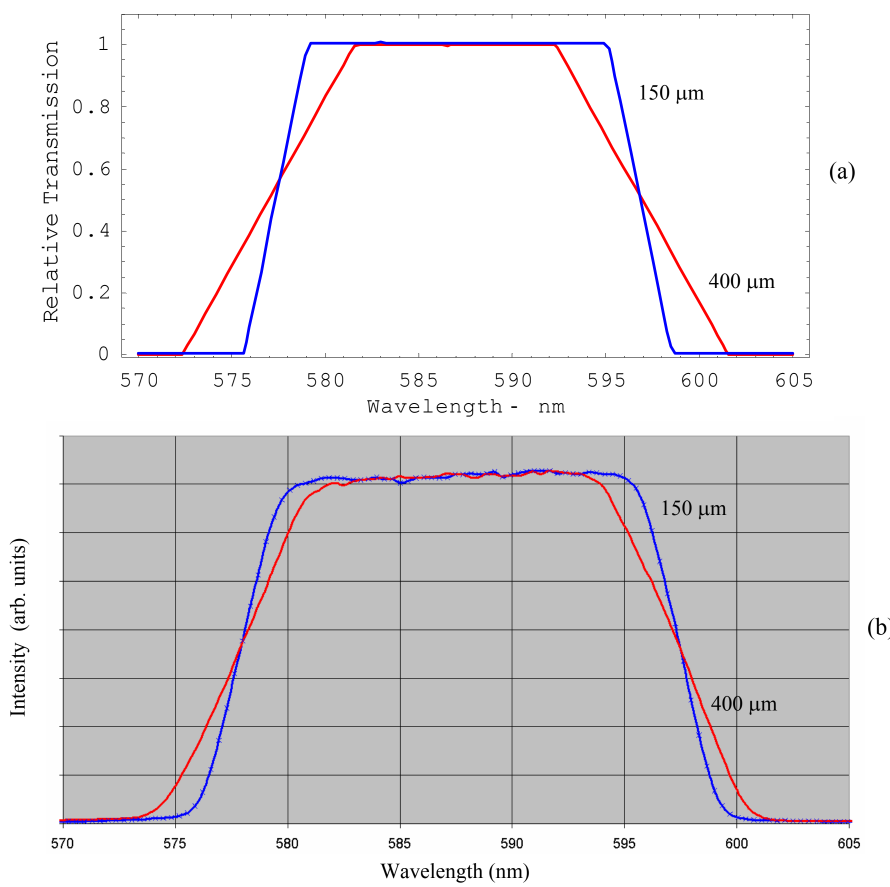

Figure 10: (a) Calculated and (b) measured transmission curves comparing a 150-μm entrance slit width to a 400-μm slit show performance comparable to current precision dichroic filters.

The spectral characteristics shown in Figures 7 through 9 of the current prototype system can be predicted by a numerical convolution model and tailored to suit various applications. A number of tradeoffs are possible. For example, sharper band edges can be obtained with a narrower entrance slit width (fewer TDI columns) or a wider GEMS device. This tradeoff is illustrated in the transmission curves of Figure 10, which shows modeled and measured results comparing two different slit widths (150 µm and 400 µm). Alternatively, as another tradeoff option, the bandwidth of each individually selectable spectral band can be narrowed if the transmission grating dispersion is selected to cover a smaller spectral range on the GEMS device.

Various other system parameters have been modeled, characterized and are being optimized. Currently, the large 1st generation GEMS devices for the MPSI system have rise and fall times of several hundred nanoseconds, as shown in Figure 11. A simple design change can improve the response times of the devices significantly, by a factor of two or more. For certain MPSI applications, the design could be modified so that the response times approach those of the fastest GEMS structures (see Figure 3). Another important parameter, the efficiency of the MPSI system can be modeled to allow optimization of the imaging performance. Figure 12 shows results for the throughput efficiency calculations for a previous generation device. This model supports the evaluation of different components as well as materials in the construction of the GEMS device.

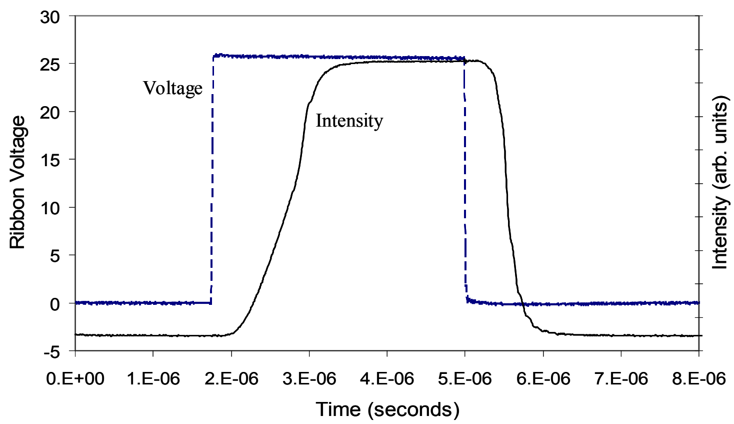

Figure 11: Measured optical response of large GEMS devices for programmable spectral imaging.

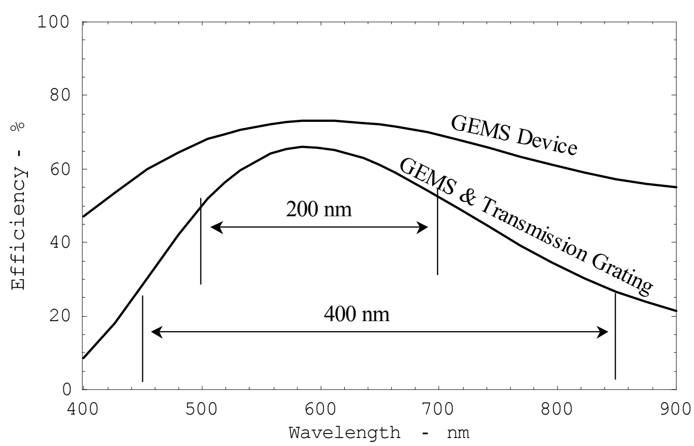

Figure 12: Model calculations of the efficiency of the MPSI system shows the losses due to the GEMS device alone as well as the total system (without lens losses).

4. CONCLUSION

The MEMS programmable spectral imaging (MPSI) system enables high-performance imaging of arbitrary, narrow or wide spectral bands of interest across the visible spectrum without any moving mechanical parts. The architecture combines the scan-rate advantage of a TDI multispectral system with the spectral capability of a hyperspectral system. The flexibility provided by MPSI enables new modes of target detection. To that end, we have studied matched filter detection of camouflaged military targets placed in a desert irradiance model. Using only 4 or 7 bands of programmable spectral channels, it has been shown that the probability of detection is equivalent to performance obtained when a full spectrum of wavelengths are collected in 128 bands, as in a hyperspectral system. These results will be published in a separate paper. Future generations of MPSI systems will be designed to support the SWIR, MWIR and LWIR bands.

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