Micro-optics for Simultaneous Multi-spectral Imaging Applied to Chemical/Biological and IED Detection

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ABSTRACT

Using diffractive micro-lenses configured in an array and placed in close proximity to the focal plane array will enable a small compact simultaneous multispectral imaging camera. This approach can be applied to spectral regions from the ultraviolet (UV) to the long-wave infrared (LWIR). The number of simultaneously imaged spectral bands is determined by the number of individually configured diffractive optical micro-lenses (lenslet) in the array. Each lenslet images at a different wavelength determined by the blaze and set at the time of manufacturing based on application. In addition, modulation of the focal length of the lenslet array with piezoelectric or electro-static actuation will enable spectral band fill-in allowing hyperspectral imaging. Using the lenslet array with dual-band detectors will increase the number of simultaneous spectral images by a factor of two when utilizing multiple diffraction orders.

Configurations and concept designs will be presented for detection application for biological/chemical agents, buried IED's and reconnaissance.

The simultaneous detection of multiple spectral images in a single frame of data enhances the image processing capability by eliminating temporal differences between colors and enabling a handheld instrument that is insensitive to motion.

Keywords: Simultaneous multispectral imaging, hyperspectral imaging, lenslet arrays, single frame spectral image processing, MOEMS, IED's, chemical/biological agents, ammonia nitrite, TICs, IMSS

1. INTRODUCTION

The concept of using an array of diffractive optical elements to perform spectral imaging has been considered for a number of years. Under an SBIR program with the Missile Defense Agency [3] the lenslet array concept went through an extensive design process to examine problematic issues. It was shown that the lenslet array concept could be used in conjunction with a dual-band MWIR/LWIR focal plane array and image in both bands simultaneously using first and second order diffraction, thus allowing simultaneous spatial, spectral and temporal data collection.

This paper will discuss the work performed under an SBIR contract with Edgewood Chemical Biological Command[4] to develop a small simultaneous multi-spectral imaging sensor that can be used for the detection of chemical/biological agents, TIC's, buried IED's and ammonium nitrate material. The multi-spectral imaging system based on lenslet array technology will enable rapid processing of spectral images each frame of the camera thus making the imager unaffected by motion and allowing hand carried applications used by a dismount.

1.1 Concept behind Image Multi-Spectral Sensing IMSS

With funding from several branches of the Department of Defense (Air Force, Navy, Army and MDA) a new approach to hyper-spectral imaging (or imaging spectroscopy) was developed and patented [5]. This new and innovative approach was based on Image Multi-Spectral Sensing (IMSS) which employees a single optical element to perform both imaging and chromatic dispersion along the optical axis. The concept is shown in figure 1 where it is contrasted with a conventional dispersion spectrometer approach.

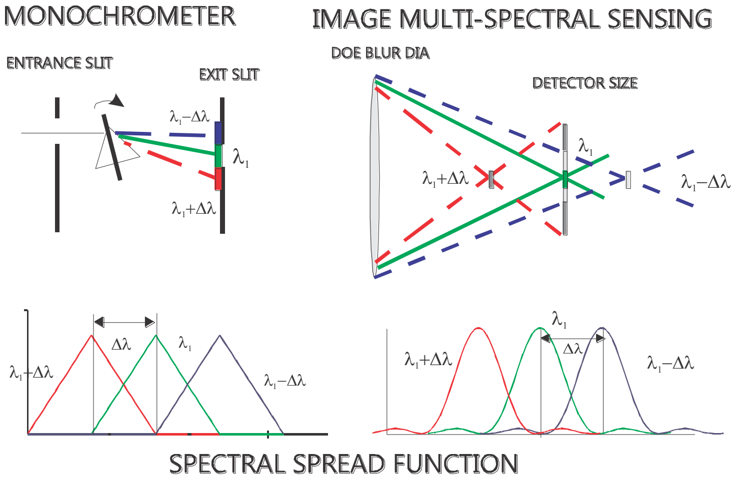

Figure 1. Shows the dispersion of IMSS along the optical axis as opposed to a dispersive spectrometer where the dispersion is perpendicular to the optical axis.

A conventional dispersive spectrometer has an entrance and exit slit and a dispersive element such as a prism or grading. Light coming through the entrance slit is dispersed onto the plane of the exit slit and the prism or grating is rotated to scan the dispersed light impinging on the exit slit. To obtain fine spectral resolution using a dispersive spectrometer, one must reduce the size of the entrance and exit slits, which reduces the throughput of the instrument.

The IMSS uses the dispersive power of a circular blazed grating embedded in an optical element to disperse the light along the optical axis. The light gathering capability of the lens allows development of a very high throughput instrument in comparison to a slit spectrometer. The IMSS has an added advantage that no other spectral imaging approach has, multiplexing of imaging and the dispersion using a single element which allows high throughput (light impinged on the area of the lens as opposed to a narrow slit) resulting in a much greater signal to noise performance.

The IMSS collects spectral images in a band sequential mode as shown in figure 2. Each image frame is of a specific spectral color and subsequent frames can be of different colors if the IMSS lens is scanned along the optical axis. For other applications the same color is imaged in multiple frames if no scanning is performed between frames. The IMSS based imaging spectrometer is extremely adaptive collecting only those spectral bands of interest or dwell at a single spectral band for multiple frames.

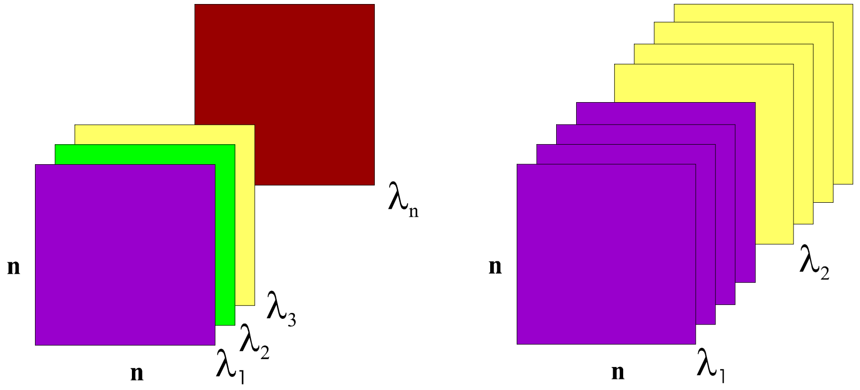

Figure 2. IMSS collects band sequential data.

1.2 Lenslet Array

The lenslet array concept using the same principle in IMSS but applied to circular blazed gratings on micro-lenses configured in an array as shown in Figure 3. This example uses a 4 element lenslet array mounted a few millimeters above a focal plane array. Each lenslet in the array has a different blaze to focus a different wavelength of light at the common focal length of the array. Adding a collimating lens in the fore-optics will allow 4 different spectral images of the same scene each frame of the camera.

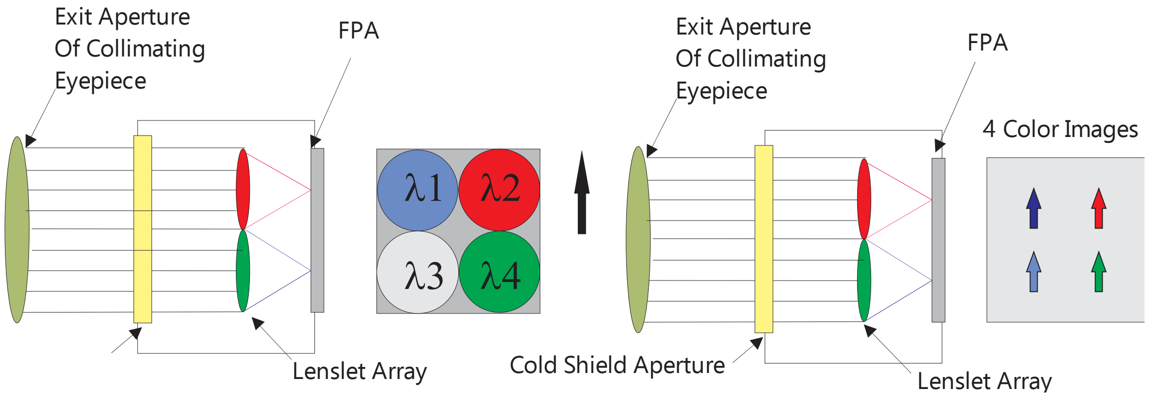

Figure 3. Show the concept of a 2 x 2 lenslet array imaging on a focal plane array.

Shown in figure 4 is the instantaneous spectral coverage of a 16 element lenslet array (4 x 4) with 16 different blazed grating as indicated by the red dash lines. The spectra is for BG aerosol which is a simulant for biological agents that can be encounter in biological warfare. By translating the lenslet array along the optical axis the bins between can be filled in for a hyperspectral imaging. For this example each frame 16 images with 16 different colors are collected in the spectral region from 8 to 11 microns. A lenslet array is placed close to the focal plane array with a short focal length of 5 to 10 mm and the translation between wavelength bins is on the order of microns. This type of translational control can easily be performed with a piezoelectric or electro-static actuation. When using cooled FPA's (required for chemical and biological applications) the challenge is to incorporate the actuation mechanisms inside the Dewar of the cryogenically cooled focal plane array. This is where MOEMS technology and electrostatic actuation approaches is an attractive approach.

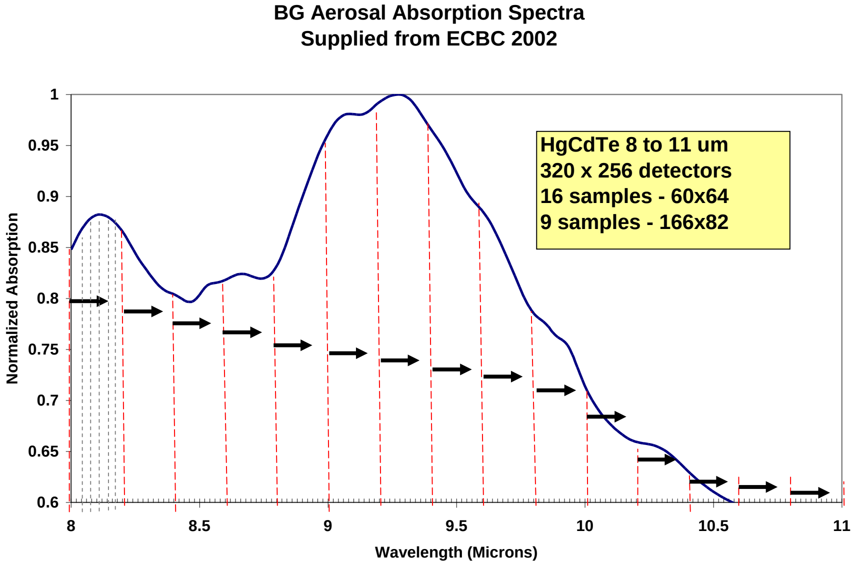

Figure 4. Concept for a 4 x 4 lenslet array showing discrete bands. The lenslet array may translate along the optical axis to fill in the bands between as indicated by the arrow.

Advances in the state-of-the-art of micro machining and gray scale processing have made it possible to configure IMSS lenslets in an array that can be placed close to the focal plane array. A profile of a micro-diffractive lens element is shown in figure 5[6].

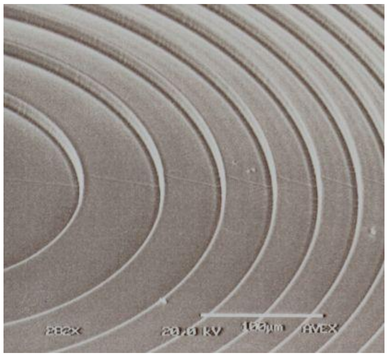

Figure 5. SEM image of typical micro-optical elements fabricated with gray scale technology.

2. EXAMPLE DESIGNS

When designing a lenslet array that will be fabricated using photolithography the size and geometry of the elements must be considered in order to meet the processing capability of the materials used. Shown in figure 6 is a schematic of a cross-section of a single lenslet. All optical power is contained in a very thin layer on the surface of the substrate which is used for mechanical strength. This is shown as “d max” in the diagram and is computed by:

$$d_{max} = \frac{\lambda_o}{n-1}$$

Where λo is the design wavelength and n is the index of refraction of the material used. The number of blazed rings (N) is determined by the focal length and f-number of the lens:

$$N = \frac{f}{8\lambda_o}\left(\frac{1}{f\#}\right)^2$$

Design of the circular blaze is a function of the first ring which is determined by the phase equation and subsequent rings have a continuously smaller radius. The radius of the center circle, r_1 is determined by:

$$r_1 = \sqrt[2]{\frac{\lambda_o}{a}} \quad where \quad a = -\frac{1}{2f}$$

Each ring after is just a multiple of the square root of the ring number:

$$r_n = r_1\sqrt[2]{n}$$

The smallest geometry that dictates the process is the blazed zone spacing at the edge which is given by:

$$(\Delta r)_{min} \cong 2\lambda_o(f\#)$$

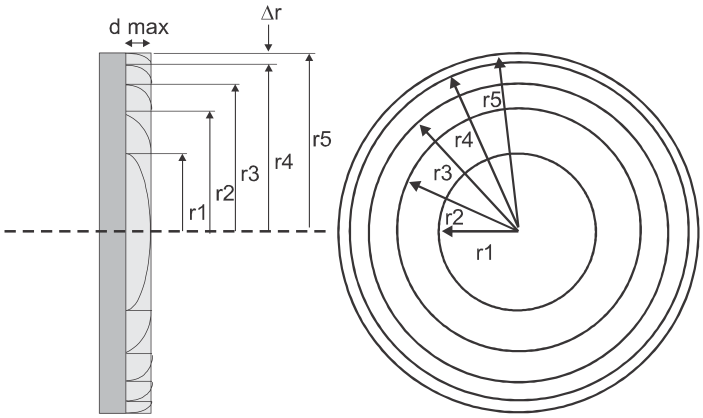

Figure 6. Schematic of a single lenslet in the lenslet array

With the above in mind it is now possible to design all the lenslets in a 16 element (4x4) array as shown in table 1 and table 2. The first design covers the region from 1 to 4 microns.

Table 1. Parameters for a SWIR-MWIR lenslet array

Lenslet Number		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Design Wavelength (um)	λo	3.94	3.76	3.57	3.38	3.18	2.99	2.80	2.45	2.30	2.15	2.00	1.70	1.57	1.47	1.28	1.19
Thickness of lens (um)	d	2.21	2.11	2.00	1.90	1.78	1.68	1.57	1.38	1.29	1.21	1.12	0.96	0.88	0.83	0.72	0.67
Total number of rings (#)	n	75	79	83	88	93	99	106	121	129	138	148	174	188	201	231	249
Delta radius min (um)	Δr_{min}	14.49	13.81	13.12	12.43	11.67	10.98	10.29	9.01	8.46	7.90	7.35	6.25	5.77	5.40	4.71	4.37

This design takes into consideration the atmospheric regions of strong absorption by selecting the blaze wavelength for each of the 16 lenses in the array as shown in figure 7. Notice that the band-width of a spectral resolution bin is wider for the longer wavelengths and narrower for the shorter wavelengths. This indicates the tighter tolerances in the blaze design which will determine the manufacturing process realizable are at the shorter wavelengths on the lenslet array.

The spectral region from 1 to 4 microns can be used for applications where ammonium nitrate is being detected as well as various forms of toxic industrial chemicals.

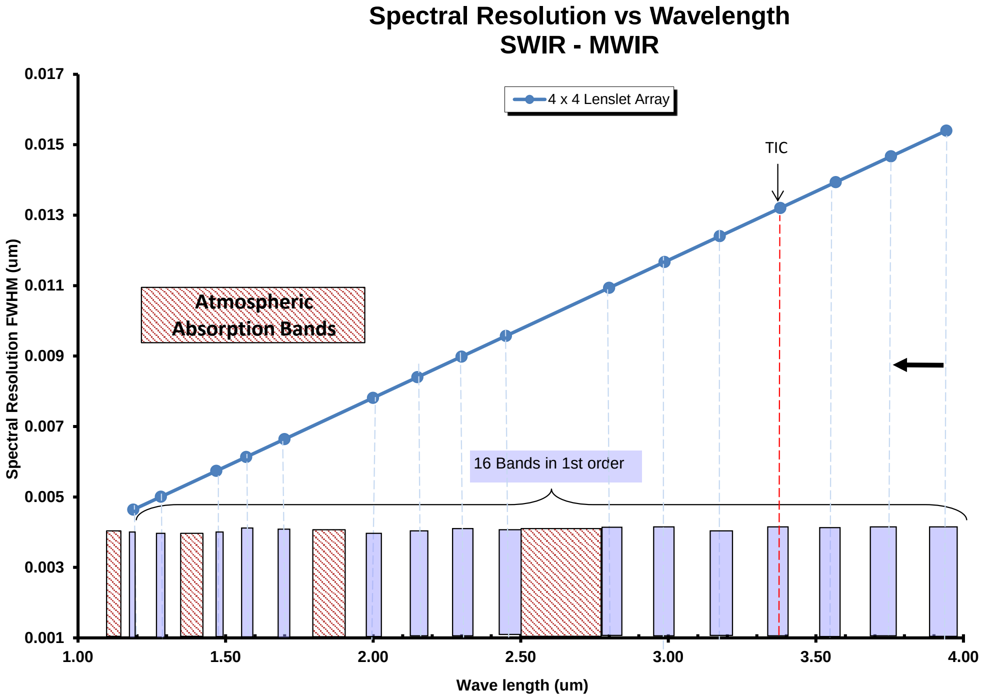

Figure 7. Selection of the center wavelengths for a 16 element lenslet array in order to avoid the atmospheric absorbing regions is shown here.

The second example that was looked at was the region from 8 to 11 microns. This is the region where the spectral signature of chemical and biological agents can be seen. Also this is the spectral region where the Reststrahlen signature of disturbed soil can be detected.

Table 2. Parameters for a LWIR lenslet array

Lenslet Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Design Wavelength (um)	λo	11.00	10.81	10.63	10.44	10.25	10.06	9.88	9.69	9.50	9.31	9.13	8.94	8.75	8.56	8.38	8.19
Thickness of lens (um)	d	6.18	6.07	5.97	5.87	5.76	5.65	5.55	5.44	5.34	5.23	5.13	5.02	4.92	4.81	4.71	4.60
Total number of rings (#)	n	8.00	9.00	9.00	9.00	9.00	9.00	9.00	10.00	10.00	10.00	10.00	10.00	11.00	11.00	11.00	11.00
Delta radius min (um)	Δr_{min}	57.29	56.30	55.36	54.38	53.39	52.40	51.46	50.47	49.48	48.49	47.55	46.56	45.57	44.58	43.65	42.66

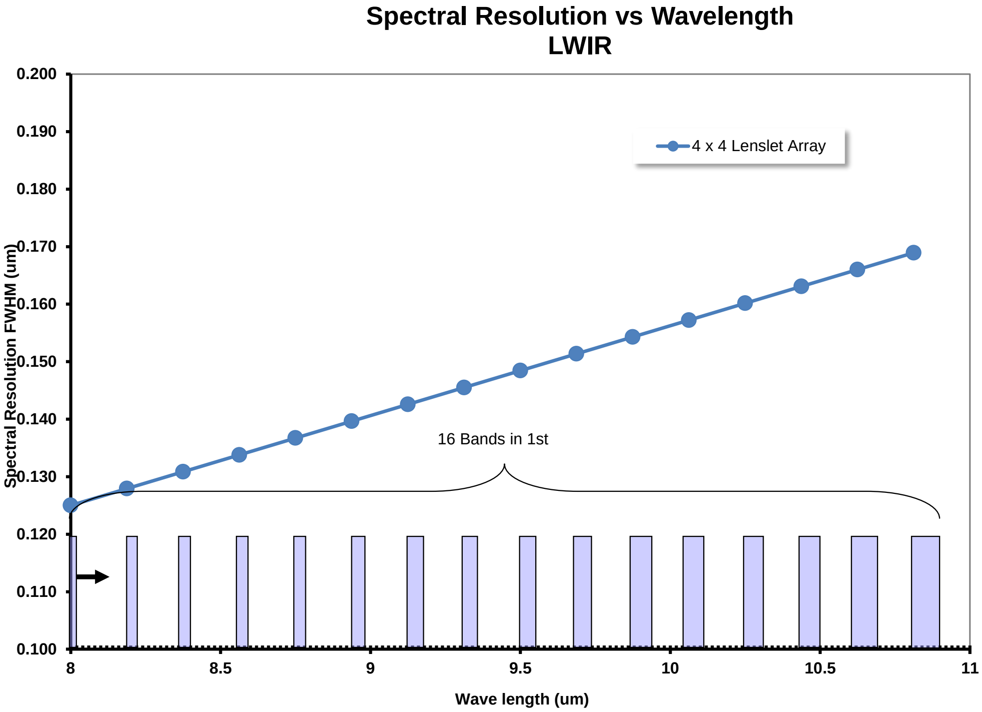

Figure 8. Selection of the center wavelengths for a 16 element lenslet array in order to avoid the atmospheric absorbing regions is shown here.

The minimum radius spacing at the outer edge of each lenslet is a linear function of the wavelength and shown in figure 9 for the SWIR-MWIR design. The number of concentric rings is a nonlinear function and increases for shorter blaze wavelength as shown in figure 10. All the optical power is contained in a very narrow thickness on the surface of a substrate and is linear with wavelength as shown in figure 11 where the shorter the wavelength the shallower the thickness of the blazed grating.

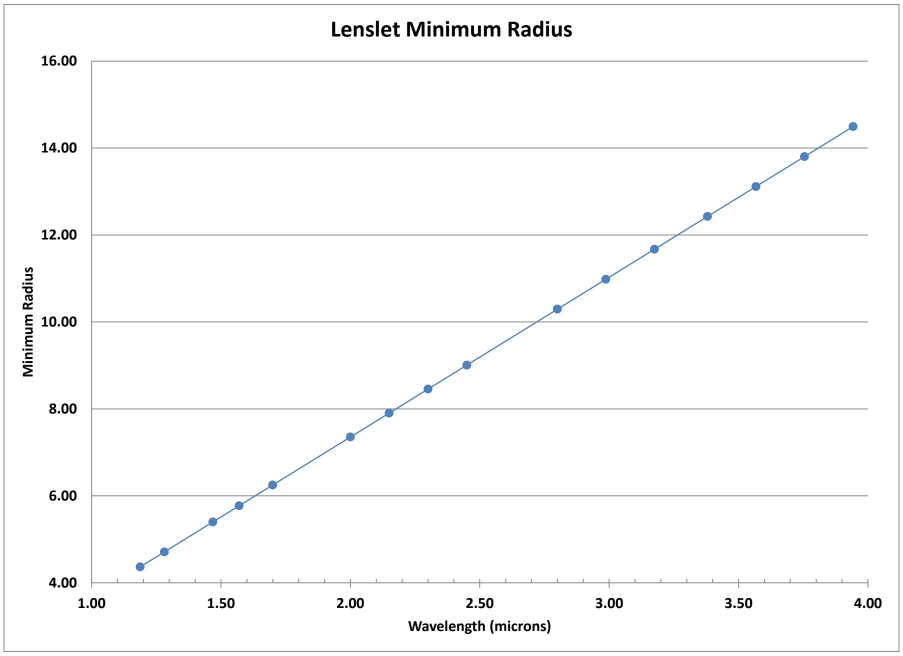

Figure 9. The minimum radius feature as a function of wavelength is linear and smaller for shorter wavelengths

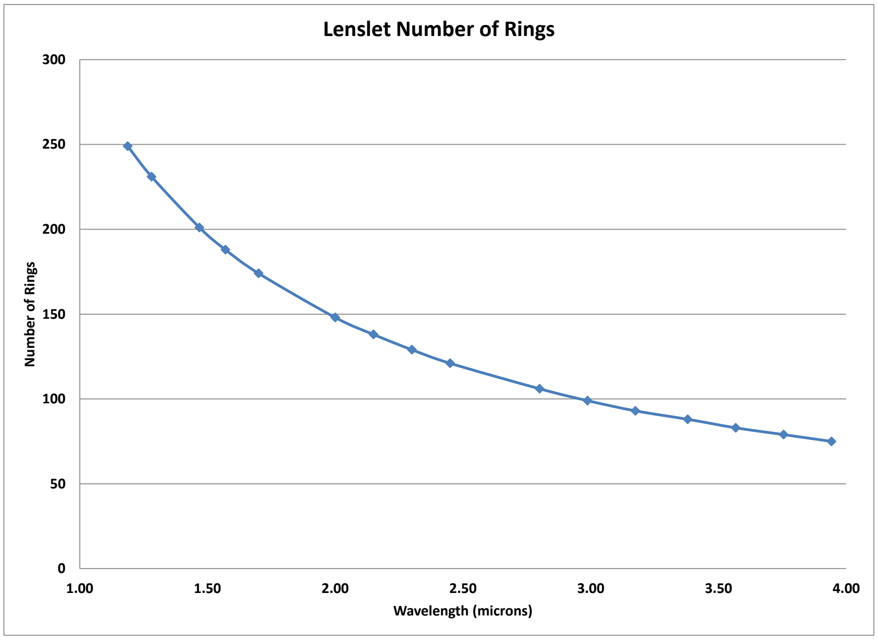

Figure 10. The number of rings as a function of wavelength is nonlinear and increases for shorter wavelengths.

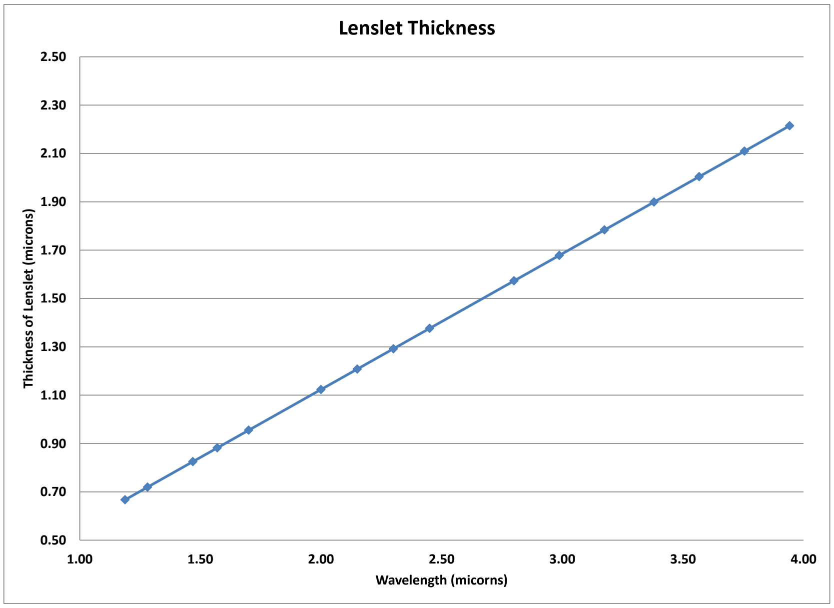

Figure 11. The thickness of the lenslet as a function of wavelength is linear with the thinner values for the shorter wavelengths

3. SUMMARY

An approach to using a blazed grating lenslet array for simultaneous multispectral imaging was presented in this paper. The advantages of simultaneous multispectral imaging enable a camera that is insensitive to motion as well as allows for robust real-time multispectral processing without the need for frame to frame registration. Algorithms are significantly simplified so that real-time processing in the camera is enabled. This approach can be used as a handheld multispectral imaging for applications such as; IED detection where disturbed earth is an indicator of a buried device, the detection of clandestine IED manufacturing facilities, detection of Toxic Industrial Chemicals (TIC's) such as petroleum products, detection of chemical and biological warfare agents and many more. Two design examples where given for the spectral region from SWIR-MWIR and another for LWIR.

4. ACKNOWLEDGEMENTS

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