MULTI-SPECTRAL SMART RETINA™

David R. Shostak, David E. Ludwig and
Chris Saunders

Irvine Sensors Corporation
3001 Redhill Ave., Building 3
Costa Mesa, CA 92646-4526

ABSTRACT

To make FPAs "smart" is to associate analog and digital signal processing electronics as intimately as possible with the detector arrays. The challenge is that there isn't enough room for the amount of signal processing required. With system requirements advancing to even higher resolution, planar FPA technologies have only the detector area available and this area is as low as one thousandth of an inch (one mil) on a side. Z-plane technology overcomes this problem by providing 2,000 mil^2 of area in the Z-direction behind each detector. However, Z-plane technology can currently only achieve four mil resolution.

Thus, the challenge! A compromise must be found between the degree of parallelism in the signal processing and the resolution achievable. Irvine Sensors has achieved the first step of a two stage process. A new IC for improving detector resolution for multi-spectral imaging has been made and is called the Multi-Spectral Smart Retina (MSSR). The second step is to bump bond this detector to a Z-plane module that has large processing power. The purpose of this paper is to report on the initial technical results of the Multi-Spectral Smart Retina.

INTRODUCTION

Developers of strategic sensors for advanced applications (automatic target recognition, surveillance and interceptor guidance) are moving from traditional scanning technologies to newer staring implementations because of the promise of increased sensitivity. This performance increase comes with the loss of two desirable features of scanning implementations: ease of multi-spectral detection and on-FPA real estate for pre-processing. The method used to make FPAs "smart" is to associate analog and digital signal processing electronics as intimately as possible with the detector arrays. The problem is that there isn't enough room for the amount of signal processing that is required. Planar FPA technologies have only the detector area available. With system requirements advancing to even higher resolution, the detector area is as low as one thousandth of an inch (one mil) on a side. Z-plane technology overcomes this problem by providing 2,000 mil^2 of area in the Z-direction behind each detector. However, Z-plane technology can currently only achieve four mil resolution.

The ultimate design must balance two conflicting goals, increased focal plane pre-processing (to the point of achieving a "smart" sensor) with the demand of finer detector pitch and lower FPA power dissipation. Typical pre-processing loads can include: gain and offset correction, clutter rejection, background subtraction, multiplexing and analog to digital conversion. In addition to all of this, is the desire to process the data scene in numerous spectral bands simultaneously and a truly innovative staring focal plane design is required.

BASIS FOR THE DESIGN AND DEVELOPMENT

Irvine Sensors has focused this MSSR effort on providing means of implementing multi-spectral detection, while at the same time reducing the down stream processing load by performing two dimensional spatial filtering within the detector substrate. The MSSR readout circuit will be bump bonded to a Z-plane FPA module for the remaining "smart" preprocessing functions. To accommodate the desire for one thousandth of an inch detector resolution with the four thousandths of an inch Z-plane module fabrication baseline, the MSSR circuit also performs a 16:1 sub-multiplexing function.

This feature allows the focal plane to be divided up into as many as 16 discrete spectral bands, between 0.4 and 12 microns. Each spectral band is sub-multiplexed onto a single output that will then be further processed and digitized by the Z-plane FPA module.

To do this Irvine Sensors has taken a two step approach to solving the conflicting requirements of increased detector resolution and increased processing power by incorporating a planar detector readout circuit with moderate processing power signal integration, spatial filtering, and a minimum of multiplexing coupled to a Z-plane FPA module with increased processing power pre-amplification, further signal integration, non-uniformity correction, analog to digital conversion and further multiplexing.

A small sub-array, typically 16 (4x4) elements, is multiplexed into an output signal lead which then forms the bump-bond interconnect in a Z-plane hybrid. In this fashion, a 128x128 parallel processing readout device with signal processing channels on four mil centers can serve a 512x512 detector array with detectors on one mil centers. The sub-array multiplexer, hereafter referred to as the sub-multiplexer, would then have a clock rate at 16 times the sensor frame rate. For example, a sensor with 60 frames per second imaging capability the sub-multiplexer and the read-out device input preamplifier would run at one kilohertz (16X60). The physical implementation of the MSSR readout and the Z-plane FPA module is shown in Figure 1.

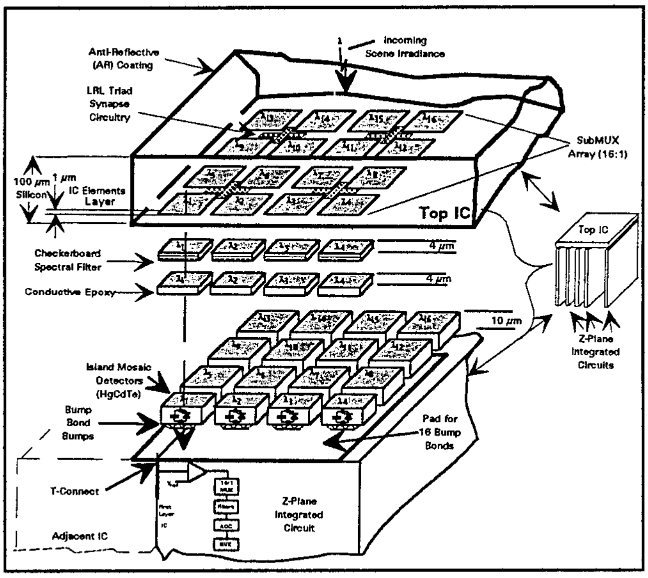


Figure 1. Multi-Color (16) Exploded View

The detector substrate is silicon. The active circuit portions of the spatial filter and the sub-multiplexer are located in the streets and avenues between the active regions. The passive components and the polysilicon routing leads can lie within the active regions. The IR signals will pass through the active substrate, through the checkerboard dielectric spectral filters, to the detectors below. The detectors can be implemented using an "Island Mosaic" approach. The detector fabrication is not part of the current MSSR effort, but has successfully been demonstrated in the past. In this approach, bulk material is conductively epoxied to the substrate and then is ion milled into discrete islands of HgCdTe, eliminating the coefficient of expansion mismatch problem between the detector and silicon substrate. Junctions are implanted into the islands of HgCdTe and the entire structure is then passivated.

The multi-spectral detection is realized by optically dither scanning the instantaneous field of view (IFOV) of each detector. This is performed over the entire 16 color staring array. The dither scan covers the scene until each element in the scene is read. Therefore, each pixel in object space is time-shared by the 16 detectors operating in each of the 16 colors. The output data stream of each detector is a sequential sampling of 16 spatial resolution elements in that detector's color.

Irvine Sensors has initially demonstrated the key electrical features of the MSSR with a foundry-fabricated analog test integrated circuit. This paper will now discuss the design of and technical results achieved from the Multi-Spectral Smart Retina .

MSSR TRADE-OFFS INVOLVED

The initial top level specifications for the MSSR IC are based on a generic ground launched optical seeker for a Kinetic Kill Vehicle (KKV). A typical top level specification for a ground launched KKV is listed in Table 1. These specifications are associated with an Endo Leap engagement.

Table 1. Top Level System Specifications For a Ground Launched KKV

PARAMETERS	VALUE	UNITS
Closing Velocity	11	Km/sec
Engagement Range	50	Km
Signal to Noise Ratio Req'd	10	
Acquisition Altitude	60	Km
Field of Regard	0 to 40	Degrees
Target Type	RV	
Acquisition Basket Size	±0.7	Degrees

The top level requirements analysis focuses on the optical considerations, background generated signals, detector considerations and calculations of noise equivalent targets. A trade-off analysis was performed that concluded with an optical system specification and a point design specification Table 2. The top level specification from the point design is the basis and the place where the lower level requirements come from for the detector readout IC.

Table 2. Summary of Optical System

PARAMETER	VISIBLE	INFRARED
Focal Length	200 mm	125 mm
Aperture	2 cm	5 cm
F Stop	10	2.5
Resolution (IFOV)	125μm	200μm
Detector Size	25 μm	25 μm

The top level specification starts with the spot size of a point source on the focal plane. It is based on the optics diameter and the spectral bandwidth. Typical optics diameters will be in the 3 to 5 cm range. At 5 cm optics, blur circle diameters for long wavelengths bands (6 microns and above) will be greater than 300 micro radians. Short wavelength bands (2 microns and below) will have blur circle diameters of 100 micro radians or less. Therefore, when broad spectral coverage is required from a single optical system, more than one size detector would optimize the diffraction limit/detector resolution ratio. This can be accomplished by combining numerous sub-multiplexed elements as shown in Figure 2.

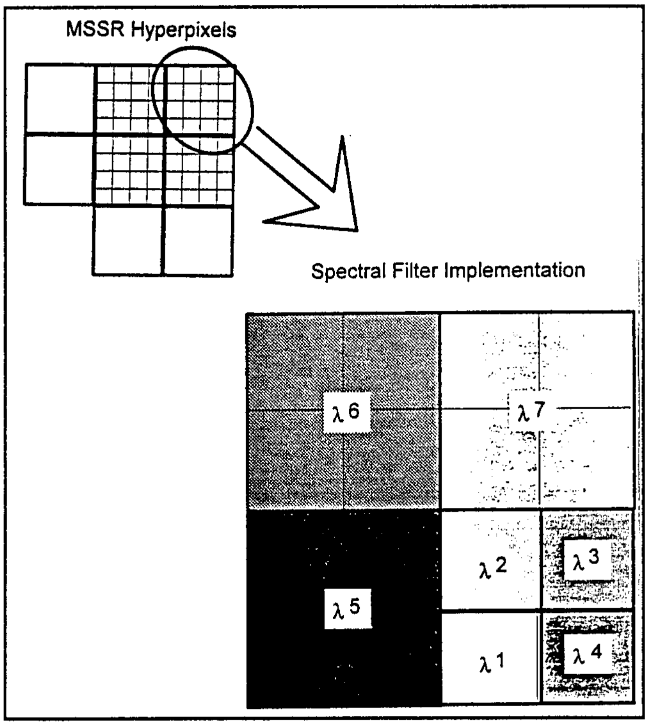


Figure 2. Various Detector Resolutions by Combining Elements

Each 4X4 sub-multiplexed array is arranged into 7 discrete spectral bands as shown in Figure 2. Lambda 1 to Lambda 4 are short wavelength bands and cover a single element of the sub-multiplexed array. Bands 5, 6 and 7 are mid and long-wave length bands. The spectral filter will cover 4 elements in the sub-multiplexed array to contain twice the diffraction limited blur circles of the shorter wavelengths.

SMART DETECTOR

The detector is broken down into two domains of operation, visible and IR. The visible detection will occur in the active silicon detector substrate. The IR detection occurs in the Island Mosaic HgCdTe detectors. It also shows the spectral filter that is sandwiched between the detector and the substrate.

The infrared Island Mosaic array has the unique feature of not requiring indium bump bonds as the attachment medium between the substrate and the HgCdTe. Instead, the bulk material is conductively glued to the silicon substrate. The active silicon substrate is also important in the Island Mosaic concept because it provides the basis for four functions:

1. A medium for near IR detection
2. A substrate for the spectral filter
3. A processor for two dimensional spatial filtering via analog impedance mesh
4. A sub-multiplexer combining a 4 X 4 pixel group of detector elements into a fast single processing channel.

UNIT CELL DESIGN CONCEPT

Irvine Sensors has fabricated and demonstrated a 2D spatial filter using an interconnecting impedance mesh circuit as part of the MSSR development. A photograph of the first iteration demonstration IC with a 4X4 36μ unit cell is shown in Figure 3. 1.2μ IC design rules were used; when 0.8μ IC design rules are used the cell will be 25μ.

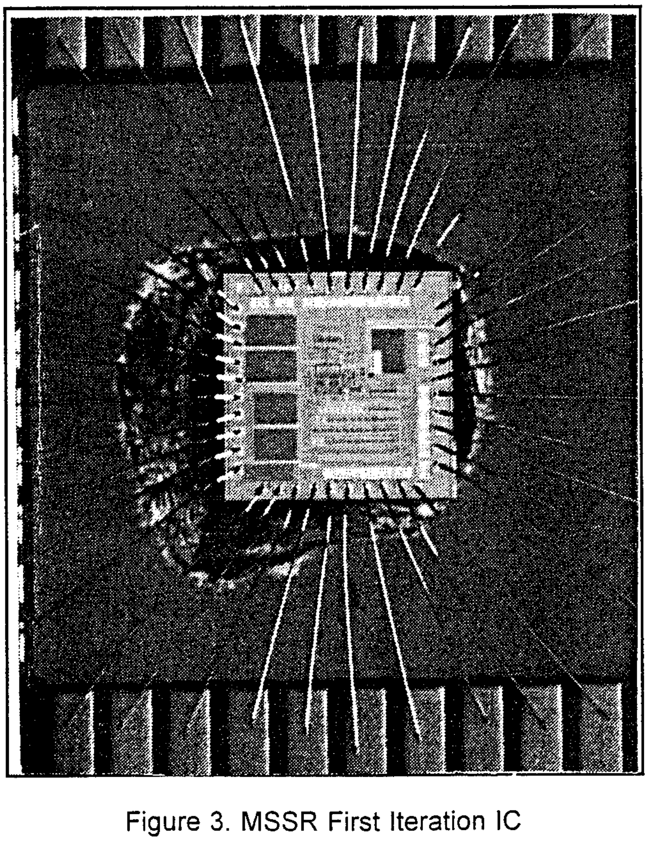


Figure 3. MSSR First Iteration IC

A simplified schematic of the unit cells is shown in Figure 4.

Features:
- High Dynamic Range Spatial Filters
- Simplest Approach
  - Fewest FETS
  - Minimum Cell Areas
- Readout Continuously or Fixed Interval
- Wide Range of Tint and Frame Rate W/O Redesign
- Spreading Function Contraoled by Cb/Cd and Number of Clock Pulses Between Readout
- High Common Mode Rejection f<fclock
- Added Z-Plane Integration Extends DR to 1E6
- Very Low Power Dissipation (Readout Dependent)

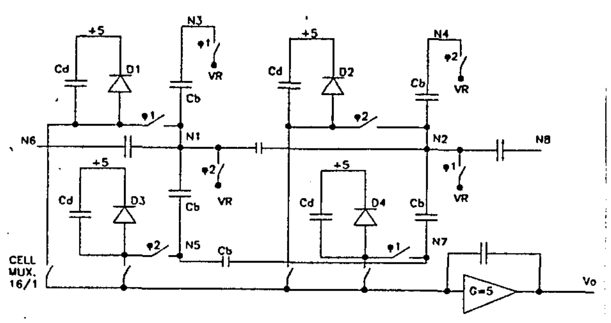


Figure 4. Visible Spatial Filter Topology Design Approach

Capacitors "Cd" are the parasitic capacitance of the detectors. Capacitors "Cb" are the interconnecting impedance network. This network shares charges between the detectors. The operating frequency of the phase clocks "ø1" and "ø2" determine the spreading function of this spatial filter. The 16 to 1 sub-multiplexer also is shown in the schematic diagram. The amplifier "G=5" located in the MSSR feasibility IC is used to amplify the output signal. Output timing of the IC is shown in Figure 5. Channel 6 (each output channel is identified on the waveform) contains a weak input signal. This channel's response is enhanced (negative), and the adjacent channels, 5 and 7, are reduced in intensity (positive), accentuating the point source as desired in a spatial filter.

IC DESIGN AND TEST CONSIDERATIONS

The IC block diagram in Figure 6 has four silicon detectors, and 12 surrounding electrical input pixels that when combined form a 4x4 matrix.
The four detectors have a MUX input that allows even these cells to have signals injected from off the IC. The function of this IC is:

1. 4x4 "switched capacitor" impedance network in a 36μ cell space
2. Matrix controlled by 4 phase clocks
3. Execute real time filters on the FPA
4. Output is a 16 to 1 multiplexer

4x4 Unit Cells
- Background Current Injector
- Photodiode Input
- Lateral Capacitive Network
- X-Y Readout Switch

Top Level IC
- X-Y Raster Clock Generator
- Read Out Amplifier
- Correlated Double Sampler
- 4 Phase Clock Buffer

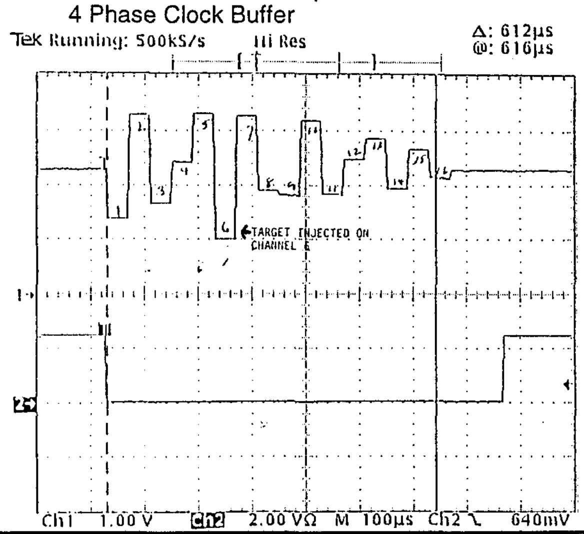
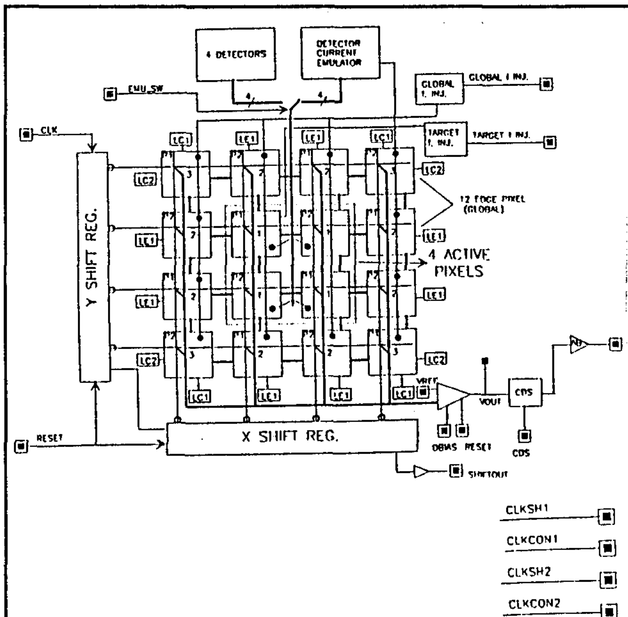


Figure 5. MSSR Features



- CLKSH1 & CLKCON1 Go To Block (P1)
- CLKSH2 & CLKCON2 Go To Block (P2)
- Center Cell (1), Edge Cell (2), Corner Cell (3)

Figure 6. MSSR Test Chip Block Diagram

Tables 3, 4, 5, and 6 show the path of the requirements from the top level, to the lower level simulated using a Sparc 10 workstation, to the measured test data taken. The conclusions from the measured test data are the first iteration MSSR IC works end to end and demonstrates the functionality of 16 elements (4x4) "switched capacitor" impedance matrix and real time visible spatial filter. The four phase clocks which control the 4x4 switch capacitance impedance matrix should be reduced in the future to two phase clocks to minimize the number of clocks and reduce IC real estate.

Table 3. MSSR System Level Specifications

PARAMETER	VALUE	UNITS
Top Level Spec		
Operating Temperature	77	Kelvin
Sample Rate of element	100	Hz
Sub-Multiplexing Ratio	16:1	
Unit Cell Dimension	25	Micron
Sub-Multiplexing Rate	1600	Hz
Power Dissipation	TBD	Watts
Active Area (Fill Factor)	>75	Percent

Table 4. Visible Detector Specifications

VISIBLE		
Wavelength	0.4 to 0.7	Microns
IFOV	125	μrad
Maxi Detector Current	1x 10^10	Amps
Dynamic Range	1000:1	
Detector Impedance	100	MΩ
Noise Equivalent Target	75	Watts/sr
Detector Noise Current	1.18x10^-14	Amp/√Hz
D*	4.63x10^10	cm-√Hz/W
Backgrnd Photon Flux	2x10^14	Ph/Cm^2/Sec

Table 5. Simulated MSSR IC Specifications

PARAMETER	REQ'D	SIMULATED
Detector Capacitance	REF	100 ffd
Integrated Charge	REF	2E6
Readout Noise e	2500/250	200
Dynamic Range	1,000	10,000
Linearity	<5%	<5%
Readout Mode	RSS	Row Snapshot
Readout Channels	16	By Design
Frame Rate	100	100 Hz
Spatial/Resistance	6 bits	4 bits
Resistance Range	0.1- 2 meg	0.2 - 8E9Ω
Crosstalk	TBD (<2%)	TBD
Power/Pixel	TBD (3)	2 μwatts

Table 6. Measured MSSR IC Test Data

PARAMETER	MEASURED
Multiplexer Readout	Target Pixels Interact
Output Buffer	10 MHz Bandwidth
Linearity	<7%
Dynamic Range (S/N)	101 dB
Spreading Function	Graphically Demo'd
Fixed Pattern Noise	20% Average
Noise Measurements	1-10 μV/√Hz
Detector Response	Active
Gain Variation	74% Average

FUTURE CONSIDERATION AND APPLICATIONS

This powerful new concept currently being developed with BMDO funds through S&SDC can provide multi-spectral imaging in the 0.4-12 micron spectral regime. The new imaging system when fully realized will provide the following capabilities when integrated with ISC's Z-plane technology:

1. 512x512 image resolution in each of 16 colors

2. Rejection of bright, extended, constant or time varying sources, to suppress potential jamming countermeasures

3. 30 -100 Hz frame rate

4. On-FPA non-uniformity correction (NUC)

5. On-FPA signal conditioning and analog-to-digital conversion (ADC) with at least 10 bit resolution, linear or non-linear (e.g., logarithmic) transfer function

6. Electronic image motion compensation

7. Spatio-temporal-spectral processing (3D filter) to perform target recognition in the presence of active and passive countermeasures

8. Noise-equivalent-target (NET), in the relevant spectral bands, an order of magnitude superior to scanning sensors

There are several advanced applications for MSSR:

1. The MSSR can detect and minimize the effective of LASER jamming, as it functions in a multi-color environment. The MSSR will also have night vision capabilities, eliminating the dark as an enemy advantage and establishing the night as U.S. Government territory.

2. The MSSR will provide improved pattern recognition. This will insure the first hit success rate of any weapons system using the MSSR technology. The neural network processing with a lateral resistance network allows the system to perform computational comparisons and be more effective with each mission.

3. The MSSR will aid in the detection of camouflaged and masked objects. This will increase the survivability of any individual soldier using the MSSR technology. MSSR also has the capability of being used as an image and clutter extractor or collector.

4. The MSSR technology will establish the optimal conditions for day or night, open or restricted, light or heavy intensity conflict for the 21st Century Land Warrior. This future mission is yet to be addressed by the other DOD services.

CONCLUSION

The Multi-Spectral Smart Retina is able to supply means for a detector to work in a multi-spectral regime with increased detector resolution. Combined with a Z-plane processor module, it has the processing power for preamplification, non-uniformity correction and analog to digital conversion on the FPA. This allows MSSR to work with the next generation advanced applications. In addition, the MSSR has the capability to be bump bond to the Z-plane module. The performance increases because of the ability to process multi-spectral images faster with a small module that has closer interconnects than currently exists. Irvine Sensors has a stress-free process that will allow HgCdTe to be used with silicon with no thermal mismatch. The MSSR concepts will operate in extreme military environments, and the MSSR and Z-plane module are producible.

Irvine Sensors has designed, fabricated, tested and performed the initial step that leads to a successful demonstration of the Multi-Spectral Smart Retina during June of 1994.

ACKNOWLEDGMENT

The authors would like to thank John Carson, Senior Vice President and Chief Technical Officer of Irvine Sensors, for his technical and management assistance. Also, a thank you to Mau Pham, Bruce Lee for their design work, Mike Skow and Bernie Carpio for the engineering and test work. The work reported here was funded by U. S. Army Space & Strategic Defense Command, Huntsville, AL.