Hybrid Dual-Color MWIR Detector for Airborne Missile Warning Systems


SemiConductor Devices (SCD), P.O. Box 2250, Haifa 31021, Israel

ABSTRACT

Dual-color imaging in the Mid-Wave Infrared (MWIR) is required in some airborne Missile Warning Systems (MWS) due to its ability to reduce the number of false alarms in this application by comparing the signal in the two spectral bands. Furthermore, such systems demand high frame rate, spatial resolution, and spectral resolution, while at the same time call for simultaneous collection and readout of the two color images. Monolithic dual-color Focal Plane Arrays (FPAs) lack at least some of these requirements. In this work we introduce a new hybrid dual-color detector based on two 480×384/20μm digital InSb FPAs, assembled in a single Dewar, where the high degree of spatial registration between the two color channels enables a solution that achieves the above requirements. Each FPA has its own cold shield and spectral filter, and the signal is snapshot integrated and read out in parallel to obtain complete dual-color simultaneity. The sensor imaging optics is integrated inside the Dewar for both channels in order to reduce the overall system size and weight, and improve its performance at the extreme environmental conditions imposed by this application. In this case the hybrid dual-color Integrated Dewar-Cooler Assembly (IDCA) is designed for a very wide field of view (>100°), suited for the specific airborne Missile Warning System (MWS). We present the independent electro-optical results of both the red and the blue channels, together with the measured negligible spectral cross-talk and high spatial registration between them.

Keywords: Infrared Detector, Dual-color, MWS, Integrated optics, epi-InSb

INTRODUCTION

There is a growing demand over the last years for sensors optimized to Missile Warning Systems (MWS) application, for air, sea and ground platforms. MWS are in use for many years in different types of military aircrafts, and are now also entering commercial airplanes. These systems are based on Radar, Ultra-Violet (UV) or Infra-Red (IR) technologies. In recent years, IR imaging technology is increasingly adapted for use in this application. The main challenge for modern MWS is the ability to distinguish a real missile target from the surrounding clutter, which can include rapid sun glints and radiant objects with an IR signature similar to the real target. In order to meet this challenge, the advantages of two-dimensional (2D) IR detector arrays are exploited. High spatial resolution, high
sensitivity, high frame rate, smart signal processors, and dual color detection are the features that make these detectors very attractive candidates for MWS applications. The challenge in optimizing IR detectors for MWS applications is to make all these features exist together and function simultaneously.

The use of dual color Mid-Wave IR (MWIR) detectors for MWS is expected to improve dramatically the performance of the systems in many aspects, and essentially minimize the False Alarm Rate (FAR), which is a major problem in such systems\(^1\). The main problem of the system is the ability to distinguish the missile IR signature from the clutter background, such as sun reflections and other blinking objects. Since the missile plume has its own spectral signature, the way to handle it is to use a two color detector with two spectral bands, above and below the CO\(_2\) absorption band around 4.2\(\mu\)m ("red" and "blue" bands). The ratio of intensities between the blue and the red band signals in the case of a missile target is very high compared to the IR background, and enables the system to discriminate easily between the missile plume and other events.

Monolithic in-pixel dual-color IR detectors based on technologies such as HgCdTe (MCT)\(^2\), QWIP\(^3\) and Antimonide based Superlattice\(^4\) are considered today as the solution for dual-color MWS. In these monolithic structures each pixel has two layers of absorbing semiconductor (active layers), one on top of the other. The top layer absorbs the short wavelengths (blue band), and transmit the long wavelengths (red band), while the bottom layer has a narrower bandgap in order to absorb these lower energies. There are several techniques to connect the Read-Out Integrated Circuit (ROIC) pixel to this double layer photo-detector pixel, with 1-3 conducting In bumps per pixel. Although very elegant, the monolithic dual-color solution is still immature and suffers from some fundamental disadvantages, which tend to counteract the improvements that can be achieved relative to a single color detector with high level of performance. The main drawbacks of the monolithic dual-color IR detector are:

- Limited pixel fill-factor due to extra electrical connection metal pads and In bumps. This leads to lower sensitivity of the detector.
- The amount of data per pixel is doubled compared to single band detectors, so the frame rate reduces by a half due to readout rate limitations.
- The spectral crosstalk between the two bands is relatively high due to insufficient IR absorption in the top layer. Very thick layer structure (~20\(\mu\)m) is required in order to minimize this effect, which results in high cost material growth and low operability.
- Single In bump connection per pixel imposes sequential operation in two distinct bias states in order to switch the direction of the electrical current in the device for readout of the two color signals. Such sequential operation means that the two color signals are not instantaneous, which can be a limiting factor in this application, especially in high speed maneuvering aircrafts.
- Alternatively, 2-3 In bumps per pixel can allow for instantaneous readout. However, it is hard to achieve small pixel area with such architecture, both in the photo-detector and in the ROIC, resulting in lower resolution Focal Plane Array (FPA).
- Optical focus could be problematic, particularly in low F\# systems, due to the different depths of the two absorbing layers.
A straight forward solution to all these problems is to use two completely separate detectors or cameras, one for each band. However, besides the problems of size, weight and cost, the requirement for a high level of spatial registration between the two pixel arrays cannot possibly be fulfilled in this arrangement over a significant period of time. Therefore, a new type of hybrid dual-color detector was developed at SCD in order to achieve such a device, which avoids the problems associated with two separate cameras. The Integrated Dewar Cooler Assembly (IDCA) is based on two FPAs assembled in the same Dewar with a very high degree of registration. Each FPA has its own cold shield, which includes the cold filter with the desired spectral band and a cryogenic integrated optics sub-assembly. The hybrid solution was enabled by the maturity of three key technologies developed by SCD in the last few years:

- Epi-InSb FPA with high electro-optical performance at relatively high FPA temperature of 95 K. Such operation temperature allows for the use of rather small closed-cycle cryo-cooler at extreme ambient temperatures.
- Cryogenic Integrated Optics\(^5\,\text{and}\,\text{6}\), which reduces the overall size of the sensor and improves the electro-optical performance and its stability over a wide range of ambient temperatures.
- Rigid Dewar\(^7\), which enables operation at extreme environmental conditions imposed by the aircraft platform, while maintaining reasonable low Dewar heat load.

In the conventional approach to IR imaging, the imaging optics is located outside the IDCA, at the system level. A typical imaging optics arrangement includes few imaging lenses and/or mirrors, as well as a focus correction mechanism, which allows the system to remain in focus over a wide range of ambient temperatures. With this conventional approach, the IR imaging system suffers from thermal noise and sensitivity to thermal drifts, reducing the overall system performance. Imaging optics (lenses and their mechanical assembly) at room temperature emit thermal energy in the IR, which presents both unwanted background signal and additional noise component to the detected IR signal, thus reducing the signal to noise ratio of such systems. Moreover, imaging optics at room temperature is highly sensitive to ambient temperature variations, because the refractive index of the optics in the IR spectral range greatly depends on its temperature. A change in the refractive index unavoidably introduces optical aberrations and focus changes, which require focus correction by means of lens translation mechanisms and adjustment control.

Introducing cryogenically cooled optics within the Dewar, eliminates both the thermal emission from the optics to the detector and the thermal defocusing due to ambient temperature drifts. Utilizing cryogenically cooled and stabilized imaging optics practically eliminates the need for focus correction, and also reduces significantly the need for periodic non-uniformity corrections (NUC). In such a system, two to four imaging lenses are mounted inside the Dewar, with a negligible impact on the size, weight, heat load and thermal mass of the resulting IDCA. This kind of integrated imaging system can be utilized in wide-angle, single field-of-view (FOV) imaging. Due to the much smaller size and the smaller number of optical elements, the overall cost and size of the cooled integrated optics can be substantially lower than that of conventional pupil-imaging, room-temperature IR optics.

In the following we summarize the design, properties and electro-optical performance of the new hybrid dual-color MWIR IDCA.
IDCA DESIGN

In Figure 1 we show a schematic representation of the IDCA. As can be seen in this figure, the two FPAs with their integrated optics are assembled in one Dewar with two proximity electronic boards. This design allows for the simultaneous and independent operation of each FPA at its optimized set of parameters and its full performance. This includes operation at the full frame rate of each FPA, and the selection of the appropriate integration capacitor for each FPA according to the flux from its spectral band. The Dewar is assembled with an optimized integral rotary Stirling cooler, which is based on Ricor's K543 model, suited for high heat load detectors operating at extreme ambient temperatures. The cooler was slightly modified to withstand the harsh environmental conditions and to accommodate for the required mechanical accuracies imposed by the specific application.

Figure 1: The dual-color IDCA

In Figure 2 we present schematically the inner structure of the IDCA. The dual-color imager is based on high accuracy placement of two FPAs and their integrated optics cold shield sub-assemblies on one ceramic substrate. Each cold shield is integrated with its own optimized set of lenses and spectral filter. The FPAs are independently connected through the feed-through unit to their proximity electronics boards. The proximity board that was designed for the dual-color IDCA contains only analog and digital power supplies, buffer for the digital signals, and a memory component. To reduce the overall power consumption the proximity electronics does not contain an FPGA and the control of the FPAs and video pre-processing is performed at the system electronics. The IDCA produces dual channel un-corrected image of the field of view without any additional external optical elements.

The IDCA main characteristics are summarized in Table 1 below.
The two FPAs in the dual-color detector are based on standard Sebastian-480 ROIC, flip-chip bonded to epitaxialy grown, low dark current InSb (epi-InSb).

The Sebastian-480 is a digital ROIC with 480×384 array format of 20μm pitch, and is widely used in various MWS applications due to a combination of high spatial resolution, high frame rate, excellent linearity and low Residual Non-Uniformity (RNU). On top of the excellent radiometric performance\(^8,9\), the ROIC supports some special operation modes which are useful for MWS applications in general, and for dual band detectors in particular\(^10\). In the dual-color IDCA and system, both FPAs are operated simultaneously at 240 frames per second. Sebastian-480 ROIC also supports two pixel gain modes. In the dual-color IDCA, the gain can be chosen independently for each FPA and can be suited for each spectral band flux level, which results in optimized performance for each color. The FPAs can also be operated in a High
Dynamic Range (HDR) mode. In this mode, two consecutive frames with very different exposure times are fused into one frame. Simultaneity of the two exposures is achieved by splitting the long integration period into two halves and inserting a short integration period in between them. In this mode high sensitivity for low flux targets and non-saturated image with lower sensitivity for high flux targets or clutter is achieved.

The selection of epi-InSb diode array as the sensing material was mandatory in order to reduce the Dewar heat load and increase the cryo-cooler efficiency. Epi-InSb detector allows for FPA operation at an elevated temperature of 95 K with no performance degradation compared to SCD's standard implanted-planar-InSb technology at 77 K.

As mentioned above, cryogenically cooled integrated optics within the IDCA has the potential for both electro-optical improved performance and system size, weight and cost reduction. Assembling several lenses into the cold radiation shield poses several challenges. Due to the small F-number (F/#) in MWS applications, the Back Focal Length (BFL) is short and the tolerances on production and placement of the lenses are tight. Moreover, after mounting the lenses in the radiation shield and sealing of the Dewar there is no focusing mechanism. The optical apparatus and its assembly are designed for achieving the right focus in the IR at the cryogenic operation temperature. In order to meet the required accuracies, each lens and each assembly step are optically characterized at room temperature prior to the final assembly of the radiation shield on the ceramic substrate.

In order to cover the entire space around the protected platform with a minimum number of sensors, the requirements from a detector in MWS application is to have a high and uniform performance in a very wide FOV. This is translated to low Noise Equivalent Temperature Difference (NETD), constant Instantaneous FOV (IFOV), narrow Point Spread Function (PSF), low cross talk (XT), and low RNU over the entire FOV. Such requirements are met by careful optical design and an excellent linearity of the FPA over a wide Dynamic Range (DR). The large FOV optical design must take into consideration the large incident angle of incoming radiation, which if not taken cared of, can cause appearance of ghost images and imaging of strong illumination sources outside the FOV.

In the dual-color IDCA, each optical channel design is based on several lenses, a cold stop, and a cold filter mounted in the cold radiation shield. The system is designed to have optimal performance at cryogenic temperatures with the following main characteristics:

- Energy on pixel larger than 80% of the total energy on the FPA for a point source
- Horizontal FOV larger than 100º
- Vertical FOV larger than 100º
- Illumination at the field edge higher than 80% of the field center
- IFOV uniformity higher than 90%
- Mean transmission larger than 85%

The performance is maintained for a very large range of environmental temperatures due the stabilized cryogenic temperature of the optics. Each lens is coated with an Anti-Reflection (AR) coating optimized for the highest transmission in the specific spectral band and the relevant incident angles. The coatings are also designed so that the spectral crosstalk between the bands is minimal, typically lower than 0.1%, as can be seen in Figure 3. This low spectral crosstalk is almost two orders of magnitude better than in monolithic dual-color detectors.
ELECTRO-OPTICAL PERFORMANCE

The electro-optical performance of the dual-color imager (the IDCA) is determined by its different components (two FPAs and integrated optics channels) and their mutual optical correspondence, which is critically governed by the mechanical design and assembly. In this section we present the performance of each optical channel and some of their mutually-dependent characteristics.

In the two images of Figure 4 we present the raw signal measured in each spectral channel, when facing a uniform extended black-body at 40ºC. The "blue channel" signal is shown on the left and the "red channel" on the right. The FOV of each FPA is larger than ±50º along the array diagonal. The pixels with low signal at the four corners of the image are pixels that are out of the required FOV, and thus are shadowed by the cold shield. The signal uniformity of the raw image in the valid FOV is a measure for the quality of the design and assembly of the optics. We find that the raw signal non-uniformity is low and as expected from the optical design for both channels.

Figure 4: Raw signal measured in digital levels on both FPAs, when facing a uniform extended black-body at 40ºC. The pixels with low signal at the four corners of the image are outside the valid FOV, and thus are shadowed by the cold shield.
Figure 5: NETD distribution of the two optical channels.

Figure 6: Top, corrected image (in digital levels) from both FPAs, the blue channel on the left and the red channel on the right (the white corners are areas outside the valid FOV). Bottom, RNU versus well fill.
In Figure 6 we present images from both spectral channels of a uniform extended black body, following two-point non uniformity correction. We find that even with such a wide FOV the corrected image is uniform after NUC and the RNU in the valid FOV is low (bottom in Figure 6). In this figure the RNU is presented in standard deviation (STD) divided by the dynamic range (DR), as a function of the well (integration capacitor) fill. The two points where the RNU is identically zero are the correction points.

The Energy on Pixel (EP) is a measure for the detector (IDCA) spatial resolution. EP is defined as the energy (number of photons) measured in a pixel, divided by the total energy measured in the FPA, while viewing a point source located at the center of the pixel IFOV. This parameter is a direct result of the optical design and its assembly quality, combined with the FPA crosstalk performance. In actual measurements, while viewing a target point source, the surrounding pixels are exposed to energy from additional sources in the FOV, so this background signal must be subtracted. The measured energy distribution over the illuminated pixel in an FPA and its surrounding pixels is shown on the left side of Figure 7. In this example, EP equals 75.4%. The right side of Figure 7 shows the EP results in various field angles for both spectral bands. The ultimate EP value for a diffraction limited optics and zero FPA cross talk is about 85%. The measured results are above 65% in all field angles. The variation in the results for large angles might result from the spread over different areas on the FPA, with slightly different crosstalk performance. The better EP results in the blue channel are expected from the optical design. Another important property of the EP is its stability at different ambient temperatures. Although the optics is cooled to cryogenic temperature, slight variations in its temperature or position might occur due to the Dewar heat radiation, which depends on the outside temperature. Therefore, the EP performance must be verified for a range of ambient temperatures. EP measurements in pixels spread on the entire FOV were performed at surrounding temperatures between -25°C and 95°C. We find that the EP stability is excellent, with small variations of less than 1%, which is close to the measurement accuracy.

![Energy on Pixel distribution in a FPA (5x5 pixels region) when the central pixel is illuminated by a point source. The measured signal in the illuminated pixel is the Energy on Pixel. Right, Energy on Pixel at different field angles for the red and blue channels of the IDCA.](image)

Figure 7: Left, measured energy distribution in a FPA (5x5 pixels region) when the central pixel is illuminated by a point source. The measured signal in the illuminated pixel is the Energy on Pixel. Right, Energy on Pixel at different field angles for the red and blue channels of the IDCA.
Some of the most critical and challenging characteristics of the hybrid dual-color detector are the commonality of the two bands FOV, Line Of Sight (LOS), and pixel pointing function. The FOV is larger than 100º for each channel and for the mutual two-channel FOV. The LOS is defined as the angle between the projection in object space at the center of the FPA and the perpendicular to the mounting interface between the IDCA and the system. LOS deviation can be a result of improper optics assembly or FPA position. The measured values for LOS deviation of both spectral channels are typically below 10 mrad, with channel to channel LOS deviation below 20 mrad.

In Figure 8 we present FPA rows and columns as horizontal and vertical curves projected to the spatial field angle, for both spectral bands. The curves are generated by measuring approximately 250 points over each of the FPAs. For each measured pixel, a target point source is centered on that pixel by adjusting the IDCA angle with respect to the source. The spatial angle of the IDCA is then measured and registered for that pixel. These measurements produce a sample of the pointing function of the FPA, i.e. a function that translates the pixel coordinates to vertical and horizontal pointing angles. Using a two dimensional fifth order polynomial fit, a continuous pointing function is achieved, for both channels. The figure shows the excellent registration reached between the two bands over the whole field. For this measured IDCA the band to band pointing function registration is better than half a degree over the whole field of view.

Figure 8: The two bands FOV. The horizontal and vertical curves represent rows and columns of the FPA translated to the horizontal and vertical view angles. The red and blue bands are represented with red (solid) and blue (dashed) lines respectively. The black (dash-dot) line shows a circle of the maximal FOV boundaries. Left, a view of the entire FOV. Top right, zoom on the FOV center. Bottom right, zoom on the FOV edge.

Finally, in Figure 9 we present a fisheye image from the laboratory window obtained by both channels of the IDCA.
SUMMARY

In this paper we presented the new hybrid dual-color MWIR IDCA developed by SCD for airborne MWS application. The IDCA is actually an imager, where two optical channels, each with a specific cold band-pass filter, are integrated inside a single Dewar. Each spectral channel has its own epi-InSb 480×384/20μm digital FPA, and specially designed integrated cryogenic optics assembled in the cold shield. The IDCA shows excellent electro-optical performance with high commonality between the spectral bands, and outstanding stability over a very wide range of environment temperatures. These results represent typical behavior of the several, so far, manufactured IDCAs. The new IDCA is currently at the qualification tests stage.

REFERENCES


7. L. Shkedy, T. Markovitz, Z. Calahorra, I. Hirsh, I. Shtrichman “Megapixel digital InSb detector for midwave infrared imaging”, Optical Engineering vol. 50(6), June 2011, pp 061008-1-8


