A New Dual Band Line Scan Camera for Rapid Inspection

G.E. Carver, M. Entwistle, C. Knurek, T. Koch,
D. Lyons, M. Owens, S. Rangwala, D. Salvemini

Princeton Lightwave
2555 US Route 130 South
Cranbury, NJ 08512

Abstract

Line scan cameras are used for rapidly monitoring moving objects. Due to the optical properties of materials, using both visible and near-infrared wavelengths allows for more contrast mechanisms. Line scan cameras with either silicon or III-V arrays exist, but combining images from two separate packages is difficult. Our dual band camera simultaneously views the 400-900 nm band with one array and the 1100-1700 nm band with a second array while keeping both bands in focus and spatially/temporally co-registered.

Introduction

Line scan cameras are used for monitoring rapidly moving product – including assembled parts, paper, currency, fabrics, plastic sheet, produce, and recycleables. Figure 1 shows a typical example where a stripe on the moving belt is conjugate with a 1D array in the camera. As the belt moves in the X direction, the camera generates a 2D image. Most applications use silicon based detector arrays for operation in the visible and short near infrared (400 to 1000 nm). Operating at wavelengths out to 1700 nm can provide additional contrast due to the optical properties of materials. The optical constants of a sample are a function of the sample's composition and structure, including material inhomogeneity. The specular reflectance (R) at normal incidence is determined by the relative magnitude of the real (n) and imaginary (k) parts of the refractive index and is given by:

$$R = [(n - 1)^2 + k^2] / [(n + 1)^2 + k^2] .$$

R can also be expressed in terms of the real (ε_1) and imaginery (ε_2) parts of the dieletric function by using:

$$n = \{0.5 [(\varepsilon_1^2 + \varepsilon_2^2)^{1/2} + \varepsilon_1]\}^{1/2} \text{ and } k = \{0.5 [(\varepsilon_1^2 + \varepsilon_2^2)^{1/2} - \varepsilon_1]\}^{1/2}.$$

Figure 2 shows ε_1 and ε_2 plotted versus wavelength for a hypothetical material with two absorption bands. As wavelength is increased from left to right across the figure, the magnitudes of ε_1 and ε_2 oscillate within each absorption band. As a result, the changing relative size of ε_1 and ε_2 cause changes in reflectance.[1] Organic materials have a plethora of absorption mechanisms at near infrared (NIR) wavelengths.[2] The ε_1 and ε_2 spectra of real materials are integrations of the effects of multiple absorption bands. One therefore expects reflectance to vary significantly from the the visible to the 1 to 2 micron band. It is not surprising that many objects are brighter or darker in the near infrared than in the visible. Operation in both the visible and the NIR allows inspection algorithms to apply more degrees of freedom, and operate with higher accuracy. One example is paper currency, which is often marked with features that are only observable in the near infrared for combating counterfeiting.

Silicon based line scan cameras are used for visible applications and InGaAs based line scan scan cameras are used for NIR applications. Thin InP capped InGaAs cameras exist for detecting radiation throughout both bands. In principle, one camera can be used to acquire images in one band while a second camera can be used to acquire images in a second band. Many inspection applications, however, require that the two images be spatially and temporally registered – the two bands must view the same focused object at the same time. It is difficult to co-register the two bands if two separate packages are used (due to mechanical alignment issues and vibration). Software based corrections have problems with fractional pixel issues and response time. This paper addresses the design and development of a dual band camera that generates two registered images – one for the 400 to 900 nm band and another for the 1100 to 1700 nm band.

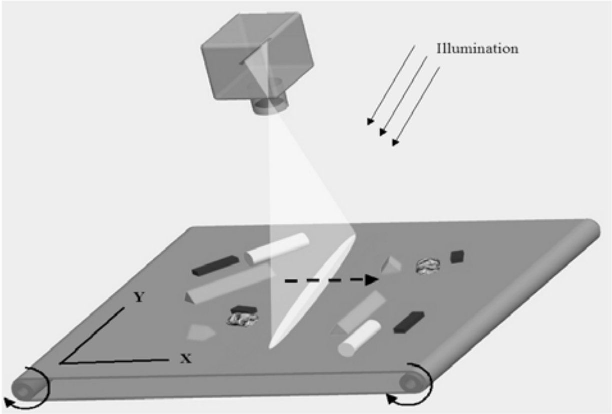

Figure 1 – Line Scan Inspection

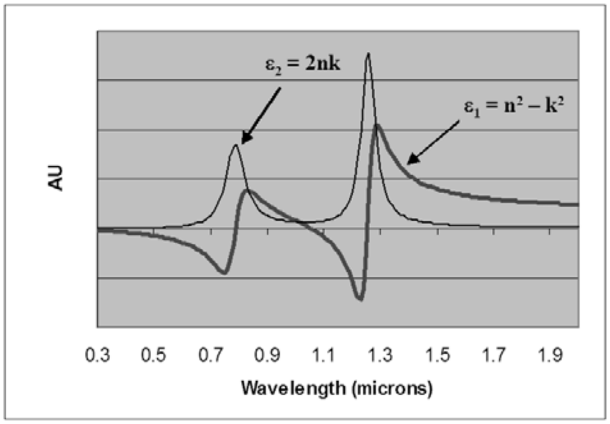

Figure 2 – Two Lorentz Oscillators

Design

To ensure spatial registration, the two spectral bands must propagate through one lens system and be detected within one integrated package. Key challenges include chromatic effects due to the spectral dependence of the refractive index of the lens elements. For example, the index of fused silica ranges from 1.47 at 400nm to 1.44 at 1600nm.[3] The general impact is shown in figure 3 where dashed rays correspond to longer wavelengths. One sees that the longer wavelengths have a longer focal distance (longitudinal color), and will walk off from the shorter wavelengths in the image plane as a function of field angle (lateral color).

A custom multi-element lens with minimal chromatic effects was designed for meeting these challenges. This lens (f = 24.5mm, f# = 2.9, field of view = ± 13 inches at a working distance of 514 mm) can resolve 0.3 mm features (visible) and 1.2 mm features (near-infrared) in the object plane. A custom dual band detector package was designed around the residual delta focal distance of this lens. Figure 4 shows the beamsplitter arrangement used to transmit the shorter wavelengths and reflect the longer wavelengths. The effects of lateral color were avoided by setting the pathlength in glass of all wavelengths to a fixed number. The effects of longitudinal color were avoided by locating the silicon (CCD – or charge coupled device) and InGaAs (PDA – or photodiode array) chips at different locations along the optical axis. Spectral selectivity is provided by the CCD and PDA response curves.

The CCD has 2048 pixels (14 by 14 microns) and generates 0.3 A/W plus 4.8 $\mu V/e^-$. The PDA has 512 pixels (56 by 200 microns) and generates 0.85 A/W plus 1.28 $\mu V/e^-$. In a free-running mode, the CCD integration time can be set from 87 to 32000 microseconds, while the PDA integration time can be set from 5 to 32000 microseconds. Triggered modes allow the CCD to be operated at shorter integration times. The CCD and PDA arrays are read-out at a line rate of 9.65KHz – both via a dual CameraLink®[4] interface that bursts at up to 60Mpixels/sec.

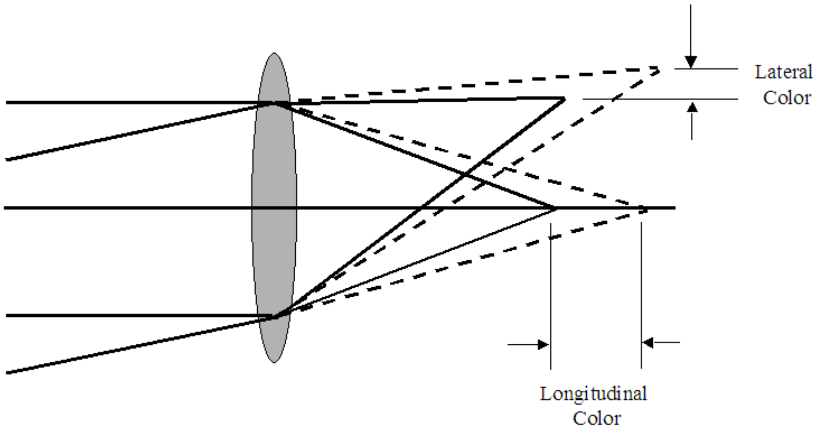

Figure 3 – Chromatic Aberrations

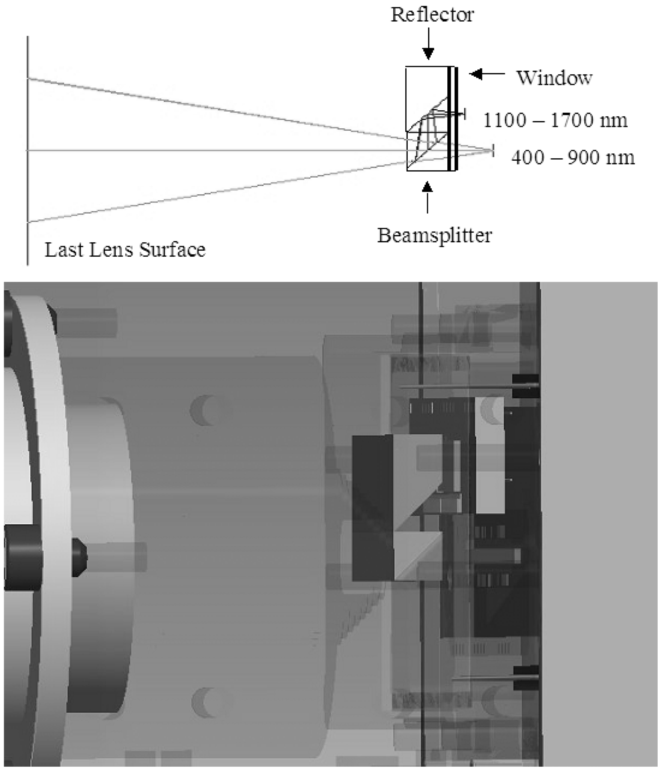

Figure 4 – Dual Chip Arrangement

Results

Figure 5 shows images taken at the same time by sweeping the new dual band camera during a roughly 1 second exposure. Several differences between the CCD and PDA images are evident, including brightness of the hair, skin, and clothing fabrics.

Figure 5 – CCD (left) and PDA (right) Images

The spatial registration and degree of walkoff of the dual band camera was tested by imaging a bar target under white light illumination. Data was acquired using both the custom lens described above and an off-the-shelf lens with similar focal length and f#. Figure 6 shows data for both on-axis bright bars and off-axis bright bars for both lenses. The custom lens images spatially registered and well focused images. The off-the-shelf lens was focused on the CCD image, and exhibits significant defocus and walkoff in the PDA image. The observed defocus of 6 PDA pixels (336 microns) is equivalent to 8 mm in the object plane. The observed walkoff of 2 PDA pixels (112 microns) in the image plane is equivalent to 2.7 mm in the object plane.

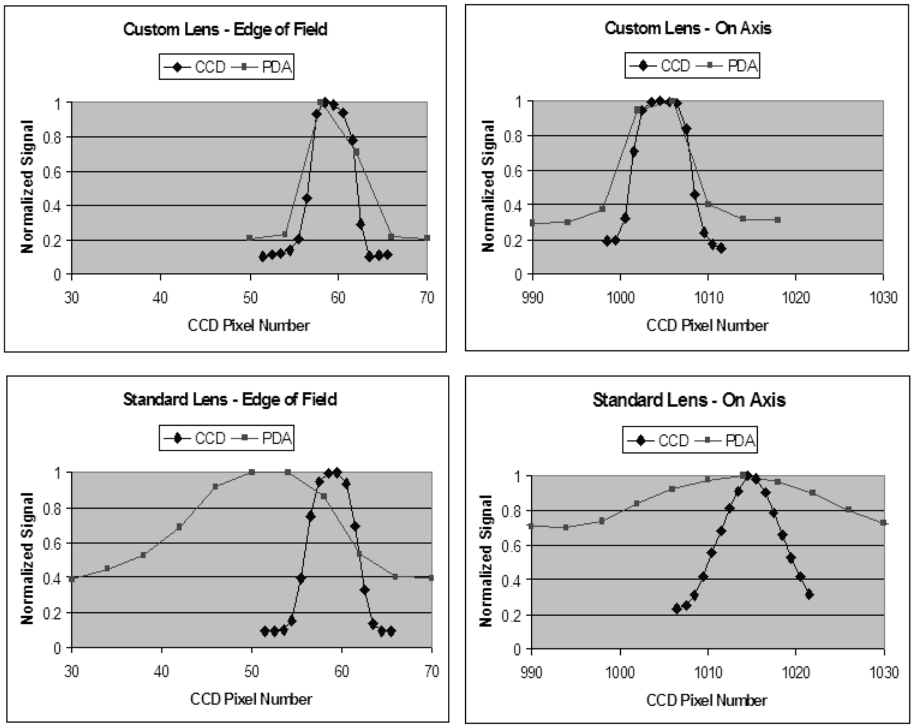

Figure 6 – Signals using Bar Target with Custom and Standard Lenses

The spot size of the dual band camera was tested by imaging a point source with white light. Data was acquired with the custom lens described above. Figure 7 shows results for both on-axis and off-axis alignments – data was shifted mathematically to show both fields on the same plot. The two top plots show CCD and PDA signals versus distance along the arrays in microns. Each point represents a pixel. These results show that the optical spot size is slightly larger than 1 CCD pixel and smaller than 1 PDA pixel. Data was also taken perpendicular to the long axis of the arrays to show that the CCD pixels are centered within the PDA pixels. The two bottom plots show the signal of one pixel as the lens was moved relative to the camera body. The CCD pixel data reveals a spot size of about 8 microns while the PDA pixel data reveals a spot size of about 35 microns. These numbers match design expectations.

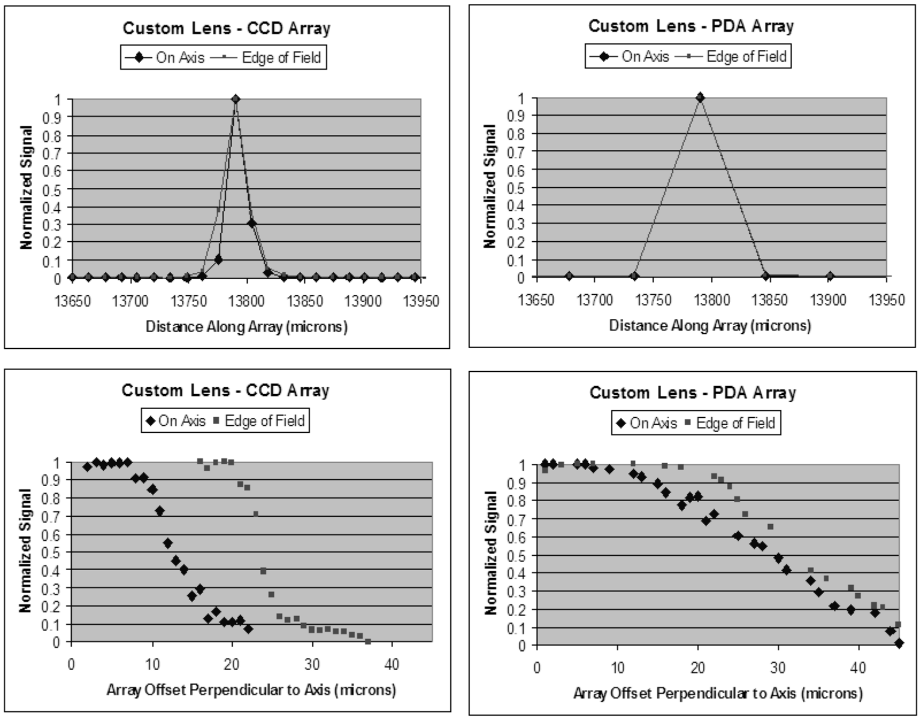

Figure 7 – Signals using Point Source with Custom Lens

The collection efficiency of the dual band camera was tested by imaging a bar target under illumination at 600 nm and 1400 nm. Bright bars in the target are Lambertian diffuse reflectors with a reflectance of about 80%. Data was acquired using both the custom lens and the off-the-shelf lens. Table 1 shows data for on-axis and off-axis alignments at both color bands. Optical power densities were measured in the object plane with meters from NRC (600 nm) and Agilent (1400 nm). Power densities given in the table were scaled from measured data such that half scale (11 bit) readings would occur at the indicated integration time. The data shows that the custom lens is more efficient in the near-infrared than the off-the-shelf lens. This information is useful in determining lighting requirements for a given application.

Lens	**Field Angle**	**Wavelength**	**Power Density (mW/cm^2)**	**Half Scale Counts**	**Integration Time (μsec)**
Custom	0^0	600 nm	5.6	2047	500
Custom	31^0	600 nm	6.8	2047	500
Custom	0^0	1400 nm	0.2	2047	500
Custom	31^0	1400 nm	0.2	2047	500
Standard	0^0	600 nm	3.6	2047	500
Standard	31^0	600 nm	8.6	2047	500
Standard	0^0	1400 nm	3.2	2047	500
Standard	31^0	1400 nm	2.8	2047	500

Table 1 – Dual Band Camera Signals

Choosing the custom versus off-the-shelf lens for a given application depends on the required object space resolution, available lighting intensity, and allowable integration time.

Measurements of pixel-to-pixel uniformity were taken with uniform illumination from the exit port of an integrating sphere. The arrays are typically flat to within ± 10%, and can be further flattened with a field correction command. Dark measurements indicate the CCD exhibits < 5 counts of noise and a signal-to-noise ratio of 10 bits, while the PDA exhibits < 1 count of noise and a signal-to-noise ratio of 12 bits.

Conclusions

A new dual band line scan camera has been designed, fabricated, and tested. The camera generates simultaneous images of the 400-900 nm and 1100-1700 nm spectral bands. The images are spatially and temporally registered over a ± 13 inch field of view. Spot size is consistent with a minimum object size of 0.3 mm in the 400-900 nm band, and 1.2 mm in the 1100-1700 nm band. Data was presented allowing a user to plan for appropriate lighting levels in both bands. Half scale readings occur with 6 mW/cm^2 in the 400-900 nm band, and 0.2 mW/cm^2 in the 1100-1700 nm band (integration time adjusted to 500 microseconds). Scan rates are compatible with high throughput inspections (9.65 KHz line rate).

The CCD and PDA based dual band images will be useful for inspection systems requiring contrast mechanisms in the visible and near-infrared. The data could also be used to frame near-infrared data with visible data, or to create false color images where one color is assigned to the 400-900 nm band while another color is assigned to the 1100-1700 nm band.

References

1) F. Wooten, *Optical Properties of Solids*, New York: Academic Press, 1972, pp. 47.
2) C.E. Miller, "Chemical Principles of Near-Infrared Technology," in *Near-Infrared Technology in the Agricultural and Food industries*, P. Williams and K. Norris, Eds., St Paul: American Association of Cereal Chemists, 2001, pp. 33.
3) H.R. Philipp, "Silicon Dioxide (SiO_2) (Glass)," in *Handbook of Optical Constants of Solids*, E.D. Palik, Ed., New York: Academic Press, 1985, pp. 749.
4) CameraLink® is a registered trademark of the Automated Imaging Association.