

Dual-Band Imaging System Based on a Compact Coaxial Folded Optic Architecture

R. L. Morrison and R. A. Stack

*Distant Focus Corporation
morrison@distantfocus.com*

G. W. Euliss, R. A. Athale, B. F. Necioglu, and R. W. Horstmeyer

The MITRE Corporation

Colin Reese

U. S. Army RDECOM CERDEC Night Vision and Electronic Sensors Directorate

Abstract: We present an unconventional coaxial architecture for simultaneous acquisition of images in two discrete spectral bands. The approach is realized by taking advantage of a novel annular folded lens design previously developed under the DARPA/MONTAGE program.

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1. Introduction

Dual-band imaging systems enable simultaneous acquisition of images from a common scene in two separate spectral bands (e.g., visible combined with an infrared band or short-wave infrared combined with mid-wave infrared). In practice, this often requires that the images be acquired along two separate channels, or optical paths, one for each spectral band. This requirement comes about for a variety of reasons. Current technology limits the spectral bandwidth of any single focal plane sensor. Therefore, certain spectral-band combinations, including visible and thermal bands, require the use of two separate focal planes. Furthermore, materials having good optical characteristics over very large spectral ranges are uncommon and/or exhibit unfavorable physical properties for use in an imaging system. In addition, designing an optic to meet performance specifications at two disparate wavelengths can be a daunting task.

Two basic architectures are commonly used to realize the two optical channels described above. In one approach, images are acquired through separate optics in combination with the two focal planes. The collection optics are placed side-by-side so that the optical axes are offset and approximately parallel. This approach is well represented by the Army's enhanced night vision goggles which combine an image intensifier through one aperture with a thermal focal plane array through a second aperture. The second approach using a common optic and separate sensor can be applied if suitable optical material is available, allowing a single aperture to be employed in the acquisition of images in both spectral bands. When this approach is taken, the two spectral channels are eventually split by a dichroic mirror and directed onto individual focal planes. Both architectures introduce challenging complexities in establishing and maintaining optical alignment, as well as image registration for post-detection processing and exploitation. One exception is represented by broadband detectors, such as quantum well infrared photodetectors, which can enable coaxial dual-band imaging on a common focal plane, but is limited to thermal wavelengths.

An alternative approach to dual-band imaging systems can be realized by taking advantage of a novel folded annular lens design that was developed and demonstrated by Tremblay, et. al. under sponsorship of DARPA's MONTAGE program [1,2]. In this design, the optical path between the entrance pupil and the focal plane is folded by means of internal, concentric, aspheric reflective surfaces. Focusing is achieved by virtue of the aspheric curvatures designed into the reflective surfaces. The DARPA/MONTAGE lens was intended for imaging at visible wavelengths; however the nature of the fully reflective technique minimizes spectral sensitivity. To extend application into the thermal regime, we redesigned the basic folded lens to enable imaging in the long-wave infrared (LWIR) spectrum at approximately 8-12 μm , replacing the CaF_2 substrate with a hollow core. The folded imager design results in a central obscuration on the front surface since light is collected exclusively through the outer annulus of the lens. The obscured region of the LWIR lens provides adequate space for placement of the visible system and alignment on the same optical axis. The stacked coaxial configuration offers the benefit of a common perspective between the two spectral channels, reducing the complexity of the subsequent alignment and registration

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required for fusion of the separate images. Furthermore, the inherently compact profile of the folded lens design results in a uniquely compact dual-band imaging system.

2. System Design and Results

The MITRE/DFC demonstrator is composed of the DARPA/MONTAGE folded imager coupled with a new thermal folded imager. A narrow field of view thermal image is pixel matched with the wider field of view visible image. In addition, there remains sufficient space to mount yet a third wide field of view cell phone type camera on the front of the DARPA/MONTAGE imager. The basic concept of the folded optic is illustrated in Fig. 1-a by the ray tracing diagram corresponding to the thermal lens designed for the dual-band system. The design strategies applied to the thermal lens are similar to those that produced the DARPA/MONTAGE lens. The primary difference is that the hollow-core design has a narrower field of view and suppressed transverse chromatic aberration due to the elimination of the interior material. In order to maintain a high light collection efficiency, a folded imager design typically incorporates an annular entrance aperture diameter larger than that of an equivalent conventional clear aperture lens. Thus the folded optic has length about one-quarter the focal length in exchange for a diameter that has

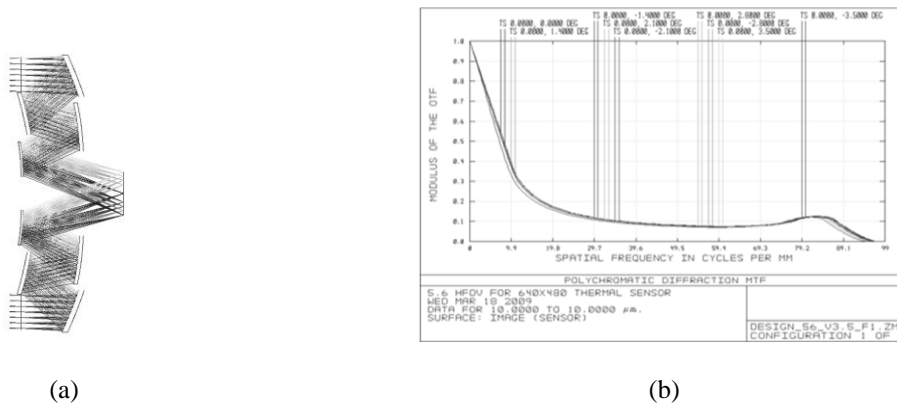


Figure 1. (a) Ray-trace diagram of the folded thermal optic. Object rays enter from the left at the top and bottom of the cross section and focus at the sensor plane to the right. (b) Computed modulation transfer function of the same lens.

increased on the order of 50% in comparison to a conventional lens. As typical with annular apertures, the high-band spatial frequencies are generally enhanced while mid-band spatial frequencies are suppressed. This can be seen in the modeled modulation transfer function of the thermal folded lens shown in Fig. 1-b.

The thermal folded imager field of view was selected to enable a pixel-to-pixel match between the LWIR sensor and the MONTAGE folded imager. The resulting design has a 5.6° horizontal field of view using a 164 mm focal length lens. The DARPA/MONTAGE folded imager included a short, honeycomb cell baffle attached to the entrance aperture to shield stray light from reaching the sensor. The thermal design includes a relief and an interior annular baffle near the exit aperture to reduce stray light. The DARPA/MONTAGE lens focus is adjusted by changing the separation between two solid half units spaced by an index matching gel. The use of gel in the solid core folded imager configuration is needed to eliminate reflection of the high angle rays at the boundary. Elimination of the gel and its reservoir system in the hollow-core lens greatly simplifies mechanical engineering of the package. The thermal camera in this instance uses translation of the sensor to adjust the focus which results in a rugged lens package.

Table 1. Comparison between the DARPA/MONTAGE (visible) and MITRE/DFC (LWIR) lenses.

	DARPA/MONTAGE System	MITRE/DFC LWIR System
Focal length	19 mm	164 mm
Optic length	5.6 mm plus 0.6 mm sensor relief	27mm plus 20mm sensor relief
Entrance aperture radius	14 mm outer; 11.5 mm inner	62.5 mm outer; 47 mm inner
F/#	0.68	1.3
Clear aperture equivalent F/#	1.15	2
Horizontal Field of View	13.6°	5.6°
Sensor Size	1600 x 1200	640 x 480
Focus	Optic gap adjusted	Sensor translation

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Lens design specifications are given in Table 1 on the previous page. The primary thermal lens structure is machined in aluminum as two separate components, one containing the front reflective surface and the second containing the back reflective surface. Each reflective surface is then diamond turned to an optical quality finish. The diamond turned surfaces are gold coated to improve reflection efficiency in the thermal band. The optic was designed to couple with a FLIR Systems Photon 640 thermal camera core. The Photon 640 is an uncooled 640x480 vanadium oxide microbolometer array with 25 μm pixels. A separate mounting fixture was designed and fabricated to integrate the visible folded imaging subsystem with the thermal subsystem. A cross-sectional drawing of the complete system is shown in Fig. 2-a, along with a front angle photograph of the assembled dual-band system in Fig. 2-b. The fixture with the visible subsystem mounted in the central obscuration of the LWIR lens can be seen in Fig. 2-b. Sample images are presented in Fig. 3.

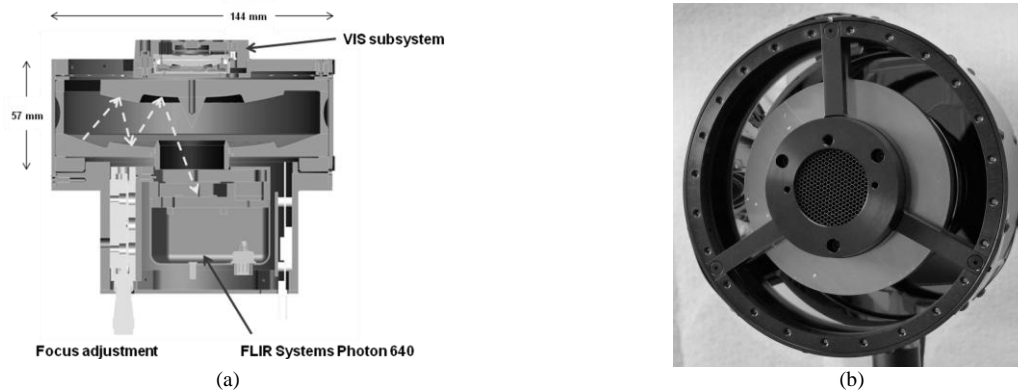


Figure 2. (a) Mechanical cross-section and (b) photograph of the assembled coaxial dual-band system .



Figure 3. Sample images acquired in the (a) visible and (b) LWIR spectral bands using the coaxial dual-band system shown in Fig. 2-b. The visible image has been cropped to match the field of view of the LWIR image.

3. References

1. Eric J. Tremblay, Ronald A. Stack, Rick L. Morrison, and Joseph E. Ford. "Ultrathin cameras using annular folded optics," *Appl. Opt.*, **46** 463–471 (2007).
2. Eric J. Tremblay, Ronald A. Stack, Rick L. Morrison, Jason H. Karp, and Joseph E. Ford, "Ultrathin four-reflection imager," *Appl. Opt.*, **48** 343-254 (2009).

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