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Monolithically integrated near-infrared and mid-infrared detector array for spectral imaging

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Abstract

A multi-band focal plane array sensitive in near-infrared (near-IR) and mid-wavelength infrared (MWIR) is been developed by monolithically integrating a near-infrared (1–1.5 μm) p–i–n photodiode with a mid-infrared (3–5 μm) QWIP. This multiband detector involves both intersubband and interband transitions in III–V semiconductor layer structures. Each detector stack absorbs photons within the specified wavelength band, while allowing the transmission of photons in other spectral bands, thus efficiently permitting multiband detection. Monolithically grown material characterization data and individual detector test results ensure the high quality of material suitable for near-infrared/QWIP dual-band focal plane array.

Keywords: Infrared imaging; Quantum well; Multicolor; Spectrometer

1. Introduction

The jet propulsion laboratory (JPL) is developing a snapshot hyperspectral imaging instrument that is capable of imaging a target in the 3–5 μm mid-wavelength infrared (MWIR) band and resolving several hyperspectral features within 1–1.5 μm near-infrared (NIR) band. The design of this instrument is based on a reflective computed-tomography imaging spectrometer (CTIS) with a monolithically integrated NIR and MWIR dual-band, 640×512 format focal plane array (FPA). The CTIS enables transient-event spectral imaging by capturing a scene's spatial and spectral information in every captured frame of the FPA. A CTIS records spatial and spectral information by imaging a scene through an optical relay system that has a two-dimensional (2D) grating disperser placed in collimated space [1–3]. This produces multiple, spectrally dispersed images of the scene that are recorded simultaneously in a single snapshot on the FPA. From the dispersed irradiance image and calibration information about the system, computed-tomography algorithms are used to reconstruct the spatial-spectral datacube representing the scene. Because CTIS systems utilize only fixed optics and do not require scanning of any type, they can be compact, rugged, and low cost.

This paper mainly focuses on the dual-band FPA design, fabrication, and performance of individual detectors. It includes a brief description of the reflective CTIS to understand the detector array requirements. A detailed description of the reflective CTIS can be found in the publications by our collaborators at JPL [1–3].

2. CTIS concept

The preliminary design of the reflective CTIS is shown in Fig. 1. A primary telescope (not shown) forms an image on the field stop of a reflective spectrometer. A 2D grating on the secondary convex mirror generates an array of spectrally dispersed images of the scene on the FPA. The zeroth order provides an undispersed gray-scale image of the scene in the center section of the FPA. The convex reflective grating of this CTIS was specifically designed to produce 3×3 diffraction orders with the following properties: (1) highly dispersed first orders with strong broadband efficiency in

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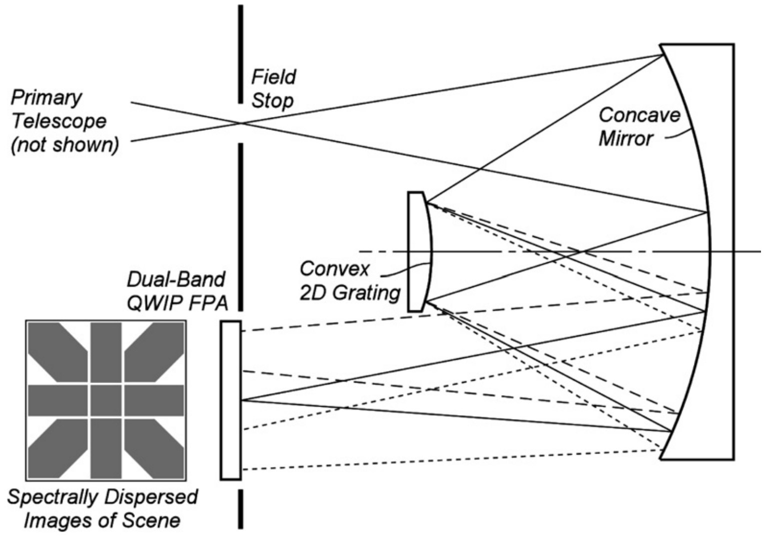

Fig. 1. The infrared CTIS and dual-band FPA. The CTIS produces an undispersed zeroth-order image with strong efficiency in the 3–5 μm band and highly-dispersed first-order images with strong broadband efficiency in the 1–1.5 μm band. The center section of the FPA is sensitive for 3–5 μm band, and surrounding sections are sensitive for the 1–1.5 μm band.

the 1–1.5 μm band and (2) an undispersed zeroth order with strong efficiency in the 3–5 μm band. The resulting grating design can be realized as a surface-relief profile fabricated by direct-write electron-beam lithography on a convex substrate. Following an initial system calibration, tomographic reconstruction algorithms are used in outer, higher-order images to determine the spectral characteristics of the scene in the 1–1.5 μm wavelength band. Spatial resolution is determined by the size of the zeroth order image on the FPA, which is naturally compressed by the surrounding dispersed orders. Thus, this CTIS requires a large-format, dual-band FPA that is capable of imaging in both MWIR (∼3–5 μm) and NIR (∼1–1.5 μm) spectral bands. Specifically, the center region of the array is sensitive in the 3–5 μm spectral band and the surrounding pixels of the array are sensitive in the 1–1.5 μm spectral band.

3. MID-IR/near-IR detector integration

The III–V materials-based QWIP technology is an excellent choice to develop the MWIR detector of the dual-band FPA because of its ability to integrate multi-quantum-well (MQW) stacks that are sensitive to different spectral bands. Each MQW stack absorbs photons within its specified wavelength band, thus permitting multiband detection. In addition, QWIP technology can provide highly uniform and stable FPAs (low $1/f$ noise) in larger formats, with pixel operability exceeding 99.9% [4–8]. Such unique properties of the FPA simplify on board data analysis, thus providing significant cost reduction in software development, data processing, and major system-level benefits upon integration. Furthermore, high yield in fabrication and reproducibility of this technology will result in a much lower cost for detector arrays than for competing technologies.

A typical QWIP consists of a 50-period MQW structure of quantum wells, separated by potential barriers, sandwiched between two contact layers [4,5]. Both contact layers and quantum-well layers are doped in order to provide carriers for photoexcitation. The QWIP detection mechanism involves photoexcitation of electrons between the ground and the first excited state subbands of quantum wells in the MQW structure (see Fig. 2) [4,5]. In order to optimize performance, MQW structure design places the first excited state exactly at the well top. This design feature is referred to a bound-to-quasibound quantum well [5]. The wavelength of the peak response and cutoff can be continuously tailored by varying well and barrier widths (layer thickness), barrier height (barrier composition), and carrier density (well-doping density) of the quantum wells. Commonly used GaAs substrate-based, GaAs/$Al_xGa_{1-x}As$ material system allows the quantum well parameters to be varied over a range wide enough to enable light detection at any wavelength range from 6 to 20 μm [4,10]. By adding a few monolayers of $In_yGa_{1-y}As$ during the GaAs quantum-well growth, the short wavelength limit can be extended to 3 μm [9]. In contrast, lattice matched InP/ $In_xGa_{1-x}As$/ In_yAl_{1-y}. As material-based quantum wells posses limited tailorability, because only a specific alloy composition, i.e., $x = 0.53$ and $y = 0.52$, could be grown nearly lattice-matched on InP substrates. This restricts the wavelength of the peak response to $\lambda_p \sim 4$ μm with $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells, or to $\lambda_p \sim 7.5$ μm with $In_{0.53}Ga_{0.47}As$/InP quantum wells [4,10]. However, these peak response wavelengths and spectral bandwidths can be altered to some extent by utilizing coupled quantum wells separated by thin barriers, while keeping the bound-to-quasibound design rule. Theoretically estimations show that the thickness of the thin barrier increases, responsivity spectrum