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Oak Ridge National Laboratory*
P. O. Box 2008,
MS-6006, Oak Ridge, TN 37831
(615)574-4730

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Abstract

New developments in 2-D, wide-bandwidth HgCdTe (MCT) and GaAs quantum-well infrared photodetectors (QWIP) coupled with Monolithic Microwave Integrated Circuit (MMIC) technology are now making focal plane array coherent infrared (IR) cameras viable. Unlike conventional IR cameras which provide only thermal data about a scene or target, a coherent camera based on optical heterodyne interferometry will also provide spectral and range information. Each pixel of the camera, consisting of a single photo-sensitive heterodyne mixer followed by an intermediate frequency amplifier and illuminated by a separate local oscillator beam, constitutes a complete optical heterodyne receiver. Applications of coherent IR cameras are numerous and include target surveillance, range detection, chemical plume evolution, monitoring stack plume emissions, and wind shear detection.

Keywords: coherent imaging, lidar, infrared

1. Introduction

Most existing IR cameras are incoherent, using the intensity of a scene's blackbody radiation to map thermal distributions over the full bandwidth of the detector array. We are developing a coherent infrared imaging camera (CIRIC) that uses optical heterodyne techniques to determine target intensity and phase information over a narrow frequency interval. The technology involved is based on new developments in two-dimensional quantum-well infrared photodetectors (QWIPs) and HgCdTe detector arrays. A schematic diagram of the coherent camera is shown in Figure 1. CIRIC consists of a 2-D photodetector array illuminated by a specially-formed local oscillator laser beam. Radiation from a target scene is combined with the local oscillator beam array on a beamsplitter element, and these two patterns are imaged onto the photodetector array where optical mixing takes place. Analysis of this signal yields information on target parameters such as temperature, range, velocity and spectral composition.

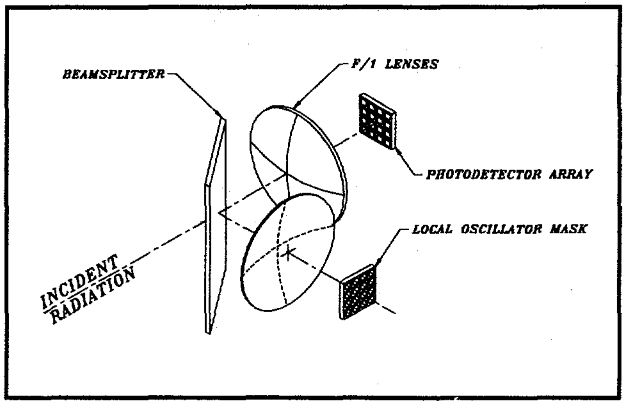

Figure 1: CIRIC System Diagram

2. Theory

2.1 Heterodyne Detection

Heterodyne detection is a very sensitive method of retrieving low level signals over a small bandwidth. A schematic diagram of a basic heterodyne receiver is shown in Figure 2. If a signal amplitude, assumed to be of the form $E_S(t)=E_S\cos(\omega_S t)$ where ω_S=signal frequency, is incident on a square-law mixer (a detector that responds to signal power) along with a locally generated signal source (referred to as a local oscillator) of the form $E_{LO}(t)=E_{LO}\cos(\omega_{LO}t)$ where ω_{LO} = local oscillator frequency, a current will appear at the output of the mixer,

$$i(t) = \frac{\rho}{\mu_0 c}[E_s(t)+E_{LO}(t)]^2 \tag{1}$$

where c is the speed of light, μ_0 is the permeability of free space, $\rho = \eta q/h\nu$ is the current responsivity, η is the video quantum efficiency, q is the electronic charge, ν is the frequency, and h = Planck's constant. Filtering out dc components and all mixing products except the difference frequency given by

$$\omega_{if} = \omega_s - \omega_{LO},$$

the output current is

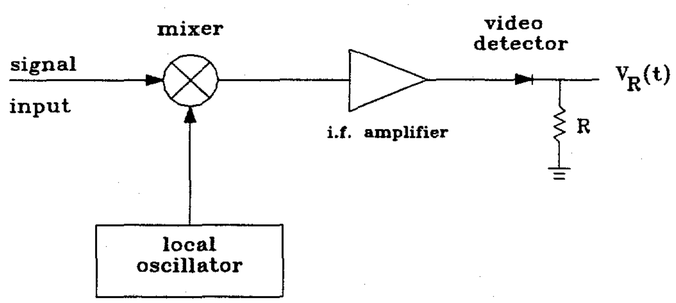

Figure 2: Heterodyne Receiver

$$i_{if}(t) = 2\rho\sqrt{P_s P_{LO}}\cos(\omega_{if}t + \phi) \tag{2}$$

This difference frequency term, referred to as the intermediate frequency (i.f.) signal, is typically amplified by an amplifier designed to pass a narrow range of frequencies around ω_{if}. The output of the i.f. amplifier is detected by a diode video detector. Thus the magnitude of the voltage impressed on the resistor R in Figure 2 is

$$V_R(t) \propto \sqrt{P_s P_{LO}} \tag{3}$$

The advantage of a heterodyne receiver may be determined by examining equations (2) and (3). The amplitude of the i.f. signal is proportional to the product of the signal amplitude and the local oscillator amplitude for frequencies that fall within the passband of the i.f. amplifier. The local oscillator power is generally large compared to the signal power, and this provides amplification which can improve the signal to noise ratio.

2.2 Detector Array

In a laser heterodyne receiver, the mixer is a HgCdTe photodiode or a quantum-well photoconductor followed by an i.f. amplifier with a bandwidth on the order of 1 GHz. Since the 10 micron wavelength laser frequency we intend to use is on the order of 28,000 Ghz, our receiver represents a method of performing very high resolution spectral analysis on the received signal.

Quantum well detectors are constructed from alternating layers of GaAs and AlGaAs. Detectors have been manufactured with detection capability in the IR region of the spectrum from 3 to 20 microns (selected by the aluminum concentration) and an individual detector can be configured for an optical bandwidth of 0.5 to 6 microns (selected by the physical dimensions of the well). High density QWIP video arrays are now becoming available[1]. Individual QWIPs have been developed with good quantum efficiency (~20%) and large bandwidths (~26 Ghz)[2]. This bandwidth is sufficient to allow complete spectroscopic coverage over the entire tuning range of the CO_2 laser[3].

Recent advances in HgCdTe photodetector technology have made possible the construction of large, sensitive, high-speed focal-plane array (FPA) detectors. Historically, HgCdTe photodetectors have been characterized by 1) low manufacturing yield (2%) in single detectors, 2) severe thermal blooming in FPA's, and 3) poor detector reproducibility. Video HgCdTe photodetector arrays are now becoming available in arrays as large as 128 x 128 with quantum efficiencies >50% and bandwidths ~ 200 MHz. These detectors have good response from 2 to 14 microns. Currently, these arrays are used as standard incoherent infrared video cameras.

2.3 Local Oscillator Array

Each detector in the array will be illuminated with a local oscillator beam formed by the image of a uniformly illuminated aperture array as indicated in Figure 1. Each aperture in the array will be imaged with unity magnification onto the detector array. The aperture array has been fabricated using commercially available grids. Diffraction-limited optics spatially filter the aperture image resulting in nearly-gaussian profile local oscillator beams at each detector. The reverse projection of these gaussian beams form an antenna beam array which in turn defines a virtual detector array at the object field. Figure 3 shows the far-field antenna beams at an object distance of 60 meters for a four detector linear array consisting of 50 micron diameter detectors on a 100 micron grid illuminated by an f/2 10 centimeter focal length lens. Our analysis indicates that the resulting near-gaussian antenna beams do not overlap for all points in the far-field object plane and beyond. Hence, this method of local oscillator beam formation provides efficient heterodyne mixing at each detector in the array.

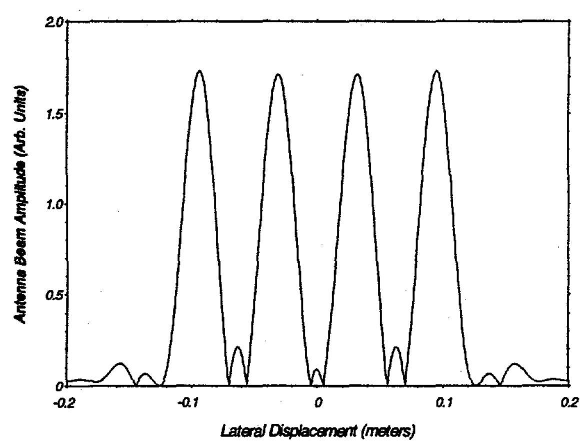

Figure 3: Antenna beam pattern for 4 x 1 detector array.

2.4 Electronics

Another major challenge for the implementation of 2-D heterodyne detector arrays has been the cost, size and power dissipation associated with the i.f. electronics attached to each infrared photomixer. Radio frequency amplifiers with 1 Ghz bandwidths are readily available, however at a cost of about $180/photodetector element. For a 128 x 128 2-D heterodyne detector, this translates to roughly $3M for the electronics alone, not to mention the connectivity issues of using discrete amplifiers.

Our approach utilizes detector array amplifier electronics fabricated using gallium arsenide-based Monolithic Microwave Integrated Circuit (MMIC) technology. This technology substantially reduces the cost and provides a realistic implementation. MMIC technology is a special case of standard integrated circuits (IC). These semiconductor processes are optimized for linear and rf applications above 1 Ghz. Typical commercially available processes allow applications up to about 20 Ghz and some experimental gallium arsenide processes have reported frequencies above 100 Ghz. Fabricating a circuit with a MMIC process has several advantages over a discrete method. One advantage is the very small size and compact features. This allows the devices to be considered as lumped elements rather than distributed elements and therefore makes analysis of the circuit much simpler. Making many repeatable copies is relatively easy both from a performance and an economical viewpoint, as the IC industry has shown many times. The estimated cost of a MMIC amplifier chip for a 128 x 128 array is $5K. In order to efficiently couple to the detector array the electronics must operate at or near liquid nitrogen temperatures, require low power consumption, and provide low noise levels over large bandwidths.

A prototype GaAs MMIC chip is presently in fabrication for use as a pre-amplifier for a single heterodyne detector. Sample transistors of the type needed for the amplifier design were obtained from the semiconductor foundry and analyzed for performance at cryogenic temperatures. The measured parameters were in good agreement with those measured by Camin, et. al., for these devices[4]. Models developed from these measurements were incorporated into the design of our MMIC circuits. There are three versions of transimpedance amplifiers on this developmental MMIC. Two of the preamplifier circuits are AC-coupled amplifiers, one operating at lower quiescent power with slightly higher noise levels, and the other at higher power and lower noise. The third amplifier is a DC-coupled cascade design with a common bias circuit. This design is capable of sourcing or sinking several milliamps of detector bias current at its input. All three amplifiers are designed to drive a 50-ohm terminated cable. The calculated bandwidth of the AC-coupled amplifiers is 8 MHZ-900 MHZ (-3 db). Noise levels for the noise-optimized version is expected to be about $0.5 nV/\sqrt{Hz}$ at a temperature of -180 °C. The trans-resistance is about 4.4 kΩ. The calculated bandwidth of the DC-coupled amplifier is DC- 1.2 GHz (-3 db). The noise level of this amplifier is expected to be approximately $4 pA/\sqrt{Hz}$ referred to the input. The design trans-resistance of this amplifier is about 3 k.

3. SINGLE DETECTOR MEASUREMENTS

Preliminary measurements have begun on a test-bed system designed to clarify the working parameters of a field camera. Figure 4. shows I-v traces for a single-element MCT photodiode with a heterodyne quantum efficiency of 38%. The data was modeled to allow precise determination of electrical parameters necessary for the amplifier circuit design. This diode has a maximum dynamic resistance of about 80 Ω . The junction capacitance and series resistance were determined with a network analyzer and found to be 12 pF and 8 Ω respectively. This give a calculated 3 db rolloff frequency of about 3 GHz indicating that the observed system bandwidth of 2 GHz may be limited by other components.

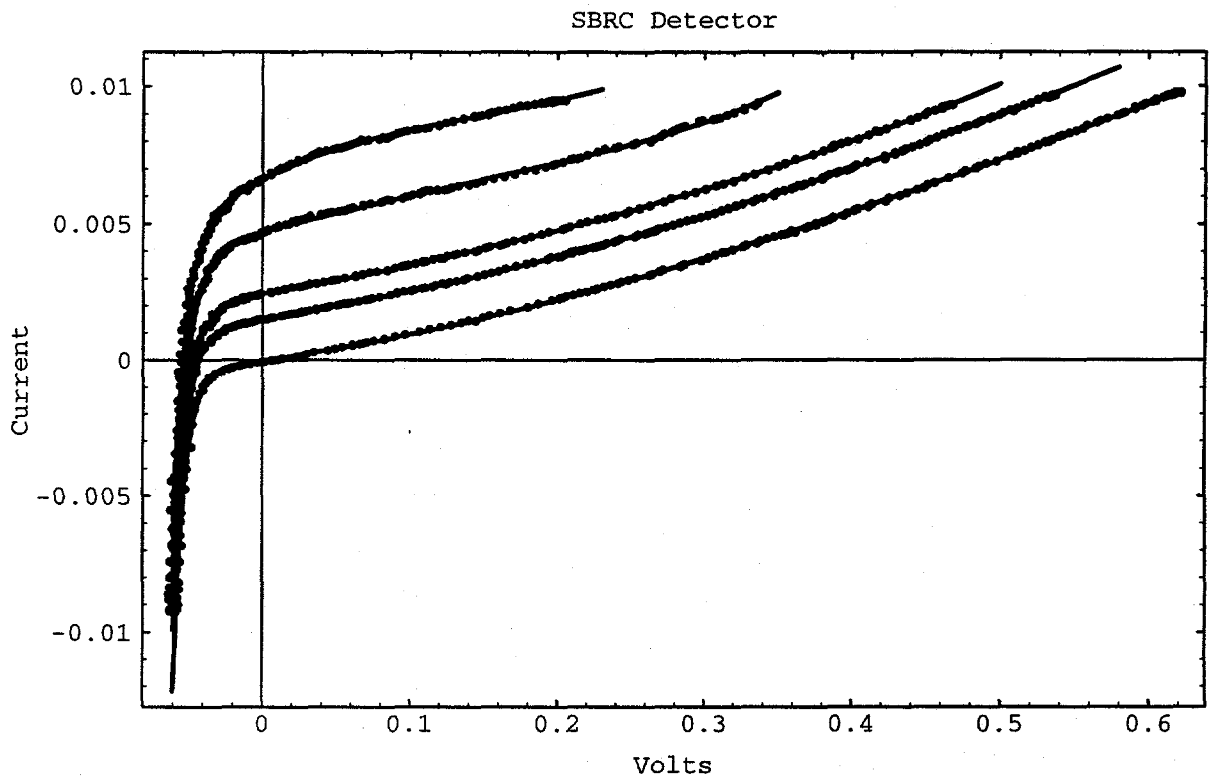

Figure 4: Current vs. voltage traces for a reverse-biased MCT photodiode. The local oscillator illumination was 0.0, 0.9, 1.4, 2.9, and 4.3 mW.

Absolute calibration of the receiver system was determined with blackbody illumination[5]. This particular diode provided maximum heterodyne performance with a LO illumination of about 3 mW. Other diodes studied provided similar performance with LO powers of around 0.5 mW. It is clear that the heat load associated with LO illumination will be a major design consideration and may require linear scans for very high density arrays.

4. SYSTEM INTEGRATION

CIRIC is designed to utilize both video detection for good temperature resolution and heterodyne detection for high resolution spectral analysis. In heterodyne mode, the camera can be used passively to detect thermal spectroscopic signatures or actively with a probe beam for high-resolution spectroscopic or range/velocity analysis. Absorbing plumes can be tracked and identified by either mode of operation, and frame subtraction will allow heterodyne information to be superimposed upon the video scene. Bragg shifting the probe and local oscillator beams by slightly different amounts will produce low frequency beat signals which can provide both range and Doppler information.

5. CONCLUSION

New developments in detector technology both for photodiode and quantum-well focal plane arrays promise new advances in coherent IR imaging. Detection bandwidths are now sufficient to enable continuous coverage over the 9-11 μm atmospheric window using the CO_2 laser as a local oscillator. This should allow operation at line-center absorption frequencies resulting in enhanced detection limits for many chemical species many of which are now hard to detect at the discrete CO_2 laser wavelengths. The ability to combine IR imaging with high-resolution spectroscopic analysis will allow enhanced chemical plume tracking and point source location. Utilization of MMIC technology for the amplifier grid will result in lower noise figures and increased portability.

6. REFERENCES

1. B. F. Levine, "Quantum-well infrared photodetectors," J. Appl. Phys **74** , pp.R1-R81,1993.
2. H. C. Liu, G. E. Jenkins, E. R. Brown, K. A. McIntosh, K. B. Nichols and M. J. Manfra, "Optical heterodyne and microwave up to 26 Ghz using quantum well infrared photodetectors, " IEEE Elec. Dev. Let., **16**, pp. 253-255, 1995.
3. E.R. Brown, K.A. McIntosh, K.B. Nichols, F.W. Smith, and M.J Manfra, "CO_2-laser heterodyne detection with GaAs/AlGaAs mqw structures," *Quantum Well Intersubband Transition Physics and Devices*, Kluwer Academic Publishers, pp. 207-220, 1994.
4. D.V. Camin, G. Pessina, and E. Previtali, "Improvements in Dynamic and 1/f noise performances of GaAs MESFET's at cryogenic temperatures by using a monolithic process," IEEE Trans. Nuc.Sci. **40**, pp. 759-763, 1993.
5. Bennett C.A., Richards R.K., and Hutchinson D.P., "Absolute broadband calibration procedure for infrared heterodyne receivers,"Applied Optics **27** , pp. 3324-3325, 1988.