ORNL/CP-96965

Instrumentation and Controls Division
Measurement Science Section

CONF-980347--

Wide-Band Coherent Receiver Development for Enhanced Surveillance

M.L. Simpson
R.K. Richards
D.P. Hutchinson

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831-6004
(423) 574-4171

IRIS Specialty Meeting on Active Systems
Albuquerque, NM
March 4-6, 1998

WIDE-BAND COHERENT RECEIVER DEVELOPMENT FOR ENHANCED SURVEILLANCE

3/6/98

M. L. Simpson, R.K. Richards, and D.P. Hutchinson
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6004

ABSTRACT

Oak Ridge National Laboratory (ORNL) has been developing advanced coherent IR heterodyne receivers for plasma diagnostics in fusion reactors for over 20 years.[1,2,3] Recent progress in wide-band IR detectors and high-speed electronics has significantly enhanced the measurement capabilities of coherent receivers. In addition, developments in new HgCdTe and quantum-well IR photodetector (QWIP) focal plane arrays are providing the possibility of both active and passive coherent imaging.[4] In this paper we discuss the implications of these new enabling technologies to the IR remote sensing community for enhanced surveillance.

Coherent receivers, as opposed to direct or thermal detection, provide multiple dimensions of information about a scene or target in a single detector system. Combinations of range, velocity, temperature, and chemical species information are all available from a coherent heterodyne receiver. We present laboratory data showing measured noise equivalent power (NEP) of new QWIP detectors with heterodyne bandwidths greater than 7 GHz. For absorption measurements, a wide-band coherent receiver provides the capability of looking between CO_2 lines at off-resonance peaks and thus the measurement of lines normally inaccessible with conventional heterodyne or direct detection systems. Also described are differential absorption lidar (DIAL) and Doppler laboratory measurements using an 8x8 HgCdTe focal plane array demonstrating

---

[1] Richards, R. K., D.P. Hutchinson, and C.H. Ma, "Design of a CO_2-laser Thomson Scattering Ion-Tail Diagnostic for Alcator C-Mod," *Rev. Sci. Instrumen.*, Vol. 66, No. 1, January 1995.

[2] Richards, R.K., D.P. Hutchinson, C.A. Bennett, H.T..Hunter, and C.H. Ma, "Measurement of CO_2 Laser Small Angle Thomson Scattering on a Magnetically Confined Plasma," *Appl. Phys. Lett.*, Vol 62, No. 1, January 1993.

[3] Bennett, C.A.., R.K. Richards, D.P. Hutchinson, "Absolute Broadband Calibration Procedure for Infrared Heterodyne Receivers," *Appl. Opt.*, Vol. 27, No. 16, August 1988.

[4] Simpson, M. L., C.A. Bennett, M.S. Emery, D.P. Hutchinson, G.H. Miller, R.K. Richards, and D.N. Sitter, "Coherent Imaging Using Two-dimensional Focal-Plane Arrays: Design and Applications," *Applied Optics*, Vol. 36, No. 27, pp. 6913-6920, 20 September 1997.

the "snapshot" capability of coherent receiver detector arrays for enhanced chemical plume and moving hardbody capture. Finally we discuss a variety of coherent receiver configurations that can suppress (or enhance) sensitivity of present active remote sensing systems to speckle, glint, and other measurement anomalies.

I. INTRODUCTION

Remote sensing applications have historically deployed multiple sensor systems that must be synchronized in time and space to extract range, velocity, termperature, and chemical species information. An example deployment would incorporate a laser range finder for distance to a target, an infrared (IR) camera for thermal signatures, and an active differential absorption lidar (DIAL) system for chemical plume detection. These types of systems measure only amplitude or time characteristics of scattered or emitted light from a target or scene and therefore have a limited purview. Coherent receivers differ in that they incorporate a reference laser (termed "local oscillator"). Thus time, phase, frequency, and amplitude of scattered or emitted light from a target can be measured by direct comparison to the reference laser light using a process called mixing or heterodyning.

The remote sensing community has recognized the advantages of coherent receivers over conventional direct IR detection with respect to increased measurement sensitivity and multi-dimensional information capability; albeit with added system complexity. Several new technology developments (i.e. very wide-band QWIP detectors and new HgCdTe and QWIP focal plane arrays) have further enhanced the measurement capabilities of coherent receivers. Coherent receivers that use the new focal plane arrays provide the capability of making parallel measurements where each pixel views a different portion of object space. In other words, each pixel in the focal plane array is an independent laser radar receiver. The major advantages of this configuration versus a scanning system are the reduction in the measurement time (i.e. PRF requirements of the laser) and the augmentation of automated target recognition (ATR) input with multiple, simultaneous measurements on the same target.

Wide-band heterodyne receivers are useful in measuring chemical species whose absorption peaks are not well aligned with the laser source line. If the species absorption peak corresponds directly with the laser line, an absorption measurement can be made using direct detection (amplitude only). For off-line (off-resonance) measurements, heterodyning is needed, where the bandwidth of the heterodyne receiver dictates how far away from the laser line an absorption peak can be measured. For example, the CO_2 laser line spacing in the 9 to 12 micron region of the spectrum averages around 50 GHz. With the new QWIP detectors theoretically having heterodyne bandwidths of 30 GHz or more, full high-resolution spectral coverage for the long wave IR is within grasp. In the following paper, research at ORNL is described that uses the new detector technology in coherent imaging receivers and wide-band heterodyne detectors. A variety of new receiver configurations are then described for enhancing present active laser systems.

II. IMAGING COHERENT RECEIVERS

Research at ORNL is taking advantage of the increasingly available infrared HgCdTe and QWIP detector arrays to provide camera systems where each pixel is an independent laser radar channel. The present ORNL coherent camera system uses an optical design based on a wire-grid (mask) to divide the local oscillator (LO) into an array of independent "beamlets" which illuminate each detector element within the focal plane array coincidentally with the incoming image wavefront.[4] Figure 1 shows an imaging configuration where the laser transmitter also provides the local oscillator illumination. In this configuration the transmitter beam is projected onto a target in object space and the return signal is imaged through the system aperture onto the detector array. The overlapping wavefronts of the return signal and the local oscillator illumination are mixed by the detector array resulting in channels that are spatially-independent (looking at different areas on the target).

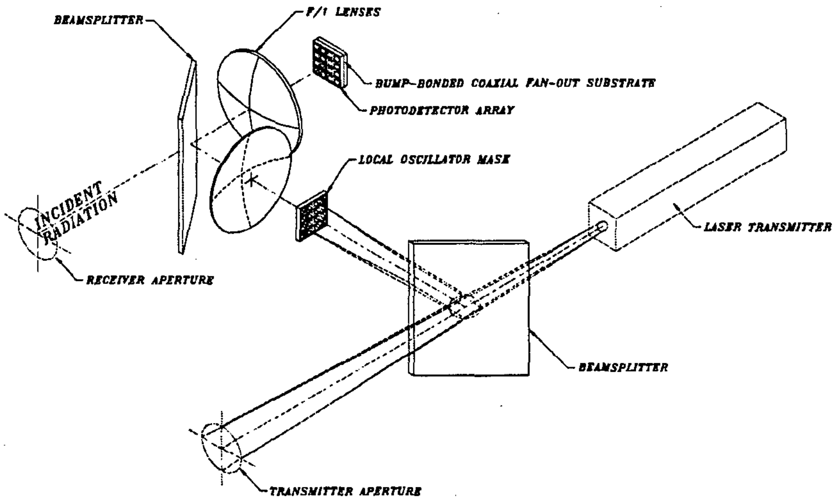

Figure 1 Coherent Imaging Receiver Configuration

To illustrate the ability of coherent imaging detectors to spectroscopically resolve chemical plumes, we show in Figure 2 a series of 10x10 pixel images of a small bottle of concentrated ammonium hydroxide against a 212°C background recorded in both passive heterodyne and direct detection mode. Figure 2a shows a heterodyne image of the bottle with the top in place where in figure 2b the top is removed and the absorbing plume is clearly imaged. The heterodyne images in figures 2a and 2b were recorded with the LO adjusted to emit the 9R(30) line which is known to be absorbed strongly by NH_3. In figure 2c, the same image was recorded by direct detection and fails to detect the ammonia plume. Similarly, in figure 2d, the LO was adjusted to emit a nearby line known not to be absorbed by NH_3 and the plume is again not detected. Both the objective and ancillary lens were f/1 38mm, and the object field was about three meters away. The top of the bottle was approximately 2 cm in diameter and is located at the bottom of the field of view. Measurements utilizing hot ammonium hydroxide imaged against a cold background resulted in similar images (albeit at substantially reduced signal to noise ratios) where the plume was bright and the background was dark.

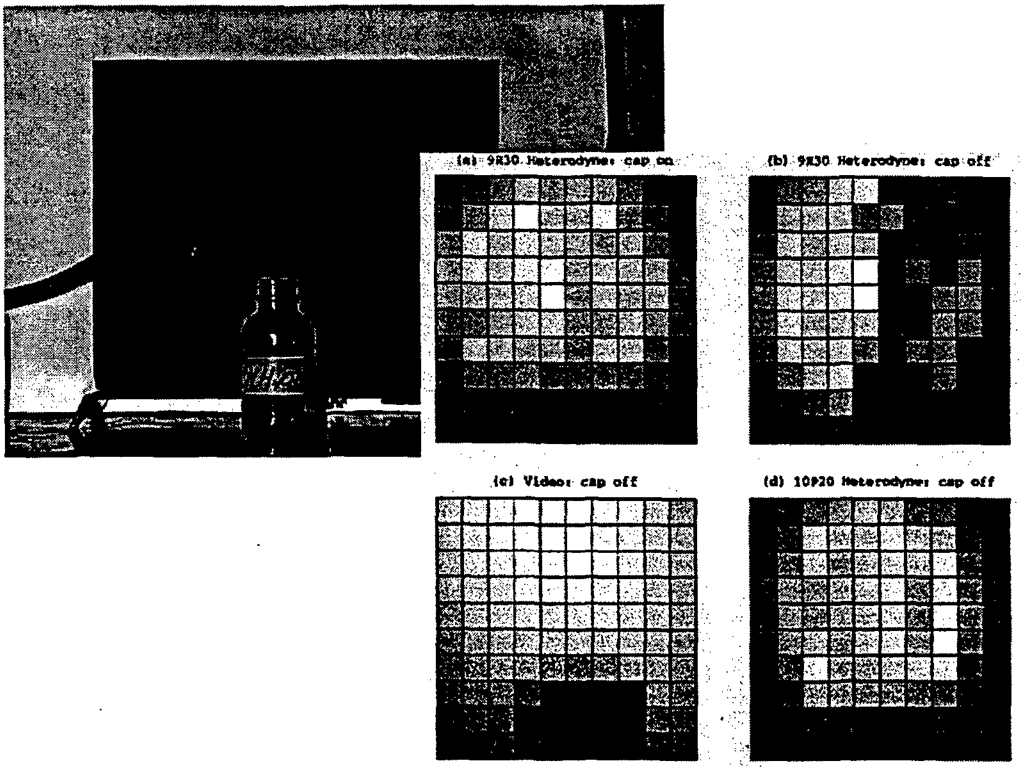

Figure 2 Ammonia Plume Characterization

In another experiment, active mode images were recorded by illuminating the scene with a portion of the LO radiation which had been shifted in frequency by 40 MHz using an acousto-optic

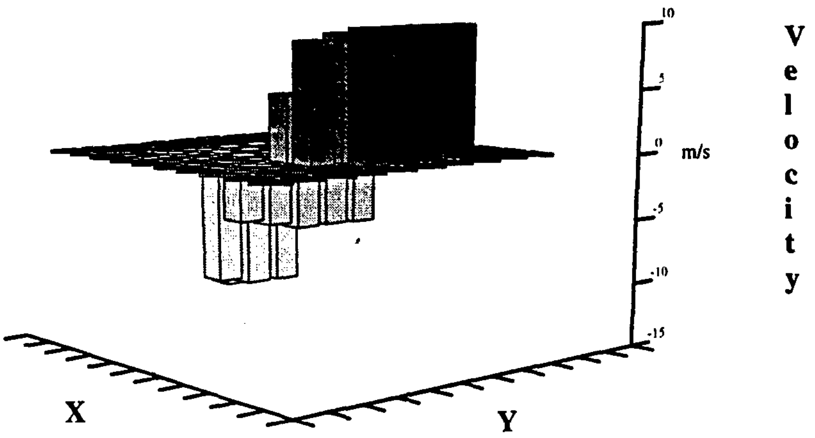

Figure 3 Doppler Image of a Rotating Squirrel Cage Fan

modulator. The Doppler image was recorded using an 8x8 HgCdTe array manufactured by Rockwell with discrete electronics for each pixel element in the array. Figure 3 shows the active image of a vertical squirrel cage fan where each pixel is rendered to represent the peak Doppler shift measured with the detector at the corresponding location in the image plane. The moving target scatters incoherently and thus speckle effects do not degrade the image. The measured Doppler shifts are consistent with the known rotational velocity of the target.

III. WIDE-BAND HETERODYNE RECEIVERS

Most heterodyne IR detectors used in the remote sensing community have bandwidths in the 10 to 100 MHz region. These detectors are very suitable for velocity or vibration measurements where typical aircraft velocities of 100 m/s translate into Doppler frequency shifts of 20 MHz at CO_2 wavelengths. Also, for chemical plume detection, detector bandwidths have not been considered a limiting factor. Many active laser systems developed for detecting and characterizing plumes and exhausts use direct detection via DIAL (differential absorption lidar). These systems send laser transmitter pulses of different wavelengths toward a target and measure the intensity of the return pulses. Non-absorbing and absorbing wavelengths are compared to extract chemical species concentrations. Essentially the bandwidth of the detector must be wide enough not to distort the return laser pulse. Thus a 1-microsecond laser pulse needs a detector with a bandwidth of several MHz.

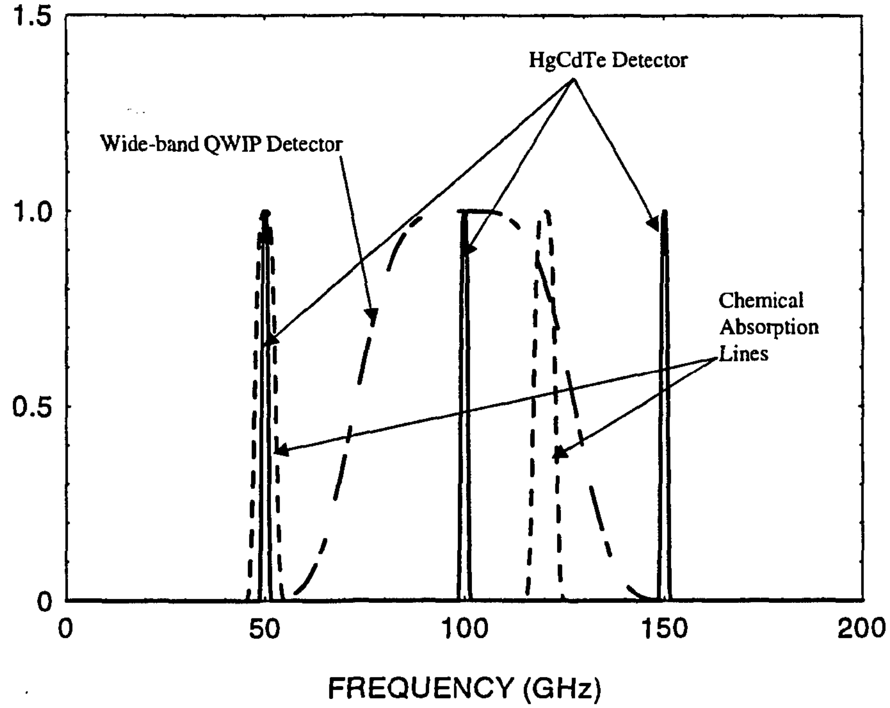

Figure 4 Illustration of Various Heterodyne Detector Bandwidths

For high-resolution spectroscopy, where several chemical species are present and where it is important to selectively distinguish between, for instance, chemical simulants and chemical agents, bandwidth is important. The role heterodyne bandwidth plays in high-resolution spectral measurements is shown pictorially in figure 4. Consider the signal from a standard HgCdTe detector with a 1 GHz bandwidth resulting from mixing a local oscillator signal with laser transmitter return pulses at 3 CO_2 lines. The down-converted frequencies from the output of the HgCdTe detector align with the 3 corresponding CO_2 resonances and are approximately 50 GHz apart. If a chemical species has a line that absorbs at the same frequency as the CO_2 line, the HgCdTe detector will have no trouble seeing the signal (50 GHz measurement in figure 4). If the absorption peak is off-resonance (between CO_2 lines), the absorption is still excited thermally (thermo-luminescence), but the resulting emission cannot be measured with the HgCdTe detector due to the limited bandwidth. If a QWIP detector with a 30 GHz bandwidth is used to mix the LO and return signals, the off-resonance absorption peak can be measured, as shown in the figure.

As part of our programs in fusion energy research for the Department of Energy, we have investigated wide-band heterodyne receivers. Unlike measuring velocities of aircraft, the measurement of Doppler shifts from nuclear particles in a fusion reactor with CO_2 laser scattering requires a very wide-band heterodyne receiver (around 10 GHz). Since the bandwidth of HgCdTe detectors is limited to a maximum of about 2 GHz, we explored the heterodyne bandwidth of quantum-well infrared photodetectors (QWIPs). The initial results of this study are given in figure 5 which shows the Noise-Equivalent-Power (NEP) as a function of frequency shift from the CO_2 laser line at 10.6 microns. For a photoconductive detector, the minimum noise is generated by the fluctuations due to detection of individual photons which is $2h\nu$ or 4×10^{-19} W/Hz. Figure 5 indicates that over the measured spectrum of 7 GHz, the detector has an efficiency of approximately 5%.

As described above, for chemical detection, a wide-band heterodyne detector at the 10 micron wavelength will offer the capability of measuring chemical lines normally inaccessible with the narrower-band detectors. These types of measurements have not been performed in the past due to the unavailability of wide band heterodyne IR detectors and yet now (with QWIP technology) hold great potential for yielding unique signatures for high-resolution spectroscopy.

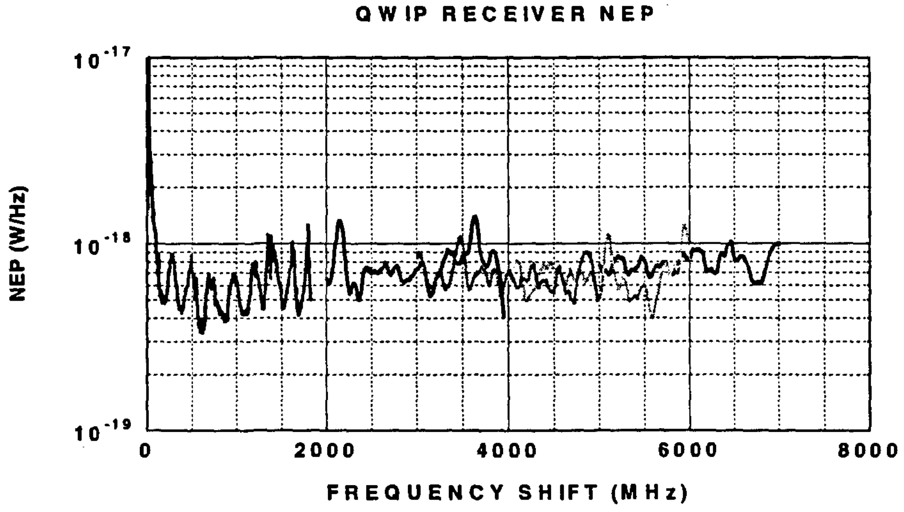

Figure 5 QWIP Heterodyne Performance Curves

IV. CONCLUSIONS AND FUTURE DIRECTIONS

We believe that coherent receivers with wide-band focal plane arrays will comprise the next generation in remote sensing. Due to the parallel, multi-function measurement capability of these new receivers, search, track, and ID can be performed using temperature, range, velocity, and chemical composition with a single sensor system. In addition to the sensor fusion advantages, snapshot imaging will allow the capture of high speed, rapidly evolving events that elude present scanning systems. Finally, new spectroscopy is enabled with the wide-band QWIP technology that provides much richer spectral data for characterization and identification. Some possible new coherent receiver configurations for surveillance using these technologies include:

1. ***Enhanced forward looking IR (FLIR) detector*** – 2nd or 3rd generation FLIR retrofitted with a local oscillator/transmitter laser and processing circuitry to provide coherent detection over a subset of pixels. Range, velocity, or chemical composition of specific features within the FLIR field of view can be extracted and overlaid with the normal thermal image.

2. ***Enhanced time-resolution DIAL*** – Differential absorption lidar with the thermal detector replaced by an 8X8 (or larger) coherent receiver. By spatially averaging speckle over the pixels in the coherent array (rather than laser pulse averaging), the time to make a measurement and therefore the required number of laser pulses is reduced by the square root of the number of pixels (in this case a factor of 8). This configuration could also be used to reduce the pulse repetition frequency (PRF) requirement on the laser transmitter.

3. ***Enhanced hyperspectral detector*** – Coherent receiver using a single wide-band QWIP operating in the passive mode (blackbody source) or active mode (thermo-luminescence). The very wide bandwidth allows the measurement of off-resonance lines with respect to the frequency of the local oscillator laser (i.e. greater sensitivity and spectral resolution than conventional filter wheel implementations). Ideally with this configuration, the local oscillator could be tuned between 9 and 11 microns to provide a nearly continuous high-resolution spectrum of warm plumes.

M98003390

Report Number (14) ORNL/CP--96965

CONF-980347--

Publ. Date (11) 199803

Sponsor Code (18) DOE/ER, XF

UC Category (19) UC-400, DOE/ER

DOE