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Wide-Band Heterodyne Receiver Development for Effluent Measurements

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

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831-6004
(423) 574-4730

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D.P. Hutchinson, R.K. Richards, M.L. Simpson and
C.A. Bennett; *Oak Ridge National Laboratory*
H.C. Liu and M. Buchanan; *National Research Council of Canada*

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Abstract

Oak Ridge National Laboratory (ORNL) has been developing advanced infrared heterodyne receivers for plasma diagnostics in fusion reactors for over 20 years. Passive heterodyne radiometry in the LWIR region of the spectrum has historically been restricted by HgCdTe (MCT) detector technology to receiver bandwidths of only 2 GHz. Given typical atmospheric line widths of approximately 3 GHz, a CO_2 (or isotope) laser local oscillator with an average line spacing of 50 GHz, and an MCT detector, only chemical species whose absorptions fall directly on top of laser lines can be measured. Thus, with traditional narrow-band heterodyne radiometry, much of the LWIR spectrum is missed and the less complex direct detection DIAL has been the preferred technique in remote sensing applications. Wide-band heterodyne receivers offer significant improvements in remote measurement capability. Progress at the Institute for Microstructural Sciences (IMS) at National Research Council of Canada and at ORNL in wide-band quantum-well infrared photodetectors (QWIPs) and receivers is significantly enhancing the bandwidth capabilities of heterodyne radiometers. ORNL recently made measurements in the lab using QWIPs developed at IMS that demonstrate heterodyne quantum efficiencies of 5% with a heterodyne bandwidth of 7 GHz. The path forward indicates that > 10% heterodyne quantum efficiencies and 30-GHz bandwidths are achievable with current QWIP technology. With a chopped, 30-GHz passive heterodyne receiver, a much larger portion of the LWIR spectrum can now be covered. One potential advantage of wide-band heterodyne receivers for effluent measurements is to dramatically reduce the number of laser lines needed to characterize and distinguish multiple chemical species of interest. In the following paper, we discuss this and other implications of these new technologies to the characterization of effluents using both passive heterodyne radiometry and thermo-luminescence.

Introduction

Heterodyne receivers differ from active lidar "direct detection" systems in that they incorporate a reference laser (termed "local oscillator" or LO). 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 the process called "mixing" or "heterodyning".

Most heterodyne IR receivers in the remote sensing community have bandwidths in the 10 to 100 MHz region. These narrow-bandwidth systems 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 effluent 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 only needs a detector with a bandwidth of several MHz.

For passive heterodyne radiometry, bandwidth is important. Passive heterodyne receivers measure blackbody radiation or thermal emission and therefore do not necessarily incorporate a laser transmitter to interrogate a scene or target. The role heterodyne bandwidth plays in high-resolution spectral measurements is shown pictorially in Figure 1. 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 a CO_2 line, the HgCdTe detector will have no trouble seeing the signal (50 GHz measurement in Figure 1). If the absorption peak is off-resonance (between CO_2 lines), the absorption is still excited thermally (thermo-luminescence or blackbody radiation),

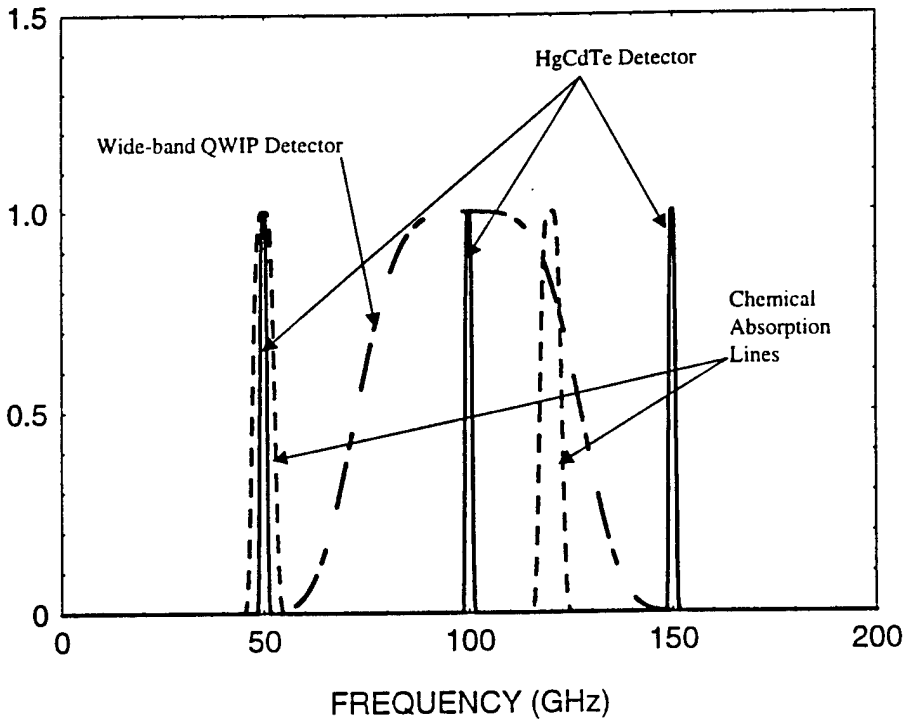

Figure 1 Illustration of Various Heterodyne Detector Bandwidths

but the resulting signal cannot be measured with the HgCdTe detector due to its 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.

A realizable implementation of a wide-band heterodyne receiver would actually use a QWIP detector in conjunction with a bank of filters. Each filter in this configuration would be optimized for noise performance given the bandwidth of the absorption features of interest.

Current Efforts in Wide-band Heterodyne Detector Development

As part of our programs in fusion energy research for the Department of Energy Office of Fusion Energy Sciences (DOE-OFES), we have investigated wide-band heterodyne receivers and detectors.[1,2,3] Currently we are developing a diagnostic for confined fast ions based on 10.6μ Thomson scattering for the Japanese fusion reactor, JT-60U. 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 are exploring the heterodyne performance of QWIPs which inherently have very wide bandwidth capabilities (~ 30 GHz).[4]

QWIPs are GaAs/$Al_xGa_{1-x}As$ structures whose physical dimensions and doping levels dictate the device band-gap and therefore wavelength sensitivity.[5] Prior applications of QWIP devices have been in thermal imaging where detector arrays as large as 640 X 480 have been developed for surveillance in both the 3 to 5μ and 8 to 12μ bands. These devices are optimized for dark current and thus noise-equivalent differential temperature performance.

In conjunction with the Institute for Microstructural Sciences (IMS) at National Research Council of Canada, we are investigating new QWIP devices that are optimized for heterodyne performance. Since in heterodyne detection, the QWIP dark current is not the primary concern, we are now exploring changing the doping density and the number of wells in the QWIP structure. In comparison with QWIPs that are optimized for thermal performance, a factor of six enhancement in heterodyne quantum efficiency is expected if one doubles the doping density (from $5x10^{11}/cm^2$ to $10^{12}/cm^2$ per well) and triples the number of wells (from 32 to 100). These values are well within practical reach and are expected to have no degradation effects. From our past experience, however, increasing the doping much above the $10^{12}/cm^2$ value results in leaky devices (i.e., high

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[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. Instr.*, Vol. 66, No. 1, (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, (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, (1988).

[4] H.C. Liu, G.E. Jenkins, E.R. Brown, K.A. McIntosh, K.B. Nichols and J.M. Manfra, "Optical heterodyne detection and microwave rectification up to 26 GHz using quantum well infrared photodetectors", *IEEE Elect. Dev. Lett.* Vol. 16, No. 6, (1995).

[5] B.F. Levine, "Quantum-well Infrared Photodetectors," *J. Appl. Phys.*, Vol. 74, No. 8, (1993).

dark current); while increasing the number of well substantially beyond 100 results in degraded material quality.

The initial results of our work for DOE-OFES using non-optimized QWIPs are given in Figure 2. In the figure, the Noise-Equivalent-Power (NEP) is plotted 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 $2h\upsilon$ or 4×10^{-20} W/Hz. Figure 2 indicates that over the measured spectrum of 7 GHz, the QWIP detector has a heterodyne quantum efficiency of approximately 5%. In contrast, the measured thermal quantum efficiency for the QWIP detector was about 10%.

Passive Heterodyne Radiometry using Array Detectors

Besides wide-bandwidth capability, an additional advantage of QWIP technology is the high yield during manufacturing. This high yield results in very uniform array

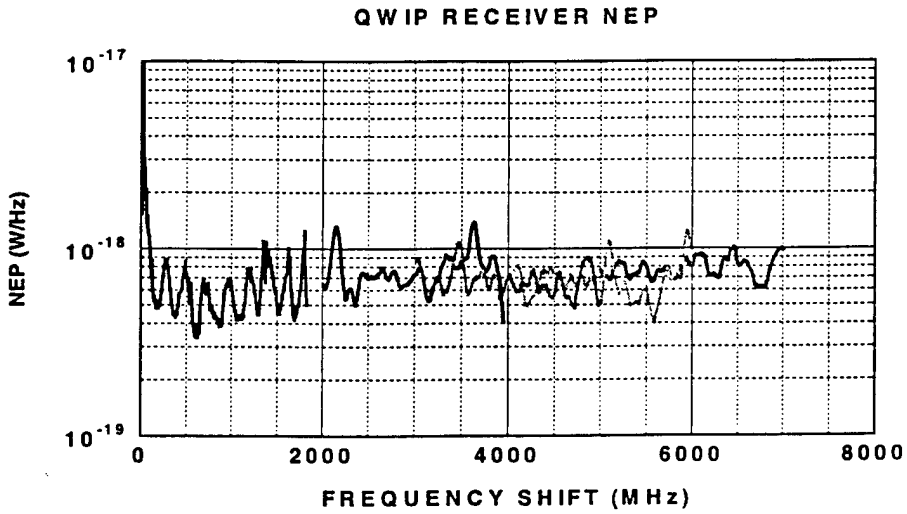

Figure 2 QWIP Heterodyne Performance Curves

detectors with high operability. Third generation FLIR systems are taking advantage of the large uniform QWIP arrays for thermal imaging, and now possibilities are opening up for using arrays in heterodyne receiver technology. Researchers at ORNL have been exploring optical configurations for imaging heterodyne receivers where each pixel of the detector array is an independent laser radar channel.[6] The present ORNL configuration uses an optical design based on a wire-grid (mask) to divide the local oscillator into an array of independent "beamlets" that illuminate each detector element within the focal plane array coincidentally with the incoming image wavefront. The sizes of the apertures in the mask and stops in the optical system are adjusted to give optimal heterodyne

[6] M.L. Simpson, 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," *Appl. Opt.*, Vol. 36, No. 27, (1997).

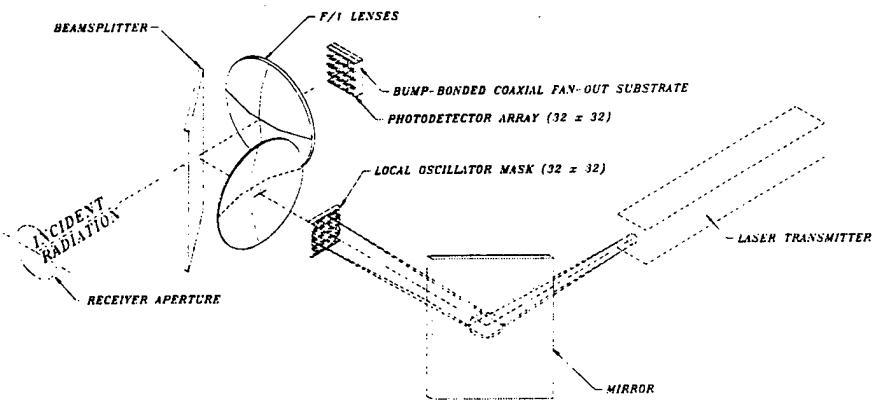

Figure 3 Imaging Heterodyne Receiver Configuration

performance. Figure 3 shows a diagram of the ORNL system where the blackbody signal is imaged through the system aperture onto the detector array. The overlapping wavefronts of the blackbody 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).

To illustrate the ability of imaging heterodyne receivers to spectroscopically resolve chemical plumes, we show in Figure 4 a series of 10 X 10 pixel images of a small bottle of concentrated ammonium hydroxide against a 212°C background recorded in both passive heterodyne and thermal imaging modes. These initial measurements were made using an available 1 GHz HgCdTe detector to demonstrate the principle of heterodyne array imaging. Figure 4a shows a heterodyne image of the bottle with the top in place where in Figure 4b the top is removed and the absorbing plume is clearly imaged. The heterodyne images in Figures 4a and 4b were recorded with the LO adjusted to emit the 9R(30) line which is known to be absorbed strongly by NH_3. In Figure 4c, the same image was recorded by thermal imaging and fails to detect the ammonia plume. Similarly, in Figure 4d, 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 warm 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.

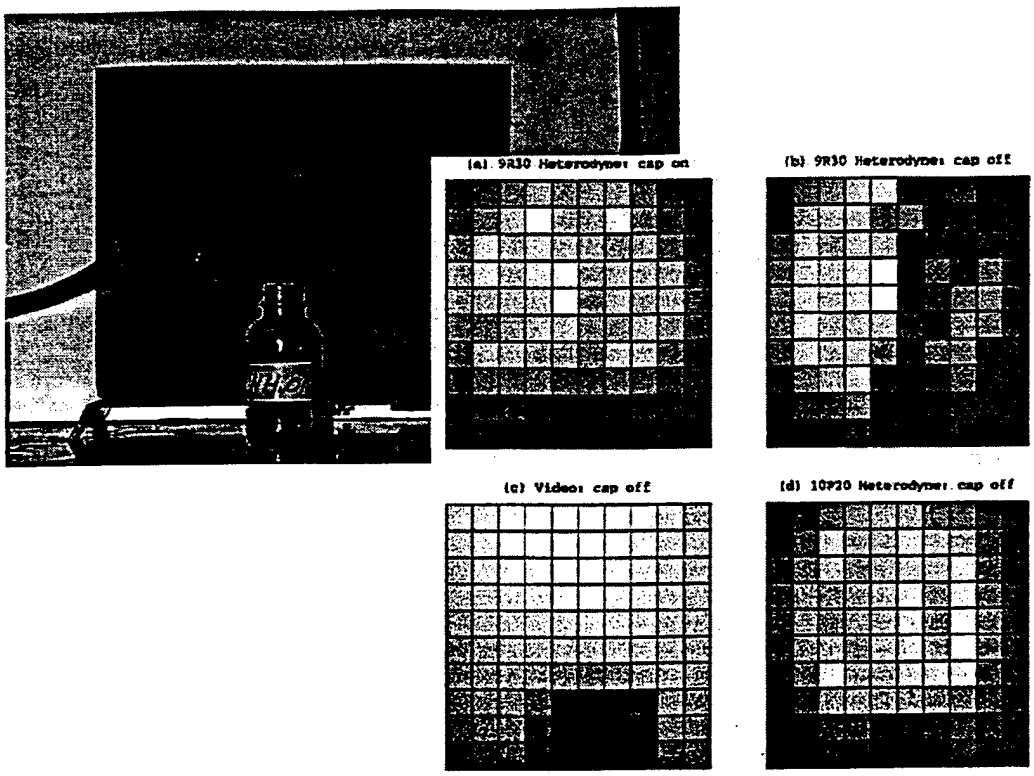

Figure 4 Ammonia Plume Characterization

In Figure 5 below, a remote passive heterodyne measurement of the effluent from a power facility smoke stack is shown at a range of about 300 m. Again, this measurement used a 1 GHz HgCdTe detector that was translated in the image plane to simulate an array detector. In this measurement, the output of the detector was integrated for a time period of several minutes and the resulting image shows the thermal signature of the stack as well as the heterodyne signal from the plume emission.

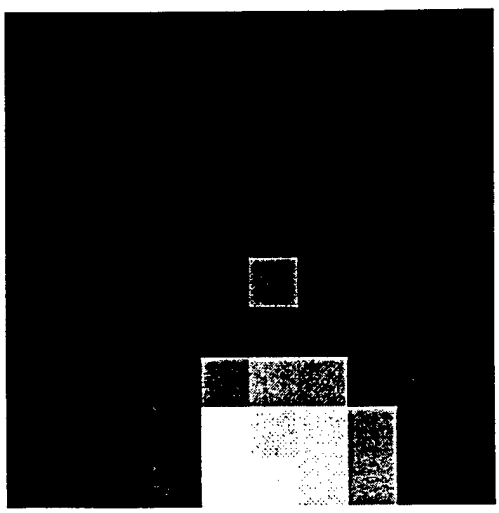

Figure 5 Passive Heterodyne Image of a Smoke Stack at 300 m

Order-of-magnitude improvements in the S/N and integration time are expected for similar measurements with a chopped 30 GHz heterodyne receiver based on QWIP technology.

Minimum Detectable Plume Temperature using a Passive Heterodyne Receiver

The signal-to-noise ratio, S/N, for a heterodyne receiver is determined by the factors of signal level, noise, bandwidth, and integration time. These are related by:

$$(1) \qquad \frac{S}{N} = \frac{P_S}{P_S + P_N}\sqrt{B\tau + 1}$$

where P_S is the signal power, P_N is the noise power, B is the receiver bandwidth, and τ is the integration time. The signal power per unit frequency available to a heterodyne receiver from a blackbody source is given by:

$$(2) \qquad P = \frac{h\nu}{\exp^{h\nu/kT} - 1}$$

and the noise per unit frequency for a heterodyne receiver with a photoconductive detector is expressed by:

$$(3) \qquad N = \frac{2h\nu}{\eta}$$

where h is Plank's constant, ν is the frequency of the radiation being measured, k is Boltsman's constant, T is the temperature of the blackbody, and η is the receiver quantum efficiency. For radiation in the 10μ wavelength region (the wavelength of the CO_2 laser), the value of hν/kT is around 1400 °K. Under conditions where the blackbody temperature is low (i.e. T << 1400 °K) then,

$$(4) \qquad P \cong h\nu \exp^{-h\nu/kT}$$

Since the receiver quantum efficiency is always less than unity, then the receiver signal-to-noise can be approximated by:

$$(5) \qquad \frac{S}{N} \cong \frac{\eta}{2}\exp^{-h\nu/kT}\sqrt{B\tau + 1}$$

As an application of this expression consider the measurement of a chemical plume from an airborne platform with the earth as a background blackbody. The plume will possibly have absorption/emission lines that can act as blackbody sources at a slightly different temperature than the earth. Given the parameters of the detector efficiency and the temperature of the earth, what is the temperature difference between

the earth and a plume that a heterodyne receiver can detect? First, consider the detection of the earth. Using a wideband detector (30 GHz) with a quantum efficiency of 50%, and a dwell time of 3 seconds, then a 300 °K earth will yield a signal to noise ratio of 997. The plume measurements will have a lower signal-to-noise ratio, first, because pressure broadened lines are typically only 3 GHz wide, and second, the heterodyne receiver will pick up a double side band of noise but only a single sideband of radiation signal from the plume. Defining the plume temperature as T_P, which differs from the earth's temperature, T_E, by

$$(6) \qquad T_P = T_E + \delta T$$

then the signal-to-noise ratio becomes,

$$(7) \qquad \frac{S}{N} = \frac{\eta}{4}\left[\exp^{-h\nu/kT_E} + \exp^{-h\nu/kT_P}\right]\sqrt{B\tau + 1}$$

For the case where $T_P = T_E$, the signal-to-noise is 223. If the plume is at a different temperature from the earth, the signal must change by a factor greater than $\sqrt{2}/223$ to be detectable. The $\sqrt{2}$ factor is required in determining the difference in two measurements. With half the signal derived from the earth, the signal originating from the plume must change by a factor greater than $2\sqrt{2}/223$. For small changes in temperature this becomes,

$$(8) \qquad \exp^{-h\nu/kT_P} > \exp^{-h\nu/kT_E}\left[1 + \frac{2\sqrt{2}}{223}\right]$$

Expanding the exponential:

$$(9) \qquad \exp^{-h\nu/kT_E}\left[1 + \left(\frac{h\nu}{kT_E}\right)\frac{\delta T}{T_E}\right] > \exp^{-h\nu/kT_E}\left[1 + \frac{2\sqrt{2}}{223}\right]$$

which reduces to,

$$(10) \qquad \frac{h\nu}{kT_E}\frac{\delta T}{T_E} > \frac{2\sqrt{2}}{223}$$

giving the result that δT must be greater than 0.815 °C. To achieve a certainty (99.99% probable detection or $\sigma = 9$) in the observation of a chemical line from the plume requires a difference in temperatures (either positive or negative) of $\delta T > 10$ °C.

Factors that may alter this sensitivity include a less than unity emissivity from the plume or the earth, a reflectivity from the earth, having a partially transparent plume at the absorption wavelength, multiple chemical lines that overlap, and time varying signals.

Conclusion and Future Work

For chemical effluents, a wide-band passive heterodyne receiver in the 9 to 11μ wavelength region will offer the capability of measuring chemical lines normally inaccessible with the narrower-band detectors or with direct detection. From the analysis above, using a chopped, 30 GHz QWIP detector with a 50% heterodyne quantum efficiency and a filter bank optimized for absorption lines of interest, plumes with a ~1°C differential temperature from the background can be characterized within a 3 second time window. These types of spectroscopic 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 high-resolution signatures in the region of the spectrum between CO_2 lines. One plausible result from wide-band passive heterodyne detection for remote sensing could be a substantial reduction in the number of lines needed to provide chemical specificity and therefore reduced measurement time. Another result could be the augmentation of present direct detection systems to provide characterization of hard-to-detect chemical species.

With the benefits of wide bandwidths and array configurations using QWIP technology, one possible next-generation remote sensor for effluence characterization is an enhanced FLIR. In this implementation, the QWIP two-dimensional array would perform two functions; thermal imaging and passive heterodyne radiometry. Unlike present FLIR systems with all detector outputs connected to a central multiplexer, the fanout of the enhanced imager could be designed to provide direct rf connections to a subset of pixels within the larger array. As a thermal imager, the FLIR would locate plumes of interest. The subset of pixels having the rf link could then be illuminated with a local oscillator laser to provide capability over the "subarray" for performing passive heterodyne radiometry. Therefore chemical effluents are captured and characterized with one sensor.

We believe that heterodyne receivers with wide-bandwidth QWIP detector 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 with a single sensor system using temperature, range, velocity, and chemical composition. 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 that is enabled by the wide-bandwidth QWIP technology will provide rich spectral data for characterization and identification.

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