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PHASE SENSITIVE IMAGING IN FLOWS

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Abstract

A commercially available imaging system, using a 1030 x 1300 pixel, interline transfer CCD, is modified to produce a phase sensitive imaging device that is also capable of reducing the level of integrated background light. The camera is able to extract a weakly modulated signal, that carries useful information, from a large amount of background intensity, or dc offset. Based on initial results, the imaging system can reduce the integrated dc offset by an order of magnitude and detect a modulation depth of 10^{-4}.

Introduction

Two-dimensional imaging of radical species concentrations in reacting flows (e.g. OH, CH, NO etc.) has yielded a large amount of useful information. As one example, Planar Laser Induced Fluorescence (PLIF) has become the technique of choice for turbulent flame studies.[1] While PLIF has proven invaluable, there are a number of data manipulations required in order to make the measurement quantitative, such as a system calibration and the collisional quenching correction. In non-premixed, turbulent flames it is difficult to quantify the collisional environment within each pixel area in the flow. This has proven to be a significant limitation to the PLIF technique.

We have demonstrated a Pump/Probe diagnostic technique based upon picosecond, mode-locked Ti:sapphire lasers.[2] The principal advantages of this technique include:

1. Pump/Probe spectroscopy is a spatially resolved absorption-based diagnostic - even species with poor fluorescence yields can be observed;
2. The Pump/Probe technique offers a determination of absolute number density, free of corrections and without the need for calibration; and
3. Picosecond Pump/Probe spectroscopy is not expected to be strongly affected by the collisional environment.

While Pump/Probe techniques offer significant advantages, it is not a background-free technique. With respect to Laser Induced Fluorescence (LIF), Pump/Probe spectroscopy is somewhat more complex to set up and has not been as well proven. LIF is a very well known, simpler approach which is background-free, but is subject to corrections and calibrations.

While there are trade-off's to each diagnostic, either one could be used with the imaging system described herein. Our principal goal has been to develop a camera that will take advantage of the attributes associated with a Pump/Probe diagnostic system. This required that we overcome the challenge posed by a dc-offset problem.

A phase sensitive imaging system could be used with other diagnostic techniques as well. For example, the system could be applied to a modulated filtered Rayleigh scattering experiment to measure velocity cross sections and two-dimensional velocity profiles. Modulated filtered Rayleigh scattering using solid state diode lasers has been demonstrated as a technique for making single point velocity measurements.[3] When the laser beam traverses a flow, the Rayleigh scattered light is Doppler shifted. Velocity fluctuations are converted to intensity fluctuations bypassing the scattered light through an atomic line filter.

To improve detectability the solid-state laser is modulated and a heterodyne detection system is utilized. The laser source is modulated at a frequency of 50 kHz and the laser frequency is scanned repetitively by a 10 Hz triangle wave, which provides a 10.5 GHz tuning bandwidth. Ambient light interference can be a problem because the Rayleigh signal is weak, particularly when using a cw, solid-state laser. An intensifier would need to be used with this diagnostic technique, however, the intensifier would not be gated. The intensifier would be set in a constant, minimum noise, gain state and the phase sensitive detection would be performed on the CCD chip. Consecutive in and out of phase demodulated images, at the same laser frequency, can be subtracted to remove steady state and low frequency noise, resulting in multidimensional velocity and mass flow information.

In what follows, we describe the development and testing of a phase sensitive imaging system. The concepts implemented in this imaging system were introduced in an earlier paper.[4]

Demodulation Imaging

In initial demodulating array research,[5] we used a liquid crystal mounted in front of a normal CCD camera to modulate optical gain (similar to the mixer in a lock-in amplifier). That approach had several problems but it proved sufficient for a proof-of-concept demonstration. Similar ideas have been demonstrated in the field of phase fluorometry for medical imaging. In phase fluorometry, photocathode or mcp gain is modulated in front of the camera and this serves as the mixer[6] and the references found therein). The principal difference between the two approaches is that the liquid crystal modulates loss and the image intensifier modulates gain. Both systems suffer from a large dc background problem, and this limits the performance of such camera systems.

Phase Sensitive Detection

Phase sensitive detection, or heterodyne detection, is a process used to detect a modulated signal. Heterodyning means the translating or shifting in frequency. In a heterodyne receiver the incoming modulated signal is translated in frequency, thus occupying equal bandwidth centered about a new frequency. If the heterodyne detection or the phase sensitive detection is performed at the same frequency of the incoming modulated signal, then the modulated signal will be shifted to the baseband.

Let $f(t)$ be a bandlimited signal that is amplitude modulated by $m(t)$, shown in equation 1.

$$m(t) = a(t)\ cos[\ \omega_c t + \gamma(t)\ ] \tag{1}$$

In equation 1, $a(t)$ is the carrier signal gain, or envelope, and ω_c is the carrier frequency. In amplitude modulation, the phase term, $\gamma(t)$, is zero, or a constant value. This characteristic allows us to use a phase sensitive detection system, to recover the information signal, since the phase is fixed. If we assume the envelope $a(t)$ is proportional to $f(t)$, then we obtain the amplitude modulated signal $\phi(t)$.

$$\phi(t) = f(t)\ cos\ \omega_c t \tag{2}$$

The frequency spectrum of the modulated signal, $\phi(t)$, shows us that the complete spectral shape of $f(t)$ is shifted in frequency by $\pm\omega_c$. Low frequency noise, below ω_c minus the bandwidth of $f(t)$, will at this point not effect the spectral content of $f(t)$.

To detect the original signal $f(t)$, we use the modulation property of the Fourier Transform for demodulation. Convolving the modulated signal, in frequency space, with a signal equal to (same frequency and phase) the original carrier signal, is the same as multiplying by the signal $d(t)$ in time, if $d(t)$ is set equal to $m(t)$. To demodulate a signal, this multiplication is literally performed, by electronic devices, as described below. Multiplying the modulated signal, $\phi(t)$, by $d(t)$ gives us equation 3.

$$\phi(t).d(t) = f(t)\ cos^2\omega_c t \tag{3}$$

Which, using a trigonometric identity can be rewritten as equation 4.

$$\phi(t).d(t) = \frac{1}{2}\ f(t)\ +\ \frac{1}{2}\ f(t)\ cos 2\omega_c t \tag{4}$$

The frequency spectrum of the demodulated signal, in equation 5, shows us that the spectral content of $f(t)$ is shifted again in frequency to $\pm 2\omega_c$ and to its original baseband state.

$$F[\phi(t).d(t)] = \frac{1}{2}F(\omega)\ + \frac{1}{4}F(\omega + 2\omega_c)\ +\ \frac{1}{4}F(\omega - 2\omega_c) \tag{5}$$

If the Nyquist sampling rate is satisfied, then a low-pass filter can be used, following detection, to filter out the double-frequency terms from the original spectral components.

Both the correct phase and frequency of the modulated signal must be known to perform synchronous or phase sensitive detection. A phase error in the detection system will cause a variable gain factor in the recovered signal that is proportional to the cosine of the phase error. Small phase errors are tolerable, however, the signal is wiped out when the error approaches $\pm 90^o$. On the other hand, if there is a frequency error, the signal $f(t)$ is multiplied by a low frequency sinusoid producing unacceptable distortion.[7]

Imaging Issues

Mixers themselves can be thought of as simple amplifiers, in which the amplifier gain is synchronously modulated at the reference phase and frequency. The amplifier output is the linear product of the input and the gain (now modulated). Thus, a mixer can demodulate an incoming signal by multiplying it with its carrier as described in 3. For imaging, it is possible to accomplish a similar task using optical loss (e.g. by polarization modulation, using liquid crystals for example) or gain (e.g. by use of an mcp or photocathode) directly in front of the camera. It can also be accomplished by clocking photo-electronic charge within the camera architecture, as described herein. Since the objective is to develop a system that can be utilized with background intensive diagnostics, the camera's architecture is attractive because it will provide us with a way to reject some of the dc background.

An important characteristic of a phase sensitive imaging systems using loss or gain is that the optical demodulator is capable of reducing the light level to zero and then driving it up to some maximum level characteristic of the system. The optical signal will not go negative. Thus, the input and the synchronously detected signal are square waves with a dc offset as described by equation 6. In this equation, T_c is the carrier period and τ_c is the width of the pulse in time. The duty cycle is then the ratio of τ_c to T_c. The amplitude of each pulse is defined as a.

$$p(t) = \sum \frac{a\tau_c}{T_c} Sa(n\pi\frac{\tau_c}{T_c})e^{j2\pi\, n\frac{t}{T_c}} \qquad (6)$$

The frequency spectrum of equation 6, in Figure 1, shows that the dc value of the signal accounts for 50% of the signal power. The dc magnitude is a function of the diagnostic technique used. At worst, the modulated portion of the signal is carried directly within a laser beam that is from 10^4 to 10^7 larger. Laser extinction in a particle-laden flow is one example. For scattering measurements (elastic and inelastic), the background is much lower, caused by flame emission and noise in the camera (including the mcp if one is used).

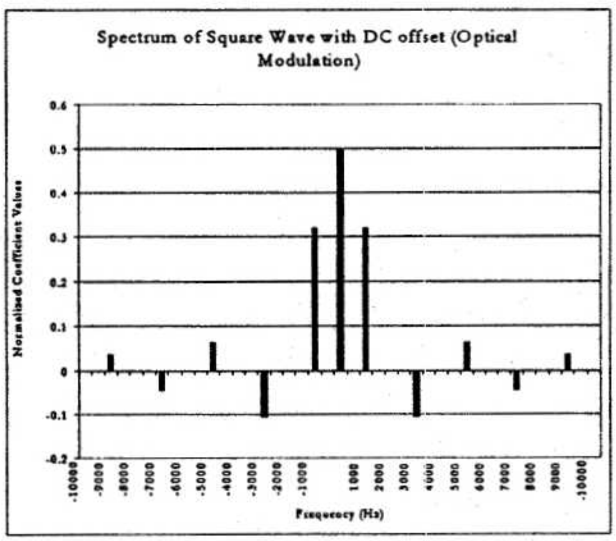

Fig. 1 Frequency Spectrum of Pulse Train

The dc magnitude can severely limit the minimum modulation depth detected by the camera, unless we can reduce it at the sensor. The problem manifests in one of two limiting electronic areas. First, the charge storage wells in a CCD camera have a finite limit, which is 20,000 electrons for the system we are using. In an ideal detector, the minimum modulation depth is obtained when the electron well fills with background (dc) to the point where the modulated portion of the signal occupies the last two photoelectron sites. In practice, the situation is much worse because electronic and optical noise will also fill a portion of the well, which requires the modulated signal be larger than the noise level by a measurable amount. In a real (e.g. noisy) detector, therefore, the minimum modulation depth is given by (2 x noise)/(total electron well depth). Commercially available cameras are then limited to modulation depths on the order of 10^{-3} to 10^{-5}. 10^{-3} is a useful level of performance, but some applications will need to detect smaller modulation depths.

The second limiting factor in most imaging systems is the analog to digital converter (ADC) resolution. For example, an 8-bit ADC has 48dB of dynamic range, which results in a minimum modulation depth of 0.4 %, which is much too large to be useful. The resolution of the ADC used in our phase sensitive imaging system is 16-bit, giving us 96dB of dynamic range.

Imaging System Development

Modifications have been made to a CCD camera system, model RTE/CCD-1300-Y manufactured by Roper Scientific (Princeton Instruments, Inc.), to provide gated integration control at the imaging chip level. The modifications and additions have been made in the camera controller logic, and the camera head circuitry and logic. The changes allow us to perform phase sensitive detection of a modulated light source, given that the modulation frequency and phase are known *a priori*.

Essentially, there are two unusual characteristics incorporated in the phase sensitive imaging system. The first is the ability to synchronously detect a modulated two-dimensional signal, by synchronizing to the modulated signal's frequency and phase. The second unusual characteristic is the imaging system's ability to sample a representative portion of the total integrated signal per integration period.

Phase Sensitive Detection

In order to perform phase sensitive detection imaging, we must synchronize charge shifting and storage, in the CCD, with the incoming modulated information signal. Thus, we must have adequate control over the Read Out Gate (ROG) and the Overflow Drain (OFD) in the interline transfer CCD architecture, shown in Figure 2. The ROG and OFD control the flow of charge from the photo sensors to the vertical register and to the substrate respectively.[8,9] The vertical register is masked by an aluminum shield that prevents direct entry of photoelectrons. Photoelectrons integrated and stored in the sensor can either be dumped into the vertical register or discarded in the substrate. This is better illustrated in Figure 3. Charge in the sensor will migrate to the vertical register, under the

Al mask, when the Read Out Gate voltage is increased (voltage potential increases in the downward direction). Charge in the sensor will also migrate to, and be discarded in, the substrate when the Overflow Drain voltage is raised. Electronic shuttering is, thus, accomplished and controlled with the voltage applied to the OFD.

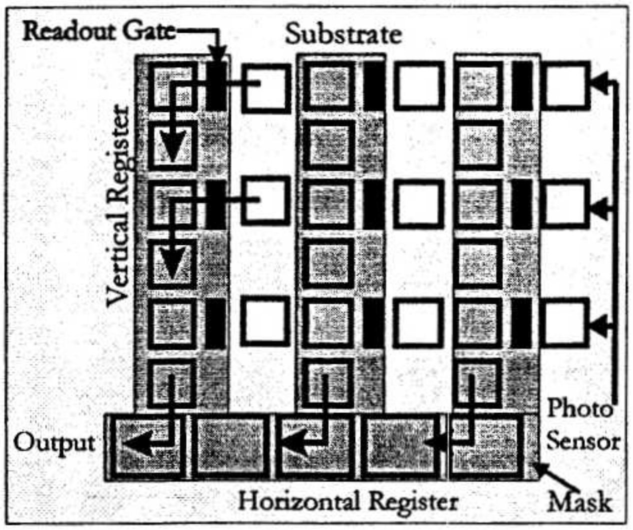

Fig. 2 Interline Transfer CCD Architecture

The ROG and OFD allow us to control the integration of the signal, to the extent that the signal is either integrated or not integrated. Assuming then that we are interested in detecting a laser source that is mechanically chopped, we can synchronize the imaging system to the chopper. Incorporating the phase lead or lag time with respect to the chopper 'sync' signal allows us to detect the signal when it is present and dump any noise when the signal is not present. As previously shown in Figure 3, the in-phase signal is integrated into the vertical register by raising the ROG voltage and lowering the OFD voltage. Then, as shown in Figure 4, the out-of-phase light is dumped to the substrate by raising the OFD voltage and lowering the ROG voltage. This synchronous process shifts the signal modulated at ω_c back down to the baseband, by mixing it with the same detection frequency of ω_c, as described earlier. The vertical register then performs lowpass filtering on the rectified signals, since multiple integrations are summed in the vertical register prior to reading out the image. The bandwidth of the lowpass filter depends on the number of integrations performed prior to readout.

As an aside, it is also possible to capture two separate images on the CCD chip prior to readout. A set of separate, high resolution images can be integrated on the CCD with a minimum temporal separation of $1\mu s$. If a pulsed diagnostic is used, such as Planar Laser Induced Fluorescence (PLIF) or Partical Imaging Velocimetry (PIV), then the first image can be directly integrated and stored in the vertical register and a

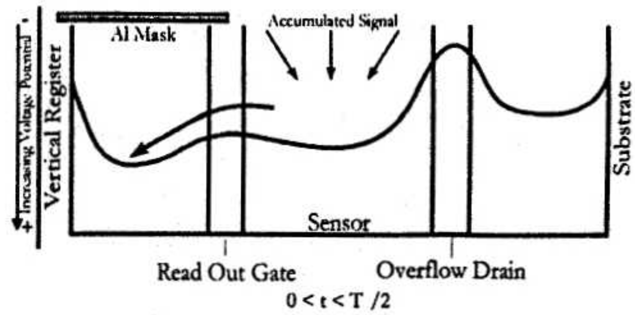

Fig. 3 Charge Flow Diagram (In-Phase)

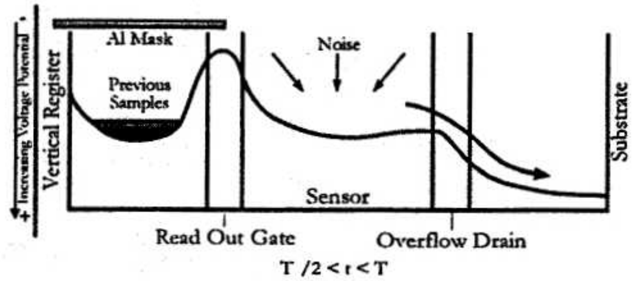

Fig. 4 Charge Flow Diagram (180° Out-of-Phase)

separate second image can be integrated and stored in the sensor area. Capturing two separate images is performed by lowering the voltage on the ROG after the first image is integrated, which prevents the second image from migrating to the vertical register, causing the second image to be stored in the sensor area. The two images can then be read out of the CCD separately. The double image feature has been used with a PLIF diagnostic in recent investigations.[10]

Integration Threshold

The second unusual characteristic incorporated into the imaging system is the ability to reduce the amount of stored photoelectrons per integration. A Pump/Probe type of diagnostic will quickly saturate the CCD with its large dc value, after only a few or one integration period. Since we know that the signal has a consistent dc offset intensity, in which the modulated signal resides, we would like to only sample the signal above a certain threshold. We would like to increase the number of integrations performed by reducing the overall magnitude at each integration. This is accomplished in the CCD with a non-linear integration threshold value associated with the Read Out Gate.

To better explain the idea of dc reduction with an integration threshold parameter, we will first briefly look at the 'normal' operation of an interline transfer CCD in block form, as shown in Figure 5. The well depth of the CCD is determined by the charge storage capacity of the sensor. After an image is integrated in the sensor, the accumulated charge is quickly dumped, via the ROG, to the vertical register for readout. The OFD controls the electronic shutter and the anti-blooming functions. Applying a high voltage to the OFD will activate the electronic shutter function and send any charge in the sensor directly to the substrate. In a lower potential state, the OFD allows the sensor to store charge up to a certain integration level, which is the well depth of the sensor. Once the sensor is saturated, any additional charge will 'overflow' to the substrate, so that CCD blooming is eliminated.

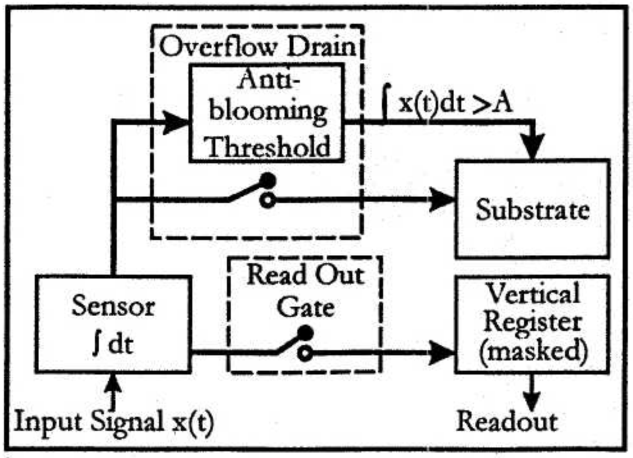

Fig. 5 Charge flow of normal CCD With Anti-blooming

Now, referring to Figure 6, we are using the ROG, instead of the OFD, to set the integration threshold on the sensor. Then, as long as the potential on the OFD is less than the potential on the ROG, relative to the sensor, additional charge, exceeding the integration threshold, will migrate to the vertical register, where it is stored. The OFD is now used as a switch to dump the charge built up in the sensor after an integration period. This process is performed by setting an 8 bit digital to analog converter (DAC), with the serial inter-integrated circuit (I^2C) protocol, prior to imaging. The DAC output sets the ROG level during an integration period through an analog switch. The ROG level can be set from 12.75 V to 0 V, during integration, with a resolution of 50 mV. Future studies will relate the ROG level to the dc reduction level.

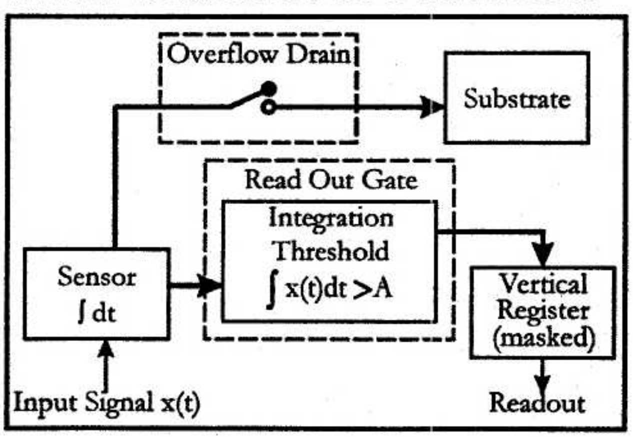

Fig. 6 Charge Flow of CCD with Integration Threshold

Imaging System

Putting the two characteristics, the phase sensitive detection and the integration threshold, together, the imaging system functions as shown in Figures 7, 8, and 9. At the first synchronous trigger, the imaging system performs the first integration by lowering the OFD to its minimum potential and raising the ROG to a voltage level proportional to the DAC (In Figures 7, 8, and 9, increasing voltage potential is as shown on the left hand side of the figures, thus increasing voltage lowers the gate threshold.). Once the integration threshold is exceed by charge in the sensor, additional integrated charge will migrate to and be stored in the vertical register. Once the exposure time for that integration period has elapsed, the ROG is lower to its minimum to prevent any further migration of charge from the sensor to the vertical register, and the OFD is set to its maximum to dump the charge from the sensor to the substrate (Figure 8). During this time, when no signal is present, the ROG and OFD remain as shown in Figure 8, activating the electronic shutter and dumping the steady state background, which includes noise, to the substrate. During the next, and the n^{th}, integration period, the ROG and the OFD are set as shown in Figure 9, summing each integrated signal period in the vertical register. In other words, lowpass filtering the integrations in phase with the signal.

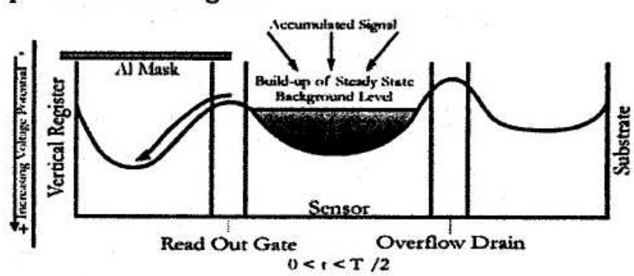

Fig. 7 Charge flow Diagram (In-Phase Integration)

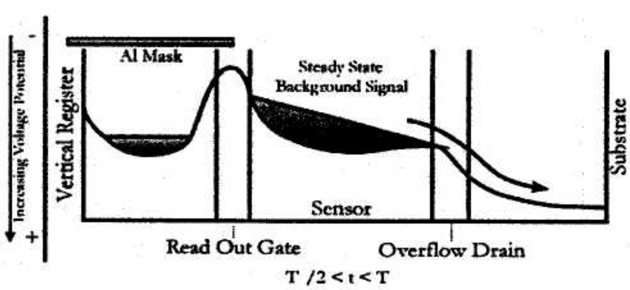

Fig. 8 Charge Flow Diagram (Not Sampling When Out-of-Phase)

Established Instrument Comparison

The phase sensitive imaging system can be compared to two established and commonly used instruments, which are the Lock-in Amplifier and the Boxcar Integrator. The imaging system can be compared to a

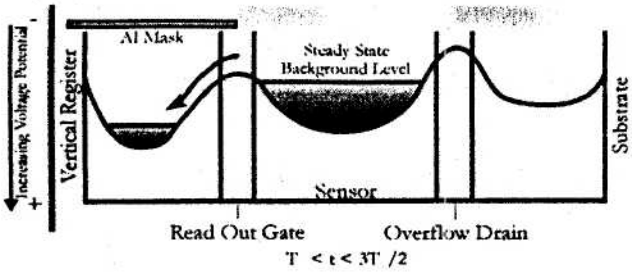

Fig. 9 Charge Flow Diagram (In-Phase [Nth] Integration)

Lock-in Amplifier, in the sense that it synchronously rectifies the signal of interest. A Lock-in Amplifier, however, has an advantage over the imaging system in its demodulation process. A Lock-in Amplifier mixes the signal of interest with a sinusoidal signal, with zero dc offset, which prevents the signal's power spectrum from mixing with the dc value and into low frequency noise. Also, either a bandpass filter, prior to demodulation, or a lowpass filter, after demodulation, is used in a Lock-in amplifier, to eliminate any noise outside the power spectrum of the information signal. The imaging system can only mix the modulated signal with a positive square wave, thus, convolving the power spectrum of the information signal with the dc and low frequency noise spectrum. The advantage of the imaging system, however, is that detection occurs in two dimensions and the Lock-in Amplifier is only capable of single point processing.

The imaging system is probably more comparable to a boxcar integrator. A boxcar integrator is a more appropriate instrument for measuring a train of short pulses that are separated by relatively long durations of zero information, which is the case when the duty cycle is $\ll$ 50%. A boxcar integrator greatly improves the SNR by detecting the signal only when it is present and not detecting anything when there is nothing but noise. The detection is performed simply by switching, or gating, the signal input, to an amplifier, ON and OFF. Significant amplification of the gated signal, on the order of 10^8, is possible, to detect small amplitude signals. The time-pulse information is then fed into a lowpass filter, which integrates all of the 'ON' gates. Thus, the boxcar integrator is essentially a gated lowpass filter. The final signal value on the filter (which is the sum of the contributions from all the members of the Fourier series) is equal to the average value of the signal pulse over the ON interval of the gate. The SNR is improved by reducing the noise bandwidth and patiently gathering information, which is spread out over time.

The phase sensitive imaging system operates in much the same manner. The signal is gated, by the Read Out Gate, either ON or OFF. The time-pulse information is stored in the vertical register, which performs the lowpass filtering function, as described in the boxcar integrator. Unlike a typical boxcar integrator, the imaging system is not capable of amplifying the signal prior to lowpass filtering the gated signal. In fact, there is actually a slight loss in signal due to the quantum efficiency of the detector. However, as previously stated, the phase sensitive imaging system captures two-dimensional data, which is not possible with a boxcar integrator.[11]

Experimental Results

Experimental Setup

The phase sensitive detection imaging system uses a Sony 1300 x 1030 Interline Transfer CCD. Each pixel in the array is 6.7μm square and have microlenses to improve the fill factor. The system uses a 16 bit ADC with a clock speed of 1 MHz. The minimum integration time is on the order of 10μs, resulting in a maximum signal modulation frequency of 100 kHz. Currently the number of integrations per image can be set from 1 to 255. A region of interest (ROI), a specified subsection of the entire CCD array, was used in the results presented here. The images shown are 301 x 301 pixels, which are captured at a framing rate of 11 Hz or less depending on the number of integrations and integration period. The analog to digital conversion rate limits the maximum framing rate speed. The charge in the CCD can be clocked out at a much faster rate than the ADC rate. Princeton Instruments, Inc. now offers a 5 MHz, 12 bit system, that uses the same CCD.

In order to test the phase sensitive imaging system, we set up a simple scattering experiment, shown in the Appendix as Figure 15. The basic objective of the experimental setup is to combine an intense, steady state beam of light, with a weak, modulated beam of light. The imaging system then extracts the weak modulated light from the intense steady state, background light. As shown in Figure 15, the beam is first split by a beam splitter. Thirty percent of the beam passes through a neutral density filter, is modulated with a mechanical chopper, and then recombined with the steady state beam at the second beam splitter. A lens expands the beam so that it completely covers the object of interest, which in this case is simply an integrated circuit (IC) package. Scattering from the object is then collected by the CCD camera. An image of the IC package is shown in Figure 10, which was taken under ambient light conditions to show the resolution of the camera.

A 1 kHz modulation frequency was applied to the chopper, and a photodiode was first used to determine the phase lead or lag time between the chopper sync output and the modulated beam. The sync output from the chopper was used as an external trigger to a Stanford Research Systems Inc., DG535, delay generator. The imaging system was then triggered by the rising edge of a 20μs pulse from the DG535, which allowed us to control the phase delay setting, based on the chopper sync signal.

Initial Results

The first imaging experiment was set for a $100\mu s$ exposure time per integration (duty cycle = 10%) and 255 integrations per image. Also worth mentioning, the camera system is thermo-electrically cooled and was set at $-10°C$. Also, to perform dc reduction, the 8 bit DAC was set to 165 (maximum setting is 255), which reduced the maximum Read Out Gate voltage during integration by 30%. This is only a measurement of the voltage applied to the Read Out Gate and not a measure of the integration threshold. Further study is needed to completely characterize the integration threshold and the camera's ability to reduce the background intensity.

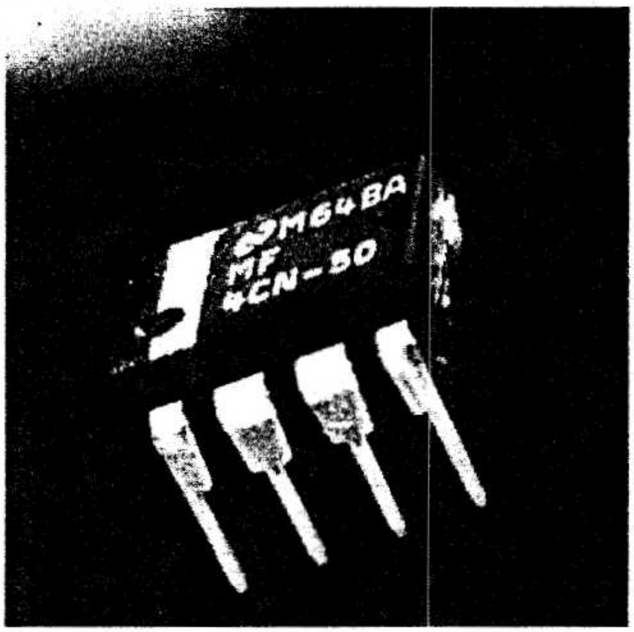

Fig. 10 IC Package Image

The power of the two beams, the steady state beam and the modulated beam, was measured with a Spectra Physics 404 power meter. The steady state beam power, for the first test, was measured at 1.6mW, and the modulated beam power was found to be 8μW. Thus, the steady state beam power is 200 times larger than the modulated beam power. If we define 'modulation depth' as the ratio between the modulated beam power and the steady state beam power, then the modulation depth for the first test is 5×10^{-3}.

The results of the first test are shown in Figures 11 and 12. Figure 11 shows the in-phase integrated image and Figure 12 shows the result of integrating 180° out-of-phase. A mask bleed-through image (not shown) was also captured by setting the integration threshold DAC to zero. The aluminum mask on the CCD is not perfect and some small portion of the image 'bleeds' through the mask and into the vertical register. Thus, by setting the DAC to zero, no integration is performed

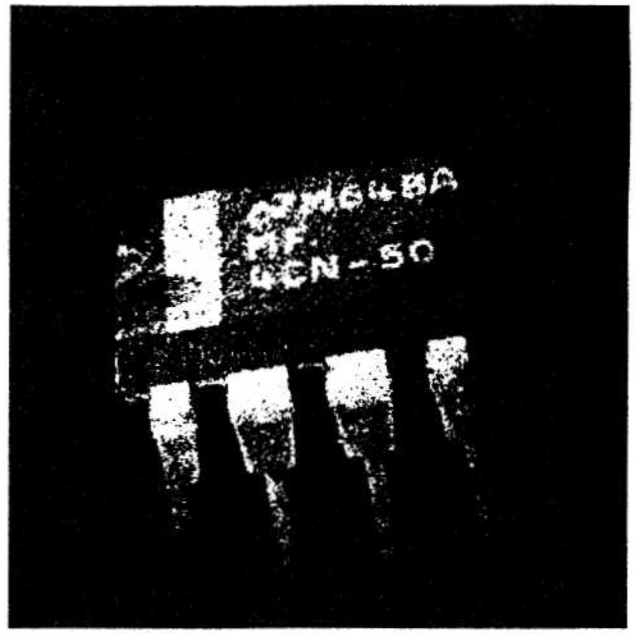

Fig. 11 In-Phase Image (Includes Modulation)

Fig. 12 Out-of-Phase Image (Modulation Absent)

over the total time it takes to capture the image and a mask bleed-through image is obtained. The in-phase and out-of-phase images are initially corrected by subtracting the mask bleed-through image from them. Then the 'corrected' in-phase and out-of-phase images are subtracted from each other. By subtracting the out-of-phase image, which contains only steady state beam intensity, from the in-phase image, which contains both modulated beam intensity and steady state beam intensity, we obtain an image that contains only modulated beam intensity. The result obtained from subtracting the image in Figure 12 from the image in Figure 11 is shown in Figure 13.

The resulting image in Figure 13 shows that the phase sensitive imaging system is capable of detecting a modulation depth on the order of 10^{-3}. There are some interesting characteristics seen in Figure 13. The interference pattern between the steady state beam and the modulated beam is definitely apparent and is an expected result. Also, the area around the chip, in the image, is canceled out since in-phase scattering only occurs in the small focal length volume of the object, creating very defining edges.

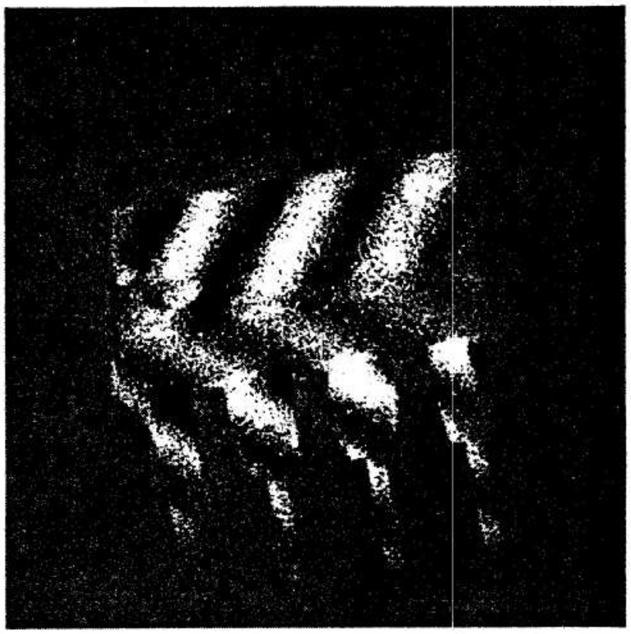

Fig. 13 Image Detected at 10^{-3} Modulation Depth

A second imaging test was then performed at a smaller modulation depth. The steady state beam was set at 2.88mW and the modulated beam was attenuated to 0.92μW with a neutral density filter. This resulted in a modulation depth of 3.2x10^{-4} for this test. The exposure time per integration was lowerd to 50μs and the integration threshold DAC was set at 180. The integrations per image remained at 255. Again, an in-phase image and an out-of-phase image were obtained and corrected for mask bleed-through. The result from subtracting the out-of-phase image from the in-phase image is shown in Figure 14. The signal to noise ratio of Figure 14 is approximately 2 to 3. This image shows that the system is capable of detecting a minimum modulation depth on the order of 10^{-4}, which is an exciting and promising result.

Future Phase Sensitive Imaging System Research

In the near future, the imaging system will be utilized with both background free and background intensive diagnostics. Initially, we plan to image acetone seeded flows with Pump/Probe techniques. The imaging system will be carefully characterized in terms of the dc reduction capability and absolute detection limits. Future work will also include studies on image enhancement with image processing techniques.

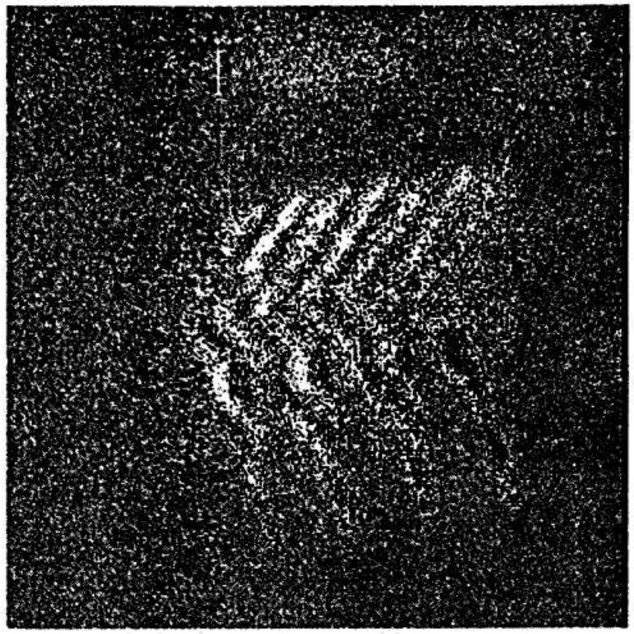

Fig. 14 Image Detected at 10^{-4} Modulation Depth

Future Detection System Development

The offset level, or dc reduction process described in the phase sensitive camera systems does not remove all of the dc signal entering the detector. In imaging, the dc level, or background intensity, is, for example, the largest undesireable attribute in a pump/probe diagnostic setup. Thus, minimizing the background intensity would greatly improve the signal to noise ratio of the detection system and improve on the minimum detectable modulation depth. Background noise elimination can be accomplished by bandpass filtering the signal at a center frequency near the carrier frequency, prior to demodulation. The bandpass filter will allow the modulated signal to pass unattenuated, but greatly attenuate the dc level that is outside the bandwidth of the filter. This would require that continuous signal processing be done at the photo site prior to demodulation, integration, and image readout.

CCD's are limited in their signal conditioning capabilities. Charge in a CCD can be transferred, dumped, or summed. Active pixel sensors (APS) designed with CMOS technology are now finding their way into more and more applications. The active pixel sensors are providing attractive alternatives to CCD devices by incorporating processing blocks that are impossible in CCD devices. Based on initial studies, we are initiating the development a CMOS imaging device that incorporates temporal filtering at the pixel level. Signal processing at the pixel level will greatly improve the detector performance and detectable modulation depth.

To test the concept of temporally bandpass filtering the signal, prior to demodulation, we setup a test circuit using discrete components. An LED, driven by a summing amplifier, which allowed us to add various levels of dc, modulation, and noise to the signal, was set directly in front of a photodiode. The signal from the photodiode was converted to a voltage, amplified, and then passed into a CMOS, switched capacitor, bandpass filter. A switched capacitor filter was used since it is developed with CMOS processes (which is, therefore, compatible with APS technology) and the center frequency of the filter is adjusted with a clock input. The signal from the bandpass filter was analyzed with an Hewlett-Packard HP89410 vector signal analyzer. Based on the individual dc and modulation power applied to the LED, the test circuit showed that by temporally filtering the signal, prior to demodulation, a modulation depth of 10^{-5} is obtainable.

Conclusions

A commercially available CCD camera has been modified, resulting in a phase sensitive two-dimensional detection system. The imaging system improves the signal to noise ratio by synchronously detecting the information signal, by detecting the signal only when it is present, and by integrating multiple exposures into one image, which lowpass filters the signal. Thus, the imaging system can be related to a two-dimensional boxcar integration system. Also, the maximum intensity accumulated in the pixels is reduced by sampling each exposure with the same integration threshold, which is set prior to capturing an image. This allows the CCD to acquire a greater number of integrations per image and keeps the CCD from becoming saturated.

Using a simple scattering experiment, the data shows that the imaging system is capable of detecting a minimum modulation depth on the order of 10^{-4}. Further studies will be pursued to determine the system's absolute detection ability, and improve detectability through post-processing. The phase sensitive imaging system will be used with background intensive and background free diagnostic techniques to acquire useful flow field information. Finally, the lessons learned and experiences gained through the development of this system will be applied to new detector designs intended to greatly improve detection limits and increase the obtainable signal to noise ratio.

Acknowledgments

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References

[1] R.K. Hanson, "Combustion Diagnostics: Planar Imaging Techniques", *Twenty-first Symposium (International) on Combustion / The Combustion Institute*, Pittsburgh, PA, pp. 1677-1691, 1986.

[2] G.J. Fiechtner and M.A. Linne, "Absolute Concentrations of Potassium by Picosecond Pump/Probe Absorption in Fluctuating, Atmospheric Flames", Combustion Science and Technology, Vol. 100, pp. 11-27, 1994.

[3] J.J. Mach and P.L. Varghese, "Velocity Measurements Using Filtered Rayleigh Scattering of Near-IR Diode Lasers", *36th AIAA Aerospace Sciences Meeting & Exhibit*, Reno, NV, AIAA-98-0510, 1998.

[4] T. Settersten, C. Fisher, N. Middleton, and M. Linne, (Colorado School of Mines); J. Gord (USAF, Research Laboratory, Wright-Patterson AFB); P. Paul and G. Fiechtner (Sandia National Labs., Livermore, CA), "Demodulating Camera System for Picosecond Pump/Probe Imaging", *35th AIAA Aerospace Sciences Meeting & Exhibit*, Reno, NV, AIAA-97-0158, 1997.

[5] M.A. Linne, D.C. Morse, J.L. Skilowitz, G.J. Fiechtner, and J.R. Gord, "Two-dimensional Pump/Probe Imaging in Reacting Flows", Opt. Lett., Vol. 20, No. 23, pp. 2414-2416, 1995.

[6] T.E. French, "The Development of Fluorescence Lifetime Imaging and An Application in Immunology", Ph.D. Thesis, University of Illinois at Urbana-Champaign, 1996.

[7] F.G. Stremler, "Introduction to Communication Systems", Third ed., Reading, MA: Addison-Wesley Publishing Company, Inc., 1990, Chapter 5.

[8] Personal Communication with Jim Paton, Design Engineer, Roper Scientific (Princeton Instruments, Inc.), 1998

[9] Personal Communication with A. Paterson, Product Operational Support Center, Business & Industrial Systems, Sony, Montvale, NJ, 1996

[10] M.C. Thurber, R.K. Hanson, "Simultaneous imaging of temperature and mole fraction using acetone planar laser-induced fluorescence", submitted for publication to *Experiments in Fluids*, 1999.

[11] American Dynamics Corporation, "Lock In The Devil, Feed Him To The Cat, Or Take Him For The Last Ride In A Boxcar?", Tek Talk, Vol. 6, No. 1.

Appendix

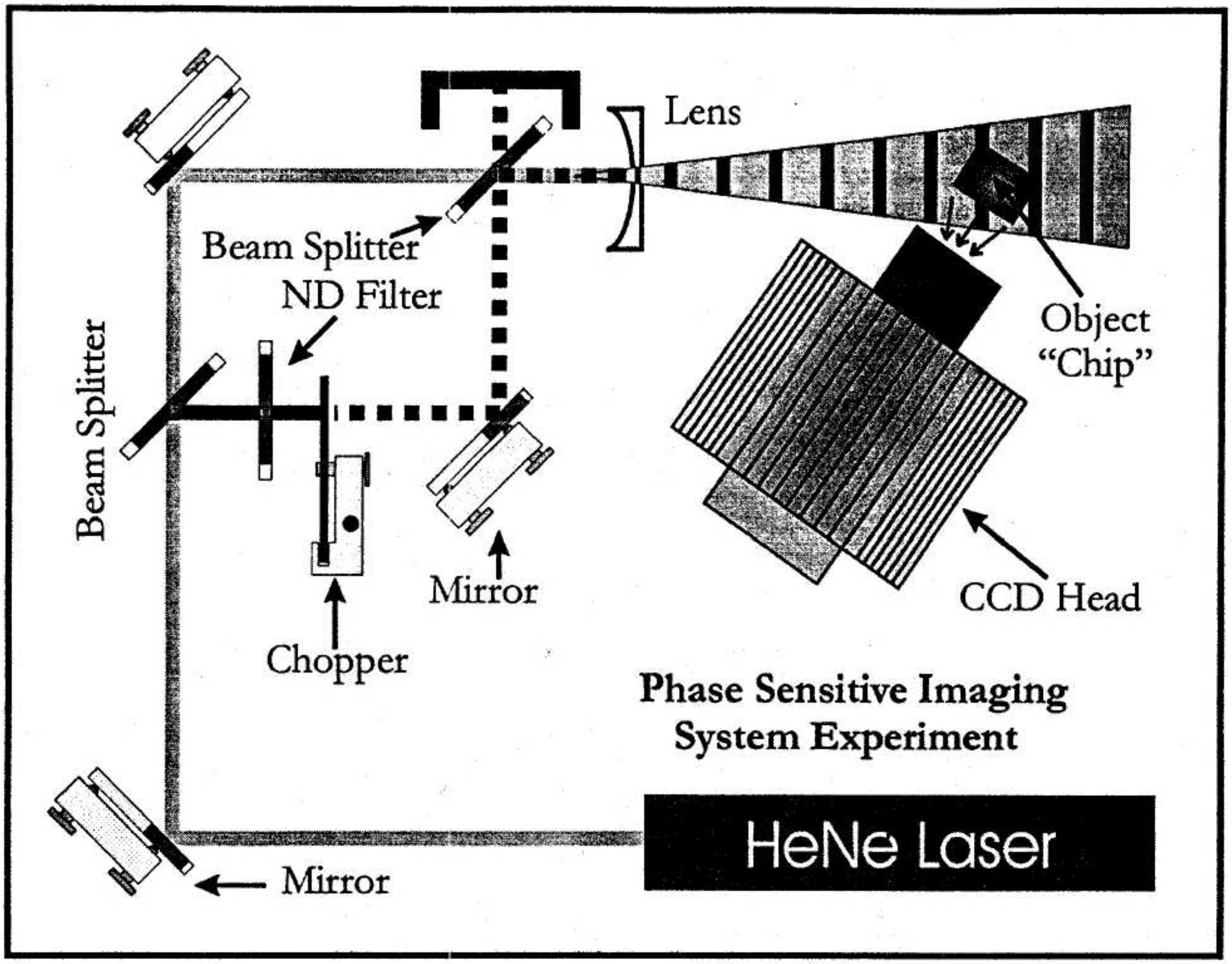

Fig. 15 Experiment Setup