

Parallel detection in laser ultrasonics

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Abstract. One of the ever present problems in laser ultrasonic techniques is the relatively poor signal to noise ratio, which means that in many cases the data acquisition rates are unacceptably slow or the necessary laser power can damage the sample. Here we present our approach to parallelising the detection process which can greatly speed up measurement times. We describe results using both a commercial detector array and custom arrays designed in house. The approach we have taken is generally applicable for a range of pump probe experiments and we give examples where applicable

1. Introduction

Laser ultrasonics is one of many pump probe techniques where optimising the signal to noise ratio (SNR) of the detected signal is of crucial importance. Since such techniques involve a pump (excitation) beam and a probe (detection) beam the SNR may be optimised in either. This paper concentrates on our recent attempts to improve the detection process by using many parallel channels, each of which performs in an analogous way to a photodiode and a lock-in amplifier.

In this paper we will discuss our improvements to a picosecond laser ultrasonic system. We believe the instrument to which we have applied our techniques serves well as a representative pump probe system where the detection problems are mirrored in a great range of modalities including photoreflectance microscopy [1], photoreflectance spectroscopy [2], measurements of carrier dynamics in semiconductors, photothermal detection of nanoparticles [3]. The detection methods we present are not restricted to pump probe measurements and can also be applied in other areas where lock-in amplifiers are traditionally used for synchronous phase detection such as surface plasmon sensing [4] and heterodyne interferometry [5]. This paper describes parallel synchronous detection both with commercial sensors and some very recent work with custom detectors.

1.1. Picosecond laser ultrasonic system

The system used for most of the experiments presented here is shown in figure 1. The pump beam generates the fast ultrasonic pulse, this then propagates through the sample. The stress wave associated with the pulse causes a *small* change in the optical properties which are detected with the probe beam. The probe beam is synchronous with the pump beam and therefore senses the ultrasonic signal at one

moment in time. The short duration of the probe beam confers the temporal resolution of the system since the electronic detection system is many orders of magnitude too slow to resolve the pulses temporally. This means that to recover a complete waveform it is necessary to scan the delay of the probe beam. This greatly slows the measurement time and means that such measurements are generally very slow. The changes in the reflectivity seen by the probe beam are extremely small, typically of the order of 10^{-5} or less, and for this reason it is necessary to modulate the pump beam with a chopper so that the signal change induced in the probe beam is detected at the chopping frequency. This is normally achieved with a photodiode and a lock-in amplifier, although we show an array detector in figure 1 to represent the essential changes that we present here.

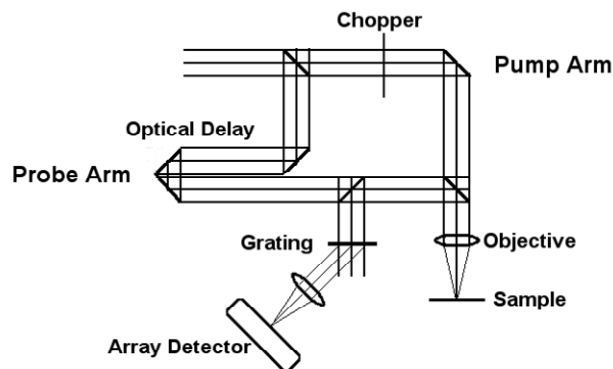


Figure 1. Schematic a picosecond laser ultrasonic system with array detector.

1.2 The measurement problem.

Section 1.1 described the measurement problem associated with a picosecond laser ultrasonic system. In fact this represents a generic problem. A modulated pump beam imposes a periodic change in the probe beam, however, the magnitude of this change is extremely small, the challenge is therefore to extract a small periodic variation imposed on a large constant background, as indicated above. These changes can be typically between 4 to 6 orders of magnitude smaller than the constant background. This poses a fundamental measurement requirement that is an essential theme in all our measurements involving the particulate nature of light detection. The shot noise limit dictates that in order to obtain a signal to noise of \sqrt{N} it is necessary to collect N photons, so to measure a change in reflectivity of, say, 10^{-5} with unity SNR, it is necessary to detect at least 10^{10} photons.

2. Detection with arrays

Our early work to produce lock in amplifiers in parallel attempted to make continuous time cameras, which operated in a manner somewhat analogous to a conventional lock in amplifier [4]. Although this approach worked well, the ultimate noise performance was somewhat limited, which is hardly surprising when one considers that the amount of silicon dedicated to each photodiode/lock in is only a few thousand square microns. For this reason the approach we have adopted is more akin to that used in phase stepping interferometry.

The principle of integrating detection is shown in figure 2. The signal is integrated for a portion of a cycle, and the application of a standard phase stepping algorithm allows one to extract the amplitude and phase of the modulated signal. In most cases we are interested in the amplitude of the time varying signal rather than its phase. For a four phase algorithm this is given by the well-known

$$\text{AC component} = \sqrt{(I_1 - I_3)^2 + (I_2 - I_4)^2} .$$

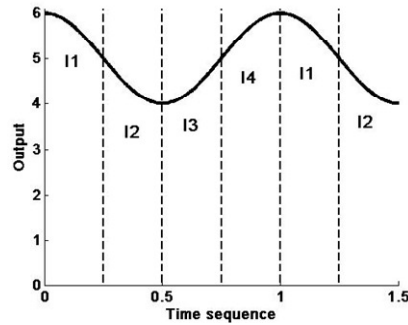


Figure 2 Phase stepping explanation

2.1 Detection with a commercial array

The lock in detection process can be performed with a conventional CCD camera. The problem here lies in the fact that the typical well depth of these cameras is of the order of 30000 electrons which means that even if several pixels are averaged the minimum detectable modulation depth is rather limited unless an impractical amount of temporal averaging is used. Few commercial detectors meet the specification for deep well capacities, however, we have used one such detector for our applications. This is a linear array of 512 pixels (HamamatsuS3924-512Q,F). Each pixel has a saturation charge of 50 pC which allows up to 3.12×10^8 photons to be stored. This large well depth gives the potential to detect very small modulations. The maximum read-out speed per pixel is 500 kHz: this gives a theoretical maximum frame rate of approximately 1kHz. This camera can be employed as an integrating pixel array to recover the AC modulation with modulation depths close to 10^{-6} . We have applied this camera to both laser ultrasonics [6] and parallel photothermal spectroscopy [7]. For the latter application it is necessary to use a probe beam with very short wavelengths (down to c. 350nm), so that commercial camera with back thinning have crucial advantages. For this application a speed up of at least two orders of magnitude compared to a serial measurement has been achieved. For most other applications, however, where the probe beam has longer wavelengths the commercial array has several disadvantages which have been overcome with our custom arrays. These are itemized below:

- The commercial camera has a rolling shutter which means that each pixel is read at a different time with different phase. The effect of this is that the simple four phase algorithm above gives pixel dependent amplitude phase crosstalk. To overcome this it was necessary to use a 7 step algorithm which meant the maximum modulation frequency was restricted to around 140Hz which greatly restricted the total rate at which photons can be absorbed thus limiting the SNR for a given measurement time.
- Using a global shutter, as we did in our custom detectors, rather than a rolling shutter, means it is not necessary to read all the pixels so that only those where the signal is of interest need to be addressed.
- The commercial camera requires some custom electronics to make best use of the signals which mean, at least for our applications, it was ultimately no more 'off the shelf' than the custom detectors discussed below.

2.2 Custom detector arrays.

The custom chips developed are based on the well known active pixel sensor architecture which is used in many consumer applications and, as the quality improves, is becoming more prevalent in the scientific market. The standard active pixel sensor is charged to V_{dd} by the closing the reset. This switch is then opened to begin the exposure. When illuminated the voltage across the diode will decrease in proportion to the total amount of light falling on the detector in the exposure time. In a standard active pixel sensor the capacitance is simply that associated with the junction of DI . In our designs a discrete capacitor, C , is added so that the amount of charge stored is greatly increased (see figure 3). This means that the sensitivity in terms of volts per photon (the conversion gain) is rather poor, however, the SNR is excellent when the wells are filled because the signal to shot noise ratio is greatly improved. This is analogous to fast photographic film which is grainy (noisy) compared to slower film which gives much less granular noise but requires brighter illumination.

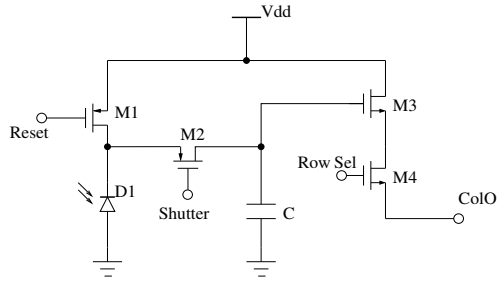


Figure 3 Schematic diagram of 'enhanced' active pixel sensor.

Using this concept we have designed both linear as well as 2D arrays. Figure 4 shows a single pixel from a 2D array and figure 5 shows the linear array we have used in the most recent laser ultrasound experiments reported in section 3. Figure 4 shows the essential concept behind the pixel, where each photodiode is connected to 4 capacitors via an independently controllable shutter switch. This allows the photodiode to be connected to different capacitors for each quarter of a cycle, so that the 4 phase steps may be acquired in a single cycle of the modulation, thus removing the problems of the rolling shutter encountered in the commercial detector. Presently 64 by 64 pixel cameras have been fabricated and tested and a 256 by 256 camera is being fabricated. Figure 5 shows the linear chip which gives performance similar to that of many lock in amplifiers and photodetectors in parallel for the picosecond laser ultrasound applications. There are 64 photodiodes arranged in a line and the 4 storage capacitors associated with each pixel are marked on the diagram. The advantage of the linear array is the large amount of space available for each capacitor. The electronic storage available on each capacitor is approximately 6.7×10^8 electrons. Another crucial feature is the speed with which the chip may be addressed: the maximum pixel read rate is 40MHz meaning that 256 chip (not shown) may be read out, in principle, at a rate of more than 37,000 frames a second, this accounts for the fact that four channels per frame need to be addressed. In this case the limitation is often that the available optical power needs to be of order one mW to fill the wells.

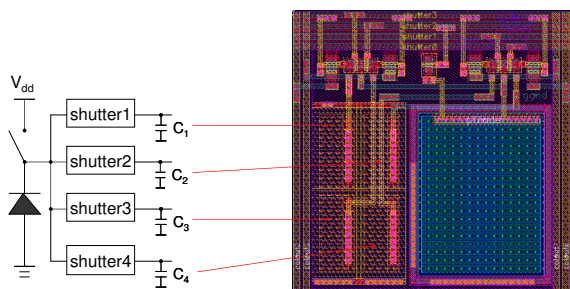


Figure 4 Diagram of lock in pixel

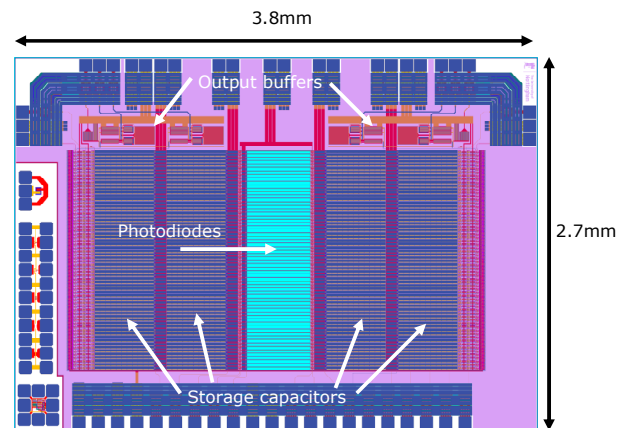


Figure 5 Schematic of linear array with large storage capacitors.

2.3 Noise performance of the array detectors

The noise performance of the detector arrays is of course crucial. The results of noise tests on the commercial and custom linear arrays are presented in figure 6. The blue and the red lines show the theoretical photon noise associated with the custom camera and the commercial chip respectively as a

function of the number of frame averages. The larger well capacity of our custom chip is offset by the fact that more averages are used with the commercial chip. Moreover, no allowance is made for the fact that the custom chip can be addressed more quickly allowing many more averages to be made in a similar time. The cyan curve shows the experimental results for readout noise obtained with the Hamamatsu chip and our custom electronics. We see the performance is approximately 1.8 times worse than the shot noise limit and averaging will allow one to measure $\Delta R/R$ values down to approximately 10^{-6} , further averaging does not improve the SNR greatly presumably because coherent noise sources start to dominate the random noise. The readout noise (green curve) associated with custom chip is far smaller than the photon noise limit indicating that shot noise limited performance is achievable with this chip. Again we note that even with the custom chip successive averaging eventually fails to improve the SNR, however, in this case this occurs at much lower modulation depths (around 2×10^{-7}).

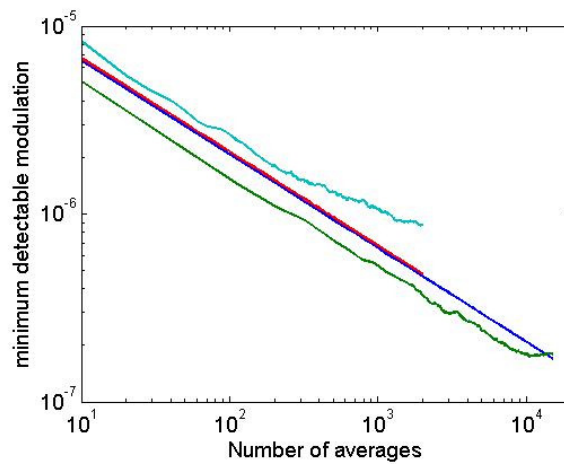


Figure 6 Noise comparison versus number of averages. Cyan dark noise of commercial chip, red theoretical photon noise commercial chip, blue theoretical photon noise custom chip, green measured dark noise custom chip.

3. Experimental results with picosecond ultrasonics

The ability to perform measurements in parallel greatly improves the measurement speed. We have demonstrated this with two different experiments involving imaging (multiplexing spatial position) and spectroscopy (multiplexing probe wavelength) respectively. In the latter case Brillouin oscillation measurements [6] can be separated spectrally and measured in parallel. Here we will present only the results for spatial multiplexing. The sample used in the experiments is shown schematically in figure 7. A pump beam produces a short ultrasonic pulse which is reflected from at the chromium/silicon interface returning to the surface, where the stress induced by the sound induces a small change in reflectivity. The time of arrival of the induced ultrasonic waves is measured by varying the delay as



Figure 7 Schematic of sample showing stepped chromium layer, thin region c . 50nm, thick region c . 70nm.

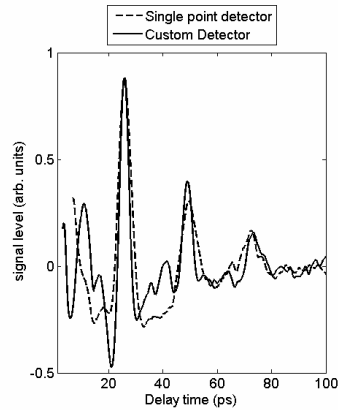


Figure 8 Echoes from single pixel on custom detector and single point detector showing comparable SNR.

shown in figure 1. In order to perform the parallel measurement a weak cylindrical lens was inserted into the optical path, to spread the pump and probe beams into a line whose width was less than 2 microns and whose length was approximately 60 microns. Reimaging the probe beam onto the detector allowed many spatial positions to be measured simultaneously. Figure 8 compares a trace measured from a single pixel of the custom detector to one using a conventional lock in photodiode with similar measurement time. The SNRs in each case were comparable. The measurement time obtained with the chip is approximately 30 times less than would be achieved by scanning a single point and with a point detector. The speed up is less than the number of pixels due to the fact that the light distribution is not even so that the SNR on the outer pixels is not optimum. In future work we will overcome this problem as discussed in the summary. Figure 9 shows a two dimensional scan of the chromium thickness obtained by measuring the arrival times of the first acoustic echo reflected at the interface between the chromium layer and the silicon (similar images were obtained using the time difference between the first and second echoes).

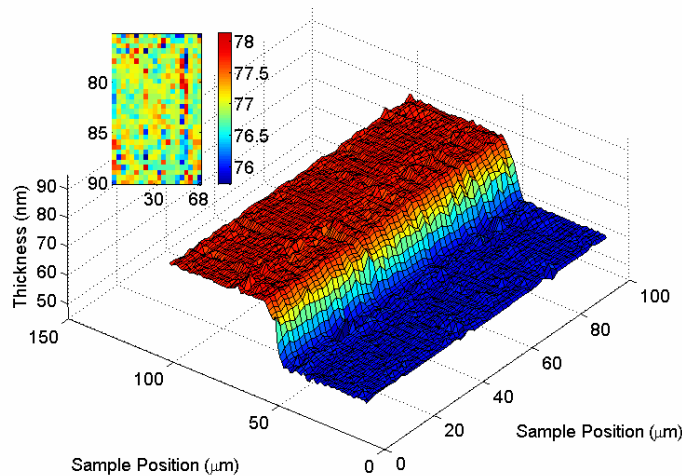


Figure 9 Two dimensional thickness scan obtained with custom linear detector. The image was obtained approximately 30 times faster than a corresponding image with a point detector.

4 Summary and conclusions

We have demonstrated that by using linear detector arrays with a deep well capacity it is possible to get performance equivalent to several lock in amplifiers in parallel. This has been applied to photothermal spectroscopy using a commercial camera. Superior performance both in terms of signal to noise ratio and data acquisition speed has been obtained with a custom detector with four local storage capacitors to integrate the signal over different parts of the cycle. Further developments are underway to improve the custom chips still further, by allowing the gain on each pixel to be varied externally thus allowing one to cope with different light levels in different parts of the image (or spectrum). More sophisticated on chip processing is also under development to reduce the cost and complexity of the A/D converters used read the output from the chips. The techniques are presently being exploited in new imaging applications for both engineering and biological samples.

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