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# Parallel detection in picosecond ultrasonics with both commercial and custom array detection

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**Abstract**
Picosecond laser ultrasonics is a well established technique for measurement and diagnosis of micro- and nano-scale structures. One of the major drawbacks preventing widespread acceptance of this technique is that the data acquisitions speeds are slow making imaging applications impractical. We are engaged in a research program to accelerate the data capture rate by use of parallel detection methods. This involves both optical and electronic developments. We have investigated the use of commercial and custom built integrating linear array detectors, which combined with suitable algorithms for signal reconstruction can attain comparable performance to a typical photodetector and lock-in amplifier combination. Modulation depths below 1 part in $10^6$, over 512 pixels can be readily detected with the commercial detector and smaller modulation depths are possible with the custom detector on account of the larger well depth and hence higher signal to noise ratio. Results demonstrating an order of magnitude increase in data acquisition speed will be presented.
**Keywords:** Picosecond ultrasound, Parallel Detection, Custom Linear Array, Phase stepping,

## 1. Introduction

Recovering a weakly modulated signal on a large background is a common problem in optical measurements. The situation arises in most pump/probe experiments where there is a tiny change in the probe beam induced by the modulated pump beam. Examples include: photoreflectance [1], photothermal techniques [2] and laser ultrasonics [3]. These measurements are typically performed with a point detector and usually employ a modulator, a photo detector and a lock in amplifier. The modulator is often a mechanical chopper or an acousto-optical modulator and is used to impose the modulation frequency on the pump beam. The signal from the photodiode is connected to the input of the lock in amplifier with the reference frequency provided by the modulator. This forms an extremely sensitive detection system [4]. However, these measurements are generally quite slow; an exciting and important challenge is to perform many such measurements in parallel making hitherto impractical experiments possible. The method employed here uses a commercial array detector, some custom interface electronics and a suitable phase stepping algorithm to suppress the odd harmonics inherent to square wave modulation. We will also discuss a custom design detector that has been fabricated that overcomes most of the limitations of the commercial detector.

In our case we require parallel detection to speed up the experiment time and reduce the impact of environmental drift. The results presented here show parallel detection of several hundred channels of laser generated GHz ultrasound; in this paper we will describe the detection issues necessary to achieve these measurements. Measuring these small signals in parallel places certain requirements on the detection approach adopted. For example, the approach needs to be scalable up to a large number of channels and have realistic demands on any analogue to digital converter (ADC) employed. Coherent noise should be sufficiently reduced to reach the required SNR and the detector should capture sufficient photons for the required dynamic range. The ability to measure amplitude and phase as well as work correctly with squarewave modulation is also important for this application.

## 2. Parallel Detection

Due to the single point data acquisition and the number of averages that are usually required for each probe position or wavelength used, experiments can take a very long time to perform. Providing a way to perform many measurements in parallel would have a dramatic impact on the experiment time and range of experiments that could be performed. However, moving to parallel detection presents many challenges due to the impracticality of using multiple photodiode and lock-in amplifiers. We have tackled this problem by initially using a commercial detector in combination with a suitable algorithm. This paper describes the choice of algorithm and hardware required to perform lock-in detection to measure very small modulation depth signals on many channels simultaneously.

## 3. Our Approach

We have parallelised the detection by employing an integrating linear array detector, which combined with a suitable algorithm can perform the task of parallel lock-in detection. A carefully chosen phase stepping algorithm is used to demodulate the signal of interest.

### *3.1 Phase Stepping*

Phase stepping [5] is a well established technique which is used to recover the amplitude and phase of a modulated signal. The signal of interest is sampled N time or integrated over N periods during one cycle of the sinusoidal modulation frequency. Using the 4 samples the amplitude and phase can be reconstructed without error. If as is often the case the modulation is not sinusoidal but is square in nature then the amplitude and phase recovered become sensitive to the harmonics of the modulation frequency and errors are introduced. To overcome these errors the number of phase steps used needs to be chosen carefully. It is easy to generalise the phase stepping algorithms to $N$ equal steps as described in Equations 1-5.

$$\Delta\alpha = \frac{2\pi}{N} \quad \textbf{(1)}$$

$$S_1 = \sum_{m=0}^{N-1} I_m \cos\alpha_m \quad \textbf{(2)}$$

$$S_2 = \sum_{m=0}^{N-1} I_m \sin\alpha_m \quad \textbf{(3)}$$

$$Amplitude = \sqrt{S_1^{\,2} + S_2^{\,2}} \quad \textbf{(4)}$$

$$Phase = \tan^{-1}\left(\frac{S_2}{S_1}\right) \quad \textbf{(5)}$$

Where $\Delta\alpha$ =Phase step increment, $I_m$ = measured signal for step $m$, $\alpha_m$ = phase step angle for the $m^{\text{th}}$ step.

If the phase of the signal is fixed then the error introduced by the amplitude-phase crosstalk is fixed. However if the phase of the signal is varying then the errors also change and by a significant amount when the number of steps is small.

Figure 1 shows how the recovered amplitude and phase vary with the phase of the signal for squarewave modulation as the number of steps is varied. It is clear that the even stepped algorithms are particularly sensitive to the odd harmonics present in the square wave modulation while the odd stepped algorithms are affected to a much lesser degree.

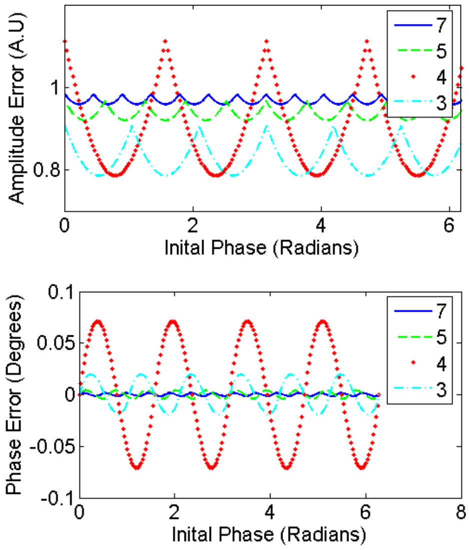


**Fig.1 Amplitude and phase cross talk as phase of signal changes**

We have adopted a 7 step algorithm as the error levels are acceptable for our application.

### *3.2 The Choice of Detector*

The Detector used is the S3924-512Q,F by Hamamatsu. It is a 512 pixel linear array camera. Each pixel has a saturation charge of 50pC corresponding to a photon capturing ability of $3.125 \times 10^8$ photons before saturation. The detector employs a rolling shutter so that the data can be output in serial; while a pixel is being readout the others are integrating the signal. The pixels are read out at 500 KHz which gives a maximum frame rate (including dead time) of 969Hz. This obviously introduces a compromise between the overall data acquisition rate and the number of steps used, as the chopping frequency equals the maximum frame rate/N (969/N Hz). The mechanical chopper needs to be synchronised with the detector and for this reason a custom clock generator board was built to provide all of the clocks to the detector and also generate the required chopper sync signal.

The specifications of the detector set the demands for the ADC card used to capture the data. The ADC needs to be at least 15 bits and have a 500 KHz sample rate. The ADC chosen was the NI-6281 which is an 18bit ADC and has a single channel operation of 625K samples per second. We also utilise a custom built sample and hold circuit to hold the sample voltage high for the entire sample period as this reduces the requirements on the ADC card.

In summary, we employ a 512 pixel integrating linear array detector used in conjunction with an 18 bit ADC card and custom sample and hold circuit. The mechanical chopper is synchronised by the custom clock generator control board. The signals recorded by the ADC card are demodulated by a 7 step phase stepping algorithm to reduce the impact of the amplitude and phase cross talk introduced by the detectors rolling shutter and the squarewave modulation of the mechanical chopper.

## 4. Results

An experiment was performed to demonstrate the ability of the detector scheme. The system setup is shown in figure 2. Output from the laser (spectra physics tsunami - 100fs pulse width 80MHz repetition rate, wavelength 780nm) is split into the pump and probe beam by the first beam splitter, the pump beam is modulated by a mechanical chopper and focused onto the sample. The probe pulse travels through the optical delay line and is focused to the same position on the sample as the pump beam. The reflected probe beam is passed through a diffraction grating and lens to spread the wavelengths present in the probe beam across the array detector. Each pixel of the array will record the signal for a different probe wavelength. The sample chosen was a GaAs 111 substrate due to the semi-transparent nature of GaAs at the wavelengths used (780+/-10nm). The sample acts as an interferometer with the front surface reflection and the reflection from the travelling acoustic wave interfering to produce an oscillatory signal. The frequency $(f_b)$ of these so called Brillouin oscillations[6] are dependant on the real part of the refractive index $(n)$ of the material, the acoustic velocity$(v_a)$ and the wavelength$(\lambda.)$ of the probe beam, such that $f_b=2v_an/\lambda$. The oscillation recorded on each pixel of the array will correspond to the acoustic frequency which reflected the probe beam. Figure 3 shows the data obtained from a single pixel of the array detector after 400 averages. The signal comprises of three components, a large step change at t=0 as the pump power is absorbed (dR/R $0.7\text{x}10^{-3}$) a slow thermal relaxation of the sample and superimposed on this is the oscillatory signal of interest (dR/R $5\text{x}10^{-5}$). Figure 4 shows the data obtained across the array. The top figure shows the oscillations after the co incidence peak and the thermal back ground have been removed. The bottom figure shows the frequency of the oscillation for each pixel.

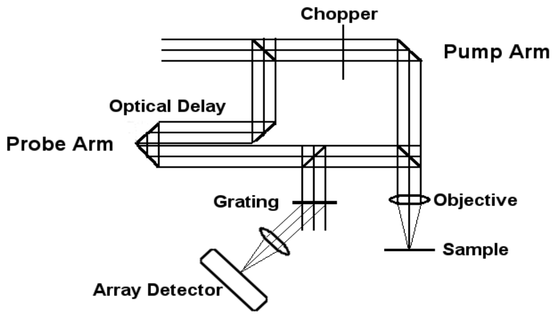


**Fig.2 System schematic**

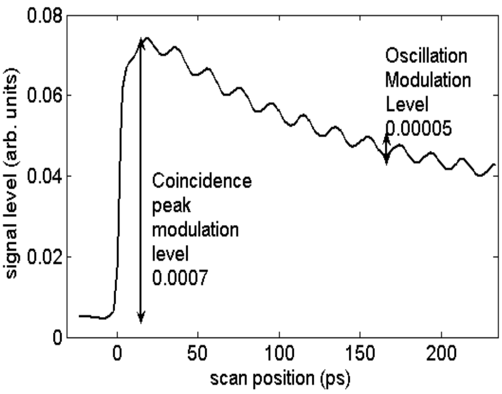


**Fig.3 signal obtained for a single pixel of the array detector**

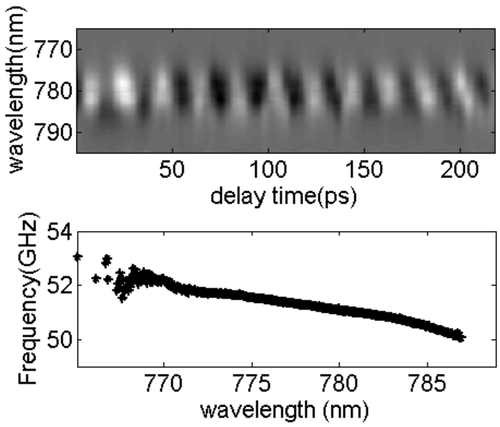


**Fig.4 signal recorded across the array (top) and frequency of the oscillations (bottom)**

The frequencies measured agree with the values expected using the published values of the acoustic velocity and refractive index [7]. The experiment used 400 averages and the data took approximately 22 minutes to acquire all 512 channels from the array. The single photodiode & lock-in amplifier setup we have would have taken 3 ½ hours to produce 512 wavelength scans with comparable SNR. This makes the array approximately **10** times faster. Additionally the data obtained by the array is more robust as all of the channels see the same experimental environment all are affected equally. Whereas in the single channel case any variations in the operating environment during the 3 ½ hour experiment would effect each channel differently.

The performance of the detector scheme with respect to the theoretical shot noise level has been considered. We calculated the dR/R due to shot noise for each average based on the number of photons captured and compared it to the actual measurement. The actual measurement does decrease with a sqrt(averages) relationship as we would expect but is a factor of 1.7 times worse than the shot noise limit. Most of this difference (a factor of 1.46) is due to read out and other electronic noise sources. After 1000 averages had been taken the modulation depth measured was $10^{-6}$ of the measured DC light level. More details can be found in reference [8].

It is also worth pointing out that the array detector reached this level of performance while only using a fraction of the light used in the single channel detector case.

## 5. Custom Detector

The limited amount of light that the commercial detector can capture before saturating and the low chopping frequency prompted us to create a custom detector. This detector was designed to overcome several of the limitations of the commercial detector and increase the total photon capturing ability of the detector by an order of magnitude. The detector is a 64x1 linear array. It was fabricated on the AMSC35B4 process which is a 0.35 micron 2 poly 4 metal process. The active array is 460 x 22 microns; this is considerably smaller than the commercial detector at 2500 x 50 microns.

The custom detector has the following improvements:

- Uses a global shutter so the phase for each pixel is the same
- Random addressability allows pixels of lower incident light level to be acquired more often to improve the SNR
- Can capture approx. $4 \times 0.83 \times 10^9$ photons per pixel before saturating, which is 10 times more than the commercial device
- Data throughput is much faster with a sample rate of up to 10MHz, maximum chopping frequency is therefore 40KHz (~280x higher than commercial detector)

The camera is built on the active pixel sensor principle. In this type of pixel, the inherent capacitance of the photodiode is charged up to the supply voltage during the reset phase and then allowed to discharge due to the photocurrent during the integration phase. The final voltage across the photodiode will be an indication of the light which struck the detector during the integration period. Each pixel in the detector also contains four large capacitors which can be independently connected to the photodiode. These capacitors provide an increased well depth which helps to reduce the influence of shot noise and also mean that the pixels can cope with higher light intensities before saturating. The detector has a four phase mode of operation; these are reset, integration, idle and readout. Each of the four capacitors in the pixels follow this operation so that only one of the capacitors in a pixel is in a given phase at once. The four phase design allows for long integration periods accompanied with continuous readout of the photodiode outputs. This custom detector (figure 5) should allow much smaller modulations depths to be measured and reduce experiment times still further.

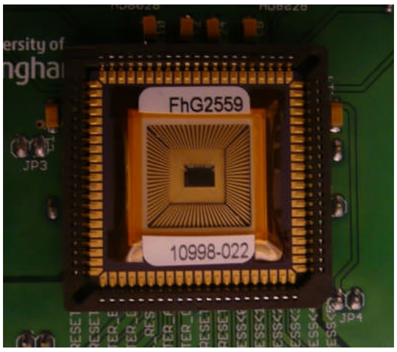

Fig.5 The custom linear array detector

## 6. Conclusions

We have presented a method to perform parallel detection of several hundred channels of GHz ultrasound. This technique employs an integrating detector and a suitable phase stepping algorithm. The performance is comparable to that of a photodiode and lock-in combination. The parallel approach is more resilient in the presence if environmental drift and experiment time is reduced by a factor of 10 compare to the single channel approach. The custom detector which has been fabricated to increase performance still further has been introduced.

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