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ADVANTAGES AND LIMITATIONS OF THE TWO PICOSECOND ULTRASONICS SETUPS: THE HOMODYNE AND THE HETERODYNE SETUPS

1. INTRODUCTION

The product line JAX designed by Neta is based on picosecond ultrasonics with a heterodyne setup to inspect thin films. The main difference of this setup compared to the historical homodyne setup is the electronic delay management between the two pulses [1] instead of a mechanical delay line, which offers new possibilities in terms of performance.

Historically, acoustic waves were first generated with piezoelectric materials [2]. To increase the spatial resolution of these waves, it is necessary to increase their frequency. Whereas the frequency of the acoustic waves generated by piezoelectric transducers is still limited to a few hundreds of MHz [3], this frequency can extend up to several hundreds of GHz for acoustic waves generated by femtosecond lasers [4]. Consequently, the sample thickness can be typically evaluated from a few microns to several millimeters with high-frequency transducers. Considering ultrafast laser properties, picosecond ultrasonics is able to evaluate the sample thickness from a few nanometers to several microns.

After a description of the two picosecond ultrasonics setups, we will go into more details regarding the practical settings that must be optimized for these two setups. Finally, thanks to a comparison between the results obtained with a typical sample, this paper will highlight the advantages and limitations of these setups.

2. CONTEXT

There is a constant need in exploring materials at nanoscale, both in the industry and in the research laboratories (for the semiconductor industry, the display industry, thin film characterization, nanotechnology and nanoscience…). This implies ever more accurate ways of characterization. Some testing and evaluation methods exist, but a part of them have the main drawback to be destructive methods or to be very slow, such as X-ray diffraction, FIB or the Calotester method.
This paper presents how picosecond ultrasonics can fulfill the requirements imposed by the new characterization needs, and a comparison of the characteristics of the two picosecond ultrasonics setups: the homodyne setup and the heterodyne setup.

3. OPTICAL SETUPS

3.1 The homodyne setup

A typical homodyne setup, such as the one we used to perform the measurements presented in this paper, is represented in Figure 1.

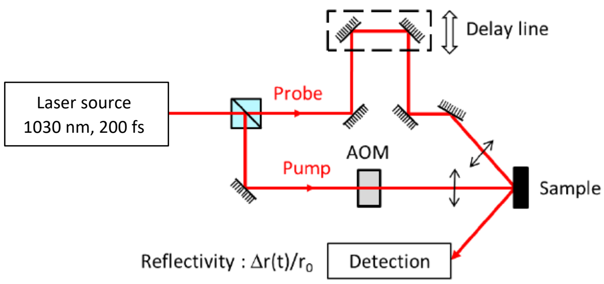

Figure 1. Homodyne setup principle. AOM: acousto-optic modulator

The homodyne setup is based on a single laser (in our setup a 1 030 nm 200 fs in duration femtosecond laser Goji from Amplitude Laser) that is split into two secondary beams, one of them being delayed compared to the other thanks to a mechanical delay line (in our setup a motorized translation stage FMS300PP from Newport Corporation). Thanks to this delay line, the response of the sample to the pump beam is scanned by the probe beam with a time delay that is proportional to the position of the delay line.
In order to significantly improve the signal to noise ratio, a lock-in detection is necessary. Therefore, an acousto-optic modulator (in our setup the model MT80-A1-1064 from A&A Opto-electronic) is inserted on the pump beam path to modulate its power. The modulation signal and

the detection signal are two inputs of a lock-in amplifier (in our setup the model MFLI 5 MHz from Zurich Instruments) that will extract a low-noise information.
Regarding the detection, three kinds of measurement can be performed: reflectivity [4], deflectometry [5] or interferometry [6]. As far as we are concerned, we will focus on the reflectivity measurement.
As the pump beam and the probe beam have the same wavelength, two main solutions exist to avoid the pump beam to disturb the measurement. Either they are colinear (usually normal) to the sample but cross polarized, this implies that the sample must not affect the polarization of the beams; or the two beams are not colinear (as represented in Figure 1), but that implies that the sample must not significantly scatter the light.

3.2 The heterodyne setup

The results presented in this paper have been obtained with an asynchronous optical sampling-based system (ASOPS system) whose principle of measurement is illustrated in Figure 2.

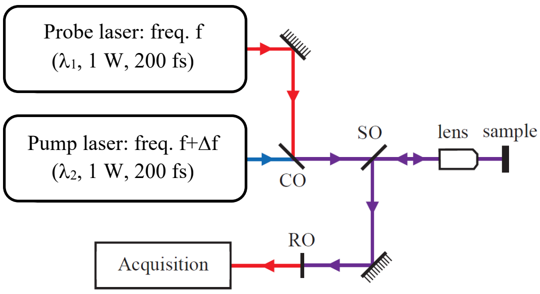

Figure 2. Heterodyne setup principle. CO: combining optics; SO: sampling optics; RO: rejection optics

Where the delay between the pump beam and the probe beam is managed by a translation stage with the homodyne setup, an ASOPS system embeds two lasers whose delay is electronically managed). Here, the repetition rate of the pump laser is enslaved to the repetition rate of the probe laser with a slight difference Δf.
Thanks to this electronic delay management between the two lasers instead of a mechanical delay line, considering the same signal to noise ratio and the same time span, we will see on this paper how measurements with a heterodyne setup are much faster than the same kinds of measurement with a homodyne setup [7]. Typically, it usually takes less than one second to get an exploitable signal.

Another advantage of the heterodyne setup regards the two wavelengths of the laser, hence facilitating the distinction between the two lasers. As illustrated on Figure 2, a simple rejection optics allows to detect only the radiation from the probe beam, even if the sample affects the beams polarization or if it scatters the beams.

Please also note that the system does not need a severe level of vibration control or clean room to operate. Particularly, measurements can be performed in a workshop environment.

4. PRACTICAL APPLICATIONS

4.1 Homodyne setup settings

As mentioned above, the homodyne setup settings are more numerous than the heterodyne settings, especially because of the use of a lock-in detection.
The main parameters of this setup are:

- Number of acquisition points
- Number of averagings
- Lock-in time constant
- Lock-in filter order
- MAO modulation frequency
- MAO modulation type
- MAO modulation amplitude

The number of acquisition points directly impacts the total acquisition time as the translation stage must control that it has moved to the right position before the beginning of the next measurement. In our case, an average time of 0.5 s was necessary to fulfill the translation stage requirements.

The number of averagings also impacts the total acquisition time, depending on the sampling rate of the acquisition card. It is obviously useful to choose the maximum sampling rate available, in our case 25 MHz. This allowed us to increase the number of averagings up to 10 MSamples with only 0.4 s acquisition time for one measurement point.

The lock-in amplifier has two options to set up: the time constant, which is similar to the time constant of an RC filter for the input signal, and the filter order that corresponds to the number of cascaded RC filters.

Finally, three parameters must be set for the modulation signal of the AOM: its frequency, its type and its amplitude.

A preliminary study has been performed to evaluate the best setting for each of these parameters. The results are shown on
Table 1, highlighting in green font the parameters giving the best signal to noise ratio (SNR).

Number of averagings	1 000	10 000	1 000 000	10 000 000
Time constant (ms)	1	10	100	
Filter order	3	5	8	
Mod. frequency (kHz)	100	300	500	1000
Mod. type	square	sine	triangle	
Mod. amplitude (V)	0 - 1	0 - 3	1 - 4	0 - 5

Table 1. Study on the parameters of the homodyne setup. In green, the parameters giving the best SNR

Some results were predictable (the higher the number of averagings and the higher the amplitude of the modulation signal, the better the SNR). Regarding the other parameters, some are unexpected (low time constant and low filter order) but the settings in Table 1 will be considered later in order to get the best SNR.

4.2 Heterodyne setup settings

The settings for the heterodyne setup are:

- Number of acquisition points N_{acq}
- Number of averagings N_{av}
- Sample rate f_s
- Δf

The number of acquisition points N_{acq} and the sample rate f_s give the maximum time of the measurement t_{max}:

$$t_{max} = \frac{N_{acq}}{f_s} \quad (1)$$

The acquisition time t_{acq} only depends on the number of averagings N_{av} and the difference in repetition rate between the two lasers Δf:

$$t_{acq} = \frac{N_{av}}{\Delta f} \quad (2)$$

In order to optimize the jitter of the lasers, a preliminary study proved that the best setting for Δf was 500 Hz [8]. As a few hundreds of averagings are sufficient to get a good signal to noise ratio, this gives a typical acquisition time of less than one second.

4.3 Measurement on a typical sample

Let us now compare the signal measured with the two picosecond ultrasonics setups. A typical measurement is represented in Figure 3.

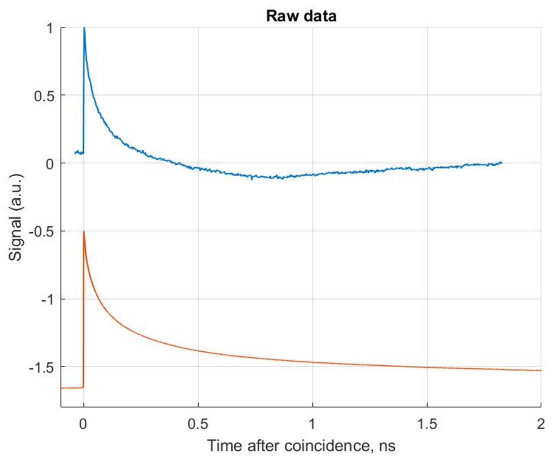

Figure 3. Typical measurement obtained with the homodyne setup (top) and with the heterodyne setup (bottom)

4.3.1 Setup time

For the two setups, time is needed to get the best measurement parameters, especially to optimize the distance between the lens and the sample.

With the homodyne setup, a first measurement with a long travel distance (hence a large time span) is necessary to notice the position of the translation stage corresponding to the coincidence, i.e. equal optical paths for the pump beam and the probe beam. Next experiments only need to scan the position near the noticed position to set the best experimental parameters. Typically, scanning 10 positions before and 10 positions after the noticed position with 0.1 mm step (corresponding to 1.33 ps time step) is a good compromise to efficiently visualize the coincidence in a minimized time. Nevertheless, considering typically 0.5 s for one measurement point, this takes for each scan around 10 s and optimization is only performed on the shape of the coincidence.

With the heterodyne setup, the acquisition time only depends on the number of averagings and Δf (see formula 2). With typical settings ($N_{av} = \Delta f = 500$), optimization is performed each second with the whole signal.

4.3.2 Noise

For the two setups, the noise must be considered with measurement points before the coincidence (before the time t = 0 ns in Figure 3). Then, there is no expected variation at all for the homodyne setup and we consider that the previous signal is highly attenuated for the heterodyne setup.

Let us consider the standard deviation amplitude of measurement points before the coincidence for the two setups. In order to take into account all the differences between the two setups, especially the electronics sensitivity, the meaningful data is the relative standard deviation (the absolute standard deviation divided by the amplitude of the coincidence). Please refer to Table 2 that mentions the results obtained with a ps resolution and 2 ns total signal duration for the homodyne setup, and N_{av} = 1 000 (hence 2 s acquisition time) for the heterodyne setup.

Setup	Homodyne	Heterodyne
Rel. Std dev. noise (%)	0.850	0.035

Table 2. Relative standard deviation compared with the amplitude of the coincidence for the homodyne setup and the heterodyne setup

4.3.3 Acquisition time

As mentioned on paragraph 4.1, the total acquisition time for the homodyne setup is proportional to the number of measurement points. A typical heterodyne measurement has the following characteristics: 4 ns in time duration with 0.5 ps resolution. That means a typical acquisition time of 4 000 s for the homodyne setup (more than 60 min).

Regarding the heterodyne setup, the total acquisition time is given by formula (2). For Δf = 500 Hz, compared to the homodyne setup, similar time span and resolution and a better signal to noise ratio (see 4.3.2) are then performed in typically 2 s for N_{av} = 1 000.

Hence, the heterodyne setup gives better measurements than the homodyne setup in 2 000 times less time.

The results represented in Figure 3 have been obtained with the mentioned settings.

4.3.4 Overall dimensions

Excepting the laser sources, the overall dimensions of the homodyne setup are necessarily higher than the ones of the heterodyne setup.

With 4 round trips of the light on the delay line and a maximum time span of 4 ns, that implies a 300 mm translation stage. Its dimensions dramatically impact the dimensions of the whole setup.

For information, our heterodyne setup that includes top-top and top-bottom measurements with two different wavelengths (hence 4 optical paths) is included in a housing ca. 400 x 500 x 660 mm^3 (400 x 800 x 660 mm^3 with the sample holder).

4.3.5 Effect of the delay line

With the homodyne setup, long time delays mean a high difference in optical path between pump and probe beams. For instance, 4 ns in time delay means 1.2 m in optical path difference. To avoid misalignment effects, retroreflector prisms are mounted on the delay line. Nevertheless, the natural divergence of the probe beam affects the dimension of the beam on the sample, hence the power density on the sample and the focus on the detector. Therefore, the thermal decay of the signal is not perfectly exponential.

On the contrary, with the heterodyne setup, the beams always take the same optical path. Therefore, as scheduled theoretically, the thermal decay of the signal is purely exponential (see Figure 3).

5. CONCLUSION

Homodyne and heterodyne setups give close results. Nevertheless, thanks to the electronic delay and compactness of the system, the heterodyne setup gives less noisy measurements (ca. one order of magnitude) with a better resolution and a higher time span. These last parameters can be improved with the homodyne setup, but this would be highly time-consuming. With typical settings that allow a comparison between the two setups, the heterodyne setup is faster than the homodyne setup by a factor 2 000.

For demanding applications, such as imaging on a living cell, the heterodyne setup is the only one that fulfills the requirements.

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