High Sensitivity Scanning Pyroelectric Microscope: Interdigitated Comb Electrodes and Advanced Image Processing

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ABSTRACT

To observe the pyroelectric response of bio-organic materials, several innovations have been proposed and implemented to push the sensitivity limits of a Scanning PyroElectric Microscope (SPEM). These include the use of noise reducing software, interdigitated comb electrodes instead of parallel plate electrodes and the use of rotating mirrors. Using these suggested techniques, the general performance of a SPEM measurement has been improved and allows the successful study of materials with a naturally weak spontaneous polarization and thus extremely low pyroelectric coefficients.

Index Terms - SPEM, pyroelectricity, IDE, comb electrodes, conditional averager, sliding Fourier transformation, mirror scanning, LASER intensity modulation method

1 INTRODUCTION

PYROELECTRICITY is the property of solid materials to respond to temperature changes by an electric current or potential difference. The magnitude and direction of the pyroelectric current is proportional to the local permanent polarization. By measuring the pyroelectric current, the spatial macroscopic polarization in a sample can be detected and mapped [1, 2]. Scanning Pyroelectric Microscopy (SPEM) has been used successfully for organic and inorganic materials, a schematic setup is given in Figure 1.

Figure 1. A sketch of the SPEM setup. A lock-in amplifier modulates the output of a laser diode, the pyroelectric current is proportional to the current that originates from the capacitor and is amplified by a current amplifier with a conversion factor of 10^6 to 10^{10} V/A. The lock-in amplifier correlates the real and imaginary part of the signal from the current amplifier output and the data are stored on a computer.

A modulated laser beam induces a local time dependent temperature change, if the illuminated region is pyroelectric it will generate a small electric current which can be measured by two parallel plate electrodes. The pyroelectric current vector is proportional to the local electrical polarization vector [2], by translating the laser beam over different regions of the sample, the polarization distribution map can be obtained. The power modulation of the laser output is typically in the order of 10 to 100 mW peak to peak with laser beam spot sizes ranging from 20 to 2 micrometers diameter, depending on the optics and laser source used.

1.1 SCANNING PYROELECTRIC MICROSCOPE

Scanning pyroelectric microscopy (SPEM) is a proven technique for the determination of a polarization distribution map with both lateral and depth resolution by translating the laser beam over the sample surface and modulating the laser output of different frequencies [1]. This method has been used successfully for pyroelectric crystals with dimensions in the order of tens to hundreds of micrometers [2,3]. The technique shows similarities with the Focused Laser Intensity Modulation Method (FLIMM), which also allows the detection of space charges for both depth and in plane spatial distribution [4]. This paper focuses on the SPEM technique.

Bio-organic samples with a smaller size, higher structural complexity and weaker pyroelectric activity require certain innovations to analyze their polarization distribution [5]. In this paper we describe three major innovations, viz. a noise-reducing algorithm, the use of interdigitated comb electrodes (IDE) acting as a microelectrode along with deconvolution

software in the form of a sliding Fourier transformation, along with a rotating mirror scanning system.

1.2 EXPERIMENTAL DETAILS

All results in this study were obtained using a 10mW LISA-laser red laser module HL25/M2 modulated with the sine output of a SR830 Stanford Research lock-in amplifier. The current was amplified using a Keithley 428 Current Amplifier and the data were processed using Matlab.

2 PUSHING THE EXPERIMENTAL SENSITIVITY

Generally, the pyroelectric current is measured by placing a pyroelectric sample in a capacitor configuration (e.g. parallel plate electrodes) and by monitoring the resulting displacement current while a modulated laser beam heats the sample. By spacing the electrodes closer, the signal strength is increased. A comb electrode is an electrode array, effectively containing many tightly spaced electrodes, onto which the sample is placed and which is able to efficiently sense the pyroelectric charges. Since the IDE causes a periodical alternation in current direction, an additional deconvolution is required to obtain the correct signal sign and thus the spatial pyroelectric information of the sample under investigation. To increase the signal-to-noise ratio, we have also employed a conditional averager to reduce the influence of random current spikes.

2.1 CONDITIONAL AVERAGER

When a polarization distribution or pyroelectric current image is obtained, the Johnson and voltage noise are usually responsible for pixellating the image, making it difficult to interpret them [6]. To reduce this influence, noise reduction algorithms such as a conditional averager can be used. It takes a 2by2, 3by3, 4by4 or larger matrix of pixel values around a central pixel and evaluates their distribution. If the value of the central pixel deviates too much from the surrounding values, it is likely to be a fluke or a non-representative number of the true value and the value of the pixel is replaced by the average of its surroundings. Alternatively it can be replaced by the weighted average of its surroundings, assigning a larger weight to the pixels closest to it.

The conditional averager is in fact a statistical hypothesis test for each pixel of the image. The null-hypothesis H_0 is that all values of pixels near the central pixel are the same. Since the standard deviation of the distribution is unknown, a t-hypothesis test is applied. The null-hypothesis is overthrown with 99 % certainty when the central pixel differs more than 4, 2 or 1 standard deviations from the average of the pixel matrix for a surrounding area of 2by2, 3by3 or 4by4 respectively. Overthrowing the null-hypothesis indicates acknowledging that the value of the pixel comes from a different source than the sample under investigation and is thus irrelevant to the measurement. The value of the pixel is replaced by the average value of the matrix, which is assumed to be generated by the response of the sample. A small graphical illustration can be seen in Figure 2, where a pixel of value 8 deviates from

its surroundings and is considered an anomaly and originating from noise.

Figure 2. Graphical illustration of the conditional averager. (a) The original measurement, containing a deviating pixel value. (b) An 3by3 area is taken as sample data around the deviating pixel. (c) The hypothesis test indicates the pixel value is significantly above the average level and is most likely due to noise, its value is replaced by the average of its surroundings.

A demonstration of the conditional averager is given in Figure 3, where the real part of the pyroelectric response of a trans-4-chloro-4'-nitrostilbene (CNS) crystal is measured in a noisy environment (i.e. no adequate electromagnetic shielding or electrical grounding). The noise spikes make it difficult to interpret the image, but after applying the conditional averager and polarization distribution of the CNS crystal become more apparent.

Figure 3. (a) The real part of the pyroelectric current response of a CNS crystal in a high noise electrical environment, the occasional high current spikes make it more difficult to interpret the obtained current map. (b) After applying the conditional averager using a sliding 3x3 window, the apparent noise level of the image is dramatically reduced.

Care must be taken when using the conditional averager. One can never be 100 % sure that the value of a deviating pixel does not originate from the sample itself. This technique should therefore not be employed if the size of the polarization domains are in the order of the pixel size or smaller. Since the size of the domains is not always predictable or known, all

effort must first go toward prevention of noise sources. If uncertainty still exists, it should be possible to repeat the measurement or perform more measurements per pixel, as the Signal-to-Noise ratio increases with the square root of the number of measurements.

2.2 INTERDIGITATED ELECTRODES AND SLIDING-FOURIER DECONVOLUTION

When using interdigitated electrodes, the electrodes are closely spaced to each other in the order of 10 to 40 micrometers. Most samples are too large to fit in between the electrodes and being part of the dielectric material in the capacitor gap. The pyroelectric current is still measurable, because an alternation in dipole moment in the sample changes the electric field lines protruding from the sample and passing through the space between capacitors. The arrangement of the electrodes also means the sign of the current is alternating for each space in between two electrodes. An efficient solution to obtain the real polarization distribution is to deconvolve the data using a sliding Fourier-transformation [6]. To this end a Gaussian frame of the form $\exp(-(x - x_0)/c)^2)$ is multiplied with the result for several values of x_0 . For each value of x_0 the product of frame and measurement is then Fourier-transformed. An example of such a joint transformation is given in Figure 4, the sample is a region of a tooth with dentine. The current changes its sign periodically in between the electrodes, so the value for c should be chosen in a manner that the full-width-half-maximum of the Gaussian frame spans over at least one inter-electrode region. For the two-dimensional case, a two-dimensional Gaussian frame is translated over the measured image.

Figure 4. Example of a one dimensional Sliding Fourier transformation (top) applied to a linescan of a human tooth (bottom). The pyroelectric current arises from a region of dentine.

The amplitude of the wavenumber corresponding to the wavenumber of the comb electrode structure is the value of the deconvolved pixel around which the frame was centered. The complete sliding Fourier transformation determines the amplitude of the wavenumbers k in function of the position x_0 . The deconvolved pyroelectric current associated with position x_0 is the amplitude of the wavenumber k corresponding to the spacing of the electrodes, calculated at position x_0 . An example of a deconvolution of CNS crystals on a comb electrode is given in Figure 5.

(a)

(b)

(c)

Figure 5. (a) Photograph of CNS crystals on a comb electrode. (b) Pyroelectric response of a crystal with mono-domain permanent polarization, alternation in current sign is the alternation of the comb electrode. (c) A deconvolution that recovers the correct domain structure.

This deconvolution also functions as a noise filter, since only signal components with a wavenumber corresponding to the wavenumber of the comb electrode structure contribute to the final image. Other sources of noise that are location independent, such as the amplifier noise or nearby electromagnetic interference, are filtered out. An example is given in Figure 6. An unknown noise source, time or position dependent, gives rise to a large varying background signal that makes visual confirmation of mono-domain CNS crystals difficult. A deconvolution to the wavenumber of the 10-

micrometer spaced comb electrode nearly eliminates this background noise and reveals two crystals in the left upper corner.

Figure 6. (a) Real part of the pyroelectric current as measured by the Lock-in amplifier, showing a large varying background signal that is either time- or position dependent. (b) The same image after Sliding-Fourier deconvolution; the gradient-type background has nearly disappeared and two CNS crystals become apparent.

2.3 STEPPER MOTOR MIRROR SCANNING

The use of a stepper motor mirror device allows us to guide a laser beam by employing two rotating mirrors with perpendicular rotational axes, as illustrated in Figure 7. The laser light reflects off one mirror onto the next and is finally directed towards the sample. By moving the location of the laser beam on the sample instead of a translation of the sample itself, a mechanical decoupling takes place. Due to this decoupling there is less noise generated from piezoelectric activity in sample and sample holder [6].

The stepper motor has multiple "toothed" electromagnets arranged around a central gear-shaped iron piece. When the electromagnets are powered in a certain pattern, the central gear aligns with either of the electromagnets, causing a rotation. It is possible to partly power a coil, causing the

rotational axis to be in an intermediate position between two partly powered coils, being closer to the electromagnet that is driven by the highest current. This is called microstepping [7]. The most common form is sine-cosine microstepping, where the two sets of coils are each powered by a current source 90 degrees out of phase.

Figure 7. Sketch of a galvanometer scanner. It uses a mirror pair sized to the input beam aperture over a range of rotation angles for the required scan field. [8].

By using a light load in the form of small mirrors on a lightweight aluminum mount, it is possible to freeze the rotational position in between two steps with a high degree of reproducibility. The stepper motors are driven by the digital to analog converter (DAC) of the Lock-in amplifier in combination with a linear amplifier. A computer program calculates the next position of the laser beam, translates it to the two appropriate angles for the stepper motors, and applies the correct current to the two coils of each stepper motor via the DAC of the Lock-in. These commands can be given in between readouts of the measured pyroelectric current.

When an xy mirror system is used, it is often used in combination with an F-theta lens, an optical component that projects each incoming laser beam on the same focal plane, regardless of the incident angle. Due to the small displacements and dimensions used here, an F-theta lens is not a necessity. If areas larger than 1 mm^2 are to be scanned in a single measurement, the F-theta lens is recommended.

3 CONCLUSION

The introduction of noise minimizing techniques such as stepper motor mirrors to reduce piezoelectric contribution,

interdigitated electrodes to increase signal strength and the conditional averager and sliding Fourier-deconvolution image processing techniques to reduce noise, allows for a higher signal to noise ratio which makes the SPEM-setup accessible to a wide variety of both bio-organic and inorganic materials, such as human teeth, fluorapatite biocomposites, fish bones and cat claws [6].

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