Improvement of contrast of Terahertz Images of a Terahertz Chemical Microscopy using Adaptive Digital Filter

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***Abstract*— A Terahertz Chemical Microscope has been proposed and developed for the visualization of chemical reactions in the solutions. To visualize chemical reactions with higher imaging quality and higher scanning speed, it is required to improve the contrast of the images. In this study, we applied an adaptive filter to the TCM system and evaluate the imaging quality qualitatively. The contrasts without filter and with filter are 0.33 and 0.74 respectively. This result shows that our system with the filter could improve the imaging quality without losing the scanning speed of the microscope.**

Keywords*— Terahertz Images, Adaptive Filter, Contrast, Standard Deviation, Least Mean Square, Step Size.

I. Introduction

Terahertz; the electromagnetic wave with the frequency components between 100 GHz and 10 THz, is expected to be one of excellent options to measure chemical reactions of bio−related materials with high sensitivity and selectivity; e.g. reactions of immunoglobulins, lectins, and enzymes etc. So, a lot of researchers in the world are attracted by applications of the terahertz technology to medical diagnosis such as cancer detection and high−sensitive blood test.

In our group, we have proposed and developed a Terahertz Chemical Microscope (TCM) [1−4, 8−11] to measure distributions of chemical reactions in the water solutions. While conventional terahertz spectroscopy, whose sample size is limited by the wavelength of THz ($\lambda = 300\ \mu m$), the sample size of TCM is limited by the wavelength of an ultrafast laser pulses ($\lambda = 0.8\ \mu m$), so that measurement of extremely small amount of water solutions less than 16 nL could be realized [1]. We have demonstrated simultaneous detection of bio−related materials in the small amount of solution onto a single chip for medical diagnosis of the diseases in early stage [2, 9]. measurements of immunoassay reactions, we have observed Avidin−Biotin interaction using a micro−fluidic channel inside TCM which are very small in molecular weight to analyze [8]. So, TCM can be a smart candidate to medical diagnosis and biomaterials research. In very near future, we are coming out with capturing of maps of faster spreading out of chemical solutions and/or movie clip. Thus, a breakthrough of faster scanning procedure for the faster movement of chemical solutions will be the latest addition in our novel cutting edge research of TCM.

In this research, for measuring reactions of chemical solutions in detail with higher quality of images and faster scanning speed, it is necessary to improve the contrast of the images. So, in this paper, an Adaptive Filter (AF) using digital signal processing technique has been implemented and integrated to our TCM system by analyzing the improvement for capturing high contrast images. For testing the filter's effectiveness, it was used four wells sensing plate where each well was poured with Milli−Q water solutions onto the Sensing Plate (SOS) which is shown below in conceptual diagram of Fig. 1.

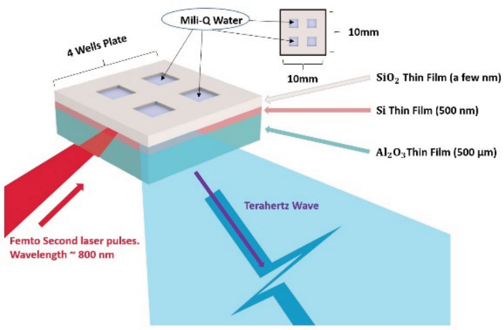

Fig. 1. Conceptual Diagram of four wells plate of TCM.

II. Theoretical Background of AF

An AF itself adjusts the filter coefficients according to an adaptive Least Mean Square (LMS) algorithm. Fig. 2 shows the diagram of an LMS adaptive linear Filter [5]. As a computational device, an AF iteratively models to establish

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the relationship between the input and output signals of a filter.

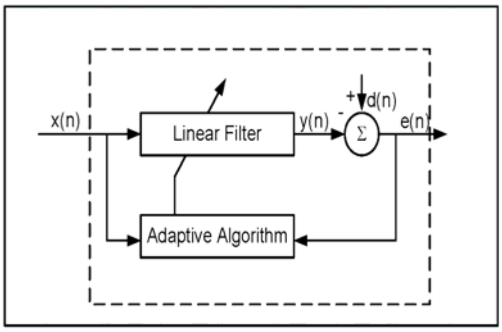


Fig. 2. LMS Adaptive Filter's operation.

Where n is number of current input samples, $x(n)$ is the input signal to a linear filter, $y(n)$ is the corresponding output signal, $d(n)$ is an additional input signal to the AF and $e(n)$ is the error signal that indicates the difference between $d(n)$ and $y(n)$ This proposed LMS algorithm adjusts the coefficients of the linear filter in iterative process to minimize the power of $e(n)$ [5]. The LMS does the following arithmetical operations to update the coefficients of an adaptive Finite Impulse Response (FIR) filter:

$$y(n) = \vec{u}^{T}(n).\vec{w}(n) \tag{1}$$

Where, $\vec{u}(n)$ is the filter input vector and

$$\vec{u}(n) = [x(n)x(n-1)...x(n-N+1)]$$

$$\vec{w}(n) = [w_0(n)w_1(n)...w_{N-1}(n)]$$

Where, $\vec{w}(n)$ is the filter coefficients vector.

2. Calculating the error signal $e(n)$ as follows:

$$e(n) = d(n) - y(n) \tag{2}$$

3. Updating filter coefficients from following equation:

$$\vec{w}(n+1) = (1-\mu)\vec{w}(n) + \mu.e(n).\vec{u}(n) \tag{3}$$

Where μ is the Step Size (SS) as a gain constant parameter of the AF [5].

An AF implementation following LMS was developed by Laboratory Virtual Instrument Engineering Workbench (LabVIEW®). The reasons to choose AF over other filters are for following reasons: (i) Convergence Speed (CS) follows optimal solution with iteration method effectively (ii) Miss−adjustment ability to measure the amount by which the final value of Mean Square Error (MSE), averaged over a gross calculation of filtering, deviates from the MSE (iii) Tracking ability to follow statistical variations in a non−stationary, time varying signal's environment. (iv) Robustness implies that small disturbances from any source would produce small estimation errors which AF be able to adjust (v) Computational simplicity in comparison with other methods of signal processing filters [6].

III. Experimental Set Up

The laser light source used here was a Ti : Sapphire laser. The center wavelength of laser pulse was 780 nm containing pulse width of 100 fs at half−maximum of full−width. The output

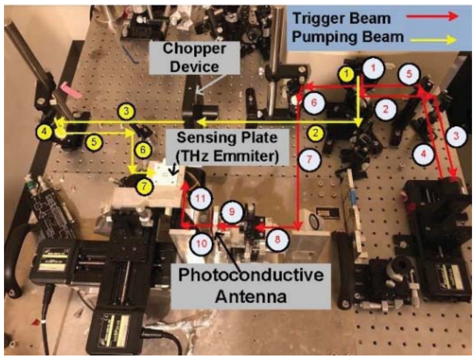


Fig. 3. Prototype of TCM system.

is 790 mW with 82 MHz repetition rate. Terahertz waves were generated in the SOS and radiated into free space by irradiation of femtosecond laser pulses which were produced by the Ti : Sapphire laser. The amplitude of the terahertz pulses was detected by a terahertz detector. We used a bow−tie type photoconductive antenna as the detector, which made from a low−temperature−grown−GaAs thin film on semi−insulating−GaAs substrate. The optical delay of the trigger pulses to the detector was fixed at where the peak amplitude of THz wave was observed. A lock−in technique was applied to reduce noise of the terahertz signals. In lock in, THz data were synchronized using chopper (the frequency of chopper for our system was 2 kHz) to reduce noise of signal data. The overview of the system is shown in Fig. 3.

The measurement of TCM started after the alignment of pumping, trigger beams of THz laser according to Fig.3. Then according to Fig.4. the position of laser was moved to start scanning of samples on SOS. The detector detected the optical signal. The delay stage of chopper was used to identify the position of peak amplitude of THz data. Analog to Digital (AD) converter was used to choose correct sampling frequency, number of samples of signal data to be sampled according to Nyquist sampling theorem. The sampled data were then filtered with averaging of data using simulation of LabVIEW®. From the Personal Computer (PC), the THz imaging data were recorded and plotted. Finally, the filtered data with average were analyzed, calculated by measurement of points by points of imaging step. LabVIEW® represents system design platform and development environment for Visual Programming Languages (VPL) from National Instruments (NI) corporation. VPL defines any programming language by manipulating program elements graphically rather than textually. LabVIEW® is used for data acquisition, instrument control & industrial automations on a variety of computer Operating Systems (OSs). NI is an American multinational company for manufacturing automated test equipment and virtual instrumentation software for the clients [7]. Fig. 4 shows the block diagram from the detector to the recording of data via lock−in amplifier to Computer (PC) which is our measuring environment.

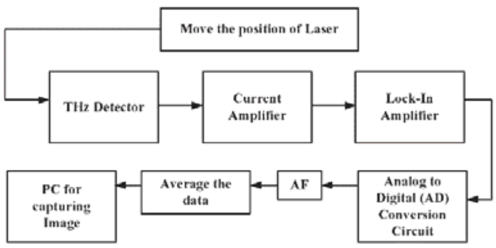


Fig. 4. Schematic Diagram of Recording of THz data.

IV. Result

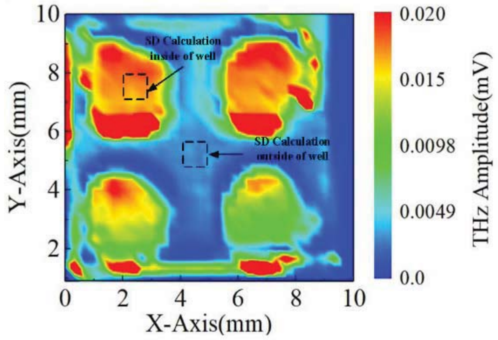


Fig. 5. SDs calculation for several pixels of data of THz images inside upper well and outside Well of SOS.

To evaluate the quality of images using AF, Standard Deviations (SD) and contrast of the images were estimated by following process:

1. Taking the values of pixels inside and outside of the well, which is indicated by red−yellow dashed squares in the image of Fig.5
2. Calculating the SDs of the pixels both of inside and outside of wells
3. For evaluating the contrast, the values of pixels inside I_{max} and outside of wells I_{min} and calculated by:

$$(I_{max} - I_{min})/(I_{max} + I_{min}) \qquad (4)$$

The characteristics curves for showing variation of SDs with respect to SS were developed with the optimization of SS as gain constant of a filter parameter. In AF, CS is very much important to adjust the minimum error with main input signal. Here our target was to choose the condition of optimum CS of LMS algorithm with respect to SS which in turn increased the THz imaging speed by internally applied AF. Fig. 6 shows SD as a function of SS where the Time Constants (TC) of lock in amplifier were set to be 30 ms and 100 ms.

According to the LMS algorithm, SS values of 0.001, 0.01, 0.05, 0.5, 1,1.5, 2 were checked to find out comparatively higher precision of AF in terms of optimum SD with higher quality of contrast of images corresponding to higher scanning speed.

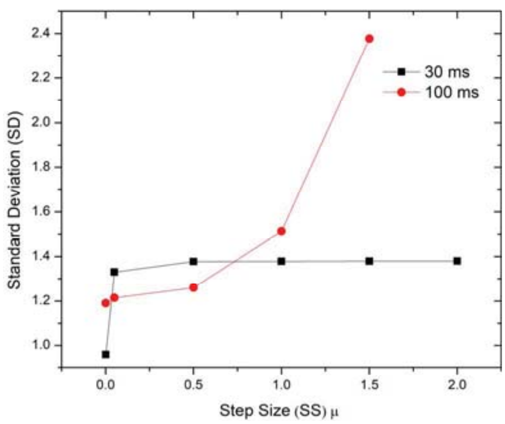


Fig. 6. SD vs SS curves to evaluate the characteristics for 100 ms and 30 ms TC of lock−in.

We had chosen SS = 0.001 as an optimum value to get higher speed with optimum value of SD for analyzing higher quality of THz images. So, we evaluated the SDs of images as a function of SS and plotted in Fig.6.

From two different curves of Fig. 6, it is found that the signal was not saturated for 100 ms while the curve for 30 ms showed early saturation even at SS = 0.01 value. From two qualitative results, it is found that for SS = 0.001 of AF, we got comparatively higher contrasts in comparison with optimum level of SD for which there were higher speed of TCM. So, the data recorded with filter were (i) contrast of 0.74 for 30ms TC corresponding to SD = 0.96 and (ii) contrast of 0.73 for 100ms corresponding to SD = 1.19. In case of lock−in, we know, TC is inversely proportional to the bandwidth of Low Pass Filter (LPF) of lock−in. So, the lower the TC, the wider the bandwidth of LPF with lower Signal to Noise Ratio (SNR) and the faster measurement. Higher TC means narrower bandwidth of LPF with higher SNR but making slower measurement. An AF was working on 30 ms TC which brought saturation early in comparison with 100 ms because AF got wider bandwidth by collecting much signal information to adapt with the input THz signal for minimizing error.

In the next step, we evaluate the quality of contrast without and with filter. From Table I, it is found that both two results with filter are more than double of contrasts of that of without filter. So, our preliminary chosen contrast values for capturing higher contrast of images with higher scanning speed are 0.74 and 0.73 respectively. As our target was to consider as lower as possible of SD corresponding to a SS value of AF with the achievement of higher quality of contrast of images, we recommend here the lowest value of SD = 0.96 with respect to SS = 0.001 containing contrast of 0.74 for 30ms TC of lock in amplifier.

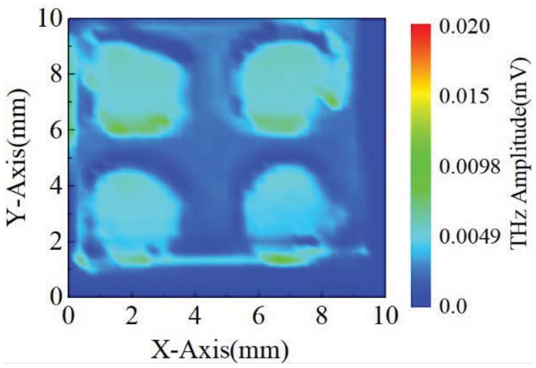
Finally, we improved contrast of images dramatically. Also, comparing TC, the contrast was not reduced by decreasing the TC to 30 ms from 100 ms which suggests that we can reduce measurement time of THz data.

The qualitative calculation without filter and with filter for SDs and the contrast of THz images are shown in Table I.

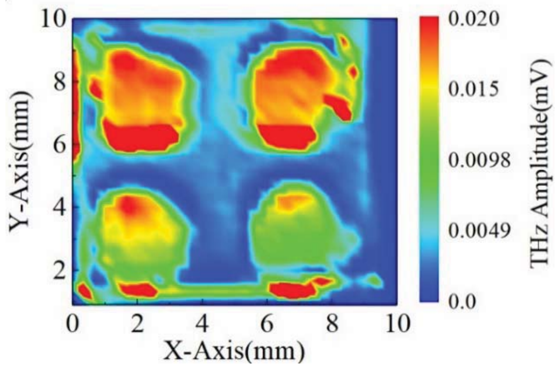
TABLE I. SD AND CONTRAST ESTIMATION

With or Without Filter	**100 ms Time Constant**			**30 ms Time Constant**		
	SS	***SD***	***Contrast***	***SS***	***SD***	***Contrast***
Without Filter	N/A	0.01	0.32	N/A	0.07	0.34
With Filter	0.001	1.19	0.73	0.001	0.96	0.74

The output of Terahertz images without and with filter for 30 ms time constant of lock in amplifier are given below in (a) and (b) of Fig. 7 respectively.



(a) THz Imaging data without filter.



(b) THz Imaging data with filter.

Fig. 7. THz imaging data corresponding to contrast of (a) 0.34 and (b) 0.74 respectively for 30 ms time constant of lock in amplifier.

THz data were obtained from PC which were averaged without and with filter in two cases shown in Fig.7 (a) and (b) respectively. For 30 ms, with and without filter, we used two−stage controlling LabVIEW® simulation by adjusting AD converter's number of samples data = 100, sampling frequency, f_s = 1kHz following Nyquist sampling theorem for the time interval of 1 ms.

The total acquisition time for measurement of both cases = (time constant of Lock−in + (No. of samples x Time interval of AD converter)).

For (10 mm x 10 mm) dimensions of SOS, we programmed 1mm = 6300 points with resolution of 333 μm of total scanned images. That means, for our experimental (10 mm x 10 mm) dimensional area of SOS, the system scanned 63000 by 63000 points to finish each measurement following above said acquisition time of capturing images for (a) and (b) of Fig. 7.

So, sample of Mili−Q water was tested using adaptive filter by capturing higher contrast of recorded data and images.

V. Conclusion

In our work, TCM system with filter could improve the contrast double without compromising existing scanning speed. And, from optimum value of SS of AF, our measurement time was reduced. Our future work with this filter is to capture the map of spreading out some chemical solutions like salt solution or movie clip in a faster scanning speed. Our target is to establish bio−materials solutions information in detail in the form of THz images.

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