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Novel algorithm for Background Correction of the Quantitative Spectroscopic Tomography of the Biogenic-substances

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ABSTRACT

The non-invasive blood sugar sensor by using imaging-type 2-dimensional Fourier spectroscopy is to be realized in this work. The spectroscopic imaging, that observes the biological tissue by the dark-field image, can measure the biogenic substance quantitatively such as the glucose concentration. For the quantitative analysis with high accuracy, the correction of the background such as the light-source fluctuation and the phase-shift uncertainty is inevitable issue. Thus, the quantitative band-pass plate on which the grating is locally formed has been already proposed by [1]. In that paper, the diffractive light, whose diffraction angle depends on the wavelength, has been used as the reference light. Object lens is used to narrow down the reference light and narrowed band pass diffraction light is obtained. The changes of imaging intensities with interference phenomenon on whole area of the observation image can be confirmed using the quantitative band pass filter. This paper proposed background correction method of the interferogram in spectroscopic tomography. Correction algorithm mainly contained two parts as light source fluctuation error correction and phase shift error correction.

Keywords: Spectroscopic Tomography, Biogenic-substances, Background Correction, Double angle method, non-invasive blood sugar sensor

I. INTRODUCTION

Imaging type 2-dimensional Fourier spectroscopic [2] has been using for development of non-invasive blood sugar sensor and Wide-field-of-view spectroscopic imaging. Spectroscopic tomography of the mouse's ear by using the imaging-type 2-dimensional Fourier spectroscopy was obtained at Ishimaru laboratory in Kagawa University, Japan [3]. The spectroscopic imaging, that observes the biological tissue by the dark-field image, can measure the biogenic substance quantitatively such as the glucose concentration. However, for the quantitative analysis with high accuracy, the correction of the back ground such as the light-source fluctuation and the phase-shift uncertainty is inevitable issue. Thus, the quantitative band-pass plate on which the grating is locally formed is proposed previously. The diffractive light, whose diffraction angle depends on the wavelength, is used as the reference light. The object lens is used to narrow down the reference light and narrowed band pass diffraction light is obtained. This paper proposed to background correction method of the interferogram in spectroscopic tomography. It consists two parts as light source fluctuation error and phase shift error correction. Compared to the signal frequency, light source fluctuation error is low frequency signal. This low frequency error signal is estimated by using envelop detection method. Those estimated signal is used to correct the measured interferogram which is measured using imaging type two-dimensional Fourier transform spectroscopy. Phase shift error was corrected by suitable filtering followed by convolution of phase error spectrum with measured data.

This paper has been organized as follows. Paper starts with introduction and section II describes the imaging-type 2-dimensional Fourier spectroscopy. Section III explained the spectroscopic tomography of the biological tissues. The background correction is described in section IV. The paper is concluded with conclusion.

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II. IMAGING-TYPE 2-DIMENSIONAL FOURIER SPECTROSCOPY

The proposed imaging-type 2-dimensional Fourier spectroscopy is the wavefront-division interferometer, as shown in Figure 1. Thus, the rays from one of the single bright-points on the object surface interferes each other on the imaging plane. Meanwhile, the rays from the out-of-focus plane, which are illustrated as dotted lines, cannot intersect on the imaging plane and cannot interfere in each other. So, imaging-type 2-dimentional Fourier spectroscopy method can limit the measuring depth into the focal plane. If we scan the measurement plane mechanically in the depth direction, the spectroscopic tomography can be obtained. Next, the principle of this method is explained. The variable phase-filter in to the infinity optical system on the Fourier transform plane was installed. This can give the arbitrary phase difference to the half wavefront. The variable phase-filter consists of the two mirrors. One is the fixed-mirror, another one is the moving-mirror. The phase difference is given between the reflected rays from the each mirror. In accordance with the phase-shift value caused by the mirror movement, the cyclic intensity changes are observed on the imaging plane at every pixel simultaneously. The summation of the cyclic interference intensity changes in each wavelength is detected as the interferogram on the light-receiving device. As known as the Fourier transform spectroscopy, the spectrum is analytically acquired from the interferogram. Hence, the spectrum distribution on the focal plane can be acquired.

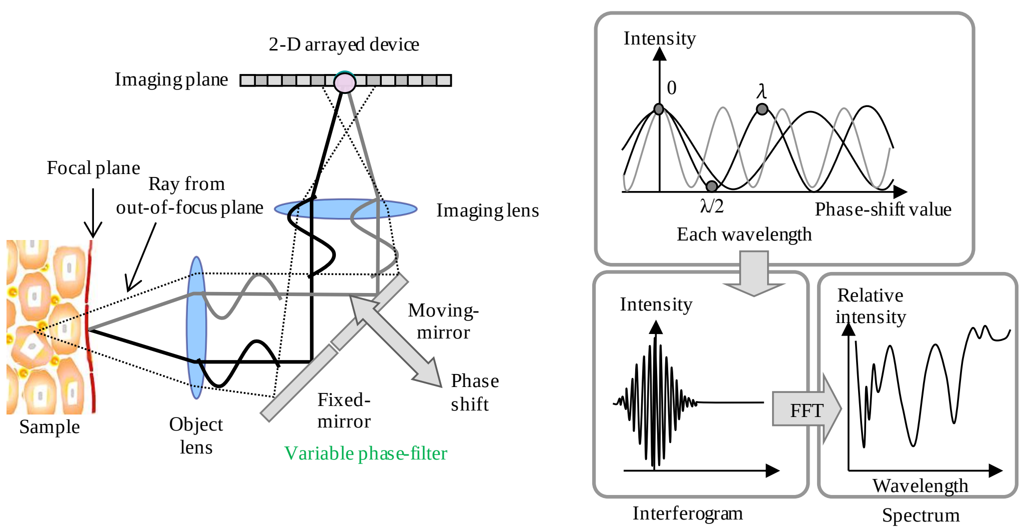

Figure 01-Imaging-type 2D Fourier spectroscopy by phase shift interference between object beams

III. SPECTROSCOPIC TOMOGRAPHY OF THE BIOLOGICAL TISSUES

The spectroscopic tomography of the living biological tissue in the near-infrared region was successfully acquired.

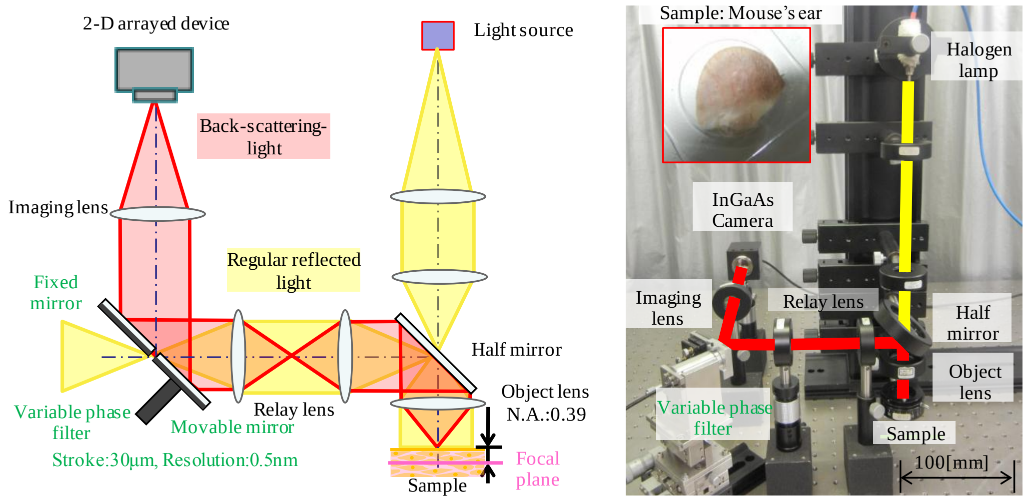

Figure 02. Schematic diagrams for the dark field spectroscopic tomography of the biological tissue with the near-infrared light

Based on the distinct feature of our method, the spectroscopic tomography near the skin surface was obtained. Figure 2 shows the experimental optics whose reflection-illumination is applied also for the light-path-length clarification that will be explained in the next section. However, the regular reflected light from the tissue surface is extremely stronger than the back scattering light from the inner structure. Thus, to detect the weak back-scattering-light by eliminating the regular reflected light, the dark-field imaging-optics was introduced for the tomographic image. The fixed and moving mirrors were set up with the spaced gap. The regular reflected light was passed through the gap of these 2 mirrors not to reach the imaging device. The sample is illuminated through the condenser lens (Material: BK7) using the halogen lamp (Maker: KLV, Inc., Type: 64528) as the light source. The object lens (N.A.:0.39, Material: BK7) is used for the observation optics for the detection of the weak back scattering light. The interference of the weak back scattering light is formed by the imaging lens using the relay lens on the InGaAs camera (Maker: Hamamatsu Photonics, Type: C10633-13).

Upper left-hand side photo in Figure 3 (a) shows the observed image of mouse's ear with the near-infrared light. These computed false-colored images were generated from the spectral absorptance in the each pixel. The false color is determined by the area of the spectral absorptance within the certain wavelength area as shown in upper right in Figure 3. Figure 3 (b-1), (b-2) and (b-3) shows the absorptance ration within 1100nm to 1300nm, 1300nm to1500nm, and 1500nm to 1700nm respectively. The different textures that are indicated by the solid circle and the dotted circle can be confirmed from different wavelength regions. The quantitative cluster analysis of the biological components from these spectroscopic tomographic images will be our future studies. The quantitative cluster analysis of the biological components will be carry out to realize the non-invasive blood sugar sensor.

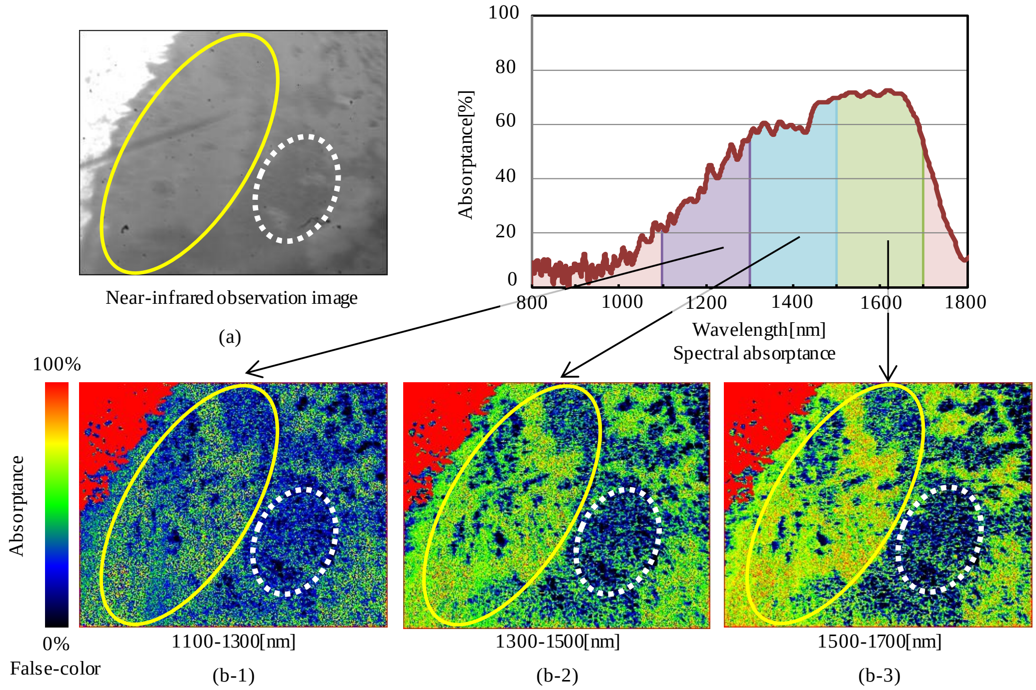

Figure 03. Spectroscopic tomography of the mouse ear near the skin surface in the near-infrared region

IV. BACKGROUND CORRECTION METHOD

A. Why the Background Correction is Necessary

Our researches are aiming at the realization of the non-invasive measurement of the biogenic-substance, such as the blood glucose concentration, by using imaging-type 2-dimensional Fourier spectroscopy. Here, high accuracy of the quantitative analysis and precision measurement of components are very crucial. The background such as the light-source fluctuation (vertical axis, about 2%) and the phase-shift uncertainty (horizontal axis, about 0.2%) are inevitable issues when obtaining high accuracy. Reference light is necessary to correct errors due to light source fluctuation and phase shift uncertainty. The quantitative bandpass plate in which the grating is locally formed has been proposed to make reference light on the measurement plane. The reference photon detection area can be established on the spectroscopic image which can be obtained by using imaging-type 2-dimensional Fourier spectroscopy. Also, the mirror reflection light from a skin surface has about 1,000-time strong light volume compared with scattering light. So, we use the dark field optics to eliminate the mirror reflection light with the oblique lighting (as shown in figure 4).

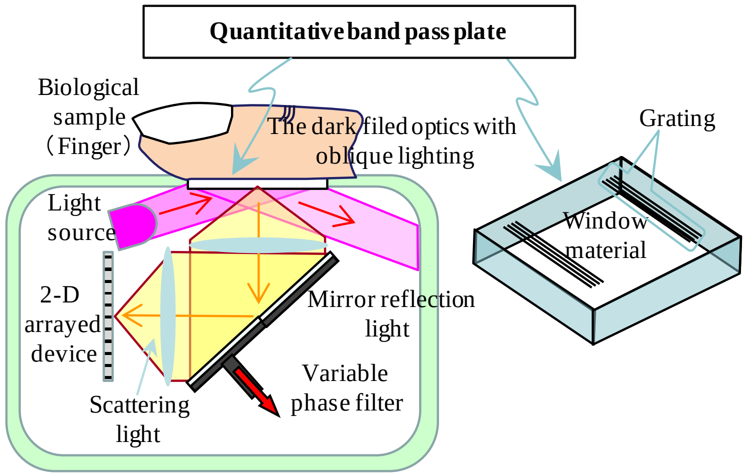

Figure 04. Use of dark field optics to eliminate the mirror reflection

For achievement of high accuracy measurement, error has to be controlled less than 0.01%. As explained earlier, the diffractive light, whose diffraction angle depends on the wavelength was used as the reference light. This reference light is the narrowed band-pass diffractive light, which is passed through the objective lens. Thus, the light-source fluctuation from the amplitude of the reference light intensity and the phase-shift uncertainly from the interference-phase can be corrected respectively.

However, the reference light's bandwidth and light volume serve as a relation of a trade-off. That is, if the reference light's bandwidth is narrowed too much, light volume will decrease, and amplitude compensation becomes difficult. So, it is necessary to take the bandwidth and light volume of reference light into balance.

B. The Narrowed Bandpass Reference Light

The quantitative band-pass plate for correction of the light-source fluctuation (vertical axis) and the phase-shift uncertainly (horizontal axis) was used. Because the reference light and the weak scattering light can be obtained at the same time from the image, the reference light's interferogram is used for correction of the vertical axis and horizontal axis. The mimetic diagram of the optical system for the biological measurement which used the quantitative bandpass plate is shown in Figure 05.

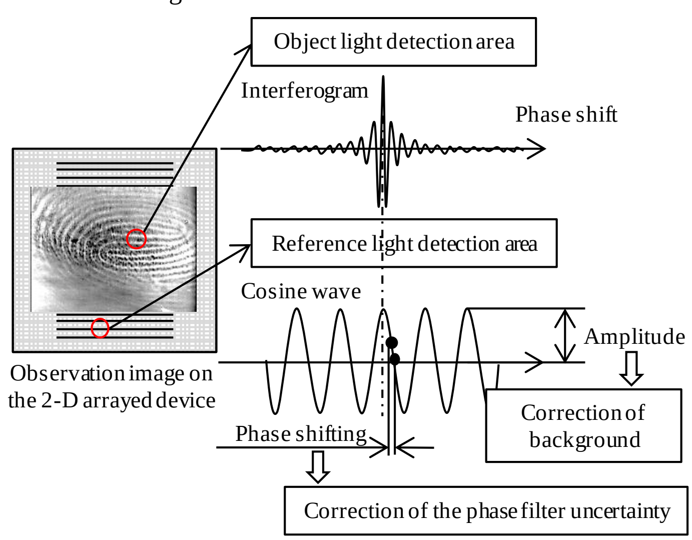

Figure 05. Background correction using reference light

Reference area with grating is designed such a way that it is different from measurement area. Moreover, since the diffraction angle is different for each wavelength, the long wavelength has the big diffraction angle, the short wavelength has the small diffraction angle. So, the wavelength band can be limited by the N.A. (Numerical Aperture) of the object lens. The longest wavelength's diffraction angle is the $\theta_{\max}$, the shortest wavelength's diffraction angle is the $\theta_{\min}$. Thus, the narrow wavelength band can be chosen for the reference light. The reference light and the weak scattering light pass through the phase shifter and the imaging lens, then will be imaged on the image plane. The interferogram can be obtained from the image plane, then the correction of the light-source fluctuation and the phase-shift uncertainty can be conducted with the interferogram at the same time.

C. Design of the grating period

Proper design of grating period is very important for the selection of reference light wavelength. Grating is established on the quantitative band pass plate and grating period is designed to obtain the suitable bandwidth. Narrow bandwidth was obtained using the optical system shown in figure 6.

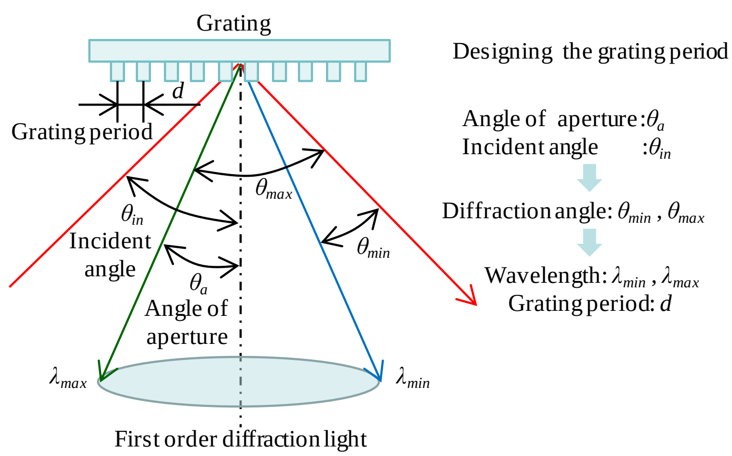

Figure 06. Design of grating angle

Initially, the focal distance (f) and diameter (ϕ) of the object lens can be decided based on the resolution of the measurement object. Thus, the angle of aperture (θ_a) can be calculated. Then, the incident angle (θ_{in}) is decided. From the difference between the incident angle (θ_{in}) and the angle of aperture (θ_a), the short wavelength's first order diffraction angle (θ_{min}) can be calculated.

$$\theta_{min} = \theta_{in} - \theta_a \qquad (1)$$

And the long wavelength's first order diffraction angle (θ_{max}) can be obtained as shown in equation (2).

$$\theta_{max} = 2\theta_a + \theta_{min} \qquad (2)$$

The relation of grating period (d), diffraction angle θ and the wavelength (λ) are shown as the equation (3).

$$\lambda = d \sin\theta \qquad (3)$$

Then, based on the wavelength (λ_{min},λ_{max}) and the diffraction angle (θ_{min}, θ_{max}) the grating period (d) can be calculated.

D. Feasibility demonstration of obtaining narrow band reference light from the halogen lamp

Feasibility demonstration of obtaining narrow band reference light from the wide wavelength band of halogen lamp is explained in this section. As explained in section (C), the object lens's focal distance (f) and the diameter (ϕ) are selected as 400mm and 25mm respectively. Thus, the angle of aperture (θ_a) was calculated as 1.8 [deg.]. Moreover, the incident angle (θ_{in}) was obtained as 44.21 [deg.]. Then, using equation (1), the short wavelength's first order diffraction angle was calculated as 38.78 [deg.]. From the equation (2), the long wavelength's first order diffraction angle was calculated as 42.41 [deg.]

In this experiment, the grating period d=0.83 [μm]. The short wavelength λ_{min} =522 [nm] and the λ_{max}=562 [nm] can be calculated by equation (3). So, the wavelength band is 522~562 [nm], the width is 40nm.

The halogen lamp with the wide wavelength band was used as the light source. The light from the halogen lamp with the incident angle (θ_{in}=44.21[deg.]) is diffracted by the grating. Then, the first-order diffraction of light passed through the object lens and it is reflected by the variable phase filter that is installed at the angle of 45 degrees on the Fourier transform plane. Then the reflected beams form an image on the camera (Maker: SONY, Type: XC-75) through the imaging lens.

The experimental results of the narrow wavelength band for the reference light by the quantitative bandpass plate as shown in figure 4. Phase differences are given to the half flux of objective rays by variable phase filter. We confirmed the changes of imaging intensities with interference phenomenon on whole area of the observation image. Because the curve of interferogram is nearly same the sine curve, the single wavelength is approached. A bright-line spectrum that is transformed by Fourier transform from the interferogram.

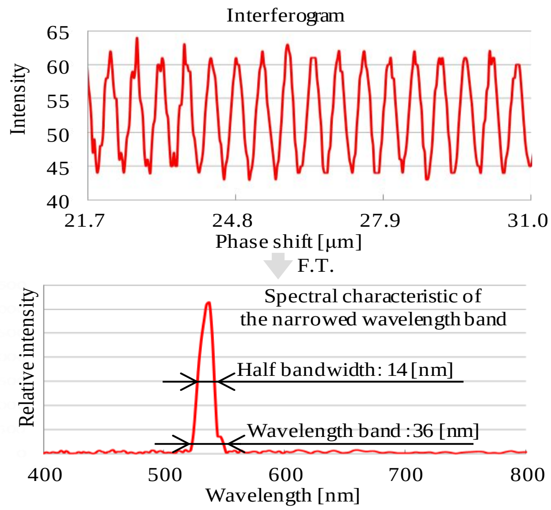

Figure 07

The bright-line spectrum has the half bandwidth 14nm and the wavelength band about 36nm which is very nearly about the calculated value 40nm. So, the narrow wavelength band from the wide wavelength band was obtained by the proposed quantitative band-pass plate. Thus, the nearly single wavelength which is obtained by the quantitative band-pass plate as the reference light can be expected.

E. Background Correction Method

a. Light source fluctuation error correction

Light source fluctuation error is the low frequency signal compared to the signal frequency. Therefore in this approach, low frequency signal which included in the interferogram is to be extracted. Following steps were used to extract the low frequency signal associated with signal frequency.

1. Apply moving average filter
2. Then, calculate the square of intensity
3. After filter using buttorworth low pass filter
4. Take the square root of filtered data

Moving average filter was applied to reduce random noise without deteriorating the original signal shape. Equation of moving average filter is given in equation (4).

$$y[i] = \frac{1}{M}\sum_{j=0}^{j=M-1} x[i+j] \qquad (4)$$

In our interferogram , 12 data points have been collected during one cycle. Therefore, we selected M =3. Then square of intensity values were taken. This will result the all positive values so that any envelop can be easily detected. Butterworth filter is the recursive filter which has excellent passband response.

$$x'_n = a_0 x_n + a_1 x_{n-1} + a_2 x_{n-2} + b_1 x'_{n-1} + b_2 x'_{n-2} \qquad (5)$$

Where, $x'_n = filtered\ output\ data$, $x_n = Unfiltered\ Data$, $a_0 \sim b_2 - Filter\ Coefficien\ ts$

$n = Sample\ number$

Coefficients $a_0 \sim b_2$ are functions of cut-off frequency and sampling frequency. By applying Butterworth lowpass filter high frequency components can be eliminated. Taking square root of filtered signal law frequency signal can be extracted. This extracted signal will be used to correct the light source fluctuation error in the interferogram.

Intensity values were collected using imaging type 2-Dimentional Fourier Transform Spectroscopy and Figure 8 shows the interferogram. Light source was the He-Ne laser light.

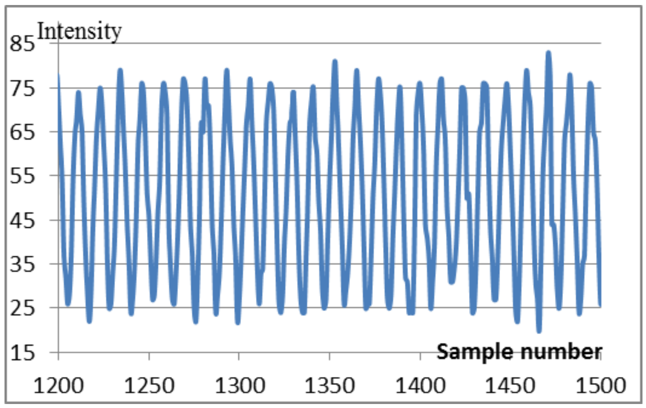

Figure 08. Interferogram obtained using imaging type 2D Fourier spectroscopy

Figure 9 shows the extracted law frequency signal and Figure 10 shows the corrected interferogram with original interferogram.
Using Figure (10), it is clear that the error has been reduced from the original interferogram. Figure (11) show the spectral characteristics.

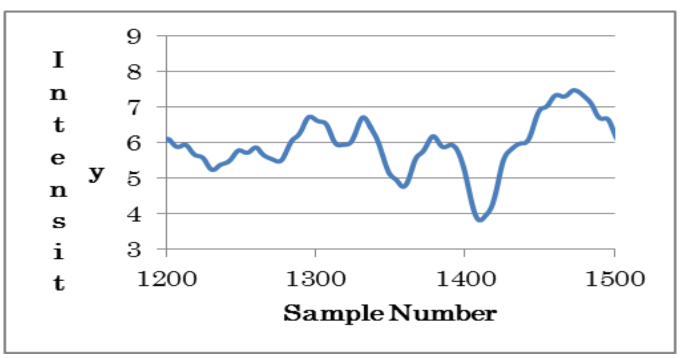

Figure 9. Extracted low frequency signal

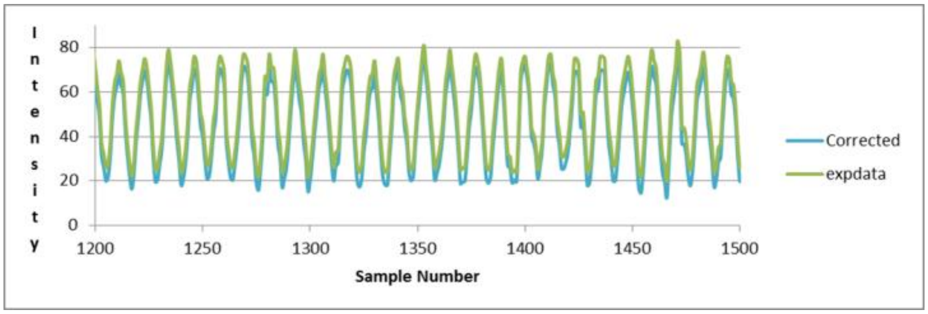

Figure 10. Corrected interferogram

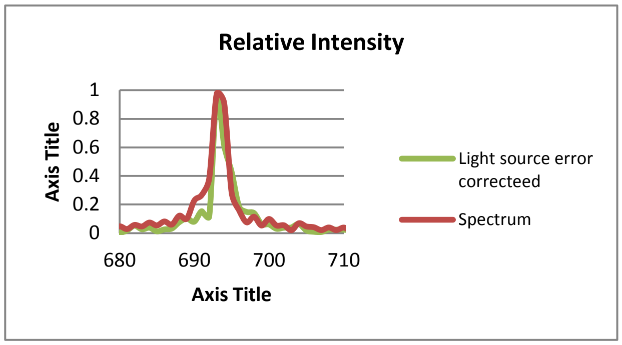

Figure 11. Spectral characteristics of corrected signal

b. Phase shift error Correction

This section explains the effect of phase error and correction algorithm. Equation of Interferogram is given by

$$S(\delta) = \int_0^{\infty} B(\tilde{\upsilon}) \cos 2\pi \tilde{\upsilon}(\delta) d\tilde{\upsilon} \qquad (6)$$

If the interferogram has the retardation of $-\varepsilon$, equation (6) can be modified and it is given by equation (7).

$$S(\delta) = \int_0^{\infty} B(\tilde{\upsilon}) \cos 2\pi \tilde{\upsilon}(\delta - \varepsilon) d\tilde{\upsilon} \qquad (7)$$

Phase error is wave number dependent. Therefore

$$S(\delta) = \int_0^{\infty} B(\tilde{\upsilon}) \cos 2\pi \tilde{\upsilon}(\delta - \theta_{\tilde{\upsilon}}) d\tilde{\upsilon} \qquad (8)$$

Expanding cosine term, equation (9) can be obtained.

$$\cos(\alpha + \beta) = \cos\alpha \cos\beta + \sin\alpha \sin\beta \qquad (9)$$

According to above eqation, phase error add the sine component to the cosine interferogram. Removing this sing part or effect of this sine part is called **Phase Correction.**

Object of the phase correction is to produce true spectrum. Recorded interferogram is given by the equation (10).

$$J'(\delta) = \int_{-\infty}^{+\infty} B'(\tilde{\upsilon}) e^{i2\pi\tilde{\upsilon}\delta} d\tilde{\upsilon} \qquad (10)$$

Using Fourier transform, spectral characteristics can be obtained. A spectral characteristic contains real and imaginary parts. Angle spectrum of can be calculated using those real and imaginary part. This complex transform of spectral characteristics can be represented as given in equation (11).

$$\theta_{\delta} = \int_{-\infty}^{+\infty} e^{-i\theta\tilde{\upsilon}} e^{i2\pi\tilde{\upsilon}\delta} d\tilde{\upsilon} \qquad (11)$$

Taking Inverse Fourier transform, angle variation can be found. Self-convolution of measured interferogram and angle variation gives corrected interferogram

$$J(\delta)=\int_{-\infty}^{+\infty} J'(\delta)\theta(\delta-\delta')d\delta \qquad (12)$$
$$= J'(\delta) * \theta_{\delta}$$

First proposed method was checked using simulation. Interferogram was constructed using personal computer and random error was introduced to it. Then proposed method was applied and error was corrected. Figure (12-a), Figure (12-b) and Figure (13) show interferogram made using computer, error added interferogram and corrected interferogram respectively.

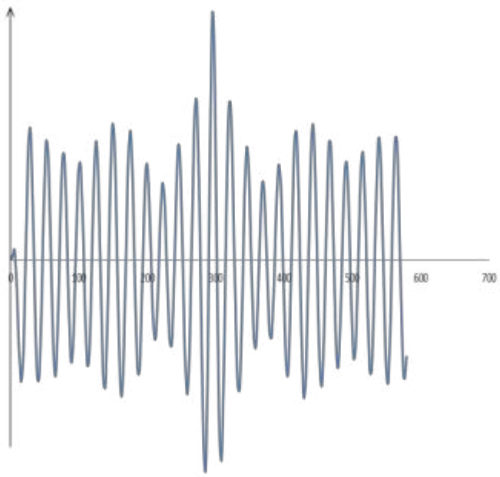

Figure 12-a. Interferogram made by using PC

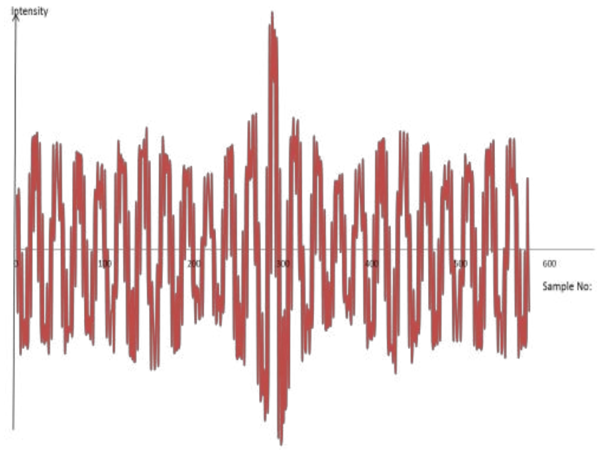

Figure 12-b. Interferogram with random error

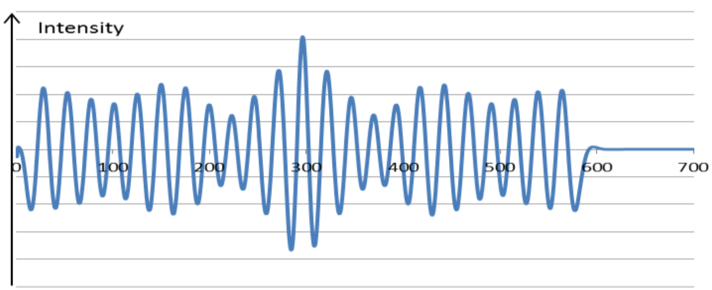

Figure 13. Corrected interferogram

Proposed phase shift correction method was implemented for the data which was obtained from 2 dimensional Fourier transform spectroscopic method. First Noise filtering was done to remove unwanted noise in the measured data. Then, Fouerier transform of interferogram was taken. Then, self-convolution was taken to find the interferogram with slowly varying phase. Due to the self-convolution angle was doubled. Then phase spectrum was found. Now, phase angle spectrum and phase error variation is derived. With suitable shifting variable, phase error spectrum was convoluted with interferogram. Then result was enhanced at fourier domain and Results are shown in Figure (14) and Figure (15).

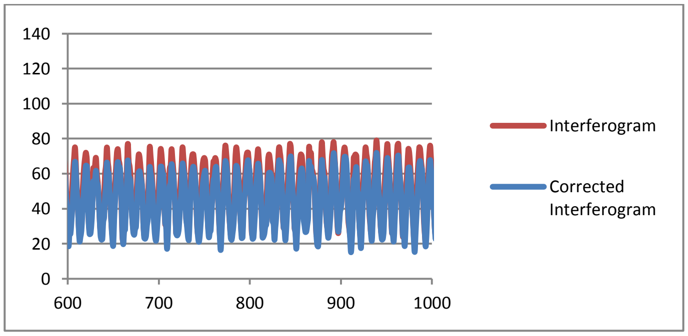

Figure 14. Interferogram

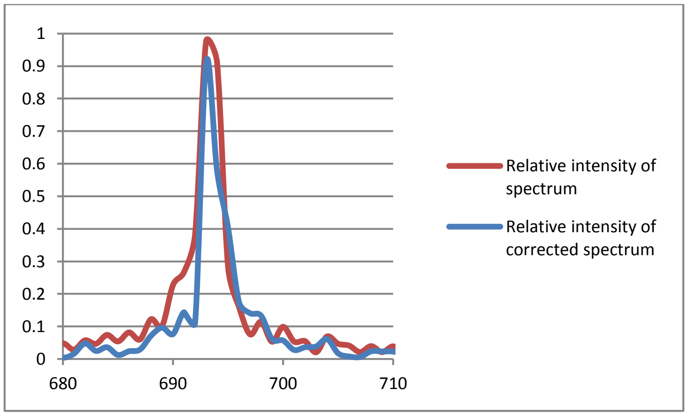

Figure 15. Spectral Characteristics

V. CONCLUSION

The spectroscopic tomography of the living biological tissue in the near-infrared region was successfully acquired. Based on the distinct feature of our method, the spectroscopic tomography near the skin surface was obtained. To realize the non-invasive the blood sugar sensor, the theoretical accuracy of Fourier spectroscopy that was calculated with the numerical simulation. The background correction is very important for the accuracy. There are two error sources which affects the accuracy of the system. Light source fluctuation and phase shift error. This paper proposed the light source fluctuation error correction through the estimation of low frequency error signal. Results showed the method was effective. As the future work, we are working to correct error due to phase shift and to develop solid background correction algorithm,

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