

Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

Sensitivity improvement of one-shot Fourier spectroscopic imager for realization of noninvasive blood glucose sensors in smartphones

Natsumi Kawashima
Kosuke Nogo
Satsuki Hosono
Akira Nishiyama
Kenji Wada
Ichiro Ishimaru

SPIE.

Natsumi Kawashima, Kosuke Nogo, Satsuki Hosono, Akira Nishiyama, Kenji Wada, Ichiro Ishimaru, "Sensitivity improvement of one-shot Fourier spectroscopic imager for realization of noninvasive blood glucose sensors in smartphones," *Opt. Eng.* **55**(11), 110506 (2016), doi: 10.1117/1.OE.55.11.110506.

Sensitivity improvement of one-shot Fourier spectroscopic imager for realization of noninvasive blood glucose sensors in smartphones

Natsumi Kawashima,^a Kosuke Nogo,^a Satsuki Hosono,^a Akira Nishiyama,^b Kenji Wada,^b and Ichiro Ishimaru^{a,*}

^aKagawa University, Faculty of Engineering, 2217-20 Hayashi, Takamatsu 761-0396, Japan

^bKagawa University, Faculty of Medicine, 1750-1 Ikenobe, Miki, Kita-gun, Kagawa 761-0793, Japan

Abstract. The use of the wide-field-stop and beam-expansion method for sensitivity enhancement of one-shot Fourier spectroscopy is proposed to realize health care sensors installed in smartphones for daily monitoring. When measuring the spectral components of human bodies noninvasively, diffuse reflected light from biological membranes is too weak for detection using conventional hyperspectral cameras. One-shot Fourier spectroscopy is a spatial phase-shift-type interferometer that can determine the one-dimensional spectral characteristics from a single frame. However, this method has low sensitivity, so that only the spectral characteristics of light sources with direct illumination can be obtained, because a single slit is used as a field stop. The sensitivity of the proposed spectroscopic method is improved by using the wide-field-stop and beam-expansion method. The use of a wider field stop slit width increases the detected light intensity; however, this simultaneously narrows the diffraction angle. The narrower collimated objective beam diameter degrades the visibility of interferograms. Therefore, a plane-concave cylindrical lens between the objective plane and the single slit is introduced to expand the beam diameter. The resulting sensitivity improvement achieved when using the wide-field-stop and beam-expansion method allows the spectral characteristics of hemoglobin to be obtained noninvasively from a human palm using a midget lamp.

© The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.55.11.110506]

Keywords: one-shot Fourier spectroscopy; tomography; near-common-path wavefront-division phase-shift interferometer; relative inclination phase-shifter; sensitivity improvement; beam expanders.

Paper 160918L received Jun. 14, 2016; accepted for publication Nov. 7, 2016; published online Nov. 30, 2016.

1 Introduction

Recently, the “internet of things” has become a hot topic for researchers worldwide. One result of this development is

that wearable terminals for health monitoring in daily life have appeared. At present, however, only a few sensors can be installed in these terminals, especially when implemented in smartphones. The sensors that are installed in smartphones can only realize a few applications, e.g., pedometers and heart rate monitors. In addition, because spectroscopic imagers for smartphones have not yet been put into practical use, it is currently impossible to measure spectral components using smartphones. The objective of this work is the realization of a noninvasive blood glucose sensor using a proposed one-shot Fourier spectroscopic imager for installation in a smartphone.

Our proposed one-shot Fourier spectroscopic imager¹ is configured with a near-common-path wavefront-division interferometer,^{2,3} is strongly robust against mechanical vibration, and will be realized as a low-cost and small-sized spectroscopic unit (the optical system dimensions are $\sim 5 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}$, which is compatible with the thickness of a typical smartphone) because the imager consists of only three lenses. In addition, the spectral distribution can be obtained with a single shot (using one frame of image data). Therefore, it is easy to perform measurements of active biological tissues because the proposed spectroscopic imager has a high time resolution. Additionally, our proposed method has high resolution and high accuracy⁴ in a similar way to blood glucose sensing by optical coherence tomography⁵⁻⁷ (OCT). OCT can monitor the optical properties of tissue without any unwanted signal from other layers. Our proposed one-shot Fourier spectroscopic imager can also achieve this because of limiting the focal plane and scanning the depth. Furthermore, our proposed method can obtain the spectroscopic characteristics without a refractive index between wanted and unwanted components for confirming the high contrast of the image, and the imager is smaller for installation into smartphones.

To realize a noninvasive medical sensor within a smartphone, it will be necessary to miniaturize the high sensitivity spectroscopic imagers. Demand for compact-size spectrometers already exists and they have been researched,⁸⁻¹⁰ but it will also be necessary for spectroscopic imagers to use the weak reflected light from biological tissues for blood glucose measurements. However, in the conventional microelectromechanical system Fourier transform infrared spectroscopy method, which is based on the use of a Michelson interferometer, the light efficiency is poor because the mirror processing accuracy is low. In addition, acousto-optic tunable filter-based and dispersive spectrometers cannot improve the sensitivity, at least in principle,¹¹⁻¹⁴ because these spectroscopies receive narrowband light. It is therefore impossible for conventional methods to achieve the required wavelength resolution and sensitivity because smartphones cannot accommodate expensive and large-scale cameras with high sensitivity and we cannot use strong light sources that are unsafe for use on human skin.

Because a one-shot Fourier spectroscopic imager introduces a field stop, which is a diffraction grating, into the Fourier transform plane, the resulting spectroscopic method shows a lack of sensitivity.¹⁵ However, we have improved the sensitivity using the wide-field-stop and beam-expansion method while simultaneously maintaining the required wavelength resolution. In this paper, we explain the principle and availability of the method and demonstrate the feasibility

*Address all correspondence to: Ichiro Ishimaru, E-mail: ishimaru@eng.kagawa-u.ac.jp

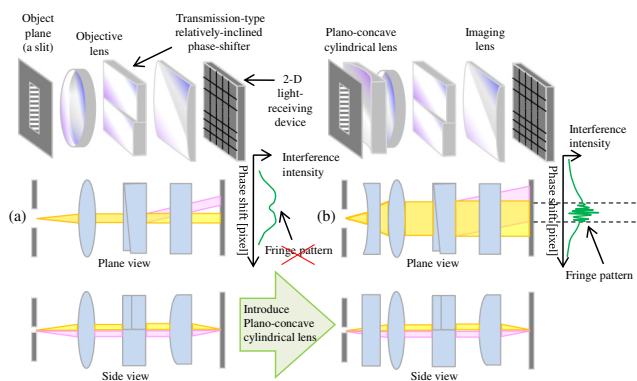


Fig. 1 Principle of the sensitivity improvement method using (a) the wide-field-stop and (b) the planoconcave cylindrical lens.

of biomedical measurements for the realization of a noninvasive blood glucose sensor.

2 Principle of the Wide-Field-Stop and Beam-Expansion Method

In this section, we explain the principle of the wide-field-stop and beam-expansion method for the sensitivity enhancement of one-shot Fourier spectroscopy. One-shot Fourier spectroscopy uses a special phase-shift interferometer, in which the horizontal axis on the imaging device is assigned to the phase-shift value. The spectroscope is a simple optical system that consists of three lenses: an objective lens, a cylindrical lens, which is the imaging lens, and a transmission-type relative-inclined phase-shifter, which is configured using a wedge glass and a cuboid glass.

First, the objective beam is emitted from a single bright point on the object plane and is then collimated by the objective lens. The transmission-type relative-inclined phase-shifter provides a continuous spatial phase difference between the objective beams. Subsequently, two beams are formed by the cylindrical lens on the imaging plane and these beams interfere with each other. We then confirm the interferogram as a fringe pattern spatially. In addition, our proposed method can realize a one-dimensional spectroscopic measurement with one shot (i.e., using a single frame of image data) because interferograms can be obtained simultaneously at each line on the light-receiving device. However, the spectroscopy system has low sensitivity because a slit, which acts as a field stop, is introduced into the optical system.

To increase the detected light intensity, use of a wider slit in the field stop would obviously produce a higher light intensity. However, because our method is based on wavefront-division interferometry, a problem arises where the use of a wider single slit also makes the diffraction angle narrower, as shown in Fig. 1(a). This means that the narrower diameters of the collimated objective beams would cause the visibility of the interferograms to deteriorate. By installing a relative-inclined phase-shifter on the optical Fourier transform plane of an infinity-corrected optical system, the collimated half flux of the objective beams that are derived from single bright points on the objective surface penetrate through the wedge prism and the cuboid glass. The two beams then interfere with each other and form an interferogram in the form of spatial fringe patterns. We thus installed a plane-concave cylindrical lens between the wider slit and the objective lens to act as a beam expander.

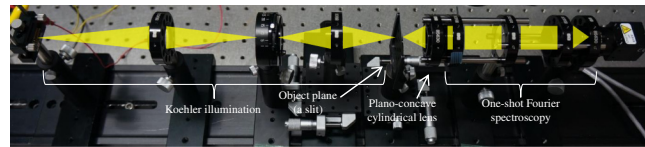


Fig. 2 The optical system used for the verification experiments.

Two main configurations are available for beam expanders: Keplerian and Galilean. In the proposed method, we installed a Galilean beam expander so that the spectrometer may be introduced into a smartphone, as the Galilean beam expander requires a shorter optical path length than the Keplerian device. A Galilean beam expander requires a planoconcave lens, but when we used a planoconcave lens as the Galilean beam expander, the optical path lengths were extended not only on the horizontal axis but also on the vertical axis. We then used a planoconcave cylindrical lens rather than a planoconcave lens to extend the optical path length on the horizontal axis only, as shown in Fig. 1(b), because it avoids cancellation of the adjacent bright spots that prevent us from obtaining the interferogram.¹⁶ As a result, the continuous spatial-phase-difference objective beams coincide with each other on the imaging plane and can be interfered. Therefore, we have improved the sensitivity of the proposed one-shot Fourier spectroscopy method using the wide-field-stop and beam-expansion method.

3 Verification Experiments

We confirmed the results of the wide-field-stop and beam-expansion method through verification experiments, as shown in Fig. 2. In the experiments, the one-shot Fourier spectroscopic imager consisted of an objective lens (focal length of 50 mm), an imaging lens (cylindrical lens, focal length of 50 mm), and a transmission-type relative-inclined phase-shifter. We then structured the Koehler illumination to average the distribution of the light source. We also introduced a planoconcave cylindrical lens (focal length of -25 mm) into the optical system to act as a Galilean beam expander. We used a complementary metal-oxide-semiconductor camera (XCD-MV6, Sony Corporation) on the imaging plane, the slit (horizontal pattern length of $54\ \mu\text{m}$; vertical pattern length of $6\ \mu\text{m}$) on the object plane, and a white light-emitting diode (OSW54L5111P, OptoSupply). The objective beams that were collimated by the objective lens formed on the imaging plane but did not interfere because the beam diameter was short and the beams coincided with each other without the Galilean beam expander. We did not obtain the interferogram and the spectral characteristics of the light source, as shown in Fig. 3(a). However, the objective beams that were collimated by the objective lens formed on the imaging plane and interfered with each other when using the Galilean beam expander. We could therefore obtain the required interferogram and the spectral characteristics of the light source because of the expansion of the length of the beams by the beam expander, as shown in Fig. 3(b). Therefore, we demonstrated the sensitivity enhancement required for the one-shot Fourier spectroscopic imager when using the wide-field-stop and beam-expansion method by confirming the target spectral characteristics and acquiring the

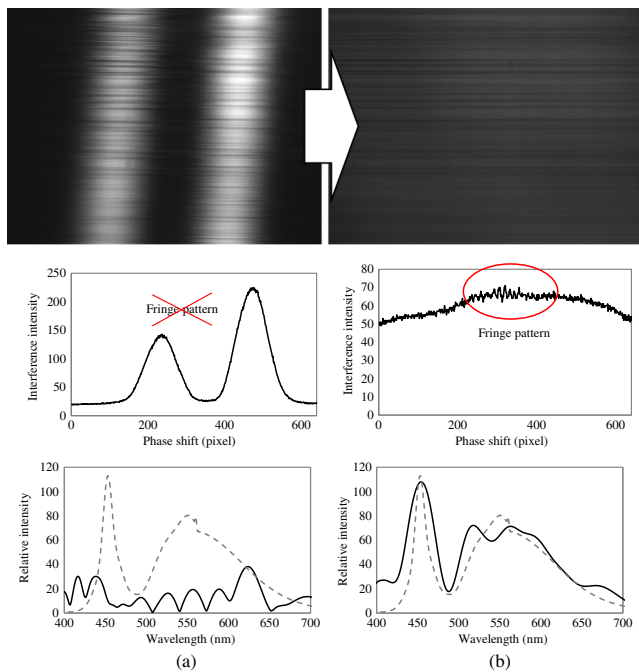


Fig. 3 Results from the verification experiments (a) without and (b) with a Galilean beam expander.

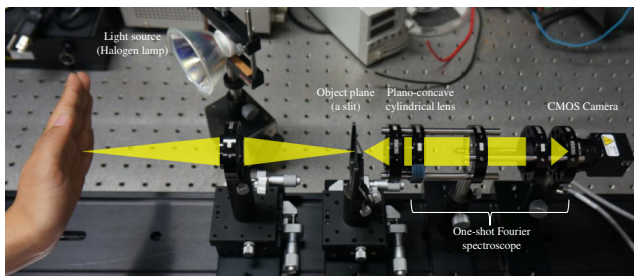


Fig. 4 Optical system used for the biomedical measurements.

interferogram after the amount of light available was increased by expanding the slit width.

4 Biomedical Measurements

We measured the absorbance of rat blood using a dispersive spectrometer (SolidSpec-3700, Shimadzu) and the absorbance of a human hand using the proposed one-shot Fourier spectroscopic imager with enhanced sensitivity. In this experiment, a halogen lamp (JR12V50WLN/NZ/EZ-IR, Ushio) was used as the light source, as shown in Fig. 4. Then we obtained the image and the interferogram as shown in Figs. 5(a) and 5(b), respectively. The two samples show similar absorption characteristics for hemoglobin, with a decrease from 600 to 700 nm and increase from 700 to 900 nm, as shown in Figs. 5(c) and 5(d). We have therefore confirmed the diffuse reflection of light from human skin and have demonstrated the feasibility of performing non-invasive biomedical measurements using the one-shot Fourier spectroscopic imager after the proposed sensitivity enhancement.

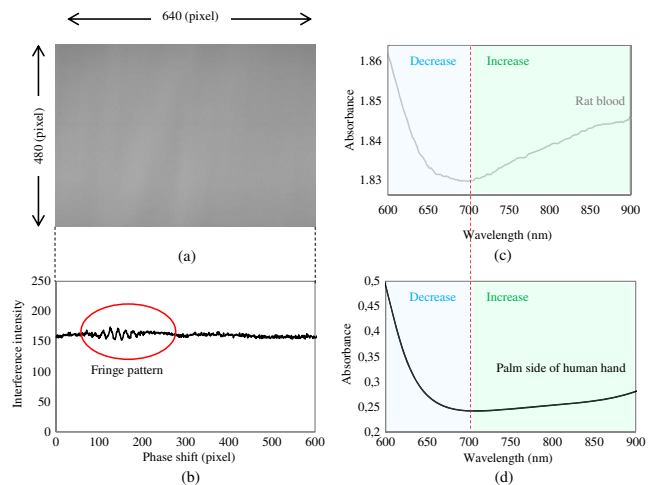


Fig. 5 (a) The image and (b) the interferogram from the biomedical measurements. Absorption characteristics of (c) rat blood and (d) the human hand.

5 Summary

We propose the use of the wide-field-stop and beam-expansion method for sensitivity enhancement of the one-shot Fourier spectroscopy method. We discuss the principles of the sensitivity improvement method, which supports both the sensitivity and wavelength resolution requirements of this spectroscopic method. Additionally, we confirm the suitability of the method through verification experiments and biomedical experiments. We have thus demonstrated the feasibility of realizing a spectroscopic imager that can be installed in smartphones for health monitoring applications.

Acknowledgments

This work was supported by JSPS KAKENHI through Grant No. 2510270.

References

1. S. Sato et al., "Proposal of one-shot-type spectroscopic-tomography for non-invasive medical-measurement," *Proc. SPIE* **8798**, 879801 (2013).
2. J. Szlachetko et al., "Wavelength-dispersive spectrometer for x-ray microfluorescence analysis at the x-ray microscopy beamline ID21 (ESRF)," *J. Synchrotron Radiat.* **17**, 400–408 (2010).
3. Y. Yasuno et al., "One-shot-phase-shifting Fourier domain optical coherence tomography by reference wavefront tilting," *Opt. Express* **12**, 6184 (2004).
4. A. Ishida et al., "Quantitative measurement of biological substances in daily-life environment with the little-finger-size one-shot spectroscopic tomography," *Proc. SPIE* **8951**, 89510Y (2014).
5. H. Ullah et al., "Autocorrelation optical coherence tomography for glucose quantification in blood," *Laser Phys. Lett.* **12**(12), 125602 (2015).
6. K. Larin et al., "Specificity of noninvasive blood glucose sensing using optical coherence tomography technique: a pilot study," *Phys. Med. Biol.* **48**(10), 1371–1390 (2003).
7. R. Esenaliev et al., "Noninvasive monitoring of glucose concentration with optical coherence tomography," *Opt. Lett.* **26**(13), 992 (2001).
8. M. Servin et al., "A novel technique for spatial phase-shifting interferometry," *J. Mod. Opt.* **42**, 1853–1862 (1995).
9. S. Nakadate et al., "Real-time vibration measurement by a spatial phase-shifting technique with a tilted holographic interferogram," *Appl. Opt.* **36**, 281 (1997).
10. S. Murata et al., "Spatial phase-shifting digital holography for three-dimensional particle tracking velocimetry," *Jpn. J. Appl. Phys.* **48**, 09LB01 (2009).
11. Y. Inoue et al., "Variable phase-contrast fluorescence spectrometry for fluorescently stained cells," *Appl. Phys. Lett.* **89**, 121103 (2006).

12. H. Kobayashi et al., "Spectroscopic tomography by imaging-type two-dimensional Fourier spectroscopy," *Optics* **41**, 136–144 (2012).
13. S. E. Harris and R. W. Wallace, "Acousto-optic tunable filter," *J. Opt. Soc. Am.* **59**, 744–747 (1969).
14. J. Kutrašnik et al., "Spectral characterization and calibration of AOTF spectrometers and hyper-spectral imaging system," *Chemometr. Intell. Lab. Lab.* **101**, 23–29 (2010).
15. N. Kawashima, S. Hosono, and I. Ishimaru, "Built-in hyperspectral camera for smartphone in visible, near-infrared and middle-infrared lights region (second report): sensitivity improvement of Fourier-spectroscopic imaging to detect diffuse reflection lights from internal human tissues for healthcare sensors," *Proc. SPIE* **9855**, 985505 (2016).
16. W. Qi et al., "Enhanced interference-pattern visibility using multislit optical superposition method for imaging-type two-dimensional Fourier spectroscopy," *Appl. Opt.* **54**(20), 6254–6259 (2015).