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主　論　文　の　要　旨

論文題目　**Study on high resolution and speckle reduction optical coherence tomography using tunable quasi-supercontinuum laser source**
(波長可変擬似スーパーコンティニュームレーザー光源を用いた高分解能・スペックル低減光干渉断層計に関する研究)

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論　文　内　容　の　要　旨

Biomedical imaging plays a crucial role in the field of medicine by providing abundant information for diagnosis, treatment, and research. For instance, biomedical imaging technology assists doctors in detecting and diagnosing lesions in the early stages of diseases, thereby improving the success rate of treatment. This technology offers real-time anatomical structure information, aiding doctors in precise navigation during surgical procedures. This not only reduces surgical risks but also minimizes the invasion of healthy tissues. In basic scientific research, biomedical imaging is instrumental in providing key insights into life processes, disease mechanisms, and drug actions. These technologies lay the foundation for new discoveries and innovations. Biomedical imaging is irreplaceably significant for the development of modern medicine and the well-being of patients. Through various imaging techniques, doctors can gain a comprehensive understanding of disease states, enabling them to formulate more effective treatment plans.

Since the 1990s, optical coherence tomography (OCT) with micrometer resolution and cross-sectional imaging capabilities has become a prominent biomedical tissue-imaging technique, which continuously picked up new technical capabilities and was gradually being applied to diagnostics in fields such as ophthalmology, gastroenterology, and cardiology. OCT has always been dedicated to fine-scale structure imaging with higher resolution, larger penetration depth, and enhanced image contrast with more detailed information. The progress of OCT imaging technology is inseparable from innovations in the light source, which largely determines the imaging performance of OCT, including sensitivity, resolution, penetration depth, and so on.

This thesis deals with research on 1.7 μm spectral tunable quasi-supercontinuum (SC) source with respect to different applications in biological imaging. The main focus was quasi-SC generation based on wavelength tunable ultrashort pulse source, where the insertion of a fast-optical intensity modulator enables the output ultrashort pulse tuning with high speed. In this way, the quasi-SC spectrum was observed with high tunability in terms of spectral shape, bandwidth, and wavelength range, due to the adjustable intensity modulation function. The successful application in the field of biological imaging is optical coherence tomography (OCT), where quasi-SC source allows for both high-resolution deep tissue imaging and speckle-reduced imaging. Several characteristics of OCT using quasi-SC, such as sensitivity, axial resolution, lateral resolution, penetration depth, and speckle reduction with improved imaging contrast were investigated. To this end, this study is divided into three phases in detail.

First, one important part of the research work was the development and characterization of 1.7 μm quasi-SC source, which is based on wavelength-tunable ultrashort pulse generation and fast intensity modulation. The spectral tunability of quasi-SC output in terms of spectral shape, bandwidth, and central wavelength were investigated by adjustable intensity modulation. Then, the noise property was evaluated with a comparison of conventional SC.

The second part of the research work focused on the investigation of high-resolution deep tissue OCT imaging using a broadband quasi-SC. The characteristics of OCT imaging, including sensitivity, lateral resolution, axial resolution, and imaging depth, were examined for the demonstration of the possibility of quasi-SC as the light source of OCT. Then, the comparison of imaging between quasi-SC and conventional SC for the biological tissue was performed to validate the feasibility of quasi-SC.

In the final stage, the speckle reduction and image contrast enhancement were investigated by using multiple quasi-SC outputs in OCT imaging. The uncorrelated speckle pattern was obtained by utilizing the wavelength tunability of quasi-SC, and the speckle reduction was achieved through compounding average.

The contents of the chapters making up the thesis are listed below with brief summaries:

Chapter 1 Introduction

The background of this thesis has been introduced. At first, the background of the OCT was presented. Next, the development of OCT with respect to the imaging speed, sensitivity, spatial resolution, penetration depth, and imaging contrast was described. The development in these aspects relies on innovations in SD-OCT detection methods, and the choice of light sources. Finally, the purpose and overview of this thesis were presented.

Chapter 2 Theory of optical coherence tomography

The theory of optical coherence tomography, which is based on the Michelson interferometer used in this study was presented. The fundamental theory of interferometer with low-coherence light was explained at first. Then the basic characteristics of interferometer for imaging, such as imaging range, lateral resolution, confocal gating, and lateral resolution, were described. The fundamental law governing the axial resolution, which depends on the full width at half maximum (FWHM) of the interference signal and its shape, was shown to be inversely proportional to the spectral bandwidth of the used light source. The principles of time-domain (TD) OCT and Fourier-domain (FD) OCT were explained. The principle, axial resolution limitations, and detected sensitivity for spectral-domain (SD) OCT were explained. The speckle, an inherent property in OCT, which degrades the image contrast, was explained.

Chapter 3 Supercontinuum and quasi-supercontinuum sources for optical coherence tomography

The supercontinuum (SC) and quasi-supercontinuum (SC) generation for OCT have been presented. The principle of SC and the development of quasi-SC were described. In addition, the optical nonlinear effects in optical fiber are introduced for understanding the spectrum broadening in supercontinuum. The theories of the ultrashort pulse propagation were described with various phenomena in optical fibers such as linear effect (absorption and dispersion) and nonlinear effect (self-phase modulation and stimulated Raman scattering and so on). The interplay of self-phase modulation (SPM) and group-velocity dispersion (GVD), which leads to the soliton pulse formation, was described. The principle of wavelength tunable Raman soliton pulse was also described.

Chapter 4 Development of tunable quasi-supercontinuum laser source

The development of a tunable quasi-supercontinuum (SC) generation at 1.7 μm spectral band has been demonstrated based on wavelength-tunable soliton pulse generation and fast intensity modulation. First, a 1.5 μm Er-doped ultrashort-pulse fiber laser using a SWNT polyimide film was used for seed pulse generation. The ultrashort pulse intensity was amplified to 360 mW of the maximum power by an Er-doped fiber amplifier (EDFA) to obtain a wider wavelength-tunable range from 1600 to 1900 nm. A fast intensity modulator has been inserted between the seed pulse source and EDFA to change polarization-maintaining (PM) fiber-input power continuously and rapidly. After a 300 m PM fiber, many newly shifted Raman solitons have been generated at almost the same time. The observed spectra seemed to be super-continuous. A quasi-SC with a bandwidth of 138 nm and the central wavelength of 1743 nm was obtained. We evaluated and compared the noise properties of quasi-SC, 1750 nm Raman soliton, and 1700 nm conventional SC. The generated quasi-SC exhibited similar noise characteristics compared to 1750 nm Raman soliton and 1700 nm SC below 100 kHz.

Chapter 5 High resolution and larger penetration depth imaging using 1.7 μm broadband quasi-supercontinuum

We have investigated the spectral domain (SD) -OCT performance and demonstrated the highly sensitive, high-resolution OCT imaging using broadband quasi-SC in the 1.7 μm spectral band. First, a Gaussian-shaped quasi-SC with a central wavelength of 1743 nm and a bandwidth of 138 nm was obtained. We connected the quasi-SC to the SD-OCT system. Then, the characteristics of OCT imaging were examined in terms of sensitivity, axial resolution, lateral resolution, and imaging depth successively. We used a reflective mirror to examine the sensitivity and axial resolution. A total imaging sensitivity of 98 dB and an axial resolution of 10.7 μm in tissue sample were obtained. The sensitivity and axial resolution were also examined while tuning the bandwidth and modulation frequency of the quasi-SC source, and the tunability of quasi-SC did not affect the OCT performance. We used a resolution target card to examine the lateral resolution by edge profile method, and the measured value was 33.5 μm. We evaluated the penetration depth in the reconstructed imaging of a human tooth, and the superior penetration depth of 1.6 mm was obtained for quasi-SC. Finally, we successfully observed the cross-sectional image for the samples of tape stacks, human fingertips, and human fingernails. We also repeated the above experimental operations using the 1.7 μm conventional SC, which has close spectral specifications to quasi-SC. The similar index and the compared images indicated that the quasi-SC source is as capable of highly sensitive high-resolution deep tissue imaging for biological samples as the SC source, and confirmed the availability of quasi-SC in realizing high-resolution deep tissue imaging.

Chapter 6 Speckle reduction imaging using tunable quasi-supercontinuum generation

We have demonstrated that a tunable quasi-SC source configured for OCT allowed us to obtain uncorrelated speckle patterns for speckle reduction via the spectral compounding method. First, we generated seven different quasi-SCs, and examined the characteristics of SD-OCT using quasi-SCs in terms of sensitivity and spatial resolution. Similar sensitivity at around 98 dB, close axial resolution at around 17 μm in tissue imaging and lateral resolution at around 33μm were obtained by varied quasi-SCs. Then, we successfully demonstrated the speckle-reduced imaging for the samples of tape stacks and pig thyroid glands. The compounded images had a clearer structure as the speckle noise was suppressed. As the averaging number increased and the difference in the wavelength range became greater, the image quality improved. In tape stack imaging, correlation-coefficients were measured by pairs of initial images obtained by quasi-SC, and the result indicated effectiveness of speckle decorrelation with the spectral tunability. In the imaging of pig thyroid gland, the 1.82 mm penetration depth in low speckle image was examined. We confirmed the improvement of penetration depth for the developed speckle-reduced OCT. The quantitative parameters SNR, C, and CNR were increased by at least 2 dB, 20, and 2 dB, respectively, which corroborated the improved speckle-reduced imaging results.

Chapter 7 Conclusions

The thesis has been summarized, and the conclusions and future prospects of the study have been described. This study achieved high-sensitivity, high-resolution, and large-penetration-depth imaging of biological tissues, as well as speckle reduction imaging, by developing a 1.7 μm quasi-SC light source and integrating it into an OCT system. The quasi-SC source developed in this study is adjustable, allowing for high-resolution imaging by increasing the bandwidth. Its usability in OCT imaging was demonstrated through a comparison with conventional SC source. On the other hand, by changing the detection wavelength of the quasi-SC source and utilizing its spectral diversity output, speckle decorrelation in OCT was achieved, demonstrating its superiority in speckle reduction in OCT imaging. Therefore, the outcome of this research is the development of a variable quasi-SC, providing a new detection light source for OCT imaging. This accomplishment enables multifunctional OCT imaging to aid in the detection and observation of the fine-scale structure of deep biological tissues. Consequently, the results of this study are expected to play a significant role in the development of biology and medicine.