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Detection system for optical coherence tomography - Czerny - Turner spectrometer

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ABSTRACT

Research methods based on spectral analysis have powerful impact on development in many field of science. Signal spectrum can be a source of useful and important data. It enables to obtain information about physical and chemical properties of tested materials.[1 2] This paper has been devoted to describe optical design for high resolution spectrometer, which is significant element of optical coherence tomography (OCT) systems. Designed spectrometer is working in visible range (450 – 830 nm). Czerny – Turner configuration enables to correcting astigmatism and coma aberration over full bandwidth. Moreover, spectrometer has uncomplicated construction. Merely, two mirrors and diffraction gratings allows to design low – cost spectrometer with satisfying optical properties. Spectrum detection has been realized using CMOS line scan sensors with 6144 pixels. It provides high speed and resolution of the system.

Keywords: Optical coherence tomography, Czerny - Turner spectrometer, spectral analysis, optical designing, astigmatism correction

1. INTRODUCTION

Optical coherence tomography is a non-invasive method of investigation of internal structure of materials with micrometer resolution. It enables to cross-sectional and three - dimensional visualization of tested samples. This technique is using optical scanning beam and signal detection based on low-coherence interferometry. Nowadays, OCT is applied in medical diagnosing,[3] especially in ophthalmology. However development of this method, enables to be used in other, non-medicine fields.[4 5] Principally, the systems based on signal processing in spectral domain (SD-OCT – Spectral Domain Optical Coherence Tomography) determine a new development directions. This is due to the progress in speed of imaging in high resolution and it makes, that OCT are real time systems.

2. PRINCIPLE OF OPERATION

OCT systems are using interferometric techniques. The principle of operation consists in analyzing backscattered light form the sample. Figure 1 shows example of simplified OCT system using Michelson interferometer. In case of SD-OCT the broadband light sources have been employed. Wide wavelength range provides better resolution of the OCT systems. To obtain broadband signal superluminescent diodes or supercontinuum are used. For analyzing and detection broadband signals spectrometers are applied.[6]

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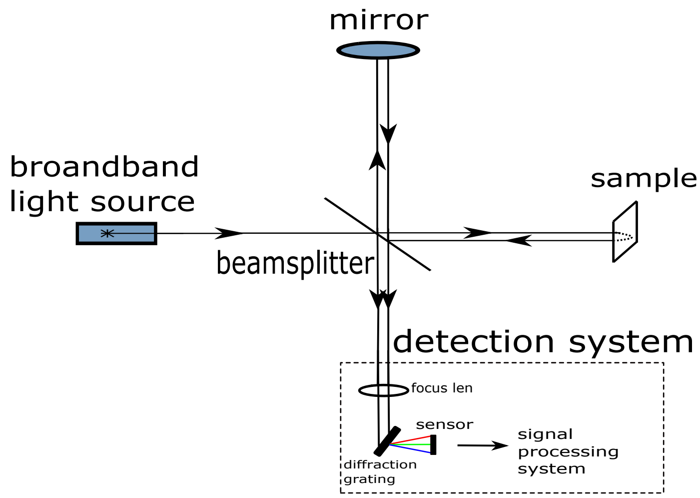

Fig. 1. Spectral Domain Optical Coherence Tomography based on Michelson interferometer.

The light source emits radiation in the visible range to beam splitter. Incident beam is divided into two paths. Radiation in one of them propagates to the mirror. The second path contains tested sample. Radiation is backscattered and both beams come back to the beam splitter. Backscattered light from the sample interferes with reflected beam from the mirror. Interference signal is propagating to the detection system. Detection system is based on Czerny - Turner spectrometer. Figure 2 shows schema of the Czerny - Turner configuration.

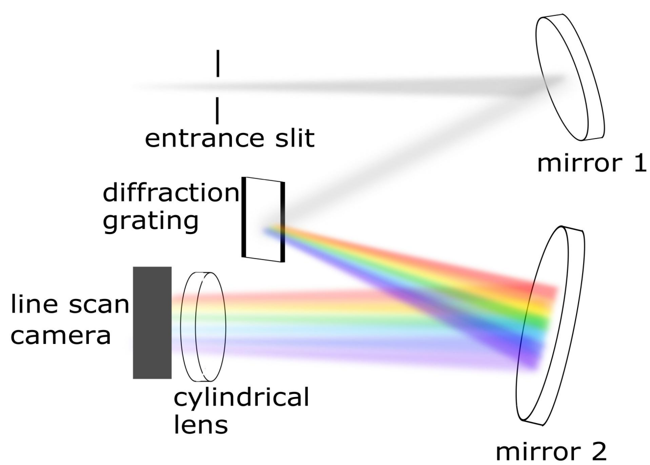

Fig. 2. Diagram of the Czerny–Turner spectrometer.

Presented schema has symmetric construction and contains two mirrors, diffraction grating and cylindrical lens.[7] To record radiation CMOS camera has been applied. This system has been described in details in subsection 3.1

3. REALIZATION

Realization of the Czerny- Turner spectrometer required to choose components of the system. It was necessary to specify parameters of elements and dimensions between them. Moreover, designed system should provide fitting spectral resolution (better than 0.2 nm) and not to introduce optical aberrations.

3.1 Design assumptions

The design and implementation of a spectrometer dedicated to the OCT system requires the determination of metrological properties such as system speed, the spectral range of the light source and others. Based on this data initial values have been evaluated. Results have been summarized in Table 1.

Table 1. Parameters of the system

Parameter	**Value**
Wavelength range	450 – 830 nm
Resolution of the CMOS camera	4096 pixels
Speed of data acquisition of the CMOS camera	more than 20kHz
Length of sensor	43mm
Pixel size	7 µm x 7 µm
Reflected angle from the mirror 1	5^o
Focal length of the mirror 1	75 mm
Focal length of the mirror 2	100 mm
Numerical aperture of the fiber	0.14
Blaze angle of the diffraction grating	$8^o37'$
Dispersion of the diffraction grating	1.65 nm/mrad

The design of the detection system required matching the spectrometer components to OCT system. OCT system has been designed and developed at the department of Metrology and Optoelectronics at Gdańsk University of Technology. The basic parameters ware the spectral range of the source and CMOS camera properties. In this system supercontinuum has been applied. It provides a very broadband spectrum (in visible range). The bandwidth is connected with axial resolution of the OCT system. Axial resolution is one of the most important factors of the OCT system and it is directly related with quality of OCT images.

$$\Delta z = \frac{2ln2}{\pi} \cdot \frac{\lambda^2}{\Delta\lambda}, \tag{1}$$

where Δz is axial resolution, $\Delta\lambda$ is spectral range and λ is central wavelength of the light source.

To implement spectrometer two concave mirrors have been aplied. The mirrors have been covered with the silver coating. Spherical mirrors do not introduce chromatic aberration but they are cause of astigmatism.
The light has been diffracted using blazed diffraction grating. This type of grating is optimal for one order mode. Designed diffraction order is zero. The advantage of this configuration is uncomplicated construction and possibility of compensation of optical abberations. Coma abberation is corrected by the symmetrical design of the spectrometer. However, in this configurations astigmatism remains, what has the effect of different focal lengths in the tangential and sagittal planes. Astigmatism compensation can be ensured using convex cylindrical lens.[8,9]

3.2 Calculations

Using parameters in table 1, Czerny - Turner spectrometer has been designed. This chapter presents all necessary formulas and calculations. The most optimal distances between the components and the bounce angles of the components were calculated. Scheme of the project is presented on figure 3.

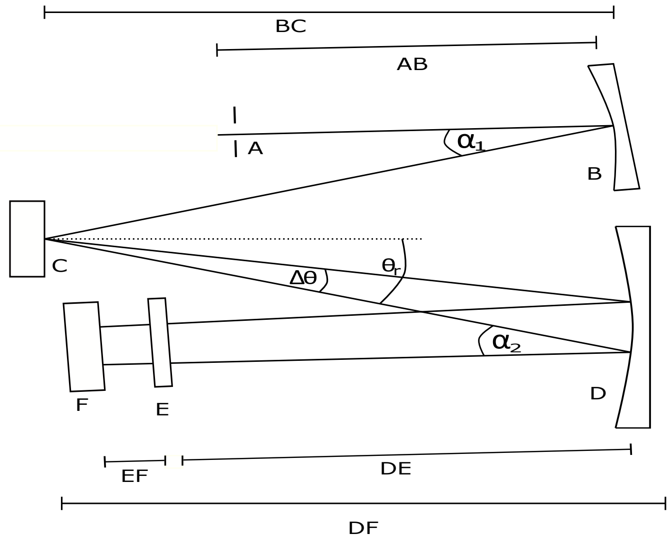

Fig. 3. Project of spectrometer with components: A - entrance slot, B- spherical mirror 1, C- diffraction grating, D - spherical mirror 2, E - cylindrical lens, F - linescan camera.

First of all angle of reflection from the second mirror α_2 and radius of curvature R_2 have been calculated using formulas 2 and 3.

$$\mathrm{tg}(\alpha_2) = \frac{l}{f_2}\,, \tag{2}$$

$$f_2 = \frac{R_2}{2\cos\alpha_2}\,, \tag{3}$$

where f_2 is focal lenght of mirror 2 and l is lenght of detector.
To calculate reflection angle from the diffraction grating $\Delta\theta$ and divergence angle θ_r, bandwidth $\Delta\lambda$, dispersion D and blaze angle γ of diffraction grating must be known.

$$\Delta\theta = \frac{\Delta\lambda}{D}\,, \tag{4}$$

$$\theta_r = \theta_i - 2\gamma\,, \tag{5}$$

To calculate beam diameter Φ reflected from mirror 1 equation 6 has been used.

$$\Phi = 2NA \cdot f_1\,, \tag{6}$$

where NA is numerical aperture and f_1 is focal length of mirror 1. The last stage of the design includes astigmatism correction. Difference in focal length is introduced by spherical mirrors and it has been described by formula 7.

$$\Delta_z = \frac{R_1}{2}\sin\alpha_1\,\mathrm{tg}\,\alpha_1 + \frac{R_2}{2}\sin\alpha_2\,\mathrm{tg}\,\alpha_2\,, \tag{7}$$

To compensate difference in focal length distance between lens and detector L_d must be calculated using formula 8.

$$L_d = \frac{P + \sqrt{P^2 + 4Pf_s}}{2}\,, \tag{8}$$

where $P = \frac{\Delta_z - t_0 \cdot (n-1)}{n}$, t_0 is central thickness of the lens, n is the refractive and f_s is is the sagittal focal length of the lens.

It follows that dimension between lens and mirror L is equal:

$$L = f_2 - t_0 - L_d \tag{9}$$

4. RESULTS

Designed spectrometer Was implemented and tested. Calculated values differ slightly from final values. Final parameters have been summarized in Table 2.

Table 2. Final parameters of the system

Parameter	**Value**
Dimension AB	8.3 mm
Dimension AC	16.7 mm
Dimension DE	10.7 mm
Dimension EF	1 mm
Dimension AB	17.1 mm
α_1	5^o
α_2	22.8^o
$\Delta\theta$	11.74^o
θ_r	13.2^o

The system has been mounted on solid aluminum breadboard. The construction is compact and easy to modify. Figure 4 presents a photo of the system.

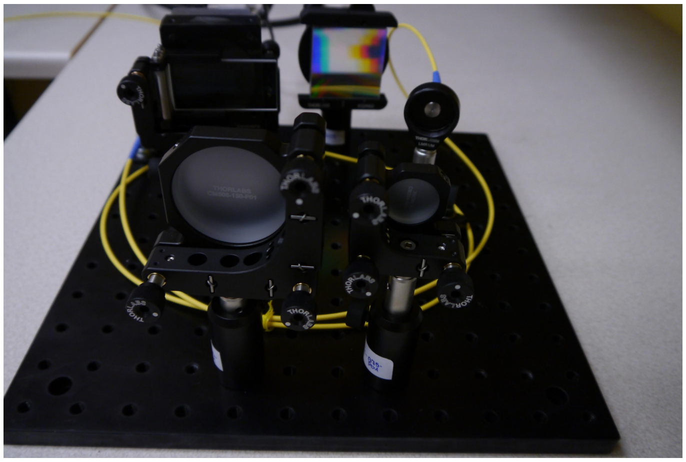

Fig. 4. Realized project of Czerny - Turner spectrometer.

Data acquisition and analysis of measurement data is made using an application designed in the National Instruments LabView environment. The application enables also control of the system.

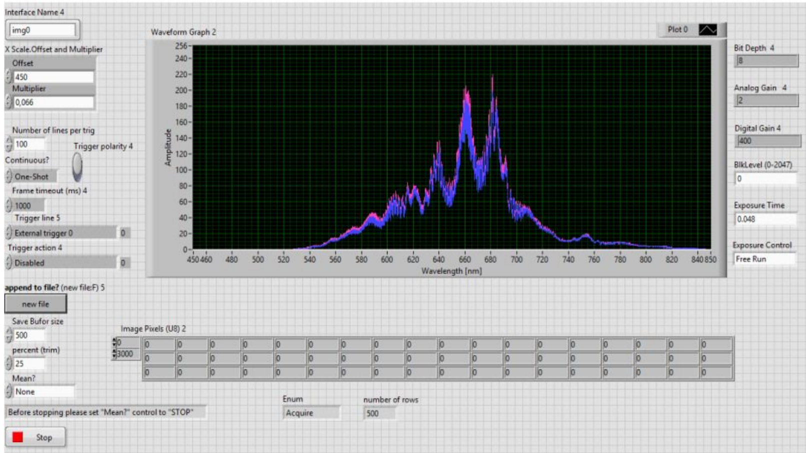

Fig. 5. User interface in LabVIEW program for data acquisition and analysis of measurement data.

5. CONCLUSION

Realized Czerny - Turner spectrometer is comply with assumptions. Broadband astigmatism has been corrected using cylindrical lens. This project is characterized by low - cost and easy construction using unsophisticated optical elements. Moreover, it provides correct optical properties.

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