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ENHANCING EYE IMAGING MODALITIES WITH ACOUSTO-OPTIC INTERACTION

Ireneusz Grulkowski[1*] **Daniel Ruminski**[1]
[1] Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Toruń, Poland

ABSTRACT

Optical imaging of the eye is a common clinical procedure in the diagnosis and management of the ocular disorders. Rapid advances in photonics technologies enabled development of optical modalities for diagnostics and management of ocular pathologies. Confocal Scanning Laser Ophthalmoscopy (cSLO) is a confocal microscope modality for visualization of the fundus of the eye. Optical coherence tomography (OCT) is a non-invasive imaging modality enabling generation of micrometer resolution, two-dimensional cross-sectional images and three-dimensional volumetric data presenting internal structure of ocular structures. Acousto-optic interaction facilitates ultrafast manipulation of the optical beam through precise shaping (modulation) of the wavefront. In particular, focus tunable lenses are active optical components that enable engineering of light delivery in optical imaging systems. Acousto-optic devices allow for enhancement of the performance of eye imaging instrumentation. Integration of acousto-optic lenses into OCT and cSLO systems enable improved in vivo imaging of the human eye.

Keywords: *acousto-optics, tunable focus, acousto-optic lens, imaging, ophthalmology, optical coherence tomography.*

[*]***Corresponding author***: *igrulkowski @fizyka.umk.pl*

1. INTRODUCTION

Acousto-optics is a branch of physics devoted to fundamental and applied studies of interaction of light with ultrasound. When an acoustic wave travels through an optically transparent material, periodic variations in the refractive index are generated—a phenomenon known as the photoelastic effect. This modulation appears as a dynamic diffraction grating, allowing the light to be modulated, deflected, or shifted in frequency depending on the acoustic signal. By leveraging the interaction between acoustic waves and light within a medium, acousto-optic devices such as modulators (AOMs), deflectors (AODs), tunable filters (AOTFs) and tunable lenses (AOLs) can dynamically alter the intensity, frequency, and direction of light beams in real time with high speed and precision [1]. Those components are currently widely used in imaging, telecommunications, spectroscopy, and laser systems. The advantages of acousto-optic technologies such as non-mechanical operation and rapid response times, make them especially valuable in modern optical and biomedical applications [2].

Eye imaging has become a standard procedure in modern ophthalmic diagnostics, offering visualization of ocular structures essential for early disease detection and monitoring. Advances of optical imaging modalities observed in last few decades provided tools for non-invasive and high-resolution assessment of subtle changes in tissue architecture and functionality, which are crucial for early diagnosis of the conditions like glaucoma, cataract, diabetic retinopathy, macular degeneration, and retinal vascular diseases.

As an important family of photonics industry, acousto-optic devices have been employed in ophthalmology related techniques, offering precise, high-speed control of light. Although we concentrate on imaging modalities, non-imaging applications of acousto-optics in ophthalmology include also modulation of the intensity and duration of laser pulses, thus enabling precise targeting of ocular tissue during laser surgical procedures while minimizing damage to surrounding healthy structures.

2. ACOUSTO-OPTICS IN OPTICAL COHERENCE TOMOGRAPHY

Optical Coherence Tomography (OCT) is an interferometric modality that detects light that is back-scattered or back-reflected from the internal structures of the object. High-sensitivity and high axial resolution independent on numerical aperture of the objective lens enable OCT to generate cross-sectional or three-dimensional (volumetric) images of the semi-transparent objects such as ocular tissues. OCT has become an indispensable tool in ophthalmology, particularly for high-resolution imaging of the retina and the anterior segment. In recent years, the incorporation of acousto-optic (AO) technology into OCT systems has introduced substantial improvements in imaging speed, precision, and system adaptability.

One of the key contributions of acousto-optics to OCT is the implementation of acousto-optic deflectors (AODs). These devices allow for fast, inertialess beam steering by changing the frequency of the acoustic wave propagating through the crystal. In contrast to traditional mechanical scanning systems, AODs provide high-speed lateral beam scanning across the eye without moving parts. This non-mechanical approach significantly reduces motion artifacts through minimization of the examination time, which translates into improvement of patient comfort during imaging procedures [3].

Furthermore, acousto-optic tunable filters (AOTFs) are widely used in swept-source OCT systems, where rapid and precise wavelength selection is required in wavelength-tunable laser technology [4, 5]. AOTFs enable dynamic control over the central wavelength and bandwidth of the swept laser, facilitating fast tuning speeds (and high axial scan rates) essential for real-time imaging. Additionally, the flexibility of AOTFs supports advanced imaging techniques such as spectroscopic OCT, where wavelength-dependent tissue contrast can provide further diagnostic insights.

The integration of acousto-optic modulation also improves signal processing in OCT systems. For example, acousto-optic modulators (AOMs) can be employed for frequency shifting in interferometric detection schemes, helping to separate signal from noise and enhancing image contrast. This is particularly useful when the tissue is characterized by low scatter.

In addition, acousto-optics facilities enhancement of OCT image quality in terms of scan depth. Acousto-optic lenses enable fast focus tuning. When a series of OCT images is acquired at instances corresponding to different focusing depths, appropriate averaging of OCT scans results in effective extension of the depth of focus of scanning beam, which in turn improves signal in OCT image [6].

3. ACOUSTO-OPTICS IN CONFOCAL SCANNING LASER OPHTHALMOSCOPY

Confocal Scanning Laser Ophthalmoscopy (cSLO) constitutes another retinal imaging technique that enables high-resolution, real-time visualization of the retina and optic nerve head. Unlike traditional fundus photography, which captures a wide-field static image, cSLO uses a focused laser beam that scans across the retina. Like in confocal microscopy, a confocal pinhole is used to block out-of-focus light, allowing for sharp and high-contrast images of specific retinal layers. cSLO is widely used in ophthalmology for diagnosing and monitoring diseases such as glaucoma, macular degeneration, and diabetic retinopathy. Confocal SLO systems can be integrated with acousto-optic lenses to enable high-speed, inertialess axial scanning (z-scanning). Those approaches allow for rapid volumetric imaging of ocular structures.

4. CONCLUSIONS

Overall, acousto-optic technologies have contributed to the development of more compact, faster, and more stable OCT systems for ophthalmic applications. The advantages of acousto-optic devices allow for elimination of mechanical components, facilitate better image quality by high-speed scanning and support real-time visualization of ocular structures. As research advances, further integration of acousto-optic components is expected to enable even more powerful imaging systems.

5. REFERENCES

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