Stereoscopic 3-dimensional spectral imaging systems based on a single acousto-optical tunable filter

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Abstract. The novel technique for 3-dimensional (3D) spectral imaging is proposed. It is based on simultaneous spectral acousto-optic filtration of a pair of stereoscopic convergent light beams via single acoustic wave. A few promising configurations of such acousto-optic tunable filters (AOTFs) is proposed, discussed and compared. It is shown that these elements may be ultra-compact and PC controlled modules, ready to be integrated into many existing schemes of stereoscopic 3D imagers. The experiment carried out with the help of single-AOTF-based spectral stereomicroscope demonstrates the efficiency of proposed technique.

1. Introduction
Imaging acousto-optic tunable filters (AOTFs), in which dynamic ultrasound grating provides effective spectral filtration of light, nowadays have a lot of applications in spectroscopy [1-3]. These filters have no moving elements and provide fast (less than 1 ms) arbitrary spectral addressing in the wide range (up to 400 nm), rather high spectral (up to 0.1 nm) and spatial (up to 1000 resolved elements along each direction) resolution. Among the most promising applications are microscopy, aerial photography, machine vision, where the spectral filtration in the particular wavelengths produces contrast patterns of physical, chemical and other properties of the inspected objects. The multi- and hyperspectral imaging reveals important additional features in comparison with the ordinary color visualization.

In particular, two-dimensional (2D) spectral imaging is used for 3D structure reconstruction by means of spectral-domain optical coherent tomography thus providing information about the location and the shape of the inner elements in the object of interest [4]. At the same time, there are many optical 3D imaging techniques (stereomicroscopy, 3D television) which do not use spectral filtration. And they obviously can be more effective with use of the spectral characterization.

General outline of this tendency is illustrated in Fig. 1. Addition of any new dimension to the imaging system $I(x,y)$ provides essentially new capabilities: either 3D imaging $I(x,y,z)$ or spectral imaging $I(x,y,\lambda)$. And incorporation of both coordinates ($z$ and $\lambda$) provides even more information. In Fig. 1 two possible approaches to the development of 3D spectral imagers are shown: departing from 2D spectral systems or from 3D systems. In the first way, it is necessary just to combine two ordinary spectral imagers into the stereo system. But probably the most direct way is an integration of filters

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into the existing 3D system. In this way, for example, stereomicroscopes are often supplied with a set of color glass filters. However, it is not enough for precise spectrum characterization.

**Figure 1.** Evolution of optical systems from an imaging system to 3D spectral imager.

Utilization of an AOTF may solve this problem. However, unlike glass filters, the integration of AOTF into the system encounters some difficulties. Available AOTFs cannot be used for these purposes without significant upgrade. One needs either rather small AOTFs to insert them in both channels of the conventional stereoscopic system or very large AOTF with the input aperture filtering two parallel spatially separated light beams. Moreover, a pair of small AOTFs must be identical to ensure the same spectral dependence \( \lambda(f) \) on ultrasound frequency \( f \). For a large AOTF, there should be provided identical conditions of light acousto-optic interaction of both stereoscopic beams. The divergence and attenuation of ultrasonic wave may lead to significant difference of image distortions between two channels.

Thus, this straightforward approach for the development of 3D spectral imagers is not ideal. Therefore, it is necessary to analyze other ways to create and implement specialized AOTFs which are capable to filter two stereoscopic beams in the same volume by the same ultrasound column. This requirement is non-trivial as the Bragg condition of diffraction unambiguously associates the incident angle of light beam, selected wavelength, ultrasound parameters and aberration characteristics [5]. To find an appreciable solution of the described problem, it is necessary to analyze the whole optical system including the principles of diffracted stereoscopic beams detection. Classical stereoscopic systems form stereoscopic images directly at operator’s eyes for visual observation or project these images on the screen for the observation via special glasses [6]. Two stereoscopic beams must be distinguishable at least by one characteristic of light: incident angle \( \Theta \), polarization \( p \), wavelength \( \lambda \). And also they can be separated in time \( t \). In each of these modes detection principles is different: while the angle-separated beams can be observed directly, the beams differed in polarization or wavelength can be detected via polarization or spectral glasses accordingly. And for the time-divided beams synchronously switched glasses are used.

Ultrasound-controlled AO cell is capable to operate any of these physical characteristics (Fig. 2). Consider the incident light beam propagating in the direction \( \mathbf{m} \) and characterized with ordinary (‘o’) or extraordinary (‘e’) linear polarization \( p \). The wavelength of diffracted light \( \lambda \) is defined by the ultrasound frequency \( f \) and the incident angle \( \Theta \). The polarization \( p' \) of the output beam and its propagation direction \( \mathbf{m}' \) (and accordingly output angle \( \Theta' \)) are determined by the crystal shape and the ultrasound characteristics. The intensity of diffracted beam \( I(t) \) repeats the time variations of the
ultrasound power \( P(t) \). Therefore, AOTF changes one or few parameters of the light beam and may be used in each operation mode.

It should be noted, however, that one of the mentioned above methods (spectral) of the stereopair separation is not applicable for 3D spectral imaging because it requires identical wavelengths \( \lambda \) for both stereoscopic beams after AO diffraction. Three other methods are examined in this paper.

**2. Configurations of single AOTF-based 3D spectral imagers**

2.1 Angular separation of stereo images

For this method the wave vectors \( k = (2\pi m/\lambda) \) of two stereoscopic light beams must have the same amplitude but different directions \( \theta_1 \) and \( \theta_2 \). It is realizable by means of anisotropic diffraction (Fig. 3b). Additional condition is “wide-aperture” filtering [7] which leads to the single solution (i.e. single configuration) for each incident angle \( \theta \). The difference between the angles \( \theta_1 - \theta_2 \) may vary from 0 to the maximal value defined by the refractive indexes of the AO cell \( \Delta n = n_e - n_o \). So, one can choose the angle \( \theta_1 - \theta_2 \) so that both beams provide necessary separation angle after diffraction. Optical scheme for this method is shown in Fig. 3a.

2.2 Time separation of stereo images

Stereoscopic systems with time separation of images use the single image sensor while two images are alternatively demonstrated. An appropriate AOTF-based optical spectral imager is presented in Fig. 4.
Two channels are formed with input optomechanical system comprising two slits 8, two static mirrors 9 and bi-position mirror 10 (Fig. 4a,b). The basic path of the system is the same for both channels: objective 2, polarizers 3, 5, AO cell 4, output lens 6 and photodetector 7. For visual perception, time-synchronous glasses are used. The main advantage of the scheme is that most elements are used in both channels. It allows the development of devices with relatively simple and compact design. Time separation may be implemented also by the use of specialized AOTF. It is possible to provide such incident angles $\theta_1$ and $\theta_2$ that corresponding frequencies of ultrasound $f_1$ and $f_2$ will differ greatly (Fig. 4c,d). Then, filtration of both beams may be done by varying $f$. Changing the frequencies $f_1$ and $f_2$ but keeping the ratio $f_2/f_1$ other wavelengths may be selected. It may be done in a particular spectral range out of which one acoustic frequency matches two different wavelengths $\lambda$ in the stereoscopic channels. To limit the range it is necessary to insert additional band-pass filter. Changing this filter it is possible to change the spectral range.

2.3 Polarization separation of stereo images

Imaging AOTFs use the change of polarization mode for spectral selection the light. This fact can be exploited in the separation of stereoscopic beams. If two incident beams ($k_1$, $k_2$) have different polarizations: ordinary («o») and extraordinary («e»), then diffracted beams ($k'_1$, $k'_2$) also differ in polarization (Fig. 5b) and can be separated by polarizing glasses.

However, two conditions must be fulfilled: first, the diffraction of both beams must meet wide-aperture condition [7] and, second, both beams must be diffracted via the same acoustic wave $q$. These two requirements can be completed with an extra condition, assuming that both diffracted beams propagate in the same direction. As it follows from the analysis of formulae describing wide-aperture diffraction [8], for each angle of diffraction $\theta_{day}$ there are single values of incident angles $\theta_1$, $\theta_2$ and ultrasound direction angle $\gamma$. Then, one can define the optimum angles [9] corresponding to the maximum value of stereo parallax ($\theta_2-\theta_1$):
\[ \theta_1^{opt} = \arctg \left( \left( \frac{n_r}{n_o} \right)^2 \right), \]
\[ \theta_2^{opt} = \arctg \left( \left( \frac{n_r}{n_o} \right)^2 \right). \]

The principle implementation of this scheme is shown in Fig. 5a.

**Figure 5.** Optical scheme of single AOTF-based 3D spectral imager with polarization separation of stereo images (a) and corresponding wave vectors diagram (b)

### 3. Example. AOTF-based stereo microscope

To prove the effectiveness of single-AOTF 3D spectral imagers the device based on stereomicroscope was developed and tested. AOTF with two entrance pupils was integrated into the optical scheme of Abbe stereomicroscope after zoom lenses where the light beams in both channels are parallel to the optical axis [10]. It provides the identical geometry of AO interaction for both beams.

The wavelength to be selected is assigned by the user via PC. Controller board, radiofrequency generator and two amplifiers are integrated into AOTF. Illumination from the inspected object is collected by the microscope objective, is transmitted through set of zoom lens. After AO filtration spectral image is formed by tube lenses and may be observed through the oculars or focused on the detector of video camera.

**Figure 6.** Stereoscopic spectrometer based on Abbe microscope

| a) optical scheme: 1 – inspected object, 2 – common main objective, 3 – stereo zoom lens, 4,6 – polarizers, 5 – AO cell, 7 – tube lenses, 8 – image inversion, 9 – eyepieces, 10 – objectives of digital cameras, 11 – registered images |

In Fig. 7a the stereoscopic images I and II obtained by the device described are shown. The 3D structure of blood smear reconstructed by means of digital image processing [11] shows vividly an erythrocyte among all other cells (Fig. 7b). Such a 3D imaging system may be useful in biology – for contrast selection of 3D elements in various objects, medicine – for cytometry, gemology – for discovery and localization of foreign inclusions, research of plasma – for visualization of chemical composition and temperature distribution and many other applications.
4. Conclusion
For the first time, the implementation of single-AOTF-based stereoscopic 3D spectral imaging is analyzed. It is shown that there are several AOTF configurations applicable for spectral filtration of two stereopair beams. All the schemes are divided into three classes based on angle, time and polarization separation. The experiment with use of the single dual-channel AOTF shows the principal efficiency of AOTF-based 3D spectral imaging.
In future, 3D spectral imagers based on proposed AOTF configurations may be widely used for 3D image reconstruction in microscopy, film industry and other fields.

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