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Spectral instruments based on acousto-optical tunable filters: advantages and prospects

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Brief review of modern spectral techniques and instruments based on acousto-optical tunable filters (AOTF) is presented. New approaches for spectrometers and spectral systems development are considered. There are presented and described a series of compact spectrometers and spectrophotometers of ultra-violet, visible, and infra-red ranges for Raman, fluorescence, and absorption spectroscopy for various applications, including out-of-door measurements, spectroradiometers for environment monitoring (open air, Earth surface, and depth seawater), specialised spectral equipment for industrial monitoring (microelectronics, alcoholometry), imaging spectral devices, and instruments for differential spectroscopy.

Also some fundamental problems of AOTF-based spectroscopy are considered: spectrogram correction of instrument function distortions, spectral resolution of different methods, modulation techniques for instrument function synthesizing, optimization of measurement procedures, including adaptive algorithms. Basic trends of past 30 year's AOTF-based spectroscopy development are formulated. The most promising ideas are discussed.

1 Introduction

Acousto-optical tunable filters (AOTF) are optical elements controlled via ultrasound [1]. Therefore, to study all their capabilities one should consider both optical and acoustic aspects of the device. Here, we present comprehensive analysis of AOTF functionalities and a review of AOTF-based devices. Also there are listed basic problems related to measurements accomplished with such instruments. In conclusion, basic trends of acousto-optical spectral instruments developments are formulated.

2 Acousto-optical tunable filters

AOTF is tripolar element having optical input and output, and acoustic driving terminal. And spectral window λ_f is determined by ultrasound frequency *f*. In comparison with other optical filters, AOTF exhibits a lot of important features, which can be for convenience divided in three groups. The optical features possess large optical aperture and wide input angle (∅ 1 cm × 2°), rather high (for compact devices) spectral resolution ($\lambda/\Delta\lambda \sim 10^3$), and imaging quality. Its mechanical properties are characterized by no-moving-parts design, compact sizes, low power consumption, so that AOTF can be efficiently used for out-of-door measurements. The third group of features is specified by filter exceptional wide controllability, which is accomplished with help of volume phase grating inside crystal generated by acoustic wave. First, it makes possible quick tuning (respond time equals to ultrasound propagation time 10^{-5} s). Second, jumping at any wavelength takes the same time, therefore filter can be addressed arbitrary. Third, generated diffraction grating can be apodized via acoustic wave intensity variation that results in changing transmission function (TF) of filter. This collection of properties specifies potential areas of applicability of AOTFs.

In particular, acousto-optical filters are used as pre-selector in combination with other spectral elements, for example, Fabry-Perrot interferometers [2], echellet diffraction gratings [3] and also with other acousto-optical filters. For example, a pair of identical AOTFs ensures at least one order extra suppression of out-of-window transmission coefficient. Basic problem of double monochromator production is creation of pair identical acousto-optical cells [4]. Manufacturing technique developed have made possible regular production of spectrometers of various types providing double monochromatization.

Nowadays there exists a variety of AOTF types, which use different diffraction geometries, various means of sound waves excitation, all available crystal materials for operation in different spectral ranges. Most of them are built in accordance to classical diagram. Various filters correspond to this diagram, including collinear AOTFs having light beam along sound column, as well as backward-reflection mode filters, where light diffracts at angle 180° [19].

Another design have multi-channel filters, which comprises several piezotransducers in the single crystal. This approach is used for spectral range expansion as resonant transducers generated ultrasound only covers single octave. With multi-section transducer this configuration can be used for variation of acoustic field cross-section for apodization purposes.

One more AOTF group should be emphasized, which are similar in structure to classical ones, but differ in driving signal complexity. It contains multi-frequency filters, which are fed with several frequencies and provide multiple windows [5,6]. There are also modulation filters, where acoustic wave is modulated along its direction that leads to AOTF transmission function apodization. [7].

3 AOTF-based instruments

With use of AOTF elements a variety of spectral instruments were created. Simplest spectroradiometer, beside AOTF, comprises photodetector unit, control means, and a computer. Such devices cover spectral range from 0.25 up to 4.4 mcm: for ultraviolet and visible ranges there are used collinear quartz AOTFs (0.25-0.8 mcm), non-collinear paratellurite (TeO_2) filters are suitable for visible and infra-red ranges (0.4-4.4 mcm), while collinear AOTFs made of calcium molybdate ($CaMoO_4$) spans visible range (0.4-0.9 mcm). All listed AOTFs have also been designed in a double-monochromator form. Developed spectrometers provide detection of emission, absorption (reflection) characteristics, of scattering spectra both Raman and fluorescence, and additionally polarimetric parameters, in particular spectral dichroism.

The most diverse is a family of spectroradiometers, which includes compact versatile devices for optical spectra measurements (fig.1) as well as instruments for industrial processes control, and environment monitoring. The last group is represented by mobile systems for Earth surface remote sensing mounted at ship, airplane, helicopter, satellite [8], apparatus for deep-water measurements [9], equipment for ambient air monitoring with differential absorption spectroscopy technique. Specific characteristic of gas analyzers [10] as well as some other these instruments is optimized measurements procedure, which supposes only detection at wavelength corresponding to absorption lines of pollutant gases and, thus, provides more than order reduction of analysis time compared with spectrum scanning procedure.

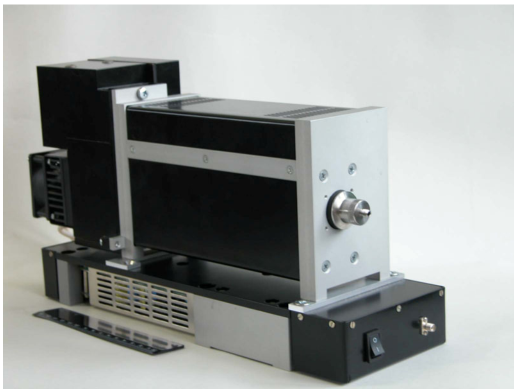

Fig.1. Double-AOTF compact spectrometer.

In industrial applications, AOTF spectrometers are used to control plasmochemical etching [11], in particular for precise process timing based on detection of rapid alteration of emission spectra caused by changing composition of substrate being etched at the moment. Besides, AOTF spectrophotometers have found application in accounting liquid products consumption, for example for assessment of ethanol discharge in alcoholic beverage industry by continuous measuring of ethanol concentration in combination with flowmeter.

Rather specific group is spectral imaging AOTF instruments. They are capable of spatial structure detection of spectral characteristics at filter wavelength. For instance, if AOTF is tuned at absorption line of specific chemical compound then spatial distribution of this substance over the sample is visualized. It allows to display physical, chemical, biological, etc. features by tuning AOTF at appropriate characteristic spectral lines. These devices are arranged in form of monochromator-camera assembly usually mounted over microscope (fig.2). They are of great interest for biomedical and industrial applications [12].

Fig.2. Double-AOTF microscopic monochromator with CCD camera.

Along with these devices based on well-known principles, recently there have been developed essentially new instruments with use of AOTFs having modulated acoustic grating. They are specialized spectrometers differing in detection procedure, which supposes selection of photocurrent components at modulation frequency or at harmonics. It permits hardware detection of optical spectrum derivatives [13], which is necessary in differential spectroscopy. That is highly important for detection of weak-emitted or low-absorption spectral features in presence of intense background radiation.

All types of modulation can be effectively used: amplitude, phase, frequency. For example, frequency-modulation collinear-type acousto-optical dispersive element first suggested and grounded in our work [13] for ultra-short pulses compression was later implemented for practical use [14].

However, not all acousto-optical units and instruments, which has been suggested, have been created and put into practice. E.g., there was not realized multi-crystal AOTF comprising few spatially separated acousto-optic cells, in which diffraction takes place consequently with preservation of waves phase relations. Another actual example is resonator formed by two reflecting acoustical gratings. This particular unit is of special interest because of its unique feature, which is appearance of exponentially narrow transparency windows inside wide highly reflection stop-band [15]. This property is very promising for creation of extremely sensitive resonance detectors of gravitational waves.

4 Specific techniques for AOTF instruments

Specific features of AOTF-spectrometers require new specialized techniques for measurement procedure. For instance, due to spectral agility of this instruments, random spectral access procedure can be implemented for spectrum recording and therefore there must be a method of determining the optimum algorithm of measurements. It is quite clear that this algorithm should be based not only on *a priory* information but also on data incoming during measurement process. Hence, such algorithm is intrinsically adaptive because the consequence of addressed wavelength (λ_1, λ_2, …, λ_n, …) is variable depending on object information being obtained [16].

The second reason to develop new methods is caused by AOTF ability of changing its transmission function. Thus, there is a problem of finding instrument function, which is the optimum among technically realizable functions. Instrument function $H(\lambda)$ is a kernel of equation, which describes measurement procedure

$$S(\lambda) = \int H(\lambda-\lambda') I(\lambda') d\lambda' , \qquad (1)$$

here $S(\lambda)$ is spectral function recorded, $I(\lambda)$ is input radiation spectrum.

Moreover, there appears one extra problem, which is finding (reconstruction) of the spectrum shape $I(\lambda)$ from measured spectrogram $S(\lambda)$. It is especially actual because of variability of instrument function $H(\lambda)$. And this recalculation stage is really necessary for multi-windows functions [5,6]. It has been proved [17] that this task is of ill-posed kind of problems. However, some approximate techniques were developed. [17].

Beside needs for development of new measurement approaches, there should be solve some fundamental tasks concerning AOTFs. Following two problems are remarkable. 1. Estimation of spectral resolution for any particular AOTF instrument regarding measurement procedure and data post-processing (fundamental limits were found in work [18]). 2. Solving the problem of light diffraction on a pair of acoustic gratings, which forms a resonator.

5 Conclusion

All these considerations show following trends in AOTF-based instruments development.

1. Changing priority in developments from acousto-optical filters to complicated AOTF-based instruments and systems.
2. Development of specialized AOTFs and apparatuses, which are best-suited for particular problems.
3. Development of new methods and techniques for AOTF-spectrometers measurements including optimization of their characteristics and detection procedure, and post-measurement data processing.
4. Development of dispersive elements based on effect of light diffraction on sound waves for telecommunication applications and for highest accuracy measurements, in particular for gravitational waves detection.

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