Technical implementation of acousto-optical instruments: basic types

V E Pozhar1,2, M F Bulatov1, A S Machikhin1,3 and V A Shakhnov1,2

1 Scientific and Technological Center of Unique Instrumentation of Russian Academy of Sciences; 15, Butlerova street, Moscow, 117342 Russia
2 Bauman Moscow State Technical University; 5/1, 2nd Baumanskaya street, Moscow, 105005 Russia
3 National Research University “MPEI” (Moscow Power Engineering Institute); Krasnokazarmennaya 14, Moscow, 111250 Russia

E-mail: vitold@ntcup.ru

Abstract. The comparative analysis of the basic characteristics of acousto-optical instruments of different levels of integration and complexity: functional elements, devices and systems. The basic characteristics and their interrelations are determined. It is shown that each class requires individual approach to design. We indicate a novel trend of development of special class of instruments – modules, which are easy-to-integrate into existant devices or systems extending their functionality. The principle requirements for this kind of instruments are their connectivity with the device in each channel, port, protocol, so that the module adding and removing need not the device retuning or adjustment. This tendency has universal nature. The presented analysis is convinient for prognosing prospects and basic directions of acousto-optical instruments development.

1. Introduction

The technology of dynamical Bragg grating based on light diffraction on acoustic waves, is widely used for creation of various functional units like modulators, deflectors, tunable optical filters, etc. [1]. These so-called acousto-optical (AO) units are used as components in devices and complicated stand-alone systems. In cases when they are key elements (like in optical spectrometers [2]), the total device or system is titled ‘acousto-optical’ and these units should meet specific requirements and usually should be developed together with the total complex.

Thus, AO equipment is developed at different levels of integration and complexity: element, device, and system. Taking AO tunable filters (AOTFs) as an example, we present a comparative analysis of the characteristic requirements and technical approaches to their design and development. We also show that there is a new essential class of AO instruments – add-on modules.

Schematically, the hierarchy of AO spectral instruments is presented in figure 1. Here, it displays 3 basic levels of complexity, simpler one being a component for more complex ones. The AO instruments stratification across the levels is following. An AO element is a functional unit, which performs the simplest operation: spectral filtration, deflection, modulation, etc. A device is intended for wide range of applications (for example, spectra detection). The device is a user-oriented
instrument, so it contains all additional units necessary for performance, in particular power unit, control panel, display, information means.

![Diagram of AO system](image)

**Figure 1.** Relations between basic classes of AO instruments differing in complexity.

As a system, we regard the specialized instrumental complex intended for the solution of particular problem. Therefore, it comprises a set of units and devices as well as additional equipment, methods and software, which are sufficient for the problem solution. Usually, systems exists in one or several exemplars, each is in fact unique. And with every upgrade of the working technique, the system is usually modified by adding some new units. That is why, the characteristic feature of the systems is openness.

In addition to elements, devices and systems, there is another class of AO instruments – AO modules. In contrast to these three classes, the discriminating sign of modules is operational features: the module should be capable for prompt connection or disconnection to the instrument complex with no need to noticeable retuning, adjustment or calibration. In fact, the module is an extension of the element. It comprises the set of specialized units like device, but it is not an autonomous device as its goal is secondary or supplementary compared to the complex, which it is inserted into.

Consider the basic features of AO spectral instrument of different classes.

### 2. AO elements

Primary functional spectral AO element is AOTF. It performs the single operation – optical radiation selective transmission at wavelength $\lambda$ specified by the user. It is characterized by the global transmission function $T(\nu; f; P; C)$, which depends on optical wavenumber $\nu=1/\lambda$, electric-control-signal frequency $f$ and power $P$ as well as on AO crystal cell temperature $C$ detected by means of thermoelectrical sensor. This function originates a family of characteristic relationships (figure 2): spectral profile $T(\nu, f)$, power dependence $T(P; f)$ and tuning curve at different temperatures $\nu(f; C)$. The primary characteristics of AOTF are following: spectral range $\nu_{min}$–$\nu_{max}$, bandwidth $\Delta \nu$, diffraction efficiency $dT/dP$, temperature drift $dv/dC$, maximum achievable transmission value $T_{max}$, spectral contrast $K_{sp}=T_{peak}/T_{out}$, where $T_{peak}$, $T_{out}$ – transmission coefficients inside the window and out of it (on the “tail”). Another important characteristic is relative background radiation level $T_{bg}$, which in particular depends on the contrast of the pair of cross-polarizers $K_{pol}$.

Theoretical form of the global transmission function is

$$T(\nu; f; P; C) = T_{peak}(P; f) \cdot \text{sinc}^2[(\nu-\nu)/(\Delta \nu/2)],$$

(1)

where $\text{sinc}(x) = \sin(\pi x)/(\pi x/2)$. The real profile may significantly differ from it and be asymmetric, but always has the bandpass form. The window peak value is described by formula $T_{peak}(P; f) = \sin^2(f P^{1/2})$, though in practice, it does not reach 100%. Spectral tuning curve exhibits close to linear form $\nu(f; C) = \alpha(\nu; C) f$, but in the range of AO crystal dispersion, the factor $\alpha$ depends on $\lambda$, and, therefore, on a bandwidth location $\nu$. As it depends on crystal temperature $C$, one needs to use thermostable crystal orientation or place a temperature sensor to AO crystal cell for tuning curve correction.
The most important additional characteristics are optical (form and area of the input pupil $\Delta S$, field-of-view $\Delta \Omega$) and temporal (tuning time $\tau_t$, delay time $\tau_{del}$, warm-up time $\tau_{temp}$). Also important are the weight ($m$), sizes ($L\times W\times H$), connecting dimensions, as well as permissible use conditions (temperature range, etc.).

![Figure 2](image-url) **Figure 2.** Characteristic relationships of AOTF: (a) spectral transmission function; (b) dependence of transmission coefficients on ultrasound power; (c) spectral tuning curve at different temperatures.

In principle, AOTF can be represented as functional element (figure 3 (a)) with optical input, optical output and control input, which is supplied with radiofrequency (RF) electrical signal generating ultrasound wave with use of piezotransducer and inducing in that way Bragg grating for wavelength selection. Except this simple AO element, there are more complicated configurations, which comprise a pair of AOTFs and some other additional elements [3]. Besides, for imaging AOTFs, the specific aberrational characteristics are of fundamental importance [4].

![Figure 3](image-url) **Figure 3.** Diagrams for electronically-tuned AOTF (a) and program-controlled AO monochromator (b): 1, 3 – cross-polarizers, 2 – AO cell, 4 – electrical matching board, 5 – thermal sensor, 6 – AOTF, 7 – RF synthesizer, 8 – RF amplifier; I – optical input, II – optical output; III – control RF input, IV – temperature control output, V – digital port, VI – power supply input.

The simple AOTF driven by external RF generator can be converted into AO spectral module (figure 3 (b)), which contains computer-controlled built-in RF synthesizer. Such module must be equipped with electric power supply input to produce enough acoustic power.
3. AO devices

Depending on the problems to be solved, AOTF can be used in various ways. The most straightforward application is spectroscopy. AOTF can be a key element of the spectrometric devices, used for optical spectra detection $I(\nu)$. Fundamental characteristic of spectrometers is spectral sensitivity $U(\nu, \nu_j)$, which connects the photodetector signal $S$ with the input radiation spectrum

$$S(\nu_j) = \int U(\nu, \nu_j) I(\nu) \, d\nu. \quad (2)$$

For rather smooth spectra $(dI/d\nu << I/\Delta \nu)$, the bandwidth is negligible $U(\nu, \nu_j) = A(\nu) \cdot \delta(\nu - \nu_j)$, so the input spectra can be calculated just by normalization $I_{\text{calc}}(\nu) \approx S(\nu)/A(\nu)$ with use of calibration spectral curve $A(\nu)$. In general case, we can reconstruct only smoothed spectral curve [5].

Spectral sensitivity is obviously connected with AOTF spectral transmission function $T_{\text{AOTF}}(\nu_f, P)$, transmission of other optical elements $T_{\text{opt}}(\nu)$ and photodetector sensitivity $\beta(\nu)$

$$U(\nu, \nu_j) = T_{\text{AOTF}}(\nu_f, P) \cdot T_{\text{opt}}(\nu) \cdot \beta(\nu). \quad (3)$$

This relationship, in fact, includes spectral tuning curve $\nu_f(f,C)$, and spectral profile $P(f)$ of the power supplied to the AOTF, which is adjusted in so way to equalize sensitivity across the spectral range.

The basic characteristics of the spectrometer are spectral range $\nu_{\text{min}} \leq \nu \leq \nu_{\text{max}}$, the number of resolvable spectral lines $N_{\text{res}} = (\nu_{\text{max}} - \nu_{\text{min}})/\Delta \nu$, optical throughput $G = (\Delta S \times \Delta \nu) \cdot T_{\text{opt}}(\nu) \cdot T_{\text{peak}}/\Delta \nu$, sensitivity threshold $I_{\text{min}}$, which is determined by the throughput, noises and leakage radiation connected with value $T_{\text{bg}}$.

Among the additional characteristics, the most important are temporal especially switching time $\tau_{\text{sw}}$ between random wavelengths. In fact, this time is greater than AOTF actuation time $\tau_{\text{tr}}$, $\tau_{\text{del}}$, being determined by electrical circuits. Also operation speed is influenced by the algorithm of spectral tuning: scanning or random spectral access. If the second mode is implemented, the spectrometer can be tuned over the informative spectral points so that the operation speed is comparable to the speed of spectrometers with parallel registration.

Besides, weight, dimensions, power consumption, power source and operation conditions do matter. Principle diagram of the spectrometer is depicted in figure 4.

**Figure 4.** Principal diagram (a) and exterior (b) of AOTF-based spectrometer: 1, 2 – input and output lenses, 3 – photodetector, 4 – photocurrent amplifier, 5 – program-controlled AO monochromator, 6 – power supply; 7 – microcontroller; I – optical input, II – power supply input; III – digital data exchange port.
Except classical spectrometer based on AOTF, other devices are developed, which are capable of detection wider collection of data, such as hyper-spectrometers \(I(v,x,y)\), imaging spectrometers \(I(x,y;\nu)\), stereo-spectrometers \(I(x,y,z;\nu)\) and similar devices with temporal resolution \(I(\nu,t)\).

4. AO systems

Systems based on AO units possess the specific features like spectral selectivity, agility, configurability and variability. Such systems comprise a great complex of jointly operating units. AO component is a small but important part, which defines the principle characteristics of the complex. Many AO systems have been developed, in particular for gas analysis [6], biomedical research [7] and remote sensing [8] applications. In each AO system, AOTF performs the only, but the key function, and determines spectral and analytical capabilities. These features differ from those of spectral elements and devices and this is illustrated by UV AOTF-based spectral absorption gas analyzer (figure 5). This system detects concentration of contaminants in the air area between the optical unit and retroreflector with use of a spectral absorption database of pollutant gases.

Spectral characteristics (range, resolution) determine the list of substances, which can be detected, and resolvability of substances with overlapping spectra (for example, in [9] up to 10 substances can be detected in the range 0.25-0.45 \(\mu\)m). The sensitivity affects the detection limit, which must not exceed the allowable level for each substance. (In system “GAOS” [9], this requirements transfer into pathlength limitation ensuring substances detection at the threshold limit value for industrial zone: 15 m for aromatic hydrocarbons and 100 m for oxides \(SO_2\) and \(NO_2\)). Temporal characteristics (measurement time) are determined by two factors: sensitivity and random-spectral access algorithm. (In “GAOS” system, for each substance the detection, it is specified of up to 3 spectral lines, each describing with triplet – so the measurement time turn out to be approximately 1 minute per substance [9].) The mass (3 kg) and sizes (6 \(dm^3\)) of AOTF spectrometer were not significant in the total weight and dimensions of the system (75 kg, 300 \(dm^3\)), while insensitivity of AOTF to vibrations and stability during temperature variations make it possible to use the system in out-of-lab environment as van-installed mobile apparatus.

![Diagram](a)

![Image](b)

**Figure 5.** Principal diagram (a) and exterior (b) of AOTF-based for long-path gas analyzer “GAOS” 
1 – input lenses, 2 – beam splitter, 3 – AOTF spectrometer, 4 – microcomputer, 5 – power supply, 6 – ignition unit for discharge lamp; 7 – light source, 8 – standalone corner retroreflector, 9 – monitored air mass; I – optical input, II – power supply input; III – digital data exchange port.

Operation of AOTF gas analyzer is described by multi-stage algorithm, which presumes determination of target pollutant substances with use of measured absorption data at the characteristic wavelengths of the substances [10]. The system inherently includes a program unit and a database referring the substances spectral specific absorption characteristics. In result, the source data for AO
unit development for its integration into a complex system are the characteristics of the system: the number of target substances the detection threshold, detection time, the exploration requirements. Therefore, a descending iterative development scenario is necessary.

5. AO modules

An extremely important sphere of AO units instrumentation is development of modules. They can be inserted into the device or system without any affect on that. Their development principles are quite similar to other units, but they should only be “insertable”, that must be matched with all the parameters of the target device. Thus, modules must be unified in each channel (conjugation): optical path, control contour, data exchange protocols, software. One of the examples is endoscopic add-on spectral AO module (figure 6) [11].

The importance of AO module indication as a separate instrument class is caused by the modern trends in optical instrumentation. Rapid development of new measurement procedures and analytical techniques demand intensive modification of instrument base. That is why, many classical devices are now based on the modular concept acquiring features of open systems. It gives opportunity for modules exchange or an upgrade for acquiring new properties. For this purpose, a lot of standards are developed: from mechanical connectors, plugs and sockets to analog and digital signal characteristics. The modules being developed must correspond to standards and must be insertable into the existent devices. The same principles are also applied to control software.

![Figure 6](image)

**Figure 6.** Principal diagram (a) and interior (b) of AO endoscopic module [12]. 1 – object; 2 – conventional optical endoscope; 3 – light source; 4 – optical coupling system; 6 – AO crystal cell; 9 – polarizer; 10 – objective lenses; 11 – cameras; 12 – frame grabber; 13 – processing unit; 14 – controller board; 15 – RF generator; 16 – RF amplifier; 18 – flat mirror

6. Conclusions

Thus, each class of AO spectral instruments is characterized by specific technical parameters as well as individual additional features. It means that their development processes follow different algorithms, in particular, in design of AO crystal cell.

It should be noted that some earlier developed AO elements [3, 12, 13, 14] have module features (see figure 3 (b)). Surely, the collection of spectral modules will be permanently expanded and in near future they will become the typical units of optical systems such as light sources, lenses, photodetectors. The significant problem on this way is that classical ray-tracing methods of optical system design do not suit for AO instruments, operating on the wave optics principles. This technique [15, 16] should use the special designed program units (subroutines) for ray-tracing optical system
design. These units describe light beams transmission through AOTF and are based on the theory of image transmission [4].

For convenient comparing AO instruments we joint their basic characteristics in table 1.

Table 1. Characteristics of Acousto-optical instruments.

| Characteristics          | AO element              | AO device              | AO system              |
|--------------------------|-------------------------|------------------------|------------------------|
| Spectral                 | Range                   | Resolvable lines number| Detectable substances list|
| Optical                  | Input aperture          | Throughput             | Range distance         |
| Energetic                | Diffraction efficiency  | Transmission coefficient| Detection threshold |
|                          | Transmission contrast    |                        |                        |
| Temporal                 | Switching time          | Single-point detection time| Detection time |
|                          | Delay time              |                        |                        |
| Constructional           | Sizes                   | Dimensions and Weight  | Weight and Dimensions  |
|                          |                         | Power consumption      |                        |
| Operational              | Temperature stabilization| Portability            | Mobility                |
|                          |                         | Power supply           | Working environment    |
| Software and methodical  | Spectral tuning curve   | User software          | Measurement procedure  |
|                          | Power transmission profile| Calibration procedure | Analytical technique   |

It is obvious that the classification does not cover all the types of AO spectral units. For instance, there are multi-band AOTFs [17], variable-bandwidth AOTFs [18], bichannel AOTFs [19]. However, in principle, it displays the characteristic features of AO instruments on different integration levels.

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