INVESTIGATION OF INFORMATION TRANSMISSION PROCESSES IN ACOUSTO-OPTIC SPECTROPHOTOMETER

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Abstract

Acousto-optic spectrophotometer based on acousto-optic tunable filters (AOTF) with non-collinear interaction is considered as a consequence of links, each of which transmits and processes information. Each link is characterized by the set of parameters describing information transmission. Simple increasing of output signal generally does not allow to optimize the amount of the processed information, and the noise is required to be decreased. The reported device has been described and its physical and information characteristics have been studied. The basic reasons of information losses in the device have been studied and discussed. The power expenses for information transmission and processing (both total and optical expenses) have been analyzed from the point of view of the approach elaborated earlier for holographic memory devices.

Introduction

AOTF are most commonly used as basis of electronically tuned spectrometers [1, 2] and multispectral imagers [3, 4]. Both kinds of application are connected with information processing and transmission, although in the first case all useful data are contained in light intensity wavelength distribution whereas in the second case spatial and spectral information sets are practically of equal importance.

In order to follow the process of information transmission in acousto-optic spectrometer, it is useful to divide the device schematically into the set of links by the same way as it has been done earlier [4, 5] for the other kinds of acousto-optic devices. This approach is also fruitful for any system dealing with systems in which information is carried by light at least in one stage of data conversion. The distinctive feature of this approach is that the links are not connected with certain units of the device but with certain physical processes. Each process performs information conversion from one carrier to another.

Link-by-link representation of AOTF

Figure 1 represents an acousto-optic device as a consequence of links providing data conversion. Each link of a system may be described of a set of parameters which directly influence the information abilities of a system. These parameters are: input and output value of the signal S_i, input and output value of signal-to-noise ratio Ψ_i, transmission factor α_i (or function if the corresponding signal conversion is nonlinear), and signal-to-noise ratio (SNR) variation from input to output Ψ_i.

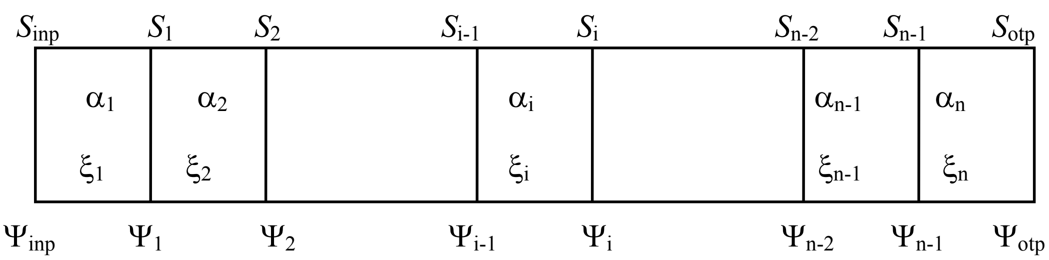

Figure 1. Representation of an acousto-optic device as a consequence of links.

Ideally, we may suppose that inside the dynamic range all the signal conversions are linear, and transmission functions α_i become factors. Hence, we may write

$$S_{otp} = \alpha_1\alpha_2...\alpha_i...\alpha_{n-1}\alpha_n S_{inp}, \quad (1)$$

where S_{otp} and S_{inp} - output and input signal values of the whole device, correspondingly.

SNR falls from input to output. It is evident because noise is the signal fluctuation, and growing of the signal is accompanied by the corresponding growing of its fluctuations; besides that, each operation with the signal introduces new noise, and the total SNR must decrease. In reality the total amount of noise in the previous link output multiples by factor α_i in the current link together with the signal. Besides that, signal may fluctuate additionally in the current signal due to the conversion, and, at least, noise of some accompanying non-informative signals occurring in the present links, may add. Of course, addition is geometrical.

The output noise value may be expressed as a geometrical sum of the noise components multiplied by the corresponding factor

$$S_{Notp} = [(S_{N\,inp}\alpha_1\alpha_2...\alpha_n)^2 + (S_{N1}\alpha_2\alpha_n)^2 + ... + S_{Nn}{}^2]^{1/2}, \quad (2)$$

where $S_{N\,inp}$ - noise accompanying the input signal, $S_{N\,i}$ - noise which adds after i-th link. This noise may be considered as a geometric sum of the previous signal fluctuations connected with the signal conversion (multiplicative noise) and noise introduced by the processes accompanying the conversion (fluctuations of non-informative signals - additive noise).

If information is introduced into the device via piezoelectric transducer, so the 1st link correspond to signal conversion from electric voltage to oscillations of piezoelectric transducer, second link – conversion of these oscillations into spatially-temporal distribution of the active medium refractive index variations, the third link is described by conversion of refractive index distribution into light intensity distribution after the Bragg cell, and the fourth link (more correct, group of links) corresponds to the detection procedures. However, this consequence of links is correct for acousto-optic deflectors, modulators, and especially signal spectrum analyzers.

As for AOTF, information input for this kind of acousto-optic devices coincides with incident light beam. Hence, another consequence of links takes place in this case. We consider the case of acousto-optic spectrometer, where no spatial information is required to transmit.

In fact, only two basic links can be included into acousto-optic spectrometer schematic representation. The 1st one converts light intensity distribution by wavelength into light intensity time distribution, and the second link (group of links) provide optical signal output detection. Let us consider the first link.

Generally, input light beam is constant in time. Its intensity I can be represented as integral of the light intensity wavelength distribution across all the range of interest. Output value of light intensity for the first link can be generally written as

$$dI'(t)/dt = (dI/d\lambda)(d\lambda/dt), \quad (3)$$

where first derivative in the right part of equation is light distribution by wavelength, and second derivative defines procedure of light wavelength selection. It is possible to write

$$k\lambda = F(\omega, t), \quad (4)$$

where k is proportionality factor, and $F(\omega, t)$ – spectrum of the signal which is introduced into the AOTF Bragg cell piezoelectric transducer. This spectrum is variable in time, and its time dependence defines the second derivative of expression (3). Hence,

$$I' = \int_0^T I_\lambda\, k\, d[F(\omega, t)]/dt, \quad (5)$$

where I_λ is wavelength distribution of input light intensity, T is accumulation time during which operation remains inside certain selectivity interval. The minimum value of T is close to the device temporal aperture τ. It is of the order of dozen milliseconds.

Expression (5) contains a controversy. Indeed, according to this expression, if the spectrum of service signal which is input on piezoelectric transducer, is invariable, so output light intensity is equal to zero. However, it is really so if AOTF selectivity is unlimited, and it selects light with zero frequency bandwidth. But in practice AOTF has selectivity of $\delta\lambda$ which is defined by Bragg diffraction peculiarities, and can be calculated using theory of coupled waves [7]. It can be supposed that finite selectivity is equivalent to the spectrum variation inside the space defined by the selectivity value.

$$I' = \int_0^T I_\lambda k\, [F(\omega,t)]\Delta\lambda\;\; d\lambda/dt \quad (6)$$

Hence, expression (6) demonstrates the 1st link transmission function. The second link transmission function is the same as for fourth link of other acousto-optic devices; it has been considered in details in [6].

Sources of noise in AOTF and their influence on information transmission in acousto-optic spectrophotometer

The noise sources in AOTF are the same as in other acousto-optic devices but some significant differences take place:

1. As no laser is used commonly for AOTF incident light beam formation, so the typical noises of lasers are absent.
2. Noise of input light beam carrying information, is added. This noise becomes multiplicative, and in many cases it can be the decisive noise source among the others.
3. Such important noise source as input electric circuit before control signal input in piezoelectric transducer produces not multiplicative but additive noise.

The noise connected with input light incident to Bragg cell of the device, depends on many factors. For example, light source, collimation system, character of the medium containing the matter which modulates light spectrum, play significant part in this noise value. Hence, it is difficult to express the total input noise in certain mathematical expression. However, noise connected with light source can be calculated proceeding from its initial spectrum. As photons which compose light beam are distributed according to normal law, so noise value of light source can be defined as

$$N_{eln} = (N_{els})^{1/2}, \qquad (7)$$

where N_{els} is number of photons corresponding to the information element of transmitted light. In the case of acousto-optic spectrometer it represent number of photons contained in spectrum range of $\delta\lambda$ which defines the device resolving power by wavelength. In the case of imaging AOTF this amount of photons must be divided to the number of pixels of the image to be processed. However, influence of this noise is much less in the first case as signal-to-noise ratio is $\psi = N_{els}/(N_{els})^{1/2} = (N_{els})^{1/2}$. Obviously this noise in the case of acousto-optic spectrometer is negligible.

As for noise sources which create noise added further, let us note that the control signal came from the transducer is accompanied by noise defining by the features of output circuit of the electric amplification driver; the most important are schrot noise and Johnson noise. Their calculations are widely known. At the final stage of signal conversion it is necessary to mention noise of photogeneration as well as noise of charge accumulation – both are defined by quantum features of these processes.

Anyway, the most important noise source is usually connected with the medium to be studied, and its calculation can be made in each case separately.

Experimental sample of spectrophotometer on the basis of AOTF

We have designed the acousto-optic spectrometer intended for operation in visible region. The device includes light source based on halogen lamp, input optics, AOTF, output optics, and photomultiplier. Signal from this photomultiplier comes to PC through interface.

The spectrophotometer spectral characteristics without software corrections are shown in figure 2.

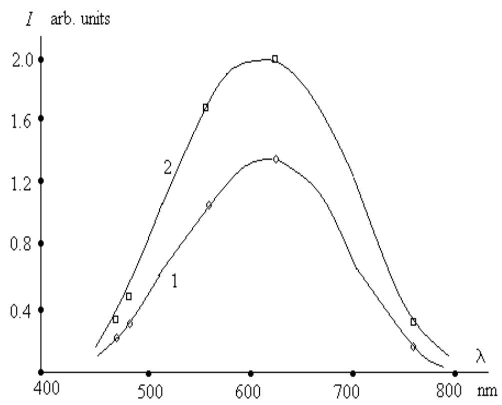

Figure 2. Spectral characteristics of acousto-optic spectrophotometer.

Curve 1 represents dependence of diffracted light intensity on wavelength of the selected light if acoustic power is 0.75 of that providing 100% diffraction in maximum. Curve 2 corresponds to the acoustic power providing this 100% diffraction. Light intensity is given in arbitrary units.

AOTF for this spectrophotometer has been designed on the basis of TeO_2 single crystal. The geometry of crystal provided normal incidence of input light on the crystal facet. This facet was oriented at 10^0 to the normal to the plane of piezoelectric transducer. In its turn, crystallographic axis [110] was oriented at angle of 6.5^0 to this normal in such way that the total angle between input facet and [110] axis was 16.5^0.

AOTF also includes piezoelectric transducer connected with TeO_2 crystal. The transducer has been made with lithium niobate single crystal and connected with active medium by means of vacuum welding. The frequency bandwidth of the transducer allowed to excite shear acoustic waves in the band of 70...115 MHz.

Optical aperture of the AOTF was inside size of 3.5x3.5 mm.

Estimation of the spectrophotometer resolving power by wavelength (selectivity) have shown that it is not worse than 7 nm at λ = 630 nm. Obviously, the value of selectivity at blue was much better.

The considered AOTF can be used not only in acousto-optic spectrophotometer but also in multispectral imaging device.

References

1. I.C.Chang, «Tunable acousto-optic filters: an overview», *Optical Engineering,* 1977, vol. 16, No. 5, pp. 455-460.
2. V.E.Pozhar and V.I.Pustovoit, “Acoustooptic spectrometry”, in: *Acoustooptics: Researches and Developments, School-Seminar, June 27 – July 1, 1990,* Leningrad, 1990. I.C.Chang, «Tunable acousto-optic filters: an overview», *Optical Engineering,* 1977, vol. 16, No. 5, pp. 455-460
3. L.J.Denes, M.S.Gottlieb, and B.Kaminsky, “Acousto-optic tunable filters in imaging application”, *Optical Engineering,* 1998, vol. 37, No. 4, pp. 1262-1267.
4. N.Gupta, R.Dahmani, K.Bennett, S.Simizu, D.R.Suhre, and N.B.Singh, "Progress in AOTF hyperspectral imagers", Proceedings of SPIE, 2000, vol. 4054, pp. 30-38.
5. V.N.Sokolov, B.S.Gurevich, S.B.Gurevich, V.I.Popkov, and A.A.Rodiontsev, "A transmission function of a generalized acousto-optical deviice", Proceedings of .SPIE, 1997, vol. 3238, pp. 38-45.
6. B.S.Gurevich, S.V.Andreyev, V.V.Vorobiev, A.A.Rodiontsev, and V.N.Sokolov, «Information losses in acousto-optics, their reasons, and ways to minimize them», Proceedings of the SPIE, 1998, vol. 3464, pp.55-63.
7. H.Kogelnik, "Interaction theory for thick holographic gratings", Bell Syst. Tech. Journ., 1969, vol. 48, p. 2909.