Features of Electroencephalographic Signals Acousto-Optic Processing

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ABSTRACT

Earlier we proposed the method of electrocardiographic signals acousto-optic processing based on application of acousto-optic spectrum analyzers with time integration. This method can be extended also for the electroencephalographic signals processing. However, some features of such signals make some special demands to the acousto-optic device performing the processing. Some elements of electroencephalographic signal which can be the signs of the cerebrum and central nervous system pathologies, can be found and selected only in specific frequency regions which differ from each other by 4…5 orders. Hence, the acousto-optic device which provides the signal processing must operate in very wide frequency range. This range can be attained only using acousto-optic spectrum analyzers with combined space and time integration. Moreover, some specific demands must be made to 2D multielement photodetector used in the mentioned above spectrum analyzers – its accumulation time must bt about 5…20 s because frequency resolution of the device must be of the order of 0,1 Hz. It requires application of the cooler based on Peltier phenomenon. The signal features and the corresponding demands made to the spectrum analyzer, are considered in the paper.

Keywords: electroencephalographic signal processing, acousto-optic spectrum analyzer, time and space integration, photodetector cooling

1. INTRODUCTION

It was considered for a long time that acousto-optic spectrum analyzers (AOSA) which are widely used for different radio frequency (RF) signals Fourier processing, cannot be used for processing of bioelectric signals (BES) of different nature because the frequency range of these signals is located in the area of much lower frequencies than that of RF signals. Usually AOSA deal with the signals with spectral resolution of several hundreds kHz whereas BES frequency resolution which is required for their analysis is located in the range of 1…500 Hz. Nevertheless, the way of acousto-optic processing of BES (especially electrocardiographic signals) has been proposed\(^1\) using AOSA with time integration\(^2\). The sense of the method is that AOSA with time integration (which include 2 Bragg cells with information input signal and linear frequency modulated (LFM) signal) have spectral resolution which is defined by the accumulation time of multielement photodetector (linear array, CCD or CMOS) in this AOSA.

The AOSA with time integration deficiency is rather low frequency bandwidth. Amount of resolved frequency intervals remains about several hundreds, so if the accumulation time is several seconds, the frequency bandwidth appears insufficient in order to satisfy the demands of different BES processing. The method considered earlier\(^1\) is related to electrocardiography. Now we consider the possibility of the method application to electroencephalographic (EEG) signals processing, and it is necessary to take into consideration some features of different kinds of EEG signals which are rather diverse.

2. FEATURES OF EEG SIGNALS TO BE PROCESSED BY ACOUSTO-OPTIC METHOD

EEG signals include many very specific kinds of potentials such as

- alpha, beta, delta, theta, and some other rhythms;
- EEG signal aperiodic and quasi-periodic components inherent for different pathologies of the cerebrum and central nervous system (peaks, sharp waves, and spikes);
- combined complexes of periodic and aperiodic elements, such as “slow wave – sharp wave” and “slow wave – peak”;
- all kinds of evoke potentials connected with action of different kinds of stimuli irritating the receptor and effector ways.

The listed diversity of the EEG signals represent some difficulties for their processing and extraction of useful information from the total mixture of EEG signals accompanied noises and obstacles. One of the most common ways to perform this extraction is synchronous accumulation of EEG signal brief epochs. However, the synchronous accumulation method cannot be used successfully for all kinds of EEG signals. For example, in the case of the evoked potentials processing it is very difficult to divide the evoked potential to be studied and physiological artifacts appeared at expense of eyes movement or blinking at the moment of the stimulus action. If we take into consideration that the frequency regions and required frequency resolutions of EEG signals different kinds can differ significantly, so it is clear that the total frequency range of the signal recording and processing must be extended at least for an order.

As for the EEG signals recording in the extended frequency range, this problem can be solved by application of ultra high resolution technology developed earlier for electrocardiography. This technology can be applied to EEG also in order to find the EEG signal components which were not taken into consideration earlier but can be accepted as signs of cerebrum and central nervous systems pathologies appearing at the more early stages of their development. However, in order to provide the acousto-optic processing of EEG signals in the extended frequency range, it is necessary to use a specific kinds of AOSA which are known as AOSA with time integration and AOSA with combined time and space integration.

### 3. AOSA WITH TIME INTEGRATION

AOSA with time integration were developed in order to increase the frequency resolving power of the devices. The operation principle of AOSA with time integration is the same as that of acousto-optic correlators. However, the reference linear frequency modulated (LFM) signal is used as one of two correlated signals. The optical circuit of such device is demonstrated in figure 1. Signal $s_0(t)$ represents LFM signal with rectangular envelope (reference LFM signal), and $s_1(t)$ – LFM signal modulated by the analyzed signal by amplitude. Photodetector in this circuit represents 1D CCD or CMOS array Analysis demonstrates that if charge accumulation time in this photodetector is set to be equal to LFM oscillation duration, so the accumulated charge in photodetector is proportional to the analyzed signal spectrum.

The resolvable frequency interval for AOSA of the described kind is defined by accumulation time of linear photodetector. Hence, it can be of the order of several Hz and even less. However, the total resolving power of such
AOSA does not exceed that of AOSA with space integration, hence the total bandwidth analyzed frequencies can appear very narrow (by 2-3 orders bigger than the resolved frequency interval, depending on the parameter of applied Bragg cell). Due to this the device is applicable for solution of limited number of problems.

If the EEG signal is the subject of processing, it seems that the frequency bandwidth of AOSA with time integration may appear insufficient for this kind of the signal. Especially it is clear when different kinds of EEG signals are processed by the device. Hence, another kind of AOSA is required for this problem solution.

4. AOSA WITH COMBINED TIME AND SPACE INTEGRATION

On the contrary of the time integration AOSA based on 2 Bragg cells, AOSA with time-and-space integration use 4 Bragg cells, 3 of which are fed by reference LFM signals and one – by LFM signal modulated by information signal \( \gamma \). Two pairs of cells are oriented perpendicularly to each other, hence, the diffraction process is carried out in two coordinates. The scheme of this kind of AOSA is presented in figure 2.

![Diagram of AOSA with combined time and space integration](image)

Figure 2. Circuit of AOSA with combined time and space integration

The \( 1^{st} \) spherical lens provides \( 1^{st} \) diffraction order focusing from the first cell at third cell aperture, and \( 1^{st} \) diffraction order focusing from the second cell at fourth cell aperture. This signal can be expressed as

\[
u_1(t) = u_2(t) = \cos (\omega_1 t + \gamma_2 t^2/2),\]  

where \( \omega_1 \) is angular frequency of the signal whereas \( \gamma_2 \) is duration of linear modulation period. \( 3^{rd} \) cell is fed, as two first cells, by LFM signal with period equal to \( L/v \) where \( L \) is the cell aperture size and \( v \) - acoustic wave velocity.

\[
u_3(t) = \sum_{n=0}^{N_1-1} \text{rect} \left( \frac{t - \frac{2L}{v}}{\frac{L}{v}} \right) \times \cos \left[ \omega_2 \left( t - \frac{n2L}{v} \right) + \frac{\gamma_2}{2} \left( t - \frac{n2L}{v} \right)^2 \right],\]  

where \( N_1 = T/(2Lv) \); \( T \) – duration of the analyzed signal sampling. Fourth Bragg cell is fed by the signal which spectrum is the subject of analysis.
During this device operation the second spherical lens focuses 2D pattern in the plane of the photodetector array. This pattern corresponds to the processed signal spectrum. The 1D spectrum is converted into the raster by such way that the vertical readout corresponds to rough frequency counts whereas horizontal readout corresponds to fine counts.

The calculations show that the vertical readout provides the device operation in the mode which corresponds to AOSA with space integration. On a level with that the horizontal readout provides all the functions which can provide very fine resolution by frequency.

In order to provide the lower part of the total frequency range between several kHz and 0.1…0.05 Hz it is necessary to use the photodetector array with cooling system. The cooling can be provided be Peltier element connected to the array by means of thermal interface such as heat-conductive paste. It will allow to increase the charge accumulation time in the array up to decades of seconds which will provide the necessary frequency range for the complete complex of EEG signals acousto-optic processing.

Another version of AOSA with space and time integration which can be used for EEG signals processing, is shown schematically in figure 3.

![Figure 3. Circuit of modified AOSA with time and space integration](image)

The presented device is 2D AOSA with time and space integration\(^2\) in which light irradiated by laser is divided into 2 parts by means of semitransparent mirror. One part of the beam is expanded along vertical axis and irradiates the vertically oriented Bragg cell 1, which is fed by the analyzed signal \(s_1(t)\). This signal modulates the carrier frequency which is of the order of decades MHz. Fourier lens forms at the multielement photodetector the signal spectrum along the vertical axis. Another beam is expanded along horizontal axis and illuminates horizontally oriented Bragg cell 2.
which is fed by the reference signal \( s_0(t) \). Then 1st diffraction order components are projected to the photodetector plane where it interferes with the 1st part of the beam. Photodetector based on CCD od CMOS accumulates the charge which corresponds to light intensity distribution during the analysis time. The charge distribution at the photodetector at the final moment of accumulation cycle has a raster form, i.e. the set of lines which are oriented horizontally. The number of line corresponds to rough frequency count, and the charge distribution inside the line is proportional to the complex spectrum of the analyzed signal.

This modification specific feature is that the basis functions of Fourier transform obtained by digital method, are used as reference signal. It provides elimination the LFM signal nonlinearity influence on AOSA operation and increasing of amount of resolvable spectrum intervals. Instead of the second LFM signal the short pulses of laser beam irradiation is used as second reference signal. This decision allows to use only one time Bragg diffraction and which acts positively to the signal-to-noise ratio in charge distribution at photodetector.

Note that the design of AOSA with combined space and time integration (1st version) provides very interesting possibilities of the wavelet EEG processing organization. This kind of AOSA can be classified as processor od spectral kind by its intention but also it can be classified as the device of correlation kind by its structure. Hence, if the third Bragg cell is fed by the signal modulated by the mother wavelet function, hence the signal at the output along fine axis can represent the wavelet transform of the signal because the design of the device corresponds to the acousto-optic correlator.

If EEG signals are processed by means of wavelet processing, the choice of mother wavelet (wavelet transform kernel) plays an important part. There are two possibilities – to choose one of well-studied standard mother wavelets or to create special wavelet which is formed taking into consideration the known beforehand features of the processed signal. In practice, it is common to use the standard mother wavelets. However, our analysis shows that in many cases the standard set of mother wavelets looks insufficient, and it is necessary to develop a new set of these functions, especially for evoked potentials processing. In this case the data of original mother wavelets copying the form of stimulus signals for evoked potentials, can be successfully used.

Hence, the signal along the fine axis of 2D photodetector is the result of correlation feature of AOSA with combined integration. However, the signal-to-noise ratio for the correlation function between the studied signal and wavelet transform kernel can appear not high enough in order to be sure in the diagnostic abilities of the device based on this kind of processor. Nevertheless, the application of cooling by means of Peltier cooling can depress some part of low-frequency noise, and the wavelet processing of EEG signal can be successful.

5. PROBLEMS WHICH MUST BE SOLVED FOR SUCCESSFUL PROCESSING OF EEG SIGNALS

EEG signals contain both low frequency (0…100 Hz) and high frequency (100…2000 Hz) components which carry important information exercising influence on diagnostic procedures. It is necessary to select different kinds of EEG signals and to define which additional processing in the expanded frequency range can be required for each kind.

Basic rhythms of EEG signals seem to be good for processing in the traditional frequency range. However, it is necessary to seek the high frequency components in order to be sure that they have no diagnostic significance. Quasi periodic EEG signals such as spikes and sharp waves represent complexes of relatively sharp peak and more smooth wave, and differ from each other mostly by the total complex duration. The traditional methods allow to record these complexes mostly qualitatively, without definition of quantitative characteristics although exactly these characteristics may have important diagnostic significance. For example, spike duration is in the range of 5…50 ms, and sharp wave duration may exceed 50 ms. Low frequency components describe the necessary data regarding smooth wave as a component of the total complex but as for the peak, they can only record the fact of its presence. However, the high frequency components can describe the peak fine structure quantitatively. Hence, just the part of quasi periodic complex involving the peak can be successfully analyzed using the proposed acousto-optic processing method. Due to this important diagnostic data can be obtained which allow, for instance, to predict soon development of such pathologies as Creutzfeld-Jacob disease or subacute sclerosing panencephalitis.
On a level of that, the evoked potentials which are the results of action of different stimuluses on human organism, also must be the subjects of processing by means of the considered acousto-optic method. The evoked potential pulse leading front carries very important diagnostic information which corresponds to certain stimulus pulse. Traditional methods of EEG processing allows to find the evoked potential pulse presence, and to estimate its form approximately. However, the exact analysis of leading front of evoked potential pulse is possible using the proposed method which provides processing in expanded frequency range.

6. CONCLUSION

Application of AOSA with combined time and space integration equipped by the cooling system will allow to provide successful processing of different kinds of EEG signals obtained by means of ultra high resolution technology. A deficiency of the proposed method is that the cooling application is possible photodetector saturation after durable accumulation at normal light intensities. It causes breaking of the response linearity, which, in turn, causes distortions in the signal processing procedures. In order to avoid distortions, the nonlinear compensating corrections must be introduced. In any case, too long accumulation time produces signal-to-noise ratio deterioration, and, hence, information losses.

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