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QUADRATURE COMPONENTS FORMING METHOD FOR HOMODYNE ACOUSTO-OPTIC SPECTRUM ANALYZER

Abstract.
Introduction. *Among acousto-optic spectrum analyzers with spatial integration, schemes based on optical interferometers provide the largest dynamic range. Nevertheless, they form the signal amplitude spectrum on a certain spatial carrier. Formation of quadrature components can eliminate this spatial carrier. The two-dimensionality of the transformations performed in optical processors provides this elimination by reading of the additional charge of matrix photosensor lines. A renowned method implements this approach using four lines, which in turn determines the estimation time of the signal spectrum.*
Objective. *The objective of the work is to study the possibility of time reduction of the spectrum estimation.*
Materials and methods. *The paper presents the description of two methods of forming the necessary components.The first method uses three photosensor lines, the charge distribution in which has the spatial carrier phase-shifted by 90 ° from line to line. The second method forms the necessary distributions sequentially in three accumulation cycles by means of variation of the initial phase of the reference signal. By the mathematical proof, three distributions with a 90 ° relative phase shift are sufficient to eliminate the spatial carrier.*
Results*. In the first method, reduction of the spectrum estimation time is insignificant, but the parallel distributions formation affords not to impose additional requirements on the signal spectrum. The second method, due to the possibility of using any three sequentially formed distributions for estimation, is potentially three times faster than the first method, but requires the stationary signal spectrum within three accumulation cycles. Researchers can implement this meth-od using a linear photosensor or TDI photosenor. In addition, the method is less demanding to optical scheme parameters.*
Conclusion. *The proposed quadrature components formation methods provide time reduction of the spectrum estimation in interference acousto-optic spectrum analyzers and simplify their design.*

Key words: homodyne acousto-optic spectrum analyzer, interferometric acousto-optic spectrum analyzer, quadrature channel, Young's interferometer, two-dimensional optical processing

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МЕТОД ФОРМИРОВАНИЯ КВАДРАТУРНЫХ КОМПОНЕНТ СПЕКТРА В ГОМОДИННОМ АКУСТООПТИЧЕСКОМ СПЕКТРОАНАЛИЗАТОРЕ

Аннотация.
Введение. *Среди акустооптических спектроанализаторов с пространственным интегрированием схемы на основе оптических интерферометров обеспечивают наибольший динамический диапазон. При этом амплитудный спектр сигнала формируется на некоторой пространственной несущей, для устранения которой необходимо сформировать квадратурные компоненты. Двумерность преобразований, выполняемых в оптических процессорах, позволяет сделать это за счет считывания заряда дополнительных строк матричного фотоприемника. Известен метод, в котором данный подход реализован с использованием четырех строк, что в свою очередь определяет время получения оценки спектра сигнала.*
Цель работы. *Исследование возможности уменьшения времени получения оценки спектра.*
Материалы и методы. *Представлено описание двух методов формирования необходимых компонент. Первый метод задействует 3 строки фотоприемника, распределение заряда в которых имеет сдвиг по фазе пространственной несущей на 90° от строки к строке. Второй метод основан на формировании необходимых распределений последовательно в трех циклах накопления за счет варьирования начальной фазы опорного сигнала. Математически показано, что трех распределений с относительным фазовым сдвигом на 90° достаточно для устранения пространственной несущей.*
Результаты. *Уменьшение времени анализа в первом методе несущественно, но параллельное формирование распределений позволяет не предъявлять дополнительных требований к спектру сигнала. Второй метод за счет возможности использования для оценки любых трех последовательно формируемых распределений потенциально в 3 раза быстрее первого метода, но требует, чтобы спектр сигнала был стационарен в пределах трех циклов накопления. Он также может быть реализован с использованием линейного фотоприемника или фотоприемника с временной задержкой и накоплением и менее требователен к набору параметров оптической схемы.*
Заключение. *Предлагаемые методы формирования квадратурных компонент позволяют сократить время получения оценки спектра в интерференционных акустооптических спектроанализаторах, а также при необходимости упростить их реализацию.*

Ключевые слова: гомодинный акустооптический спектроанализатор, интерференционный акустооптический спектроанализатор, квадратурный канал, интерферометр Юнга, двумерная оптическая обработка

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Introduction. Spectral analysis based on the phenomenon of acousto-optic interaction and spatial Fourier transformation is a wide field for research [1], which is relevant in solving problems of radio monitoring, electronic warfare activities, as well as in signal detection devices. The algorithm of simple circuits of acousto-optic spectrum analyzers with spatial integration (AOSSI) operation [1]–[4] enables to form only the power spectrum, which leads to a significant decrease of the dynamic range. Circuits based on optical interferometers [5]–[7], in which is performed the optical heterodyning, provide a significant— twice when measured in decibels [6] – increase of the dynamic range of the device in comparison with simple AOSSI. In [5]–[7] are considered and practically confirmed optical heterodyning algorithms with transfer to zero frequency – homodyning – by introducing the necessary light modulation into the reference optical channel. Unfortunately, these

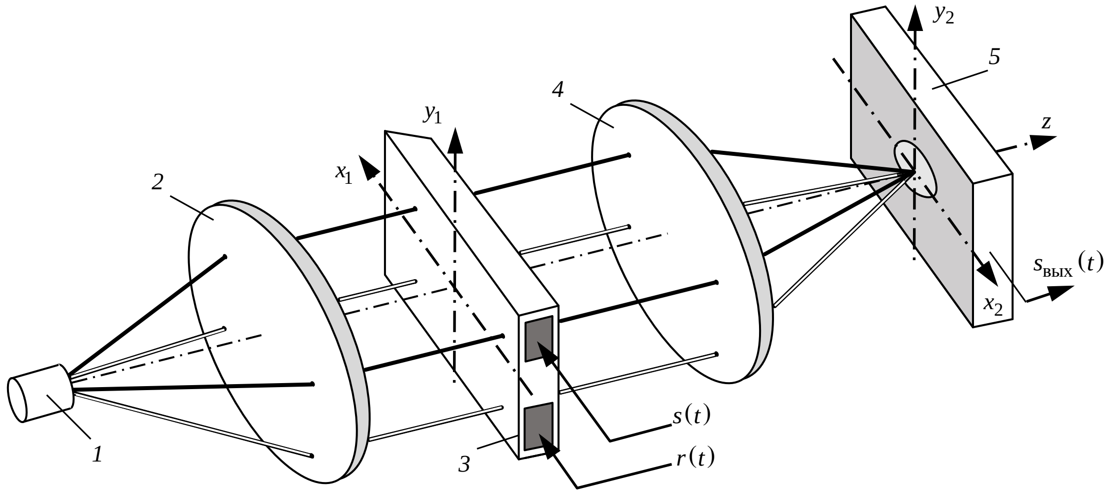

Fig. 1. The scheme of the homodyne acousto-optic spectrum analyzer based Young interferometer

works do not take into account the requirement to eliminate the influence of the spatial carrier.

With the advent of photosensors with accumulation of a wide dynamic range, researchers [8] proposed implementation of a heterodyne scheme with array photosensor based on CCD, which significantly simplified the design of the device and provided a higher frequency resolution. The work [9] considers method of the spatial carrier influence elimination based on the use of four lines of a matrix photosensor. However, the reading of additional lines increases the time taken to obtain an estimation of the input signal spectrum.

This article introduces the modification of this method, which enables to select the amplitude spectrum of the analyzed signal based on the reading of three lines. In addition, the article presents version for the method implementation using a linear photosensor or a photosensor with a time delay, accumulation and sequential reading of the charge distributions.

Reduction of the number of readable distributions decreases the time required to form the signal spectrum. Application of a linear photosensor reduces the requirements for matching the parameters of an acousto-optic modulator, a spatial Fourier transform unit, an optical wavelength, and geometric parameters of a photosensor.

Researchers can implement optical heterodyning, for example, according to the scheme of the Mach–Zehnder or Young interferometer. For consideration of the material presented below, this the scheme itself is not fundamental. The figure one presents the scheme of a homodyne acousto-optic spectrum analyzer (HAOSA) based on a Young interferometer (Fig. 1). The scheme includes *1* – a source of monochromatic radiation; *2* – collimating lens; *3* – two-channel acousto-optic modulator (AOM); *4* – spherical lens; *5* – matrix photosensor (MPS).

As a radiation source *1*, it is advisable to use a semiconductor or gas laser. The collimating lens *2* converts the generated by the laser diverging radiation at the wavelength λ_l into a plane wave. Next, the luminous flux irradiates the aperture of the two-channel AOM *3*. The lux feds the analyzed signal $s(t)$, to one of the inputs and the reference signal $r(t)$. to the other one. After AOM passing, the spherical lens *4* focuses the light flux in the aperture plane of the photosensor *5*. As a reference signal for the HAOSA, researchers can use broadband chirp pulses [10] or radio pulses based on a pseudo-random sequence [11], which provide optical heterodyning in a wide radio frequency range.

The method of quadrature components forming based on three lines of a photosensor. Let us consider the HAOSA mathematical model. The expression [1] describes the charge distribution in the MPS aperture:

$$Q(x_2, y_2, T_{\text{ac}}) = \\ = R_\lambda A\Big\{W_s(x_2, y_2, T_{\text{ac}}) + W_r(x_2, y_2, T_{\text{ac}}) + \\ + 2\,\text{Re}\left[\int_0^{T_\text{н}} \dot{S}(x_2, y_2, t)\dot{R}^*(x_2, y_2, t)\,dt\right]\Big\}, \quad (1)$$

where R_λ is the spectral sensitivity of the photosensor; A is scale factor, taking into account the conversion of input signals into the light flux in the AOM; T_{ac} is the accumulation time; $W_s(x_2, y_2, T_{\text{ac}})$ and $W_r(x_2, y_2, T_{\text{ac}})$ is the spatial energy spectra of the analyzed and reference signals, respectively, formed during T_{ac}; $\dot{S}(x_2, y_2, t)$ and $\dot{R}(x_2, y_2, t)$ are instantaneous spatial spectra of the analyzed and reference signals, respectively; * is the complex conjugation symbol[1].

The third term in (1) enables to select information about the amplitude and phase spectrum of the analyzed signal. After taking of the real part (1) we get the expression below[2]:

$$Q(x_2, y_2, T_{ac}) = \\ = A_v(y_2)\{W_s(x_2, y_2, T_{ac}) + W_r(x_2, y_2, T_{ac}) + \\ +2\int_0^{T_н} \left|\dot{S}(x_2, y_2, t)\right|\left|\dot{R}^*(x_2, y_2, t)\right| \times \\ \times \cos\left[(kD/F)y_2 + \psi_s(x_2, t) - \psi_r(x_2, t)\right]dt\}, \quad (2)$$

where $A_v(y_2)$ is the vertical charge distribution; k is the radian wave number of the light wave; D is the distance between AOM channels; F is the focal length of the lens *4*; $\psi_s(x_2, t)$ and $\psi_r(x_2, t)$ are the instantaneous phase spectra of the analyzed and reference signals, respectively.

The function $A_v(y_2)$ in case of the spherical lens *4*, which implements the two-dimensional spatial Fourier transform, has the following form

$$A_v(y_2) = \mathrm{sinc}^2\{[kH_a/(2F)]y_2\},$$

where H_a is the height of the acoustic beam in AOM; F is the focal length of the lens *4* (Fig. 1).

In the expression (2), the amplitude spectrum of the analyzed signal is multiplied by the amplitude spectrum of the reference signal and by the spatial carrier with the full phase formed by the instantaneous phase spectra of both signals and the term linearly varying along the vertical coordinate y_2. We can eliminate the spatial carrier by forming an additional quadrature component of the spectrum. The article [8] describes this process by reading four MPS lines. However, the reading of additional lines is not parallel through separate registers of the MPS; it multiplies the information output time and, accordingly, the spectrum wave length scanning time.

Below, the paper considers the modification of this method, which enables to limit the spatial carrier elimination to reading of three lines. The full phase of the spatial carrier in (2) contains a term that varies linearly in the coordinate y_2 and is independent of time t and horizontal coordinate x_2. This component can be considered as an initial phase, constant relatively mentioned variables, which makes it possible due to the shift along y_2 to introduce on Δy_2 the given phase shift:

$$\Delta\varphi = (kD/F)\Delta y_2. \quad (3)$$

It is also necessary to take into account the variation of the intensity along the coordinate y_2 in accordance with $A_v(y_2)$. The necessary additional charge shifts will be formed in the lines with the ensured phase shift $\Delta\varphi = \pm\pi/2$. The charge distributions in the read lines have a view:

– the first line

$$Q_{\cos}(x_2, y_2, T_{ac}) = A_v(y_2)[W_s(x_2, T_{ac}) + \\ +W_r(x_2, T_{ac}) + 2S_{\cos}(x_2, T_{ac})]; \quad (4)$$

– the second line

$$Q_{\sin}(x_2, y_2, T_{ac}) = A_v(y_2 + \Delta y_2)\times \\ \times[W_s(x_2, T_{ac}) + W_r(x_2, T_{ac}) + 2S_{\sin}(x_2, T_{ac})]; \quad (5)$$

– the third line

$$Q_{-\sin}(x_2, y_2, T_{ac}) = A_v(y_2 - \Delta y_2)\times \\ \times[W_s(x_2, T_{ac}) + W_r(x_2, T_{ac}) + 2S_{-\sin}(x_2, T_{ac})], \quad (6)$$

where

$$S_{\cos}(x_2, T_н) = \int_0^{T_{ac}} \left|\dot{S}(x_2, t)\right|\left|\dot{R}(x_2, t)\right| \times \\ \times\cos\left[(kD/F)y_2 + \psi_s(x_2, t) - \psi_r(x_2, t)\right]dt;$$

$$S_{\sin}(x_2, T_н) = \int_0^{T_{ac}} \left|\dot{S}(x_2, t)\right|\left|\dot{R}(x_2, t)\right| \times \\ \times\sin\left[(kD/F)y_2 + \psi_s(x_2, t) - \psi_r(x_2, t)\right]dt;$$

$$S_{-\sin}(x_2, T_н) = -\int_0^{T_{ac}} \left|\dot{S}(x_2, t)\right|\left|\dot{R}(x_2, t)\right| \times \\ \times\sin\left[(kD/F)y_2 + \psi_s(x_2, t) - \psi_r(x_2, t)\right]dt$$

– variants of the third term from (2), in which the shift assures the law of the spatial carrier variation according to the functions of the form of cos, sin and $-\sin$ respectively. It is important to note that:

[1] Expression (1) does not take into account the discrete structure of the photoreceiver and integration within the photosensitive elements.

[2] In the following expression, the non-fundamental constants for consideration R_λ and A are omitted.

$$S_{-\sin}(x_2,\ T_{ac}) = -S_{\sin}(x_2,\ T_{ac}).$$

After the charges reading, it is necessary to equalize the amplitude distributions in accordance with the factors $A_v(y_2)$, $A_v(y_2+\Delta y_2)$ and $A_v(y_2-\Delta y_2)$. The listed factors should not vanish. We can verify this by setting the following parameters typical for practice, wherein: laser wavelength $\lambda = 650$ nm; focal length of lens *4* $F = 200$ mm; distance between AOM channels $D = 10$ mm; height of acoustic beam in AOM channel $H_a = 1$ mm. We place the first line in the section $y_2 = 0$, then from (3) we obtain the shift of the other two lines relative to it: $\Delta y_2 = 3.25\ \mu$m up and down. Wherein

$$A_v(0) = 1;\ A_v(\Delta y_2) = A_v(-\Delta y_2) \cong 0.998. \quad (7)$$

Thus, for the selected parameters, all three lines lie within the main lobe of the function $A_v(y_2)$ (Fig. 2).

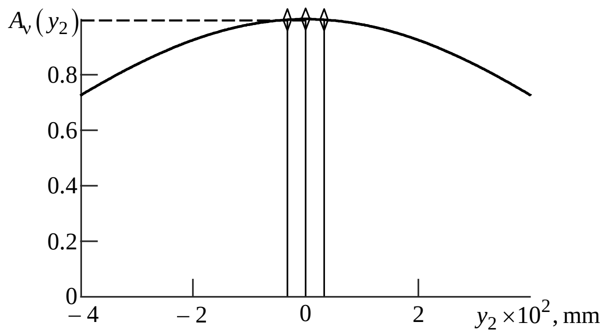

Fig. 2. Vertical section of spectrum analyzer instrument function

Further, without loss of generality, we can assume that distributions (4)–(6) are normalized to the corresponding values A_v.

Based on (4)–(6) we can write:

$$Q_{\cos}(x_2, y_2, T_{ac}) - Q_{\sin}(x_2, y_2, T_{ac}) = = 2\left[S_{\cos}(x_2,\ T_{ac}) - S_{\sin}(x_2,\ T_{ac})\right]; \quad (8)$$

$$Q_{\cos}(x_2, y_2, T_{ac}) - Q_{-\sin}(x_2, y_2, T_{ac}) = = 2\left[S_{\cos}(x_2,\ T_{ac}) + S_{\sin}(x_2,\ T_{ac})\right]. \quad (9)$$

Then:

$$S_{\cos}(x_2,\ T_{ac}) = (1/4)\left[2Q_{\cos}(x_2, y_2, T_{ac}) - -Q_{\sin}(x_2, y_2, T_{ac}) - Q_{-\sin}(x_2, y_2, T_{ac})\right]; \quad (10)$$

$$S_{\sin}(x_2,\ T_{ac}) = (1/4)\left[Q_{\sin}(x_2, y_2, T_{ac}) - -Q_{-\sin}(x_2, y_2, T_{ac})\right]. \quad (11)$$

We raise both sides of (8) and (9) in the square and sum the result

$$2Q_{\cos}^2(x_2, y_2, T_{ac}) - - 2Q_{\cos}(x_2, y_2, T_{ac})Q_{\sin}(x_2, y_2, T_{ac}) + + 2Q_{\cos}(x_2, y_2, T_{ac})Q_{-\sin}(x_2, y_2, T_{ac}) + + Q_{\sin}^2(x_2, y_2, T_{ac}) + Q_{-\sin}^2(x_2, y_2, T_{ac}) = = 8\left[S_{\cos}^2(x_2,\ T_{ac}) + S_{\sin}^2(x_2,\ T_{ac})\right]. \quad (12)$$

The propagation of signals along the aperture of AOM channels determines the dependence of the total phase of the spatial carrier on time for all three lines, which is equivalent to a time shift and the presence of the same linear additive in the phase spectrum of both signals, which does not affect the final result. Since the accumulation in the lines runs parallel in time, the sum of the squares in the right part of the expression (12) does not contain a spatial carrier. Extracting the square root and designating the result as $S_R(x_2,\ T_{ac})$, we get

$$S_R(x_2,\ T_{ac}) = 2\sqrt{2}\int_0^{T_{ac}} \left|\dot{S}(x_2,\ t)\right|\left|\dot{R}(x_2,\ t)\right| dt. \quad (13)$$

We can estimate in advance and take into account later in the normalization the multiplier corresponding to the amplitude spectrum of the reference signal in the expression (13). The accuracy of this operation depends on the stationary of the amplitude spectrum of the reference signal.

The left part of the expression (12) describes the obligatory mathematical operations performed for the charge distributions in the lines of the photosensor. However, it is rational to perform calculations based on (8) and (9), to square the results and to add. The digital post-processing device can perform these operations, as well as taking the root to find (13) and normalization, after reading and digitizing the charge distributions in the MPS lines.

The ratio of the expression (10) to (11) enables to obtain the information about the phase spectrum of the analyzed signal:

$$\psi_s(x_2, T_{ac}) = \operatorname{arcctg}\left[\frac{S_{\sin}(x_2,\ T_{ac})}{S_{\cos}(x_2,\ T_{ac})}\right] + \psi_r(x_2, T_{ac}),$$

which requires knowledge of the phase spectrum of the reference signal $\psi_r(x_2,\ T_{ac})$.. We can obtain this spectrum by, for example, applying a radio signal with a simple phase spectrum to the spectrum analyzer input and performing a calibration.

In accordance with the expression (3), in order to form the required field distribution in the MPS lines, it is necessary calculate the focus distance *F* of the Fourier lens for given values of the distance *D* between channels in AOM, the laser λ_l, wavelength, which determine the wavenumber, and the vertical size of the MPS pixel, which define the axis y_2, pitch. We should note that the pixel dimensions determine the accuracy of the formation of distributions (4)–(6).

The quadrature components are formed simultaneously, which does not impose additional restrictions on the analyzed signal, and the analyzer retains the ability to operate in real time without gaps. The analysis time is determined by the time required to read the three lines of the photosensor and to perform the calculations.

The method of quadrature components forming based on the sequential reading of three charge distributions. We can also be form distributions presented (4)–(6) by varying the phase spectrum of the reference signal, since this signal is deterministic and can be formed with any given parameters, and its phase determines the total phase of the spatial carrier.

Suppose that the first charge accumulation cycle was performed with a reference radio signal $r_1(t)$, and we obtained a charge distribution of the form of (4). We form one more reference signal $r_2(t)$, that differs from the first one only by changing the initial phase $+\pi/2$. The accumulation cycle with $r_2(t)$ obviously gives the charge distribution (5). The third accumulation cycle is feasible for the reference signal $r_3(t)$, which is shifted for $-\pi/2$ by the signal $r_1(t)$, so we obtain the charge distribution (6).

The described method does not require the use of the MPS. To register radiation and charge accumulation, researchers can use linear accumulation sensors, having a pixel with size along the axis y_2 substantially exceed the size along the axis x_2 (Fig. 1), which have a greater dynamic range [12]. HAOSA with time delay and accumulation sensors [13]–[15] also allow the expansion of the dynamic range and, as consequence, allow implementing this method.

The disadvantage of the latter method lies in the increased requirements for the stationary of the analyzed signal $s(t)$: its spectrum must be the same in each of the three accumulation cycles.

Formation of reference signals. We can use a simple from a technical point of view scheme to form the required sequence of reference signals (Fig. 3). For the organization of accumulation cycles, The reference signal generator *1* generates a video signal with specified spectral characteristics. The generator *4* sends the signal to the input of the local oscillator of the mixer *2*, which in turn transfers it to the working frequency of the AOM. The controlled phase shifter *3* provides the required phase shift in each of the accumulation cycles. The amplifier *5* provides the level of the reference signal necessary for the HAOSA operation.

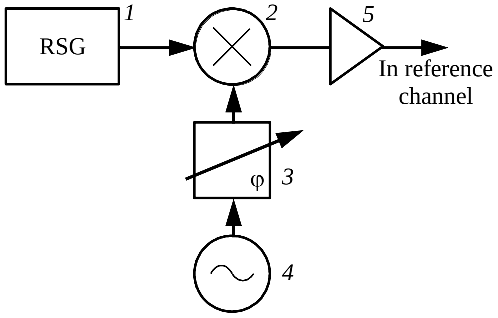

Fig. 3. The generator of reference signal with varied phase

The accumulation cycles repeat sequentially. In this case, we can use any three adjacent cycles of such a sequence to calculate quadrature components, since after reading of every next accumulated charge, changes only the order of the distributions (4)–(6) in the last three output signals of the photosensor. Thus, based on this sequence, we can organize a more flexible calculation with updating the frame of the signal spectrum with each new accumulation cycle, which further reduces the analysis time to the value spent on reading one line instead of three or four.

The phase shifter sets the phase relationship accuracy, which does not require a comprehensive selection of the parameters of the device nodes (laser wavelength, photosensor geometry, lens focal length, distance between AOM channels and acoustic beam height in the channel) as in the previously discussed method using a two-dimensional MPS and reading of additional lines.

The effect of phase relationships installation error. Numerical simulation showed (Fig. 4) that the phase deviation between the quadrature components of the spectrum from $\pi/2$ leads to errors in estimating the amplitude spectrum of the input signal, depending on its phase, which is a random variable. Fig. 4 shows the dependence of the HAOSA output signal Δ_{IF} variation on the additional shift α of the total phase of the spatial carrier in (4). We can consider the scatter of the analyzer output signal as a degradation of the signal-to-noise ratio and a decrease in the dynamic range of the device.

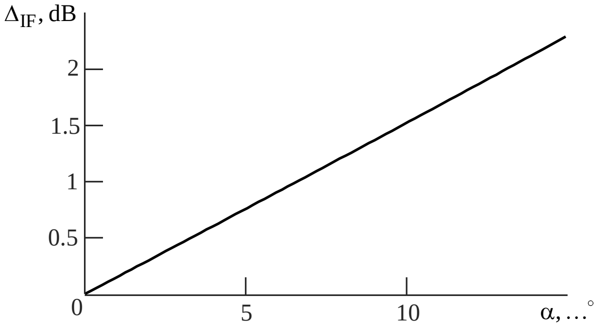

Fig. 4. The variance of instrument function

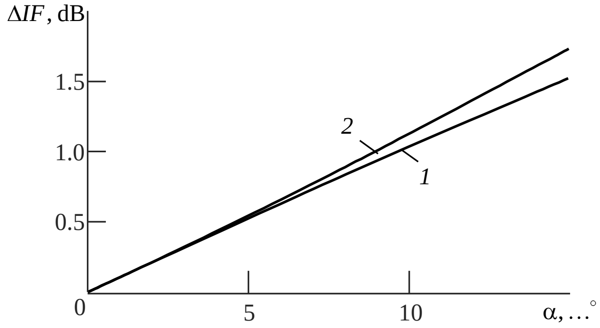

Fig. 5. Dependences of the spread value on the phase error

The simulation also showed that the level of variation varies depending in which of the lines described by distributions (4)–(6) the phase relations break. The distribution (4) provides the greatest variation when an error occurs. As follows from fig. 5, the scatter levels in distributions (5) (curve *1*) and (6) (curve *2*) also differ. This difference is stipulated by the feature of obtaining quadrature components in three lines, embedded in the proposed algorithm. Considering the relativity of the phase correspondences in (4)–(6), it is advisable to consider the charge distribution in the top (first with sequential spectrum formation) of three lines described by expression (5), the middle (second) line – (4) and the bottom (third) – (6).

It is also necessary to take into account that charge distributions must be obtained when the input signal is stationary for a time $3T_{ac}$, that, taking into account the speed and the number of pixels of linear photosensors with an accumulation, is from several tens of microseconds to few milliseconds. That means that the device is not able to analyze qualitatively single signals with duration of less then $3T_{ac}$ and signals which spectrum is non-stationary during the specified time interval.

Conclusion. The methods of forming quadrature components of the spectrum in a homodyne acousto-optic spectrum analyzer presented in this paper, in comparison with the approach described in [9], can reduce the analysis time, which is one of the essential parameters for spectrum analyzers operating in real time. From the point of view of practical implementation, the method based on the variation of the initial phase of the reference signal is simpler and more accurate.

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