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SIGNAL-RESPONCE PROCESSING IN KAZAN PROJECT OF GRAVITATIONAL-WAVE DETECTOR "DULKYN"

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The systems for stabilizing the frequency and phase of optical radiations in the laser system resonators of the gravitational-wave detector 'Dulkyn' are considered. Algorithms for processing the optical signal-response of the detector to gravitational radiation effect are proposed, providing the possibility to observe the detected signal with signal-to-noise ratio 50 when signal-to-noise ratio at the scheme optical part output does not exceed 10^{-7}.

1. Introduction

At present theoretical backgrounds are developed for the formation of elastodynamical response of Weber-type solid state gravitational-wave (GW) antennas-detectors [1, 2], of electrodynamical response of Michelson-type long-baseline laser-interferometric systems [1, 2] and of the compact laser-interferometric antennas [3, 4] to the effect of gravitational radiation (GR) field. The Weber and Michelson-type GW-antennas are intended for the detection of short pulse GW-signals from burst sources. As Thorn emphasizes [5], our knowledge of these sources are too relative and uncertain. The lack of a priori information on spatial-time characteristics of GW-signals from these sources decreases the probability of their correct detection and reliability of their unambiguous identification. The required instant signal-to-noise ratio should be greater than unit to detect reliably the GW-signal from a burst source of GR by means of solid state and long-baseline detectors.

As it shown in [2], within the framework of gravitational-wave astronomy the following problems are being solved:

- detection of GW-signal, its gravitational-wave origin being reliably proven;
- identification of the source by its radiation characteristics;
- restoration of astrophysical processes in radiator based on the received signal structure.

The detection of GR from the burst type sources by Weber and Michelson-type antennas requires a far separated global net of land-based detectors to be arranged. The basic underlying principle of GW-antennas net functioning is realized by means of the coincidence scheme, the net orientation being optimized.

In Scientific Center for Gravitational-Wave Research 'Dulkyn' (Kazan) the compact gravitational-wave detector for detecting the periodic low-frequency gravitational-wave signals from binary relativistic astrophysical objects is developed. GW detector 'Dulkyn' presents a compact ring two-resonator laser system with common active medium and elastically coupled reflecting elements in spatially inequivalent contours [6-12]. The response of GW detector to the GW signal effect consists in phase incursion of optical radiations in laser system resonators at the cost of refraction factors variation along optical paths due to anisotropic change of dielectric constant and magnetic permeability of vacuum between the reflective elements. Geometrical or spatial nonequivalence of contours relative to the GW signal effect results in different phase incur-

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sions in resonators optical radiations, what provides non-vanishing phase difference of optical radiations in resonators, changing by the law of the detected GW signal variation. When developing the GW detector they took into account that predicted by the theory spatial-frequency characteristics of GW signal from periodic sources and their long-term existence allow to provide (e.g., by methods of long-term coherent intra- and interperiodic accumulation) the consequent filtration of the signal from noise with the required signal-to-noise ratio not less than 10 at the GW detector output [11-15].

Methods of constructing the measuring system with GW detector for solving the problem of GW signal characteristics identification are considered below by the example of the source PSR 1537+1155.

2. The GW detector signal-response to GW signal effect

Gravitational-wave detector 'Dulkyn' contains (see the Fig. 1): ring pentagonal spatially nonequivalent two-resonator laser interferometer with common active medium and fixed on a single basement mirrors, common for the resonators [9,11]; system of frequencies difference stabilization, providing the regime of synchronization of radiations ($\omega_1 = \omega_2$) in the first and the second resonators (first stabilization stage (1SS)); system of automated stabilization of phase difference of resonators output radiations, providing this difference stabilization at the level exceeding that of the friendly signal not less than by two orders of value (the second stabilization stage (2SS)); system of phase difference disturbance component compensation below the friendly signal level; optimal threshold detector [13]; intraperiodic comb accumulation filter (CAF) [11,14].

The main part of the scheme is the ring two-resonator laser system [9,11] with active medium (AM), providing generation of linearly and orthogonally polarized optical radiations. The reflective elements forming two spatially nonequivalent ring resonators (1 is the mirror with piezoelectric cell, 2 is semitransparent mirror with a thin phase grating on the back side, providing simultaneous propagation of radiations in the resonators over two loops, 3, 4, 5 are hologram diffraction reflective elements, PTE and PTM are polarization prisms), are rigidly fixed on a single basement. Optical radiation with TE-polarization passes over the contour 1-2-3-4-5-1 (the first resonator), and radiation with TM-polarization passes over the contour 1-5-4-1-3-2-1 (the second resonator).

Gravitational-wave signal changes the vacuum dielectric constant tensor and, by virtue of the resonators spatial nonequivalency, causes different shifts of longitudinal eigenfrequencies in them. So, addition appears in the difference frequency $\Delta\Omega_{12}(t)$ of optical radiations in the first and second resonators, conditioned by the signal-response $\Delta\Omega_g(t)$, caused by the GW signal effect on GW detector, presented in the following general form

$$\Delta\Omega_g(t) = \omega_0 H(t) sin[\omega_g t + \varphi(t)] \,, \qquad (1)$$

where ω_g is the GW signal carrier frequency; ω_0 is the optical radiation frequency. Functions $H(t)$ and $\varphi(t)$ correspondingly allow for the possible amplitude and phase modulations of GW signal due to the Earth rotation, to the precession of orbit plane of binary system, which is the GW signal source, to the gravitational wave polarization components rotation etc.

Amplitude and phase modulations [16] of periodic signal, which is the GW signal from the binary relativistic astrophysical object, result in the signal spectrum spreading, the appeared side frequencies being symmetrically arranged relative to the carrier (central) frequency ω_g. In this case the formula (1), according to [16], can be presented as follows:

$$\Delta\Omega_g(t) = \omega_0 H_0 sin(\omega_g t + \varphi_0) + \Delta\Omega_{gn}(t) \,, \qquad (2)$$

where $\omega_0 H_0$ is spectral component of signal-response at the carrier frequency Ω_g with initial phase φ_0; $\Delta\Omega_{gn}(t)$ is a function describing the influence of the side frequencies spectral components of the GW signal spread spectrum. At that the case, when the component $\omega_0 H_0$ is very small or equal to zero, can be realized. The value H_0 can be presented as $H_0 = hk_{GWD}$, where k_{GWD} is coefficient characterizing the GW detector response to the effect of GW signal spectrum component at the carrier frequency depending on the GW signal source celestial coordinates; h is a non-dimensional quantity characterizing the gravitational wave amplitude.

The GW detector under consideration is developed for the case $h \sim 10^{-22}$ and $0,1 \leq k_{GWD} \leq 1$, when the GW signal spectral component at the carrier frequency ω_g is apparently manifested. Accounting for (2), let's write the resonators eigenfrequencies difference as follows:

$$\Delta\Omega_{12}(t) = \omega_0 H_0 sin(\omega_g t + \varphi_0) + \Delta\Omega(t) \,,$$

where $\Delta\Omega(t) = \Delta\Omega_n(t) + \Delta\Omega_{gn}(t)$ is the noise, conditioned by technical and natural fluctuations of the difference frequency.

3. Systems of the difference frequency and phase stabilization

Under synchronization conditions, when the generation frequencies of the first and the second resonators $\omega_1 = \omega_2 = \omega_0$, the phase difference at the laser system output can be presented in the form [9]

$$\Delta\varphi_{12}(t) = \Delta\varphi_{12g} sin(\omega_g t + \varphi_0 - \varphi_1) + \Delta\varphi_{12n}(t)\,, \qquad (3)$$

where $\Delta\varphi_{12g} = H_0\omega_0/\sqrt{\Delta\omega_z^2 + \omega_g^2}$ is phase modulation amplitude; $\Delta\varphi_{12n}(t)$ is phase noise, caused by the difference frequency fluctuations $\Delta\Omega(t)$; $\varphi_1 = \mathrm{arctg}(\frac{\omega_g}{\Delta\omega_z})$ is the signal-response phase shift in the laser system; $\Delta\omega_z$ is the locking zone width. At $\Delta\omega_z$ =1 Hz, $H_0 = 10^{-22}$, $\omega_g \leq 1$ mHz and $\omega_0 = 10^{15}$ Hz we obtain $\Delta\varphi_{12g} = 10^{-7}$ rad.

By means of polarizers 10 and 11, which light transmission plane forms the angle 45^0 with that of the laser system, the orthogonal radiations of the first and the second resonators form correspondingly the interference patterns at the inputs of photodetectors PD1 and PD2.

Fixed on the mirror 1 piezoelectric cell provides controlling the shifts of longitudinal eigenfrequencies to make the deviations from the equality $\omega_1 = \omega_2$ not greater than 1 Hz. The signal-to-noise ratio at the photodetector PD2 output $q_{out} = 10^{-7}$ will correspond to this stabilization level.

To control the piezoelectric cell (1SS) functioning the error signal (ES) is formed in the frequency autotuning (FAT) unit, operating by the output voltage of photodetector PD1. After passing through the Wollaston prism 6 optical radiations of both resonators are splitted in TE and TM components correspondingly. Then they form the interference field at the photodetector PD2 input by means of the mirrors 7 and 8, of the Wollaston prism 9 and of the polarizer 10. Phase modulator PM, placed in the optical path of the first resonator, is intended to stabilize the phase difference of output radiations of the first and the second resonators at the level exceeding that of the friendly signal not less than by two orders of magnitude. To control the phase modulator (PM) (2SS) functioning the ES is formed in the phase autotuning (PAT) unit by the input voltage of photodetector PD2.

Further processing of the laser system output signal, implying the information on the GW signal parameters, can be performed in analog or digital form. However the specific character of measurement problem under consideration consists in the necessity of long-term accumulation of extremely weak signal-responses to GW signal to provide its parameters reliable identification. In this connection the used processing algorithms imply representation of the signal-response in the form of a sequence of readings for a subsequent processing of the signal by computer.

4. Maximization of signal-to-noise ratio in the GW detector 'Dulkyn'

To compensate the disturbance signals the channel 'disturbance+signal' (photodetector PD2 output being one of the inputs of subtraction circuit SC) and the channel 'disturbance' (photodetector PD2 output, being the disturbance channel adder Σ_{DC}, presents another subtraction circuit SC input) are formed. The subtracted from Σ_{DC} friendly signal is formed in the system of correlative auto-compensation of the extracted GW signal (SCACS). This system (see the figure) contains the quadrature correlative auto-compensator (AC) of the signal and simulator of signal-response of GW detector to the detected GW signal. After setting the regime of synchronization of radiations in the resonators using the FAT unit the photodetector PD2 output voltage is described by expression

$$V_{12}(t) = V_{12g}(t) + V_{12n}(t)\,, \qquad (4)$$

where $V_{12g}(t) \cong 10^{-7}$ is the GW detector signal-response component, conditioned by the phase difference $\Delta\varphi_{12g}(t)$; $V_{12n}(t) \cong 1$ is a component, conditioned by the total effect of all the disturbances. Hereafter the photodetector transmission coefficient is supposed to be equal to unit (for the sake of simplicity) and its output signal to be non-dimensional.

As experimental study has demonstrated [11], in the presence of friendly signal component in the ES, the system 2SS stabilization threshold should exceed, at least, by two orders of magnitude the phase difference value, conditioned by the friendly signal effect, i.e. $V_{12n}(t) \cong 10^{-5}$. This condition violation results in $\Delta\varphi_{12g}(t)$ distortion up to its complete compensation. $q_{out} \cong 10^{-2}$ will correspond to the level $V_{12n}(t) \cong 10^{-5}$ at the output of photodetector PD2.

The output signals of the auxiliary quadrature channels of correlative AC of the extracted GW signal are applied to the other inputs of GW detector to extract the friendly signal from the adder Σ_{DC}.

Let's consider the operation of AC of the extracted signal-response (see the fig. 1) preface. The additive mixture of signal-response $V_{12g}(t)$ and disturbance signal $V_{12n}(t)$ comes from the photodetector PD2 output to the main input of adder $\Sigma\ AC$. To exclude the uncertainty factor of initial phase φ_0 the AC contains two auxiliary quadrature channels.

From the simulator output the signal-response

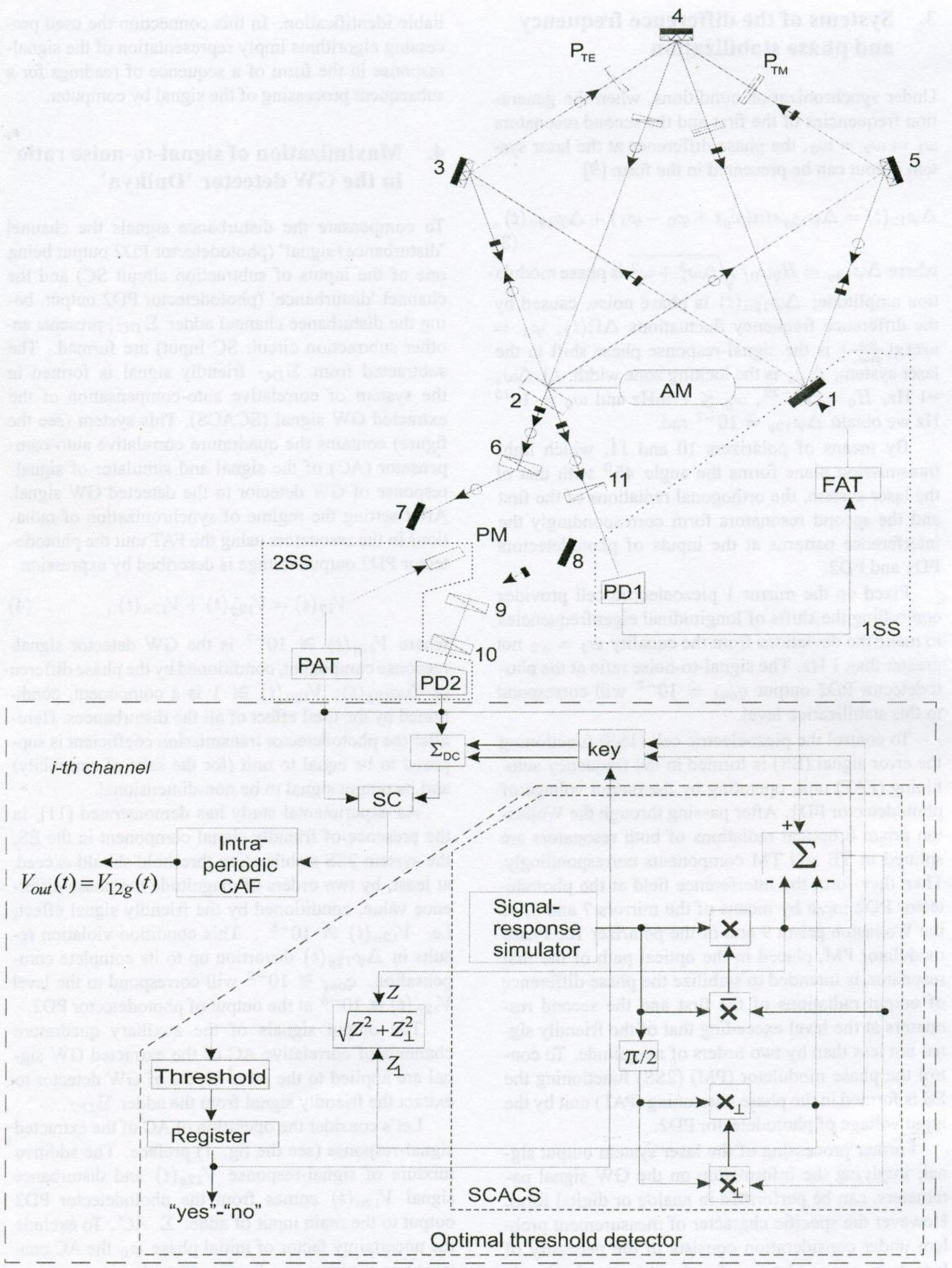

Fig. 1. *Optical arrangement and block diagram of GW - detector "Dulkyn."*

$V_{ug}(t) = U cos\omega_g t$ at the frequency $\omega_g = \frac{2\pi}{T_g}$ (T_g is the detected GW signal period) with unit amplitude U, after being multiplied by the coefficient $\beta k(t)$ in the multiplier $\times$, comes to the auxiliary input of the AC adder Σ. The same signal comes to another auxiliary input of the adder Σ after its phase being shifted by $\frac{\pi}{2}$ $V_{\perp ug} = U sin(\omega_g t)$ (i.e. the quadrature ($\perp$) component) and after being multiplied by the quadrature coefficient $\beta_\perp k_\perp(t)$ in the multiplier $\times_\perp$. The adder output voltage [17] is

$$V_\Sigma(t) = V_{12n}(t) + V_{12g}(t) + \beta k(t) V_{ug}(t) +$$

$$+\beta_\perp k_\perp(t) V_{\perp ug}(t) \ , \qquad (5)$$

$$\beta k(t) = -\frac{\overline{[V_{12n}(t) + V_{12g}(t)]V_{ug}}}{\overline{V_{ug}^2(t)}} \ ,$$

$$\beta_\perp k_\perp(t) = -\frac{\overline{[V_{12n}(t) + V_{12g}(t)]V_{\perp ug}}}{\overline{V_{\perp ug}^2(t)}} \ ,$$

where $\beta k(t)$ and $\beta_\perp k_\perp(t)$ are the control voltages (the transmission coefficients) formed in the correlators $\overline{\times}$ and $\overline{\times}_\perp$ correspondingly (overline denotes time averaging in the interval $T_g = N\Delta t$); $\beta \gg 1$, $\beta_\perp \gg 1$ are the amplification factors in the correlative negative feedback circuit; Δt is the reading step (its value being not less than the phase noise correlation time, determining the value $V_{12n}(t)$); N is the number of readings for a period T_g ;   is the periods number.

Since the PAT provides the spectral density of phase noise amplitude being less than $10^{-4} rad/\sqrt{Hz}$ in the frequency band $0 \div 10 Hz$ [9] (the broadband disturbance amplitude being equal to $V_{12n} = \Delta\varphi_{12d} \approx 3 \cdot 10^{-4} rad$ at the signal level $V_{12g} = \Delta\varphi_{12g} = 10^{-7} rad$), then in (3) and (4) at the values $\Delta t \simeq 0.025$ s, $N = 1.157 \cdot 10^5$ for $T_g = 2.8927 \cdot 10^3$ (the source of GW signal of PSR 1537+1155 type [18]) and   = 900 we obtain the root-mean-square deviation

$$\sigma_V = \{\overline{V_{12n}(t) \cdot V_{ug}(t)}\} = \frac{\sqrt{\overline{V_{12n}^2}}}{\sqrt{2NM}} = 2 \cdot 10^{-8} \ ,$$

$$\sigma_V = \{\overline{V_{12n}(t) \cdot V_{\perp ug}(t)}\} = 2 \cdot 10^{-8} \ ,$$

$$\overline{V_{12n}(t) \cdot V_{ug}(t)} = \frac{1}{2} V_{12g} = 5 \cdot 10^{-8} \ ,$$

$$\overline{V_{12n}(t) \cdot V_{\perp ug}(t)} = \frac{1}{2} V_{12g} = 5 \cdot 10^{-8} \ , \qquad (6)$$

$$\overline{V_{ug}^2(t)} = \overline{V_{\perp ug}^2(t)} = \frac{1}{2} U_{ug}^2 = \frac{1}{2} U_{\perp ug}^2 = 0.5 \ .$$

Let's note that the use of intraperiodic CAF only does not allow to achieve immediately the required signal-to-noise ratio. This result could be achieved only by means of SCACS.

Actually $V_\Sigma(t) = V_{12n}(t) + \Delta_n + \Delta_c$, where $\Delta_n \approx 4 \cdot 10^{-8}$ is the disturbance signal component, conditioned by the finite averaging time in the correlator; Δ_c are the uncompensated remainders of the friendly signal at the AC adder output Σ. At that the coefficient of suppression $\gamma = (1 - \rho^2)^{-1}$ of correlated components in the output signal $V_\Sigma(t)$ is determined by their correlation coefficient ρ.

The exact information of the detected GW signal period T_g (accurate to the fourth decimal place and higher) will allow one to simulate the signal-response of GW detector to GW signal with correlation coefficient $\rho = 0,999$ and more. Then $\gamma = 500$, and the noncompensated remainder at the adder output Σ_{DC} will amount $\Delta_s \approx V_{12g}(t)/\gamma = 10^{-7} rad/500 = 2 \cdot 10^{-10} rad$.

The voltage $V_{\Sigma_{DC}}(t)$ at the adder output Σ_{DC}, taking into account of (4), is expressed as

$$V_{\Sigma_{DC}}(t) = V_{12n}(t) + V_{12g}(t) + \beta k(t) V_{ug}(t) +$$

$$+\beta_\perp k_\perp(t) V_{\perp ug}(t) \ ,$$

or, taking into account of (6),

$$V_{\Sigma_{DC}}(t) = V_{12d}(t) + \Delta_d + \Delta_s .$$

So, the disturbance component $V_{12d}(t)$ (at the level $3 \cdot 10^{-4} rad$), the disturbance component conditioned by the finite averaging time in the correlator (at the level $4 \ 10^{-8} rad$) and the friendly signal noncompensated remainders (at the level $2 \cdot 10^{-10} rad$) come to the SC input by the 'disturbance' channel.

The voltage at the SC output is equal to

$$V_{SC}(t) = V_{12}(t) - V_{\Sigma_{DC}}(t) = V_{12g}(t) - \Delta_d - \Delta_s \ .$$

Since $V_{12g}(t) = 10^{-7} rad >> \Delta_s \approx 10^{-10} rad$, then $V_{SC}(t) = V_{12g}(t) - \Delta_d$, what is equivalent to the attainment of signal-to-noise ratio $q_{out} \cong q_{in}$ equal to the (detected GWS)/(GWS from other sources) ratio at the measuring facilities input. As it has already been mentioned in [10], the q_{in} ratio is close to unit. Then the signal with $q_{out} \cong q_{in} \cong 1$ from comes from the SC output to the CAF input. Its operation provides in $T_g/2$ [12-15]:

$$q_{out} = q_{in} \cdot \sqrt{\Delta t \cdot N} \approx 53 \ .$$

Thus, the signal-to-noise ratio of the order of unit at the measuring device input will increase at the CAF output up to the value of the order of 50 in $900 T_g$ (averaging time in AC correlators) plus $T_g/2$ (time of semiperiodic accumulation in CAF) for the source of

GW signal of PSR 1537+1155 type, the CAF output signal being that of the GW detector.

To take a decision on the detected GW signal presence the output signals $Z = \beta k(t) V_{ug}(t)$ and $Z_\perp = \beta_\perp k_\perp(t) V_{\perp ug}(t)$ of the quadrature channels of the disturbances autocompensator are used, forming together with the unit of computing $\sqrt{Z^2 + Z_\perp^2}$, with the threshold scheme and with the data recorder the optimum threshold detector, operating by the criterion 'yes'-'no' (see the details in [13]). The threshold detector output signal comes to the controlling input of the key circuit to connect the outputs of the auxiliary channels of the signal-response autocompensator to the adder Σ_{DC} inputs only in the presence of the friendly signal (criterion 'yes').

The multichannel variant of developing the scheme is evident: the functional scheme is repeated by the number of the detected GW signals starting from the photodetector PD2 output.

So the consequent systems of stabilization of the resonators optical radiations frequencies and phases differences and the system of signal-response processing provide:

- stabilization of the frequencies difference of the resonators optical radiations to the level $\omega_1 = \omega_2$, what guarantees the operation within the locking zone (the first stage);
- stabilization of the phases difference of the resonators optical radiations to the level, exceeding that of the phase difference by the expected GW signal not less than by two orders of value (the second stage);
- compensation of the phase difference disturbance component under the friendly signal level.

This provides the multichannel extraction of the detected GW signals all over the low-frequency range of gravitational radiation using the intraperiodic CAF.

5. The GW signal detection as the measurement problem of identification

Although the GW signal wavelength is considered to be known, the problem of its detection (structural-parametrical identification) should be treated as the initial problem of mathematical statistics. The compactness maximum method (CMM) [19] presents the body of mathematics for solving the measuring problems of this type.

Let's present the data of GW detector measurements $u(t_n) = \widehat{u}_n$, $n = \overline{1, N}$, in terms of interpretive model of maximal complexity

$$U_g(t) = A_0(t) + \sum_{m=1}^{M} A_m \cdot sin(2\pi f_m t + \varphi_m) + Z(t) + \Xi(t)\,, \quad A_m << |\Xi(t)|\,, \qquad (7)$$

where $A_0(t)$ is the position characteristic; A_m, f_m and φ_m are the amplitudes, frequencies and initial phases of harmonic components; $Z(t)$ is the error of discrepancy of interpretation model; $\Xi(t)$ is the measurements error.

It should be noted that a standard problem of a random process expansion in Fourier series is regarded as an ill-conditioned by the following reasons:

- this expansion presents just the procedure of parametric identification;
- determination of expansion coefficients in terms of integral relationships yields substantially by accuracy to the algorithms based on the orthogonality property [20];
- parametric identification algorithms, based on orthogonality property, are not designed for application in the scheme of the errors cross observation, aimed at structural identification.

Let's preliminary identify the situation characteristics taking into account the above-mentioned reasons. Thereto one may use the system of metrological tracking the metering problems "CMM-stat" [21]. Then the GW signal harmonic component is to be subjected to identification, the system of metrological tracking the statistical metering problems "spectrum-CMM" [21] may be used with that end in view.

The distinctive feature of solving the problem by means of CMM-identification is substantially higher reproducibility of the problem solution results compared to the quadrature citeria and to standard representation of the required signal in terms of a discrete Fourier series. It's particularly important in the cases, when the disturbances level exceeds substantially the friendly signal level or the signal-response splashes take place. The possibility to solve more properly the problem of GW signal structural identification in the time domain, but not in the frequency domain, should be emphasized as well, since both solutions variants are customarily considered to be equivalent for a standard Fourier series.

6. Conclusions

The consequent systems for stabilizing the frequency and phase of optical radiations in the resonators and the correlative processing of the signal-response of gravitational-wave detector to the expected effect of the source of PSR 1537+1155 type radiation provide the possibility to observe the detected signal with signal-to-noise ratio ~ 50 when signal-to-noise ratio at the scheme optical part output does not exceed 10^{-7}.

The proposed algorithm of processing the results of the repeated consequent measurements, based on the compactness maximum method, makes provision for both positive and negative solutions of the GW signal detection problem.

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ОБРАБОТКА СИГНАЛА-ОТКЛИКА В КАЗАНСКОМ ПРОЕКТЕ ГРАВИТАЦИОННО-ВОЛНОВОГО ДЕТЕКТОРА "ДУЛКЫН"

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Рассматривается система для стабилизации частоты и фазы оптического излучения в резонаторах лазерной системы гравитационно-волнового детектора "ДУЛКЫН". Предложены алгоритмы обработки оптического сигнала-отклика детектора на воздействие гравитационно-волнового излучения, дающая возможность наблюдать сигнал с отношением сигнал-шум равным 50.

ОБРОБКА СИГНАЛУ-ВІДГУКУ У КАЗАНСЬКОМУ ПРОЕКТІ ГРАВІТАЦІЙНО-ХВИЛЬОВОГО ДЕТЕКТОРА "ДУЛКИН"

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Розглядається система для стабілізації частоти і фази оптичного випромінювання у резонаторах лазерної системи гравітаційно-хвильового детектора "ДУЛКИН". Запропоновані алгоритми обробки оптичного сигналу-відгуку детектора на дію гравітаційно-хвильового випромінювання, яка дає можливість спостерігати сигнал з відношенням сигнал-шум, що дорівнює 50.