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Effect of intense background radiation on the sensitivity of a laser receiver with an iodine active quantum filter

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***Abstract*. The effect of background light on the sensitivity of a laser receiver with an iodine active quantum filter ($\lambda = 1.315$ μm) was theoretically and experimentally investigated. Upon the reception of a 40-ns pulsed signal against the background of 2.5-fold attenuated radiation of a pulsed light source with a brightness temperature of 4×10^4 K, the sensitivity of this receiver for a signal-to-noise ratio of three and a diffraction-limited acceptance angle was experimentally shown to be equal to 20 photons, which exceeds the quantum limit by about a factor of two. This is consistent with the results of theoretical treatment and suggests that upon the detection of optical signals against the background of the solar disk, the sensitivity of this receiver should decrease by only 12 %. This receiver was compared with a receiver employing a photomultiplier of the visible range. Upon the reception of optical signals with the same parameters against the background of the solar disk and an interference filter with a transmission band width of 5 nm, the sensitivity of a receiver equipped with an FEU-115 photomultiplier was shown to be equal to about 1400 photons for a signal-to-noise ratio of three.**

Keywords: *iodine active quantum filter, photodiode, laser receiver, background radiation, radiation statistics, photocurrent dispersion, quantum sensitivity limit.*

1. Introduction

A laser receiver (LR) of optical signals with an iodine active quantum filter (AQF) at 1.315 μm [1 – 5] has an extremely high sensitivity, which is bounded by the quantum limit, and a wide field of view. These properties have made it possible to record an optical signal consisting of several photons [4] and to amplify the image brightness by a factor of 3000 with retention of diffraction-limited resolution [5]. Since the iodine AQF features a very narrow amplification band (the full width at half-maximum (FWHM) of the spectral line is $\Delta\nu^{\mathrm{c}}_{1/2} \approx 0.01$ cm^{-1} [1]), it can be used, as shown by preliminary estimates [6], to extract, amplify, and record single-photon signals even in the presence of an intense background radiation, for instance against the background of the solar disk.

The background optical radiation that falls into the AQF amplification band is added to the quantum noise, is amplified, and increases the LR noise. Outside the amplification band, it passes through the AQF without amplification and also arrives at the photodetector as noise. To suppress this background noise, i.e., to improve the interference immunity of the LR, advantage can be taken of passive optical filters, e.g. interference ones. Note that the possibility to attain high amplification factors when using an iodine AQF in the LR furnishes an opportunity to manage without interference filters. For instance, neutral density light filters can be placed between the amplification stages of the AQF, with the corresponding increase in the amplification factor of the AQF. In this case, the background discrimination will be improved while the AQF immunity to self-excitation will not change.

To draw a well-reasoned conclusion regarding the feasibility of practical application of an iodine AQF for the reception of weak optical signals against a strong background radiation, we performed comprehensive theoretical and experimental investigations.

2. Experimental

Experiments were performed as follows. The radiation pulse from a master oscillator (Fig. 1) with a FWHM duration of 40 ns was focused with a mirror (*6*) on a diaphragm (*7*). A fraction of the radiation that passed through the diaphragm was directed by a mirror (*8*) to a photodiode (*9*) to serve as a reference. The radiation transmitted through a mirror (*8*) was attenuated by filters (*10*) to the desired level, and was incident on a mirror (*12*), which focused it in the AQF cell with an active medium (*13*). After the passage through a cell (*13*) and amplification, the radiation passed through the neutral density light filters (*14*) to become attenuated and focused with a mirror (*16*) through the filters (*14*) into the cell (*13*) once again. The resultant transmittance of the filters (*14*) for a double passage of the radiation was 8.9×10^{-3}.

After passing through the cell in the opposite direction and experiencing additional amplification, the signal radiation passed through a KS-14 filter (*20*) and a polariser (*21*) to arrive at the sensitive area of an avalanche photodiode (*22*), was amplified by an electronic amplifier, and was recorded with an oscilloscope. The radiation of a pulsed ISI-1 light source (Podmoshenskii source), which has a

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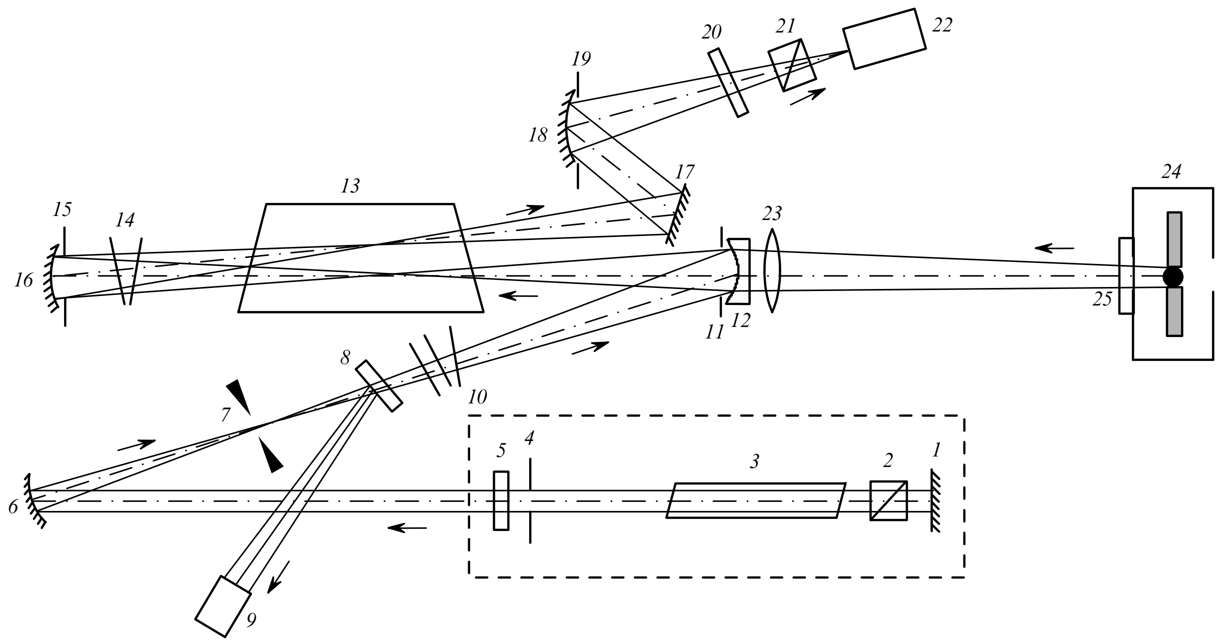

Figure 1. Optical schematic of the experimental setup: (*1*), (*5*) cavity mirrors of the master oscillator (MO); (*2*) optical modulator; (*3*) MO cell; (*4*) diaphragm 4 mm in diameter; (*6*) totally reflecting spherical mirror with a focal length $f = 50$ cm; (*7*) diaphragm 0.2 mm in diameter; (*8*) dielectric mirror, R = 30 %; (*9*) photodiode; (*10*) optical filters (attenuators); (*11*) diaphragm 12 mm in diameter; (*12*) semitransparent spherical mirror with a reflectivity of ~ 55 % and $f = 75$ cm; (*13*) cell of the iodine amplifier; (*14*) interstage filters; (*15*) diaphragm 12 mm in diameter; (*16*) totally reflecting spherical dielectric mirror with $f = 75$ cm; (*17*) totally reflecting plane mirror; (*18*) totally reflecting spherical dielectric mirror with $f = 75$ cm; (*19*) diaphragm 12 mm in diameter; (*20*) KS-14 red light filter; (*21*) polariser (Glan prism); (*22*) LFD-2 photodiode; (*23*) lens with $f = 60.3$ cm; (*24*) discharge chamber of a standard light source of the ISI-1 type (Podmoshenskii source) with a protective glass (*25*).

brightness temperature of about 40000 K, was focused in the AQF cell with a lens (*23*) through a mirror (*12*) simultaneously and coaxially with the signal radiation. The planes of sharp imaging of the ISI-1 plasma and the diaphragm (*7*) coincided. After passing the entire optical path, the ISI-1 radiation arrived at the photodiode (*22*). The diameter of the plasma image was approximately ten times the diameter of the image of the diaphragm (*7*).

The signal radiation, the spontaneous radiation of the AQF, and the ISI-1 radiation propagated in the solid angles defined by a diaphragm (*11*) and a diaphragm (*19*) matched to it. The focal length of a lens (*23*) was so selected that it made up, in combination with a semitransparent mirror (*12*) as a negative lens, an optical system with an equivalent focal length equal to the focal length of a mirror (*12*) operating at reflection.

The signal and noise radiation, which was focused by a mirror (*18*), was accepted within a plane angle defined by the dimensions of the acceptance surface area of the LFD-2 photodiode and was equal to $1.2\vartheta_{\rm d}$, where $\vartheta_{\rm d} = \lambda/d$ is the plane diffraction-limited angle and d is the diameter of the diaphragm (*19*). The averaging time $\tau_{\rm e}$, defined by the bandwidth of the electronic amplifier, was 90 ns. The transmission bandwidth of the optical path $\Delta\nu$ was defined by the width of the reflection peaks of the dielectric mirrors (*16*–*18*) and was equal to about 3000 cm^{-1}. To eliminate the radiation reflected by these mirrors in the blue spectral range, use was made of a KS-14 light filter.

3. Sensitivity equation of a laser receiver in the presence of background radiation

Consider the LR operation in the presence of a background radiation source. The background radiation that finds its way to the AQF input is assumed to be isotropic within the solid acceptance angle $o_{\rm r}$, which characterises the field of view of the photodiode: $o_{\rm r} = \sigma_{\rm r}/f^2$, where $\sigma_{\rm r}$ is the acceptance surface area of the photodiode; and f is the equivalent focal length of the optical system. For a round acceptance surface area $o_{\rm r} = \pi(\vartheta_{\rm r}/2h)^2$, where $\vartheta_{\rm r}$ is the plane radiation acceptance angle. The background radiation at the input of the active medium of the AQF per one polarisation selected by the polariser (*21*) will be characterised by the spectral brightness density $I_{\nu o}^{\rm bgr}$ of the background radiation source, which is constant during the course of the laser pulse and is measured in W m^{-2} cm sr^{-1} [7]. Then, the spectral brightness density of the radiation with a frequency ν for the above polarisation at the output of the optical path is

$$I_{\nu o}^{+\rm out} = \{I_{\nu o}^{\rm vac}[K^+(\nu)-1]T_{\rm n}^2T_{\rm w}^3(\nu)R_{16}K^+(\nu)$$
$$+ I_{\nu o}^{\rm vac}[K^+(\nu)-1]T_{\rm w}(\nu) + I_{\nu o}^{\rm bgr}[K^+(\nu)]^2\,T_{\rm n}^2T_{\rm w}^3(\nu)R_{16}\} \quad (1)$$
$$\times R_{17}R_{18}T_{\rm r}(\nu)T_{\rm i}(\nu)T_{\rm p}(\nu),$$

where $I_{\nu o}^{\rm vac} = c\varepsilon_\nu/\lambda^2$ is the spectral brightness density of vacuum for one of the polarisations; λ is the wavelength; ε_ν is the energy of photons with a frequency $\nu = 1/\lambda$; $K^+(\nu)$ is the single-pass AQF amplification factor at a frequency $\nu \geqslant 0$; $[K^+(\nu)]^2$ is the double-pass amplification factor; $T_{\rm i}(\nu), T_{\rm n}, T_{\rm w}(\nu), T_{\rm r}(\nu), T_{\rm p}(\nu)$ are the respective transmittances of the interference filter, the neutral density interstage filters (ISFs), each of the AQF cell windows, the KS-14 filter, and the polariser; and R_{16}, R_{17}, and R_{18} are the respective reflectivities of the mirrors (*16*), (*17*), and (*18*).

We represent expression (1) as

$$I_{\nu o}^{+\text{out}} = [(I_{\nu o}^{\text{vac}} + I_{\nu o}^{\text{bgr}})K_2 + \frac{1 - T_{\text{n}}^2 T_{\text{w}}^2(\nu) R_{16}}{T_{\text{n}}^2 T_{\text{w}}^2(\nu) R_{16}} I_{\nu o}^{\text{vac}} K_1 + I_{\nu o}^{\text{bgr}}]\, T(\nu), \qquad (2)$$

where $K_1 = K^+(\nu) - 1$; $K_2 = [K^+(\nu)]^2 - 1$; and $T(\nu) = T_{\text{n}}^2 \times T_{\text{w}}^3(\nu) T_{\text{r}}(\nu) T_{\text{p}}(\nu) R_{16} R_{17} R_{18}$ is the optical path transmittance. The first term in square brackets describes the spontaneous and background radiation, each of which is amplified by the factor K_2. This notation allows us to compare in the first term the background radiation with the quantum noise of the amplifier itself reduced to its input. The difference between the background radiation and the quantum noise is accounted for by the third term. It describes the background radiation that would reach the optical path output without amplification, which would be the case when the AQF were not operating. The frequency band of the unamplified background radiation reaching the photodiode is defined by the transmission bandwidth of the optical path. This radiation is therefore broadband in comparison with the background radiation amplified by the factor K_2.

We write expression (2) as

$$I_{\nu o}^{+\text{out}} = I_{\nu o}^{\text{vac}}(1 + \beta) K_\Sigma^+(\nu),$$

where

$$K_\Sigma^+(\nu) = \left[K_{\text{sb}} + \frac{\beta}{1 + \beta}\right] T(\nu)$$

is the resulting amplification factor;

$$K_{\text{sb}} = K_2 + \frac{1 - T_{\text{n}}^2 T_{\text{w}}^2(\nu) R_{16}}{T_{\text{n}}^2 T_{\text{w}}^2(\nu) R_{16}} \frac{K_1}{1 + \beta}$$

is the effective amplification factor for spontaneous and background radiation falling into the AQF amplification band; and $\beta = I_{\nu o}^{\text{bgr}} / I_{\nu o}^{\text{vac}}$. Note that the resultant transmittance of the protective mirror (*19*), the lens (*23*), the mirror (*12*), and the entrance window of the laser cell of the AQF was about 0.4. That is why at a wavelength $\lambda = 1.315$ μm the spectral brightness density of the ISI-1 plasma $I_{\nu o}^{\text{bgr}}$ viewed through the above-enumerated optical elements is practically equal to the spectral brightness density of vacuum $I_{\nu o}^{\text{vac}} \approx 2.6 \times 10^3$ W m^{-2} cm sr^{-1}, i.e., $\beta = 1$. As shown below, the value of β for the solar disk is significantly lower.

The quantities $T_{\text{w}}(\nu)$, $T_{\text{r}}(\nu)$, and $T_{\text{p}}(\nu)$ are assumed to be constant and equal to $T_{\text{w}}, T_{\text{r}}$, and T_{p} throughout their transmission bands, whose widths will be denoted as $\Delta\nu_{\text{w}}$, $\Delta\nu_{\text{r}}$, and $\Delta\nu_{\text{p}}$. Beyond each of the bands, $T_{\text{w}}(\nu)$, $T_{\text{r}}(\nu)$, and $T_{\text{p}}(\nu)$ are assumed to be zero. Then, the transmittance of the optical path $T(\nu) = T_{\text{n}}^2 T_{\text{w}}^3 R_{16} R_{17} R_{18} T_{\text{r}} T_{\text{p}} = T$ is also constant within the $\Delta\nu$ range and is zero beyond the transmission band.

The spectral brightness density of the noise at the output of the optical path, defined for all frequencies, both positive and negative, is $I_{\nu o}^{\text{out}} = I_{\nu o}^{\text{vac}}(1 + \beta)\, K_\Sigma(\nu)$, where $K_\Sigma(\nu) = {}^1/_2 \times K_\Sigma^+(|\nu|)$. Since ϑ_{r} is less than unity by more than an order of magnitude, the radiation transmitted through the AQF can be treated to a good accuracy as uniform within the acceptance angle ϑ_{r}. Then, the fraction of radiation $I_{\nu o}^{\text{out}}$ which feeds the photodiode is

$$I_{\nu o}^{\text{r}} = \begin{cases} I_{\nu o}^{\text{vac}}(1 + \beta) K_\Sigma(\nu), & \vartheta \leqslant {}^1/_2 \vartheta_{\text{r}}, \\ 0, & \vartheta > {}^1/_2 \vartheta_{\text{r}}. \end{cases}$$

This representation of the spectral density in the analysis of RL sensitivity in the presence of background noise allows us to take advantage of the approach developed in Ref. [4], where the RL sensitivity was investigated in the absence of background noise. Note that here we have taken into account the shot noise of the photodiode current caused by the action of the useful signal on the photodiode. As shown below for a LR with an iodine AQF, the shot noise is negligible in comparison with the quantum noise of the AQF itself. However, this shot noise should be included if we want the resultant relationships to yield correct results even for a small AQF amplification factor or without the AQF at all.

We take into account that the random fields of the background and spontaneous radiation at the AQF output can be considered as stationary random processes in a time $\tau_{\text{e}} \leqslant 10$ μs, which is much shorter than the characteristic variation times of the background and spontaneous radiation. We also take into account that they are Gaussian random processes to obtain the equation for the smallest detectable number of photons in the useful signal pulse $N_{\min}^{\beta \neq 0}$ for τ_{e} longer than the pulse duration of the useful signal (see also Ref. [8]):

$$\left(N_{\min}^{\beta \neq 0}\right)^2 - \frac{\gamma N_{\text{ql}}/T}{L(o_{\text{r}}/o_{\text{d}}) K_{\text{s}}} N_{\min}^{\beta \neq 0} = 2\left[\frac{m i_{\text{sb}} \tau_{\text{e}} / e\eta T}{L(o_{\text{r}}/o_{\text{d}}) K_{\text{s}}}\right]^2 \times \left[\Phi(\tau_{\text{e}}) \Psi(o_{\text{r}}) + \frac{eF\Pi_{\text{e}}}{i_{\text{sb}}}\left(1 + \frac{i_{\text{der}}}{i_{\text{sb}}}\right)\right], \qquad (3)$$

where $N_{\text{ql}} = 2m^2 F/\eta$ is the quantum sensitivity limit of the photodiode (compare with expression (12.6.5) on p. 325 and expression (14.4.14) on p. 355 of monograph Ref. [9]); m is the signal-to-noise ratio; F is the noise factor of the photodiode [9]; η is the quantum efficiency of the photodiode; $o_{\text{d}} = \pi(\vartheta_{\text{d}}/2)^2$ is the diffraction-limited solid angle;

$$L\left(\frac{o_{\text{r}}}{o_{\text{d}}}\right) = 1 - J_0^2\left[\frac{1}{2}\pi\left(\frac{o_{\text{r}}}{o_{\text{d}}}\right)^{1/2}\right] - J_1^2\left[\frac{1}{2}\pi\left(\frac{o_{\text{r}}}{o_{\text{d}}}\right)^{1/2}\right]$$

is the Rayleigh function [10]; J_0 and J_1 are the Bessel functions; K_{s} is the amplification factor for the useful signal [if the spectral width of the signal is substantially smaller than the width of the AQF spectral line profile, $K_{\text{s}} \approx [K^+(\nu_0)]^2 + \equiv K_0$]; e is the electron charge;

$$i_{\text{sb}} = e\eta T\left(\frac{\pi}{4}\right)^2 \frac{o_{\text{r}}}{o_{\text{d}}} c\Delta\nu_{\text{eff}}^{\text{c}}(1 + \beta)\left(\langle K_{\text{sb}}\rangle + \frac{\beta}{1 + \beta}\frac{\Delta\nu}{\Delta\nu_{\text{eff}}^{\text{c}}}\right)$$

is the average photodiode current due to the total intensity of the amplified spontaneous and background radiation; $\Delta\nu_{\text{eff}}^{\text{c}} = 1/g(0)$ is the effective amplification line width of the AQF with a profile $g(\nu - \nu_0)$ [for a Gaussian profile, $\Delta\nu_{\text{eff}}^{\text{c}} = {}^1/_2 \Delta\nu_{1/2}^{\text{c}}(\pi/\ln 2)^{1/2} \approx \Delta\nu_{1/2}^{\text{c}}$];

$$\langle K_{\rm sb}\rangle = \langle K_2\rangle + \frac{1-T_{\rm n}^2T_{\rm w}^2R_{16}}{T_{\rm n}^2T_{\rm w}^2R_{16}}\frac{\langle K_1\rangle}{1+\beta};$$

$$\langle K_1\rangle = \frac{1}{\Delta\nu_{\rm eff}^{\rm c}}\int_0^\infty K_1{\rm d}\nu; \quad \langle K_2\rangle = \frac{1}{\Delta\nu_{\rm eff}^{\rm c}}\int_0^\infty K_2{\rm d}\nu;$$

$$\Phi(\tau_{\rm e}) = \int_{-\infty}^{\infty}\frac{\sin^2(\pi c\nu\tau_{\rm e})}{(\pi c\nu\tau_{\rm e})^2}\Gamma(\nu){\rm d}\nu; \tag{4}$$

$$\Psi(o_{\rm r}) = \frac{1}{\sigma_{\rm r}^2}\int\int\left\{2\frac{J_1[\pi(o_{\rm r}/o_{\rm d})^{1/2}s/d_{\rm r}]}{\pi(o_{\rm r}/o_{\rm d})^{1/2}s/d_{\rm r}}\right\}^2 r_1{\rm d}r_1{\rm d}\varphi_1 s{\rm d}s{\rm d}\varphi; \tag{5}$$

$$\Gamma(\nu) = \int_{-\infty}^{\infty}K_\Sigma(\nu')K_\Sigma(\nu'-\nu){\rm d}\nu'\bigg/\left(\int_{-\infty}^{\infty}K_\Sigma(\nu){\rm d}\nu\right)^2 \tag{6}$$

is the normalised-to-unity spectrum of the Gaussian noise transmitted through a quadratic detector [11, 12]; $d_{\rm r}$ is the diameter of the acceptance surface area of the photodiode;

$$i_{\rm der} = i_{\rm dc} + \frac{1}{2eFM^2}\left[V_{\rm e}^{*2}\left(\frac{1}{R^2}+\frac{4\pi^2}{3}\Pi_{\rm e}^2C^2\right) + I_{\rm e}^{*2} + \frac{4k_{\rm B}T_{\rm r}}{R}\right]; \tag{7}$$

$i_{\rm dc}$ is the average dark current; M is the photodiode multiplication factor; R is the resistance of the equivalent resistor; $T_{\rm r}$ is the resistor temperature; $I_{\rm e}^{*2}$ is the spectral density of current fluctuations of the so-called equivalent source of current noise of the electronic amplifier; C is the resultant input capacitance; $V_{\rm e}^{*2}$ is the spectral density of voltage fluctuations of the equivalent noise source amplifier voltage [9]; $\gamma = \tau_{\rm e}\Pi_{\rm e}$; and $\Pi_{\rm e}$ is the electronic amplifier bandwidth (in Hertz units) at a level of $1/\sqrt{2}$ of the peak of the modulus of its amplification factor. When the electronic amplifier can be treated as an ideal integrator, $\gamma \approx 0.44$, and when as an RC circuit, $\gamma = 1/\pi \approx 0.32$. For a uniform frequency response, $\gamma = 1/2$.

4. Approximation of long fluctuation-averaging time

Subsequent analysis calls for a more detailed discussion of the $\Phi(\tau_{\rm e})$ function appearing in Eqn (3). Note that $c\Delta\nu_{1/2}^{\rm c}\tau_{\rm e} \approx 30$; for an amplification factor at the peak of amplification line $K_0 \leqslant 10^7$ this is significantly greater than ${}^1/_2\langle K_{\rm sb}^2\rangle/\langle K_{\rm sb}\rangle^2 > {}^3/_2$ (Fig. 2), where $\langle K_{\rm sb}\rangle$ was defined above;

$$\langle K_{\rm sb}^2\rangle = \langle K_2^2\rangle + 2\frac{1-T_{\rm n}^2T_{\rm w}^2R_{16}}{T_{\rm n}^2T_{\rm w}^2R_{16}}\frac{\langle K_2K_1\rangle}{1+\beta} + \left(\frac{1-T_{\rm n}^2T_{\rm w}^2R_{16}}{T_{\rm n}^2T_{\rm w}^2R_{16}}\right)^2\frac{\langle K_1^2\rangle}{(1+\beta)^2}; \tag{8}$$

$$\langle K_2^2\rangle = \frac{1}{\Delta\nu_{\rm eff}^{\rm c}}\int_0^\infty K_2^2{\rm d}\nu; \quad \langle K_2K_1\rangle = \frac{1}{\Delta\nu_{\rm eff}^{\rm c}}\int_0^\infty K_2K_1{\rm d}\nu;$$

$$\langle K_1^2\rangle = \frac{1}{\Delta\nu_{\rm eff}^{\rm c}}\int_0^\infty K_1^2{\rm d}\nu.$$

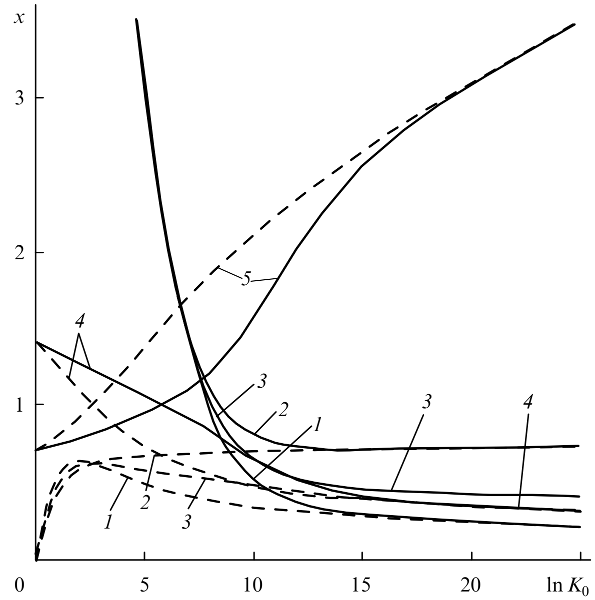

Figure 2. Dependences of $x \equiv \langle K_{\rm sb}\rangle/K_0$ (*1*), $\langle K_{\rm sb}^2\rangle/(\langle K_{\rm sb}\rangle K_0)$ (*2*), $\langle K_{\rm sb}^2\rangle^{1/2}/K_0$ (*3*), $\langle K_{\rm sb}\rangle^2/\langle K_{\rm sb}^2\rangle$ (*4*), and $\langle K_{\rm sb}^2\rangle/\langle K_{\rm sb}\rangle^2$ (*5*) on $\ln K_0$ in the presence of ISFs and background radiation with $\beta = 1$ (solid lines) and in the absence of ISFs and background radiation (dashed lines). The portions of solid curves *1–3* about the zero point are not shown in the drawing.

This means that the fluctuation-averaging time of the voltage at the output of the electronic amplifier is much longer than the correlation time of the total noise radiation $\tau_{\rm c} = \Gamma(0)/c$ at the AQF output. In this case, when

$$\Delta\nu > \frac{\langle K_2\rangle^2}{\langle K_2^2\rangle}\Delta\nu_{\rm eff}^{\rm c} > \sqrt{2}\Delta\nu_{\rm eff}^{\rm c},$$

$\tau_{\rm c}$ is shorter than the correlation time of the amplified spontaneous radiation in the absence of an AQF and background radiation;

$$\tau_{\rm c}^{\rm sp} = \Gamma_{\rm sp}(0)/c = \frac{1}{2c\Delta\nu_{\rm eff}^{\rm c}}\frac{\langle K_2^2\rangle}{\langle K_2\rangle^2}$$

(which is evident from Fig. 2, curves *5*). In this case, $\Gamma(\nu)$ can be taken outside the integral sign in expression (4) for $\nu = 0$. We integrate the expression remaining inside the integral sign to obtain

$$\Phi(\tau_{\rm e}) \approx \frac{1}{2c\Delta\nu_{\rm eff}^{\rm c}\tau_{\rm e}}\frac{\langle K_{\rm sb}^2\rangle + 2\dfrac{\beta}{1+\beta}\langle K_{\rm sb}\rangle + \dfrac{\beta^2}{(1+\beta)^2}\dfrac{\Delta\nu}{\Delta\nu_{\rm eff}^{\rm c}}}{\left(\langle K_{\rm sb}\rangle + \dfrac{\beta}{1+\beta}\dfrac{\Delta\nu}{\Delta\nu_{\rm eff}^{\rm c}}\right)}. \tag{9}$$

We substitute expression (9) in Eqn (3) to obtain the equation for the minimal detectable number of photons in the presence of background radiation:

$$\left(N_{\rm min}^{\beta\neq0}\right)^2 - \frac{\gamma N_{\rm ql}}{L(o_{\rm r}/o_{\rm d})K_{\rm s}T}N_{\rm min}^{\beta\neq0} = m^2\left(\frac{\pi}{4}\right)^4 c\Delta\nu_{\rm eff}^{\rm c}\tau_{\rm e}\frac{\langle K_{\rm sb}^2\rangle}{K_{\rm s}^2} \times(1+\beta)^2\Theta^2\Lambda + \frac{\gamma N_{\rm ql}}{L^2(o_{\rm r}/o_{\rm d})K_{\rm s}^2T^2}\frac{i_{\rm der}\tau_{\rm e}}{\eta e}, \tag{10}$$

where

$$\Lambda = 1 + \frac{\Xi + 2\beta}{1+\beta}\frac{\langle K_{\rm sb}\rangle}{\langle K_{\rm sb}^2\rangle} + \frac{\beta(\Xi+\beta)}{(1+\beta)^2}\frac{1}{\langle K_{\rm sb}^2\rangle}\frac{\Delta\nu}{\Delta\nu_{\rm eff}^{\rm c}}; \qquad (11)$$

$$\Theta = \Theta(o_{\rm r}/o_{\rm d}) = \frac{o_{\rm r}/o_{\rm d}}{L(o_{\rm r}/o_{\rm d})}[\Psi(o_{\rm r}/o_{\rm d})]^{1/2};$$

$$\Xi = \Xi(o_{\rm r}/o_{\rm d}) = \frac{(4/\pi)^2}{(o_{\rm r}/o_{\rm d})\Psi(o_{\rm r}/o_{\rm d})}\frac{2\gamma F}{\eta T}.$$

The second term in expression (11) shows the contribution to the dispersion of voltage fluctuations at the output of the electronic amplifier caused by the statistical properties of the interference of the total intensity of amplified spontaneous and background radiation with the intensity of unamplified background radiation, and also by the statistics of shot noise of the total intensity referred to the contribution due to its own statistics. The third term in expression (11) shows the fraction contributed by the statistics of the intensity of unamplified background radiation and the statistics of its shot noise.

5. Analysis of the effect of background radiation on the sensitivity of the laser receiver

For subsequent analysis we should discuss the behaviour of the $\Psi(o_{\rm r}/o_{\rm d})$ function. We employ the definition (5) to represent it as

$$\Psi(o_{\rm r}/o_{\rm d}) = \left(\frac{4}{\pi}\right)^2 \times \frac{1 - \dfrac{4}{\pi}\displaystyle\int_0^1 \left\{J_0^2[\pi\xi(o_{\rm r}/o_{\rm d})^{1/2}] + J_1^2[\pi\xi(o_{\rm r}/o_{\rm d})^{1/2}]\right\}(1-\xi^2)^{1/2}{\rm d}\xi}{o_{\rm r}/o_{\rm d}}.$$

When $o_{\rm r}/o_{\rm d} \ll 1, \Psi(o_{\rm r}/o_{\rm d}) \simeq 1$, and when $o_{\rm r}/o_{\rm d} \gg 1$, $\Psi(o_{\rm r}/o_{\rm d}) \simeq (4/\pi)^2(o_{\rm r}/o_{\rm d})^{-1}$. The product $(o_{\rm r}/o_{\rm d})\Psi(o_{\rm r}/o_{\rm d})$ increases monotonically with $(o_{\rm r}/o_{\rm d})$; initially this increase is linear, and then, when $o_{\rm r}/o_{\rm d} \gg 1$, it tends to the value $(4/\pi)^2$. When $o_{\rm r}/o_{\rm d} \simeq 1, (o_{\rm r}/o_{\rm d})\Psi(o_{\rm r}/o_{\rm d}) \simeq 0.6$. Therefore, the Ξ function decreases monotonically with increasing $o_{\rm r}/o_{\rm d}$ and tends to $2\gamma F/(\eta T)$. When $o_{\rm r}/o_{\rm d} \approx 1$,

$$\Xi \approx \frac{(4/\pi)^2}{0.6}\frac{2\gamma F}{\eta T} \simeq 5.4\frac{\gamma F}{\eta T}.$$

Consequently, in the angular acceptance range from the diffraction-limited angle and above, Ξ varies by no more than a factor of 2.7.

In what follows we assume that $T_{\rm n}^2 \simeq 8.9\times10^{-3}$, $T_{\rm w} \simeq 1$, $R_{16} \simeq 1$, $R_{17} \simeq 0.96$, $R_{18} \simeq 1$, $T_{\rm r} \simeq 0.91$, and $T_{\rm p} \simeq 0.85$. With these values we conclude that in the presence of the ISFs $T = 6.6\times10^{-3}$. In the absence of the ISFs, $T_{\rm n}^2 = 1$, and then $T \simeq 0.74$. If the ISFs are replaced with an interference filter, which is placed in lieu of KS-14, in the above expressions we should put $T_{\rm n}^2 = 1$ and use the interference filter transmittance $T_{\rm i}$ in lieu of $T_{\rm r}$. For $T_{\rm i} \simeq 0.3$, the coefficient $T \simeq 0.24$. When $\gamma = 0.44$, $F \approx 12$, and $\eta \approx 0.5$, $3000 < \Xi < 9000$, in the first-, $90 < \Xi < 200$, in the second-, and $30 < \Xi < 80$ in the last-enumerated case. In all the cases, Ξ is many times larger than β both for natural sources and for ISI-1. That is why in the second and third terms of expression (11) we will neglect the quantity β in comparison with the quantity Ξ. Then, expression (11) takes on the following form:

$$\Lambda \simeq 1 + \frac{\Xi}{1+\beta}\frac{\langle K_{\rm sb}\rangle}{\langle K_{\rm sb}^2\rangle} + \frac{\beta\Xi}{(1+\beta)^2}\frac{1}{\langle K_{\rm sb}^2\rangle}\frac{\Delta\nu}{\Delta\nu_{\rm eff}^{\rm c}}. \qquad (12)$$

One can see from Eqn (10) and expression (12) that the effect of intrinsic noise of the photodiode and the electronic amplifier and also the unamplified background radiation on the minimal detectable signal becomes weaker as the AQF amplification factor increases. We will investigate this issue in greater detail. We first consider the second term in expression (12), which is due to the shot noise of the photodiode, which in its turn is determined by the total intensity of the amplified spontaneous and background radiation. We take into consideration that for $K_0 > 10^3$ the magnitude of $\langle K_{\rm sb}^2\rangle/(\langle K_{\rm sb}\rangle K_0)$ is hardly changed and is equal to ~ 0.7 (see Fig. 2, curve *2*). It is seen from this term that with the use of ISFs the photodiode noise can be neglected in comparison with the noise caused by the amplified spontaneous and background radiation when

$$K_0 > 10\frac{\langle K_{\rm sb}\rangle K_0}{\langle K_{\rm sb}^2\rangle}\frac{\Xi}{1+\beta} \simeq \frac{14\Xi}{1+\beta} \simeq \frac{1.2\times10^5}{1+\beta}.$$

When use is made of the interference filter, a weaker constraint occurs: $K_0 > 3\times10^3/(1+\beta)$; in the absence of the above filters, the condition $K_0 > 1.1\times10^3/(1+\beta)$ should be fulfilled.

Consider now the third term in expression (12). It stems from the shot effect due to the unamplified background radiation. We assume this term to be smaller than 1/10 to arrive at the following constraint:

$$\left\langle K_{\rm sb}^2\right\rangle^{1/2} > \frac{(10\beta\Xi\Delta\nu/\Delta\nu_{\rm eff}^{\rm c})^{1/2}}{1+\beta} = (2.5\Xi\Delta\nu/\Delta\nu_{\rm eff}^{\rm c})^{1/2},$$

when $\beta = 1$. With ISFs, when $\Delta\nu \simeq 3000$ cm^{-1}, we arrive at the condition $\left\langle K_{\rm sb}^2\right\rangle^{1/2} > 8\times10^4$. Using the dependence of the ratio $\left\langle K_{\rm sb}^2\right\rangle^{1/2}/K_0$ on $\ln K_0$ (Fig. 2, curve *3*), we find that this ratio is practically equal to 0.5 for the experimental values of $K_{\rm s} \approx K_0$ from Table 1 (see below). Hence the condition obtained for $\left\langle K_{\rm sb}^2\right\rangle^{1/2}$ corresponds to the amplification factor at the peak of the line $K_0 \simeq 2\left\langle K_{\rm sb}^2\right\rangle^{1/2} > 1.6\times10^5$. With an interference filter with $\Delta\nu_{\rm i} \simeq 30$ cm^{-1} ($\Delta\lambda_{\rm i} = 5$ nm), the requirement is that $K_0 > 2.4\times10^3$; in the absence of the filters ($\Delta\nu \simeq 3000$ cm^{-1}), $K_0 > 1.2\times10^4$.

We therefore arrive at the conclusion that the noise due to the unamplified background radiation will hardly affect the LR sensitivity when the above conditions are fulfilled. As a result, we can put $\Lambda \simeq 1$ and solve the quadratic equation (10) to obtain the following formula for $N_{\rm min}^{\beta\neq0}$:

$$N_{\rm min}^{\beta\neq0} = \frac{\gamma N_{\rm ql}}{2L(o_{\rm r}/o_{\rm d})K_{\rm s}T}\left\{1 + \left[1 + \frac{4i_{\rm der}\tau_{\rm e}}{\gamma\eta N_{\rm ql}e} + 4m^2\left(\frac{\pi}{4}\right)^4 \times c\Delta\nu_{\rm eff}^{\rm c}\tau_{\rm e}\frac{\langle K_{\rm sb}^2\rangle}{\gamma^2N_{\rm ql}^2}T^2\left(\frac{o_{\rm r}}{o_{\rm d}}\right)^2\Psi\left(\frac{o_{\rm r}}{o_{\rm d}}\right)(1+\beta)^2\right]^{1/2}\right\}. \qquad (13)$$

LFD-2 photodiodes have $i_{\rm dc} < 2\times10^{-7}$ A [13]; for experiments we selected a photodiode with $i_{\rm dc} \simeq 4\times10^{-8}$ A. With this dark current and $m = 3$, and also considering that $N_{\rm ql} = 2m^2F/\eta$, we obtain

$$\frac{4i_{\mathrm{der}}\tau_{\mathrm{e}}}{\gamma\eta N_{\mathrm{ql}}e} > \frac{2i_{\mathrm{dc}}\tau_{\mathrm{e}}}{\gamma m^2 Fe} \approx 10^3 \gg 1,$$

and the unity in the square brackets in formula (13) can therefore be neglected.

When the AQF amplification factor is high enough, the third term under the root sigh is much greater than the second one. We neglect the noise of the electronic amplifier and impose the requirement that the third term be ten times greater than the second one. The following condition should then be imposed on $\langle K_{\mathrm{sb}}^2\rangle$:

$$\langle K_{\mathrm{sb}}^2\rangle^{1/2} > \left(\frac{4}{\pi}\right)^2 \frac{(20F)^{1/2}}{(1+\beta)\eta T}\left(\frac{\gamma i_{\mathrm{dc}}}{ec\Delta\nu_{\mathrm{eff}}^{\mathrm{c}}}\right)^{1/2}$$

$$\times \frac{1}{(o_{\mathrm{r}}/o_{\mathrm{d}})[\Psi(o_{\mathrm{r}}/o_{\mathrm{d}})]^{1/2}}. \qquad (14)$$

Because $(o_{\mathrm{r}}/o_{\mathrm{d}})[\Psi(o_{\mathrm{r}}/o_{\mathrm{d}})]^{1/2}$ increases monotonically with $o_{\mathrm{r}}/o_{\mathrm{d}}$, the right-hand side of inequality (14) decreases monotonically. We take its value for $o_{\mathrm{r}} = o_{\mathrm{d}}$ to obtain the following condition:

$$K_0 \simeq 2\langle K_{\mathrm{sb}}^2\rangle^{1/2} > \frac{20}{\eta T(1+\beta)}\left(\frac{4}{\pi}\right)^2\left(\frac{Fi_{\mathrm{dc}}}{3ec\Delta\nu_{\mathrm{eff}}^{\mathrm{c}}}\right)^{1/2}$$

$$\simeq \frac{2.6\times 10^3}{(1+\beta)T}.$$

When ISFs are used, K_0 should be greater than or equal to 2×10^5 if $\beta = 1$. With the use of an interference filter, when $T = 0.24$, the condition $K_0 > 5.4\times 10^3$ should be fulfilled. Without filters, K_0 should exceed 1.8×10^3. When these conditions are fulfilled, formula (13) is simplified:

$$N_{\mathrm{min}}^{\beta\neq 0} \simeq m\left(\frac{\pi}{4}\right)^2 \Theta(o_{\mathrm{r}}/o_{\mathrm{d}})(c\Delta\nu_{\mathrm{eff}}^{\mathrm{c}}\tau_{\mathrm{e}})^{1/2}\frac{\langle K_{\mathrm{sb}}^2\rangle^{1/2}}{K_{\mathrm{s}}}(1+\beta). \qquad (15)$$

When $o_{\mathrm{r}}/o_{\mathrm{d}} \gg 1$, $\Theta(o_{\mathrm{r}}/o_{\mathrm{d}}) \simeq (4/\pi)(o_{\mathrm{r}}/o_{\mathrm{d}})^{1/2}$, and in the absence of background radiation ($\beta = 0$)

$$N_{\mathrm{min}}^{\beta=0} \simeq m\frac{\pi}{4}\frac{\langle K_{\mathrm{sb}}^2\rangle^{1/2}}{K_{\mathrm{s}}}\left(c\Delta\nu_{\mathrm{eff}}^{\mathrm{c}}\tau_{\mathrm{e}}\frac{o_{\mathrm{r}}}{o_{\mathrm{d}}}\right)^{1/2}.$$

For a Gaussian profile of the AQF amplification line and a uniform frequency response of the electronic amplifier, this formula takes on the form in which it was derived in Ref. [4]:

$$N_{\mathrm{min}}^{\beta=0} = m\left(\frac{\alpha}{2}\frac{c\Delta\nu_{1/2}^{\mathrm{c}}}{\Pi_{\mathrm{e}}}\frac{o_{\mathrm{r}}}{o_{\mathrm{d}}}\right)^{1/2}\frac{\langle K_{\mathrm{sb}}^2\rangle^{1/2}}{K_{\mathrm{s}}},$$

where

$$\alpha = \frac{\pi^2\sqrt{\pi}}{32(\ln 2)^{1/2}}.$$

When $o_{\mathrm{r}}/o_{\mathrm{d}} \simeq 1$, $\Theta \simeq (4/\pi)^2$, and from formula (15) we obtain

$$N_{\mathrm{min}}^{\beta\neq 0} \simeq m(c\Delta\nu_{\mathrm{eff}}^{\mathrm{c}}\tau_{\mathrm{e}})^{1/2}\frac{\langle K_{\mathrm{sb}}^2\rangle^{1/2}}{K_{\mathrm{s}}}(1+\beta)$$

$$= m\left[\frac{\sqrt{\pi}}{2(\ln 2)^{1/2}}c\Delta\nu_{1/2}^{\mathrm{c}}\tau_{\mathrm{e}}\right]^{1/2}\frac{\langle K_{\mathrm{sb}}^2\rangle^{1/2}}{K_{\mathrm{s}}}(1+\beta). \qquad (16)$$

Because the plane acceptance angle is 1.2 times the diffraction-limited angle, in experiments $\Theta \simeq 1.69$ and the product $(\pi/4)^2 \times 1.69 \simeq 1.04$. Accordingly, for comparison with the experiment we will employ formula (16) whose right-hand side is multiplied by a factor of 1.04.

The ratio $N_{\mathrm{min}}^{\beta\neq 0}/N_{\mathrm{min}}^{\beta=0} = 1+\beta$ shows the factor by which the occurrence of background radiation lowers the LR sensitivity. We see: the higher β, the lower the receiver sensitivity. A two-fold lowering of sensitivity corresponds to $\beta = 1$, i.e. $I_{\lambda o}^{\mathrm{bgr}} = I_{\lambda o}^{\mathrm{vac}}$ at the wavelength of signal reception. Recall that the spectral brightness density of the ISI-1 plasma viewed through the above optical elements of the optical path is practically equal to the spectral brightness density of vacuum. In the reception of signals against the ISI-1 radiation background, under the above experimental conditions one would therefore expect a two-fold reduction of sensitivity of the LR under consideration.

6. Experimental results and discussion

Fig. 3 shows a typical oscilloscope trace of voltage at the output of the electronic amplifier recorded on feeding the photodiode with a pulsed optical signal and the ISI-1 radiation from the AQF output. Prior to the instant of ISI-1 actuation (up to the point in time 7.5 μs), the voltage fluctuations are due to spontaneous radiation amplified in the AQF. After the ISI-1 actuation, the amplitude of fluctuations is determined by the combined action of amplified spontaneous radiation and the amplified background radiation that fell within the AQF amplification band. To determine the LR sensitivity, measurements were made of the variance of amplitude fluctuations of the voltage at the output of the electronic amplifier. When the ISI-1 was in operation, the amplitude variance was measured only during the action of its radiation pulse. The experimental data are collected in Table 1. From this

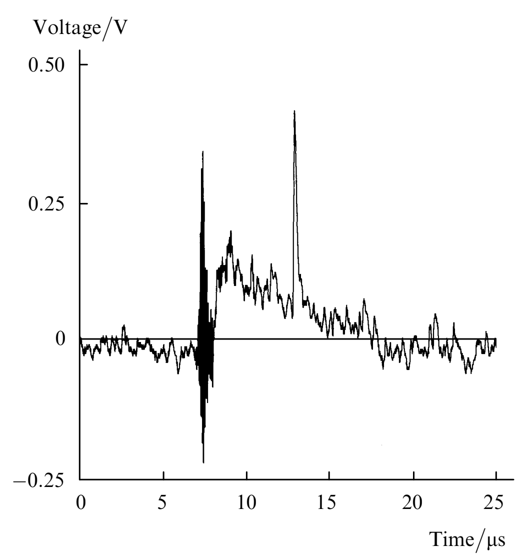

Figure 3. Oscilloscope trace of the voltage at the output of the electronic amplifier on feeding the photodiode with a pulsed optical signal and the ISI-1 radiation from the AQF output (the averaging time $\tau_{\mathrm{e}} = 90$ ns).

Table 1.

Experiment No.	$T_n^2 T_w^2 R_{16}$	T	K_s	$\langle K_{sb}^2 \rangle^{1/2}/K_0$	N_{min}^{exp} (photons)		N_{min}^{theor} (photons)	Notes
1		0.74	7.7×10^3	0.49	6			–
2	1	0.74	1.7×10^3	0.51	13	9	8	–
3		0.74	2.1×10^3	0.50	8			–
4			3.1×10^5	0.49	12	11	9	ISF
5			2.5×10^5	0.49	10			ISF
6	8.9×10^{-3}	6.6×10^{-3}	5.4×10^5	0.47	17			ISF + ISI-1
7			4.0×10^5	0.48	19	20	18	ISF + ISI-1
8			2.8×10^5	0.49	24			ISF + ISI-1

Table one can see that for $m = 3$ the LR sensitivity in the absence of the ISFs was 9 photons on the average (Experiment Nos 1–3), 11 photons on the average with the ISFs (Experiment Nos 4 and 5), and 20 photons on the average on actuation of the ISI-1 (Experiment Nos 6–8). The mane contribution to the experimental error was made by the calibration errors for the photodiodes and filter transmittances; the total error was within $\pm 20\,\%$.

We now calculate the sensitivity of the LR investigated in our work, taking into account that the active medium was heated during photolysis to about 450 K in experiments 1–3 and to 600 K in experiments 4–8. We substitute the $\langle K_{sp}^2 \rangle^{1/2}/K_0$ ratios (Table 1), calculated by formula (8), in formula (16) to obtain, for $m = 3$ in the absence of ISI-1 radiation, that $N_{min}^{\beta=0} \simeq 8$ and ~ 9 photons for experiments 1–3 and 4, 5, respectively. This is quite close to the experimental average values equal to 9 and 11 photons. We multiply the second theoretical value $N_{min}^{\beta=0}$ by $1 + \beta \simeq 2$ to conclude that the sensitivity of this LR operated against the ISI-1 plasma background is 18 photons, which is also in good accord with the average value of 20 photons obtained in experiments 6–8.

We now can calculate with confidence how the LR sensitivity would change in the operation against the background of the solar disk. To compare I_{vo}^{vac} with the spectral brightness density of the solar disk given in handbooks, the latter is more conveniently defined not for a unit frequency interval, but for a unit wavelength range expressed in micrometres.

These two definitions of spectral brightness density are related as $I_{\lambda o} = 10^4 \times I_{vo}/\lambda^2$, where λ is expressed in micrometres. For $\lambda = 1.315$ μm we then obtain $I_{\lambda o}^{vac} = 1.5\times 10^7$ W m^{-2} μm^{-1}sr^{-1}. The spectral brightness density of the solar disk calculated by the Planck formula [7] for the same wavelength was 2.9×10^6 W m^{-2} μm^{-1}sr^{-1}. However, due to the effect of the atmosphere it is, according to the data of Ref. [14], approximately 1.6 times lower than beyond the atmosphere and is equal to 1.88×10^6 W m^{-2} μm^{-1}sr^{-1} for one of polarisations, i.e. $\beta_{sun} \simeq 1/8$. In the operation against the background of the solar disk, the sensitivity of an LR with an iodine photodissociation AQF would therefore be lower by only 12 %.

Note that the AQF amplification factor whereby the solar radiation not falling into the AQF amplification line would have no effect on the sensitivity of this LR will change, owing to the smallness of β_{sun}, by a factor $2\sqrt{\beta_{sun}}/(1+\beta_{sun})$. In particular, when using an interference filter with the above characteristics, the condition $\langle K_{sb}^2 \rangle^{1/2} > 7.7\times10^2$ should be fulfilled, which corresponds to the condition $K_0 > 1.5\times10^3$.

Thus, we can say that the LR with an iodine AQF is a device with a high interference immunity, whose operation can be disturbed by high-intensity noise that is significantly brighter than the solar disk and falls into a very narrow AQF amplification band.

We now analyse the effect of background radiation on the sensitivity of a receiver without an AQF, in which the function of a photodetector is fulfilled by a photomultiplier – the most sensitive photodetector of the visible range [15, 16]. The equation for the sensitivity of a receiver without an AQF can be derived from Eqn (11) if we pass to the limit $K_{sb} \to 1$. Then, $\langle K_{sb} \rangle \to 0$ and $\langle K_{sp}^2 \rangle \to 0$, and Eqn (11) rearranges to the equation for the sensitivity of a receiver which no longer contains an AQF, the signal and the background radiation being directly incident on the interference filter:

$$\left(N_{min}^{\beta\neq0}\right)^2 - \frac{\gamma N_{ql}/T}{L(o_r/o_d)} N_{min}^{\beta\neq0} = m^2\left(\frac{\pi}{4}\right)^4 c\Delta v \tau_e \Theta^2 \beta(\Xi+\beta) + \frac{\gamma N_{ql}/T^2}{L^2(o_r/o_d)}\frac{i_{der}\tau_e}{\eta e}. \quad (17)$$

Note that the noise figure for a photomultiplier is $F = 1$, and nevertheless $\Xi \gg \beta$ for all natural sources of background radiation. When use is made of an interference filter with $T_i = 0.3\,(T = 0.25)$ and a photomultiplier with $\eta = 0.25$, even for $m = 1$ we obtain $\Xi > 10$, which is many times higher even than β for a radiation source brighter than the Sun. This implies that the statistics of the background radiation makes no contribution to the variance of voltage fluctuations at the output of the electronic amplifier, which is primarily caused by the photocount statistics. Then, on solving Eqn (17) we obtain that the receiver sensitivity in the presence of the background radiation is

$$N_{min}^{\beta\neq0} = \frac{\gamma N_{ql}}{2L(o_r/o_d)T}\left\{1 + \left[1 + \frac{4\tau_e}{\gamma N_{ql}}\left(\frac{i_{der}}{\eta e} + \left(\frac{\pi}{4}\right)^2 \times \frac{o_r}{o_d} c\Delta v \beta T\right)\right]^{1/2}\right\}. \quad (18)$$

Note that if we put $\beta = 0$ and the dark current $i_{dc} = 0$ in formula (18), i.e. retain only the electronic amplifier noise [see formula (7) for i_{der}], formula (18) will correspond, for instance, to formula (14.4.35) on page 361 of the monograph Ref. [9].

Since the Rayleigh function $L(o_r/o_d) \to 1$ with increasing o_r, $N_{min}^{\beta=0}$ tends to the lowest sensitivity, which is obtained from formula (18) if we put $\beta = 0$ and $L(o_r/o_d) = 1$. We calculate this lowest sensitivity for a receiver with an FEU-115 photomultiplier ($\lambda = 694$ nm, $\hbar\omega = 2.86\times10^{-19}$ J, $\eta \simeq$

$0.25, i_{dc} \leqslant 10^{-12}$ A) [16] and an interference filter. The interference filter is assumed to possess a transmission $T_i = 0.3$, the same as in the analysis of an LR with an iodine AQF, and the same bandwidth $\Delta\lambda_i = 5$ nm, but centred at $\lambda = 694$ nm ($\Delta\nu_i \simeq 100$ cm^{-1}). For $\tau_e = 90$ ns we have $4i_{dc}\tau_e/(\gamma N_{ql}\eta e) \leqslant m^{-2}$; hence the noise related to the dark current of the photomultiplier has practically no effect on the receiver sensitivity. The same will be assumed regarding the electronic amplifier noise. Then, putting $F = 1$, we obtain $N_{\min}^{\beta=0} = \gamma N_{ql}/T = 8m^2\gamma/T = 120$ photons for $m = 3$. However, it should be borne in mind that the effect of background radiation on the receiver sensitivity increases with increase in o_r/o_d [see formula (18)]. In every specific situation there exists an optimal o_r/o_d ratio, whereby $N_{\min}^{\beta\neq 0}$ assumes its minimal value.

We estimate the receiver sensitivity with a photomultiplier in the reception of signals against the background of the solar disk. At a wavelength $\lambda = 694$ nm, $I_{\lambda o}^{\text{vac}} \simeq 3.7 \times 10^8$ W m^{-2} μm^{-1}sr^{-1} and the spectral brightness of the solar disk $I_{\lambda o}^{\text{sun}}$ observed through the atmosphere at the surface of the Earth at this wavelength is $\sim 7.5 \times 10^6$ W m^{-2} μm^{-1}sr^{-1}, and therefore $\beta_{\text{sun}} \simeq 2 \times 10^{-2}$. For $\tau_e = 90$ ns, the sensitivity of the receiver under consideration assumes its lowest value $N_{\min}^{\beta\neq 0} \approx 1400$ for $o_r/o_d \simeq 1.9$. In comparison with nighttime operation, this sensitivity is 12 times lower, and almost 150 lower than the sensitivity of a LR with an iodine AQF.

7. Conclusions

Our experimental study of the effect of background radiation on the sensitivity of a laser receiver with an iodine active quantum filter ($\lambda = 1.315$ μm) showed that upon the reception of a 40-ns pulsed signal against the background of the 2.5-fold attenuated radiation of a pulsed light source with a brightness temperature of 4×10^4 K, the sensitivity of this receiver was 20 photons for a signal-to-noise ratio of three and a diffraction-limited acceptance angle. This is consistent with the results of theoretical consideration and allows a statement that the sensitivity of this receiver would be lower by only 12 % in the reception of optical signals against the background of the solar disk, i.e. would practically remain at the level of the quantum limit. Therefore, the background radiation of the solar disk, much less the daylight sky radiation, would have virtually no effect on the sensitivity of the LR with an iodine AQF, which has the capacity to operate with the limiting quantum sensitivity both at night and in the daytime.

This receiver was compared with a receiver utilising a photomultiplier of the visible range. The sensitivity of the receiver with an FEU-115 photomultiplier estimated for an interference transmission bandwidth of 5 nm, a signal-to-noise ratio of three, and optical signals with the same parameters against the background of the solar disk was found to be about 1400 photons, which is 12 times more than at night-time operation. Therefore, the interference immunity of an LR with an iodine photodissociation AQF is considerably superior to that of a receiver with a photomultiplier. That is why the LR with an iodine AQF can be characterised as a receiver with a high immunity to interference.

The results obtained show that the LR with an iodine AQF, capable of operation under any natural background irradiation, can be used to extract and record single-photon signals from point-like objects against the background of the solar disk. It can also be employed to produce against the background of the solar disk the images of remote objects illuminated by laser radiation with a wavelength falling within the AQF amplification band.

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