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Laser receiver with a quantum detection limit in the near-IR range

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Abstract. A laser receiver (LR) with an active quantum filter (AQF) ($\lambda = 1.315$ μm) based on an iodine photodissociation laser is studied. It is shown that the LR sensitivity can be brought up to the quantum detection limit by increasing the AQF gain. Taking into account the space-time statistics of spontaneous emission of the AQF, the LR sensitivity is determined as a function of the reception solid angle and the recorder response time. Under the conditions of the experiments performed, the LR sensitivity is, to a good approximation, proportional to the square root of the product of the reception solid angle and the recorder time constant. The above dependence is confirmed experimentally upon more than a hundred-fold variation of the response time. For the reception angle that was three times greater than the diffraction-limited angle, the quantum detection limit was achieved, which amounts to approximately three photons for a 40-ns pulse for the unit signal-to-noise ratio.

1. Introduction

Increasing the sensitivity of receivers for the optical range to the natural limit imposed by the quantum structure of the electromagnetic field is one of the most topical problems in laser location and long-range laser communication [1 – 3]. Until recently, the most sensitive photodetectors (PDs) were photomultipliers, which are capable of operating in the photon counting mode. However, even at the maximum of the sensitivity where the photoelectron quantum yield of a photomultiplier is about 0.2, a reliable separation from the noise and recording of a single light pulse requires that it should contain approximately 20 photons [4].

Semiconductor photodiodes exhibit a higher photoelectron quantum yield, but their intrinsic noise is significantly higher than the photomultiplier noise. For this reason, a 40-ns pulse detectable, e. g., by an LFD-2 germanium avalanche photodiode [5], which is the most sensitive in the near-IR region, should contain approximately 5000 photons as a minimum.

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As we see, the existing PDs cannot record single photons with a high probability. In principle, the probability of recording single photons may be increased in a receiver [which we will call a laser receiver (LR)] where light signals are pre-amplified in an optical quantum amplifier (OQA) to such a degree that they will significantly exceed the intrinsic PD noise. In this case, the quantum efficiency of amplification in the OQA should be close to unity.

It is known [6, 7] that the minimal noise of an OQA is one photon into a mode in a time $1/c\Delta\nu$, where $\Delta\nu$ is the width of the OQA amplification band expressed in inverse centimetres. Hence, it is in principle possible to record pulses of duration $1/c\Delta\nu$ consisting of one-to-two photons if they are pre-amplified in the OQA. However, attempts to realise this approach have failed for a long time, because the required pulse duration for the ruby OQA used in Ref. [7] is several picoseconds and lies in the femtosecond range for the Nd-glass OQA used in Ref. [6].

We formulate which characteristics should be offered by an OQA employed as a preamplifier of single-photon optical signals in an LR intended for laser location:

– the amplification line width should be ~ 0.01 cm^{-1}, since the characteristic length of laser pulses used in location is several nanoseconds;

– the optical uniformity of the OQA active medium should be nearly perfect to offer the possibility of selecting specific angular modes;

– the population density of the lower working level should be far less that that of the upper one to minimise the intrinsic noise of the OQA;

– the OQA gain should be no smaller than 10^3 to exceed the PD noise;

– the OQA wavelength should fall within the atmospheric 'transparency window.'

A consideration of the parameters of presently existing lasers showed that a unique combination of the above-listed parameters is inherent in an iodine photodissociation laser with a wavelength of 1.315 μm on the $^2P_{1/2} \rightarrow {}^2P_{3/2}$ transition of atomic iodine [8, 9]. Note that the photodissociation OQA used as a preamplifier of the signals to be detected fulfils at the same time the task of filtering and extracting the desired signal, which is extremely important for laser location. In the subsequent discussion, it will be referred to as an active quantum filter (AQF) because, unlike conventional passive filters which extract the signal by suppressing the frequencies outside of the spectrum of the signal, the signal extraction in the AQF is attained by amplifying the frequencies that belong to the signal spectrum. The AQF amplification line is so narrow that even the power of direct solar radiation into one mode of the AQF averages to only about a quarter of a photon in a time $1/c\Delta\nu$. This implies that it will be possible to extract and amplify desired single-photon signals with the aid of the AQF even against the background of the solar disk [2]. A schematic diagram of the LR is shown in Fig. 1.

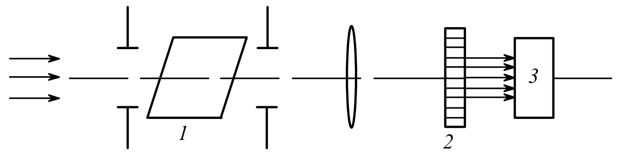

Figure 1. Schematic of the LR:
(*1*) active quantum filter; (*2*) photodiode used as a PD; (*3*) electronic video amplifier.

As already noted, an AQF should possess a high gain. We were able to obtain a gain of over 10^6 with a single-stage double-pass AQF. A significantly higher gain may be obtained employing an AQF comprising several amplification stages combined with optical isolators. Thus, we can say that AQF-based receivers are always capable of pre-amplifying a signal to significantly exceed the noise of semiconductor PDs and electronic amplifiers (EAs). The reception sensitivity will then be determined only by the intrinsic AQF noise. We will analyse in detail the AQF noise characteristics to determine the dependence of the LR sensitivity on the experimental conditions. In addition, we will consider the PD and EA noise to find the conditions for matching the AQF characteristics with those of the PD and the EA and also perform the corresponding experiments.

2. Spectral characteristics of quantum noise

It is known [6, 7] that in the near-IR range, where $\hbar\omega/k_{\rm B}T \gg 1$, the spectral radiance of spontaneous emission of one of the polarisations at the amplifier output may be, provided the population density of the lower laser level can be neglected, represented as

$$I^{(+)\rm out}_{\omega,\Omega} = I^{\rm vac}_{\omega,\Omega} K_{\rm sp}, \qquad (1)$$

where

$$I^{\rm vac}_{\omega,\Omega} = \frac{(1/2)\hbar\omega_0}{4\pi(\lambda/2)^2}$$

is the spectral radiance of zero-point vacuum oscillations; $K_{\rm sp} = K^{+}(\omega) - 1$; $K^{+}(\omega) = \exp[L_{\rm a}\sigma(\omega)\varDelta]$ is the gain at a frequency $\omega \geqslant 0$; $\varDelta$ is the population inversion on the laser transition; $L_{\rm a}$ is the length of the active region; $\sigma(\omega) = (\lambda/2)^2 A\phi_{21} g(\omega-\omega_0)$ is the transition cross section; A is the Einstein coefficient; ϕ_{21} is the quantum yield equal, in our case, to unity; λ is the wavelength of the electromagnetic radiation with the frequency ω_0 corresponding to the centre of the radiated line; and $g(\omega-\omega_0)$ is the profile form factor. If the pressure of the working gas mixture in the AQF is so selected that the pressure broadening is small in comparison with the Doppler one, the line profile will be Gaussian [10] and

$$\frac{g(\omega-\omega_0)}{g(0)} = \exp\left[-\left(\frac{\omega-\omega_0}{\Delta\omega^{\rm c}_{1/2}/2}\right)^2 \ln 2\right],$$

where

$$g(0) = \frac{2}{\Delta\omega^{\rm c}_{1/2}}\sqrt{\frac{\ln 2}{\pi}};$$

$\Delta\omega^{\rm c}_{1/2}$ is the line full width at half maximum (FWHM). Note that $K^{+}(\omega)$ may be represented as $K^{+}(\omega) = K_0^{g(\omega-\omega_0)/g(0)}$, where $K_0 = \exp[L_{\rm a}\sigma(\omega_0)\varDelta]$.

Along with the spectral radiance defined only in the range of positive frequencies (1), we will also consider the spectral radiance defined for all frequencies, both positive and negative: $I^{\rm out}_{\omega,\Omega} = I^{\rm vac}_{\omega,\Omega}[K(\omega)-1]$, where $K(\omega)-1 = [K^{+}(\omega)-1]/2$ if $\omega \geqslant 0$ and $K(\omega)-1 = [K^{+}(-\omega)-1]/2$ if $\omega < 0$.

The sensitivity of the LR under consideration is determined not by the power of AQF output spontaneous radiation itself, which acts on the PD, but by the fluctuations of the PD current whose statistics is related to that of the amplified spontaneous emission directed from the AQF output to the PD. In this connection, we will consider the issues related to the statistics of the spontaneous emission at the PD and of the PD current.

3. Correlation properties of the spontaneous emission at the AQF output

Let the spontaneous emission of the AQF be focused with a lens of focal length f on a PD having an acceptance area of diameter $d_{\rm r}$. The statistics of radiation at the PD will then be determined by the part of AQF emission that propagates within the cone with the apex angle $\vartheta_{\rm r} = d_{\rm r}/f$, which we will call the reception angle. Because the ratio between the correlation radius and the beam diameter is a statistical invariant [11], the statistical properties of the radiation may be considered not at the PD but at the AQF output, the angular radiation spectrum being restricted to the angle $\vartheta = \vartheta_{\rm r}$.

With the above restriction, we consider the correlation properties of spontaneous emission at the AQF output assuming this radiation to be stationary and statistically isotropic. Because the length of the AQF exceeds its lateral dimensions by more than an order of magnitude, the angular radiation spectrum may, to a good accuracy, be treated as uniform:

$$I^{\rm out}_{\omega,\varkappa} = \begin{cases} \dfrac{I^{\rm vac}_{\omega,\Omega}}{k^2}[K(\omega)-1], & \varkappa \leqslant \frac{1}{2}k\vartheta_{\rm r}, \\ 0, & \varkappa > \frac{1}{2}k\vartheta_{\rm r}. \end{cases}$$

where $k = 2\pi/\lambda$. Then, the correlation function of the spontaneous emission at the AQF output is

$$B(s,\tau) = 2\frac{\Omega_{\rm r}}{\Omega_{\rm d}}\frac{P^{\rm vac}_{\omega,\rm d}}{S_{\rm a}}\frac{J_1(\pi\sqrt{\Omega_{\rm r}/\Omega_{\rm d}}\,s/d_{\rm a})}{\pi\sqrt{\Omega_{\rm r}/\Omega_{\rm d}}\,s/d_{\rm a}} \times \int_{-\infty}^{\infty}[K(\omega)-1]\exp({\rm i}\omega\tau){\rm d}\omega, \qquad (2)$$

where

$$P^{\rm vac}_{\omega,\rm d} = I^{\rm vac}_{\omega,\Omega}\Omega_{\rm d}S_{\rm a} = \hbar\omega_0(\pi/32) \qquad (3)$$

is the spectral power density of zero-point vacuum oscillations per diffraction solid angle $\Omega_{\rm d} = \pi(\vartheta_{\rm d}/2)^2 = \pi^2\lambda^2/16S_{\rm a}$; $\vartheta_{\rm d} = \lambda/d_{\rm a}$; $\Omega_{\rm r} = \pi(\vartheta_{\rm r}/2)^2$ is the reception solid angle; J_1 is the Bessel function; $s = |\boldsymbol{r}_2 - \boldsymbol{r}_1|$; and $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the radius vectors of the points in the plane of the exit AQF aperture with diameter d_a and area $S_a = \pi d_a^2/4$.

From expression (2), we obtain the average intensity of the spontaneous emission at the AQF output

$$I_{sp}^{out} = \langle I(\boldsymbol{r},t)\rangle = B(0,0) = \frac{P_{\omega,d}^{vac}}{S_a}\frac{\Omega_r}{\Omega_d}\int_0^\infty K_{sp}d\omega$$

and the degree of coherence $\gamma(s,\tau) = B(s,t)/B(0,0) = \gamma(s)\gamma(\tau)$, where

$$\gamma(s) = 2\frac{J_1\left(\pi\sqrt{\Omega_r/\Omega_d}\,s/d_a\right)}{\pi\sqrt{\Omega_r/\Omega_d}\,s/d_a};$$
$$\gamma(\tau) = \frac{\int_{-\infty}^{\infty}[K(\omega)-1]\exp(i\omega\tau)d\omega}{\int_{-\infty}^{\infty}[K(\omega)-1]d\omega}. \quad (4)$$

4. Energy characteristics of spontaneous emission

If the function I_{sp}^{out} is uniform, the average output power of spontaneous emission is

$$P_{sp}^{out} = P_{\omega,d}^{vac}\Delta\omega_{ef}^{c}\frac{\Omega_r}{\Omega_d}\langle K_{sp}\rangle, \quad (5)$$

where

$$\langle K_{sp}\rangle = \int_{-\xi_0}^{\infty}\left[K_0^{g(\xi\Delta\omega_{ef}^c)/g(0)} - 1\right]d\xi;$$

$\Delta\omega_{ef}^c = 1/g(0)$ is the effective profile width; $\xi = (\omega - \omega_0)/\Delta\omega_{ef}^c$; and $\xi_0 = \omega_0/\Delta\omega_{ef}^c$. For a Gaussian luminescence line profile $\Delta\omega_{ef}^c = (1/2)\Delta\omega_{1/2}^c\sqrt{\pi/\ln 2}$ and in view of (3), we have

$$\langle K_{sp}\rangle = \int_{-\xi_0}^{\infty}\left[K_0^{\exp(-\pi\xi^2)} - 1\right]d\xi,$$
$$P_{sp}^{out} = \hbar\omega_0\alpha c\Delta\nu_{1/2}^{c}\frac{\Omega_r}{\Omega_d}\langle K_{sp}\rangle, \quad (6)$$

where

$$\alpha = \frac{\pi^2\sqrt{\pi}}{32\sqrt{\ln 2}} \simeq 0.657;$$

and $\Delta\nu_{1/2}^c$ is the line FWHM in inverse centimetres. The dependence of $\langle K_{sp}\rangle/K_0$ on $\ln K_0$ for a Gaussian profile is given in Fig. 2.

5. Correlation and fluctuation characteristics of the photocurrent

As is well known [12], the PD photocurrent is proportional to the incident radiation power averaged over a time interval equal to the EA time constant T_e. The power of spontaneous emission averaged over T_e is

$$P_T(t) = \frac{1}{T_e}\int_t^{t+T_e}dt'\int I(\boldsymbol{r},t')d^2\boldsymbol{r} = \frac{1}{T_e}\int_0^{T_e}dt'\int I(\boldsymbol{r},t+t')d^2\boldsymbol{r}.$$

The average photocurrent in the PD circuit arising from spontaneous emission is

$$Mi_{sp} = M\Re\langle P_T\rangle = M\Re P_{sp}^{out},$$

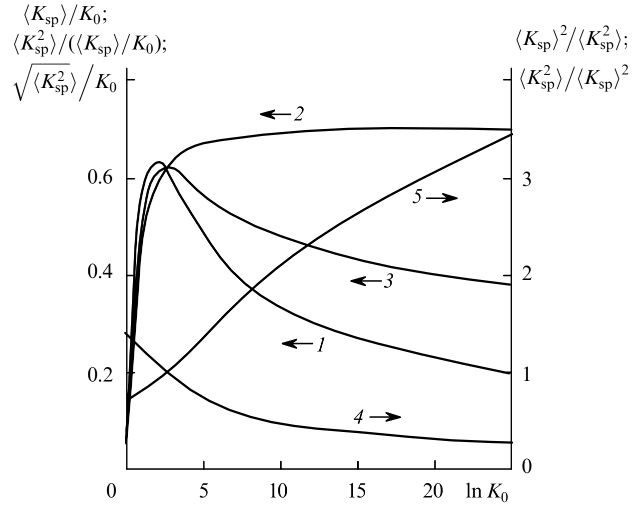

Figure 2. Dependences of $\langle K_{sp}\rangle/K_0$ (*1*), $\langle K_{sp}^2\rangle/(\langle K_{sp}\rangle/K_0)$ (*2*), $\sqrt{\langle K_{sp}^2\rangle}/K_0$ (*3*), $\langle K_{sp}\rangle^2/\langle K_{sp}^2\rangle$ (*4*), and $\langle K_{sp}^2\rangle/\langle K_{sp}\rangle^2$ (*5*) on $\ln K_0$.

where $\Re = \eta e/\hbar\omega_0$ is the PD sensitivity [12]; η is the quantum efficiency of the PD; e is the electron charge; and M is the photodiode multiplication factor. Taking into account (3) and (5), we have

$$i_{sp} = \eta e\frac{\Omega_r}{\Omega_d}\frac{\pi}{32}\Delta\omega_{ef}^c\langle K_{sp}\rangle. \quad (7)$$

The correlation function for the power of spontaneous emission at the AQF output is

$$B_P(\tau) = \langle P_T(t)P_T(t+\tau)\rangle$$
$$= \frac{1}{T_e^2}\int_0^{T_e}\int_0^{T_e}dt'dt''d^2\boldsymbol{r}_1d^2\boldsymbol{r}_2\langle I(\boldsymbol{r}_1,t'+t)I(\boldsymbol{r}_2,t''+t+\tau)\rangle.$$

Because the AQF operates below threshold, the random field at its output is Gaussian [11, 13]. It can be treated as stationary over a time $T_e \leqslant 10$ μs because the lifetime Δ of the population inversion is significantly longer than T_e. Then, as is known [11], $\langle I(\boldsymbol{r}_1,t'+t)I(\boldsymbol{r}_2,t''+t+\tau)\rangle = \langle I(\boldsymbol{r}_1)\rangle\langle I(\boldsymbol{r}_2)\rangle\left[1 + |\gamma(\boldsymbol{r}_2-\boldsymbol{r}_1,t''-t'+\tau)|^2\right]$. Because $|\gamma(\boldsymbol{r}_2-\boldsymbol{r}_1,t''-t'+\tau)| = \gamma(s)\gamma(t''-t'+\tau)$, by assuming the average intensity $\langle I(\boldsymbol{r})\rangle$ at the AQF to be uniform as before, we can express the variance of fluctuations of the photocurrent arising from the spontaneous emission in the form

$$\sigma_{sp}^2 = \left[\Re^2B_P(0) - i_{sp}^2\right]M^2 = i_{sp}^2M^2\Phi(T_e)\Psi(\Omega_r),$$

where, taking into account the transformation to the polar coordinates r_1, φ_1, and s, φ,

$$\Phi(T_e) = \frac{1}{T_e^2}\int_0^{T_e}\int_0^{T_e}\gamma^2(t''-t')dt'dt'';$$
$$\Psi(\Omega_r) = \frac{1}{S_a^2}\int\int\gamma^2(s)r_1dr_1d\varphi_1s\,ds\,d\varphi. \quad (8)$$

Consider the structure of $\Phi(T_e)$ in greater detail. To this purpose, we substitute $\gamma(\tau)$ from (4) into (8), with $\tau = t''-t'$. As a result, we obtain

$$\Phi(T_e) = \int_{-\infty}^{\infty} \frac{\sin^2(\omega T_e/2)}{(\omega T_e/2)^2} \Gamma(\omega) d\omega, \quad (9)$$

where the function

$$\Gamma(\omega) = \frac{\int_{-\infty}^{\infty} [K(\omega') - 1][K(\omega' - \omega) - 1] d\omega'}{\left\{ \int_{-\infty}^{\infty} [K(\omega) - 1] d\omega \right\}^2}$$

is the normalised to unity spectrum of photocurrent fluctuations upon the square-law detection [11, 13] of the Gaussian noise; $\int_{-\infty}^{\infty} \Gamma(\omega) d\omega = 1$.

To estimate the effect of T_e on the fluctuation characteristics of the photocurrent, we discuss the main properties of the function $\Gamma(\omega)$. It is symmetric in ω with respect to zero and has three maxima: one at the zero frequency and two at the frequencies $\omega = \pm 2\omega_0$. We are interested in the central maximum, because $\omega_0 \simeq 1.4 \times 10^{15}$ s^{-1} is many times greater than the PD transmission band and the EA band $\Pi_e = 1/T_e$. For this maximum,

$$\int_{|\omega| \leqslant \omega_0} \Gamma(\omega) d\omega = \frac{1}{2},$$

which corresponds to the uniform distribution over the components of the Gaussian noise [11]. The width of the central maximum of the photocurrent spectrum can be determined from the condition $\Delta\omega_{i0}\Gamma(0) = 1/2$, where

$$\Gamma(0) = \frac{1}{2} \frac{\int_0^{\infty} K_{sp}^2 d\omega}{\left(\int_0^{\infty} K_{sp} d\omega \right)^2} = \frac{1}{2\Delta\omega_{ef}^c} \frac{\langle K_{sp}^2 \rangle}{\langle K_{sp} \rangle^2}; \quad (10)$$

$$\langle K_{sp}^2 \rangle = \int_{-\xi_0}^{\infty} \left[K_0^{g(\xi\Delta\omega_{ef}^c)/g(0)} - 1 \right]^2 d\xi.$$

Therefore, the width of the central maximum is $\Delta\omega_{i0} = \Delta\omega_{ef}^c \langle K_{sp} \rangle^2 / \langle K_{sp}^2 \rangle$. The dependences of $\langle K_{sp} \rangle^2 / \langle K_{sp}^2 \rangle$ and $\langle K_{sp}^2 \rangle / \langle K_{sp} \rangle^2$ on $\ln K_0$ for a Gaussian profile are shown in Fig. 2.

6. Sensitivity of the LR

In addition to current fluctuations caused by the random nature of the spontaneous emission at the AQF output, also present in the PD circuit are the fluctuations caused by the shot effect of the PD, the thermal noise of resistive elements, and the EA noise. Assuming the above-listed fluctuations to be statistically independent, we can represent the total variance of current fluctuations in the PD circuit in the form

$$\sigma_i^2 = \sigma_{sp}^2 + \left(I_{sh}^{*2} + I_t^{*2} + I_e^{*2} \right) \Pi_e.$$

Here, $I_{sh}^{*2} = 2e(i_{sp} + i_d)FM^2$ is the spectral density of the current fluctuations arising from the shot effect; i_d is the average dark current; F is the photodiode noise factor; $I_t^{*2} = 4k_B T_r / R$ is the spectral density of thermal fluctuations of the current of the equivalent resistor with the resistance R; T_r is the resistor temperature; and I_e^{*2} is the spectral density of current fluctuations of the equivalent current source of the amplifier noise. At the EA output, the variance of voltage fluctuations is

$$\sigma_V^2 = K_e^2 \left[\left(1 + \frac{4}{3}\pi^2 \Pi_e^2 C^2 R^2 \right) V_e^{*2} \Pi_e + R^2 \sigma_i \right],$$

where K_e is the EA gain at the lower boundary of its amplification band; C is the resultant input capacitance; and V_e^{*2} is the spectral density of voltage fluctuations of the equivalent voltage source of the EA noise [12].

We will seek the minimal detectable input signal for the AQF by comparing the signal-induced voltage V at the EA output with the rms fluctuation σ_V of the noise-generated voltage. According to the Chebyshev inequality, $P(|V - \langle V \rangle| \geqslant m\sigma_V) \leqslant m^{-2}$. Hence, the probability that the departure of the voltage from its average value caused by a random fluctuation is greater than or equal to $m\sigma_V$ cannot exceed m^{-2}. Therefore, the signal for which the signal-to-noise ratio is equal to m will be recorded with a probability of no less than $1 - m^{-2}$.

Let a pulsed optical signal with duration t_p, frequency $\omega_s \simeq \omega_0$, and wave vector $\boldsymbol{k}_s$ parallel to the optical axis of the AQF be applied to the AQF input. The PD current induced by this signal is

$$Mi_s(t) = \frac{\Re M}{T_e} \int_t^{t+T_e} P_s^r(t) dt,$$

where P_s^r is the part of the signal power that comes from the amplifier exit to the PD acceptance area. It depends on the ratio between Ω_r and Ω_d. When the AQF and PD apertures are round, in accordance with the law of radiation diffraction by a circular aperture,

$$P_s^r = P_s^{out} L(\Omega_r/\Omega_d),$$

where P_s^{out} is the signal power at the AQF output and

$$L(\Omega_r/\Omega_d) = 1 - J_0^2\left(\frac{\pi}{2}\sqrt{\frac{\Omega_r}{\Omega_d}} \right) - J_1^2\left(\frac{\pi}{2}\sqrt{\frac{\Omega_r}{\Omega_d}} \right)$$

is the Rayleigh function [14].

If the spectral width of the signal is far less than the profile width, as is the case in the experiments described below, the signal gain is $K_s \simeq K^+(\omega_s)$ and the pulse durations at the AQF input and output coincide. If in this case $T_e \geqslant t_p$, the peak voltage at the EA output, $V_s^{max} = K_e M i_s^{max} R$ (Mi_s^{max} is the maximum photodiode current), can be expressed in terms of the energy E_s^{in} of the signal at the AQF input as $V_s^{max} = \Re L(\Omega_r/\Omega_d) K_s K_e M R E_s^{in} / T_e$.

Let us compare V_s^{max} with $m\sigma_V$. Then, for the number $N_{min} = (E_s^{in})_{min}/\hbar\omega_0$ of photons detectable with a probability of no less than $1 - m^{-2}$, we obtain the expression

$$N_{min} = \frac{m i_{sp} T_e}{\eta e L(\Omega_r/\Omega_d) K_s} \left\{ \Phi(T_e)\Psi(\Omega_r) + \frac{2eF}{i_{sp} T_e} \left(1 + \frac{1}{i_{sp}} \left[i_d + \frac{1}{M^2} \frac{1}{2eF} \left(V_e^{*2} \left(\frac{1}{R^2} + \frac{4\pi^2}{3} \Pi_e^2 C^2 \right) + I_e^{*2} + \frac{4k_B T_r}{R} \right) \right] \right) \right\}^{1/2}. \quad (11)$$

Because the conditions $\Delta\omega_{i0} T_e / 2\pi \approx \Delta\omega_{i0} t_p / 2\pi \geqslant 1$ ($c\Delta\nu_{ef}^c / \Pi_e \geqslant \langle K_{sp}^2 \rangle / \langle K_{sp} \rangle^2$) and $(\pi/2)\sqrt{\Omega_r/\Omega_d} \geqslant 1$ were fulfilled in the experiments outlined below, we consider the asymptotics of the functions $\Phi(T_e)$ and $\Psi(\Omega_r)$ corresponding to these conditions.

First, we find the asymptotics of $\Phi(T_e)$. If T_e is so long that $[\sin^2(\omega T_e/2)]/(\omega T_e/2)^2$ limits the range of integration in expression (9) to a band that is much narrower than the central peak of the photocurrent spectrum, i.e., if $2\pi/T_e \ll \Delta\omega_{i0}$, then $\Gamma(\omega)$ may be factored outside the integral sign in expression (9). Since [15]

$$\int_{-\infty}^{\infty}\left[\frac{\sin(\omega T_e/2)}{\omega T_e/2}\right]^2 d\omega = \frac{2\pi}{T_e},$$

we have

$$\Phi(T_e) \simeq \frac{\pi}{\Delta\omega_{ef}^{c} T_e}\frac{\langle K_{sp}^2\rangle}{\langle K_{sp}\rangle^2}.$$

Now we find the asymptotics of $\Psi(\Omega_r)$ when $(\pi/2)\sqrt{\Omega_r/\Omega_d} \gg 1$. In this case,

$$\Psi(\Omega_r) \simeq \frac{2\pi}{S_a}\int_0^{\infty}\gamma^2(s)s\,ds.$$

By taking $\gamma(s)$ from expression (6) and using the tabulated integral $\int_0^{\infty} J_1^2(x)x^{-1}dx = 1/2$ [15], we obtain

$$\Psi(\Omega_r) \simeq \frac{16}{\pi^2}\left(\frac{\Omega_r}{\Omega_d}\right)^{-1}.$$

Let us substitute expression (7) and the asymptotics of $\Phi(T_e)$ and $\Psi(\Omega_r)$ in expression (11), and take into account that, when $(\pi/2)\sqrt{\Omega_r/\Omega_d} \gg 1$, the function $L(\Omega_r/\Omega_d) \simeq 1$. Then,

$$N_{min} \simeq m\frac{\pi}{8}\frac{\sqrt{\langle K_{sp}^2\rangle}}{K_s}\sqrt{\frac{\Delta\omega_{ef}^{c}}{\pi\Pi_e}\frac{\Omega_r}{\Omega_d}}\left\{1+\frac{4F}{\eta}\frac{\langle K_{sp}\rangle}{\langle K_{sp}^2\rangle}\right.$$
$$\times\left(1+\frac{32}{\pi\eta}\frac{(\Omega_r/\Omega_d)^{-1}}{\langle K_{sp}\rangle}\frac{1}{e\Delta\omega_{ef}^{c}}\left[i_d+\frac{1}{2eFM^2}\left(V_e^{*2}\left(\frac{1}{R^2}\right.\right.\right.\right.$$
$$\left.\left.\left.\left.\left.+\frac{4\pi^2}{3}\Pi_e^2C^2\right)+I_e^{*2}+\frac{4k_B T_r}{R}\right)\right]\right)\right\}^{1/2}.$$

When the quantity K_0 varies in the $10^3 < K_0 < 10^{10}$ range, the quantity $\langle K_{sp}\rangle \approx K_0^{\delta}$, where $\delta > 0.9$, and the ratio $\langle K_{sp}\rangle/\langle K_{sp}^2\rangle \propto 1/K_0$ (Fig. 2). For this reason, the second term in braces can be neglected compared to unity when K_0 is large enough. This means that the intrinsic PD noise and also the EA noise can be neglected compared to the noise caused by the fluctuations of the AQF spontaneous emission. In the experiments described below, the PD and EA noise became several times smaller than the spontaneous noise for $K_0 \geqslant 3\times10^3$. Therefore, the spontaneous emission proves to be the only factor that determines the sensitivity of the LR under consideration. In this case, for a Gaussian profile,

$$N_{min} \simeq m\left(\frac{\alpha}{2}\frac{c\Delta\nu_{1/2}^{c}}{\Pi_e}\frac{\Omega_r}{\Omega_d}\right)^{1/2}\frac{\sqrt{\langle K_{sp}^2\rangle}}{K_s}. \quad (12)$$

7. Experimental results and discussion

The LR sensitivity was investigated using averaging in the nanosecond and microsecond ranges employing the setup shown schematically in Fig. 1. In both cases, we used 40-ns pulses produced by the master oscillator and attenuated by five calibrated filters to the required energy. The initial pulse energy was measured with an IEK-1 calorimeter with an accuracy of 10 %. The attenuation produced by each filter was measured with an accuracy of 5 %. The resultant relative error of the energy measurement at the AQF input was 15 % with a confidence level of 0.68 [16].

The plane reception angle was three times greater than the diffraction-limited angle in all the experiments. Prior to arrival at the PD, the radiation passed through a Glan prism (not shown in Fig. 2), which was completely transparent to the amplified signal and amplified spontaneous emission of only one polarisation. The averaging time was determined by the EA transmission band. The main experimental parameters are presented in Table 1 and the oscillograms are shown in Figs 3 and 4.

Table 1.

FWHM pulse length/ns	Number of photons in the pulse	Averaging time/ns	AQF gain	$\sqrt{\langle K_{sp}^2\rangle}/K_0$
40	23	30	4900	~ 0.5 (Fig. 2)
40	270	5000	3000	~ 0.5 (Fig. 2)

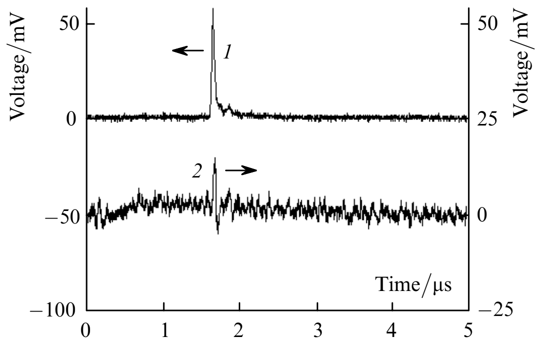

Figure 3. Oscillograms of the optical pulses recorded at the output of the master oscillator (*1*) and at the LR output (*2*) for a short averaging time (T_e = 30 ns).

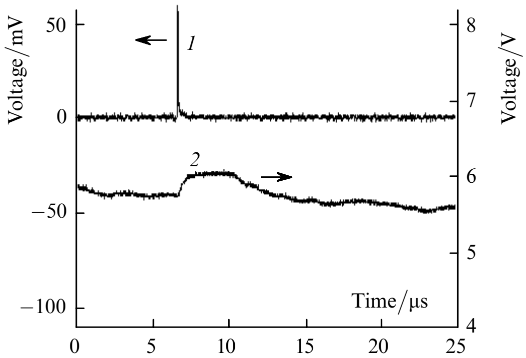

Figure 4. Oscillograms of the optical pulses recorded at the output of the master oscillator (*1*) and at the LR output (*2*) for a long averaging time (T_e = 5 μs).

Oscillograms *1* in Figs 3 and 4 correspond to the optical signals at the output of the master oscillator prior to attenuation. Oscillogram *2* in Fig. 3 corresponds to the signal at the

AQF output recorded with the PD and amplified with the help of the EA for $T_e = 30$ ns. This oscillogram exhibits the AQF noise, which determines the LR sensitivity, and the pulsed response recorded.

The distribution of the voltage fluctuation probability at the EA output is intermediate between Gaussian and exponential, because the EA averaging time exceeds the coherence time for the spontaneous emission. However, the noise level σ_V was defined as one sixth of the difference of maximal and minimal voltage fluctuations at the EA output, as is accepted for the Gaussian distribution [16]. This resulted in some overestimation of the noise level.

The signal-to-noise ratio at the PD output (Fig. 3, curve *2*) was ~ 8.5. Therefore, for a signal-to-noise ratio equal to unity, $N_{\min}^{\exp} = 23/8.5 \approx 3$ photons can be recorded. For a single pulse detectable with the probability $P \geqslant 0.75$ ($m = 2$), the results of our experiment imply, according to the Chebyshev criterion, that $N_{\min}^{\exp} = 2 \cdot 23/8.5 \approx 5$ photons. A theoretical estimate by formula (12) gives, for the above parameters of the input pulsed signal and taking into account that $\Delta\nu_{1/2}^{c} \simeq 0.012\ \mathrm{cm}^{-1}$ (the active medium of the AQF heats up to approximately 600 K during photolysis), $N_{\min}^{\mathrm{theor}} \approx 3$ and 6 photons, respectively.

Curve *2* in Fig. 4 shows the signal recorded at the LR output for $T_e = 5$ μs. In this case, the signal-to-noise ratio is ~ 9. Therefore, for a signal-to-noise ratio equal to unity, it is possible to record $N_{\min}^{\exp} = 270/9 = 30$ photons. For a single pulse detectable for this averaging time with the probability $P \geqslant 0.75$ ($m = 2$), $N_{\min}^{\exp} = 2 \times 270/9 = 60$ photons. This also agrees well with a theoretical estimate $N_{\min}^{\mathrm{theor}} \approx 35$ and 70 photons obtained by formula (12) for $T_e = 5$ μs.

8. Conclusions

Thus, the theoretical and experimental sensitivities of the LR under study agree closely with each other in a broad range of experimental conditions (the difference is within 20 %). This means that the sensitivity in the experiments described above was determined only by spontaneous emission of the AQF. An experimentally attained sensitivity $N_{\min} \approx 3$ photons for the signal-to-noise ratio equal to unity corresponds, for a 40-ns pulse, to the quantum limit for an reception angle three times greater than the diffraction-limited angle and an averaging time of 30 ns. Note that this reception sensitivity was obtained without using any special means, e. g., cooling the PD to low temperatures, because the effect of intrinsic noise of the PDs employed on the LR sensitivity was eliminated.

According to a preliminary analysis, the sensitivity of the LR under study would improve still further if the reception angle were made smaller than the diffraction-limited angle, while the pulse length were so reduced that its spectral width amounted to approximately one third of the width of the AQF amplification line profile. In this case, one might expect to extract a single single-photon signal from the noise and to record it. To specify the conditions for optimal reception, more detailed theoretical and experimental studies should be performed.

The laser receiver made on the basis of an iodine active quantum filter can be used in lidars for remote objects with a small effective reflecting surface, in long-range space communication systems, and in other fields of technology which require a high probability of enhancement and recording single photons against the background of intense irradiation.

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