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Noise-immune laser receiver – transmitters with the quantum sensitivity limit*

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***Abstract*. We consider the operation principles of noise-immune near-IR receiver – transmitters with the quantum sensitivity limit, in which active quantum filters based on iodine photodissociation quantum amplifiers and iodine lasers are used. The possible applications of these devices in laser location, laser space communication, for the search for signals from extraterrestrial civilisations and sending signals to extraterrestrial civilisations are discussed.**

Keywords: *iodine laser, active quantum filter, laser receiver, quantum sensitivity limit, diffraction divergence, space communication, optical telescope, adaptive optical systems, frequency reference, extraterrestrial civilisations.*

1. Introduction

The parameters of the basic elements of laser information systems designed to operate in space should satisfy rather high requirements. Thus, laser receivers (LRs) should have the high sensitivity, selectiveness, and noise immunity, while laser transmitters (LTs) should have the highly stable emission line wavelength, the high radiation directivity, and should be continuously tunable for compensating for Doppler shifts and matching the emission line with the reception band of an LR. The emission line should fall into the atmosphere transparency window. The development of a receiver – transmitter consisting of an LR with an active quantum filter (AQF) based on an iodine photodissociation quantum amplifier and an LT representing a magnetic-field-tunable iodine photodissociation laser made it possible to achieve the LR and LT parameters restricted only by the physical limit, thereby satisfying the requirements indicated above.

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2. Active iodine quantum filter

Experimental studies of the possibility of reception of weak laser signals by using optical quantum amplifiers have been initiated in papers [1, 2]. The quantum sensitivity limit has been achieved by using an iodine photodissociation quantum amplifier [3 – 5] operating at the $^2P_{1/2} \to {}^2P_{3/2}$ transition of an iodine atom at 1.315 μm (228.1 THz). This transition is characterised by a rigidly frequency-fixed narrow luminescence line with the FWHM $\Delta\nu \approx 0.01\ \text{cm}^{-1}$ [6] with a long radiative lifetime of iodine atoms in the $^2P_{1/2}$ excited state equal to 0.13 s [4 – 6]. Note that the iodine photodissociation quantum amplifier also solves an extremely important problem of filtration and selection of the useful signal. Unlike usual passive filters suppressing frequencies lying outside the signal spectrum, the signal in the AQF is selected due to amplification at frequencies belonging to the signal spectrum, and therefore this filter is called an active quantum filter [7 – 9].

The limiting high sensitivity of the LR with the AQF was achieved in [10] due to specific features of the active medium of the AQF such as its high optical homogeneity, the rapid recombination of iodine atoms in the ground $^2P_{3/2}$ state to the initial molecule [4, 5], and a considerable excess of the gain ($\alpha > 0.1\ \text{cm}^{-1}$) over the absorption coefficient ($\beta < 10^{-4}\ \text{cm}^{-1}$) for radiation at 1.315 μm [11]. Because of the high optical homogeneity of the active medium, a signal emitted by a point source can be focused, after amplification in the AQF, to a diffraction-limited spot, i.e. the single-mode amplification regime is realised [12]. A comparison of photographs in Fig. 1 shows that the achieved resolution is close to the diffraction-limited one. The diameters of central maxima in the absence and presence of amplification in the AQF are virtually the same. The rapid recombination of iodine atoms in the $^2P_{3/2}$ ground state to the initial molecule depletes the lower laser level, which allows the minimisation of the AQF quantum noise because the spectral brightness density of spontaneous emission (quantum noise) of one of the two polarisation states at the optical amplifier output is [1, 2, 13]

$$\mathscr{B}_{\text{qn}} = \mathscr{B}_{\text{vac}} \frac{n_2}{n_2 - (g_2/g_1)n_1} [K(\nu' - \nu) - 1], \tag{1}$$

where $\mathscr{B}_{\text{vac}} = \hbar c \nu^3$ is the spectral brightness density of vacuum [13] at the laser transition frequency; n_1 and n_2 are the populations of the lower and upper laser levels; g_1 and g_2 are their statistical weights, respectively; and $K(\nu' - \nu)$ is the gain at frequency ν'. Because the gain is high and the absorption coefficient is low, a device with the AQF has almost 100 % quantum yield. The gain index exceeding 0.1 cm^{-1} provides the gain as high as $K > 10^6$ at the gain line maximum in the AQF active medium of length ~ 60 cm [10]. This is a few orders of magnitude higher than the value $K_{\min} = 10^3$ above which the receiver noise is determined only by the quantum noise of the AQF.

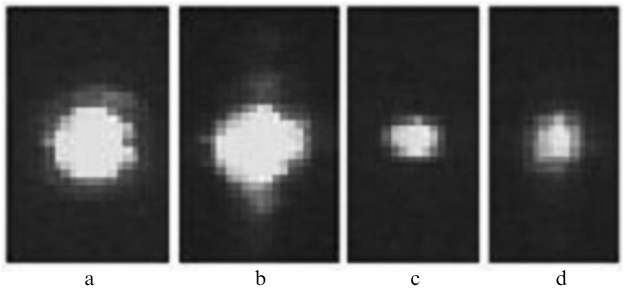


Figure 1. Images of a diffraction point without AQF pumping (a, c) and upon AQF pumping (b, d). The signal is attenuated by a factor of 5000 and intensified by a factor of 3000. To visualise the first diffraction ring of the Airy pattern, the photographs (a, b) were overexposed.

Thus, the combination of the possibility of amplification at one spatial mode, the minimal quantum noise, the 100 % quantum yield, and the high gain $K > 10^3$ provides the achievement of the limiting high sensitivity of the iodine AQF receiver, which is equal to one photon per mode for the time $\tau_o = 9 - 13$ ns ($\tau_o \approx \sqrt{\ln K}/c\Delta\nu$ [14–16]) for $K = 10^3 - 10^7$ and the signal-to-noise ratio s/n = 1. The energy sensitivity is $\hbar\omega = 1.5 \times 10^{-19}$ J.

These conclusions were experimentally confirmed in [10]. Experiments were performed with an iodine AQF pumped by radiation from a coaxial cavity flashlamp with a stabilised discharge. To improve the optical homogeneity of the active region, an optical filter was placed between a cell with the operating gas and the inner wall of the cavity flashlamp, which suppressed radiation at wavelengths shorter than 200 nm. The discharge circuit provided the continuous growth of the discharge current in the flashlamp, the current pulse being bell-shaped. The half-maximum duration of the current half period was 60 μs. The inner diameter of the AQF cell was 2 cm. The working gas was n-C_3F_7I at a pressure of 1.25 kPa. At this pressure, pumping is virtually homogeneous over the gas volume and the luminescence line at the laser transition is broadened due to the Doppler effect.

Figure 2 shows the typical oscillogram of the output voltage of an electron video amplifier recorded upon irradiation of the AQF by an optical signal attenuated with filters down to a few tens of photons and focused after amplification in the AQF on a photodiode connected with the video amplifier. For s/n = 1, the reception sensitivity equal approximately to three photons was achieved even when the reception angle exceeded three times the diffraction angle of the AQF and the signal duration was not matched with the AQF gain line width. Indeed, the duration τ_p of the signal pulse should be equal to $\tau_o \approx 1/c\Delta\nu_g$, where $\Delta\nu_g \approx \Delta\nu/\sqrt{\ln K}$ [16]; however, in fact τ_p was four times larger than the optimal duration $\tau_o \approx 10$ ns. The achieved sensitivity is well consistent with the sensitivity of the LR

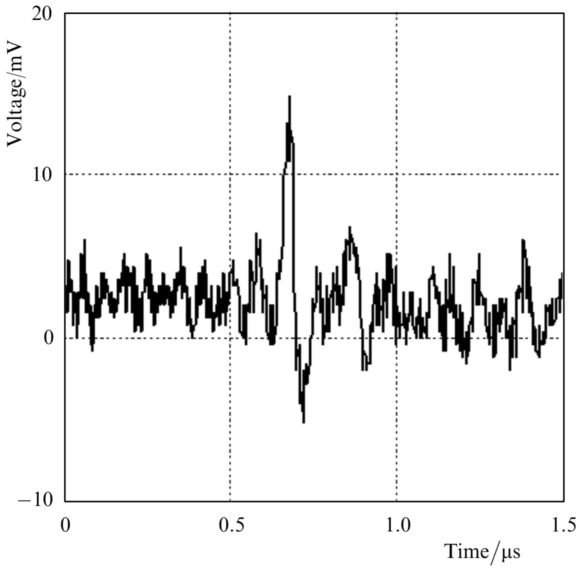


Figure 2. Output voltage of an electron video amplifier with the effective averaging time $\tau_e \approx 30$ ns observed when a 40-ns optical pulse containing approximately 20 photons was fed to the AQF input.

with the AQF calculated in [10, 17] for the case $\tau_p \gg \tau_c$, where $\tau_c = \tau_o\sqrt{\ln 2/2\pi} \approx 3$ ns is the correlation time of the quantum noise of an optical amplifier [16].

The LR sensitivity, defined as the minimal detectable number of photons in a pulse for s/n = m, is

$$S = m\Theta(c\tau_e\Delta\nu_e)^{1/2}\langle K^2\rangle^{1/2}/K_s. \quad (2)$$

Here, τ_e is the effective averaging time of the video amplifier;

$$\langle K^2\rangle = (\Delta\nu_e)^{-1}\int_0^{\infty}(K(\nu' - \nu) - 1)^2 d\nu';$$

$K(\nu' - \nu) = K^{\varphi(\nu' - \nu)}$; $K = K(0)$, $\varphi(\nu' - \nu) = g(\nu' - \nu)/g(0)$; $g(\nu' - \nu)$ is the shape of the luminescence line at the laser transition; $\Delta\nu_e = \int_{-\infty}^{\infty}\varphi(\nu' - \nu)d\nu' = 1/g(0)$ is the effective linewidth, which is related to $\Delta\nu$ for a Gaussian shape by the expression $\Delta\nu_e = \frac{1}{2}\Delta\nu\sqrt{\pi/\ln 2} \approx 1.06\Delta\nu$; K_s is the signal gain (for the condition that $\tau_p c\Delta\nu \gg 1$ and the signal frequency coincides with the gain line frequency $K_s = K$);

$$\Theta = \Theta(o_r/o_d) = (\pi/4)^2(o_r/o_d)\sqrt{\Psi}/L; \quad (3)$$

$$\Psi = \Psi(o_r/o_d) = (4/\pi)^2(o_r/o_d)^{-1}$$

$$\times\left(1 - \frac{4}{\pi}\int_0^1(J_0^2 + J_1^2)(1 - \xi^2)^{1/2}d\xi\right); \quad (4)$$

where o_r is the reception solid angle determined by the size of the reception area of a photodiode and the focal distance of a lens focusing radiation on the photodiode; $o_d = (\pi/4)^2\lambda^2/A$ is the solid diffraction angle determined by the area of the light pupil of the amplifier; $J_0 = J_0[\pi\xi(o_r/o_d)^{1/2}]$, $J_1 = J_1[\pi\xi(o_r/o_d)^{1/2}]$ are Bessel functions;

$$L = L(o_r/o_d) = 1 - J_0^2|_{\xi=1/2} - J_1^2|_{\xi=1/2} \quad (5)$$

is the Rayleigh function. The dependences L, Ψ and Θ on o_r/o_d are shown in Fig. 3. Expression (2) was obtained by neglecting all noises except the quantum noise of the AQF. This is justified if the AQF gain exceeds K_{min} at which the AQF noise is higher than photodiode and video amplifier noises [10, 17].

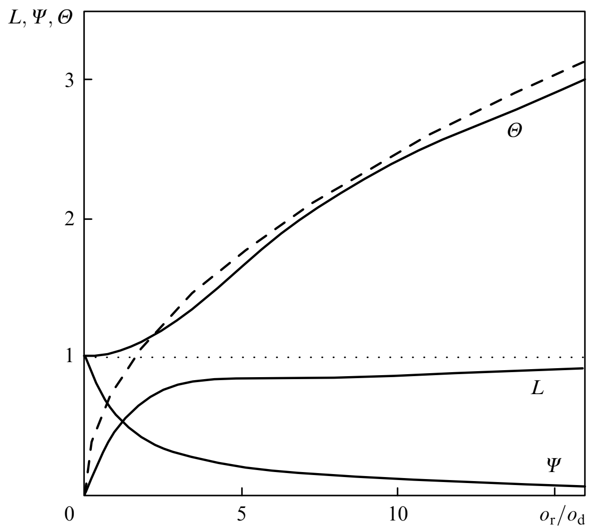


Figure 3. Dependences of L, Ψ, and Θ on o_r/o_d. The dashed curve shows the dependence $(\pi/4)(o_r/o_d)^{1/2}$, which is the asymptotics of the function Θ for $o_r/o_d \gg 1$.

3. Reception sensitivity of an array photodetector

An AQF can amplify signals within large solid angles determined by its geometrical dimensions. The solid angle within which the AQF efficiently amplifies signals with the almost constant gain can exceed the solid diffraction angle by many orders of magnitude. To realise such a broad field of view of the receiver, it is necessary to use either a photodiode array or a TV camera. However, if the angular size of the photosensitive area of a photodiode or a pixel of the TV camera is close to the AQF diffraction angle, then during the movement of the diffraction spot of a signal over the photodiode array, the output signal of the array will be strongly attenuated when the spot falls into the gaps between reception areas, which will cause the reception instability. The reception of the signal will be more stable, if the diffraction spot overlaps several photodiodes. Then, the reception angle for one array element becomes smaller than the diffraction angle, and the question arises of whether this will be accompanied by the loss of the LR sensitivity.

It follows from expressions (3)–(5) and is seen from Fig. 3 that for $o_r/o_d \to 0$ the function $\Theta(o_r/o_d) \to 1$. This value almost coincides with the value of Θ for $o_r/o_d \approx 1$, i.e. when the reception angle is equal to the diffraction angle. Therefore, as the ratio o_r/o_d decreases, the value of S tends to its limit:

$$\bar{S} = m(c\tau_e\Delta\nu_e)^{1/2}\langle K^2\rangle^{1/2}/K_s. \tag{6}$$

Thus, if the quantum noise of the AQF plays a key role, the LR sensitivity does not decrease even when the reception angle of one reception element is considerably smaller than the diffraction limit [18]. This is explained by the fact that the quantum noise decreases proportionally to o_r/o_d, i.e. as the useful signal energy does, unlike the shot noise of the photodetector and thermal noise of electrical circuits of the video amplifier. It is clear that when the ratio o_r/o_d is small enough, the signal energy can become smaller than the energy of these noises. Let us see how much the ratio o_r/o_d can be reduced without the loss of the LR sensitivity.

Taking into account the shot noise of the photocurrent caused by the spontaneous emission of AQF and the received signal, as well as taking into account the dark current of the photodetector, thermal noise of resistive elements, and noise of the electron amplifier, we obtain the reception sensitivity in the form [17]

$$\tilde{S} = \frac{\gamma S_{ql}}{2LK_sT_{op}} + \left\{\bar{S}^2\Theta^2\Lambda + \frac{1}{L^2K_s^2T_{op}^2} \times\left[\left(\frac{\gamma S_{ql}}{2}\right)^2 + \gamma S_{ql}\frac{i_{der}\tau_e}{\eta e}\right]\right\}^{1/2}, \tag{7}$$

where $\gamma = \tau\Pi_e$; Π_e is the passband (in hertz) of the electron amplifier at the $1/\sqrt{2}$ level of the maximum of its gain modulus (usually, γ is slightly smaller than 0.5); T_{op} is the optical path transmission; $S_{ql} = 2m^2F/\eta$ is the quantum limit of the photodetector sensitivity; η is its quantum efficiency; F is the noise coefficient;

$$\Lambda = \Lambda(o_r/o_d) = 1 + \frac{2\gamma F}{\eta T_{op}}\frac{\langle K\rangle}{\langle K^2\rangle}\Xi;$$

$$\langle K\rangle = \frac{1}{\Delta\nu_e}\int_0^\infty (K^{\varphi(\nu-\nu')} - 1)\mathrm{d}\nu';$$

$\Xi = \Xi(o_r/o_d) = [(\pi/4)^2(o_r/o_d)\Psi]^{-1}$; $i_{der} = i_{dc} + i_{va}$; i_{dc} is the average dark current; i_{va} is the average shot current of the video amplifier, which can be calculated from expression (7) in [17]. Expression (7) of this paper transforms to (2) if the condition

$$\frac{\gamma S_{ql}}{\bar{S}^2K_s^2\Theta^2\Lambda L^2T_{op}^2}\frac{i_{der}\tau_e}{\eta e}\left(1 + \frac{\gamma S_{ql}}{4}\frac{e\Pi_e}{i_{der}}\right) < \delta \tag{8}$$

is fulfilled, where e is the electron charge and $\delta \ll 1$ is a positive number. Because $\Theta \approx 1$, $\Psi \approx 1 - (\pi/4)^2 o_r/o_d$, and $L \approx (\pi/4)^2 o_r/o_d$ for $o_r/o_d \ll 1$, we obtain from (8) the quadratic equation in $X = (\pi/4)^2 \times o_r/o_d$:

$$X^2 + 2\frac{Q}{\eta T_{op}}\frac{\langle K\rangle}{\sqrt{2}\langle K^2\rangle}X - \frac{Q}{\delta\eta^2T_{op}^2\langle K^2\rangle} \times\frac{\sqrt{2}i_{der}}{ec\Delta\nu_e}\left(1 + \frac{\gamma S_{ql}}{4}\frac{e\Pi_e}{i_{der}}\right) > 0, \tag{9}$$

where

$$Q = \sqrt{2}\gamma F\left(1 + \frac{2\gamma F}{\eta T_{op}}\frac{\langle K\rangle}{\langle K^2\rangle}\right)^{-1}.$$

It can be shown that if $K > 10^3$, then $\langle K\rangle \approx K/\sqrt{\ln K}$ and $\langle K^2\rangle \approx K^2/\sqrt{2\ln K}$. Then, if $F \approx 10$, $\eta = 0.5$, $\gamma \approx 0.5$, we obtain $Q \approx \sqrt{2}\gamma F$ and expression (9) gives

$$\frac{o_{\mathrm{r}}}{o_{\mathrm{d}}} > \frac{(4/\pi)^2}{\eta T_{\mathrm{op}} K}\left\{\left[(\sqrt{2}\gamma F)^2 + \frac{\sqrt{2}\gamma F}{\delta}\frac{i_{\mathrm{der}}}{ec\Delta\nu_{\mathrm{e}}}\right.\right.$$
$$\left.\left.\times\left(1 + \frac{\gamma S_{\mathrm{ql}}}{4}\frac{e\Pi_{\mathrm{e}}}{i_{\mathrm{der}}}\right)2\sqrt{\ln K}\right]^{1/2} - \sqrt{2}\gamma F\right\}.$$

Let us neglect the noise of the electron amplifier, which is lower than the dark current noise (for example, $i_{\mathrm{dc}} \approx 2 \times 10^{-7}$ A for an LFD-2 photodiode). By assuming that $T_{\mathrm{op}} \approx 1$, we obtain the inequality $o_{\mathrm{r}}/o_{\mathrm{d}} > 800 \times (\ln K)^{1/4}/\sqrt{\delta}K$. By setting $\delta = 0.1$, we find that for the gain $K = 10^6$, the ratio $o_{\mathrm{r}}/o_{\mathrm{d}}$ can be reduced without the sensitivity loss down to 5×10^{-3}, i.e. the planar reception angle can be 14 times smaller than the planar diffraction angle [18]. This leads to a practically important conclusion that the size of one element of a photodiode array can be substantially smaller than the size of the diffraction spot of a received signal in the focal plane of the optical system focusing the signal on the photodiode array. In this case, the LR sensitivity should remain at the same level as during the reception within the diffraction angle. This conclusion also concerns the sensitivity of image intensifiers at the ultralow light level illumination.

4. Image intensification

As mentioned above, a solid angle within which an AQF efficiently amplifies signals with an almost constant gain can exceed the solid diffraction angle by many orders of magnitude. In this connection it was reasonable to verify the possibility of using the AQF as an image intensifier [12].

The optical scheme of the experiment is presented in Fig. 4. A radiation pulse from master oscillator (*1*) was directed by spherical mirror to object mask (*3*) and then was incident on spherical mirror (*4*) located at a double focal distance from the mask. The mask was imaged by mirror (*4*) at a 1 : 1 scale at the centre of AQF cell (*7*) and then was transferred by mirror (*8*) with a magnification of 5.8 to white mat screen (*9*) and detected with TV camera (*10*) sensitive at a wavelength of 1.315 μm.

Radiation scattered by screen (*9*) and detected with the TV camera was attenuated by more than four orders of magnitude compared to the incident radiation. In this case, the luminescence emission noise did not exceed the TV camera noise and did not remove the TV camera from its dynamic range during the operation time of the AQF which was several milliseconds. Although this optical scheme could not be used to detect extremely weak signals, it was applied to study the image intensification in the presence of optical inhomogeneities produced in the active region of the AQF during its operation. Near mirror (*4*), aperture (*5*) of diameter 1 cm was mounted, diffraction from this aperture determining the resolution of the system. The diameters of AQF cell (*7*) and mirror (*8*) were considerably larger than the diameter of aperture (*5*).

First we verified the quality of the optical path. Object mask (*3*) was a circular aperture of diameter 0.2 mm, which corresponded to the size of the diffraction point at a distance of 150 cm from spherical mirror (*4*) for aperture (*5*) of diameter 1 cm. The pumping of the AQF was not switched on, and a signal from the master oscillator was attenuated by calibrated filters (*6*) down to the required level. The image of the diffraction point recorded in this case is shown in Fig. 1a. Then, the signal was attenuated by additional filters by a factor of 5000 and amplified in the AQF by a factor of 3000 (see Fig. 1b). The photographs obtained in these experiments were specially overexposed to observe the first diffraction ring of the Airy pattern. By comparing photographs in Figs 1a and b, we see that the resolution close to the diffraction limit was achieved in both cases. The diameters of the central maxima in the photographs are almost the same. After amplification, only the intensity distribution in the first diffraction ring changes.

The first Airy ring is unnoticeable in the photographs obtained similarly but with the normal exposure (Figs 1c and d).

After it became clear that diffraction points were intensified virtually without any distortions, we performed the image intensification for a more complicated object. An object mask with a circular hole was replaced by a mask with a hole in the form of an airplane silhouette. The length of the object corresponded to seven diffraction sizes, while the span of the airplane wings was equal to five diffraction sizes. As in the previous series, we obtained photographs without amplification and after attenuation and subsequent amplification (Fig. 5). One can see that the image of a rather complicated object almost is not changed after the 3000-fold intensification in the iodine AQF and can be easily identified.

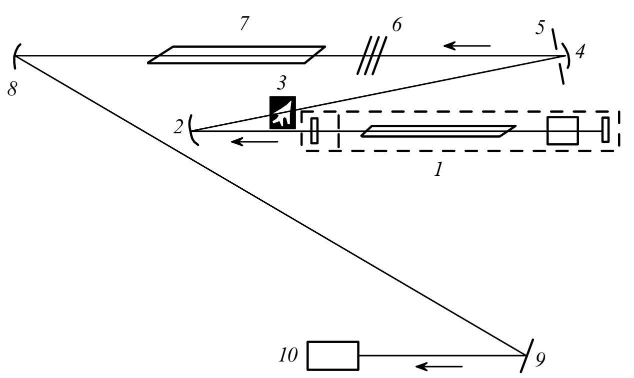
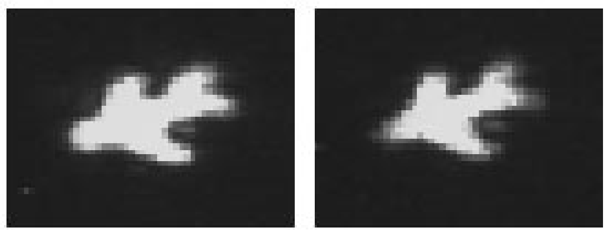


Figure 4. Optical scheme of the image-intensification experiment: (*1*) master oscillator; (*2, 4, 8*) spherical mirrors; (*3*) object mask; (*5*) aperture; (*6*) calibrated filters; (*7*) AQF cell; (*9*) white mat screen; (*10*) TV camera.



a b

Figure 5. Airplane silhouettes before image intensification (a) and after attenuation by a factor of 5000 and intensification by a factor of 3000 (b).

5. Separation of the useful signal against the background of a high-power light source

Due to the high gain $K > 10^3$ in conjunction with a small width of the AQF gain line ($\Delta\nu_{\mathrm{g}} < 0.01\ \mathrm{cm}^{-1}$), the sensitivity of the AQF receiver remains virtually invariable even when a signal is observed against the background produced in fact by any high-power natural light source. Thus, it was shown in [17] that if the signal is received against the background of a high-power light source, the reception sensitivity will be described by the expression

$$\hat{S} = \frac{\gamma S_{\mathrm{ql}}}{2LK_{\mathrm{s}}T_{\mathrm{op}}} + \left\{ \bar{S}^2\Theta^2\Lambda(1+\mathscr{B})^2 + \frac{1}{L^2K_{\mathrm{s}}^2T_{\mathrm{op}}^2} \times \left[\left(\frac{\gamma S_{\mathrm{ql}}}{2}\right)^2 + \gamma S_{\mathrm{ql}}\frac{i_{\mathrm{der}}\tau_{\mathrm{e}}}{\eta e} \right] \right\}^{1/2}, \quad (10)$$

where

$$\Lambda = 1 + \frac{(2\gamma F/\eta T)\Xi + 2\mathscr{B}}{1+\mathscr{B}}\frac{\langle K\rangle}{\langle K^2\rangle} + \frac{\mathscr{B}[(2\gamma F/\eta T)\Xi + \mathscr{B}]}{(1+\mathscr{B})^2}\frac{1}{\langle K^2\rangle}\frac{\Delta\nu_{\mathrm{op}}}{\Delta\nu_{\mathrm{e}}}; \quad (11)$$

$\langle K\rangle$ and $\langle K^2\rangle$ are calculated now by adding the background emission to the AQF quantum noise; $\Delta\nu_{\mathrm{op}}$ is the transmission bandwidth of the optical path; $\mathscr{B} = \mathscr{B}_{\mathrm{bgr}}/\mathscr{B}_{\mathrm{vac}}$ is the ratio of the spectral brightness density of the background radiation source to the spectral brightness density of vacuum at the laser transition wavelength in atomic iodine. As K is increased, the ratio $\langle K^2\rangle^{1/2}/K_{\mathrm{s}}$ tends asymptotically to the value calculated in the absence of background radiation. When the gains are high enough, the second and third terms in (11) become much smaller than unity, and expression (10) for $o_{\mathrm{r}}/o_{\mathrm{d}} \leqslant 1$ changes to the expression $\hat{S} \approx \bar{S}(1+\mathscr{B})$, from which it follows that the reduction of the sensitivity during the reception of a signal against the background of a light source with the spectral brightness density $\mathscr{B}$ times higher than the spectral brightness density of vacuum at the reception wavelength will be $\delta S = \mathscr{B}\bar{S}$.

If the background source is treated as the black body, the relative decrease in the sensitivity is equal to the ratio of the spectral brightness densities of the black body and vacuum at a wavelength of 1.315 μm:

$$\delta S/\bar{S} = \mathscr{B}_{\mathrm{blb}}/\mathscr{B}_{\mathrm{vac}} = [\exp(\hbar\omega/kT) - 1]^{-1}, \quad (12)$$

where $\mathscr{B}_{\mathrm{blb}}$ is the spectral brightness density of the black body at temperature T at a wavelength of 1.315 μm. According to (12), the sensitivity of an AQF receiver against the solar disk treated as the black body at $T = 6000$ K (in the absence of solar radiation losses in its way to the AQF) is reduced approximately by 18 %. On the Earth surface, where solar radiation is attenuated by the Earth atmosphere, the sensitivity is reduced even weaker, approximately by 12 % [17, 19, 20]. This conclusion was verified in model experiments on the reception of signals against the background of a plasma radiation source (ISI-1 Podmoshenskii source) with the brightness temperature of 40000 K [17]. Due to radiation losses in the elements of the optical path, the effective brightness temperature of the ISI-1 source was 16000 K, which corresponds to $\mathscr{B}_{\mathrm{vac}}$ by the spectral radiation density at 1.315 μm. Figure 6 presents voltage oscillograms at the video amplifier output recorded by feeding simultaneously the signal and ISI-1 radiation amplified in the AQF into the photodiode. The optical pulse duration was the same as before, while the angle ratio was $o_{\mathrm{r}}/o_{\mathrm{d}} \approx 1$.

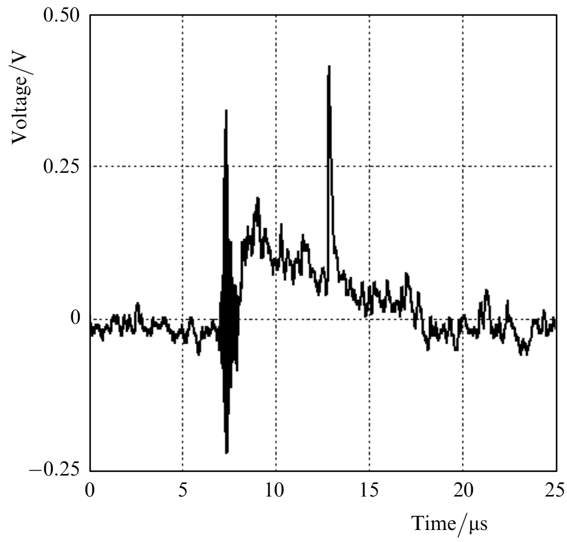


Figure 6. Output voltage of the electron video amplifier with the averaging time 90 ns observed when an optical pulse and radiation of the ISI-1 source from the AQF output was incident on a photodiode (the ISI-1 radiation pulse begins within 8 μs after the high-frequency electric induction produced by the ignition pulse; the useful signal pulse arrives after 13 μs.)

For the ratio s/n = 1, the reception sensitivity was approximately three photons outside the ISI-1 pulse and six photons within the ISI-1 pulse, i.e. the sensitivity was impaired by half against the background of the bright ISI-1 radiation source. Thus, if the pulse duration is reduced from 40 to 10 ns and a video amplifier with the effective averaging time up to 10 ns is used, then the probability of detecting a signal at 1.315 μm consisting of approximately three photons against the solar radiation background will exceed 0.9. This conclusion is also valid for stars of spectral classes included between classes M and F with the surface temperature lower or close to the solar surface temperature [21].

6. Iodine lasers

The main element of the LR described above is the iodine AQF. Optical signals that should be received by this LR are emitted by iodine lasers. At present high-energy iodine photodissociation lasers exist which emit kilojoule, nanosecond pulses in diffraction beams. Also, high-power repetitively pulsed oxygen-iodine lasers emitting nearly megawatt pulses have been developed.

The advent of such lasers was favoured by the development of a number of pump sources such as high-power xenon flashlamps [5], high-current open electric discharges [4], intense explosive shock waves [22 – 24], and high-power singlet-oxygen generators [25]. Of decisive importance were the specific properties of the active medium of iodine lasers such as a long lifetime of excited iodine atoms achieving hundreds of microseconds and providing the accumulation of energy in the active medium emitted then in the form of a giant pulse; a low absorption coefficient ($\beta < 10^{-4}$ cm^{-1}) of the active medium at the laser radiation frequency, which allows the laser length scaling in a broad range and increasing the output energy; and a high optical inhomogeneity of the active medium permitting, in conjunction with phase conjugation methods [26, 27], the emission of diffraction beams. The parameters of iodine lasers developed for well-known Iskra [28, 29] and Asterix IV laser setups [30–32] are presented in Table 1.

Table 1.

Laser setup	Beam diameter/cm	Beam energy/kJ	Pulse duration/ns	Radiation divergence /rad
Iskra* (All-Russian Research Institute of Experimental Physics, Sarov, Russia)	50	2.0–2.5	0.25–1.0	10^{-5}
«Asterix IV»** (Max-Planck-Institut für Quantenoptik, Garching, Germany)	29	2.1	5.0	2×10^{-5}

*Pump source: high-current electric discharge;
**Pump source: xenon flashlamps.

7. Magnetic-field compensation for the Doppler shift and the transmission of the 1.315-μm radiation through atmosphere

To match the spectrum of a signal coming from a moving source with the AQF amplification line, it is necessary either to shift the AQF amplification line or to shift preliminarily the spectrum of the signal. It is known [33–36] that the amplification line can be shifted with the help of a magnetic field. However, in this case the amplification line splits into many components, while the AQF gain and selectivity drastically decrease. The spectra can be matched by shifting preliminarily the laser source spectrum with the help of a magnetic field. In the magnetic field of strength of about 400 Oe, lasing at the 3–4 lines passes to the 2–2 line, and then can be continuously tuned by a few inverse centimetres with increasing the field strength up to 75 kOe.

It is important that radiation at 1.315 μm falls within the transparency window of the Earth atmosphere. Measurements showed [36] that the absorption coefficient of the surface atmospheric layer is 2×10^{-7} cm^{-1} and is manly determined by water vapours whose concentration decreases with altitude. The energy loss of a signal propagated through the whole atmosphere will be smaller than 20 % (the atmosphere transmission is $T_a > 0.8$). In this case, the dispersion of the refractive index of air [21] will not distort the signal shape because for $\Delta v/v \approx 10^{-6}$ the group delay is smaller than 2×10^{-16} s.

Based on the performed experimental and theoretical studies, we can conclude that it is expedient to use the iodine AQF and iodine lasers in laser location and laser probing, especially in the presence of intense background illuminations. In addition, they can be used for cosmic laser communications and for the search for signals from extraterrestrial civilisations and sending signals to these civilisations. The methods for receiving and processing weak pulsed laser signals in iodine AQF systems are protected by RF patents [9, 18, 37–40].

8. Possibilities of remote laser ranging by using an iodine AQF

Figure 7 presents the scheme of laser ranging setup with an AQF LR. The distance R at which diffusely reflecting objects of area A_o can be located by using such an LR with the angular diameter of the field of view $\Theta_v = 100'$ can be estimated from the expression

$$R \approx \sqrt{T_a}[(\alpha'/2\pi)(A_a A_o E_t/\Omega_v E_r)]^{1/4}. \quad (13)$$

Here, α' is the albedo of a located object; E_t is the illumination pulse energy; $E_r = m\hbar\omega$ is the input energy of the LR, which is determined by its sensitivity and specified signal-to-noise ratio; A_a is the area of a receiver–transmitter optical antenna; and $\Omega_v = \pi\Theta_v^2/4$ is the solid angle of the locator field of view. Let us assume that $T_a \approx 0.8$ and $0.1 \leqslant \alpha' \leqslant 0.5$. Figure 8 shows the dependences of R on the product $A_a A_o E_t$ for $m = 10$ and $\alpha' = 0.1$ and 0.5. At present an iodine photodissociation laser emitting 10-J pulses at a repetition rate of 25 Hz and the radiation divergence $\vartheta = \Theta_v = 100' = 0.5$ mrad can be developed.

Thus, it follows from Fig. 8 that, by using a telescope with a primary mirror of diameter ~ 1 m for transmitting and receiving signals, the laser location of diffusely reflecting objects of area ~ 1 m^2 can be performed at distances ~ 1000 km.

9. Possibilities of laser space communication by using an iodine AQF

The development of long-range noiseless space communication lines between a space craft in the deep space and a ground space communication station or a space-craft station on a circumterrestrial orbit is an urgent problem. Let us see the possibilities of the iodine AQF LR in this respect.

Let the area of aperture of the transmitting and receiving optical antennas of a laser space communication (LSC) complex is A_t and A_r, respectively, the distance between them is R, the spectral noise power density of the communication channel is ρ_n, its passband is Δf, the quantum yield of the receiver is γ_q, and the radiation wavelength is λ. By using the Shannon formula [41] for the data transfer rate, we obtain that when a diffraction-quality radiation pulse is generated, the amount of information transferred during the pulse duration τ_p is

$$B = \Delta f\tau_p \log_2[1 + (\gamma_q E_t/\rho_n \Delta f\tau_p(A_t A_r/\lambda^2 R^2)]. \quad (14)$$

If $\Delta f\tau_p \approx 1$, then by using an iodine AQF in the LR for which $\rho_n = \hbar\omega$, $\gamma_q = 1$, under the condition that a signal is detected with the probability exceeding $1 - m^2$ and the pulse energy

$$E_t > m\hbar\omega\lambda^2 R^2/A_t A_r \quad (15)$$

no less than one bit of information can be transferred. In this case, the Doppler frequency shift is assumed compensated. If the transmitting and receiving antennas of the complex are circular with diameters D_t and D_r, respectively, then $A_t = \pi D_t^2/4$ and $A_r = \pi D_r^2/4$. To receive the signal reliably, it is necessary to provide the signal-to-noise ratio $m \geqslant 3$. The LT power in the continuous operation regime is

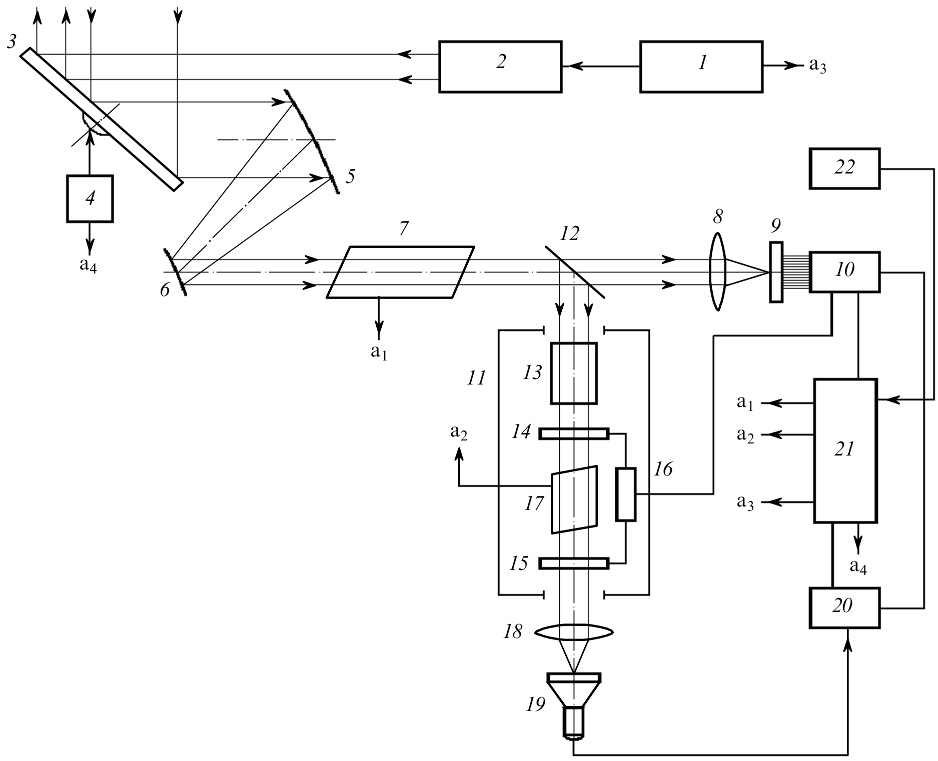


Figure 7. Scheme of a location device: (*1*) 1.315-μm laser; (*2*) pump unit; (*3*) steering mirror; (*4*) drive and mirror (*3*) control unit; (*5, 6*) concave and convex mirrors of the receiving telescope; (*7*) first AQF; (*8*) first focusing lens; (*9*) diode array; (*10*) strobe formation unit; (*11*) dynamic filtration unit; (*12*) beamsplitter; (*13*) optical delay line; (*14, 15*) first and second optical gates; (*16*) optical gate control unit; (*17*) second AQF; (*18*) second focusing lens; (*19*) TV photodetector; (*20*) functional processing unit; (*21*) data processing unit; (*22*) external target indication unit; $a_1 - a_4$ indicate electric connections of elements.

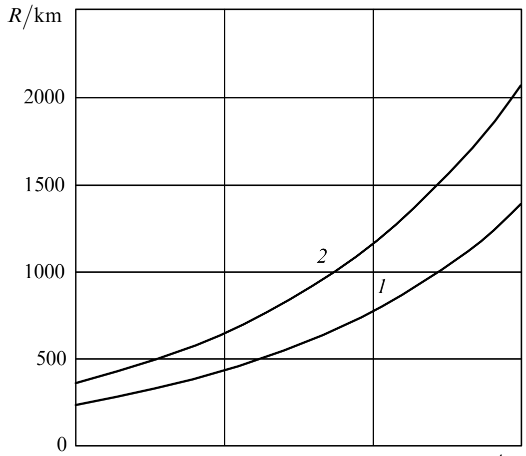


Figure 8. Dependences of the distance to an object located with an iodine AQF LR on the product of the area of a receiver-transmitter optical antenna, the object area and the illumination laser energy for $m = 10$ and $\alpha' = 0.1$ (*1*) and 0.5 (*2*).

$P_t = c\Delta\nu_g E_t$, where $c\Delta\nu_g \approx c\Delta\nu/\sqrt{\ln K} \approx 300$, which corresponds to the bit rate of 300 Mb s^{-1}.

Table 2 presents the values of D_t, D_r, E_t, and P_t for the iodine AQF LSC complex [42] used in different space paths, beginning from the near space (within the moon orbit) up to the far boundaries of the Solar system (up to the Pluto orbit). These values demonstrate the high efficiency of the complex. Within the near space, the required LT power is quite moderate ($P_t = 0.6$ mW). This allows one to use tunable laser diodes in LTs [40], which are similar to those used in modern fibreoptic communication lines. This complex can be also used for LSC with Mars, which requires the employment of a 2-W LT, as well as for LSC within the Solar system.

Table 2.

Space path	R/m	D_r/m	D_t/m	E_t/J	P_t/W
Earth – Earth's satellite on a stationary orbit	4×10^7	0.5	0.5	1.1×10^{-15}	0.2×10^{-6}
Earth – Moon	4×10^8	0.5	0.5	3.2×10^{-12}	0.6×10^{-3}
Earth – Mars	3.75×10^{11}	0.5	8	1.1×10^{-8}	2
Earth – Pluto	6×10^{12}	0.5	8	2.8×10^{-6}	560

Thus, the LSC complex with the iodine AQF LR can provide the efficient broadband communication with space crafts and stations within the Solar system. Such a complex can successfully compete with modern space communication systems operating in the radio-frequency range, which are inferior to LSC systems with respect to a number of parameters, for example, in the bit rate and amount of data transferred. Its use in the near space within the moon orbit will provide the increase in the bit rate and amount of data transferred approximately by an order of magnitude.

10. Possibilities of the search for signals from extraterrestrial civilisations and sending call signals

The problem of the search for signals from extraterrestrial civilisations (ECs) and possible establishing a communication with them involves the solution of a number of basic problems such as the choice of the signal wavelength, the separation of the signal against the galactic background and radiation background of the star under study, the reception and detection of extremely weak signals with the probability close to unity, and the provision of the required level of transmitted signals [43 – 45].

Because the EC, whose signals we want to detect, should have technical devices similar to those created on the Earth, the frequency choice in the optical range depends on whether lasers have been created on the Earth emitting radiation at this frequency with the divergence and pulsed energy sufficient for its detection at distances at least of a few tens of parsecs (1 pc $= 3.08 \times 10^{16}$ m). The choice also depends on whether a receiver has been created for this wavelength with the noise level close to the quantum limit and virtually 100 % quantum yield, i.e. a receiver with the quantum sensitivity limit.

Estimates by (15) show that in the visible and near IR ranges for diameters of the primary mirrors of a transmitting and receiving telescopes as in the space Hubble telescope (2.4 m [46]) and a distance between them, for example, 25 pc, laser pulses of energy $E_t = 7 - 25$ kJ are required even if the quantum limit of the spectral noise power density in the communication channel is $\rho_n = \hbar\omega$ and $\gamma_q = 1$. This is a rather strict requirement for lasers emitting still no more than 10 kJ in the Q-switching regime [47, 48]. The realisation of the project of the next large space telescope [49] with the aperture of diameter 6.5 m [49] would provide the reduction of E_t by a factor of 50. However, for the distance to the EC equal to 100 pc, the requirements to the pulse energy again become very strict. Therefore, it is desirable to use a communication wavelength falling into the transparency window of the atmosphere and apply ground-based optical telescopes with adaptive optical systems in which the diameters of primary mirrors have already achieved 10 m.

However, at distances more than 25 pc, even such telescopes cannot resolve optically a star and a planet separated by a distance of ~ 1 a.e. in the hypothetical EC. But if the telescope is pointed at the star, the noise in the communication channel increases. Therefore, the choice of the wavelength for the search for EC signals in the optical range also involves the creation of a narrowband filter at this wavelength for selecting the signal against the radiation background of the observed star without a noticeable decrease in the receiver sensitivity. This means that at present the most suitable receiver – transmitter pair for the search for EC signals and sending signals to ECs in the optical range is the iodine AQF – iodine laser pair [50 – 55].

Let an EC emit a laser beam with the diffraction divergence toward the Sun. This beam will overlap the Earth orbit at the distance R if the condition $R\lambda/D_t > 2a$ is fulfilled, where $a = 1$ a.e. is the distance from the Earth to the Sun. Taking into account absorption in the Earth atmosphere and assuming that absorption in the atmosphere of a planet inhabited by the hypothetical EC is the same, we obtain from (15) the inequality [50, 55]

$$D_r > (8\sqrt{3}a/\pi T_a)(\hbar\omega/E_t)^{1/2} \tag{16}$$

providing the condition ($m \geqslant 3$).

It follows from (16) that, if the sensitivity of a receiver used in experiments is close to the quantum limit even against the radiation background of the star being observed, the diameter of the mirror of the receiving telescope should exceed 7 m if the laser pulse energy is 2 kJ [55]. Table 3 lists some of the modern large optical telescopes [56 – 58] which could be used for the search for EC signals at a wavelength of 1.315 μm. It is important that the atmospheric restriction of the resolution of these telescopes is eliminated by using adaptive optical systems capable of real-time compensating for the atmospheric blurring of images [59].

Table 3.

Telescope	Mirror diameter/m	Telescope location
KECK I	10	Mauna Kea, Hawaii, USA
KECK II	10	
VLT	4 × 8.2	Paranal, Chile
GEMINI North	8	Mauna Kea, Hawaii, USA
GEMINI South	8	Cerro Pachon, Chile
SUBARU	8.2	Mauna Kea, Hawaii, USA
GTC	10	La Palma, Canary Islands, Spain

Taking into account the absorption of radiation in the Earth atmosphere and assuming that absorption in the atmosphere of a planet in the hypothetical EC is the same, we obtain from (15) the expression for the range limit of the EC signal detection with the probability exceeding 0.9 ($m \geqslant 3$):

$$R = (\pi/4\sqrt{3})T_a(E_t/\hbar\omega)^{1/2}D_tD_r/\lambda. \tag{17}$$

By substituting $T_a = 0.8$, $D_t = D_r = 10$ m, $E_t = 2$ kJ, $\rho_n = \hbar\omega = 1.5 \times 10^{-19}$ J into (17), we obtain $R \approx 103$ pc [51, 55]. This is smaller only by 20 % than the distance estimated in the case of space telescopes with the primary mirror diameter of 10 m. Note that the limiting group delay [60] for a signal at the frequency 228.1 THz and $\Delta\nu/\nu \approx 10^{-6}$ does not exceed 5×10^{-13} s even at intergalactic distances. This is much smaller than the optimal duration $\tau_o \sim 10$ ns of signal pulses when the iodine AQF receiver is used.

At present the projects of the 30-m [61], 42-m [58] and even 100-m [62] optical telescopes exist. If the primary mirror diameter of the transmitting and receiving telescopes is 30 m, it follows from (17) that $R \approx 930$ pc. A sphere of such a radius contains 10^8 stars [45] and more than 300 planets discovered at present [63].

Note also that the energy required to transfer a bit at the wavelength $\lambda_I = 1.315$ μm over the specified distance by using ground-based optical telescopes with $D_E = 10$ m is considerably lower than that at the wavelength $\lambda_H = 21$ cm by using the world's largest Aresibo radio telescope [45] with the antenna diameter $D_A = 305$ m. The ratio of these energies E_I and E_H, taking into account that ρ_n at λ_H is determined by the galactic background with the equivalent noise temperature $T_H = 10$ K [52], is described by the expression [50, 51, 55]

$$E_I/E_H = (T_a)^{-1}(\hbar\omega/kT_H)(\lambda_I/\lambda_H)^2(D_A/D_E)^4. \tag{18}$$

By substituting the above-presented values into (18), we obtain $E_I/E_H \approx 1/22$. The energy required to send one bit to the EC remote by the distance 25 pc by using ground-based 10-m optical telescopes is about 90 J, as follows from (15). If $D_E = 30$ m, then $E_I/E_H \approx 1/900$. The required energy per bit for the distance to the EC equal to 100 pc will be ~ 20 J [54, 56]. Thus, communication at $\lambda_I = 1.315$ μm requires radiation pulse of considerably lower energies than communication at $\lambda_H = 21$ cm. This result is consistent with conclusions made in [64, 65]. Note also that the noise level at 1.315 μm is independent of the orientation of the receiving telescope axis with respect to the direction to the Galaxy centre.

Thus, already at present all the conditions exist for the search for EC signals and sending, if necessary, signals to a EC with the help of ground-based optical telescopes equipped with adaptive optical systems at the 1.315-μm $^2P_{1/2} \rightarrow {}^2P_{3/2}$ laser transition in the atomic iodine, which can be used for this purpose as the natural frequency reference.

11. Conclusions

We have considered the operation principles of noise-immune near-IR receiver – transmitters with the quantum sensitivity limit, using iodine lasers and active quantum filters based on iodine photodissociation quantum amplifiers. These devices can detect signals consisting of only several photons against the radiation background of the Sun and stars of spectral classes contained between classes M and F.

It has been shown that the sensitivity of reception of a signal from a point source by using a diode array or a TV camera remains at the quantum limit level even when the size of a pixel of the diode array is considerably smaller than the size of the diffraction focal spot of the optical signal on the array. This opens up the possibilities for intensifying extremely weak images and creating all-day optical locators which are capable to recognise the mages of objects of size of several metres at a distance of thousands of kilometres against the solar disk background.

We have discussed the laser space communication complex with the iodine AQF, which can provide already at present the efficient broadband communication with space aircrafts and stations within the Solar system and has parameters that are close to those predicted for 2020 [66] in direct-photodetection systems under the condition that noticeable progress will be achieved in optical technologies, in particular, in the manufacturing of photodetectors and passive optical filters.

We have considered the possibility of using a laser receiver with an iodine AQF for the search for signals from extraterrestrial civilisations and a laser transmitter based on high-energy iodine lasers for sending signals to these civilisations in the optical wavelength range.

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