High Sensitivity Photoreceiver Design

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Abstract: The paper describes low noise preamplifiers designed for optical detectors. Analysis of operating conditions affecting signal-to-noise ratio has been carried out. Each preamplifier was carefully optimised to work with particular type of the detector.

Keywords: Optical detectors, low noise preamplifier.

1 Introduction

Optical radiation receivers are used in many up-to-date fields of science and technology determining current level of technological progress. The most important fields of their applications are industrial automation, robotics, space technology, medicine, and military technology.

The optical radiation range covers electromagnetic radiations longer than the gamma but shorter than millimetre waves. Schematic diagram of a typical photoreceiver is shown in Fig. 1.

Optical radiation from an object (signal source) is detected by a photoreceiver. It consist of optics, detector, preamplifier and signal processing system.

All objects are composed of continually vibrating atoms, with higher energy atoms vibrating more frequently. The vibration of all charged particles, including these atoms, generates electromagnetic waves.
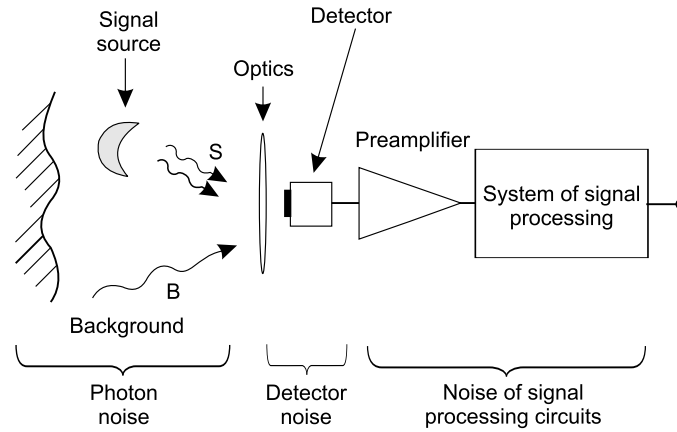
Fig. 1. Scheme of optical receiver.

The higher the temperature of an object, the faster the vibration, and thus higher the spectral radiant energy.

As a result, all objects are continually emitting radiation at a rate with a wavelength distribution that depends upon the temperature of the object and its spectral emissivity. Most of the above mentioned applications require transmission through air, but the radiation is attenuated by the processes of scattering and absorption. Scattering changes direction of a radiation beam; it is caused by absorption and subsequent reradiation of energy by suspended particles. For larger particles, scattering is independent of wavelength. However, for small particles, compared with the radiation wavelength, the process is know as Rayleigh scattering and exhibits a λ^{-4} dependence. Therefore, scattering by gas molecules is negligibly small for wavelengths longer than 2μm. Also smoke and light mist particles are usually small with respect to IR wavelengths, and IR radiation can therefore penetrate further through smoke and mists than visible radiation. However, rain, fog and aerosols particles are larger and consequently they scatter IR and visible radiation to a similar degree.

Total radiation received from any object is the sum of the emitted, reflected and transmitted radiation. Objects that are not blackbodies emit only fraction of blackbody radiation, and the remaining fraction is either transmitted or, for opaque objects, reflected. When the scene is composed of the objects and backgrounds of similar temperatures, the reflected radiation tends to reduce the available contrast. However, reflections of hotter or colder objects significantly effect the appearance of a thermal scene. The reflected sunlight is negligible for 8 - 14 μm imaging, but it is important in UV, VIS and 3-5 μm band.

In general, the 8 - 14 μm band is preferred for high performance thermal imag-

ing because of it higher sensitivity to ambient temperature object and its better transmission through mist and smoke [1, 2]. However, the $3 - 5\mu$m band may be more appropriate for hotter object, or when sensitivity is less important than contrast. Also additional differences occur, e.g. a virtue of MWIR band is smaller diameter optics required to obtain a certain resolution and some detectors may operate at higher temperatures (thermoelectric cooling) than it is usual in the LWIR band where cryogenic cooling is necessary (about 77 K).

2 Infrared Optics and Detectors

An optical block in IR receiver produces an image of the observed objects in plane of the detector. The optical elements like windows, domes and filters can be used to protect the receiver from environment or to modify detector spectral response.

The most popular materials used for manufacturing of refractive optics of IR systems are: germanium (Ge), silicon (Si), fused silica (SiO_2), zinc selenide (ZnSe), glass BK-7, and zinc sulphide (ZnS).

Photons may originate from a variety of sources: scene background, path radiance, optics, warm filters, cold filter, and housing. The background noise can be reduced by using cold shied housing (Fig. 2).
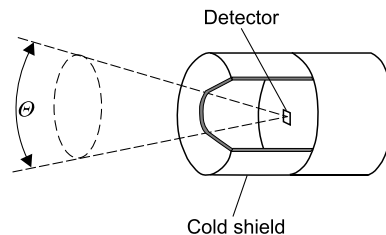

Fig. 2. Cold shield decreases photon noise.

Photon noise is unique to thermal imaging systems. It is nonexistent for visible sensors since the background in the visible does not provide any photons. If the cold shield is isolated from the cooler, it may be at an elevated temperature. A warm filter (not shown) can also contribute to photon noise.

There is no essential difference in design rules of optical objectives for visible and IR ranges. Designer of IR optics has significantly fewer materials suitable for IR optical elements, in comparison with those for visible range, particularly for wavelengths over 2.5 μm.

Progress in infrared IR detector technology is due to application of semiconductor IR detectors which belong to class of photon detectors. The photon detectors

show a selective wavelength dependence of the response per unit incident radiation power. They exhibit perfect signal to noise performance. However, the photon detectors require thermoelectric and cryogenic cooling. The second class of infrared detectors is composed of thermal detectors. Thermal effects are generally wavelength independent; the signal depends upon the radiant power but not upon its spectral content. In contrast to photon detectors, thermal detectors typically operate at room temperature. The thermal detectors are popularly believed to be rather slow and insensitive in comparison with photon detectors [3]. In the last decade, however, it has been shown that extremely good imagery can be obtained from large thermal detector arrays operating uncooled at TV frame rates. The moderate sensitivity of thermal detectors can be compensated by a large number of elements in 2D electronically scanned arrays. With large arrays of thermal detectors the best values of NETD, below 0.1 K, could be reached. The noise produced in detectors and systems of signal conversion constrained detection of low intensity signals. The works on IR detection are aimed at reduction of detector and preamplifier noise to the value lower than the photon noise one.

3   Low Noise Electronics System

The work on maximisation of S/N ratio was undertaken because of the lack of analyses on selected design parameters and operation conditions of a detector affecting signal-to-noise ratio (S/N) in direct detection systems and advanced IR methods.

The main purpose was to analyse the input stages of IR receivers (photodetector plus low noise preamplifier and biasing circuit of the detector) to optimise them providing maximal value of signal-to-noise ratio.

Preamplifiers used for photoreceivers can be classified as three categories: low impedance preamplifiers, high impedance preamplifiers and transimpedance preamplifiers.

A low impedance preamplifier can operate over a wide bandwidth, they do not provide a high receiver sensitivity. For the high-impedance preamplifier design, the goal is to reduce all sources of noise to absolute minimum, but it has a high value of input RC time constant. The transimpedance preamplifier design largely overcome drawbacks of the high impedance preamplifier. The benefits of a transimpedance amplifier are as follows:

- wider dynamic range compared with the high-impedance amplifier,
- usually no equalization is required,
- the time constant of a detector is low,

- the transfer characteristics of an amplifier is actually its transimpedance which is the feedback resistor.

A general noise model of the input stage of a photoreceiver has been accepted (Fig. 3). There is a strong relationship between detector resistance and optimum readout technology. The active device of a preamplifier can be bipolar, JFET, or it can be an IC with bipolar, FET or MOSFET input stage. Selection of active device primarily depends on detector resistance and frequency range. It is difficult to say exactly where device of each type should be used. The input active device of the preamplifier, is usually the dominant noise contributor of the readout. The noise contribution of the input transistor is a function of the source impedance exhibited by the detector. Thus, it is important to match the detector with an appropriate readout input transistor [4].

Equivalent scheme of a photodetector consists of the signal source, resistance and capacity of a detector, as well as noise sources of a detector and background [5].
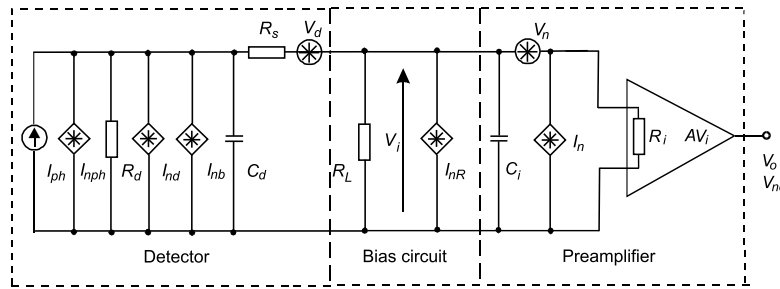

Fig. 3. Equivalent noise model of input stage of photoreceiver (I_{ph} is the photocurrent, I_{nd} is the detector noise, I_{nb} is the background noise, C_d, R_d are the capacity and resistance of a detector respectively, V_{nd} is the noise voltage of the series resistance of the detector, I_n, V_n are the current noise and voltage noise of a preamplifier respectively, R_i, C_i the are input resistance and input capacity of a preamplifier respectively, A is the voltage gain of a preamplifier).

Preamplifier noise is presented as two sources, voltage and current ones. Basing on the analysis of noise models of the receivers with photoconductive detectors, the following expression for S/N ratio can be written [5]

$$\frac{S}{N} = \frac{I_{ph}^2}{\frac{kI_b^\alpha}{f^\beta} + 4q^2\eta(\Phi_s + \Phi_b)Ag^2\Delta f + 4q^2G_{th}g^2\Delta f + \frac{4kT_d\Delta f}{R_d} + \frac{4kT_L\Delta f}{R_L} + I_a^2} \quad (1)$$

where I_{ph} is the photocurrent, k is the Boltzmann constant, I_b is the bias of the detector, f is the electrical frequency, q is the electron charge, η is the quantum

efficiency, Φ_s is the radiant incident power from the signal, Φ_b is the radiant incident power from the background, A is the detector area, g is the photoconductive gain, Δf is the electronic frequency bandwidth, G_{th} is the thermal conductance, T_d is the detector temperature, R_d is the detector resistance, T_L is the load resistance temperature, R_L is the load resistance, and I_a is the preamplifier noise.

The counter exhibits the squared average value of a photocurrent and the dominator shows the total equivalent input noise. The first term of the denominator determines the noise of $1/f$ type, the second one - generation-recombination noise resulted from fluctuations of radiation from signal and background, the third term - generation-recombination noise produced by thermally excited carriers in semiconductors, next terms represent thermal noise of detector resistance, loading, and preamplifier.

The noise of $1/f$ type depends on technology of detector manufacturing and the value of a bias current. The second term can be reduced due to narrowing the detectors field of view, application of cooled diaphragms and optical filters. Lowering the detector temperature causes reduction of the third and fourth terms. High load resistance gives thermal noise minimisation. The optimised preamplifiers of low noise should be used.

To analysis of S/N ratio of the receivers with photodiode, the following expression for S/N ratio was obtained [5]

$$\frac{S}{N} = \frac{M^2(V,T)I_{ph}^2}{2q\Delta f\left[(I_{ph}+I_b)M^2(V,T)F(M(V,T))+(I_s+I_{db}M^2(V,T)F(M(V,T)))2^{\frac{T-300}{10}}\right]+\frac{4kT\Delta f}{R_L}F_n}$$

(2)

where M is the multiplication factor, F is the photodiode multiplication factor, V is the bias voltage of the photodiode, and F_n is the noise factor of the preamplifier.

The counter includes squared average value of photocurrent multiplied by squared multiplication factor of an avalanche photodiode. Denominator represents the total substitute input noise of a receiver. The first term of Eq. (2) describes shot noise, the second one - thermal noise of load resistance and preamplifier noise. Shot noise depends on photocurrent, background current, as well as on superficial and volumetric components of dark current.

The noise in electrical circuits is often a function of frequency. For high frequencies, the noise equivalent signal current, I_{ntotal}, is given by

$$I_{ntotal}^2 = I_{nph}^2 + I_{nd}^2 + I_{nb}^2 + V_{nd}^2\omega^2 C_d^2 + I_n^2 + \frac{4kT\Delta f}{R_L} + V_n^2\omega^2(C_d^2+C_i^2)^2 \qquad (3)$$

where V_{nd} is the noise voltage of the serial resistance of the detector.

The input capacitance of the preamplifier, C_i, may considered to lie across the amplifier input on the photodiode side of the noise generator, V_n. Thus, with this assumption, the noise generator, V_n, is not a true input noise generator, as generally understood, as it should normally lie on the input side of all components (except, possibly, the noise current generator, which would have the same effect whichever side V_n it were to be connected to). The justification for this approach is firstly, that the amplifier capacitance is conveniently grouped with C_d, but secondly it enables V_n to be a "white" noise generator.

Re-writing equation (3) we obtain

$$I^2_{ntotal} = [I^2_{nph} + I^2_{nd} + I^2_{nb} + I^2_n + \frac{4KT\Delta f}{R_L}] + \omega^2 [V^2_d C^2_d + V^2_n (C_d + C_i)^2] \qquad (4)$$

There are thus two terms, a "white" noise term in the first setoff square brackets and a second term which gives a noise current increasing in proportional to frequency.

Although a capacitor does not add noise, the detector noise voltage, V_n, and preamplifier noise voltage, V_n is increased by the C_d and the $C_d + C_i$ respectively, as is evident from the coefficient of that term in Eq. 4.

Analysing Eq. 4, we see, that for matching an amplifier to a detector, it is important to minimize the sum of: $I_n + V^2_n \omega^2 (C_d + C_i)^2$.

The sensitivity of an optical receiver is most conveniently expressed in terms of its noise-equivalent power (NEP). This is defined as the optical power necessary to make the signal current, I_{ph}, equal to the noise current, I_{ntotal}, i.e.

$$NEP = (I^2_{ntotal})^{\frac{1}{2}} \frac{h\nu}{\eta q} [\text{W}] \qquad (5)$$

In many data sheets show the NEP figure for a detector, unfortunately, if we connected an preamplifier the performance will often dependent on the amplifier noise source, critically combined with parasitic features of the photodiode, particularly its capacitance and parallel resistance (see Eq. 3)

The results of the above mentioned activities were used for experimental investigations, i.e., several IR detection devices were designed, performed, and tested [6]-[8].

Many problems have to be overcome during construction of low-noise preamplifier for low-resistance detectors (e.g., HgCdTe of resistance below 100 Ω). It is due to the fact that the detectors of resistance of the order of 20 Ω produce noise voltage lower than 0.6 nV/Hz$^{1/2}$, i.e., below the noise voltage generated in the best (available) amplifying elements. So, the question arises; it is possible to

build a preamplifier of noise voltage below a detector noise? It appears that it can be achieved when several identical preamplifiers are connected in parallel and next the output signals are added.

Such a system of signal processing ensures reduction of final input signal according to the relationship

$$V_{ntotal} = V_n \cdot (n)^{-\frac{1}{2}} \qquad (6)$$

where V_n is the noise voltage of a single preamplifier and n is the number of amplifying stages.

The basic idea of increase in input impedance of preamplifier is reduction of thermal noises. However, the high resistances R_L cause narrowing of a band of the input stage of a photoreceiver. A preamplifier of high input impedance is significant load resistance for a detector so, it does not ensure wide range of signal changes. The problem of serious changes of a signal has been solved in transimpedance preamplifiers.

In order to have satisfactory signal-to-noise ratio at the amplifier output, the following requirements must be fulfilled:

a) resistance in the feedback loop must be at least several times higher than detector resistance, i.e., of the order of hundred MΩ,

b) noise current of the used preamplifier should be lower than dark current of a detector, input polarisation currents should be of the order of fAs.

4   Experimental Results

Figure 4 presents a diagram of transimpedance preamplifier that is recommended for amplification of the signals received from low-resistance IR detectors. Integrated circuits of LT 1028 type and AD 797 type were used at the input stage of an amplifier. This preamplifier can be applied both for photodiodes and photoresistors. When a photoresistor is connected, the polarising resistor R_L is required. For this system the noise voltage was 0.3 nV/Hz$^{1/2}$ for $n = 9$ and $f = 10$ kHz. Bandwidth of this preamplifier is 100 kHz.

A convenient way to convert the signals from detectors of resistances of above 10 MΩ into a usable voltage is to use an op amp as a current-to-voltage converter as shown in Fig. 5.

The diode bias is maintained at zero volts by the virtual ground of the op amp, and short circuit current is converted into a voltage. At maximum sensitivity, the feedback resistor must be very large, and the amplifier bias circuit very small. For example, 1 GΩ will yield a corresponding voltage of 30 mV for photodiode current
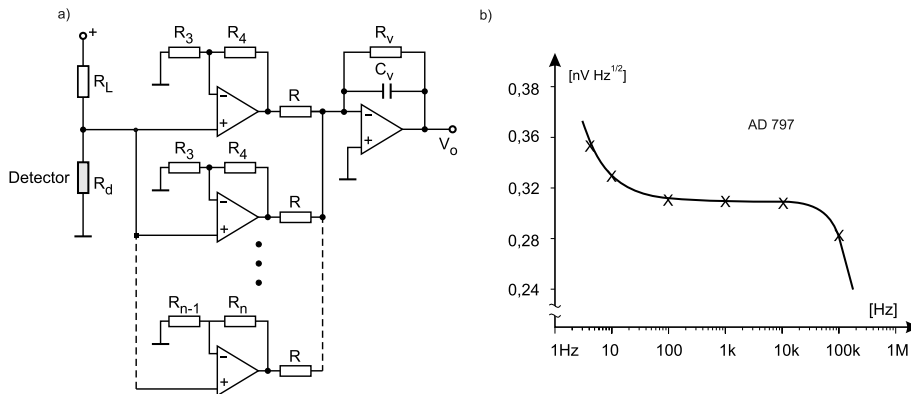
Fig. 4. Preamplifier for low-resistance detectors (a), and its noise characteristics (b).

of 30 pA. Larger resistor values are impractical, so we will use 1 GΩ for the most sensitive range. For higher values of light intensity, the gain of the circuit must be reduced by using a small feedback resistor.

To accurately measure photodiode currents in the tens of picoamps range, the bias current of op amp should be no more than a few picoamps. The critical leakage paths of the photodiode circuit are enclosed by the dotted line's in Fig. 5. The feedback resistor should be thin film on ceramic or glass with glass insulation. The compensation capacitor across the feedback resistor should have a polypropylene or polystyrene dielectric. All connection to the summing junction should be kept short. If a cable is used to connect the photodiode to the preamplifier, it should be kept as short as possible to have Teflon insulation.
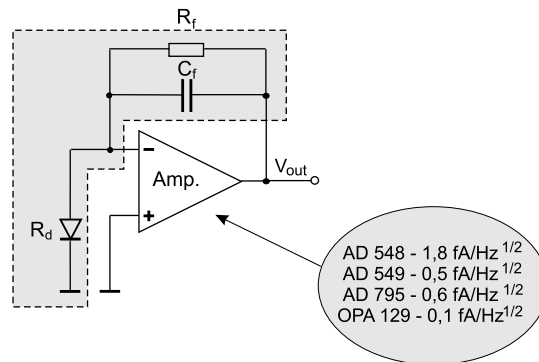

Fig. 5. Preamplifier for high-resistance infrared detectors.

Guarding techniques can be used to reduce parastic leakage by isolating the amplifiers input from large voltage gradients across the PC board. Physically, a

guard is a low impedance conductor that surrounds an input line and is raised to the lines voltage. It serves to buffer leakage by diverting it away from the sensitive nodes. In the preamplifier, the integrated circuit of, AD 548, AD 549, AD 795, and OPA 129 type were used.

In the photodiode preamplifier, the signal current from the photodiode passes through the $R_f C_f$ network. It is important to distinguish between the signal gain and the noise gain, because it is the noise gain characteristic which determines stability regardless of where the actual signal is applied. Stability of the system is determined by the net slope of the noise gain the open loop gain where they intersect. For unconditional stability, the noise gain curve must intersect the open loop response with a net slope of less than 20 dB per decade.

If a detector operates in BLIP conditions, the generation-recombination noise should be higher than Johnson noise, thus

$$4g^2 q^2 \eta (\Phi_B + \Phi_S) A \Delta f >> 4k \Delta f T R_{eq} \qquad (7)$$

where g is the photoelectric amplification, q is the electron charge, η is the quantum yield, ϕ_B is the background flux, ϕ_C is the signal flux, A is the detector surface, Δf is the noise band, k is the Boltzman constant, T is the temperature and R_{eq} is the final resistance (R_d and R_L are connected in parallel).

Table 1. Summarises the performance of used preamplifiers.

Part	V_{osmax}	TCV_{osmax}	I_{Bmax} at 25°C	0.1Hz to 10Hz Noise	V_{ni}[fA/Hz$^{1/2}$] f = 35 kHz
AD 548	250 μV	2 μV/°C	10 pA	2 mV p-p	1,8
AD 549	250 μV	5 μV/°C	100 fA	4 mV p-p	0,5
AD 795	250 μV	3 μV/°C	1 pA	2,5 mV p-p	0,6
OPA 129	2 μV	10 μV/°C	100 fA	4 mV p-p	0,1

Investigations of noise of the designed systems for signal processing were carried out using Stanford Research Lock-In SR 844 RF amplifier.

The received values of noise voltage and current are comparable with the results obtained from computer simulations. Further works on improvement in preamplifiers for low-resistance HgCdTe and GaN detectors are being made.

5   Conclusion

The preamplifiers are specially designed to infrared detectors. Each preamplifier is carrefully optimised to work with particular type of the detector. Current mode

configuration results in excellent stability of the first stage in all working conditions. Great attention has been paid to ensure maximum signal-to-noise ratio in wide range of detector's resistance.

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