

Analysis of operation conditions of avalanche photodiode on signal to noise ratio

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The paper presents analysis of influence of operation conditions of avalanche photodiode on signal to noise ratio. The special attention was paid to determination of optimal value of this ratio in dependence on temperature, power of incident radiation, and load resistance. This value of bias voltage has been defined as a function of temperature at which the noise to signal ratio is of maximal value. The supply system of APD photodiode was proposed. The system ensures a constant value of multiplication factor as a function of temperature.

1. Introduction

Detection of electromagnetic radiation of extremely low intensity is mainly performed by means of avalanche photodiodes. Such a photodiode is a power converter of radiation incident on it, into a current and it can be considered as a power-controlled current source.

Signal to noise ratio of avalanche photodiode depends on multiplication factor, temperature, load resistance and other parameters. This paper presents the analysis of a system for supply and stabilization of a working point of avalanche photodiode with consideration of maximal value of signal to noise ratio. The effect of photodiode operation conditions (supply voltage, temperature, power of incident radiation, load resistance, and the others) on the signal to noise ratio of a photoreceiver has been also examined.

2. Signal to noise ratio

Figure 1 presents a block diagram of a photoreceiver used for radiation detector in a laser rangefinder. The photoreceiver consists of five parts: preamplifier-photodiode system, signal discrimination system, comparator, system for supply and stabilization of a working point of a photodiode, and converter.

The analyzed photoreceiver comprises an avalanche photodiode of the C30954E type, made by the RCA firm. High values of the avalanche photodiode responsivity can be obtained using avalanche multiplication phenomenon. A mechanism of internal gain causes significant increase in a signal current, generated in a detector, and improves the signal to noise ratio. Such a mechanism, however, does not influence on the noises, originated from a load resistance, as well as on amplifier noises. The avalanche gain causes both, an increase in the noise originated from a dark current and in the quantum noise, to such a degree that their values are important for a proper work of the photoreceiver. It is due to the fact that a random mechanism of carries multiplication causes additional noises which are the shot noises with the values overcoming values resulting from primary generation of the unbalanced carriers. The dominant source of noises in an avalanche photodiode is the shot noise multiplied similarly to a signal multiplication. However, if the signal power rises proportionally to M^2 , the noises power rises proportionally to M^{2+x} . The values of "x" coefficient are within the interval of $0.3 \div 0.5$ for a silicon avalanche photodiode and within the interval of $0.7 \div 1.0$ for an avalanche photodiode made of germanium or chemical elements of III-IV groups [4, 5].

The $F(M)$ factor is equal to M^x and is called a multiplication factor. It characterizes the avalanche

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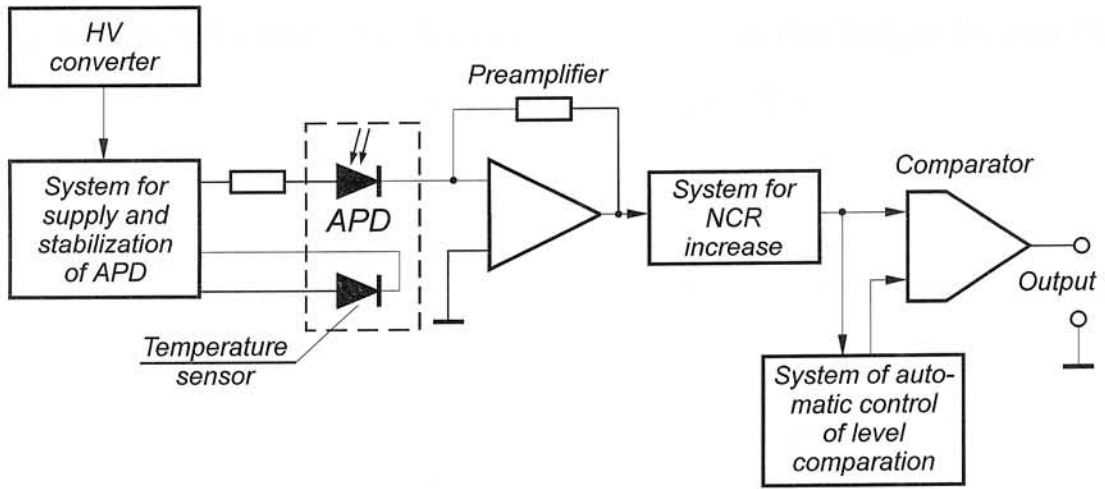


Fig.1. Block diagram of a photoreceiver (after Ref. 1-3).

noises. The multiplication factor of a photodiode can be determined as a ratio of the measured power of its photoelectric current noise I_{NP}^2/B to the power of "hypothetical" noise of a photoelectric current of an ideal photodiode ($2qI_{ph}M^2$), i.e., additional (excess) noise:

$$F(M) = \frac{I_{NP}^2}{2qBI_{ph}M^2} \quad (1)$$

where q is the electron charge, B is the noise band, I_{ph} is the photocurrent, and I_d is the dark current.

For the C30645 avalanche photodiode the multiplication factor is defined as [7]:

$$F(M) = k_{eff} M + (1 - k_{eff}) \left(2 - \frac{1}{2} \right) \quad (2)$$

A substantial characteristics for an avalanche photodiode is dependence of a multiplication factor M on its reverse bias voltage. Such characteristics are presented in the catalogue data. For the C30645 photodiode, additionally to the characteristics, the producer gave also an empirical relationship describing this characteristics in approximation [7]

$$M = \frac{k}{U_b - U_R} \quad (3)$$

where $k = 50$ is the coefficient, U_b is the breakdown voltage, U_R is the reverse bias voltage.

It can be seen that the curve drawn according to the formula (3), for $k = 50$, does not cover the characteristics curve given in the catalogue data. Taking the values $k = 38$ and $U_b = 73.5$ V, the curve in Fig. 2 was

obtained. The points belonging to the producer's characteristics are also shown in this figure.

Dependence of multiplication factor on reverse bias voltage for the C30645 photodiode is defined with adequate accuracy by the formula:

$$M(U) = \frac{38}{(73,5 - U_R)} \quad (4)$$

The average-square value of the total shot noise i_{SA}^2 is given as the relationship

$$i_{SA}^2 = 2q B \left[(I_{ph} + I_b) M^2 F(M) + I_s \right] \quad (5)$$

where q is the electron charge, B is the width of the detection band (energy band), I_{ph} is the intensity of the

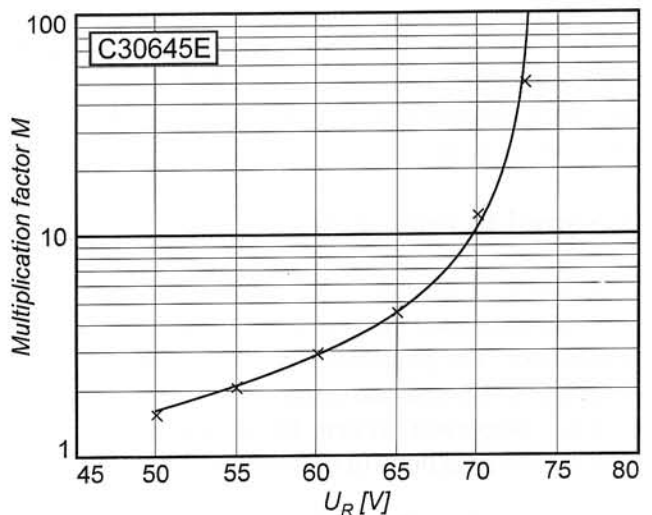


Fig.2. Multiplication factor of the C30645 photodiode as a function of reverse bias voltage.

primary unmultiplied photocurrent, I_b is the bulk component of the primary dark current, I_s is the surface leakage component of the dark current.

The catalogue data of the C30645E photodiode include the range of values of total dark current which are warranted by a producer.

$$I_d = I_s + I_b M \quad (6)$$

The component values of I_s and I_b are not given. Also for k_{eff} coefficient there is given only the range of its possible values. So, first of all, for drawing a course of signal to noise ratio as a function of multiplication factor the adequate values of I_s and I_b currents and k_{eff} coefficient should be determined.

The producer of the C30645E photodiode gave the following relationship describing spectral density of noises:

$$i_n = \sqrt{2q(I_s + I_b M^2 F(M))} \quad (7)$$

Taking into account the relationships (2) and (6) one can state that the equation (7) describes spectral density of the noises in dependence on the values of the searched by us parameters as a function of multiplication factor.

In order to determine the required current values I_s , I_b and k_{eff} coefficient the laest square method was used.

Now, choosing the values of I_s and I_b currents and the value of k_{eff} coefficient the chart $i_n = f(M)$, shown in Fig. 3, has been obtained. The points taken from the characteristics, given in the catalogue data are marked

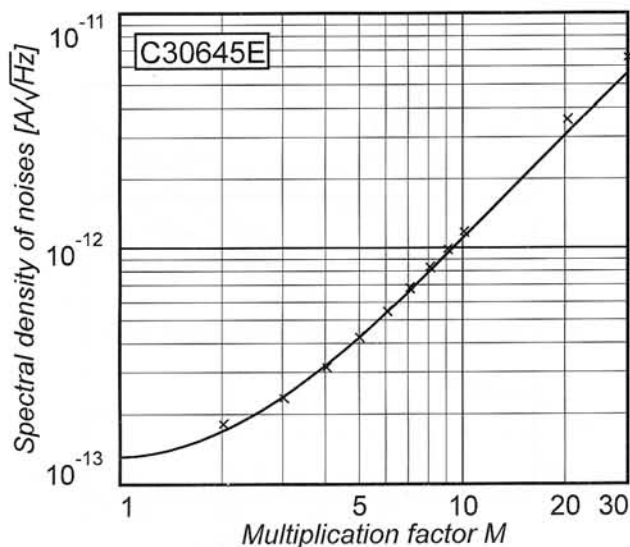


Fig. 3. Spectral density of current noises as a function of multiplication factor.

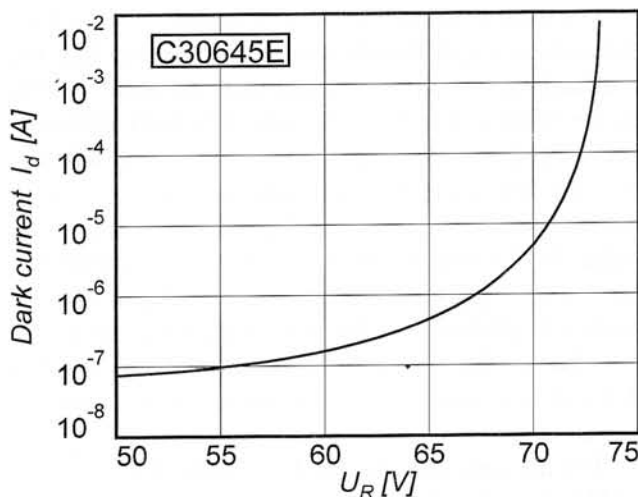


Fig. 4. Dark current as a function of reverse bias voltage.

(as crosses) in this figure. The above presented chart has been obtained with the following data; $I_s = 50$ nA, $I_b = 6$ nA and $k_{\text{eff}} = 0.6$.

Knowing the values for I_s , I_b , and k_{eff} , the course of dark current as a function of reverse bias voltage (Fig. 4) can be drawn and next the signal to noise ratio as a function of multiplication factor can be calculated.

For an avalanche photodiode the signal to noise ratio is determined by the equation:

$$\frac{S}{N}(M) = \frac{M^2 I_{ph}^2}{2qB(I_{ph}M^2 F(M) + I_b M^2 F(M)) + \frac{4kTB}{R_L}} \quad (8)$$

where k is the Boltzman's constant, T is the temperature, R_L is the load resistance. The counter of the equation presents a photocurrent and denominator presents noises. The first component of the denominator describes the shot noise but the second one the thermal noise of the load resistance.

For calculation of the signal to noise ratio as a function of power radiation the equation

$$I_{ph} = \frac{P q \eta \lambda}{h c} \quad (9)$$

has been substituted into (8) [6].

The parameters; $\eta = 0.75$, $\lambda = 1.55$ m, $T = 300$ K, $B = 100$ MHz, and $R_L = 4$ k Ω have been taken for calculations. Knowing the currents values I_s , I_b and k_{eff} coefficient, the relationship of particular noise components, as a function of multiplication factor, can be calculated. The calculation results for the power of incident radiation equal to 10 nW are presented in Fig. 5a and for the power 1nW in Fig. 5b.

For the low values of multiplication factor the thermal noises are dominant what is the reason that the resultant current noise is practically constant for the higher values of this coefficient. For high values of multiplication factor the thermal noises are not significant. The signal to noise ratio decreases also with the rate of M^{2+x} . It is due to the rise of the shot noise value. In this chart there is shown also the signal current that is proportional to the internal gain of an avalanche photodiode. For low values of a multiplication factor, the signal from radiation incident on a detector is of lower value than the value of a resultant noise.

For the case presented in Fig. 5b the higher values of M factor should be taken to have the signal of value above a resultant noise level.

The presented above calculations and charts are made for $T = 300$ K. It is obvious that these parameters will change with temperature changes what results from the fact that dark current of photodiode and multiplication factor are strongly dependent on temperature.

The catalogue data include only temperature coefficient of the changes of reverse bias voltage U_R , for the constant value of multiplication factor M . The catalogue data do not comprise temperature dependencies for a dark current. On the basis of telephone consultation with the producer we have received the information that dark current of photodiode decreases by its half value with each drop in temperature of 10°C .

As the first approximation it was defined how varies the signal to noise ratio in relation to multiplication factor, in dependence on temperature and assuming that only a dark current varies with temperature but multiplication factor is of constant value.

Assuming that a dark current decreases by a half of its value for each drop in temperature of 10°C , the following temperature relationship for a dark current can be written

$$I_d(T) = (I_s + I_b M) 2^{(T-300)/10} \tag{10}$$

Substituting such a determined relationship for a dark current into the equation (8) we have:

$$\frac{S}{N}(M,T) = \frac{M^2 \cdot I_{ph}}{2qB \left[I_{ph} M^2 F(M) + (I_s + I_b M^2 F(M)) 2^{(T-300)/10} \right] + \frac{4kTB}{R_L}} \tag{11}$$

Substituting the relationship (9) into the equation (11) and taking $P = 10$ nW, the relationship of signal to noise ratio as a function of multiplication factor for various temperatures (Fig. 6) has been obtained.

In order to have a constant value of multiplication factor, the reverse bias voltage should be changed and temperature coefficient of the voltage changes is equal to 0.18 V/ $^\circ\text{C}$. Knowing the temperature coefficient of the U_R voltage changes, the characteristics of changes of multiplication factor as a function of temperature can be determined. To have a constant multiplication factor, the changes of reverse bias voltage of the C30645E photodiode as a function of temperature should be taken in the following form:

$$U(T) = U_b + 0.18 (300 - T) - U_R \tag{12}$$

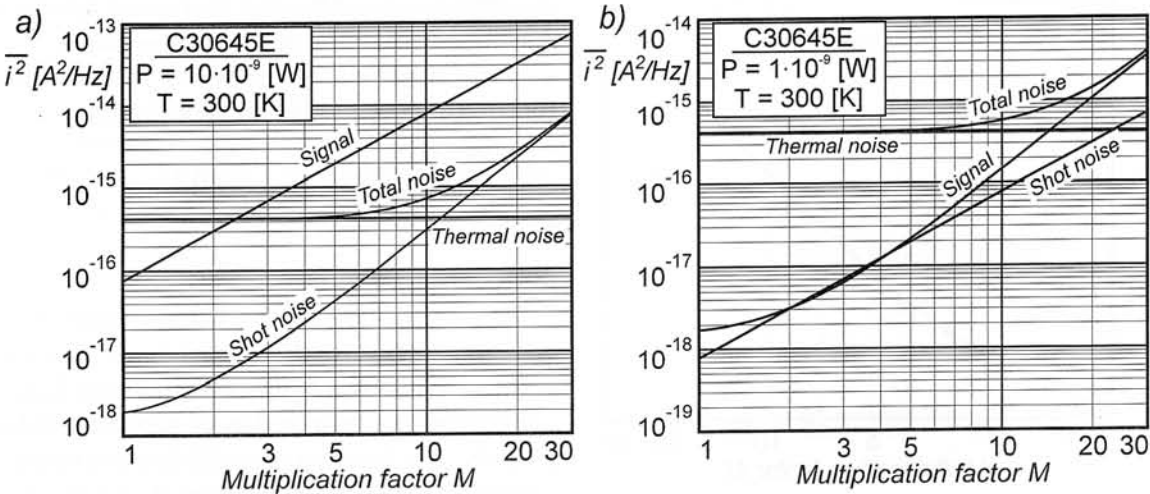


Fig. 5. Signal current, thermal noise, shot noise, and total noise of the C30645 photodiode as a function of a multiplication factor M : a) for $P = 10$ nW, b) for $P = 1$ nW.

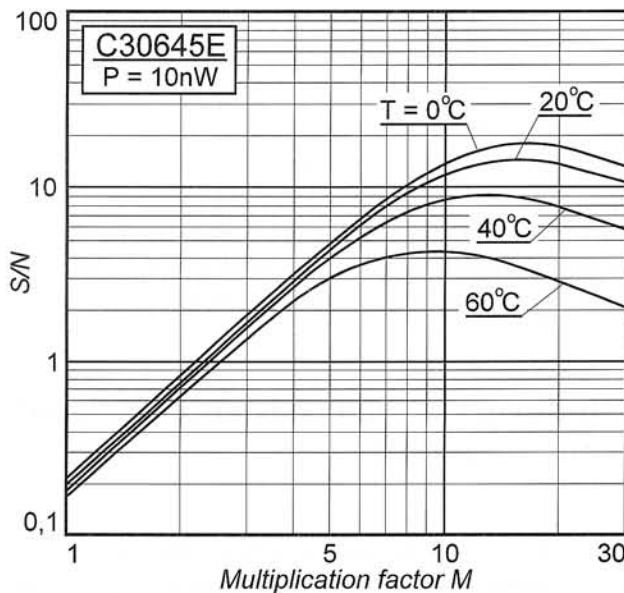


Fig. 6. Signal to noise ratio of the C30645E photodiode as a function of multiplication factor for various temperatures.

Now, substituting the value of $U(T)$, determined according to (3), into (4) we have:

$$M(U, T) = \frac{38}{73.5 + 0.18(300 - T) - U_R} \quad (13)$$

Figure 7 presents dependence of a multiplication factor as a function of reverse bias voltage for parametrically variable temperature.

In order to obtain a dependence of signal to noise ratio on reverse bias voltage for various temperatures the relationship (12) should be substituted into (10). Finally, we have:

$$\frac{S}{N}(M, T) = \frac{M^2(U, T) I_{ph}^2}{2qB \left[I_{ph} M^2(U, T) F(M(U, T)) + (I_s + I_b M_2(U, T) F(M(U, T))) 2^{(T-300)/10} \right] + \frac{4kTB}{R_L}} \quad (14)$$

The dependence of signal to noise ratio of the C30645E photodiode on the reverse bias for various temperatures, calculated according to the expression (14), is presented in Fig. 8.

Knowing the dependence of signal to noise ratio on reverse bias voltage for various temperatures and dependence of multiplication factor on such a voltage there can be drawn characteristics for the relationship between signal to noise ratio and temperature for the defined value of a multiplication factor. These characteristics are presented in Fig. 9.

One of the most important criterion for a photoreceiver design is maximal value of the signal to noise ratio. Because this ratio depends on both

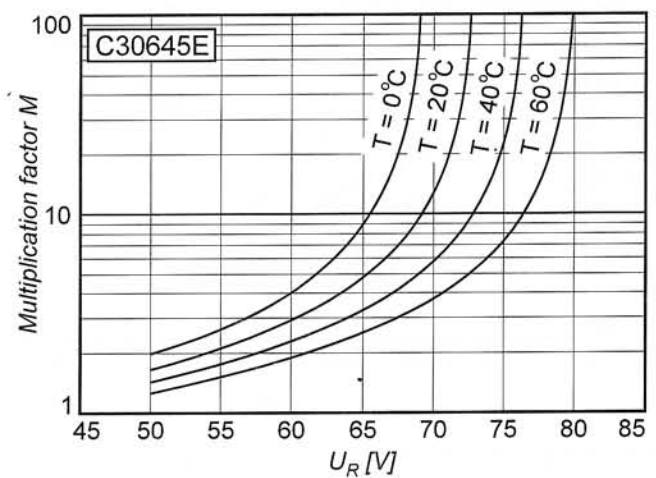


Fig. 7. Multiplication factor of the C30645E photodiode as a function of reverse bias voltage for different temperatures.

temperature and multiplication factor (which depends also on reverse bias voltage), the reverse bias voltage should be changed in such a way to obtain maximal value of signal to noise ratio for various temperatures.

In order to have a relationship for the changes of reverse bias voltage as a function of temperature for maximal signal to noise ratio, the coordinates of maxima of the courses shown in Fig. 8 have been determined. Next, the line connecting these points has been drawn. Finally, we have the course shown in Fig. 10.

3. Relationship between a power of incident radiation and optimal value of a bias voltage

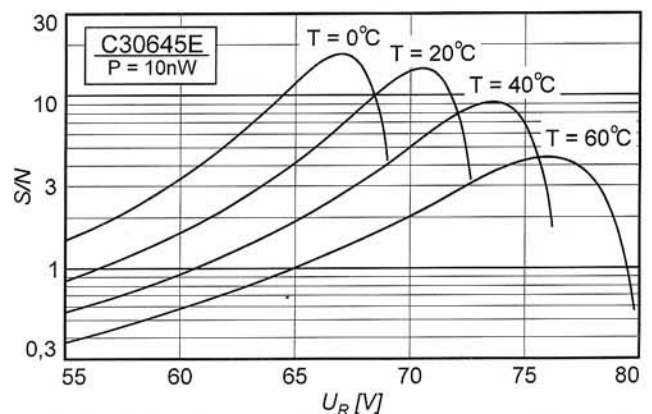


Fig. 8. Signal to noise ratio of the C30645E photodiode as a function of reverse bias for different temperatures.

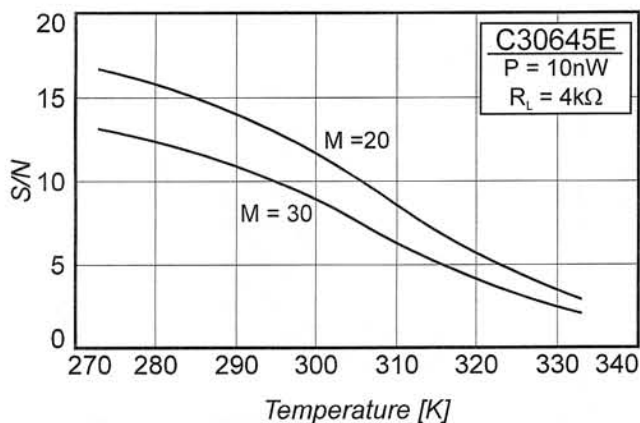


Fig. 9. Signal to noise ratio as a function of temperature for various values of multiplication factor M .

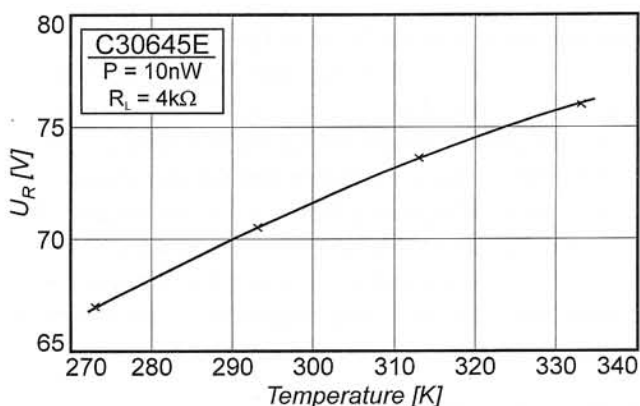


Fig. 10. Reverse bias voltage of the C30645E photodiode as a function of temperature for maximal value of signal to noise ratio.

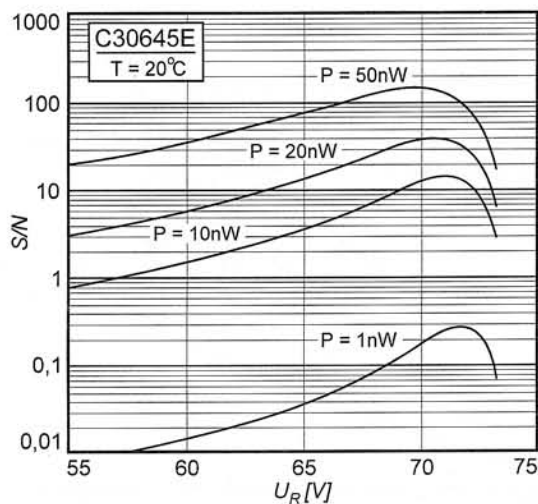


Fig. 11. Signal to noise ratio of the C30645E photodiode as a function of reverse bias voltage for various power values of incident radiation.

It results from the equation (14) that signal to noise ratio depends on the photocurrent value. The photocurrent is directly proportional to the power of radiation reaching photoreceiver (equation 9).

Figure 11 presents dependence of the signal to noise ratio on U_R voltage for several values of a power of incident radiation. As it can be seen, for the defined power of radiation, there is strictly determined the value of U_R voltage for which the signal to noise ratio is maximal.

4. Influence of load resistance on signal to noise ratio

It results from the equation (14) that signal to noise ratio depends on the load resistance R_L . Also a frequency band depends on the load resistance, according to the relationship

$$B = \frac{1}{2\pi R_L C_t} \quad (15)$$

where C_t is the resultant capacity of the input circuit. Substituting the values determined in (15) into (14) we obtain the chart shown in Fig. 12.

For the given load resistance it is exactly determined the value of reverse bias voltage for what the signal to noise ratio is maximal. When a load resistance increases the ratio is of maximal value for the lower values of U_R voltages. For the higher values of a load resistance the value of signal to noise ratio increases. In order to have maximal value of a signal to noise ratio the high values of load resistance should be taken.

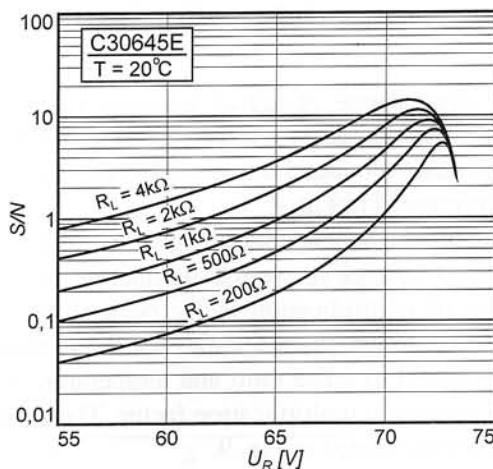


Fig. 12. Signal to noise ratio of the C30645E photodiode as a function of reverse bias voltage for various load resistance.

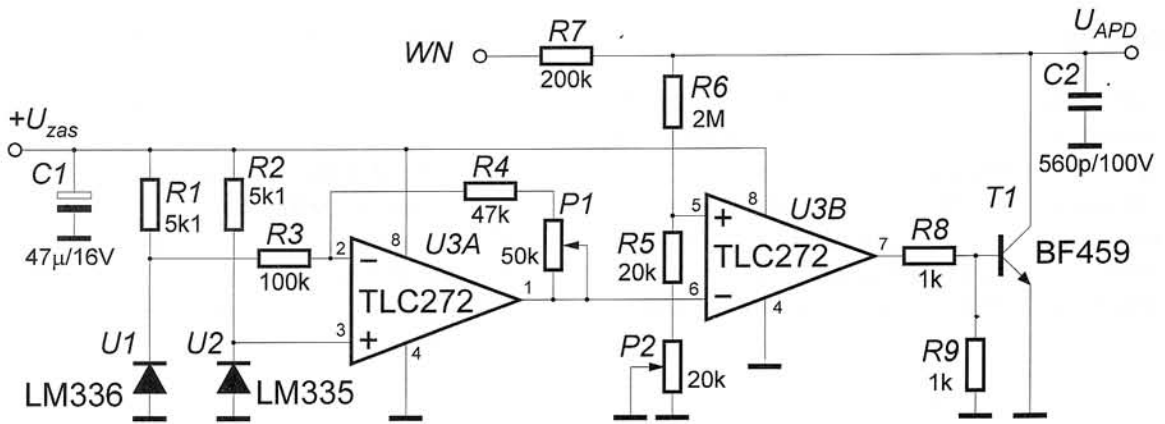


Fig. 13. Scheme of a supply voltage regulator used for an avalanche photodiode.

However, it causes narrowing of a band what should be considered at the stage of photoreceiver design.

5. Design of a system for stabilization of multiplication factor of a photodiode

As it was shown earlier an increase in photodiode temperature for a constant voltage U_R causes significant lowering of the multiplication factor, i.e., a photodiode responsivity. In order to avoid such an effect the system for stabilization of a multiplication factor has been used (Fig. 13).

It is typical example of a parallel stabilizer in which the voltage source of the LM335(U2) type was used. The temperature coefficient of this source is 10 mV/K. A reference voltage and voltage from temperature sensor were applied to the input of operating amplifier of the U3A type. The potentiometer P1 is used for control of temperature coefficient of the voltage regulator.

The voltage from the output of the U3A system was applied to the inverting input of the operating amplifier U3B.

At the non-inverting input the voltage from a divider of a resistive feedback (R5, R6) was applied. The output voltage of this amplifier controls the parallel transistor T1 (BF459). The P2 potentiometer is used for setting the supply voltage U_{APD} of an avalanche photodiode. In the load circuit of a transistor which stabilizes a supply voltage of photodiode the R7 resistor is used.

In Fig. 14, the measured values of voltages U_R , marked by crosses (x), as a function of temperature are presented for the system shown in Fig. 14. The continuous line presents theoretical course for which the signal to noise ratio is of maximal value. As it can be seen the theoretical course is consistent with the experimental one.

6. Conclusions

In order to ensure a constant value of the multiplication factor M, i.e., the constant current responsivity of a photodiode, for various temperatures, the voltage regulator of a bias voltage should be used. There exists some optimal value of M for which the signal to noise ratio is maximal. The maximal, permissible value of the signal to noise ratio depends on many factors, among others on temperature, power of incident radiation, and load resistance of detector.

For the defined temperature there exists the exactly determined value of reverse bias voltage for which the signal to noise ratio is maximal. The proposed system applied for polarization of an avalanche photodiode ensures the optimal and maximal values of signal to noise ratio within a wide range of various detector temperatures.

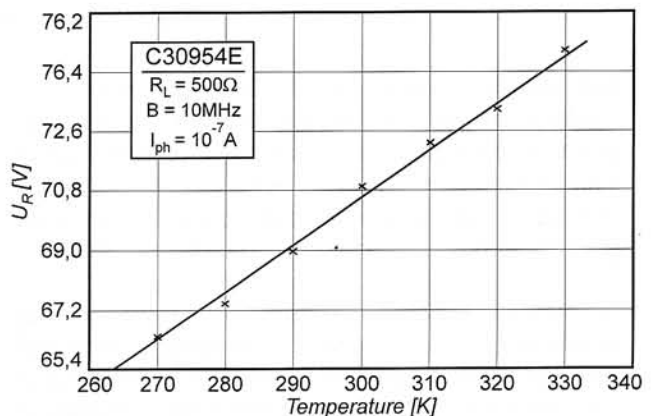


Fig. 14. Measurement results of U_R as a function of temperature and with comparison of theoretical data (continuous line).

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