Noises in Photodetectors

Ivan S. Kolev[1], Tsanko V. Karadzhov[2] Elena N. Petkova[3]

Abstract – **Noises in photodetectors (internal and external) cause a change in the form of the output signal.**

Keywords – **Noise, Photodetector, PIN Photodiode, Noise Equivalent Power.**

I. Introduction

A. Background noise

Is generated by the thermal radiation of the earth, sun, planets, moon, aurora borealis, sky, stars, earth atmosphere, vehicles, industrial sites, light sources, radiation factors of cosmic origin.

The background noise generates a noise current, which is superposed to the dark current of the photodetector – Id.

B. Thermal noise

Is caused by the chaotic thermal movement of electrons along semiconductors. It depends on temperature. Thermal noise has an even spectrum within time t. It is reduced by cooling the photodetector.

C. Shot noise

The light flux (the flux of photons) entering the photodetector input fluctuates within time thus resulting in the fluctuation of the output current signal.

The higher the level of the desired signal, the higher the shot noise. Shot noise has an even spectrum within a wide frequency range.

D. Additional noise

Is caused by the unequal structure in the volume, as well as on the semiconductor crystal surface.

E. Noises of 1/f spectral density

Are within the range of the sound frequencies**.**

Noises depend on the direct current operating point, as well as on the signal frequency.

[1]Ivan S. Kolev. Department of Electronics, Technical University – Gabrovo, Street “Hadji Dimiter” No. 4, 5300 Gabrovo, Bulgaria, phone: +359 66 801064.

[2]Tsanko V. Karadzhov. Department of Electronics, Technical University – Gabrovo, Street “Hadji Dimiter” No. 4, 5300 Gabrovo, Bulgaria, phone: +359 66 801064, e-mail: karadjov_st@abv.bg

[3]Elena N. Petkova. Department of Electronics, Technical University – Gabrovo, Street “Hadji Dimiter” No. 4, 5300 Gabrovo, Bulgaria, phone: +359 66 801064.

Noise calculations are part of the frequency analysis. The root-mean-square total in the output unit is calculated by means of the PSPICE product [10].

Today there are two quick-acting photodetectors – PIN photodiodes and avalanche photodiodes.

II. Photodiodes and PIN photodiodes

Usually shot noise I_{Ndr} is normalized towards the frequency band.

$$\frac{I_{Ndr}}{\sqrt{\Delta f}} = \sqrt{2qI_D} = 17.9\sqrt{I_D} \quad (1)$$

where: q – electron charge;

I_D – dark current.

If I_{Ndr} is entered in phemtoamperes $/\sqrt{Hz}$, then I_D is obtained in nanoamperes (1fA=10^{-15}A).

Flicker effect – photodiode noise at low frequencies.

The cut-off frequency of the Flicker effect f_{fl} does not exceed 20 Hz.

The dark current I_D consists of two components:

- leakage current
- PN-junction current

The shot noise is generated only by the PN-junction. The leakage current generates only a low thermal noise and a noise causing the Flicker effect.

If the photodiode frequency band is of $f_1 \div f_2$ ($f_2 > f_1$)

$$I_N(f_1 \div f_2) = I_{N0}\sqrt{(f_2 - f_1) + f_{fl}\ln\left(\frac{f_2}{f_1}\right)} \quad (2)$$

where: I_{N0} – noise current, standardized/normalized towards the width of the frequency band, and it is expressed by formula (1),

f_2 – upper cut-off frequency – 3 dB level

f_1 – lower cut-off frequency – 3 dB level

When the voltage in the PN-junction is 0, there is a thermal noise only in the differential resistance of the PN-junction.

$$I_{Ntherm} = \sqrt{4kT / R_{diff\,0}} = \frac{4}{\sqrt{R_{diff\,0}}} \quad (3)$$

where: K – Boltzmann’s constant

T – absolute temperature

R_{diff0} – photodiode differential resistance at zero voltage.

R_{diff} is in GΩ, I_{Nth} – fA/√Hz

The differential resistance at zero voltage is difficult to measure; however, it can be calculated by the expression:

$$R_{diff\,0} = \left(\frac{kT}{q}\right) I_0^{-1} \qquad (4)$$

$$\frac{kT}{q} \approx 0.025V = 25mV \qquad (5)$$

I_0 – reverse saturation current
kT/q – thermal potential

$$I_{Ntherm} = \sqrt{4qI_0}\, 25.3\sqrt{I_0} \qquad (6)$$

where: I_{Nth} – fa/√Hz
I_0 – nA

At zero voltage there isn't any noise due to the flicker effect. Therefore, this mode is preferred for the operation of the photodiode at low noises. There isn't any flicker noise in the $f_2 \div f_1$ frequency band.

III. TYPICAL PARAMETERS

A. Signal/noise ratio

The ratio between the photocurrent obtained upon illuminating the photodiode and the noise current in the absence of a desired signal (dark current) is

$$\frac{S}{N} = \frac{I_{ph}}{I_N} = \frac{\Phi S_\Phi}{I_N} \qquad (7)$$

$$\frac{S}{N} = \frac{EeS_\Phi}{I_N} \qquad (8)$$

Φ – light flux, lm
S_Φ – integral current sensitivity, mA(µA)/lm
Ee – illumination, lx

B. Noise Equivalent Power (NEP)

$$NEP = \frac{I_N / \sqrt{\Delta f}}{S_\Phi} \qquad (9)$$

$$NEP = EeA_\Phi \frac{U_N}{U_S}; \frac{W}{\sqrt{Hz}} \qquad (10)$$

Ee – illumination, W/m^2
A – area – m^2
NEP is proportional to $1/S_\Phi$
U_N – root-mean-square value of the noise voltage
U_S – root-mean-square value of the signal voltage
A_{ph} – area of the photodiode

The S/N ratio increases with a square root of the A_{ph} area of the photodiode, the signal increases linearly with the area, and the noise changes with a square root of the area.

$$\frac{S}{N} = \frac{A_\Phi}{\sqrt{A_\Phi}} = \sqrt{A_\Phi} \qquad (11)$$

C. Susceptibility

$$D = \frac{1}{NEP} \frac{U_S}{EeA_\Phi U_N} \qquad (12)$$

A D* parameter, referred as the "detecting" ability of the photodetector, has been used. Within it, the signal/noise ratio is standardized towards the square root of the area and illumination.

$$D^* = D\sqrt{A_\Phi} \qquad (13)$$

$$D^* = \frac{S/N}{Ee\sqrt{A_\Phi}} = \frac{S_\Phi . \sqrt{A_\Phi \Delta f}}{I_N}; cm\sqrt{Hz}W^{-1} \qquad (14)$$

$$D^* = S_\lambda \sqrt{A_\Phi \Delta f}\, I_N \qquad (15)$$

$$D^* = \sqrt{A_\Phi / NEP} \qquad (16)$$

$$I_N = \sqrt{I_N^2} \qquad (17)$$

$$D^* \equiv \lambda, f_M, \Delta f \;,\; NEP \equiv \lambda, f_M, \Delta f \qquad (18)$$

λ – wavelength
f_M – modulation frequency
I_N – root-mean-square value of the noise.

D.Noise Power

$$P_N \sim I_N^2 \sim \Delta f \qquad (19)$$

Noise power is proportional to $\sqrt{A_\Phi}$

The D* quantity is inversely proportional to the threshold power of the photodiode when the latter has an area of 1cm^2 and a frequency of 1 Hz.

If $\sqrt{A_\Phi}$ and $\sqrt{\Delta f}$ are set single values, then the $\frac{I_N}{S_\Phi}$ ratio is an illumination power where the signal/noise ratio is equal to one.

Two photodetectors have to be compared according to $\frac{I_N}{\sqrt{\Delta f}}$ rather than to I_N. The following components are included in the noise current of the photodetector:

Thermal noise (Johnson or Naiquist noise). They are determined by the thermal movement of the carriers.
root-mean-square value of the noise current
I_{ph} - photocurrent

$$I_{Ntr}^2 = 4KT.\Delta f.R \qquad (20)$$

E. Shot noise

Statistical nature of passing of the carriers through the p^+-i junction and fluctuations of the generation-recombination processes.

$$I_{Nth}^2 \approx 2q(I_{ph}+I_D)\Delta f \qquad (21)$$

F. I_N noise of 1/f spectrum

Deviation of the structure from the physical ideal form – surface recombinations and leakage; insignificant when f>10 kHz .

G. Background noise

I_{Nfon} – from the fluctuations of the radiation of the objects around the photodetector at T_{fon} temperature.

H. Photon noise

I_{Nfot} – statistical fluctuations of the photons fallen onto the photodetector. It is of quantum discrete nature.

These noises, excluding $I_{N\text{техн}}$, have an even spectrum of white (flat) noise. The photon statistics (the photon noise) responds to Poisson distribution where the root-mean-square deviation from N_Φ is equal to $\sqrt{N_\Phi}$.

N_Φ – density of the photons flow

The minimal value of the noise equivalent power when the flow is 1 photon per second

$$P_{equN}/\sqrt{\Delta f} = E_\varphi = h\nu \qquad (22)$$

where: h – Plank's constant
ν – frequency of fluctuations
E_φ – photon energy

$$E_\varphi = \frac{1.23}{\lambda} = 4.1.10^{-15} V \qquad (23)$$

λ - μm, E_φ – eV, ν – Hz

$$N_\Phi = 5.10^{15}\lambda.P_{rad} \qquad (24)$$

N_Φ, $C^{-1}cm^{-2}$

P_{rad} – density of the radiation power

При λ=0.5 μm и Δf=1 Hz $P_{\text{еквmin}}=10^{-19}$W

Such a power can be fixed by an "ideal" photodetector in heterodyne reception.

The shot noise affects the sensitivity threshold of the photodetector.

The minimum limit light flux is:

$$\Phi_{\lim} = \frac{\sqrt{2q(I_D+I_{ph})\Delta f}}{S_\lambda} \qquad (25)$$

S_λ – monochromatic sensitivity

In order to reduce the sensitivity threshold (increase the dynamic range), it is necessary to decrease the dark current I_D. However, I_D is a temperature function, therefore the photodetector should be cooled.

Signal/noise ratio of a photodiode with an amplifier.

$\frac{S}{N}$ = the power of the signal to the power of the shot noise + the power of the amplifier noise (26)

S – power of the signal

N – power of the signal + power of the amplifier noise

The shot noise has two components:

$$- I_{NS}^2 = \frac{2q[2P_{ОПТ}.q.\eta_Q]\Delta f}{h.E_\Phi} \qquad (27)$$

P_{opt} – optical power

η_Q – quantum efficiency

The quantum efficiency is equal to the number of the added electrons to the number of the falling photons.

- from the photodetector dark current

$$I_{Nd}^2 = 2q.I_d.\Delta f \qquad (28)$$

The noise of the amplifier is expressed by the John's noise over the photodiode load resistor at efficient temperature $T_{ef.}$

$$I_{NA}^2 = 4K.T_{еф}/R_L \qquad (29)$$

$$\frac{S}{N} = \frac{2[P_{opt}q.\eta_Q/h.E_\Phi]^2}{[2q.I_D + 4q(P_{opt}q.\eta_Q/h.E_\Phi) + 4KT_{eff}/R_L]\Delta f} \qquad (30)$$

The equivalent noise power

$$NEP = 4KT_{eff}.\Delta f^2(2\pi C); \Delta f = (2\pi.R_L C)^{-1} \qquad (31)$$

C – equivalent capacity

With photodiodes where C=1pF, the optimal input resistance at a frequency of 100 MHz is 10^3 Ω, and the power of the amplifier noise is 5.10^{-15}W.

If S/N=1 , the minimum optical power where the desired signal of the photodiode can be differentiated from the noise is:

$$P_{\min} = \left(\frac{h.E_\Phi}{q\eta_Q}\right) B[2nKT_{eff}.C]^{\frac{1}{2}} \qquad (32)$$

the thermal noise is:

$$I_{Nth}^2 = \left(\frac{4KT}{R}\right)\ln_2 B \qquad (33)$$

B – transmission speed

I_{n2} – Personik integral [9]

For example, with PIN photodiodes

NEP=$3.3.10^{-14}$W/√Hz

I. Detection threshold, specific susceptibility

$$D* = 3.1.10^{12}\frac{cm\sqrt{Hz}}{W} \qquad (34)$$

J. Types of sensitivity in photodiodes

- integral current sensitivity

$$S_I = \frac{\Delta I_{ph}}{\Delta\Phi(\Delta E)}; \frac{\mu A, mA}{lm(lx)} \text{ or A/W} \qquad (35)$$

- spectral (monochromatic) sensitivity – modification of the photocurrent per unit of radiant flux of the falling monochromatic radiation

$$S_{\lambda} = \frac{\Delta I_{ph}}{\Delta P(\Phi)}; A/W \qquad (36)$$

- volt integral sensitivity – the ratio between the photosignal voltage and the power of the radiation flux with a set spectral composition causing a change in the photocurrent

$$S_U = \frac{\Delta U}{\Delta P(\Phi)}; V/W$$

IV. AVALANCHE PHOTODIODES

Noises are mainly shot noises. The root-mean-square value of the noise is:

$$I_N^2 = 2q.I.\Delta f.M^X \qquad (37)$$

I – current through the avalanche photodiode

M – coefficient of avalanche multiplication

X – a number from 2 to 3

In the equivalent circuit of the avalanche diode a generator of noise I_N is included – fig. 1

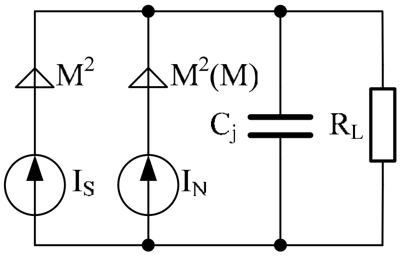

Fig. 1

With avalanche photodiodes, the signal/noise ratio depends on M. The derivative of

$$\frac{d\left(\frac{S}{N}\right)}{dM} = 0 \qquad (38)$$

has to be identified.

The minimum is at M=(50÷60)

Noise current in avalanche photodiodes

$$I_{dr}^2 = 2q\left(I_{DN} + M^2 F.I_{DM}\right)\ln_2 B \qquad (49)$$

I_{DN} – non-multiplying component of the current I_D

I_{DM} – multiplying component of the current I_D

For example, with avalanche photodiodes, NEP=2.10^{-14}W/√Hz

V. NOISES IN CHARGE COUPLED DEVICES

The noise from the dark current is known as a white or shot noise [1]. It is proportional to the thermally generated electrons, i.e. to the dark current.

$$\overline{\Delta n^2} = \sqrt{\frac{1}{q.f_T} J_g.l.w.m} \qquad (40)$$

J_g – current density

F_T – clock frequency

l, m, w – number of elements in a cell.

With these devices, the NEE parameter, Noise Equivalent Exposure, is defined. For example, NEE=$0.2.10^{-3}$μJ/cm^2

V. NOISES IN PYROELECTRICELEMENTS

The noise response– (μV) in the time function (min) (band filter 0.5÷5 Hz) of the pyroelectric element RPY 100 of Philips is given in fig. 2. The voltage, peak to peak, of the same pyroelectric element is (20÷45) μV

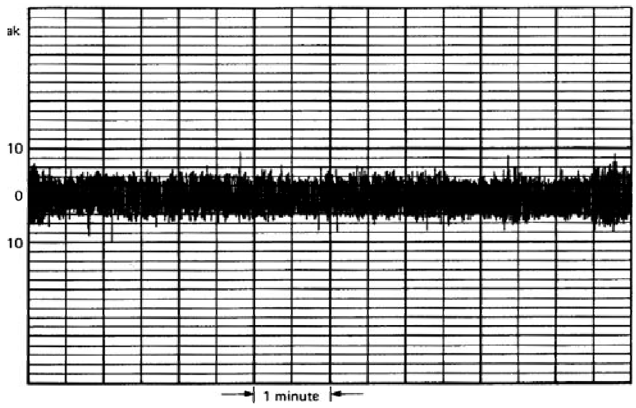

Fig. 2

VI. CONCLUSIONS

The consideration of noises in photodetectors and the reduction of their influence on their operation improve the parameters and function of the optoelectronic devices using photodetectors.

REFERENCES

[1] Atanasov, A. S. CCD – Application. Sofia, Technics, 1988.

[2] Velchev, N. B. Fundament of optoelectronics. Plovdiv, University's Publication, Plovdiv, 2002.

[3] Fiber optical communication. Devices, Circuits and Systems, Radio and Communication, 1982.

[4] Kolev, I. S. Optoelectronics. Gabrovo, Technical University, University Publication. "V. Aprilov", 2004.

[5] Kolev, I. S. Infrared optoelectronics. Gabrovo, Technical University, University Publication. "V. Aprilov", 2004..

[6] Nosov, U. R. Optoelectronics. M. Radio and Communication, 1989.

[7] Application of optoelectronic devices. M. Radio and Communication, 1981.

[8] Takov, T. B. и V. S. Minchev. Semiconductor Sensors. Sofia, Technics, 1986.

[9] Optical communication Technics. Photodetectors. Moskva, Mir, 1988.

[10] Shoikova, E. and other. Analysis and design with PSPICE. Technical University - Sofia, 2000.