THE TRANSIMPEDANCE AMPLIFIER NOISE OPTIMIZATION FOR THE ATMOSPHERIC OPTICAL LINK RECEIVER

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Abstract

This paper deals with design of wideband low-noise preamplifier of atmospheric optical link receiver. Sources of noise and the noise models for the PIN photodiode coupled to a transimpedance amplifier are described here. This paper presents the way of optimization the signal to noise ratio at the required frequency range

Keywords:

Atmospheric optical link receiver, transimpedance amplifier, PIN photodiode equivalent circuits, the wideband low-noise preamplifier.

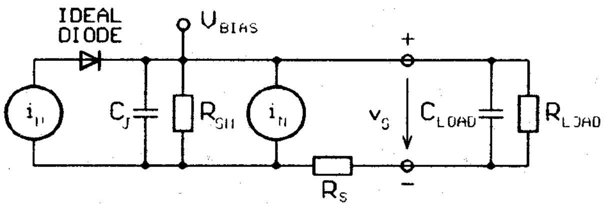
1. Introduction

The atmospheric directional optical links [3] are suitable to transmit data over distance ranging from several hundred meters up to a couple of kilometres. Data from LAN are converted into light impulses using high speed LED or semiconductor laser. After directed transmission via the atmosphere, an optical receivers detect the light flashes and converts them back into electric signal. Avalanche or PIN photodiodes are suitable as transducers.

The essential demands placed on the receiving circuit are both high sensitivity and high dynamic range. The fluctuations in attenuation in the atmosphere and the system reserve for their compensation are the reason for this. The attenuation is caused by fog, rain or snow. The receiving sensitivity of simple receivers is between -30 and -40 dBm average optical input power at a data rate of 10 MBit/s and a bit error rate of 10^{-9}.

2. Photodiode equivalent circuits

The electrical equivalent circuit for N-type PIN detectors is shown in figure 1. The flow of photocurrent is in a direction so as to develop a load voltage which will forward bias the ideal diode. It is the development of this forward voltage across the ideal diode which determines the high power limit for linear response. Application of a voltage in the reverse direction across the ideal diode will extend the high power limit for linear response. The response linearity is described as the change of current in detector output versus the change in incident light power.



C_J = Junction Capacitance
R_{SH} = Shunt Resistance
R_S = Serial Resistance
i_P = Photocurrent Generator
i_N = Noise Current Generator
V_S = Signal Voltage

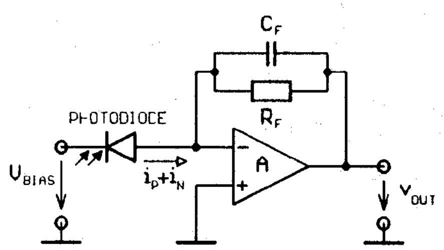
Fig. 1 N-type photodiode

Junction capacitance, in conjunction with load impedance and series resistance, can produce a system RC time constant, that will be in excess of the photodiode charge collection time. The junction capacitance increases with an increase in active area of photodiode and decreases with increasing bias voltage. Series resistance ($50\Omega > R_S > 150\Omega$) [5] is an important parameter to consider in high frequency applications. Limiting factor in this case is the RC time constant. If $C_{LOAD} \ll C_J$, the time constant is equal C_J multiplied by $(R_S + R_{LOAD})$ because practically $R_{SH} \gg (R_S + R_{LOAD})$. The series resistance decreases with increasing bias voltage. The shunt resistance is dynamic resistance of a p-n junction when PIN diode operates with no external bias voltage - photovoltalic mode. If the bias voltage is connected and a p-n junction operates in the reverse mode - photoconductive mode, then theoretically $R_{SH} \to \infty$. The signal voltage at the output of the photodiode is

$$V_s(f) = \frac{R_{LOAD} I_P}{1 + j2\pi(R_S C_J + R_{LOAD} C_J + R_{LOAD} C_{LOAD}) - 4\pi^2 f^2 R_{LOAD} R_S C_{LOAD} C_J} \qquad (1)$$

3. Photodiode - Transimpedance Amplifier

The operational amplifier, when used as a current to voltage converter (fig. 2), creates a unique solution to the linearity limitations imposed on photodiodes by terminating load impedance.



C_F = Feedback capacitance
R_F = Feedback resistance

Fig. 2 Operation amplifier in transimpedance connection

In this transimpedance configuration, the photodiode views a load impedance as shown in the following equation

$$|Z_A(f)| = \frac{R_F}{(A+1)\cdot\left[1 + (2\pi f R_F C_F)^2\right]^{1/2}} \qquad (2)$$

This equation shows that at low frequencies the photodiode load impedance is very low but increases with increasing frequency.

4. Photodiode and Transimpedance Amplifier Noise Charactericties

The various noise sources which contribute to the total output noise voltage of a photodiode / transimedance amplifier combination are shown in figure 3. The noise current generated by a PIN diode is a combination of shot noise and thermal (Johnson) noise.

4.2 Shot Noise

Shot noise is generated by current flowing through the device This current may be either the dark current (when no light is incident upon the photodiode) or the photocurrent. The predominant shot noise generator is dark current. The spectrum power density of shot noise can by calculated by the formula [1]

$$N_{iq} = q i_0 \qquad (3)$$

where q = Electronic charge (1,6· 10-19 C), i_0 = Dark current.

The RMS shot-noise current in the noise equivalent bandwidth Δf is given by

$$i_q = \left(2 N_{iq} \Delta f\right)^{1/2} \qquad (4)$$

4.2 Thermal (Johnson) noise

The thermal noise contribution is provided by the series resistance, amplifier input resistance and feedback resistance. Because $R_S \ll R_{SH}$, the spectrum power density of thermal noise is equal to

$$N_{it} = \frac{2kT}{R} \qquad (5)$$

where k = Boltzmann's constant (1.38·10-23 J/K), T = absolute temperature and

$$R = \left(\frac{1}{R_{SH}} + \frac{1}{R_A} + \frac{1}{R_F}\right)^{-1} \qquad (6)$$

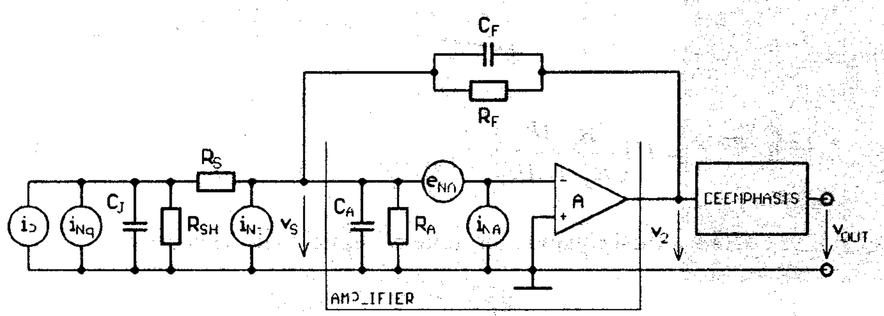
4.3 Intrinsic amplifier noise

It is represented by amplifier input noise current i_{NA} and amplifier input noise voltage e_{NA}. The corresponding spectrum power densities are N_{iA} and N_{eA}. The general rules for determining i_{NA} and e_{NA} are discussed in [3] and [4]. In applications involving large area photodiodes, the amplifier input noise voltage generator is the major contributor to the total output noise voltage. Therefore, selecting semiconductor devices these have a minimum value of input noise voltage is important for input circuit.

5. Frequency Response Characteristics

The necessary frequency range Df for digital transmission up to 16 MBit/s (Ethernet, Token-Ring) is approximately from 500 kHz to 45 MHz. In this case, the impact serial resistance on a frequency response of circuit is imponderable. We can consider that $R_S = 0$. The magnitude of output voltage is given by

$$\left|V_{OUT}(f)\right| = \frac{\left|I_P(f)\right| R_F R A}{\left[(C + AC_F)^2 4\pi^2 f^2 R_F^2 R^2 + (R_F + AR)^2\right]^{1/2}} \quad (7)$$



i_{Nq} = Shot noise current
i_{NI} = Johnson noise current
i_{NA} = Amplifier input noise current
e_{NA} = Amplifier input noise voltage
C_A = Amplifier input capacitance
R_A = Amplifier input resistance
A = Noiseless amplifier

Fig 3. Photodiode / transimpedance amplifier noise model

Hence, the maximum frequency f_{MAX} at the amplifier output is

$$f_{MAX} = \frac{1}{2\pi} \cdot \frac{R_F + AR}{R_F R (C + AC_F)} \approx \Delta f \quad (8)$$

6. Signal to Noise Ratio

The equation for determining transfer impedance $Z_A(f)$ is

$$Z_A(f) = \frac{V_2^I(f)}{I(f)}$$

$$= \frac{R_F R A}{R_F + AR} \cdot \frac{1}{1 + j2\pi f \dfrac{R_F R (C + AC_F)}{R_F + AR}} \quad (9)$$

where $C = C_J + C_A + C_F$ and I is a Fourier transform of input current $i = i_P + i_{Nq} + i_{NI} + i_{NA}$. The superscripts I respectively E (see further) agree with exciting currents respectively voltage. The frequency response must be constant at all frequency range Δf. If condition $\Delta f > (R_F + AR)/(2\pi R_F R (C + AC_F))$ is there accomplished, then the frequency response characteristics must be compensated by frequency dependent gain or by the deemphasis circuits. The transfer impedance Z_{OUT} will be

$$Z_{OUT} = \frac{V_{OUT}^I(f)}{I(f)} = \frac{R_F R A}{R_F + AR} \quad (10)$$

The noise power at the deemphasis circuit output equals to the dispersion σ_V^2 of random quantity of output voltage [1]. The noise sources create output voltage dispersion by

$$\sigma_V^{I2} = \int_{-\Delta f}^{\Delta f} \left|Z_{OUT}\right|^2 \left(N_{iq} + N_{iI} + N_{iA}\right) df$$

$$= 2\Delta f \left(\frac{R_F R A}{R_F + AR}\right)^2 \left(N_{iq} + N_{iI} + N_{iA}\right) \quad (11)$$

The transfer noise voltage e_{NA} at an amplifier output is

$$\frac{V_2^E(f)}{E_{NA}(f)} = K_A(f)$$

$$= \frac{R_F A (1 + j2\pi RC)}{R_F + AR} \cdot \frac{1}{1 + j2\pi f \dfrac{R_F R (C + AC_F)}{R_F + AR}} \quad (12)$$

Owing to a frequency compensation the transfer function K_{OUT} will be

$$\frac{V_{OUT}^{B}(f)}{E_{NA}(f)} = K_{OUT}(f) = \frac{R_F A(1 + j2\pi fRC)}{R_F + AR} \qquad (13)$$

The output voltage dispersion will be computed according to the following equation

$$\sigma_V^{B2} = \int_{-\Delta f}^{\Delta f} |K_{OUT}(f)|^2 N_{eA} df = 2N_{eA}\Delta f \left(\frac{R_F AR}{R_F + AR}\right)^2 \cdot \left(\frac{4\pi^2 C^2 (\Delta f)^2}{3} + \frac{1}{R}\right) \qquad (14)$$

The signal norm power at the output is

$$P_S = \left| 2\pi \int_{-\infty}^{\infty} Z_A(f) I_P(f) e^{j2\pi ft} df \right| = i_P^2 \left(\frac{R_F AR}{R_F + AR}\right)^2 \qquad (15)$$

With consideration to (9), (12) and (13), we obtain a final equation for ratio of signal to noise powers

$$\frac{P_S}{P_N} = \frac{P_S}{\sigma_V^{I2} + \sigma_V^{B2}} = \frac{i_P^2}{2\Delta f} \frac{1}{qi_P + \frac{2kT}{R} + N_{iA} + N_{eA}\left(\frac{4\pi^2 C^2 (\Delta f)^2}{3} + \frac{1}{R}\right)} \qquad (16)$$

This result shows, that a parallel connection of resistances R_A, R_F and R_{SH} must be maximized and sum of capacitances $C_A + C_F + C_J$ minimized for reaching maximum signal to noise ratio at the bandwidth Δf. The noise sources must produce minimal noise power. This ratio is independent on gain A.

7. Conclusion

Theoretical background for orientation at noise and frequency properties of optical preamplifier has been explained. The above results have been practically used by 10 MBit/s rate optical receiver design. Accomplished results will be presented in following papers.

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Aleš PROKEŠ was born in Znojmo, Czech republic, in 1963. He recived the M.S. degree in Electrical ngineering from the Faculty of Electrical Engineering, Technical university of Brno, in 1988. At present he is a PhD student supervised by Prof. Vladimír Šebesta at the Institute of Radioelectronics, , Technical university of Brno. He is interested in signal processing and optical communications.