Sensitivity of avalanche-photodiode opticalreceivers for avalanche gain

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Abstract

Closed-form expressions are obtained for the reduction in the signal-to-noise ratio of an optical receiver utilizing an avalanche photodiode (apd) due to non-optimal avalanche gain. An avalanche gain of double the optimal value leads to a reduction in the SNR of 1.5dB for Ge-Photodiodes and less than 0.8dB for Si units. The penalty of fixing the avalanche gain, when the received power level changes by 6dB, amounts to less than 1dB. Sensitivity analysis can be used to determine the excess factor of an APD suing relative power measurements.

Introduction

Extensive studies have been made for optical receivers utilizing avalanche photodiodes (APD) [1-8]. An APD increases the receiver sensitivity. But due to the excess noise resulting from the avalanche process, there is an optimum value of gain that maximizes sensitivity [3].

A comparison of avalanche photodiodes and PIN photodiodes has been made [4, 5]. Experimental results of the noise properties have been reported [6, 7].

In these studies optimal avalanche gain was considered. The sensitivity of an optical receiver to achieve an error rate of 10^{-9} as a function of the avalanche gain was reported [8].

Here we consider the effect of non-optimal gain on the performance of an optical receiver. The analysis is applied for experimental determination of the excess noise factor of an APD using relative power measurements.

Sensitivity analysis

An optical receiver utilizing an APD is considered.

Taking into account the different noise contributions, the signal-to-noise ratio (SNR) is given by

$$SNR = \frac{S^2P^2M^2}{2eBM^2F(SP+I_d)+N_a} \qquad \ldots\ldots (1)$$

where
- P = optical power
- M = avalanche gain
- S = photodetector unity gain responsivity (A/W)
- e = electron charge
- B = bandwidth
- I_d = detector dark current due to bulk leakage
- N_a = mean square noise current due to amplifier
- N_a = mean square noise current due to amplifier noise and surface leakage

F is the excess noise factor which MacIntyre gives as

$$F = KM+(1-K)\left(2-\frac{1}{M}\right)$$

where K is the inonization-rate ratio.

A useful practical approximation for F, when $M >> 1$, is

$F = M^x$, with $x < 1$.
$x = 1$ for Ge photodiodes, and
$x \simeq 0.3\text{-}0.5$ for Si photodiodes.

Optimizing the value of M in equation (1), one gets

$$N_a = xeB(SP+I_d)M_{opt}^{2+x} \qquad \ldots\ldots (2)$$

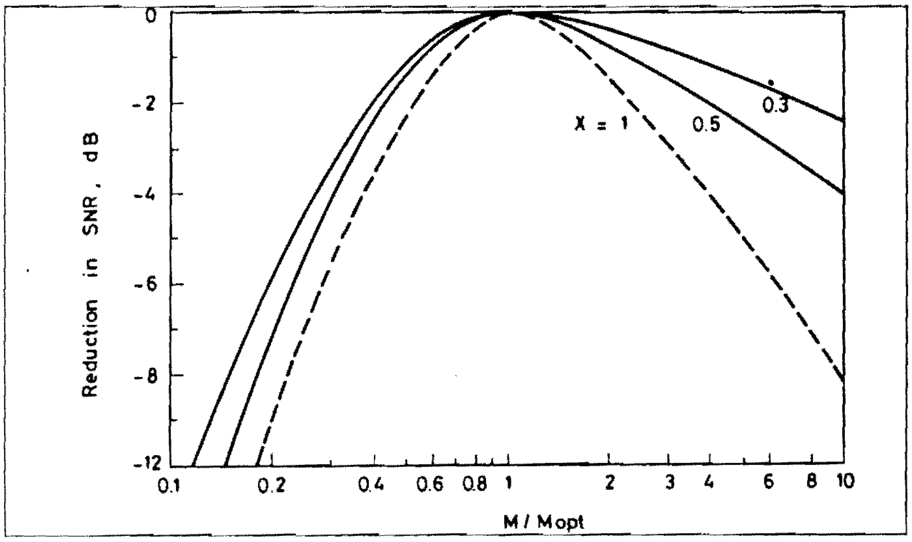

Fig. 1 The dependence of the reduction in the SNR on the relative avalanche gain ratio

Two related cases are of interest:

Varying (non-optimal) avalanche gain

For a given received optical power, the avalanche gain may value. This may occur due to imperfect temperature compensation or drift in the bias supply of the APD. Consequently, the SNR would be reduced. From Equations (1) and (2), the reduction in the SNR due to non-optimal avalanche gain may be expressed as

$$\frac{SNR}{SNR|_{M_{opt}}} = \frac{(M/M_{opt})^2(1+x/2)}{(M/M_{op})^2+x+\frac{x}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Figure 1 shows that an avalanche gain of double the optimal value leads to a reduction in the SNR of only 1.5dB for Ge photodiodes and less than 0.8dB for Si units. Thus a simpler control circuitry can be used with an APD at the expense of only a small penalty in the receiver sensitivity.

Varying received signal and fixed (non-optimal) avalanche gain

When the received optical power is varying, optimal conditions are achieved with continuous adjustment of the avalanche gain. However, the avalanche gain may be optimized at certain received power level P_1 and kept fixed at this value. If the received power level changes to P_2, the SNR obtained with the gain fixed will be less than the maximum achievable SNR if optimum gain was employed. The reduction penalty in the SNR due to fixing the gain can be expressed, using equations (2) and (3), as

$$\frac{SNR}{SNR|_{opt}} = \frac{(1+\frac{x}{2})(1+b)^{\frac{x}{2+x}}(\frac{P_2}{P_1}+b)^{\frac{x}{2+x}}}{\frac{P_2}{P_1}+b+\frac{x}{2}(1+b)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where $b = I_d/SP_1$

Dif. 2 shows that the reduction penalty amounts to less than 1dB when the received power level changes by 6dB while the gain is kept fixed. Furthermore, for an APD having a large dark current the receiver is less sensitive to signal changes. It should be noted that the change in the SNR, when the received signal changes from P_1 to P_2 while the gain is fixed (optimized at P_1), may be expressed using equations (1) and (2) as

$$\frac{SNR|_{at\,P_2}}{SNR|_{at\,P_1}} = \left(\frac{P_2}{P_1}\right)^2 \frac{(1+b)(1+\frac{x}{2})}{\frac{P_2}{P_1}+b+\frac{x}{2}(1+b)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

It depends on the relative change of power and on x and b.

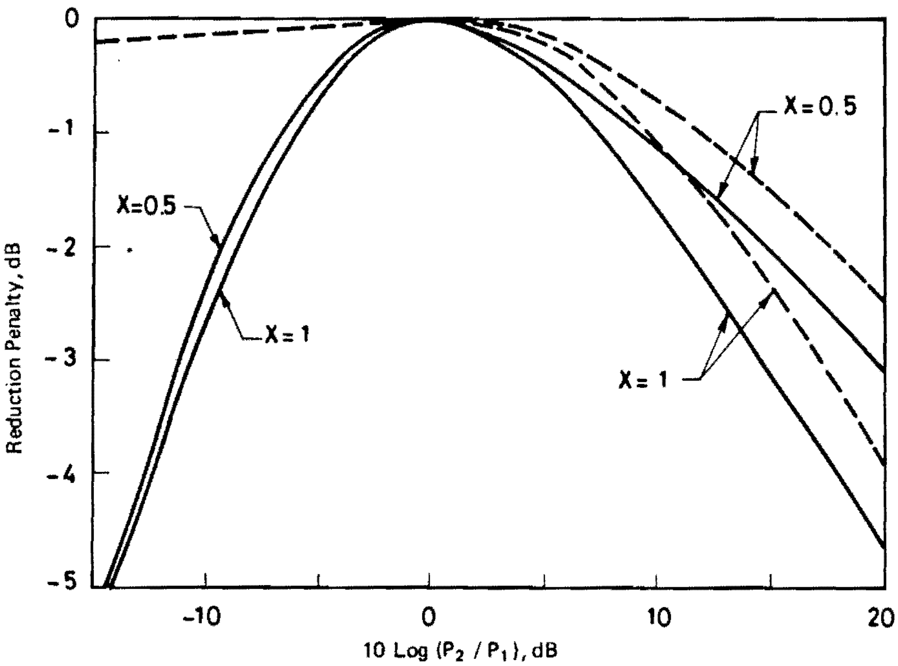

Fig. 2 The reduction penalty in the SNR due to fixed (non-optimal) avalanche gain. (Solid lines b = 0, dashed lines b = 1)

Determination of excess-noise Factor

Fig. 3 shows an experimental arrangement to determine the exponent x of the excess-noise factor of an APD. By varying the applied bias voltage, the multiplication factor M is optimized at a certain power level P_1. M is then kept fixed. The optical power is reduced to its half-value—e.g., using a polarizer oriented by 45°.

The SNR in both cases is obtained from the measured bit-error rate, P_e, assuming Gaussian statics, according to [9, 10].

$$P_e = \frac{1}{2}\left[\mathrm{erfc}\frac{1}{2}\sqrt{SNR/2}\right] \ldots (6)$$

Then equation (5) gives

$$x = (1-2R\beta)/(2R-0.5) \ldots (7)$$

where $R = SNR_2/SNR_1$ is the reduction in the SNR, and

$$\beta = \frac{1+2b}{1+b} = \frac{SP_1+2I_d}{SP_1+I_d}$$

Fig. 4 shows the dependence of the reduction in the SNR on x. For example, a reduction in the SNR of 3.68dB results with a Si APD of x=0.4, when $SP_1 >> I_d$. It is to be noted that no absolute power measurement is needed as long as the APD dark-current is small.

Conclusions

The optimization of the avalanche gain of an APD is not very critical for the performance of an optical receiver. A simpler control circuitry of the bias supply may be used with an APD at the expense of a small penalty in the receiver sensitivity. In situations where the received signal level is varying, a fixed avalanche gain may still be used at the expense of a small reduction penalty in the SNR.

The sensitivity analysis can be applied to determine the excess noise factor of an APD, using a simple experimental arrangement and relative power measurements.

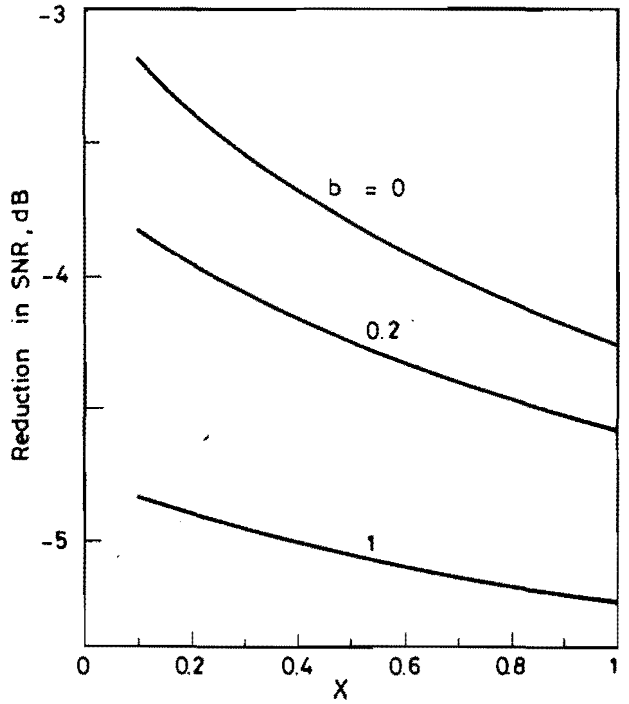

Fig. 4 The reduction in SNR, when the received power is reduced to its half-value, as a function of X.

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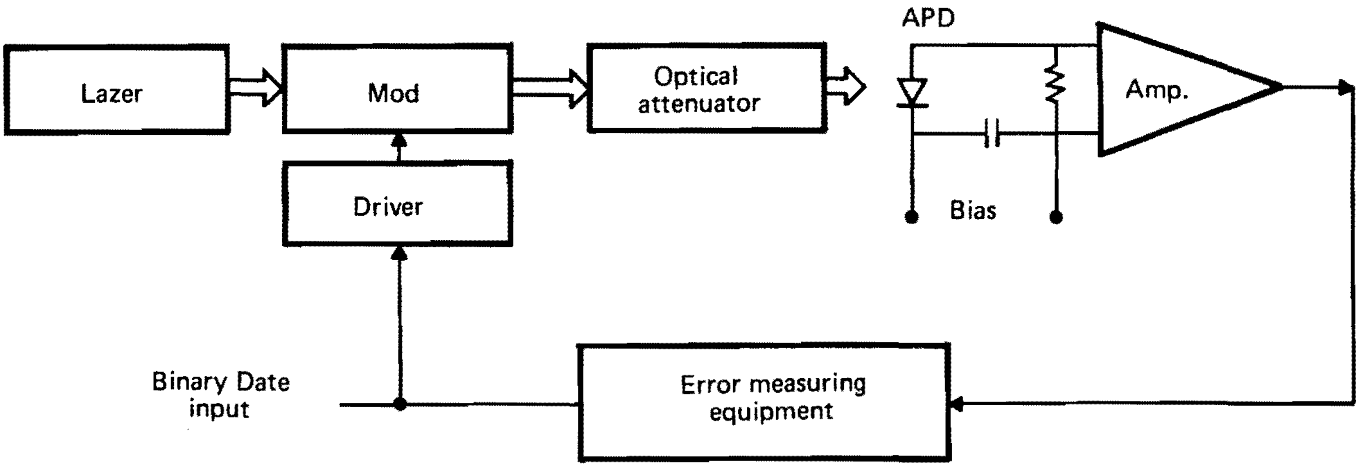

Fig. 3 Experimental set-up