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HETERODYNE OPERATION OF AVALANCHE PHOTODIODES

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SUMMARY

The effect of combining avalanche and heterodyne operations in a microwave photodiode is analyzed. The results show that, if $I_{P(o)}$, the d.c. photo current in the absence of multiplication, is below a critical value $I_{P(crit.)}$, the system S/N ratio increased with multiplication up to $M = M_{opt}$.

Conversely, when $I_{P(o)} > I_{P(crit.)}$, multiplication will always cause the S/N ratio to decrease.

Compared to the case of simple heterodyne operation (M = 1), the condition $M = M_{opt}$ for $I_{P(o)} < I_{P(crit.)}$ in silicon photodiodes can yield large reductions in local oscillator (laser) power and diode dissipation without excessive degradation in noise-equivalent-power.

INTRODUCTION

Avalanche operation of p-n junction microwave photodiodes is known to offer substantial improvement in detector performance (ref. 1). However, the realization of the advantages of this mode of operation, such as increased sensitivity and S/N ratio, depends on a rather critical choice of physical and operational parameters of the detector. Therefore it is not clear a priori whether and under what conditions an avalanche operation could be made to yield analogous improvements in heterodyne optical detection, which requires the accommodation of additional parameters.

Therefore the objective of this technical report is to analyze such heterodyne optical detection in microwave photodiodes operating under avalanching conditions. The possibility of operating in this combined mode has also been proposed independently by Emmons.* Oliver's development (ref. 2) of the S/N ratio of a heterodyne photodiode in which only shot noise

*Formerly with Philco Corp., now with Sylvania, Mountain View, California, private communication.

associated with the signal and local oscillator radiation need be considered is traced in this report, and the analysis of this simple system is expanded to include the effect of avalanche multiplication. This treatment is then generalized by incorporating the effects of junction capacitance, and diode and load resistance, explicitly including the noise figure of the following amplifier.

This analysis yields definitions of the conditions under which the avalanching mode provides superior performance and establishes some of its limitations.

The analysis is applicable to junction detectors made from a wide variety of semiconductor materials. Examples are worked out for silicon and germanium devices for system bandwidths of 2 GH_Z. The results may be interpreted in terms of device requirements and thus may serve as a guide to the design of photodetectors optimally suited for this combined avalanche-heterodyne mode.

HETERODYNE DETECTION

Consideration of Shot Noise Only

The circuit appropriate to Oliver's analysis is shown in Figure 1(a). In this figure $\overline{i_s^2}$ is the mean-square signal current, and $\overline{i_n^2}$ the mean-square noise current arising from signal and local oscillator (laser) optical excitation.

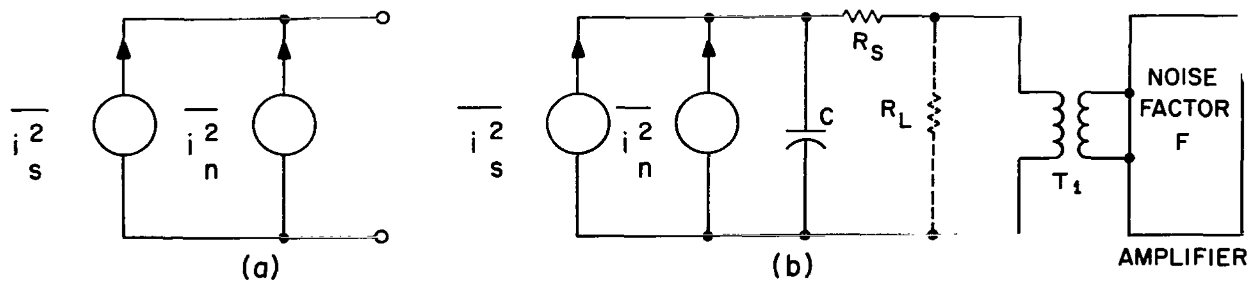

FIGURE 1

Oliver's equations for $\overline{i_s^2}$ and $\overline{i_n^2}$ and the signal-to-noise ratio are:

$$\overline{i_s^2} = 2\left(\frac{\eta q}{h\nu}\right)^2 P_o P_s \qquad (1)$$

$$\overline{i_n^2} = \frac{2\eta q^2 B}{h\nu}\left(P_o + P_s\right) \tag{2}$$

$$S/N = \frac{\eta P_s}{h\nu B}\left(\frac{1}{1 + \frac{P_s}{P_o}}\right) \tag{3}$$

where η is the quantum efficiency of the detector, q the electronic charge, h Planck's constant, ν the optical carrier frequency, B the signal bandwidth, and P_s and P_o the signal and local oscillator incident powers. For $P_o \gg P_s$. Equation (3) then becomes:

$$S/N = \frac{\eta Ps}{h\nu B} \equiv (S/N)_I \tag{4}$$

which represents the case of sufficient local oscillator power for the detection to approach the ideal limit which is established by quantum fluctuations in the input signal.

For microwave-frequency photodiodes, the transit time of photogenerated electrons and holes crossing the junction must also be considered. This is done by multiplying the signal and noise currents [Equations (1) and (2)] by reduction factors which depend on junction field width, the velocity of the carriers in the field, and the origin of the carriers (ref. 3). With avalanche operation, the transit time reduction factors will also depend on multiplication because of the finite, although short, time taken by the multiplication process. Also, both the signal and noise current expressions will be multiplied by some function of M, the multiplication factor (M as used here is defined as the ratio of the external diode current in the presence of multiplication to the diode external current with the diode voltage slightly below that required for multiplication). For the signal equation, the function is found to be M^2, while for the noise equation the function is M^x where for a given photodiode x will usually have a value between 2 and 3 with the specific value dependent on the relative role of the electrons and holes in initiating the multiplication process (refs. 4 and 5). With these inclusions, Equations (1) through (3) for the avalanche microwave photodetector become:

$$\overline{i_s^2} = 2\left(\frac{\eta q}{h\nu}\right)^2 P_o \; P_s \, M^2 \, F_s(\omega, M) \tag{1a}$$

$$\overline{i_n^2} = \frac{2\eta q^2 B}{h\nu} (P_o + P_s) \, M^x \, F_n(\omega, M) \tag{2a}$$

$$S/N = (S/N)_I \left(\frac{1}{1 + \frac{P_s}{P_o}} \right) \frac{F_s(\omega, M)}{F_n(\omega, M)\ M^{x-2}} \qquad (3a)$$

where $F_s(\omega, M)$ and $F_n(\omega, M)$ are the signal and noise transit-time reduction factors, respectively.

Equation (2a) can be fitted with x = 2.5 for the best silicon photodetectors reported, and x = 3 for germanium ones (ref. 6). To a reasonable approximation, $F_s(\omega, M)$ and $F_n(\omega, M)$ can be assumed to be equal* and cancel each other in Equation (3a). Since $x \geq 2$, Equation (3a) shows that avalanche ($M > 1$) operation of a photodiode will never allow the S/N ratio to approach $(S/N)_I$, regardless of other diode details and the noise properties of any ancillary amplifier. However, at this point whether or not avalanche operation of a heterodyne photodiode offers practical advantages cannot be determined. To answer the question, a practical detection system must first be considered.

Inclusion of Additional Noise Sources

The schematic diagram of a practical optical superheterodyne receiver is shown in Figure 1b. The analysis is now extended to include the effects of the diode series resistance R_S, the diode junction capacitance C, the detector load R_L, the noise factor F of the following amplifier, and avalanche multiplication.** The overall signal-to-noise ratio for a practical diode and amplifier will be developed in such a way as to allow its comparison with the ideal case represented by Equation (4), and showing the dependence on avalanche gain and other pertinent parameters. Transformer T_1 transforms the amplifier impedance to the value R_L at the diode terminals. The transformer may take the form of a tapered coaxial line for broadband matching.

The noise sources, which must be considered in addition to shot noise [equation (2a)], are the thermal noise from R_s and the amplifier noise. Identifying $q\eta M P_o/h\nu$ as I_P, the d.c. diode current (the multiplied current caused by the local oscillator), and recognizing $(\omega C R_s)^{-1}$ as the usual definition of diode Q, then the overall signal-to-noise ratio for $P_o \gg P_s$ is:

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*L. K. Anderson, Bell Telephone Laboratories, Murray Hill, N. J., private communication.

**Figure 1(b) is not generally applicable to avalanche photodiodes. Melchoir and Lynch (ref. 6) have shown that one must also include a current-and-frequency-dependent admittance $Y(\omega)$ across the current generators and a space-charge layer resistance R_c between the generators and the transition-region capacitance C. However, for the diode and operating conditions assumed in the examples, $Y(\omega)$ and R_c may be neglected.

$$S/N = \frac{(S/N)_I \dfrac{F_s(\omega, M)}{F_n(\omega, M)\, M^{x-2}}}{1 + \dfrac{2kT\ FH}{qI_P R_L M^{x-1} F_n(\omega, M)}} \tag{5}$$

where k is Boltzmann's constant, T the absolute temperature, and

$$H \equiv 1 + \frac{1}{Q^2} \left\{ \left(1 + \frac{R_L}{R_s}\right)^2 + \frac{R_L}{FR_s} \right\} . \tag{6}$$

As previously mentioned, the ratio of the transit-time factors can be considered as unity. Moreover, with a properly designed avalanche photodiode, they should be approximately unity in value for modest values of M and gain-bandwidth products below 60 to 100 GHz (ref. 1). Since we will restrict M to 50 or less, and the gain-bandwidth product to 40 to 100 GHz, Equation (5) may be simplified to

$$S/N = \frac{\dfrac{(S/N)_I}{M^{x-2}}}{1 + \dfrac{2kT\ FH}{qI_P R_L M^{x-1}}} . \tag{5a}$$

This is the key equation describing the overall system behavior of either an avalanche or non-avalanche heterodyne photodiode.

With M = 1, i.e., no multiplication, the d.c. diode current required for S/N to be within 3 dB of $(S/N)_I$ is

$$I_{P(0)}\Big|_{3\ dB} = 2kTFH/qR_L . \tag{7}$$

It is easy to show from Equation (5a) that if $I_{P(0)}$, the d.c. diode current in the absence of multiplication, is less than a critical value $I_{P(crit.)}$, then the system S/N ratio will initially increase with multiplication and reach a maximum for a particular value of multiplication $M_{opt.}$:

$$I_{P(crit.)} = 2kTFH/qR_L(x-2) \tag{8}$$

$$M_{opt.}\Big|_{I_P} = \left(I_{P(crit.)}/I_P\right)^{\frac{1}{x-1}} \tag{9}$$

Conversely, for $I_{P(0)} > I_{P(crit.)}$, avalanche multiplication will always decrease the S/N ratio. In the former case, and with $M = M_{opt.}$,

$$(S/N)/(S/N)_I = \frac{1}{x-1}\left(I_P/I_{P(crit.)}\right)^{\frac{x-2}{x-1}} \tag{10}$$

and the relative optical local oscillator power required is:

$$P_{L.O.} \propto \left(I_P/I_{P(crit.)}\right)^{\frac{x}{x-1}} \quad . \tag{11}$$

In Equations (9) through (11), we have chosen I_P, the actual d.c. diode current, as the independent variable rather than $I_{P(0)}$, the d.c. diode current which one would observe in the absence of multiplication ($I_{P(0)} = IP/M$). This choice was made because I_P is linearly related to diode dissipation, and also because it may be monitored continuously in an operating system.

A comparison for the general case $I_{P(0)} < I_{P(crit.)}$, the avalanche-heterodyne mode with heterodyne-only operation can now be made. Comparing Equation (10) ($M = M_{opt.}$) with Equation (5a) for $M = 1$, it may be noted that $(S/N)/(S/N)_I$ for $M = M_{opt.}$ decreases less rapidly as I_P is reduced. This means that, for a given value of I_p, and thus a given value of diode dissipation, an optimum choice of multiplication will result in an increased signal-to-noise ratio. Alternately, we can conclude from a comparison of these two equations that, for a desired signal-to-noise ratio, the diode dissipation may be reduced since the latter is proportional to I_P, and this in turn is less for avalanche operation. It is also possible to show that avalanche operation can combine these benefits to yield a simultaneous increase in $(S/N)/(S/N)_I$ and decrease in diode dissipation. Of course, if we require both, then the improvement in either is not so great as it would be if we had chosen to maximize only one.

Finally, it is noted that, for a given diode current, avalanche operation reduces the local oscillator (laser) power required. It is possible to relate to one another in a single graph the quantities discussed: $(S/N)/(S/N)_I$, diode current, diode dissipation, and local oscillator power required; both for $M = 1$ and for various values of M including M_{opt}.

In the next section we shall present the results computed for suitably designed silicon and germanium detectors.

EXAMPLES

In this section, the behavior expected from a suitably operated avalanche-optical superheterodyne receiving system is determined, and then compared with the behavior of a "heterodyne-only" system, using the same components.

For concreteness, it has been assumed that the photodiode and following amplifier have the parameter values listed in Table I.

TABLE I

Diode transit-time cutoff frequency	>	10 GHz
Diode RC cutoff frequency	=	25 GHz
Diode series resistance	=	5 ohms
Noise factor of following amplifier	=	2

It is worthwhile to relate the S/N ratio to the d. c. diode current for the non-avalanche case first since the results apply to systems currently in operation, and since an analysis of this practical case — to the degree of usefulness possible — has not been published previously. Figure 2 is a plot of Equation (7) and shows the d. c. diode current required for the S/N ratio to be within 3 dB of $(S/N)_I$ for the parameters listed in Table I and for various R_L values. The circuit is that shown in Figure 1(b). Figure 2 shows that performance within 3 dB of ideal should be realized with a diode current of about 27 mA for all frequencies below 10 GHz, and a diode current of about 3.74 mA for all frequencies below 2 GHz with load resistances of about 10 and 50 ohms, respectively.

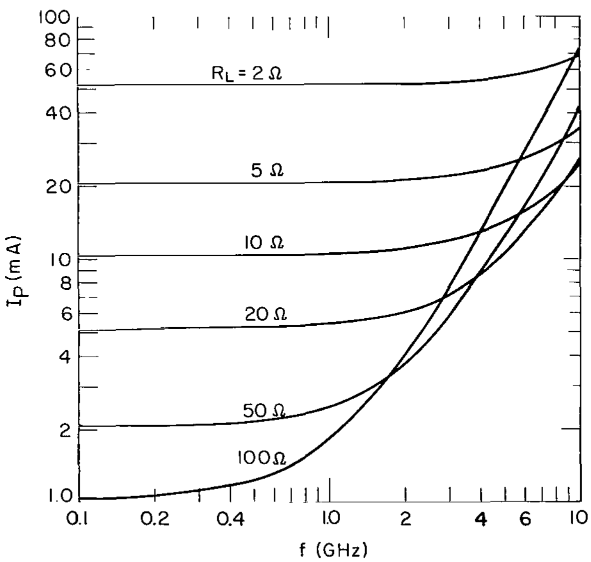


FIGURE. 2

In answer to the question whether there is any advantage to operating an optical superheterodyne detector with avalanche gain, the answer is clearly "no" if adequate local oscillator power is available, and if the photodiode can dissipate a power numerically equal to the product of diode current and diode bias voltage. However, providing sufficient local oscillator power to the detector might be a problem, particularly if one wished to attenuate the incoming signal as little as possible. Also, one might be interested in reliability and long-term stability of the system, so one might want to decrease the diode current to minimize the possibility of diode degradation.

Next the combined avalanche-heterodyne made for the same diode with x = 2.5 (appropriate for the best silicon units reported), baseband operation with a bandwidth of 2 GHz, and R_L = 50 ohms is considered. The results are shown in Figure 3. The normalized signal-to-noise ratio plotted, $(S/N)/(S/N)_I$, is somewhat conservative since in Equation (5a) the value of H

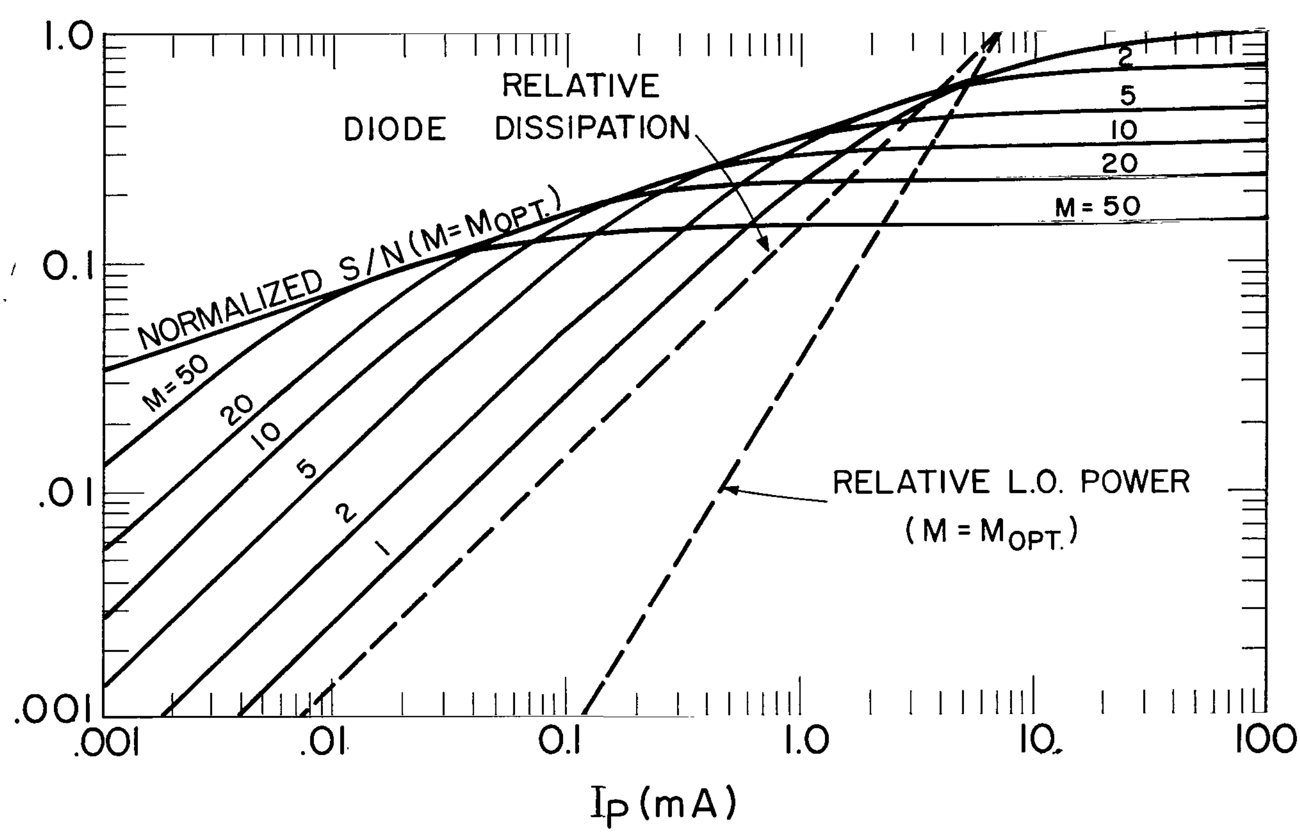
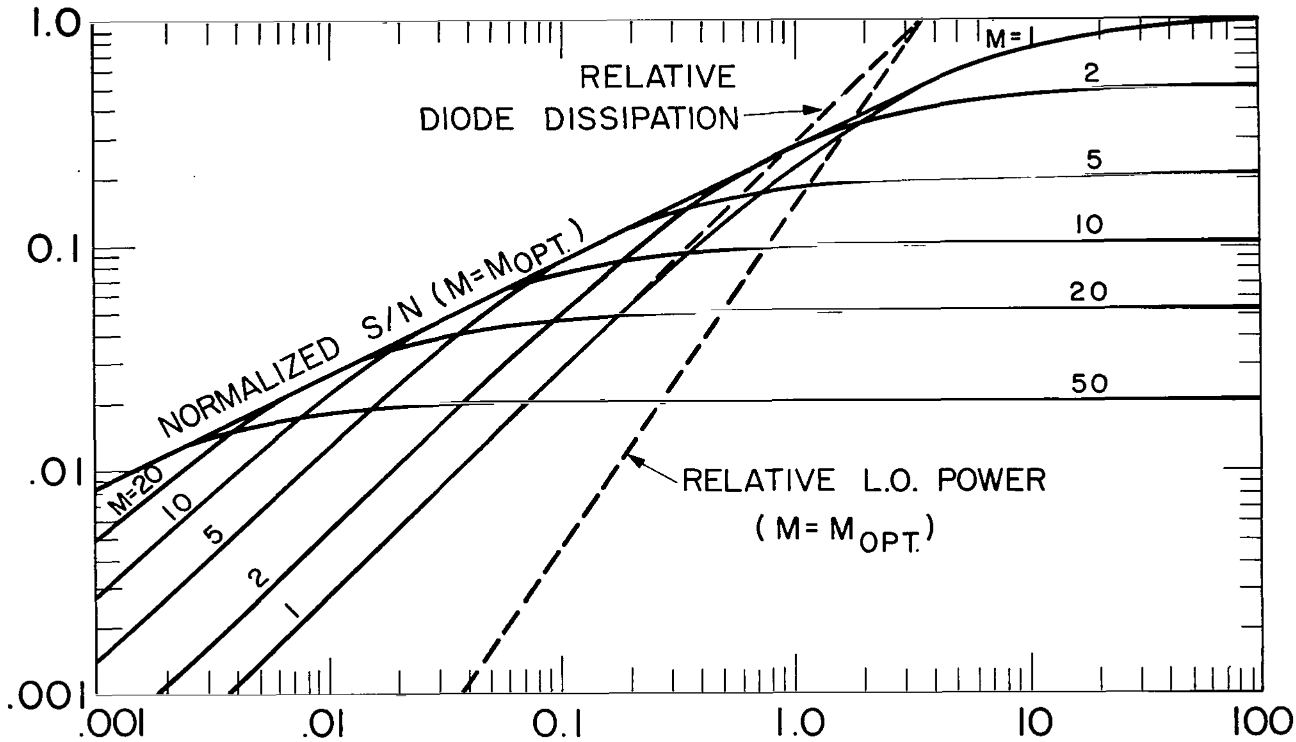


FIGURE. 3

corresponding to 2 GHz, the upper frequency, has been used. The diode power dissipation and the local oscillator power required for M = $M_{opt.}$ are also included and are normalized to unity for $I_{P(0)} = I_{P(crit.)} = 7.48$ mA. In the absence of multiplication, $(S/N)/(S/N)_I$ is constrained to follow the "M = 1" curve, and the "relative diode dissipation" curve is also the curve of required local oscillator power.

As stated previously for $I_{P(0)} < I_{P(crit.)}$, one can pick an M-value which simultaneously increases the S/N ratio and decreases diode dissipation, and achieve this with less local oscillator power than was needed to establish $I_{P(0)}$. As a related example, consider the case of $I_{P(0)} = 0.1$ mA and the requirement that the S/N ratio be optimized without an increase in diode current. It is readily seen that $M_{opt.} = 17.7$ and that $(S/N)/(S/N)_I$ can be increased 7.9 dB from 0.026 to 0.16 with a 12.5-dB decrease in required local oscillator power. Alternately, if the requirement were that the S/N ratio be maximized for the original amount of local oscillator power, then $(S/N)/(S/N)_I$ would be increased 10.3 dB to 0.28 with $M_{opt.} = 5.6$ and a 7.5-dB increase in diode dissipation.

Figure 4 shows $(S/N)/(S/N)_I$, relative diode dissipation, and relative local oscillator power required with M = $M_{opt.}$ for the same operating conditions as for Figure 3, except that x = 3.0, the reported value for germanium photodiodes. With x = 3.0, $I_{P(crit.)} = 3.74$ mA. The improvement in performance with $M = M_{opt.}$ is not so outstanding as with $x = 2.5$, but it still may be worthwhile: for the first example ($I_{P(0)} = 0.1$ mA), for the present case, $M_{opt.} = 6.1$, and $(S/N)/(S/N)_I$ can be increased 5 dB to 0.082 with a 7.5-dB decrease in local oscillator power. For the second example, $(S/N)/(S/N)_I$ may be increased 7.6 dB to 0.15 for $M_{opt.} = 3.3$ and a 5.2-dB increase in diode dissipation.



I_P (mA)

FIGURE. 4

CONCLUSIONS

An analysis of a p-n junction photodiode operated as a heterodyne detector with microwave bandwidths has been made for both non-avalanche and avalanche operations. The results have been interpreted in terms of requirements on the device, and this may serve as a guide to the design of detectors optimally suited for the combined avalanche-heterodyne mode.

Avalanche operation is recommended if the unmultiplied d.c. diode current, $I_{P(0)}$, caused by local oscillator (laser) irradiation is less than the value $I_{P(crit.)} = 2\ kTFH/qR_L(x-2)$. With an optimum multiplication

$M_{opt.} = \left(I_{P(crit.)}/I_{P(0)}\right)^{\frac{1}{x-1}}$, one can simultaneously increase the system S/N ratio and decrease diode dissipation using less local oscillator power than was required to establish the original diode current. The degree of improvement possible strongly depends on the value of x, and this is related to the details of the avalanche multiplication process. Examples are presented for x = 2.5, the value for the best silicon units reported, and x = 3.0, the value reported for germanium photodiodes. For these examples, optimum multiplication lies between 3 and 20. With such modest multiplication values, baseband operation with bandwidths of several GHz are possible

REFERENCES

1. Anderson, L. K. and McMurtry, B. J.: High-Speed Photodetectors. Appl. Opt., vol. 5, p. 1573, 1966.
2. Oliver, B. M.: Thermal and Quantum Noise. Proc. I.E.E.E., vol. 53, p. 436, 1965.
3. DiDomenico, Jr., M., and Svelto, O.: Solid-State Photodetection: A Comparison between Photodiodes and Photoconductors. Proc. I.E.E.E., vol. 52, p. 136, 1964.
4. Tager, A. S.: Current Fluctuations in a Semiconductor (Dielectric) under the Conditions of Impact Ionization and Avalanche Breakdown. Soviet Physics - Solid State, vol. 6, p. 1919, 1965.
5. McIntyre, R. J.: Multiplication Noise in Uniform Avalanche Diodes. I.E.E.E. Trans. Electron Devices, vol. ED-13, p. 164, 1966.
6. Melchior, H., and Lynch, W. T.: Signal and Noise Response of High-Speed Germanium Avalanche Photodiodes. I.E.E.E. Trans. Electron Devices, vol. ED-13, p. 829, 1966.

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