

# OPTICAL PARAMETRIC AMPLIFICATION FOR DETECTION OF WEAK OPTICAL SIGNALS

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## Abstract

Laser communication and optical remote sensing systems often require a highly sensitive detection scheme to measure extremely weak optical signals. This is particularly true for a receiver designed for a deep space optical communication link. The conventional direct detection scheme is sensitive to receiver noise and detector quantum efficiency while **heterodyne** detection requires complex wave front matching and a highly stable local oscillator. This paper considers a direct detection scheme where the optical signal is amplified by an optical parametric amplifier prior to photo detection. It is shown through analysis and simulation that such a scheme can outperform the direct detection receiver when the gain of the amplifier is large and the detector quantum efficiency falls below a certain value. A method to calculate the value of quantum efficiency below which the preamplifier is useful is presented. Performance comparisons are carried out between direct detection schemes with and without the preamplifier. Conditions under which the optical parametric amplifier results in an improvement of the performance of the receiver are pointed out,

## 1. Introduction

This research was motivated by the need to increase the sensitivity of optical receivers so that they can be operated in the photon starved regime. Such regimes are likely to occur in deep space optical communication with a ground or space based receiver, for example, an optical link from Pluto to Earth. Furthermore, weak signal detection problems can also be found in laser remote sensing as well as medical imaging. Although heterodyne reception can lead to increased sensitivity compared to direct detection, it is much harder to accomplish, requiring a very stable local oscillator and complex mode matching of the local oscillator and the received signal. Also, the incoming signal may lose a lot of its coherence due to the atmosphere and may require adaptive optics for correction. Thus, **heterodyne** systems outperform the direct detection systems, but with a much larger complexity of receiver hardware and cost. This investigation was carried out to determine if optical receiver sensitivities better than the conventional direct detection systems could be obtained without all the complexity associated with **heterodyne** detection.

The performance of conventional direct detection systems is limited by detector noise and quantum efficiency especially for high data rate systems. While almost noise free detectors do exist, they have a very low intrinsic gain or bandwidth. If the detector is to have a high internal gain, then it results in detector noise, for example, the dark currents and the multiplication noise in an APD. If, on the other hand, we use an ideal high gain amplifier prior to photo detection, then the performance of the receiver is essentially quantum limited in the absence of a strong background noise. An ideal high gain amplifier is defined as one that does not seriously degrade the signal-to-noise ratio from

the input to the output. The use of a such an amplifier will then permit detection of signals without the addition of significant noise. It is of interest to note here that even though an ideal amplifier does not degrade the signal-to-noise ratio, it will add noise to the incoming signal to satisfy the requirement that the total noise after amplification is greater than or equal to the minimum permitted by quantum mechanics.

The use of an optical amplifier in a laser communication system has been reported in the literature. The enhancement of optical receiver sensitivities by amplification of the carrier prior to detection of an optical modulated signal has been discussed by Arnaud [1]. He concludes that pre amplification is particularly useful when the input signal has a distorted wavefront and is suitable for communication in clear or possibly turbulent atmosphere, Steinberg [2], considers the use of a laser amplifier in a laser communication system and derives some general results under which it can be used, without doing a numerical performance comparison. Arams and Wang [3] experimentally verified Steinberg's theoretical treatment and reported a 32 dB gain in the minimum detectable signal,

In Section 2 the conditions under which an amplifier-detector configuration will outperform the detector alone configuration are theoretically derived, Section 3 is a brief discussion of the nonlinear mechanism that gives rise to optical parametric amplification. Optical parametric amplifiers have recently become feasible due to the availability of high damage threshold nonlinear crystals as well as good quality pump lasers with high peak powers. The performance simulation of the two receiver configurations are discussed in Sections 4 and 5. Conclusions are presented in Section 6.

## 2. Theoretical Analysis

An analytical comparison of the optical receiver performance with and without the Optical Parametric Amplifier (OPA) is now derived, The block diagram of the receiver configuration with the amplifier is shown in Fig. 1.

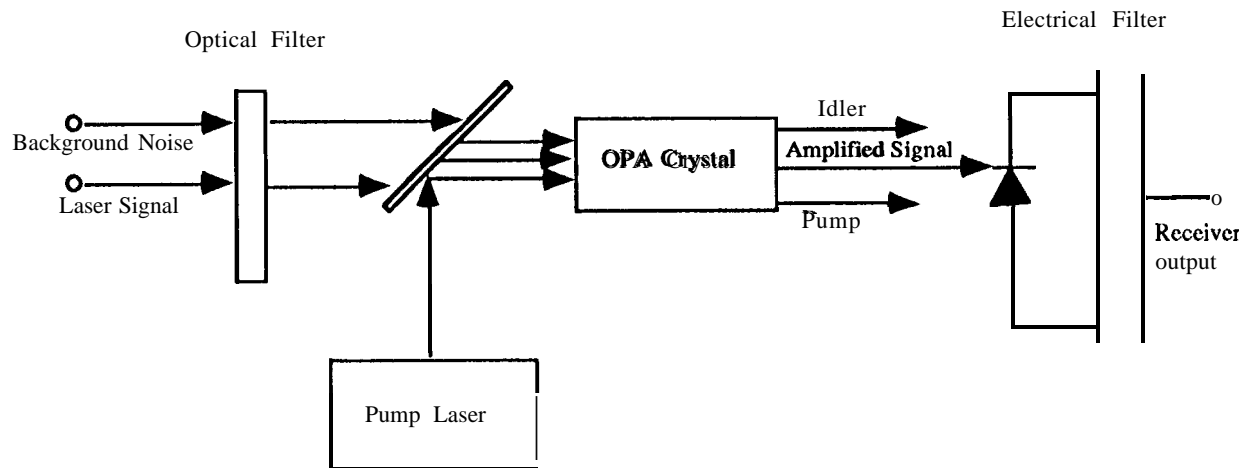


Figure 1. Block diagram of a direct detection receiver preceded by a parametric amplifier.

Let  $N_s$  and  $N_b$  denote the mean signal and background counts at the input to the parametric amplifier per decision interval. The number of photons that arrive is modeled

as a Poisson process at the OPA input, The OPA is assumed linear in the signal bandwidth of interest. Upon amplification the statistics of the number of photons at the OPA output ceases to be Poisson, In particular, if the linear amplifier has a gain  $G$ , the mean and variance of the signal count at the output of the OPA is given by

$$E(N_s) = GN_s, \quad \text{Var}(N_s) = G^2N_s \quad (1)$$

A similar relationship is true for the background count as well. The OPA output consists of three terms that result from the amplified signal, amplified background noise and the noise added by the linear amplifier. If the amplifier has a noise figure equal to unity then the amplifier adds the minimum noise so that the output signal-to-noise ratio is equal to the input signal-to-noise ratio. The amplifier added noise is given by

$$\text{Added noise of amplifier} = (GF-1)N_a \quad (2)$$

where  $N_a$  can be regarded as the input zero point fluctuations and  $F$ , is the amplifier noise figure. In this analysis, we assume  $F=1$ . The detailed statistics of fluctuations in the amplification of quanta for various scenarios are presented in reference [4]. Suffice it to say here that, because the input process at the detector is not Poisson, there will be a noise term in addition to the shot noise process, This additional noise term at the receiver is directly due to the amplification process and will not be present if the input laser signal is directly coupled to the detector, The signal-to-noise ratio (SNR) at the output of the detector can be written as

$$SNR = \frac{\eta^2 G^2 N_s^2}{\eta G(N_s + N_b) + \eta(G-1)N_a + \eta^2 G(G-1)(N_s + N_b) + \eta^2(G-1)(G-2)N_a + \sigma_D^2 + \sigma_T^2} \quad (3)$$

where  $\eta$  is the detector quantum efficiency,  $\sigma_D^2, \sigma_T^2$  are the noise terms due to the detector and thermal noise respectively. Note that the DC noise power is not included in the denominator of Eqn. (3). This is due to the fact that if the noise has a non zero mean it can be canceled without any loss of generality and will not affect the analysis of performance, If the amplifier's gain is very large i.e.  $G \gg 1$ , the signal-to-noise ratio is very closely approximated as

$$SNR_1 = \frac{\eta^2 G^2 N_s^2}{\eta G(N_s + N_b + N_a) + \eta^2 G(G-1)(N_s + N_b + N_a) + \sigma_D^2 + \sigma_T^2} \quad (4)$$

If the amplifier is not used in the schematic of Fig. 1., the resulting signal-to-noise ratio can be obtained from Eqn. 4. by substituting  $G=1$ . The SNR without the OPA is given by

$$SNR_2 = \frac{\eta^2 N_s^2}{\eta(N_s + N_b) + \sigma_D^2 + \sigma_T^2} \quad (5)$$

Some detectors will introduce an excess noise factor  $f$  into the noise terms in the denominator of Eqns. (4-5). Further, let  $\sigma_D^2 + \sigma_T^2 = 0^2$ . Then the two SNR expressions with the amplifier ( $SNR_1$ ) and without the amplifier ( $SNR_2$ ) are given by the expressions

$$SNR_1 = \frac{\eta_1^2 G^2 N_s^2}{\eta_1 G f_1 (N_s + N_b + N_a) + \eta_1^2 G^2 f_1 (N_s + N_b + N_a) - \sigma_1^2} \quad (6)$$

and

$$SNR_2 = \frac{\eta_2^2 N_s^2}{\eta_2 f_2 (N_s + N_b) + \sigma_2^2} \quad (7)$$

respectively, where  $f_1$  and  $f_2$  are the excess noise factor terms. It is also assumed that these factors are incorporated into the gain dependent dark current component of  $\sigma^2$ . As before, in obtaining  $SNR_1$ , it is assumed that  $G \cdot J \approx G$ . It is clear that if the amplifier is to be of any use  $SNR_1 > SNR_2$ .

Next, the general conditions under which the amplifier based system is useful are derived. The two questions that arise are, 1) what are the limits on the value of the detector quantum efficiency,  $\eta_2$ , for which the amplifier will help? In other words how small does  $\eta_2$  have to be for the amplifier to be beneficial and 2) how large must the amplifier gain,  $G$ , be? We will see later that the performance of the amplifier based system becomes independent of  $\eta_1$  and thus, it does not affect the performance comparison. From Eqns. (6) and (7), the condition  $SNR_1 > SNR_2$  is satisfied when

$$G^2 > \frac{\eta_2^2 [\eta_1 G f_1 (1 + \eta_1 G) (N_s + N_b + N_a) + \sigma_1^2]}{\eta_2 f_2 (N_s + N_b) + \sigma_2^2} \quad (8)$$

The answer to the first question on the limits of  $\eta_2$  is obtained by letting  $G \rightarrow \infty$ , in Eqn. (8). The maximum value for  $\eta_2 = \eta_0$  is such that

$$\eta < \frac{f_2 (N_s + N_b) + \sqrt{f_2^2 (N_s + N_b)^2 + 4 \sigma_2^2 f_1 (N_s + N_b + N_a)}}{2 f_1 (N_s + N_b + N_a)} = \eta_0 \quad (9)$$

Thus, we see that the signal-to-noise ratio of a direct detection system is improved by the addition of an optical preamplifier if the quantum efficiency of the detector is in the range  $0 \leq \eta \leq \eta_0$ . The second question on how large must  $G$  be is obtained by solving for  $G$  in Eqn. (8). The value of  $G$  is then given by the minimum value that satisfies the inequality

$$G^2 \{ \eta_1^2 \eta_2 f_2 (N_s + N_b) - \eta_1^2 \eta_2^2 f_1 (N_s + N_b + N_a) + \eta_1^2 \sigma_2^2 \} - G \{ \eta_1 \eta_2^2 f_1 (N_s + N_b + N_a) \} - \eta_2^2 \sigma_1^2 > 0 \quad (10)$$

Equation (9) and the quadratic inequality in (10) together establish the general conditions under which the amplifier may be used in a direct detection system to obtain improved signal-to-noise ratio.

### 3. optical Parametric Amplifier

Laser amplifiers have been used in the past for amplification of weak signals. To achieve any appreciable gain from a laser amplifier, the input signal power has to be above a certain threshold value. As a result, a laser amplifier is not suited to photon starved regimes. Moreover, laser amplifiers operate on the basis of transition between energy levels of atomic ions and consequently, the spectral bandwidth is very narrow. OPAs operate on a much broader bandwidth and are continuously tunable over a wide wavelength range. These properties make an OPA superior to laser amplifiers for communication application.

When an electromagnetic (EM) field propagates through a linear medium, its propagation characteristics are not influenced by its own intensity or by the presence of other electromagnetic fields. However, when the EM field propagates through a nonlinear medium, different electromagnetic fields can interact with the result that their propagation constants become intensity dependent. In particular, the propagation constants of one field are influenced by the presence of the other fields. In the parametric process discussed here, a strong high frequency EM wave called the pump, having a frequency  $\omega_p$ , interacts via the nonlinear response of the medium with two lower frequency EM waves, called the signal having a frequency  $\omega_s$  and the idler having a frequency  $\omega_i$ . The interaction produces amplification at the frequencies  $\omega_s$  and  $\omega_i$ . The optical parametric process is a nonlinear mixing process, Both parametric oscillation and amplification are possible. The parametric process involves breakdown of a pump photon propagating in a nonlinear optical crystal into two photons of frequencies  $\omega_s$  and  $\omega_i$ . The breakdown may occur due to spontaneous or stimulated emission. The total photon energy is conserved so that

$$\omega_p = \omega_s + \omega_i . \quad (11)$$

For a given  $\omega_p$ , there is no unique pair of  $\omega_s$  and  $\omega_i$ . In fact, an infinite number of such pairs is possible. The phase matching condition

$$k_p = k_s + k_i \quad (12)$$

where  $k$  is the wave vector for radiation in the nonlinear medium, determines which pair of  $\omega_s$  and  $\omega_i$  frequencies are generated. The ability to vary the phase matching condition affords continuous wavelength tunability in optical parametric oscillators (OPO) or amplifiers, Parametric oscillators are similar to lasers because the output is coherent and is emitted from a resonant optical cavity.

Recent improvements in nonlinear crystals, specifically LN (LiNbO<sub>3</sub>), KTP (KTiPO<sub>4</sub>), BBO (BaB<sub>2</sub>O<sub>4</sub>), LBO (LiB<sub>3</sub>O<sub>5</sub>) and KN (KNbO<sub>3</sub>) have made very efficient OPA devices possible. For the amplification process to be efficient the following conditions for the pump beam in relation to the received signal beam will have to be satisfied. a. Spatial overlap, b. Temporal overlap and c. Phase matching. Under these conditions the Intensity gain of the signal due to the amplifier, G, is given by [5] as

$$G = 1 + \frac{\Gamma_0^2}{\Gamma^2} \text{Sinh}^2(\Gamma z) \quad (14)$$

where  $\Gamma_0$  is the gain constant depending upon the nonlinear medium as well as the operating wavelengths,  $\Gamma^2 = \Gamma_0^2 - \left(\frac{\Delta k}{2}\right)^2$ ,  $\Delta k$  is the amount of phase mismatch and z is the length over which the waves interact. The amplifier gain as can be seen from Eqn. (14) is a function of the interaction length in the crystal. Gains of the order of 30 dB or more has been reported [6]. The value of gain chosen for this analysis was 35 dB.

#### 4. Direct Detection with Parametric Amplification

The performance of the optical receiver shown in Fig 1. is evaluated through computer analysis. The signal is considered to be M-ary Pulse Position Modulated (PPM). The signal-to-noise ratio in a parametric amplifier based receiver is given in Eqn. (6). Because the parametric amplifier affords a very large gain, a low noise, low gain detector is used, In particular, a Si-PIN photo diode is used that has an excess noise factor equal to unity and a detector gain equal to unity. The signal slot which contains one word of information bits is also the decision interval and is  $T$  wide. For background noise

calculations a worst case sky irradiance of  $\frac{0.6W}{4\pi r^2 - nm - sr}$  was taken, The receiving area is taken from the 10m deep space optical receiving antenna (DSORA) being considered at JPL [7]. The bandwidth of the OPA is of the order of 100 Ghz. The half angle field-of-view due to the DSORA system is calculated to be about  $50 \mu$  radians. The amplifier added noise in photon counts, which can also be thought of as the amplified input zero point fluctuations, is given by

$$\text{Amplifier noise} = G n \frac{v^2}{c^2} \Delta v \Delta \Omega dA \quad (15)$$

where  $G$  is given in Eqn. (14),  $v$  is the carrier frequency of the signal,  $c$  is the velocity of light,  $n$  is the refractive index of the material,  $\Delta v$  is the smaller of the pump or the gain (OPA) bandwidth,  $\Delta \Omega$  is the solid angle input as seen by the amplifier and  $dA$  is the cross sectional area of the pump at the front face of the OPA. The thermal noise count was considered to be negligible in view of the large amplifier added noise as well as the amplified background radiation. For the chosen value of the amplifier gain, the detector noise and the thermal noise are also negligible in comparison to the noise entering the detector.

In the limit of large gain the signal-to-noise ratio that results from amplifier based direct detection scheme can be obtained from Eqn. (4), by letting the gain  $G$  be very large. The SNR is given by,

$$SNR_i = \frac{N_s^2}{N_s + N_b + N_a} \quad (16)$$

Thus, in the limit of a very high gain, the performance of the optical receiver is not limited by the detector quantum efficiency of the detector and is only a function of the background noise and amplifier noise added noise. Fig. 2 shows the probability of bit error versus the required photons/bit for a PPM signal modulation with  $M=8$ . The background photon count from a worst case value of  $N_b=100$  over the decision interval to a best case value of  $N_b=0$  are considered. The statistics of the noise process has been assumed to be Gaussian. The signal and noise count that result from the amplification are very large and this assumption is easily justified.

#### 5. Direct Detection without Amplification

The direct detection system with no amplification is analyzed with the same values for signal and the various noise terms. The signal-to-noise ratio resulting in a direct detection system is given in Eqn. (7). Various choices exist for the detectors in this scenario,

depending on the application, Three of the choices are a Si-APD, Si-PIN and a PMT . PMTs have a very large gain and are almost noise free but they are limited by a very low quantum efficiency and reliability. PIN diodes also have excess noise factors close to unity. But since they don't have an intrinsic gain, detection of very low level photons may not be possible because of their inability to raise the signal above the noise floor of the post detection circuit, APDs achieve an internal gain not as large as the PMT but enough to raise the signal above the thermal noise as well as the dark currents. They can also operate at high data rates. The main limit associated with the APD is the excess noise factor, From the above reasoning, an APD seems to be the best candidate for an optical deep space receiver and was chosen for this evaluation,

The performance was obtained by assuming Gaussian statistics for the noise once again. The gain of the APD is assumed large enough to justify Gaussian statistics. A discussion of the results shown in Figs. 2-4 is presented in the next section. In this section we will revisit a theoretical comparison of performance between the direct detection systems with and without the amplifier. The question is posed as follows, How much smaller can the signal count of an amplifier based system be to obtain the same signal-to-noise ratio as a direct detection system with no amplifier? Although in a communication receiver system the ultimate value of interest is the bit error rate we will make an assumption that a signal-to-noise ratio comparison is equivalent to a comparison of the resulting bit error rates. This assumption is justified based on our earlier assumption of Gaussian statistics for the signal and noise counts, The value for the gain dependent and independent dark currents for the APD are taken as 5,2 pA and 15 nA, respectively [8].

Let the signal and noise count of the amplifier based detection scheme be reduced by a factor  $r$ . This may be due to the fact that the photon collecting area of the receiver is reduced by the same factor. Then, if the gain  $G$ , is large we have the following equation,

$$\frac{N_s^2}{r(N_s + N_b + rN_a)} = \frac{\eta_2^2 N_s^2}{\eta_2 f_2 (N_s + N_b) + \sigma_2^2} \quad (17)$$

Solving for the value of  $r$  in the above equation we get

$$r = \frac{N_s + N_b}{2N_a} \cdot \left( \sqrt{1 + \frac{4N_a[\eta_2 f_2 (N_s + N_b) + \sigma_2^2]}{\eta_2^2 (N_s + N_b)^2}} - 1 \right). \quad (18)$$

The equation for  $r$  looks rather complicated and it is not readily apparent as to what typical values of  $r$  are? However, making some simplifying assumptions a reasonable estimate for  $r$  can be obtained. Assuming that  $\sigma_2^2$  and  $N_a$  are much smaller than  $N_s + N_b$ , the solution for  $r$  is obtained as

$$r \approx \frac{f_2}{\eta_2} \quad (19)$$

which, in fact, is the approximate gain in the signal-to-noise ratio of an amplifier based system over that of a direct detection system. In deriving Eqn. (19), two assumptions were made as mentioned above. But neither of these are stringent assumptions or restrictive. For the detection scheme to perform well with the amplifier we would require that  $N_a$  be much smaller than  $N_s + N_b$  and for the detection scheme without the amplifier that  $\sigma_2^2$  be much smaller than  $N_s + N_b$ . In practice, these conditions will be usually met

to obtain the desired performance. What this says is that for the APD, the multiplication noise is much larger than the noise contribution due to the gain independent and gain dependent dark currents. Under these conditions, we notice that the factor  $r$  which is a measure of the area of the photon collecting dish can reduce by a factor of  $\frac{\eta_2}{f_2}$ . This

implies that for a circular collecting area the diameter can be reduced by a factor  $\sqrt{\frac{\eta_2}{f_2}}$ . A plot of the reduction in diameter of the collecting area versus the quantum efficiency of the detector is shown in Fig. 4.

## 6. Discussion and Conclusions

The primary motivation for this research was to investigate the possibility of improving the performance of a direct detection system for deep space communication applications. A comparison Figs. 2 and 3 reveals that the performance of a direct detection system preceded by a parametric amplifier is better than that of the direct detection receiver alone. Since the region of interest is the photon starved regime only signal count/bit up to 40 are shown in the figures. With an amplifier based system, sensitivity as low as 13 photons/bit is obtained at bit error rate (BER) of  $10^{-6}$ , for a background count of 10. Even for the worst case background considered, the sensitivity for a BER of  $10^{-6}$  is only 28 photons/bit. Roughly, the gain obtained using a parametric amplifier is about 4.5 dB over the various background levels considered. However, as we have seen from the theoretical analysis of performance in Section 5, the performance improvement is inversely proportional to the quantum efficiency of the direct detection detector. In this analysis a value for the quantum efficiency equal to 0.75, which satisfies Eqn. (9) was chosen. If  $\eta_2$  is smaller, a higher performance gain will be obtained. In this context, it may be useful to discuss the wavelengths of operation of the deep space communication link. The parametric amplifier gain depends very weakly on the wavelengths of operation and does not affect the performance, The two primary candidates of interest at JPL are 532 nm and 1064 nm. While detector efficiency is higher at 532 nm, there is  $\approx 3$  dB power loss in frequency doubling to 532 nm. If the parametric amplifier is used in the direct detection system, 1064 nm wavelength can be chosen for the signal carrier. The quantum efficiency of the detector in the amplifier based system while being poorer does not degrade the system performance.

The amplifier noise factor  $F$  was taken as being unity. In fact, even if the amplifier is less than ideal it will not result in a significant degradation of performance because the shot noise due to the signal and noise are much greater than the amplifier added noise. The background noise count as well as the amplifier noise are directly related to the pulse width of the  $M$ -ary word. A shorter pulse width will result in a smaller noise count.

Another significant possibility is the reduction of the receiving antenna size that is possible in the proposed detection scheme. From the point of view of technical difficulties as well as economic constraints, a smaller antenna is preferred. A 10m antenna is being considered at JPL presently. This antenna can be used to communicate up to 40 AU. With an amplifier based detection the size of the antenna can be reduced by

a factor of  $\sqrt{\frac{\eta_2}{f_2}}$ . To take an example, if we operate the communications link at 1064 nm wavelength where Si-APD has a quantum efficiency, about 40% and an excess noise



factor close to 3, the antenna size can be reduced to about 3.65m from a 10m one required for a direct detection system, If the antenna size remains at 10m, the signal-to-noise ratio gain is about 7.5 or approximately 8.75 dB.

A brief discussion on near earth optical communication is in order here, Both the amplifier based system and the direct detection system can support high data rates as would typically be required in a near earth link, Also, the problem of very weak signal detection does not exist. Near earth links will potentially provide a higher SNR at the ground receiver. However, the limiting factor for a parametric amplifier based high data rate ground based system is the availability of high average power, high repetition rate pulsed lasers for the pump. The constraint on the pump laser will limit the performance of the system to lower data rates compared to the direct detection receiver. The maximum data rate that an amplifier based system can support will be determined by the available high power pump laser technology.

The biggest problem in implementing this system is the synchronization between the communications signal and the pump laser. As mentioned earlier for efficient amplification to occur, the pump and the signal has to be matched temporally and spatially. The OPA has a sufficiently wide acceptance angle and the problem of spatial mode matching may not be high, The wide acceptance angle is one of the advantages compared to the heterodyne system where only the mode of the incoming signal that is matched to the local oscillator is detected, An OPA amplifies all the modes present in its angular bandwidth. This offers an interesting comparison with the heterodyne detection system. The heterodyne detection system requires good spatial mode match at the detector surface(s), whereas OPA requires good volume mode match. However, the k-vector mismatch allowed for the heterodyne detection is smaller than that of the OPA. Consequently, there is a more stringent requirement of alignment for the heterodyne receiver. For heterodyne receivers operating inside the atmosphere, the stringent alignment requirement also translates to limits on the aperture size, as the atmospheric turbulence limits the effective aperture size to that of a coherent cell size,  $r_0$ . The field-of-view of the heterodyne receiver can be increased only at the cost of reduced mode matching efficiency and increased local oscillator shot noise contribution. For an OPA based system, the mode mismatch leads to a relatively larger value for the amplifier noise. However, an inspection of Eqn. (16) shows that an M-fold increase in amplifier noise does not lead to an M-fold decrease of SNR. The other advantage of the OPA based system is that the heterodyne system is still limited by the quantum efficiency of the detector while an OPA based system is not,

If due to angle mismatch there is phase mismatch between the pump and the signal beam, it will result in a loss of gain, Since the gain from the amplifier is quite large, a small loss in the gain will not result in a degradation of the system performance. However, the problem of temporal matching between the pump and the signal can be quite large especially when the distances involved are large, like a Pluto-Earth link. This is an open problem and further work needs to be done on how the synchronization can be achieved,

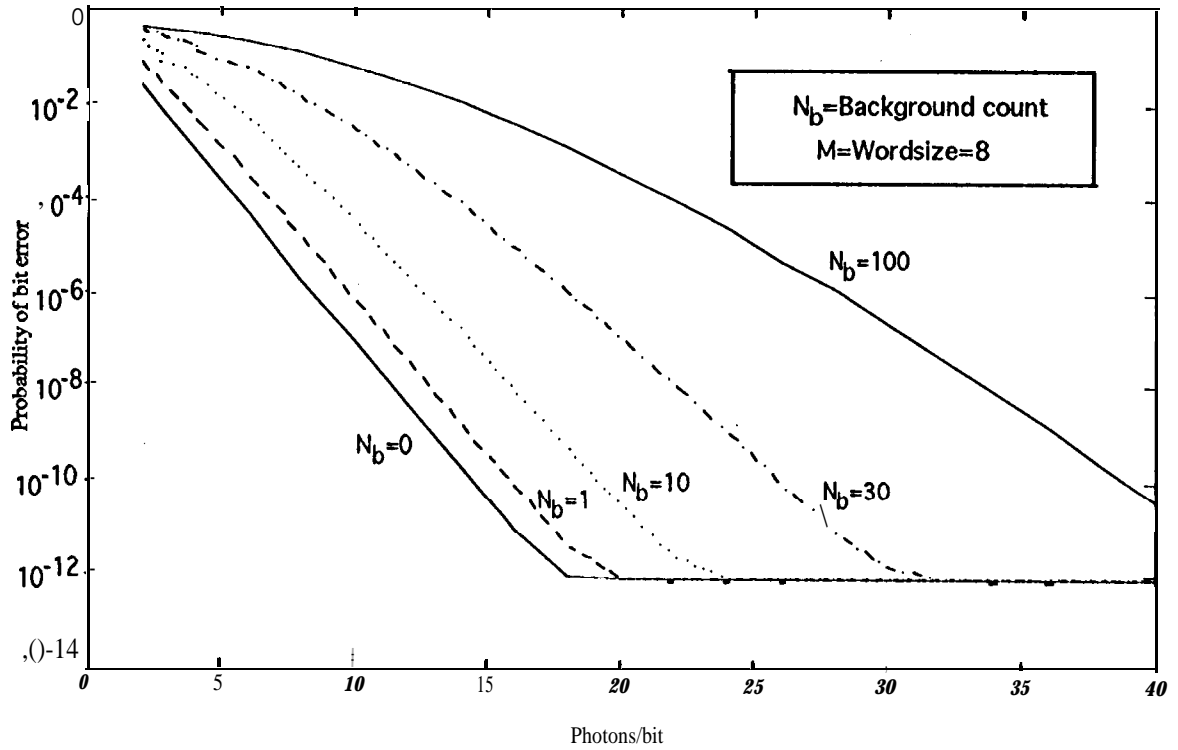


Figure 2. Probability of bit error versus signal photon count for an OPA bawd receiver. The background count is per decision slot.

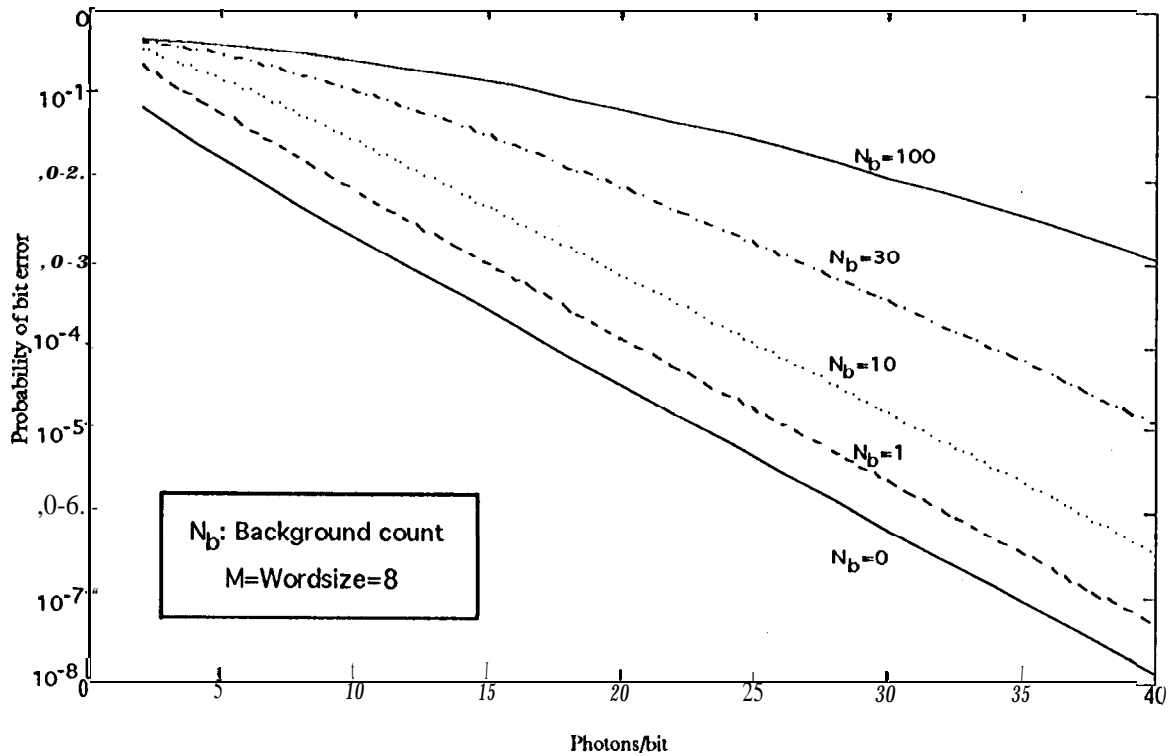


Figure 3. Probability of bit error versus signal photon count for a direct detection receiver. The background count is per decision slot, Quantum efficiency of detector=0.75.

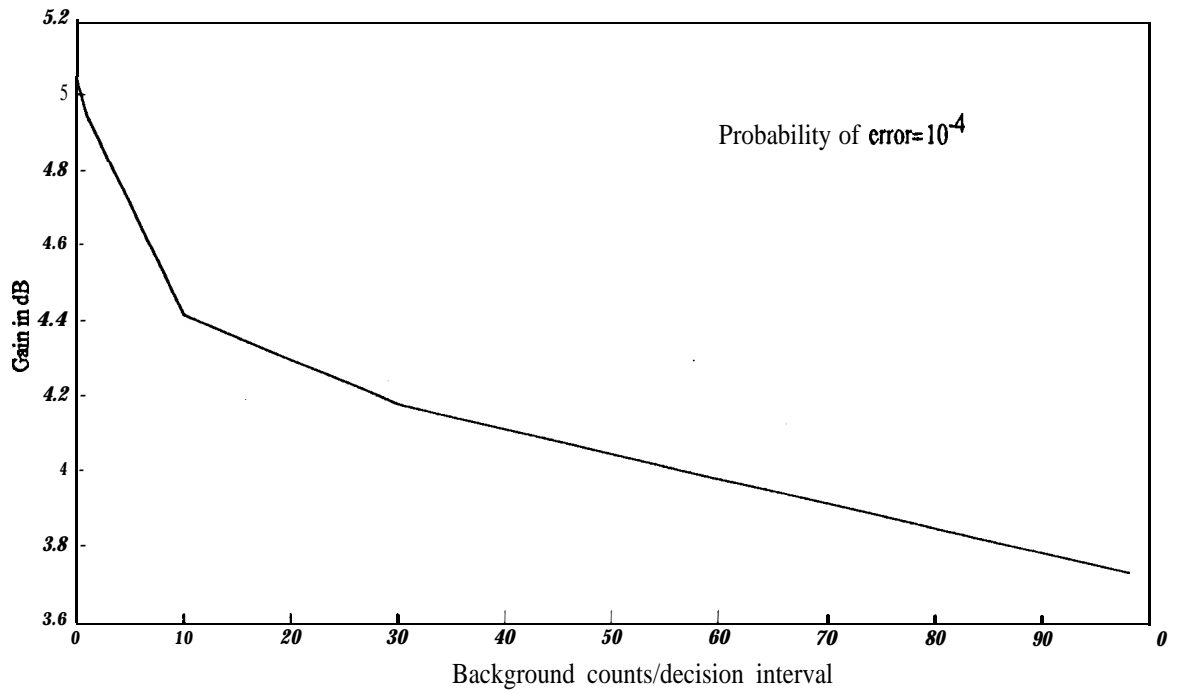


Fig 4. Gain in an OPA based system as a function of background noise count.

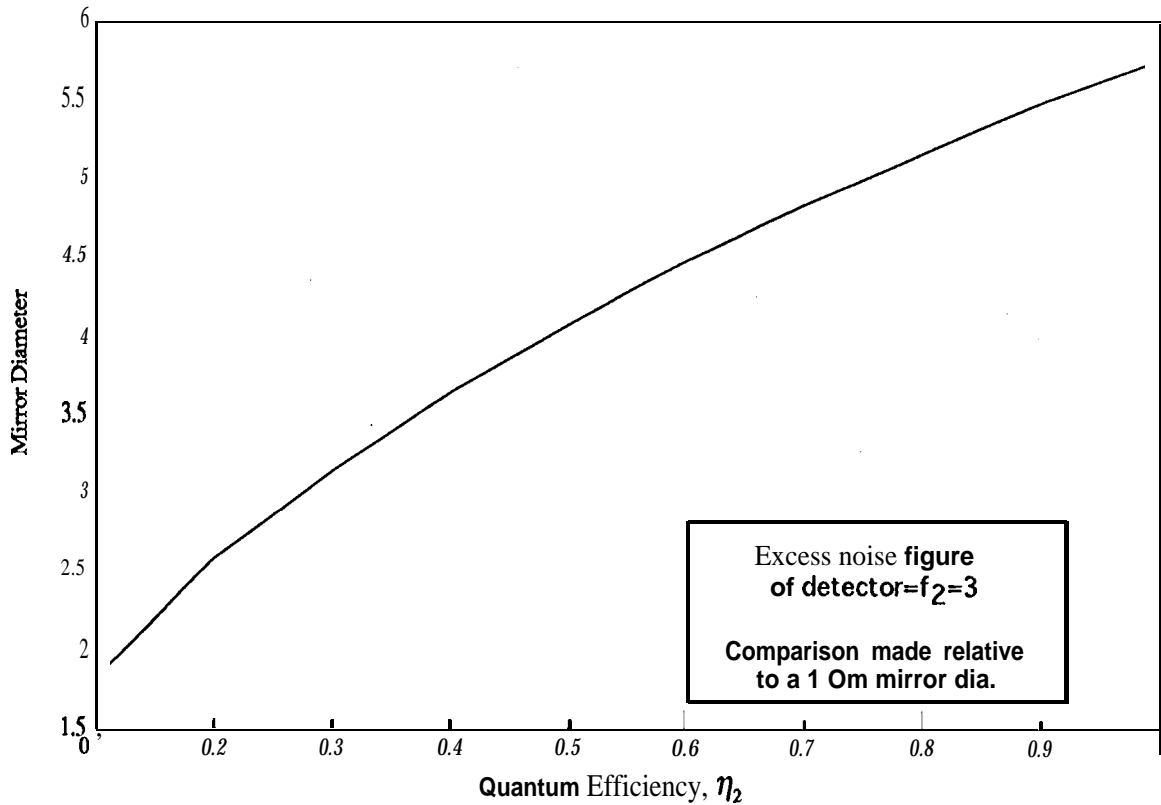


Figure 5. Mirror diameter reduction as a function of the detector quantum efficiency of the direct detection system

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