Optical communication noise rejection using correlated photons

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Abstract. This paper describes a completely new way to perform noise rejection using a two-photon sensitive detector and taking advantage of the properties of correlated photons to improve an optical communications link in the presence of uncorrelated noise. In particular, a detailed analysis is made of the case where a classical link would be saturated by an intense background, such as when a satellite is in front of the sun, and identifies a regime where the quantum correlating system has superior performance.

1. Introduction

The last few years have brought rapid advances in the understanding and application of quantum entangled photons. Exploitation of quantum correlations is important in various applications, including teleportation [1], quantum lithography [2], clock synchronization [3], and optical communications [4]. To date, most of this work has focused on characterizing quantum correlation effects at low intensities due to the lack of bright sources of correlated photon pairs. However, Lamas-Linares *et al*.'s [5] recent report of the laser-like production of polarization entangled photons now opens up the possibility that one can take advantage of correlated effects for communications. In addition, the demonstration of efficient parametric down conversion using a diode laser and a pair of solid-state parametric conversion chips [6], demonstrates that parametric generation technology is rapidly approaching the fabrication thresholds where economies of scale can be achieved. Earlier attempts by Mandel [4] to apply correlated photons to improving the signal to noise ratio in a communications link depends on coincidence counters, which, because of the detector dead time, are limited to low rates. Our approach depends on the development of a special detector that is intrinsically sensitive to two-photons [7]. This single detector replaces the coincidence counters, gating electronics, amplifiers, and the computer interface employed in the earlier effort. Consequently, it is important to do a link analysis to determine whether there is an advantage to using correlated photons and two-photon detectors for conveying information in an optical communications channel.

The answer is yes, but only for the special situation where the signal strength is swamped by in-band background noise. We refer specifically to situations where

the free space high bandwidth of optical communications is desired, but in-band solar background radiation hampers the signal to noise. The other situation of interest would be in fibre networks operating under conditions of a large background of incoherent in-band scattering, which adversely impacts recovery of the signal at the receiver. For shot noise limited telecom links there is generally no advantage to using correlated photons as opposed to classical photons for the carrier. Our approach is predicated on the development of a two-photon sensitive photodetector which eliminates the need for separate coincidence electronics. Consequently, one can define the required figure of merit that must be met for a performance advantage to be realized of the corrrelated two-photon link over a classical uncorrelated photon link in terms of the two-photon and single-photon quantum efficiencies of the detectors. Besides introducing a new method for performing the coincidence measurement, this paper defines the conditions under which one can expect the two-photon correlated detection to realize an advantage when compared to classical uncorrelated signal recovery. Finally, it briefly examines the effect of diffraction on the two-photon collection efficiency in the free space application.

2. Near-field optical communications links

The near field communication link is defined as an architecture for which the full output power of the transmitter is subtended and collected by the detector. The schematics in figures 1(a) and 1(b) depict the key differences between the classical and the correlated-photon near-field telecom links. In this analysis, a classical link, using photons of frequency ω_1, is compared with a correlated-photon link transmitting photon pairs of approximate frequency ω_1, but actual frequency $\omega_a + \omega_b = 2\omega_1 = \omega_2$. The power received at the detector is given by the following expression

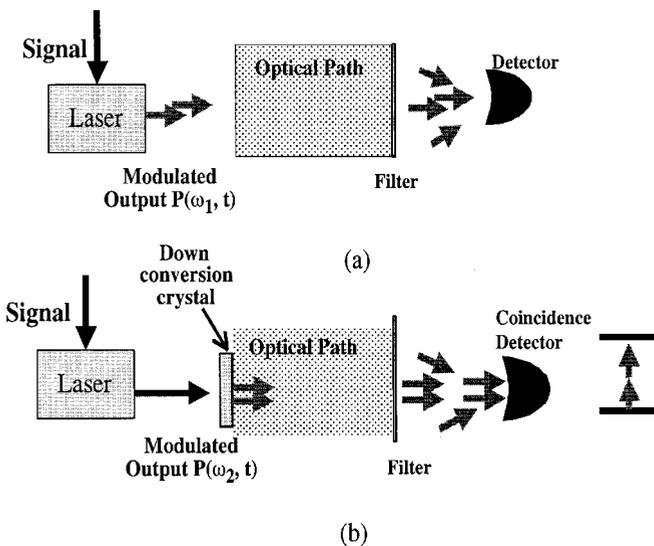Figure 1. Classical (a) and correlated-photon (b) near-field telecom link.

$$P_r(\omega_i, t) = \mu P_t(\omega_i, t) L(\omega_i) \tag{1}$$

where $P_t(\omega_i, t)$ is the modulated output power of the communications laser at carrier frequency ω_i, μ represents conversion losses suffered after emission from the transmitter, and L represents any losses that occur during transit through the communications channel. This expression assumes that the collimating optics at the transmitter and the collecting optics at the receiver are sufficiently large that the footprint of the transmitted beam is completely subtended by the receiver aperture. This would be a reasonable assumption at optical frequencies over free space transmission ranges up to $1000 \, \mathrm{km}$. To facilitate comparison of the perform- ance of both links, we assume that the initial laser output power of the classical link is identical to the laser output power of the correlated photon link:

$$P_t(\omega_1, t) = P_t(\omega_2, t) \tag{2}$$

The link designs differ by the conversion loss factor μ and the carrier frequency used to transmit the signal information through the channel. In the classical telecom link, $\mu = 1$ and the carrier frequency is ω_1. Thus the signal current generated at the receiver for the classical link is given by

$$I_0 = \eta_{det} P_r(\omega_1, t) = \eta_{det} P_t(\omega_1, t) L(\omega_1) \tag{3}$$

where η_{det} is the receiver efficiency for converting input photons to carriers in the signal current.

In contrast, the value of μ in the correlated photon link is determined by the method used to produce the correlation. Furthermore, we assume that the modulated output of the laser transmitter is passed through a nonlinear parametric down conversion crystal and correlated photons are generated with efficiency, $\mu = \eta_{PDC}$. The following additional properties apply.

- Both photons were created at the same point in time.
- Both photons were created at the same spatial point.
- Energy is conserved $\rightarrow \omega_2 = \omega_a + \omega_b$.
- Momentum is conserved $\rightarrow \vec{k_2} = \vec{k_a} + \vec{k_b}$.

One assumes that the daughter photons from the down conversion process are degenerate with $\omega_a + \omega_b = 2\omega_1 = \omega_2$. After down conversion, the output is modu- lated with the signal waveform before being sent through the transmission medium for collection at the receiver. Therefore in the correlated link, the signal current generated at the receiver is proportional to the signal power and is given by

$$I_0' = \eta_{2-ph}(2\omega_1)[P_t'(\omega_a, t)L(\omega_a, t) + P_t'(\omega_b, t)L(\omega_b)] = \eta_{2-ph}(2\omega_1)\eta_{PDC}P_t(\omega_2, t)L(\omega_1) \tag{4}$$

Even though we do not know exactly when or where any pair of twin photons are born within the down conversion crystal, the fact that they are created simul- taneously means that standard geometrical imaging optics can be exploited in a straightforward manner to reunite these photon pairs in coincidence at the receiver. The figure of merit for comparing the ultimate link performance is given by the signal to noise ratio of each approach;

$$SNR_{classical} = \frac{I_0}{\sqrt{\sum_i \sigma_i^2}} \tag{5}$$

Table 1. Definition of noise sources in classical and correlated telecom links.

Noise source	Classical photons	Correlated photons
$\sigma_{thermal}^2$	$\dfrac{8kTB}{R_i}$	$\dfrac{8kTB}{R_i}$
σ_{shot}^2	$4eI_0B$	$4eI_0'B$
$\sigma_{laserRIN}^2$	$2BF_{RIN}I_0^2$	$2BF_{RIN}(I_0')^2$
$\sigma_{background}^2$	$4e\eta_{det}P_{r-B}B$	$4e\eta_{1-ph}(\omega_1)P_{r-B}B^\dagger + 4e\eta_{accidental}(2\omega_1)P_{r-B}^2B^\ddagger$

† $\eta_{1-ph}(2\omega_1)$ is the single-photon detection efficiency.
‡ $\eta_{accidental}(2\omega_1)$ is the two-photon absorption efficiency for statistically random detection events.

$$SNR_{correlated} = \frac{I_0'}{\sqrt{\sum_i \sigma_i^2}} \tag{6}$$

where

$$\sum_i \sigma_i^2 = \sigma_{thermal}^2 + \sigma_{shot}^2 + \sigma_{laserRIN}^2 + \sigma_{background}^2 \tag{7}$$

is the sum of the variances of all noise contributions, thermal noise, shot noise, relative intensity noise due to the laser, and in-band background noise arriving with the signal at the detector. These factors are defined for each link in table 1. The expression for the correlated SNR is optimized when the source has been imaged onto the detector so that the correlated pairs, that are collected by the imaging lens, arrive at the same time and overlap at the same point of the detector. This means that correlated telecom links are practical for short range links where the footprint of the transmitter's output beam is fully subtended by the receiver collection aperture.

Here k is Boltzmans constant, B is the circuit bandwidth, T is the ambient absolute temperature, R_i is the detector input impedance, e is the electric charge, F_{RIN} is the relative intensity noise factor, and P_{r-B} is the power level of the background noise at the receiver. To compare the relative efficiencies of classical signal recovery with the signal recovery process of correlated photons, we assume similar links are established for the classical photon signal recovery and correlated photon signal recovery. $P_t, A_t, R_i, L, A_r,$ and ω_1 are chosen to be identical for both links, where A_t is the area of the transmitter aperture and A_r is the area of the receiver collection aperture. They differ in the choice of down conversion efficiencies, detector efficiencies, and the background noise contribution to the signal to noise ratio (SNR).

The differences between these two types of links are summarized as follows. The correlated photon transmitter design can never be as efficient as the classical transmitter due to the parametric down conversion factor, $\eta_{PDC} < 1$. But an advantage can be obtained if one employs a detector that is specifically designed to have a poor single-photon detection efficiency, and a two-photon detection efficiency that is significantly larger such that $\eta_{2-ph}(2\omega_1) \gg \eta_{1-ph}(\omega_1)$. To illustrate this point, we compare the correlated photon signal-to-noise to the classical signal-to-noise.

The ideal communications link is often designed so that the shot noise is dominant, which yields

$$\frac{SNR_{correlated}}{SNR_{classical}} = \sqrt{\frac{\eta_{2-ph}(2\omega_1)\eta_{PDC}L(\omega_1)}{\eta_{det}}} < 1 \qquad (8)$$

Clearly the ratio in the expression above will always be less than 1, largely because the down conversion efficiency will never be 100%. Alternatively, if one examines the case where the background noise exceeds the signal current, $I_B > I_0$, the ratios change to

$$\frac{SNR_{correlated}}{SNR_{classical}} = \frac{\eta_{2-ph}(2\omega_1)\eta_{PDC}L(\omega_1)}{\sqrt{\eta_{det}\eta_{1-ph}(\omega_1)}} > 1 \qquad (9)$$

Here we assume that $\eta_{accident}(2\omega_1)P_{r-B}$ shown in table 1 is negligible compared to $\eta_{1-ph}(\omega_1)$. Equation (9) says that the correlated photon link has a performance advantage as long as $\eta_{2-ph}(2\omega_1) \gg \eta_{1-ph}(\omega_1)$, in accordance with this relation.

3. Conclusions

Certain communications channels need to operate in the presence of severe background noise, such as when the Sun is positioned near the line of sight (LOS) between the transmitter and the receiver. In such situations, noise-immune coding techniques are of limited help due to saturation of the detector. Narrow-band filters can limit the background but with a sufficiently intense source the detectors can still be saturated by noise. In this situation two-photon correlated detection can avoid the noise in an entirely different way, where a two-photon detector does not see it, or only sees 'accidental' coincidences which are small for incoherent sources like the Sun. If this is the case, a quantum-correlated communication channel can outperform other techniques because it eliminates the background before a detector signal is generated.

In telecom links for which the footprint of the beam is larger than the collection aperture, quantum-correlated telecom links are essentially non-competitive against classical communications links because the correlation cross-section of the product, $P_t(\omega_a, t)P_t(\omega_b, t)$, falls off at a rate proportional to $1/R^4$, while the classical link has a $1/R^2$ dependence. However, over ranges of about 1000 km realizable communications links using 1 to 2 m mirror optics permit the design of links that collect most of the emitted photons, thereby making free space links under this range superior if the conditions of equation (9) are met. In addition, fibre optic links, which intrinsically permit one to image all the incident photons onto the receiver, may find an advantage in using correlated photons when the in-band background noise exceeds the signal level.

In summary, one will observe a performance advantage for correlated photon links when the classical link is limited by an intense source of uncorrelated background noise. The requirements for using this technique are (1) that an intrinsically two-photon detector be developed (this rejects noise without being saturated by it) and (2) that most of the transmitted photons be collected (which can be done in free space over distances up to about 1000 km).

Acknowledgments

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