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Executive Summary
We discuss the concept of entanglement enhanced range finding where entanglement is used to provide enhanced signal to background. We describe possible realisations based on broad band (hyperentangled) parametric pair photon sources where an SNR gain of M can be obtained where M is the number of hyperentangled modes. We go on to show that higher order entanglement could provide exponential sensitivity gain when post selection and quantum memory is used and we describe a possible implementation using spin photon entanglement devices. However it is clear that all these measurements are made in the computational basis thus could be reproduced using sophisticated classical encoding schemes.

1. Introduction

All range-finding schemes to date involve a high flux of photons at the target to ensure a measurable return to the observer. In many situations the target will also be illuminated by a background flux of light dominated by scattered sunlight in visible and near infra-red wavelengths and thermal blackbody emission (at longer wavelengths >2 μm). This background light will also limit the sensitivity of our rangefinder, the signal to noise ratio of any return being limited by the ratio of the background light noise to signal return measured in a time gating window ultimately limited by the resolution of the rangefinder which is most likely limited by the timing accuracy of the detector.

Here we describe the signal to noise achievable in pair photon range-finders [1] exploiting the time correlation inherent in the emission of energy-time entangled photon pairs. Essentially one photon of the pair is detected locally to provide a time stamp with which to time the return from the target of its partner. We show that the sensitivity can be dramatically improved (primarily by reducing background) if we exploit the hyper-entanglement inherent in these broad band sources but note that this sensitivity improvement can be reproduced in classical broad band illumination rangefinders. Similarly by exploiting multi-particle entanglement then exponential gains dependent on the number of particles might be expected. These gains are offset dramatically by the loss inherent in the path to and from the target if we consider the states leaving the source. However all experiments post-select only those photons that are detected and using only these and the correlations between them the exponential gain is retained [2], even when the photons are all detected in the computational basis. The drawback is that as these measurements are made in the computational basis they could be reproduced using sophisticated classical encoding schemes.

2. Parametric pair photon Rangefinders

In a previous experimental study we have shown that broad band CW light created in parametric downconversion can be used for rangefinding [1] of partially reflecting targets out to 60m in reduced lighting conditions. The principle of operation is that photons are created in pairs in the parametric downconversion apparatus. Detection of one photon of a pair (the idler) provides a time tag for the second photon of the pair (the signal) which is then sent to the target and the return is timed.

The return from the target is measured as

$$N_r = \eta_s \eta_i R L_r \qquad (1)$$

where R is the rate of creation of pairs, $\eta_s(\eta_i)$ are the signal (idler) detector efficiencies and L_r are the out and return losses to the target. The signal is discriminated by a time window set by the timing delay for out and return paths with a timing jitter $\boldsymbol{t}$. The counting rate due to daylight in each time window is then

$$N_d = \eta_s \eta_i R t N_b B \qquad (2).$$

when the detector is preceded by a filter of bandwidth B nm and daylight intensities are N_b photons/sec/nm. For good signal to noise we would like $N_r \geq N_d$ implying

$$\frac{L_r}{t} \geq B N_b \qquad (3).$$

This clearly shows that the effect of daylight background can be made small by reducing the timing window t and narrowing the bandpass B.

As parametric sources have become brighter the main practical limitation is now actually the rate at which we can detect the idler. At present this is limited to around 10^7 /s in a single detector limiting the system to out-and-return losses $L_r > 10^{-7}$ to give a return counting rate of order a count per second per timing window. However these sources can be engineered to be inherently broad band and a source emitting across the visible and near IR could be envisaged. If we multiplex the time tagging and detection over many (>100) narrow wavebands, as illustrated in figure 1, this would decrease the minimum out and return loss to $L_r < 10^{-9}$. Using many narrowband channels effectively also reduces the background count rate this increasing signal to noise. In the following section we give a brief analysis of the limits to this enhancement.

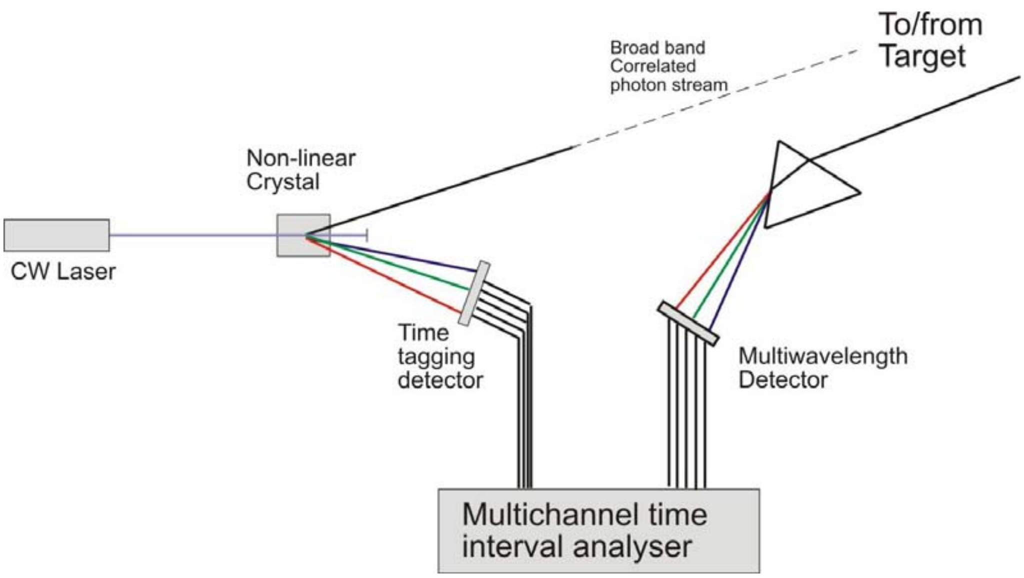

Figure 1: Multiwavelength parametric pair source used as a rangefinder. A broad band parametric source is used emitting energy-time correlated photon pairs which are separated into many small energy correlated spectral channels. The effect of background is then reduced by narrow band filtering into each channel.

The limit when using a hyperspectral pairwise entangled source

If we take a weak parametric pair photon source we see a wave function which includes hyperspectral entanglement through

$$\Psi \approx \sqrt{1-\alpha^2}\,|0> + \alpha\,|\omega_s, \omega_i> \qquad (1)$$

where we assume amplitude α is assume small enough to ignore higher terms. ω_s and ω_i represent single photons at signal and idler frequencies constrained by energy conservation

$$\omega_s + \omega_i = \omega_p \qquad (2)$$

This essentially ensures entanglement between frequency (energy) and time. The timing resolution achievable in a typical experiment t thus defines the minimum frequency uncertainty through

$$\delta\omega = 1/t \qquad (3)$$

thus limiting the number of independent frequency channels or hyperentanglement mode number

$$M = \frac{\Delta\omega_{s/i}}{\delta\omega} \qquad (4)$$

where $\Delta\omega_{s/i}$ is the phase matching bandwidth of the downconversion process. We now define a standard signal to noise ratio for a rangefinding system and then apply (from eqs (1), (2) and (4))

$$SNR = \frac{N_r}{\left(N_r + N_d\right)^{1/2}} = \frac{(\eta_s\eta_i RML_r)^{1/2}}{\left(1 + {tN_b B}\big/{ML_r}\right)^{1/2}} \qquad (5)$$

If we now redefine our daylight background in terms of photons/sec per unit angular frequency N'_b and exploit eq (3) .

$$SNR = \frac{(\eta_s\eta_i RML_r)^{1/2}}{\left(1 + {N'_b}\big/{ML_r}\right)^{1/2}} \qquad (6)$$

In the limit of high background the SNR increases linearly in *M*. Meanwhile as stated above the increased number of channels allows higher outgoing photon rates and thus more realistic losses and longer ranges that can be achieved in single channel; systems.

The question could be asked as to whether this is truly quantum enhanced rangefinding? Of course if we relate the number of modes to an entanglement dimension K such that $M = 2^K$ we could argue an exponential improvement in sensitivity with increasing K. The exponentially growing number of resources in terms of number frequency channels offsets this gain and we see this is not a truly quantum speed up. It does however tell us how many independent channels we can in principle use when requiring depth resolution $ct/2$. The fact that this is not truly quantum means we can mimic this capability with a suitably engineered frequency hopping classical pulsed source such as an extended version of that reported in [3]

Entanglement enhancement of sensitivity

The hyperspectral technique presented above does not exploit the full power of the quantum nature of the source and further sensitivity improvements might be achieved by extending this to a post selected multiphoton entanglement as schematically illustrated in figure 2. We now start with the two pairwise polarisation entanglement diluted by vacuum

$$\Psi \approx \sqrt{1-\alpha^2}\,|0> + {\alpha}\big/{\sqrt{2}}\left(|H_s, H_i> + |V_s, V_i>\right) \qquad (7)$$

emitted by a spontaneous parametric source. Of course this can easily be extended to time bin or other forms of entanglement but we specialise to polarisation here. In an ideal quantum world we can then store the signal photons locally in a quantum memory while sending the idler out through our rangefinding channel. In the real world we can detect using a simple polarisation analysis in the computation (H,V) basis and the storage can then be done simply by recording which binary outcome was achieved for each photon detected. Assuming unpolarised daylight background this is then halved by the detection scheme. However we can consider the detected photons in multiples of K each with random polarisation. The number of signal events will then drop by $1/K$ while the K-fold background drops by 2^K. Thus again we will see an apparent exponential gain in signal to noise. However because we work in the computational basis this coding can always be reproduced by a pseudo random polarisation train of classical laser pulses.

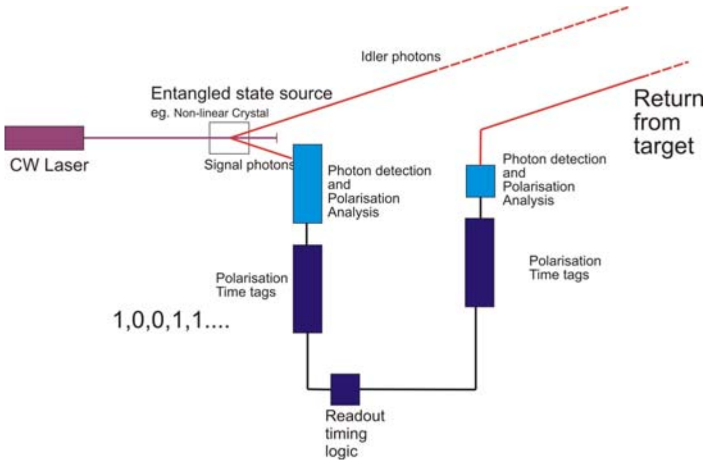

Figure 2: Schematic of a polarisation entangled range-finder.

3. Conclusions

We conclude that exponential signal to noise gain can be achieved by exploiting the quantum entanglement inherent in parametric sources used for rangefinding. However this signal to noise gain can be reproduced by suitably colour or polarisation encoded classical sources. This work does suggest a careful study of polarisation encoded classical sources should be done to assess whether the exponential gain expected from grouping returns together can be maintained in practice. Other works [4,5] have postulated finite gains from quantum sources which may not be achieved from classical systems.

We note however that all these proposed gains can always be offset by increased classical power thus only ‘dose limited’ applications will gain from this. Thus it is worth pointing out that one area where there is a gain from using a truly quantum source is when covertness is required. Using a multi-wavelength system as shown in figure 1 the spectrum of the outgoing beam can be engineered to be indistinguishable from the background illumination at the target in all aspects including the photon statistics. In a following work we will elucidate the limits to this covert rangefinding scheme

4. References

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