Design and Packaging of a Compact Entangled-Photon Source for Space Quantum Key Distribution

D. Bremner*[a], S. T. Lee [a], W. Dorward [a], S. Robertson [a], L. Caspani [b], S. Sorensen [b], L. McKnight [b].
[a]Optocap Ltd, 5 Bain Square, Kirkton Campus, Livingston, UK, EH54 7DQ; [b]Fraunhofer Centre for Applied Photonics, Level 5, Technology and Innovation Centre (TIC), 99 George Street, Glasgow, UK, G1 1RD.

ABSTRACT

Quantum Key Distribution (QKD) directly exploits the quantum phenomenon of entanglement to allow the secure sharing of a cryptographic key for information encoding. The current generation of QKD devices typically operate over dedicated and expensive private 'dark fiber' networks, where they are limited in transmission range to 200-300km due to the lack of quantum repeaters. This paper is concerned with an alternative approach that can lift this range limit by exploiting QKD over free-space links between satellites. Typically, commercial QKD systems rely on phase encoding of information on single photons, and more recently on continuously variable schemes with more powerful lasers. However, these protocols are not suitable for communications through atmosphere. On the other hand, QKD by polarization-entanglement holds great promise for satellite-based QKD encoded communications links if the entangled-photon source can be packaged in a compact, robust and commercially-viable form. This paper will describe the development and packaging of an entangled-photon source utilizing space-qualified telecoms packaging techniques, resulting in a compact device that targets satellite deployment. The key design choices that impact performance in a space environment will be discussed and the results of device characterization in the laboratory environment will be shared.

Keywords: Quantum Key Distribution, QKD, Entangled-Photon Source, space-qualified, telecoms packaging

1. INTRODUCTION

Quantum Key Distribution (QKD) directly exploits the quantum phenomenon of entanglement to allow the secure sharing of a cryptographic key for information encoding.[1] The current generation of QKD devices typically operate over dedicated and expensive private 'dark fiber' networks, where, with few exceptions[2], they are limited in transmission range to 200-300km due to the lack of quantum repeaters. This paper is concerned with an alternative approach that can lift this range limit by exploiting QKD over free-space links between satellites. Typically, commercial QKD systems rely on phase encoding of information on single photons, and more recently on continuously variable schemes with more powerful lasers. However, these protocols are not suitable for communications through atmosphere. On the other hand, QKD by polarization-entanglement holds great promise for satellite-based QKD encoded communications links[3] if the entangled-photon source can be packaged in a compact, robust and commercially-viable form.

Photon-pair sources based upon nonlinear parametric processes are well suited both for the requirements of entangled-photon production in QKD and for other applications that require photon pairs. The generation of two photons (the signal and idler photons) from a single pump photon occurs at 'the same time', resulting in a pair of photons that are highly correlated in time. This allows prediction of the existence of one photon with high temporal correlation by sacrificing (measuring) the other. This is called a heralded single photon source. These correlations are not strictly quantum in nature, however these photons are easily generated by a process that can also generate entanglement. In comparison to a very attenuated laser, this type of source generates true single photons rather than very few photons. Applications for photon-pair sources of this kind include heralded single photons for QKD (BB84-like protocols[4]), quantum optical coherence tomography[5], correlated imaging[6] and correlated spectroscopy[7].

*Douglas.bremner@optocap.com; phone +44 (0)1506 403 572; fax +44 (0)1506 403 551; optocap.com

In addition to producing temporally correlated photon pairs, these photons are entangled in polarisation. This means that the photons' polarisation is highly correlated regardless of the basis in which polarisation is measured. For example, if photon 1's polarisation is measured and found to be horizontal, the same holds for photon 2. If photon 1 is vertical, then photon 2 is also vertical. If photon 1 is +45°, photon 2 is +45°, etc. The choice of the measurement basis is made after the generation of photons, and there is no classical state that guarantees polarisation correlation in this manner despite the basis. This property can be used for secured quantum communication (E91-like protocols[8]), with application to satellite-to-ground, satellite-to-satellite or ground-to-ground links. One application could be in the upgrading of free-space optical communications links between buildings to enable quantum-security. Secure free-space communications between buildings with line-of-sight and ranges of tens of km can be very cost effective in comparison to the infrastructure cost of installing a dedicated fibre link.

This paper will describe the development and packaging of an entangled-photon-pair source utilizing space-qualified telecoms packaging techniques, resulting in a compact device that targets satellite deployment. The key design choices that impact performance in a space environment will be discussed and the results of device characterization in the laboratory environment will be shared.

2. OPTICAL DESIGN & BREADBOARD PERFORMANCE

The laser system developed in this paper is based upon on a paper by Steinlechner et.al.[1] Many of the features of this system are detailed in the Steinlechner paper and will not be discussed further in this short paper. The objective of this work is to move forward towards a packaged solution and to investigate the issues associated with that objective.

The laser system depends upon nonlinear parametric generation to produce entangled photon-pairs. The source employed is a single-transverse-mode 422nm laser diode, leading to a degenerate wavelength for the signal and idler outputs of 844nm.

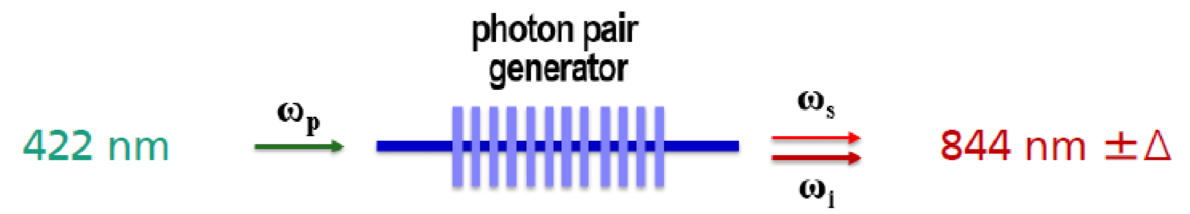

Figure 1. Parametric generation of a signal and idler photon pair at the degenerate wavelength of 844nm from a pump photon at the fundamental wavelength of 422nm.

Initial experiments to confirm system performance were carried out on a flexible breadboard setup, as illustrated in figure 2.

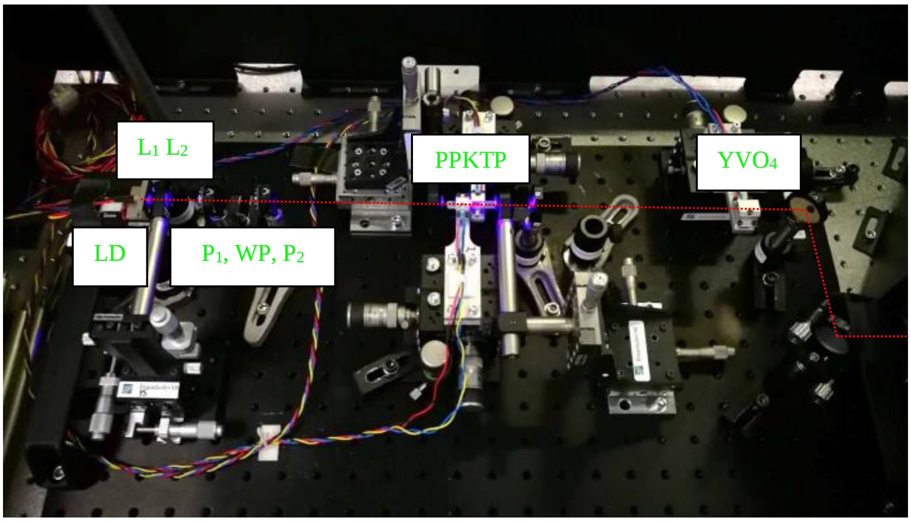

Figure 2. Breadboard entangled photon pair generator. LD is the laser diode pump photon source. L_1 & L_2 are collimation and focus optics. P_1 and P_2 are polarizers and WP is a waveplate for controlling intensity incident on the PPKTP. PPKTP is the two periodically-poled KTP crystals. YVO_4 is the yttrium vanadate crystal.

The 422nm laser diode source of pump photons was collimated with a single aspheric lens. While not the optimum optical solution for this function, this system does not require optimized nonlinear conversion efficiency and the single asphere for collimation gives adequate performance.

Generation of photon pairs occurs in two crossed periodically-poled potassium Titanyl phosphate (PP-KTP) crystals (Raicol). This solution allows the combination of two type 0 down-conversion processes for the generation of polarization-entangled photon pairs. The crystals are each 10mm in length and were specified with a 3.975μm poling period. The photon pair generation process was modelled, taking into account the Sellmeier equations for refractive index and dispersion, the phase matching conditions and the thermal expansion of the crystal[10]. The optimum waist size for conversion efficiency within the crystal was calculated to be 18μm[11]. This analysis was of great use in understanding the phase-matching behaviors encountered on building the system, as detailed below. The specified period was calculated to produce phase matching as shown in the 'theory' line on figure 3.

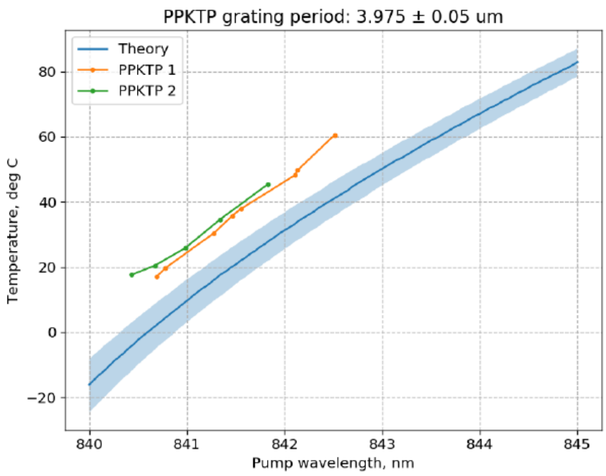

Figure 3. Phase matching temperature Vs wavelength. The 'Theory' curve shows calculated values for PPKTP with a grating period of 3.975 ± 0.05μm. For comparison, experimental results for two PPKTP parts are shown in the green and orange curves.

Figure 3 also illustrates experimental results of phase matching temperature Vs pump wavelength for two PPKTP parts. The performance achieved suggests that the poling period is 10-15nm shorter than specified value of 3.975µm. An equivalent graph calculated for a grating period of 3.960 ± 0.05µm is shown in figure 4.

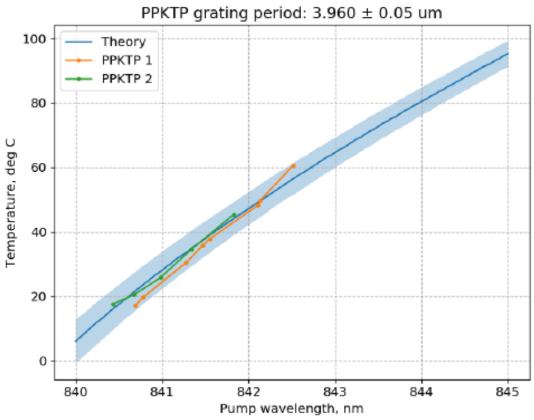

Figure 4. Phase matching temperature Vs wavelength. The 'Theory' curve shows calculated values for PPKTP with a grating period of 3.960 ± 0.05µm. For comparison, experimental results for two PPKTP parts are shown in the green and orange curves.

When manufacturing tolerances are considered, in addition to uncertainties in material parameters such as Sellmeier coefficients, it is difficult to specify the poling period and be confident that the manufactured PP-KTP part will phase match for the required wavelength. While temperature tuning can help with fine-tuning of phase matching, the change in temperature required for a small error in poling period can be large, so this is of limited use. If there is freedom to choose the pump wavelength, and corresponding freedom to choose the output wavelength, then this can also help to reduce the issue. Another route to minimizing the problem would be to move to a significantly longer wavelength. The poling period scales with wavelength, so it is simpler to hit the required tolerances at longer wavelengths

One of the changes made in comparison to the reference[9] for the purposes of miniaturization was to half the length of the PP-KTP crystals from 20mm to 10mm. As a result, we have larger bandwidth outputs, which appear to be approximately an order of magnitude larger than the literature. The output spectra measured for a range of temperatures with a 420.67nm pump wavelength are illustrated in figure 5.

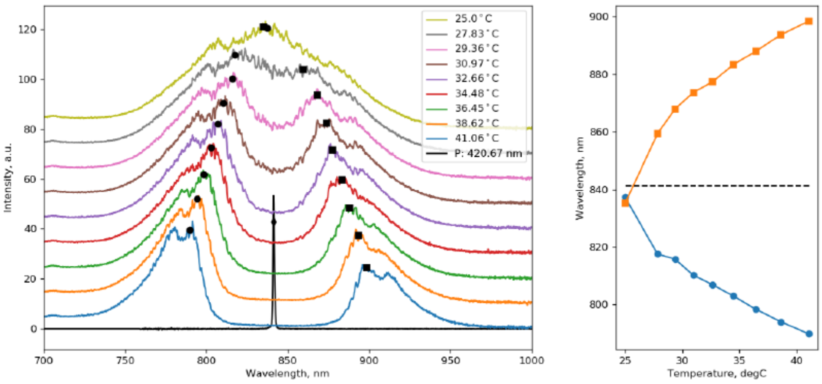

Figure 5. Output spectra obtained for a range of PP-KTP temperatures with a pump wavelength of 420.67nm, illustrating the large bandwidths produced

3. BREADBOARD SYSTEM COINCIDENCE DETECTIONS AND POLARIZATION ENTANGLEMENT

With the breadboard entangled photon-pair source completed we moved on to characterizing the usage of this source.

As a first step we characterized the pair emission from a single crystal, via coincidence detections. We filtered out the pump with a pass band filter, and used a frequency filter centered around ~841 nm to isolate degenerate photon pairs and remove the residual pump. We then separated signal and idler photons with a non-polarizing 50/50 beam splitter. While this is not the optimal choice, it is still valid for characterizing the down-conversion emission and the polarization entanglement. Non-degenerate phase matching with dichroic filters could be used instead, but the broad signal and idler spectrum we measured effectively limited the use of frequency filters. We used two single photon detectors (idQuantique ID120) and a time-to-digital converter (idQuantique ID900) to collect coincidence counts for varying pump powers. As expected, the coincidence to accidental ratio (CAR) decreases for increasing pump power after a certain value (see Fig. 6), with the optimal pump power still to be determined, but expected in the tens of μW range.

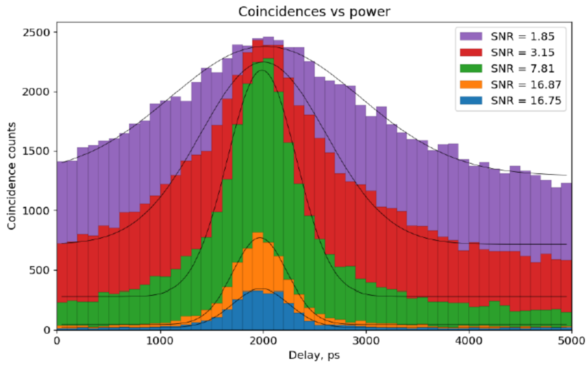

Figure 6. Coincidence peaks for increasing pump powers (blue plot, lower power – purple plot higher power).

We then investigated the variation of the coincidence peak Vs crystal temperature, effectively changing the emission wavelength of the signal and idler pairs (see also Fig. 5b). The results are reported in Fig. 7, where in the first line we show the spectrum of the down conversion emission, while the second line reports the corresponding coincidence peaks. For decreasing temperature the phase matching condition approaches degeneracy and the CAR increases as more and more degenerate photons are collected by the frequency filter (black line in Fig. 7). The abrupt cut in the red part of the spectra is due to the pass band filter used to remove the pump radiation.

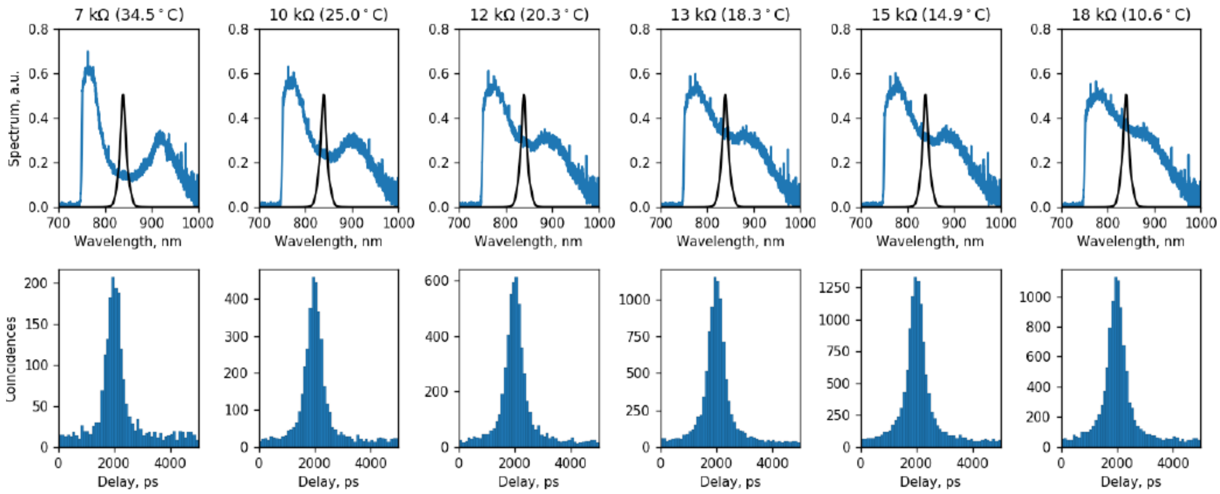

Figure 7. Spectrum (top) and coincidence peak (bottom) for different PPKTP temperatures.

The optimal condition was then used for a very preliminary test of entanglement. For this, we introduced tunable polarization filters (half wave plates plus polarizers) before the single photon detectors and we measured the coincidences for different settings. While a proper entanglement characterization has not been performed yet, we obtained promising preliminary results showing highly signal/idler correlated polarization in the H/V basis and some degrees of correlation in the +45/-45 basis (Fig. 8). Further measurements and set up optimization are required to prove entanglement and test the limits of this source.

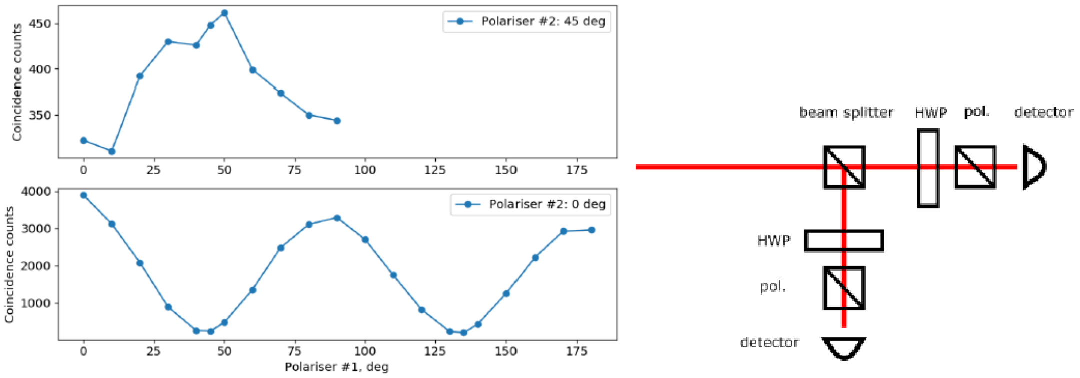

Figure 8. Coincidence counts as a function of the signal polarizer angle for two different settings of idler polarizer (0 degree for the H/V basis case and 45 degree for the diagonal basis).

4. DEVICE PACKAGING

With the performance of the breadboard entangled photon pair source demonstrated, the next step in developing a compact and robust source for real-world applications is to package the system. Figure 9 shows a diagram of the layout of the packaged system.

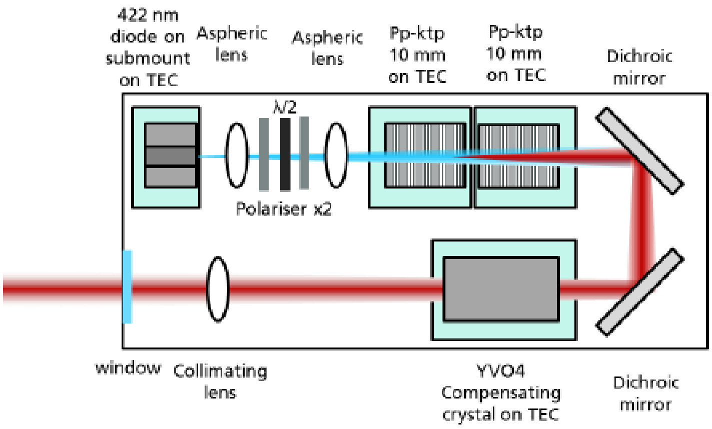

Figure 9. Layout of the packaged entangled photon pairs generator

The prototype packaged module is shown in figure 10 during manufacture. To enable usage of this source in real-world applications, and the target of space-borne applications, the packaging methods employed are selected from telecoms and space-qualified processes to ensure stability and reliability. Cleanliness and low-outgassing of components is ensured via the use of gold-coated metal components, flux-free soldering, low-outgassing space-qualified adhesives and proven cleaning techniques throughout. Production time is minimised while maximising repeatability via automated wirebonding and by utilising pick and place alignment of many components.

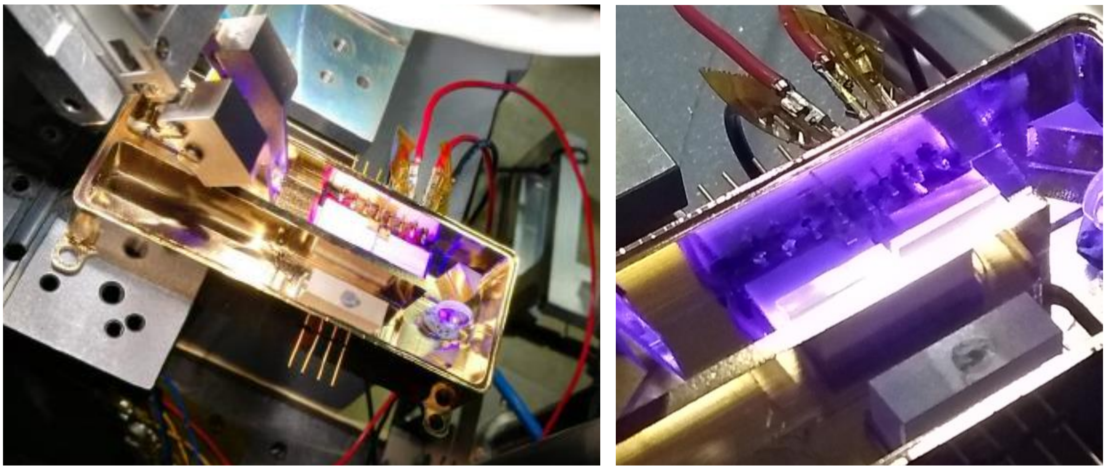

Figure 10. The entangled photon pairs generator during build.

On completion, the packaged device was found to produce slightly different results than the breadboard. The phase matching of the packaged unit behaves as if the period of the PP-KTP is 10-15nm shorter in this device than was observed in the breadboard system. This could be down to mounting stresses, or due to differences in the crystals themselves. The mounting of the crystals is somewhat different in this packaged unit where crystals are bonded directly to their TECs, rather than held in mechanical mounts via compression. This could explain different stresses on the crystals in each environment. Considering the high sensitivity of phase matching to length and refractive indices there can be many contributions to these differences and further work will investigate controlling these factors.

5. CONCLUSIONS

We have demonstrated an entangled-pair photon source, suitable for applications to QKD. Engineering work to package the system in a compact and robust format has begun and produced a first prototype. Future work will concentrate on understanding repeatability in phase-matching and optimizing the build processes for the production prototype further. A simplified configuration for applications that require correlated photon pairs without the need for entanglement will also be considered.

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