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High Altitude Demonstration of Correlated Photon Source for Satellite-Based Quantum Key Distribution

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***Abstract*—We report the design and implementation of a small and power efficient system for producing and monitoring high quality correlated photon pairs. The system is implemented in a ruggedized package and is brought to 35.5km above sea level by a weather balloon to test its robustness. This compact and rugged photon pair system is suitable for deployment on low-resource platforms such as remote nodes of a quantum key distribution network hosted on nanosatellites.**

Keywords—nanosatellites; correlated photon sources; quantum information

I. INTRODUCTION

Quantum communications such as quantum key distribution (QKD) have attracted much interest and attention since they were first proposed [1,2] due to superior privacy guarantees provided from quantum mechanics. Entanglement-based QKD protocol has distinct advantages over other implementations. For example, a certified random number generator, which itself would be a challenging implementation, is not needed. Currently, polarization-entangled photons are among the best candidates to be used because of reliable analyzing elements yielding high-fidelity measurements as well as low decoherence [3,4].

One of the goals of current QKD research is to be able to extend the protocol to a global scale. To extend the distance limit, it has been proposed that orbiting satellites could be used for free-space links to bridge distant locations on Earth [14-16], thus solving line-of-sight problem as well as reducing atmospheric scattering on Earth [4]. With the high cost in launching as well as long development circle for big satellites, nano-satellites which operate at Low Earth Orbit (LEO) have emerged to be an attractive testbed for space experiments. We present a correlated photon pair source which is designed to fit into a 1U CubeSat. This device is a prototype for a full polarization-entangled photon pair source. To demonstrate the robustness of the device, we operated it in near-space conditions using a helium filled weather balloon.

II. SYSTEM DESIGN

The basic schematic layout of the source is shown in Fig.1. All optical elements are secured in an optical unit made of aerospace grade aluminum. The correlated photon pairs are generated through type I spontaneous parametric down-conversion (SPDC), pumped by a laser diode with built in volume holographic gratings to ensure a narrow center wavelength at 405nm. The laser, which is single mode and collimated, passes through a 405nm filter to remove potential fluorescence from the diode. The half wave plate (HWP) aligns the pump photons to the optical axis of the beta-barium-borate (BBO) crystal (5mm cube) to maximize the downconversion process. The un-converted 405 nm photons are channeled to a photodiode by dichroic mirror (DM) for monitoring of the optical power in the system and a long pass filter (LP) are implemented to clean up any residue pump photons.

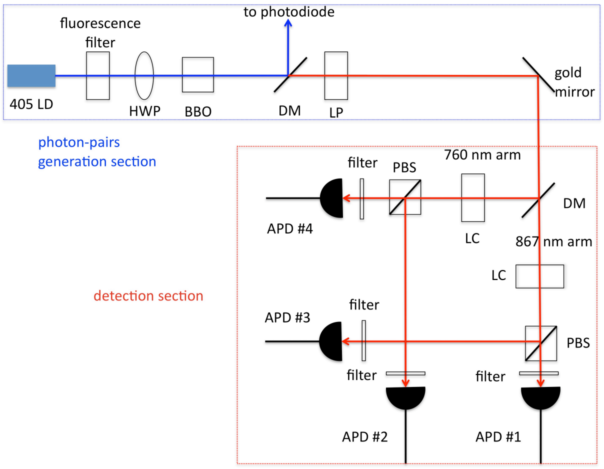

Fig. 1. Simple schematic of the optical unit. Correlated photon pairs at 760 and 867nm are generated via type I SPDC pumped by a 405nm laser diode through beta-barium-borate (BBO). Various pass filters are used in generation section to clean up the residue pump photons in the source. The photon pairs enter the detection section with 2 sets of avalanche photodiode (APDs) that can perform detection independently.

The down-converted photons, at 760 (signal arm) and 867nm (idler arm) respectively, are split by a dichroic mirror and sent to their detectors. A metal mirror is used to fit the optical unit to a 10cmx10cm printed circuit board, a physical constraint imposed by nano-satellite platform. We have replaced standard motorized polarizers with liquid crystals (LC) as polarization rotator for correlation measurement. This ensures minimal power and space consumption. It also eliminates the potential mechanical unstability arising from the torque produced by a mechanical rotator in free-space. The LC devices are wavelength optimized for the correlated photons and an extinction ratio above 100 when calibrated with a polarization beam splitter (PBS). By using two pairs of silicon avalanche diodes (APDs), we have implemented a degree of redundancy in our detection system. They can be operated independently and provide a back up plan should one set of the detectors be damaged by radiation in space. A toolkit is developed to align the crystals in optical unit and these elements are later secured using epoxy.

With 9 mW pump power and APDs with active area of 500micron in diameter, we detected single count rates of 360,000 and 330,000 per second in signal (APD#4) and idler (APD#1) arms, with coincident events of 4500 per second. The differences in the single count rates for each pair is due to the wavelength-dependent detection efficiency of silicon APDs. For the automated data collection in detector pairs, we apply a voltage to LC that enables maximum transmission of horizontally polarized photons to the idler detectors. The rotator for the signal photons is then stepped through a series of voltages that correspond to a full polarization of 2π. A similar protocol is applied when using APD#2/#3 pairs. A typical data set yields about 93±1% visibility in controlled laboratory environment with 9ns coincidence time window.

The optical unit is secured to a 6-layer printed circuit that also houses the control electronics. The electronic sub-system is built around a Programmable System-on-Chip (PSoC). In general, the PSoC monitors and adjusts the temperature of the optical unit through heaters installed. The optical power of the laser is maintained by PsoC through a feedback loop. The liquid crystal rotators and APDs have dedicated control circuits. In particular, we have designed a novel control circuit for the APDs that requires approximately 0.25W per device. At this power level, the APD can operate with a fixed detection efficiency over a 40 degree temperature range[17].

III. HIGH ALTITUDE TEST

The device is placed inside a foam box along with three environmental sensors: accelerometer, pressure and humidity gauge. The package runs on a set of 6x1.5V lithium ion batteries. An instrument package consists of GPS tracker and radio beacon is attached to the balloon. The total mass of the whole package is around 2kg while the balloon provides a lift force equivalent of 3kg.

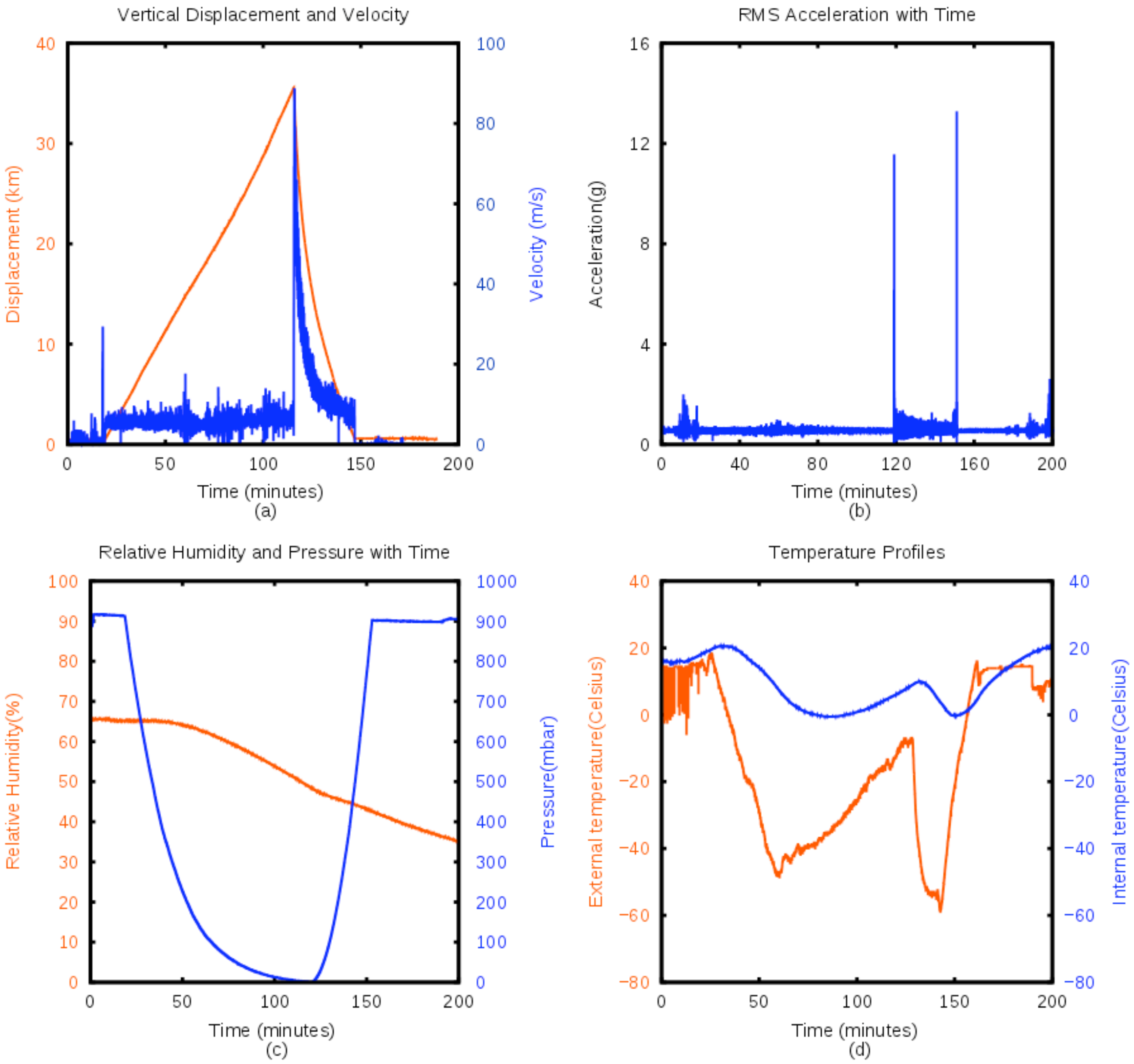

Fig. 2. Conditions experienced by the photon pair system during the test flight.

The device was activated 15 minutes prior to the release of the balloon for system checking. The release point was in Sursee, Switzerland and the package landed at Kirchberg. The whole journey, which took around 2 hours, covers more than 130km and reached a ceiling attitude of 35.5 km above sea level. The package was then recovered after landing and all experimental data were successfully retrieved.

From the 15th minutes to 118th minute the package ascended almost uniformly at 5 m/s. It reaches ceiling altitude of 35.5 km at around 118th minutes and started to free-fall after the explosion of the weather balloon. The initial free-fall velocity registered around 90 m/s and slowed down to terminal velocity at around 10 m/s before landing on the ground (Fig. 2(a)).

To study the acceleration experienced, 3-axis root-mean-square (RMS) acceleration for the source are plotted in Fig. 2(b). The accelerometer can measure up to 16g with 13-bits resolution and less than 0.1% inter-axis alignment error. The base value of 1g is due to the Earth's gravitation in Z-axis. The early fluctuations is due to the initial drag from the weather balloon during take off. There are two large acceleration events at the 118th minutes and 151st minutes in the otherwise uniform graph. The first peak corresponds to the burst of the weather balloon has an RMS value of 11g. The next higher peak has a value of 13g and marks the landing of the source. This data gives good confidence in the ability of the source to withstand shocks.

Low pressure experienced in near-space may reveal sources of outgassing that can coat optical surfaces leading to degradation of correlation quality. The pressure on the ground is 960 mbar during launching and landing while the the lowest is 10 mbar when the source is at its highest altitude. There was no evidence that pressure changes affected the performance of the source.

The temperature profile for the experiments is shown in Fig. 2(d). One thermistor is exposed to external environment while another thermistor register the temperature inside the foam box. Both temperature profiles show troughs which occur when the device ascends and descends through the jet stream. While the external temperature varies from -60 and 20^{o}C, internal temperature varies from 0 and 15^{o}C. This is a good indicator for the possible implementation on nano-satellite platforms on a LEO because the typical temperature range is around -5 and 15^{o}C [18].

The average visibility throughout the experiment is around 93±1%. There is no significant change in performance compared to the laboratory baseline measurements despite of large of amount acceleration and drastic temperature experienced.

IV. CONCLUSION

We have developed and tested a compact source producing high-quality correlated photons. Our test results demonstrate that the integrated source and detector package survives in a near-space environment without human intervention. The design of the system can be readily extended to an polarization entangled photon source. The minimal space and power consumption for the system is ideal for many mobile platforms ranging from nano-satellites to small unmanned aerial vehicles.

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