Opto-mechanical design and assembly of a Sagnac configuration of Entangled Photon Source for space applications: preliminary results

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1. Introduction

Entangled photon pairs are a key resource for a number of applications of quantum physics, such as quantum teleportation [1] and quantum cryptography [2]. A vital step towards the global-scale implementation of such applications via ground-to-satellite and inter-satellite links is the development of robust, space-proof entangled photon sources (EPS). In a simple description, entangled photons can be considered a pair of particles which are intimately correlated. In fact they are part of the same quantum state: any measurement on one of them affects the state of the other. Photon pairs can be entangled in a number of degrees of freedom (e.g. time, energy, momentum, polarization), whereby polarization-entanglement is the most established for applications in free-space optics. In this case, both photons are anti-correlated in their polarizations, i.e. measuring one particular polarization for one photon yields a perpendicular polarization state for the partner photon – the two photons are entangled irrespectively of their spatial separation (Einstein referred to this as *spooky action at a distance*).

To date the best-developed method for the generation of photon pairs is spontaneous parametric down-conversion (SPDC) in second-order nonlinear crystals. In the SPDC process, a high energy pump beam (λ=405nm) spontaneously can produce a pair of photons at lower energy (λ=810nm). The efficient generation of photon pairs requires very strict characteristics on the illuminating beam, such e.g. its size, shape, and polarization state. For these photon pairs to be entangled in their polarizations there must be a superposition of two distinct pair-generation possibilities each with orthogonal polarized photon pairs. To achieve this with a single nonlinear crystal we have chosen a set-up based on Sagnac interferometer [3]. Thus, beams must travel equal optical paths along both sides and focus on the crystal at the same point.

2. Description of the device and functioning principles

The EPS is composed of two different devices: the light source (EPS tube) and the Sagnac structure. The light source focuses the beam at a certain distance, with particular size, shape and polarization state. It is formed by a laser diode (ND405 by Nichia), two wave-plates (λ/4 and λ/2) and several lenses. The laser diode emits with different divergence in each axis and therefore two plane-cylindrical lenses are necessary to generate a Gaussian beam with circular symmetry. Besides, polarization of the beam must be circular, a priori, and manually variable to generate entangled photon pairs with different entanglement characteristics. The Sagnac structure splits the beam into two and guides them to the non-linear crystal. The Sagnac loop is composed of a dichroic mirror, polarizing beam splitter, a dual-wavelength half-wave plate, two mirrors, a non-linear periodically poled KTiOPO4 (PPKTP) crystal and two pigtailed fibers.

The functional principle of the complete device is depicted in Fig. 1. The beam emitted by the laser diode passes through lens L1, two wave-plates (QWP1 and HWP1) and lenses L2, L3 and L4. Lenses L1 and L2 are aspheric lenses. On the other side, L3 and L4 are cylindrical lenses. Wave-plates make polarization of the beam circular. We have chosen this pair of wave-plates based on experience. Once the beam has the appropriate characteristics, it is guided to the Sagnac structure by means of a dichroic mirror (DM1). Subsequently, a polarizing beam splitter (PBS) is used to divide the beam into two. After that, both beams are reflected and focused into the PPKPT crystal.

Entangled photon pairs are generated with high efficiency at the crystal by achieving the correct pumping. This depends on the size, shape, phase and polarization of the beams. Besides, both beams must overlap along the whole Sagnac loop (collinear). The photon pairs generated in the counter-clockwise propagation direction are then flipped via the dual-wavelength half-wave plate (HWP2). The orthogonally polarized photon pairs from counter-clockwise and clockwise arms of the Sagnac loop are then recombined on the PBS and collected via the pigtailed optical fibers (L5-1 and L5-2).

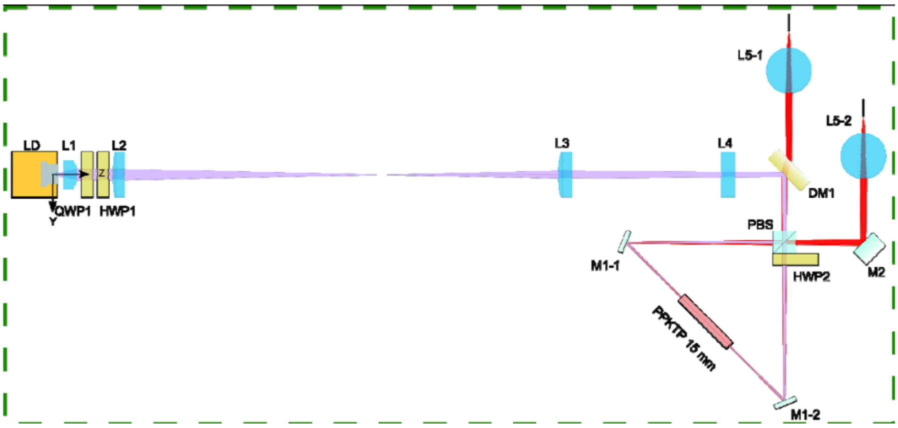

Figure 1 Scheme of the Entangled Photon Source.

3. Opto-mechanical design and environmental considerations

The scope of applicability of the present device is the higher handicap. The compatibility of an entangled photon source with space environment is one of the key factors in the development of this kind of source. The design of the device must be compact, robust and efficient.

As it can be observed in Fig. 2, the whole device has been made ad-hoc of aluminum and it is highly robust. The total size is 30x17x11 cm. The EPS tube (surrounded by the red ellipse) is place at the left side and the Sagnac structure and pigtailed optical fibers (surrounded by the blue circle) at the right side of Fig. 2.

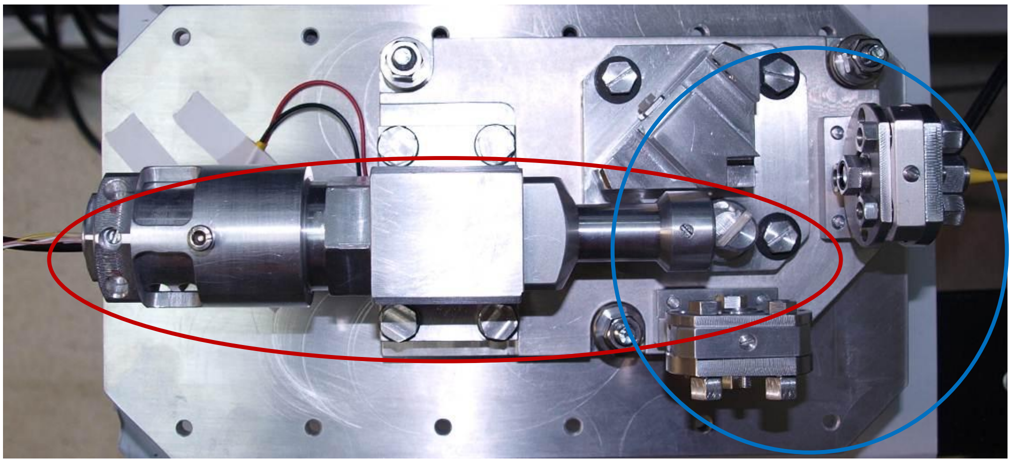

Figure 2 Entangled Photon Source assembled.

The complexity of the device is mostly due to robustness imposed by the application. Each optical and mechanical element must be able to be positioned with positioning tolerances below the micrometer limit. Besides, after positioning, all elements must remain without moving more than one micrometer even exposed to the launch acceleration. Therefore, all components must be strongly fixed. In Fig. 3a depicts a detail of the EPS, the Sagnac block and one pigtailed optical fiber holder.

Additionally, temperature variations are also very important. Laser diode emission wavelength is highly dependent on temperature. Two Peltier modules are used to assure stable operation temperature. We show in Fig. 3b the Peltier in charge of controlling the LD temperature. It is connected to the LD by several tapes of copper.

4. Assembly of the Entangled Photon Source

The assembly of the EPS has been performed by modules. Firstly, the EPS tube was assembled lens by lens until obtaining the desired focal point. The EPS tube must be accurately aligned. In addition, distances between lenses and LD must be exactly those previously calculated. Mobile parts inside the EPS tube are the laser diode (xy-axes), lens L3 (x-axis) and L4 (y-axis). Other optical elements are fixed by the mechanical mounting.

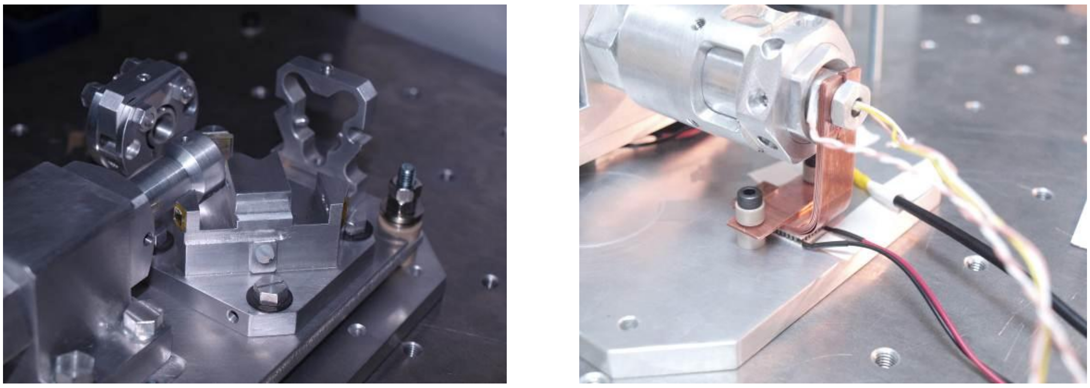

Figure 3 a) Sagnac block and pigtailed optical fiber holder, b) Peltier module for cooling/heating the laser diode.

After the assembly of the EPS tube, it has to be joined to the other parts of the device. The Sagnac structure can be divided into three parts: Dichroic mirror, Sagnac block and pigtailed optical fibers. Optical fibers can be assembled at the end of the process but EPS tube, dichroic mirror and Sagnac block must be assembled at once. Due to required robustness, the degrees of freedom to align all elements are limited. Supposing all parts are aligned in the xy plane, only slight rotations allowed by screws are possible. In addition, all elements are glued to add robustness but diminishing degrees of freedom for alignment.

Alignment of all parts was assisted by illuminating the structure from one of the outputs. Thus, by illuminating through one pigtailed fiber, the beam should go out the Sagnac through the other one. Once this fact is achieved, we may assure the correct alignment of the whole Sagnac structure. After that, the dichroic mirror and the EPS tube can be aligned according to the Sagnac structure.

5. Preliminary results

Some numerical calculations have been performed before carrying out the experiment. The theoretical beam waists of the focal spot are given in Table 1. Two different formalisms have been used, ABCD formalism and Zemax software. Both formalism give quite similar results.

	X axis waist		Y axis waist	
	Position	Size	Position	Size
ABCD formalism	-0.110 mm	16.080 µm	-0.110 mm	19.478 µm
Zemax	-0.112 mm	16.078 µm	-0.112 mm	19.470 µm

Table 1 Theoretical and numerical calculations of the focal spot waist.

On the other side, an example of the measured focal spot after aligning the whole EPS tube is shown in Fig. 4. It is circularly symmetric and its dimensions are very close to those estimated with the calculations (around 20 micrometer diameter).

The Gaussian fits to both profiles are also shown in Fig. 4. From these fittings, the waists in both axes result $\sigma_x=12.1\ \mu m$ and $\sigma_y=15.15\ \mu m$, where $y=A\ exp[(x-x_0)^2/2\sigma^2_{x-y}]$. As can be noticed, experimental beam waists are slightly smaller than theoretical ones.

6. Mechanical and environmental tests required for space applications

For space applications, a preliminary evaluation of optical elements and integration assessment of representative opto-mechanical test samples requires a series of environmental, radiation and mechanical tests in order to evaluate its compatibility for space environment. The series of tests include:

Operating temperature range: To evaluate that selected parts remain functional and stable in a specified temperature range. Required temperatures are in the range of -55 ^{o}C to +125 ^{o}C.

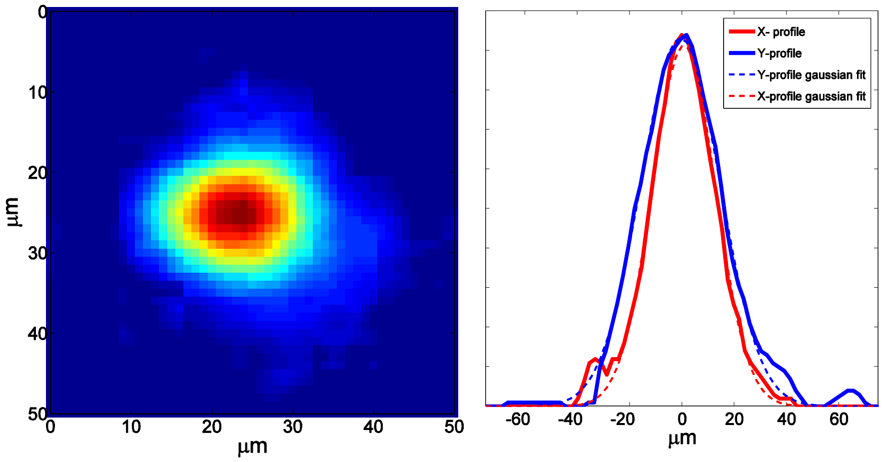

Figure 4 a) Experimental focal spot, b) profiles along x and y axes.

Vibration and accelerations: Parts and system should be capable to withstand strong vibration (random, sine and shock) conditions and accelerations during system launching.

Thermal cycles: To verify that mechanical parts do not degrade due to exposure to extreme temperature cycles produced during its rotation around the Earth

Vacuum atmosphere: To assess the optimal and stable performance under vacuum conditions. Any unit must be designed to withstand a depressurization rate of 26 Torr/s from ambient pressure down to 10^{-10} Torr in free space.

Proton, gamma and heavy ions irradiation: To estimate the potential damage caused by the exposure of the parts to radiation sources that are present in space atmosphere. Total Ionization Dose: up to 150 krad (Si), displacement damage up to a total accumulative dose of 2x10cm^{-2} using a 65MeV proton source and single event transient up to 60MeV/mg/cm^{-2} are good examples to be applied on the critical components.

7. Conclusions

We have designed, manufactured and assembled an Entangled Photon Source for space applications. A focal spot with the same dimensional characteristics as the one theoretically calculated has been achieved. Mechanical stability of the spot has been proven in laboratory conditions. In addition, global stability including the Sagnac structure has been also proven in laboratory by monitoring the output of the optical fibers during a month. This work establishes a reliable basis for future design and assembly of compact and robust Entangled Photon Sources for space and terrestrial applications.

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