Deliverable Report

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Name, title and organization of the scientific representative of deliverable's lead beneficiary (task leader):

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Deliverable table

Deliverable no.	D1.3
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D1.3 Intermediate cavity-enhanced SPDC: Intermediate report with a first analysis of the performances of the cavity enhancement approach for OAM SPDC generation. Designing a proof-of-principle OAM parametric oscillator
[Excerpt from GA-Annex I DoW]

Figure 1 shows our first proposal of an Optical Parametric Oscillator (OPO) aimed at generating the two optical beams required for Stimulated Emission Depletion (STED) microscopy. STED requires the use of two pulses: an excitation pulse with a Gaussian-like shape (*excitation wavelength*), and a STED pulse that is red-shifted (*STED wavelength*), and that presents a vortex-like spatial shape. The scheme considered here is a modified version, adapted for its use in STED microscopy, of the scheme put forward in Ganikhanov et al., *Broadly tunable dual-wavelength light source for coherent anti-Stokes Raman scattering microscopy*, Opt. Lett., 31, 1292, 2006) and Wolfgramm et al., *Bright filter-free source of indistinguishable photons*, Opt. Express, 16, 18145, 2008).

A nonlinear crystal designed for non-degenerate parametric down-conversion (pump → signal + idler) is placed inside an optical cavity which is singly-resonant with the idler wave. An important aspect of the scheme considered is that the cavity is not tuned to the fundamental Gaussian beam (indexes l=0 and p=0), but instead to a Laguerre-Gauss mode with indexes l=±1 and p=0. This is due to the fact that while the wave associated to the excitation wavelength (pump in Figure 1) presents a spatial Gaussian-like beam, the wave associated to the STED wavelength (signal in Figure 1) should present a vortex-like spatial shape. If the idler beam is resonant for mode with index l=±1, the signal beam will show a spatial shape corresponding to a Laguerre-Gauss mode with index l=±1.

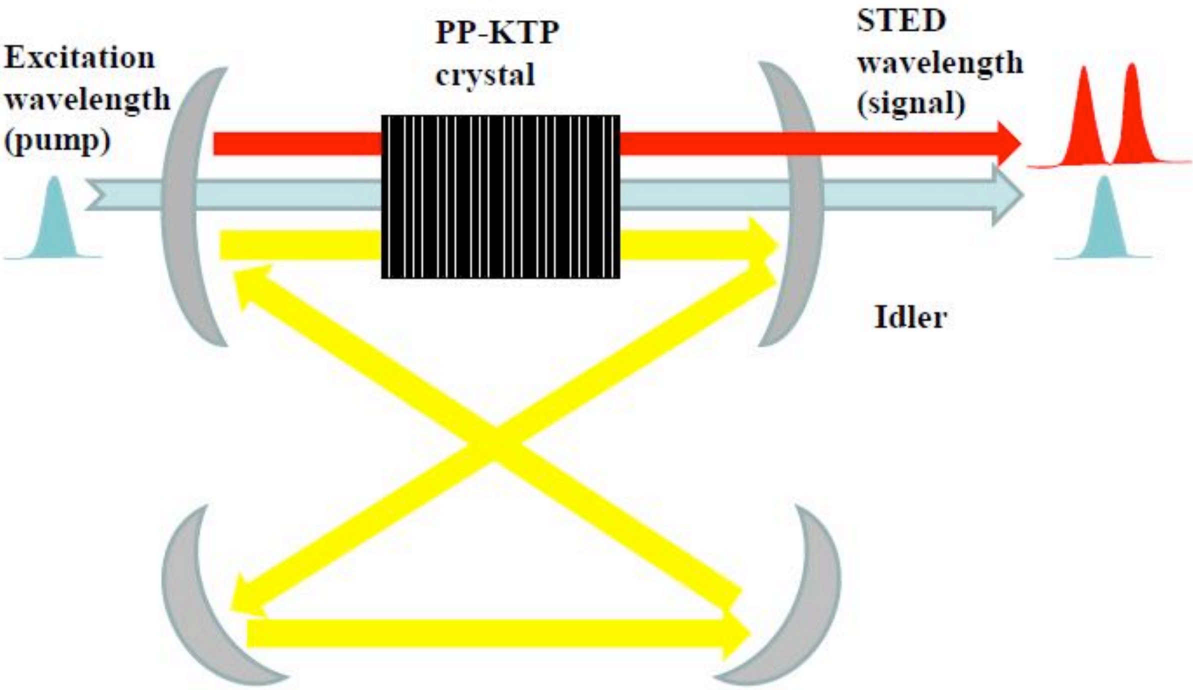

Figure 1. OPO for a STED microscopy scheme. The cavity is resonant to the idler beam (yellow). The pump beam (blue), which is the excitation wavelength, shows a Gaussian-like spatial shape, while the signal beam (red) presents a vortex-like spatial structure with a dark spot at the center. All cavity mirrors are highly reflecting at the range of wavelengths of the idler, and highly transmitting at the wavelengths of the pump and signal beams.

In the paper,

> Silvana Palacios, R. de J. Leon-Montiel, Martin Hendrych, Alejandra Valencia and Juan P. Torres, *Flux enhancement of photons entangledin orbital angular momentum*, Optics Express **19**, 14108 (2011)

(part of deliverable D1.2), which acknowledges the support of Phorbitech, we obtain optimum conditions to maximize the flux of photons with non-Gaussian spatial modes (l=±1,p=0).
The resonance frequency of the cavity reads

$$f_{n,l,p} = n\frac{c}{L} + \frac{2p + |l| + 1}{2\pi L}\tan^{-1}\frac{\lambda L}{\pi w_0^2}$$

As an example, for a cavity length L=600 mm, idler beam waist w_0=30 μm and idler wavelength λ=1 μm, the free spectral range is 500 MHz, and the resonance frequencies of the (l=0, p=0) and (l=±1, p=0) modes are separated 124.63 MHz and 249.25 MHz from the reference plane-wave resonance frequency (c/L). Even though the fact of building an optical cavity for a non-Gaussian mode is uncommon, there are reports about cavities resonant to higher-order Laguerre-Gauss modes. This is the case reported in Granata et al*., Higher-order Laguerre-Gauss mode generation and interferometry for gravitational wave detectors*, Phys. Rev. Lett. 105, 231102, 2010), where a cavity resonant to the mode with indexes l=p=3 was used.

Finally, let us remark *three potential advantages* that the use of the configuration depicted in Figure 1 in a STED microscopy scheme could bring:

- *The use of a single laser to generate the two wavelengths required (excitation and STED wavelength).* The excitation wavelength, which comes from a laser source, serves as pump beam in an OPO, which generates two new wavelengths. The signal wave serves as the STED wavelength.

- *The value of the STED wavelength can be varied by tuning the temperature of the nonlinear crystal.* KTP shows a high damage threshold and is transparent over a large wavelength range: 350-4500 nm (see Fradkin et al., *Tunable midinfrared source by difference frequency generation in bulk periodically poled KTP*, Appl. Phys. Lett. 74, 914, 1999). Let us consider an excitation wavelength of 488 nm that have been used in several STED experiments (for a list of experiments and dyes used in STED experiments, see S. Hell group webpage at Max Planck Institute for Biophysical Chemistry, Gottingen, Germany). The dye GFP makes use of an STED wavelength of 575 nm, while DY-485XL uses 647 nm. In between these two wavelengths, other dyes make use of intermediate values: Citrine and FITC (592 nm), Chromeo 488 (592 and 602 nm), ATTO 532 (600 or 615 nm). Therefore, for a 488 nm excitation wavelength, there is a range of wavelengths of 72 nm for the STED wavelength. If the required STED wavelength is 575 nm, the corresponding idler wavelength is 3225.3 nm, while if the STED wavelength is 645 nm, the idler wavelength is 1985.8 nm. These are the tunability requirements. Fortunately, these values are well inside the range of wavelengths that can be tuned in a KTP crystal (see Emanueli and Arie, Temperature-dependent dispersion equations for KTP and KTA, Appl. Opt. 42, 6661, 2003).

- *The generation of excitation and STED pulses aligned by design.* The excitation and STED pulses should be properly aligned to achieve the maximum resolution. In most cases, the excitation and STED pulses use separate optical paths before, so alignment, and therefore resolution, could deteriorate due to mechanical drifts. Experimental schemes have been devised to guarantee a proper alignment in a general way (see Wildanger et al., *A STED microscope aligned by design*, Optics Express, 17, 16100, 2009). In the scheme proposed here, the STED pulse is a Laguerre-Gauss mode that is automatically aligned with the excitation pulse, which shows a Gaussian spatial shape.