PROJECT PERIODIC REPORT

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Project acronym: PHORBITECH

Project title: “A Toolbox for Photon Orbital Angular Momentum Technology”

Funding Scheme: FET-Open

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Periodic report: 1st ☒ 2nd ☐ 3rd ☐ 4th ☐

Period covered: from 1st October 2010 to 30th September 2011

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Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate):

  ☐ has fully achieved its objectives and technical goals for the period;

  ☒ has achieved most of its objectives and technical goals for the period with relatively minor deviations.

  ☐ has failed to achieve critical objectives and/or is not at all on schedule.

- The public website, if applicable

  ☒ is up to date

  ☐ is not up to date

- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: Lorenzo Marrucci

Date: 26/ 10/ 2011

For most of the projects, the signature of this declaration could be done directly via the IT reporting tool through an adapted IT mechanism.

1 Publishable summary

1.1 PHORBITECH context and objectives

A beam of light, besides energy and momentum, can transport also *angular momentum*. In particular, the angular momentum of light is typically associated with its polarization, and more specifically with its circular polarization components. An optical beam travelling in the positive direction of the z axis that is circularly polarized carries a z-component angular momentum content of $\pm\hbar$ per photon, which is positive if the circular polarization is left-handed and negative if it is right-handed. This angular momentum content is not just a formal property, but a very concrete one that can have significant mechanical effects: it can be for example transferred to a material particle so as to set it in rotation.

Less widely known is the fact that there is a second way a light beam can carry angular momentum, in addition to polarization, which is associated with the transverse spatial structure of the wavefront. More precisely, this angular momentum appears when the wavefront acquires a "helical" structure, or equivalently, its field spatial dependence contains a helical phase factor having the form $\exp(im\varphi)$, where φ is the azimuthal phase of the position vector $\mathbf{r}$ around the beam axis z and m is any integer (positive or negative) providing the "degree of helicity". It can be shown that in this case the optical beam carries an angular momentum along its axis z that is given by $m\hbar$ per photon, *in addition* to the polarization one. By analogy with the case of elementary material particles such as electrons, this second form of angular momentum is called *orbital angular momentum* (OAM), while the first form associated with polarization is referred to as *spin angular momentum* (SAM). When m is nonzero, the helical phase factor imposes the existence of an *optical vortex* at the center of the beam where the light intensity vanishes. These concepts are pictorially illustrated in Fig 1.1.

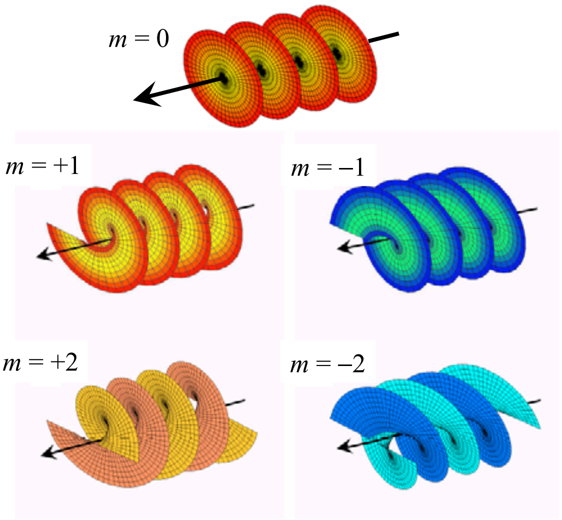

Fig. 1.1 – Wavefront shape of optical beams carrying orbital angular momentum (OAM).

Besides its fundamental scientific interest, OAM is recently emerging also as a possible new resource for future photonics information technology. In general, OAM can be seen as an additional internal degree of freedom of a light beam or even of a single photon, to be added to the standard ones ordinarily exploited in current photonic technology. In many respects OAM resembles polarization, with which it shares many features (e.g., the association with angular momentum, the fact of being an attribute of a single light beam or even a single photon, the discreteness of its possible values, the enhanced stability that fundamental conservation laws confer to such values, the possibility of using fruitful geometric-topological descriptions, such as the Poincaré sphere, etc.). However, while polarization is characterized by two orthogonal basis states, OAM is defined in an unbounded space (a Hilbert space in the case of photons). Therefore, it is in principle possible to encode a much larger amount of information in the OAM degree of freedom than in the case of polarization, e.g., achieving a greater channel capacity as well as allowing for more secure communication protocols. This makes OAM highly attractive for future photonic applications.

In spite of the many important results that have been achieved since the OAM research field began, at the time the PHORBITECH project was started OAM remained a largely unexploited resource, owing to its rather difficult and inefficient manipulation. For example, sources of optical OAM were either very rigid (only one OAM value is generated, with no switching or modulation capability) or very inefficient (typically < 40% of the input photons is converted into the desired OAM mode) and fairly expensive; electro-optical fast manipulation of OAM was virtually non-existent, while the OAM control flexibility provided by spatial light modulators (SLM) came at the expense of a slow response and a high cost; single-photon sensitive

OAM detectors are inefficient (i.e., have low quantum efficiencies) and/or complex and cumbersome (e.g., involving a layout of several cascaded interferometers), OAM free-space transmission was subject to a high sensitivity to air turbulence and other dephasing effects, and OAM integration was only a dream. Many of these limitations could be tackled by adopting new ideas and methods, some of which have been very recently demonstrated or proposed, others are yet to be investigated or even conceived.

The main objective of PHORBITECH is the development of a "toolbox" of highly innovative optical components and devices for the full and convenient control of OAM, including its generation, manipulation, transmission and detection.

These proposed components are based on *entirely new designs and ideas* or on the *innovative combination of recently introduced concepts*, and the toolbox as a whole will provide a dramatic breakthrough in our capability of controlling the OAM and exploiting it in photonic applications and in new scientific investigations.

A second objective of PHORBITECH is the advancement of scientific knowledge that will be driven by the research effort aimed at developing these new optical devices and that will arise from the fundamental investigation of the associated concepts.

1.2 Summary of the main results achieved so far

In the first year of the project we have developed the following new devices or tools for OAM control and manipulation, contributing to the first general goal of PHORBITECH (the "toolbox"):

1) We have developed a new open-source LabVIEW software which can be used for computing the holographic pattern, to be displayed on a SLM, needed for the generation and multiplexing of a controlled superpositions of several Laguerre-Gauss modes with prescribed orbital and radial indices, and a given waist size of the beam. In particular, this allows generating superpositions having a unique Gouy phase, so as to be stable in propagation. The same holograms can be also developed in the form of fixed passive optical elements, so as to obtain compact, portable devices, although of lower efficiency.

2) We have advanced the q-plate technology, first introduced only few years ago (by one of the partners in PHORBITECH), which is based on spin-orbit coupling phenomena of the light crossing a suitably patterned liquid crystal cell. In particular, in PHORBITECH we have now introduced for the first time the electric-field tuning of the q-plates, and a photo-induced alignment process of the bounding surfaces so as to obtain any desired q-plate pattern. A photo of a state-of-the-art q-plate developed in PHORBITECH is shown in the figure 1.2.

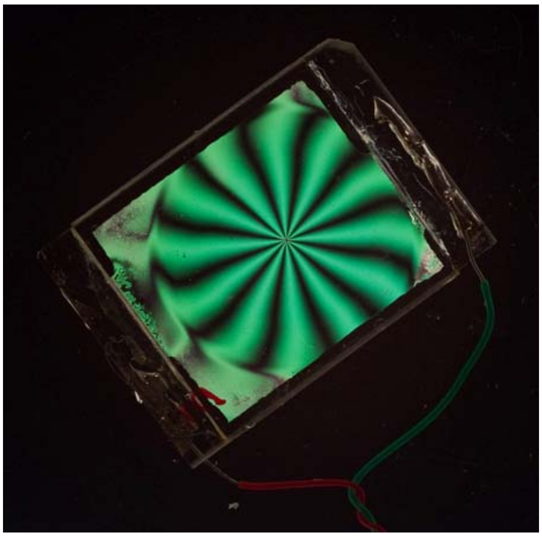

Fig. 1.2 – A q-plate prototype with q = 3 and electric tuning developed in PHORBITECH, as seen between crossed polarizers

3) By exploiting the q-plate technology in combination with a Sagnac interferometer containing a Dove prism, we have developed a device capable of transferring any given OAM superposition state defined within a OAM two-dimensional subspace into a corresponding polarization superposition state, and vice versa, in a coherent ideally loss-less way. In terms of photons, this tool can be considered as a new quantum interface device, for the deterministic transfer of a qubit of quantum information from the polarization degree of freedom to the OAM, or vice versa.

4) We have developed some first prototypes of integrated optical circuits of multiply-coupled waveguides in linear arrays and of multi-mode waveguides, which may be used to encode a higher-dimensional quantum space. In combination with suitable multiplexing devices (such as that listed at item 5) or exploiting the self-imaging principle, this approach may be used to encode OAM quantum information in integrated optical components.

5) We have developed a novel approach to OAM measurement and multiplexing that has all needed properties to become the most efficient existing method. It is based on the concept of "OAM phase unfolding" that is illustrated in Fig. 1.3, and is obtained by two specially designed optical phase transformations. These transformations map different OAM states into different propagation direction of the outgoing light, or equivalently, after suitable imaging, into different positions on a detector.

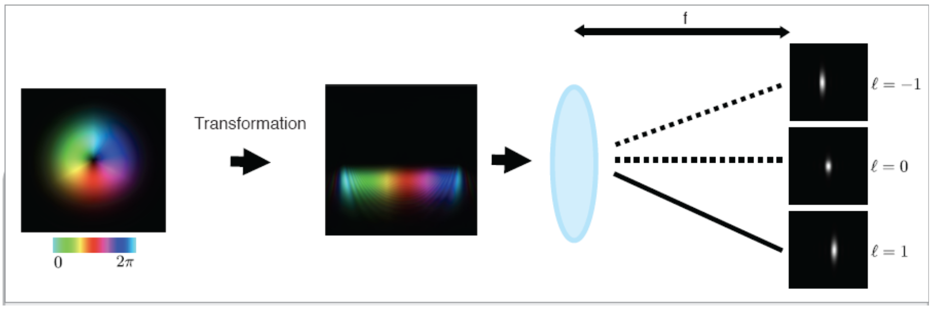

Fig. 1.3 – Principle of OAM phase unfolding, which is based on a suitable optical transformation leading an azimuthal phase gradient to be mapped into a linear one, so as to allow multiplexing different OAM states into different propagation directions or spatial positions. This multiplexing enables a very efficient detection of OAM.

6) Finally, we have manufactured a robust "quasi-monolithic" interferometer device for the high-efficiency sorting of OAM. This device builds on previous results, but improves them considerably in terms of stability and ease of alignment. A photo of the new device is reported in Fig. 1.4.

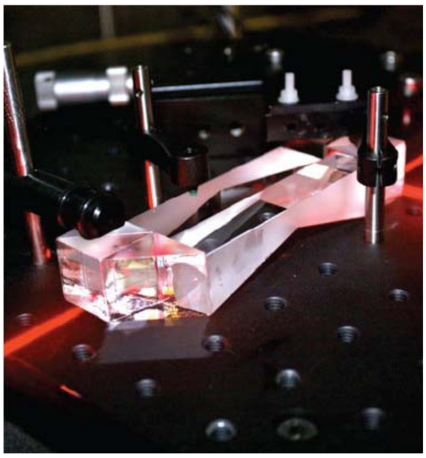

Fig. 1.4 – Robust OAM Dove-prism based sorting interferometer.

In addition to this new set of devices, contributing to the OAM technology and to the first goal of this project, we have also obtained a number of scientific results, which contribute to the second main goal of PHORBITECH (advancement of the scientific knowledge).

The research groups working in PHORBITECH have published during the first year a total of 29 project-related scientific articles in high-profile international journals (among which 1 in Science, 1 in Nature Communications, 2 in Physical Review Letters, 12 in Optics Letters, Optics Express or Applied Physics Letters). Some of these contain results specifically planned as goals (and deliverables) of the project, while others were unexpected results or new ideas arisen while working on the project and developed within PHORBITECH.

We mention here some of the most significant (in terms of relevance to the project goals and/or of broader interest) scientific achievements of this first year:

7) We have investigated the possibility of upgrading the current technology of spontaneous parametric down conversion (SPDC) to generate tuneable and powerful laser beams carrying OAM, or efficient sources of OAM-entangled photon pairs for quantum information purposes. The ideas we explored were based on using novel designs of quasi-phase-matching and/or cavity enhancement to improve the current technology.

8) We have demonstrated the first generation of hybrid-entangled pairs of photons, with one photon carrying a qubit encoded in polarization and the other photon in OAM.

9) We have demonstrated for the first time (to our knowledge) the optimal quantum cloning of qudits, i.e. quantum states of dimension higher than two, by exploiting hybrid polarization-OAM states of photons.

10) We have investigated in detail the tiny deviations from the standard reflection and refraction laws that occur when light carrying OAM impinges on a interface between two dielectric media. These subtle optical phenomena provide important generalizations of the already known Goos-Hänchen and Imbert-Fedorov effects.

11) We have reported the first observation of the peculiar "rotational drag" of the light crossing a medium that is rotating around the optical axis, by exploiting the large enhancement of this effect that can be obtained in a slow-light medium. This drag effect leads to a rotation of the optical image transmitted by the rotating medium.

12) We have proposed and demonstrated an architecture-independent technique that simplifies adding control qubits to arbitrary quantum operations—a requirement in many quantum algorithms, simulations and metrology.

Finally, it is worth mentioning here that, in an effort to disseminate the main scientific concepts behind the project to a wide non-technical audience, during this first year we have developed a set of new wikipedia pages on the angular momentum of light and on the topic of optical OAM (see dissemination activities under Section 2; main link: http://en.wikipedia.org/wiki/Angular_momentum_of_light)

All the above listed results and achievements will be discussed in more detail in the Section 1.2 of this report.

1.3 Expected final results and their potential impact

The vision of PHORBITECH is to make the OAM generation, manipulation, transmission and detection as easy and commonplace as currently is the management of the polarization degree of freedom of light, both in the classical regime and in the quantum regime.

By its end, PHORBITECH should have made this vision become much closer, by introducing a number of effective OAM manipulation tools and by advancing significantly our knowledge of the associated physics.

We identify three specific fields of science and technology in which an enhanced control of the OAM of light has the highest potential for a future impact, in the medium or long term:

i) Implementation of *quantum information channels* with new capabilities and a higher dimensionality. In this area of technology, the possibility of attaching a higher-dimensional Hilbert space to each photon may provide an important practical advantage, since it will enable a substantial increase of the information content of the optical field (e.g., the capacity of a quantum communication channel) without losing in the generation and detection efficiency, contrary to the commonly adopted schemes which implement multi-qubit states by adding other photons, which exhibit extremely low generation and detection efficiencies. Besides this purely "quantitative" advantage, the use of OAM will enable the implementation of qualitatively different quantum information protocols based on higher-dimensional systems ("qudits"), for which better theoretical performances than their qubit-based equivalents are predicted (e.g., security of quantum cryptography, enhancement in the violation of non-locality tests, more effective quantum gates for information processing, cluster states for one-way quantum computation). Moreover, when OAM is used in combination with polarization, it allows performing certain otherwise impossible quantum tasks (e.g., hyper-entanglement for full Bell-state measurement and superdense communication, quantum communication without reference-frame alignment). OAM can also provide a convenient approach to interfacing coherently photons and matter, e.g., by imprinting and reading phase vortices written in coherent material degrees of freedom. Some form of interface between light qubits, used for communication, and matter qubits, used as memories, will be a necessary ingredient of future quantum information networks.

ii) Another sector where a future OAM technology can find important applications is that of *high-density optical data storage*. In current systems, the spatial pattern encrypted in compact disks is binary. One way to enhance the capacity of compact disks is to write, and therefore read, more complicated patterns within the same spatial area, a task that can greatly benefit from the existence of better tools to generate and read light beams carrying OAM. The future development of a new photonic technology for high-density optical storage of data can thus be based on exploiting the OAM multi-value encoding potential, possibly in combination with near-field or far-field sub-wavelength microscopy methods (i.e., combining OAM and nano-optics). The practical value of these innovations is hard to predict at this stage, but it may very well be huge if these technical solutions will prove to be fully advantageous. Importantly, the comparative advantage of the proposed techniques should be based on the existence of high efficiency and reliable tools to generate and read spatially encoded information, one of the primary goals of this project.

iii) Finally, we envision a possible impact of OAM in the sector of *materials probing*, particularly for the case of biological targets. The already existing proof-of-principle demonstrations of OAM-based microscopy image enhancements, digital spiral imaging, and OAM-induced coronography effect (allowing for, e.g., the detection of very faint objects lying in the immediate surroundings of a bright source or for the selective bleaching of surrounding fluorescent probes) are extremely promising in this regard. We expect that OAM could find application in the development of new sensitive probes of material gradients and inhomogeneities, as for example of membranes or other biological spatial structures. In particular, the use of OAM offers potentially a new way to reveal chiral properties that are difficult to see by conventional optical activity. Material chirality is quite natural in living tissue since about 30% of the protein content in a human body consists of the biopolymer collagen; its structure is that of a twisted cord giving rigidity to cells. The coupling between this material twist and OAM light will be optimum if their periods coincide; this can be used to enhance contrast. Collagen may change its helical structure, for example during scarring, wound healing or the formation of bones. The helicity of collagen may therefore be studied for diagnostic purposes. This has potentially a large impact since biomedical imaging is always hungry for new and more effective approaches to non-invasive and safe diagnostic tools.

Project website address: www.phorbitech.eu

PHORBITECH partners:

Italy Università di Napoli Federico II, Department of Physics, Soft matter group, Lorenzo Marrucci and Enrico Santamato, http://people.na.infn.it/~marrucci/softmattergroup/

Italy Università di Roma “La Sapienza”, Department of Physics, Quantum Optics Group, Fabio Sciarrino and Paolo Mataloni, http://quantumoptics.phys.uniroma1.it

Spain ICFO-Institut de Ciencies Fotoniques, Quantum engineering of light group, Juan P. Torres and Lluis Torner, http://www.icfo.es

The Netherlands Universiteit Leiden, Leiden Institute of Physics, Quantum Optics and Quantum Information group, Han Woerdman and Eric Eliel, http://www.molphys.leidenuniv.nl/qo/

UK University of Glasgow, School of Physics and Astronomy, Optics Group, Miles Padgett and Sonja Franke-Arnold, http://www.physics.gla.ac.uk/Optics/

UK University of Bristol, Centre for Quantum Photonics, Centre for Quantum Photonics, Jeremy L. O’Brien and Mark Thompson, http://www.phy.bris.ac.uk/groups/cqp/

Legend of short names used to indicate the partners in the report:

UNAP – University of Naples “Federico II”
UROM – University of Rome “La Sapienza”
ICFO – ICFO Institute of Photonics Sciences
ULEID – University of Leiden
UGLAS – University of Glasgow
UNIVBRIS – University of Bristol

2 Core of the report for the period: Project objectives, work progress and achievements, project management

2.1 Project objectives for the period

The project is articulated into three main research (RTD) work-packages (WP), whose overall objectives are defined as follows:

WP1 – OAM generation. This work package is aimed at the development of high-efficiency robust sources of OAM light, both in a classical regime and in a quantum one (correlated photon pair generation). The developed sources should be tunable, e.g. in the accessible OAM subspace, in the specific quantum state generated, etc. A method for switching among different OAM states or OAM superpositions should be ideally included in the source device. This WP includes the realization of the following planned devices: holographic OAM multiplexer; polarization-OAM couplers for OAM generation; SPDC-based quantum sources. To achieve these goals, this WP will include the investigation of fundamental issues associated with OAM generation, such as those concerned with the light-matter interaction effects involving an exchange of angular momentum.

WP2 – OAM manipulation and transmission. This work package is aimed at the development of optical devices for OAM manipulation and transmission, both in free space (including in air) and in waveguides. This WP includes in particular the realization of the following planned devices: polarization-OAM couplers for OAM manipulation; correlated OAM photon robust transmission; OAM waveguides and waveguide / free-space couplers. To achieve these goals, this WP will include the investigation of fundamental issues associated with OAM propagation and with OAM effects arising in optical components.

WP3 – OAM detection and storing. This work package is aimed at the development of optical devices for OAM detection and for its coherent storing/retrieval in material devices. This WP includes in particular the realization of the following planned devices: angular phase unfolding OAM detector; chiral micro-structured media for OAM detection; optical apparatus for the OAM storing and retrieval in atomic population degrees of freedom. To achieve these goals, this WP will include the investigation of fundamental issues associated with the OAM-matter interaction.

In addition, the project includes a work-package devoted to the **project management (WP4)** and a work-package devoted to promoting **dissemination activities (WP5)**.

The RTD work-packages are further split into tasks and subtasks, with more specific objectives, as formalized by the project planned deliverables. The following table includes the set of all RTD tasks and subtasks active for the first year, with the associated deliverables (listed below are deliverables due by Month 12 and those related to tasks active in the first year, even if due at a later time):

Table 2.1 RTD work plan in tasks and subtasks active in year 1

WP No. and title	Task No.	Subtask No.	Deliverable
WP1. OAM generation	1.1 Holographic OAM multiplexing	1.1.1 Novel holographic methods	D1.1 Novel holograms
	1.2 q-plate technology	1.2.1 Novel q-plate development and quality improvement	D1.4 High quality q-plates (due at Month 18)
	1.3 OAM tunable bright source	1.3.1 Transverse quasi-phase-matching in SPDC	D1.2 Intermediate QPM SPDC
		1.3.2 Cavity-enhanced OAM SPDC	D1.3 Intermediate cavity-enhanced SPDC
WP2.OAM manipulation and transmission	2.1 – Free-space OAM optics	2.1.1 Angular and positional OAM-induced reflection/refraction effects	D2.1 OAM beam deviation matrix

	2.2 – Polarization-OAM couplers	2.2.1 –OAM-polarization single-photon couplers	D2.2 Polarization-OAM deterministic transferrer
		2.2.2 – OAM-polarization multi-photon couplers	D2.3 Hybrid polarization-OAM entanglement
	2.3 – OAM photon pair transmission	Task starts at Month 13	
	2.4 – OAM waveguides & couplers	2.4.1 Waveguide simulations and realization tests	D2.4 OAM waveguides
WP3. OAM detection and storing	3.1 – OAM phase unfolding	3.1.1 OAM-phase-unfolding preliminary study	D3.1 OAM phase unfolding simulation
	3.2 – OAM chiral media detection	3.2.1 – OAM chiral structure generation and scattering	D3.2 OAM chiral writing and detection (due at Month 18)
	3.3 – OAM material storing	3.3.1 – OAM-driven atomic populations	D3.4 Cold atom control by OAM wavefronts (due at Month 24)

In section 2.2, for each task and subtask are reported the activities as planned in Annex I followed by the description of the activities carried out during the first year. Dissemination activities (WP5) are also reported in this section.

Finally, management activities (WP4) are described in the specific section 2.3.

2.2 Work progress and achievements during the period

2.2.1 Work-package WP1

Task WP1.1: Holographic OAM Multiplexing

> Excerpt from Annex I:
>
> This task will include the development of holographic OAM-multiplexing devices to be used for coupling different OAM states with different propagation modes. In general, these devices are suitable for generating desired OAM modes starting from standard Gaussian beams. Operated in reverse, they can however also be used for detection purposes. One more specific target of this task is to tailor the generated radial modes in order to obtain coherent superpositions of OAM modes having a unique Gouy phase, so as to be stable in the subsequent propagation. […] The task includes two subtasks in series.
>
> Subtask T1.1.1 – Novel holographic methods.
>
> The work will start from the approach demonstrated already by UGLAS,[1] based on employing holographic patterns corresponding to the superposition of several more elementary patterns apt for generating different OAM modes. An important novelty to be developed will be the compensation of the Gouy phase dependence on OAM number m, as obtained by combining the radial mode quantum number p in such a way that 2|m| + p remains constant. Design issues concerning hologram cascading, the role of the numerical aperture of coupling optics and its optimal design for the mode conversion will be addressed during this subtask. All testing and development work will be performed using SLMs, while passive holographic elements will be developed for specific applications once the optimal configuration has been found. This subtask will end with a milestone (MS2) at which the effectiveness of the new developed holographic methods will be assessed and

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[1] Graham Gibson, Johannes Courtial, Miles J. Padgett, Mikhail Vasnetsov, Valeriy Pas'ko, Stephen M. Barnett and Sonja Franke-Arnold, *Free-space information transfer using light beams carrying orbital angular momentum*, Opt. Express **12**, 5448 (2004)

compared with alternative approaches, also in order to determine the extent to which this approach can be adopted also in other devices being investigated in other tasks and WPs.

The work performed within this subtask followed the plans without any significant deviation.

The standard method used at Glasgow to generate hologram patterns involves adding the phase pattern of the required mode to a fixed gradient that determines the diffraction direction. The overall phase is evaluated modulus 2π and the grating depth is adjusted to match the intensity pattern of the desired mode. The functional intensity dependence takes into account the diffraction strength of the SLM and the blazing is adjusted accordingly.[2] It is well known that, as long as the Gouy phases of all contributions to the final mode are equal, i.e. $2|\ell| + p$ remains constant, the mode propagates unchanged.[3] Otherwise the mode changes shape upon propagation and experiments ideally are confined to near or far field only.

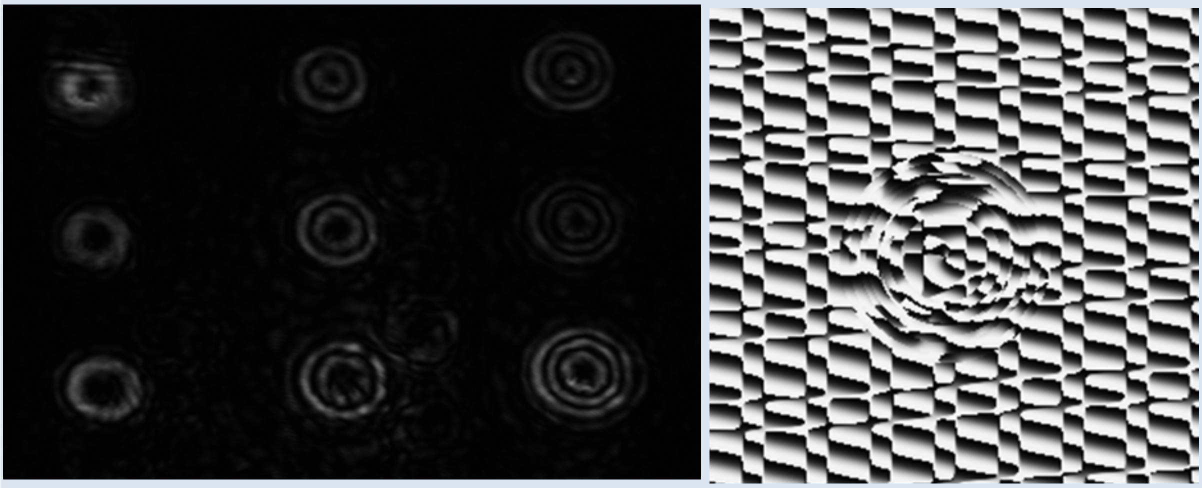

Figure 2.1 – Different LG modes in the far field generated simultaneously from a Gaussian input beam by the hologram displayed on the right (for clarity only the central region is displayed).

It is important to note that the radial profile is dependent on the accepted beam waist and hence on any numerical apertures in the system as well as the Gaussian waists defined by the generating and measuring system. We find it a useful approach to distinguish between the *generated* and *measured* modal decomposition, where the generated modes are defined e.g. by the down-conversion source, which are detected with differing probability depending on apertures and coupling to the detection devices.

We have considered two different methods that would allow generation of LG modes described by both their mode indices, the first based on the communicator approach,[1] and the second, resulting from work together with ULEID on the phase-unfolding mode-sorter (deliverable D3.1) operated in reverse.

Based on the communication system we have developed holograms that allow incorporating radial modes as well as OAM modes and specifying the diffraction directions, see Figure 2.1. The phase profile of each individual is added to a linear phase profile that acts as a grating, directing the light to the desired output direction. The mode amplitudes are added, and the argument of the resulting combined mode is displayed modulo 2π. The efficiency will in principle not exceed one over the number of channels, and is further limited by the diffraction efficiency of the SLM. We have developed a new LabVIEW software which can be used for computing the holographic pattern, to be displayed on a SLM, needed for the generation and multiplexing of a controlled superpositions of several Laguerre-Gauss modes with prescribed orbital and

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[2] J. Romero, J. Leach, B. Jack, M. R. Dennis, S. Franke-Arnold, S. M. Barnett and M. J. Padgett, "Entangled Optical Vortex Links", *Phys. Rev. Lett.* **105**, 100407 (2011)

[3] Jörg B. Götte, Kevin O'Holleran, Daryl Preece, Florian Flossmann, Sonja Franke-Arnold, Stephen M. Barnett, and Miles J. Padgett , "Light beams with fractional orbital angular momentum and their vortex structure", *Opt. Express* **16**, 993-1006 (2008)

radial indices, and a given waist size of the beam. In particular, this allows generating superpositions having a unique Gouy phase, so as to be stable in propagation. The same holograms can be also developed in the form of fixed passive optical elements, so as to obtain compact, portable devices, although of lower efficiency.

This LabVIEW code is the core of the deliverable D1.1, which is the main formal output of the present subtask.

Operated in reverse, similar holograms could be also used to detect a predefined subset of modes by generating on-axis intensity at set detector positions, see Figure 2.2.

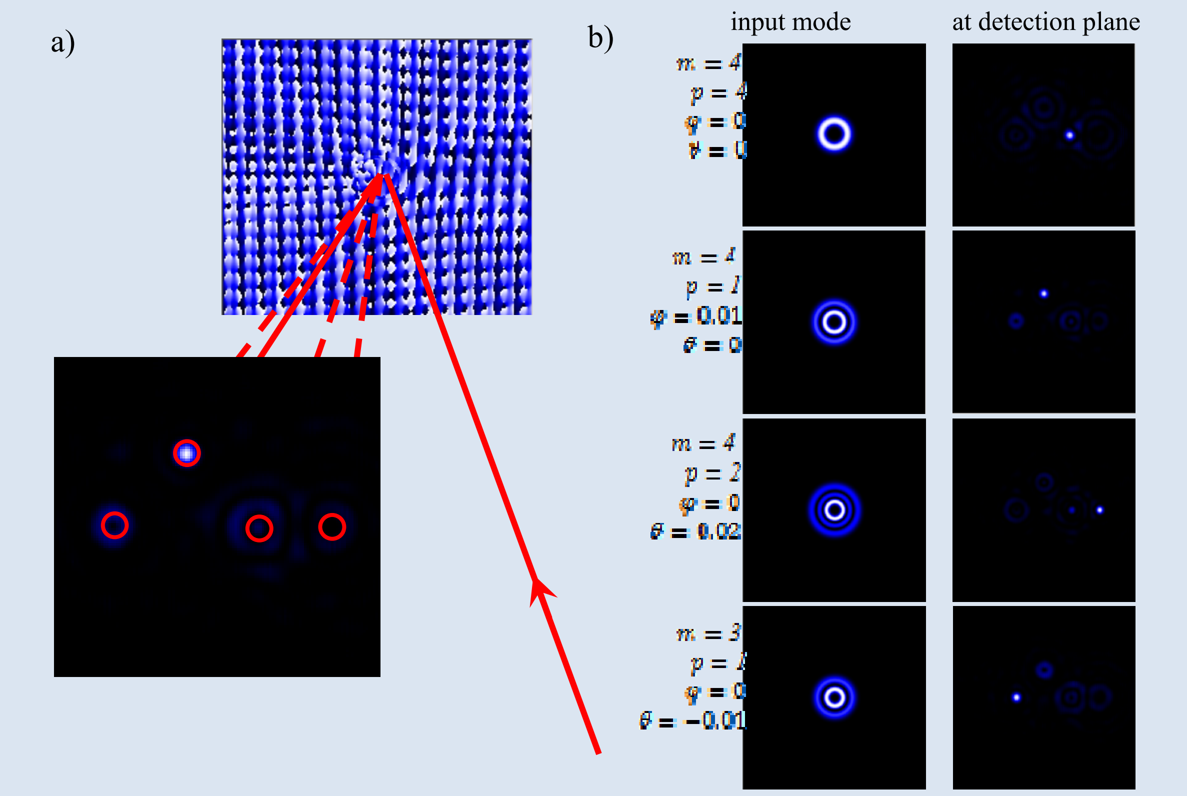

Figure 2.2 – a) Hologram that allows directing four modes specified by their angular and radial indices ℓ and p to four different locations specified by the angles φ and θ. b) Intensity profile of the input mode and its distribution in the detection plane.

As part of subtask T3.1.1, we have developed a method where a combination of two novel holograms is used to transform orbital angular momentum (OAM) states into transverse momentum states, allowing for the efficient measurement of the OAM within that beam[4]. This approach can be used in reverse to efficiently generate OAM states for use within such a system. We present modeled results for a system where transverse momentum state are generated on the surface of a spatial light modulator (SLM), and then imaged onto the first of the two holograms (Fig. 2.3 (a)). The combined holographic elements then transform input transverse momentum into OAM at the plane of the CCD (Fig. 2.3 (b)). Using an SLM however is not ideal, and the SLM can be replaced by the use of an area of laser diodes at appropriate transverse positions in the plane of

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[4] G. C. G. Berkhout, M. P. J. Lavery, J. Courtial, M. W. Beijersbergen, and M. J. Padgett, “Efficient Sorting of Orbital Angular Momentum States of Light”, *Phys. Rev. Lett.* **105**, 153601 (2010); G. C. G. Berkhout, M. P. J. Lavery, M. J. Padgett, and M. W. Beijersbergen, “Measuring orbital angular momentum superpositions of light by mode transformation”, *Opt. Lett.* **36**, 1863-1865 (2011); M. P. J. Lavery, G. C. G. Berkhout, J. Courtial, and M. J. Padgett, “Measurement of the light orbital angular momentum spectrum using an optical geometric transformation”, *J. Opt.* **13**, 064006 (2011)

the aperture generating the required input states at the first element. The efficiency can be further increased through the use of custom manufactured refractive elements or, possibly, suitably patterned q-plates.

We note that the mode sorter allows sorting and generating radial modes as well as OAM as it is based on a coordinate transform that relates linear positions to angle and $\ln(r)$. In the Fourier plane these separate modes according to their OAM and the Fourier transform of the distribution of the logarithm of the radius. A mode number of p results in a number of p+1 focussed spots, corresponding directly to the number of radial rings of the input modes.

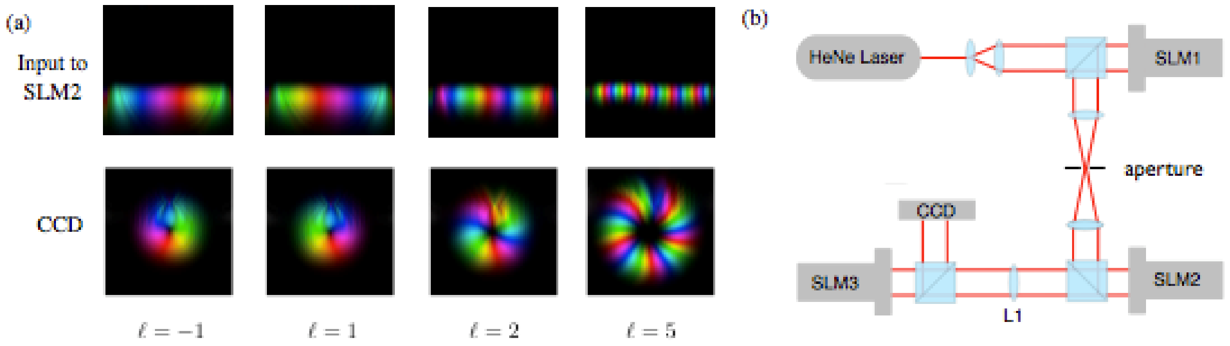

Figure 2.3 – (a) The modes shown in row 1, are the transverse momentum states generated by displaying a linear phase gradient on SLM1 with a radius equivalent to the beam waste of the expanded laser. Intensity shaping is used to generate the LG modes shown in the modeled CCD plane. (b) Diagram of the setup required to generate the modes shown in (a).

As our final assessment (milestone MS2), we believe that holograms generally offer a convenient but not very efficient method to produce any desired modes. They are ideal for proof-of-principle experiments and scientific investigations. For many applications, in particular at low light levels, different methods based on custom manufactured refractive elements (as those we are developing under task WP3.1) are expected to be of more interest.

STATEMENT ON THE USE OF RESOURCES[5]:

The actual number of person-months (PM) employed in this subtask has been 7 PM (as planned), but the initial idea on holographic sorting has been extended to include the inverse mode sorter which should allow higher efficiency.

Task WP1.2: q-plate technology

> Excerpt from Annex I: This task is aimed at designing and manufacturing novel kinds of q-plates. The q-plate is a device invented in Naples (UNAP) that introduces an interaction of polarization and OAM degrees of freedom. It may be used in particular for controlling an OAM variation with the input polarization of an optical beam, thus enabling a OAM beam generation from a Gaussian input. The basic concept of the q-plate is simply that of a suitably patterned birefringent wave-plates where the coupling with the wavefront arises from the geometrical Pancharatnam-Berry phase occurring in the optical polarization manipulations. Patterned wave-plates for the visible or near IR domain can be conveniently developed using liquid crystals technology. To obtain OAM states, the pattern must have a singularity of charge q at its center, allowing for the generation of OAM states with index m = ±2q, where the sign is determined by the input circular polarization content. Only specific simple patterns having circular symmetry have been realized so far (corresponding to q=1), but technologies for realizing arbitrary patterns do exist. Another issue is the tunability of the q-plate, corresponding to the control of the wave-plate overall birefringence retardation at a given wavelength. This task is organized into two sub-tasks put in series, which will be carried out in close collaboration between

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[5] Person-months indicated here and in all the following statements are preliminary. Exact numbers will be included in the final version of the interim report.

> UNAP (designing and manufacturing q-plates and q-plate-based optical systems and testing their performances in the classical regime) and UROM (testing the same devices in the quantum regime).
>
> Subtask T1.2.1 – Novel q-plate development and quality improvement.
>
> Different approaches to higher-quality and more flexible patterning (holographic, UV masking, micro-rubbing, laser writing) will be considered and tested. Mechanical and electrical tuning will also be developed (presently only thermal tuning has been demonstrated). The goal will be that of producing q-plates with arbitrary q values and controlled birefringent retardation. In addition, tailoring of the generated radial mode will be also pursued with the goal of obtaining propagation-stable superpositions of different OAM modes (the idea here is the same as that given for the holographic approach, see Task WP1.1). UROM will characterize the quality of the q-plates developed by UNAP in the quantum few-photon regime, by exploiting the experimental and theoretical tools developed for the reconstruction of quantum transformations, very sensitive to the mode purity. The goal will be to optimize the conversion efficiency, quality of the mode generated, the wavelength tuning in the quantum regime of the device. The results of this subtask will be assessed at milestone MS6 and provide a necessary input to task WP2.2.

As planned, this task has been organized into two sub-tasks put in series. The first sub-task (T1.2.1) has regularly started at the beginning of the project and is planned to end at month 18 (Milestone MS6), so it is still ongoing. The work is proceeding well and according to plans.

In particular, we have already developed and successfully demonstrated the electric tuning technology of q-plates[6], which guarantees a rapid switching and convenient control of the q-plate retardation. The mechanical tuning was also briefly tested, but it proved to be not sufficiently reliable so it was discarded.

Moreover, thanks to a collaboration with of a Hong Kong group specialized in manufacturing photosensitive materials, we have set up and demonstrated a first photo-induced patterning method based on blue light illumination, allowing for a more flexible patterning and leading to higher optical quality of the q-plates compared to the previous rubbing-based method. This has allowed the first demonstration of tunable q-plates having arbitrary topological charge q.[7] A photo of an electrically tunable q-plate with q=3 (for generating OAM = $\pm 6\hbar$) manufactured by this technology is shown in the figure 1.2 of Section 1.

A set of these newly produced q-plates has been given to UROM, which is currently testing their performances in the quantum regime and using them for developing novel devices for OAM control of single photons and photon pairs (see task WP 2.2).

We are now working on the materials used in the holographic patterning, to achieve also UV writing, with the purpose of having more durable high-quality devices, which can be also used with blue light. Moreover, we are presently working on the issue of radial patterning and, even more generally, of the arbitrary patterning of the q-plate devices, either by adopting a holographic approach or by a scanning method.

In addition to the main line of research based on liquid crystals, we have investigated samples of silver-doped glasses under laser exposure, demonstrating that a permanent q-plate-like structure may develop spontaneously in these systems[8]. The exposure time allows control of the birefringent retardation, so that this self-patterning approach might provide an alternative approach to q-plate manufacturing in the future.

Moreover, in order to assess the present status of the possible q-plate applications, a survey of the recent literature on this topic was completed and published in a review article[9].

Finally, some preliminary work on the subsequent subtask (T1.2.2) has been already started, by exploring different possible optical setups designed to generate and/or detect OAM states of light in a flexible and convenient way, for various optical applications. This work has already led to two publications[10,11].

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[6] B. Piccirillo, V. D'Ambrosio, S. Slussarenko, L. Marrucci, E. Santamato, “Photon spin-to-orbital angular momentum conversion via an electrically tunable q-plate”, *Appl. Phys. Lett.* **97**, 241104 (2010).

[7] S. Slussarenko, A. Murauski, T. Du, V. Chigrinov, L. Marrucci, E. Santamato, “Tunable liquid crystal q-plates with arbitrary topological charge”, *Opt. Express* **19**, 4085-4090 (2011).

[8] J. M. Amjad, H. R. Khalesifard, S. Slussarenko, E. Karimi, L. Marrucci, E. Santamato, “Laser-induced radial birefringence and spin-to-orbital optical angular momentum conversion in silver-doped glasses”, Appl. Phys. Lett. 99, 011113 (2011).

[9] L. Marrucci, E. Karimi, S. Slussarenko, B. Piccirillo, E. Santamato, E. Nagali, F. Sciarrino, “Spin-to-orbital conversion of the angular momentum of light and its classical and quantum applications”, J. Opt. 13, 064001 (2011).

STATEMENT ON THE USE OF RESOURCES:

A total of 19 person-months (PM) have been used so far within this task, in line with the plans.

In particular, two post-doc researchers (Dr. Ebrahim Karimi and Dr. Sergei Slussarenko) have been hired (with contracts starting from December 2010) to work on this task and on the other project activities involving UNAP.

Task WP1.3: OAM tunable bright source

> Excerpt from Annex I: This task is focused on improving the spontaneous parametric down conversion (SPDC) approach for generating OAM beams and OAM-correlated photons. It will be mainly pursued in the continuous-wave mode, but pulsed sources will be also developed. Emphasis will be on the brightness and tunability (not only in wavelength but in all relevant parameters of the generated light) of the source.
>
> The task is divided into three subtasks. Initial subtasks 1.3.1 and 1.3.2 run in parallel, but are in series with the final subtask 1.3.3.
>
> Subtask T1.3.1 – Transverse quasi-phase-matching in SPDC
>
> We will initially investigate the adoption of transverse-pattern quasi-phase matched structures, optimized for generating specific spatially entangled quantum states. In this way, a greater control of the OAM correlations of the paired photons is expected to be obtained. Moreover, the more conventional longitudinal quasi-phase-matching can be added in order to use configurations with the higher nonlinear index, thus enhancing the flux rate of paired photons. The quasi-phase-matching can be achieved by modulating the material composition and structure. However, the role of pump beam transverse profile and of the spectral and/or temporal shape for enhancing the down-conversion gain for specific OAM subspaces will be also investigated. For example, pancake-like spatial structures, which would correspond to a coherent superposition of different spatial modes and which can be engineered with appropriately designed holograms or spatial light modulators, are typically mirrored into the spatial correlations of the paired photons generated. This subtask will have an intermediate main checking point at milestone MS2 and it is planned to end at milestone MS9. Its results may provide a useful input to other tasks in the project exploiting SPDC sources where an enhanced brightness and/or more selective generation is required (e.g. Tasks WP2.2 and WP2.3).
>
> Subtask T1.3.2 – Cavity-enhanced OAM SPDC
>
> In this subtask, the possible use of cavity configurations designed to enhance the fluency of the SPDC process or for selecting or tuning the OAM subspace to be accessed will be investigated. The idea is essentially that of passing from parametric generation to parametric oscillation. Cavity configurations have been recently used for example for generating narrowband frequency-entangled light for driving atomic transitions. However, the cavity structures will have to be tailored to obtain appropriate resonances on the OAM higher transverse modes to be generated, while possibly introducing losses to deplete the TEM00 Gaussian mode. As the previous one, this subtask will have an intermediate main checking point at milestone MS2 and it is planned to end at milestone MS9. Its results may provide a useful input to other tasks in the project exploiting SPDC sources where an enhanced brightness and/or more selective generation is required (e.g. Task WP2.3)

The two parallel subtasks T1.3.1 and T1.3.2 are planned to start at Month 1 and end at Month 24. At the end of the first year, i.e. at the moment this report is written, they are planned to have an intermediate check-point (within milestone MS2). With respect to the plans, the work started somewhat slower, with a smaller person-month effort than anticipated, due to difficulties in hiring the needed post-doc and research assistants. Therefore, the intermediate reports that were completed as deliverables D1.2 and D1.3 are probably at a

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[10] S. Slussarenko, V. D'Ambrosio, B. Piccirillo, L. Marrucci, E. Santamato, "The polarizing Sagnac interferometer: a tool for light orbital angular momentum sorting and spin-orbit photon processing", *Opt. Express* **18**, 27205-27216 (2010).

[11] S. Slussarenko, E. Karimi, B. Piccirillo, L. Marrucci, E. Santamato, "Efficient generation and control of different-order orbital angular momentum states for communication links", *J. Opt. Soc. Am. A* **28**, 61-65 (2011).

somewhat less advanced stage than what we were hoping for initially. Nevertheless, the researchers have now been hired and the work is therefore proceeding well.

1. THE ROLE OF TRANSVERSE QUASI-PHASE MATCHING (QPM)

The main advantage of using a nonlinear crystal with transverse QPM is to generate new types of quantum states with orbital angular momentum, even though the flux of down-converted photons generated might be reduced. For the sake of simplicity, let assume a short crystal where the diffraction of the pump beam, and the signal and idler photons, can be neglected. In this case, the quantum state of the down-converted photons can be written as

$$\left|\Psi\right\rangle = \int d\vec{r}_1 d\vec{r}_2 F\left(\vec{q}_1,\vec{q}_2\right) a_1^+\left(\vec{q}_1\right) a_2^+\left(\vec{q}_2\right)$$
$$F\left(\vec{q}_1,\vec{q}_2\right) = \int dxdy\,\chi\left(\vec{r}_\perp\right) E_p\left(\vec{r}_\perp\right) \exp\left[-i\left(\vec{q}_1+\vec{q}_2\right)\cdot\vec{r}_\perp\right]$$

Where χ is the transverse varying nonlinear coefficient of the crystal, and E_p is the pump beam. We notice that now, the nature of the quantum state is determined by the multiplication of the pump beam and the nonlinear coefficient (χE_p). If the nonlinear coefficient is constant, we recover the usual result

$$\left|\Psi\right\rangle = \int d\vec{q}_1 d\vec{q}_2 \hat{E}_p\left(\vec{q}_1+\vec{q}_2\right) a_1^+\left(\vec{q}_1\right) a_2^+\left(\vec{q}_2\right)$$

In usual configurations, if the pump beam is Gaussian, the probability to project the down-converted photons into Gaussian modes is higher than that of projecting into higher order modes (see the paper mentioned in the following section). The use of transverse QPM can modify this behavior. Let us consider for example the simple transverse QPM structure depicted in Figure 2.4.

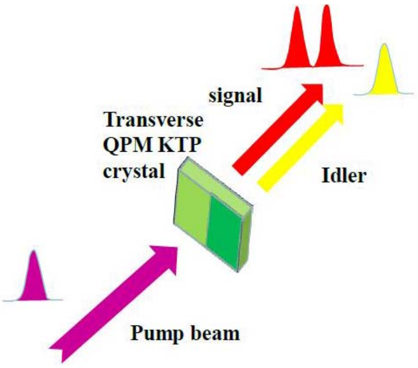

Figure 2.4 – Transverse QPM configuration, where the nonlinear coefficient is positive for half the nonlinear crystal (x>0), and negative for the other half (x<0).

In this illustrative case, since the nonlinear function is an odd function, the expansion of the down converted photons in terms of OAM modes does not contain any paired photons in Gaussian modes. This shows that transverse QPM has the potential to tailor the SPDC output, optimizing for specific applications. The problem of finding the optimum QPM structure for a given application remains to be explored.

ROLE OF THE PUMP BEAM SHAPE IN THE EFFICIENCY OF SPDC: GENERAL CONSIDERATIONS

Let us consider the excitation of a second-order nonlinear crystal with an intense pump beam, so that pairs of photons entangled in the spatial degree of freedom (including OAM) are generated by means of SPDC. The main requirement of the source is that it should offer a high output flux. More specifically:

- We aim at generating entanglement in a 2 × 2 dimensional space (such it is the Hilbert space spanned by the polarization degree of freedom alone). This is the case of quantum states that make use of the polarization and OAM degrees of freedom and are of the form

$$\left|\Psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|R;m=+1\right\rangle_1 \left|L;m=-1\right\rangle_2 + \left|L;m=-1\right\rangle_1 \left|R;m=+1\right\rangle_2\right) \quad \textbf{(1)}$$

Here indices 1 and 2 refer to two distinguishable photons (for instance, photons with different frequency or different direction of propagation). The symbol R (L) stands for right-handed (left-handed) circular polarization and m=+1,-1 represent Laguerre-Gauss modes with winding numbers m=-1,+1 and radial index p=0.

- We aim at a high efficiency. Typical experiments in quantum optics count photon coincidences after the photons have traversed appropriately designed optical systems, which reveal the properties of interest of the quantum state generated. SPDC is a highly inefficient process, so that even under optimum conditions, quantum optics experiments barely show efficiencies greater than10^{-7}. Therefore, once determined the spatial modes of interest in a particular applications, it is of great interest to optimize the SPDC process so that most of the photons generated belong to the ensemble of modes of interest.

In order to generate quantum states with the sought-after correlations, and implement high efficiency sources of entangled photons, the SPDC configurations considered in this report will make use of:

- **A Collinear configuration:** the pump beam, and the photons generated (signal and idler) propagate along the same direction in the nonlinear crystal. Increasing the efficiency usually require focusing the pump beam into a narrow spot. Non-collinear configurations are not so easily handled under tight focusing of all waves involved.
- **A Non-critical configuration**: We assume a direction of propagation inside the nonlinear crystal so that all waves do not show Poynting-vector walk-off, i.e. *spatial walk-off.* Under tight focusing conditions, the presence of spatial walk-off (*critical configuration*) produces undesirable spatial correlations between the paired photons.
- **Quasi-phase matching**: Taking into account the two conditions stated above, in most cases, it is necessary to use the (longitudinal) QPM technique to fulfill the necessary phase-matching condition between the pump, signal and idler waves. In QPM, the sign of the nonlinear coefficient of the crystal alternate periodically between positive and negative values. Moreover, the use of QPM usually allows the use of the highest nonlinear coefficient of the nonlinear medium, which results in the corresponding increase of the efficiency.

ENHANCING THE EFFICIENCY OF OAM ENTANGLEMENT

In the SPDC configuration considered here, and given a specific nonlinear crystal with a length L, the design parameters are:

- The beam waist of the pump beam (denoted as w_p).
- The beam waist of the collection mode (denoted as w_s).

The question is:

> Once chosen a specific target (*spatial modes*), what is the optimum configuration (values of w_p and w_s) maximizing the flux of down-converted photons that are generated?

The general answer is reported in our article appeared in *Optics Express*[12] (included in deliverable D1.2).

More specifically, for generating a quantum state of the form given in Eq. (1), the optimum configuration is given in Figure 2.5. In this case, an estimated 82% of all photons generated (see Eq. 26 of the paper) belong

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[12] Silvana Palacios, R. de J. Leon-Montiel, Martin Hendrych, Alejandra Valencia and Juan P. Torres, “Flux enhancement of photons entangled in orbital angular momentum”, *Optics Express* **19**, 14108 (2011).

to the Hilbert space of interest. For instance, let us consider a degenerate SPDC process in a L = 20 mm PPKTP nonlinear crystal with nonlinear coefficient $\chi^{(2)}$=10 pm/V, pumped by a CW pump at λ_p= 405 nm and refractive indices $n_p=n_1=n_2$ = 1.8. If the total losses of the optical systems are η = 0.1, the spectral brightness F is

$$F = \gamma P_p\,(mW) \quad \text{with} \quad \gamma \sim 1\times10^5\ \text{photons/s/nm/mW}$$

where P_p is the pump power. Comparing this value with the typical flux of down-converted photons measured in other experiments that also make use of the quantum state given by Eq. (1), we see that by properly choosing the optimum value of the pump beam waist w_p and the optimum size of the collection mode w_s, one could observe a noteworthy enhancement of the spectral brightness of the source.

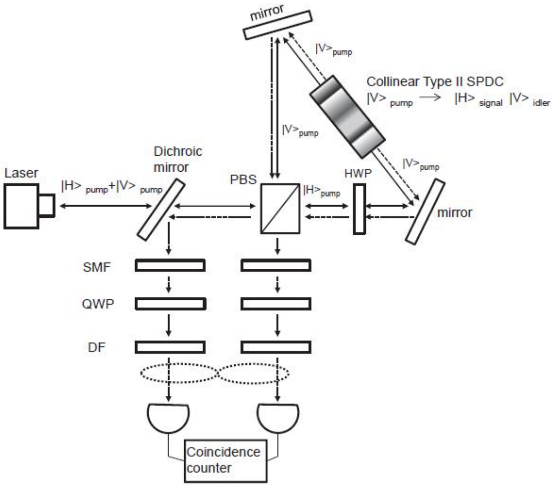

Figure 2.5: Scheme of the combination of a type-II SPDC source embedded in a Sagnac interferometer and diffractive elements to generate photons entangled in the polarization and spatial degrees of freedom with maximum efficiency. SMF: Single-mode fiber; QWP: Quarter-wave plate; HWP: Half-wave plate; PBS: Polarization beam splitter; DF: Diffractive element. The linked dot lines represent the existence of entanglement.

2. CAVITY-ENHANCED GENERATION OF MODES WITH OAM

Figure 2.6 shows the first design 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.[13] and Wolfgramm et al.[14].

A nonlinear crystal designed for non-degenerate parametric down-conversion (pump → signal + idler) is placed inside an optical cavity which is singly-resonant to the idler wave. An important aspect of the scheme considered is that the cavity is not tuned to the fundamental Gaussian beam (Laguerre-Gauss 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 2.6) presents a spatial gaussian-like beam, the wave associated to the STED wavelength (signal in Figure 2.6) should present a vortex-like spatial shape. If

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[13] "Broadly tunable dual-wavelength light source for coherent anti-Stokes Raman scattering microscopy", *Opt. Lett.* **31**, 1292 (2006).

[14] "Bright filter-free source of indistinguishable photons", *Opt. Express* **16**, 18145 (2008).

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.

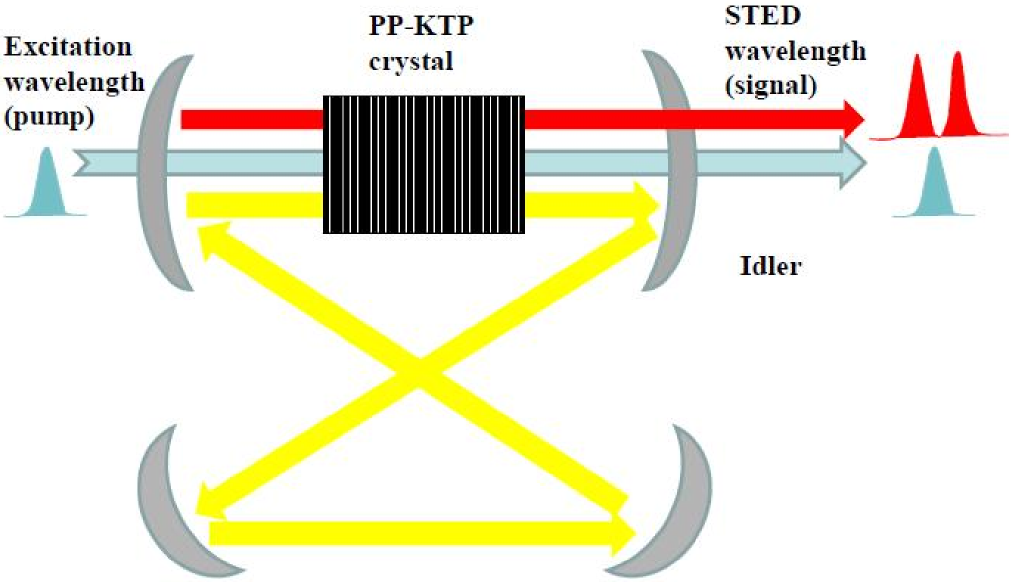

Figure 2.6. OPO for a STED microscopy scheme. The cavity is resonant to the idler beam (yellow). The pump beam (blue), which is the excitation wavelength, shows a Gaussian-like spatial shape, while the signal beam (red) presents a vortex-like spatial structure with a dark spot at the center. All cavity 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 Silvana Palacios et al.[15], 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[16], 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 2.6 in a STED microscopy scheme can 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.

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

[16] "Higher-order Laguerre-Gauss mode generation and interferometry for gravitational wave detectors", *Phys. Rev. Lett.* **105**, 231102, 2010

- *The value of the STED wavelengthcan bevaried 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[17]. Let us consider an excitation wavelengths 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). The dye GFP makes use of an excitation wavelength of 575 nm, while DY-485XL uses 647 nm. In between, other dyes make use of intermediate wavelength: Citrine and FITC and (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 values are well inside the range of wavelengths that can be tuned in a KTP crystal[18].
- *The generation of excitation and STED pulses aligned by designed.* The excitation and STED pulses should be properly aligned to achieve the maximum resolution. Experimental schemes have been devised to guarantee this important condition in a general way[19]. 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.

STATEMENT ON THE USE OF RESOURCES:

A total of 12 person-months (PM) have been used so far within this task, i.e. half of what planned, due to the initial difficulties in hiring the needed post-doc assistants.

3.2.2.2. Work-package WP2

Task WP2.1: Free-space OAM optics

> Excerpt from Annex I: This task, carried out by ULEID with the collaboration of UNAP, will investigate the deviations from simple ray-optics laws occurring in reflection and transmission of OAM-carrying beams going through simple optical components for free-space control of light. These deviations involve a counteraction on the OAM state, that needs to be addressed in order to perform OAM state free-space manipulation with high precision. The task is organized in two subtasks in series. [The first subtask covers Months 1-12]
>
> Subtask T2.1.1 – Angular and positional OAM-induced reflection/refraction effects
>
> We will start by trying to detect and study the “orbital Hall effect of light”, corresponding to an OAM-induced angular violation of the law of reflection and refraction. We will test the theoretical prediction that the angular shift (perpendicular to the incidence plane) varies linearly with the OAM value. A deviation from standard geometrical optics depending on OAM is predicted to occur also in the positions of the reflected and transmitted beams (Goos-Hänchen and Imbert-Fedorov effects). We intend to measure the entire 4x4 matrix that describes all these OAM-induced couplings between the angular and positional deviations from geometrical optics, as predicted in [A. Aiello and J.P. Woerdman, “Theory of Goos-Hänchen and Imbert-Fedorov shifts for OAM beams” , in preparation][20]. For typical configurations we expect the angular shift to be in the range 10^-5-10^-2 rad. ULEID has the necessary experimental infrastructure available since it was developed for the recent successful angular Goos-Hänchen experiment; using position-sensitive quadrant detectors, angular beam shifts as small as 10^-5 rad could be measured accurately. The results of this subtask will be evaluated at milestone MS3.

The work of this task has proceeded according to plans and partly beyond the plans. In particular, the main goal of calculating and measuring the entire 4×4 matrix that describes all OAM-induced couplings between

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[17] Fradkin et al., *Tunable midinfrared source by difference frequency generation in bulk periodically poled KTP*, Appl. Phys. Lett. 74, 914, 1999.

[18] Emanueli and Arie, Temperature-dependent dispersion equations for KTP and KTA, Appl. Opt. 42, 6661, 2003.

[19] S. Hell et al., Optics Express, 34, 2007.

[20] A. Aiello and J.P. Woerdman, “Theory of Goos-Hänchen and Imbert-Fedorov shifts for OAM beams” , in preparation

the angular and positional deviations from geometrical optics has been achieved.[21,22] Other works on related phenomena and technical issues have been also completed and published (see deliverable D2.1 or full publication list at pag. 32). An extension of the theory to the case of non-diffracting Bessel beams has been also recently completed.[23]

STATEMENT ON THE USE OF RESOURCES:

The actual number of PM used in this task has been equal to 11 (excluding the PM effort used before the project formal start), in line with the plans. A post-doc has been hired to work on this task and on the other tasks involving ULEID.

Task WP2.2: Polarization-OAM couplers

Excerpt from Annex I: This task will develop devices and schemes for controlling both the OAM and the polarization, aimed at classical and quantum information tasks, mainly exploiting the q-plate technology. It will exploit the results of Task WP1.2. Moreover, some of the most demanding applications within this task will greatly benefit from using the bright tunable OAM-entangled photon pair source that is the main goal of Task WP1.3, which should make possible significantly reduced experiment durations. This task is organized into three subtasks: two initial ones that run in parallel, divided according to the single-photon (also classical) or multi-photon (involving photon correlations) nature of the employed schemes, and a final one for putting together the outcomes of the first two and thus aim at the more complex goals of quantum information processing.

Subtask T2.2.1 – OAM-polarization single-photon couplers (plan for Months 1-12)

Our first step will be to develop an optical device for the deterministic (high efficiency) transfer of bidimensional quantum states (qubits) from polarization to OAM and vice versa, following the layout proposed by us in [E. Nagali et al., Optics Express 17, 18745 (2009)][24]. Next we will work on combined sequences of these devices to control higher-dimensional spaces of OAM using repeated polarization encoding. Electric tuning of the q-plates (which will be provided by Task WP1.2) will also be used for preparing coherent superpositions of OAM states having different values |m| of OAM. The generation, manipulation and measurement of arbitrary OAM-polarization hybrid single-photon “qudits” (d-dimensional quantum states) should be made possible by spin-orbit coupling methods for d = 4 (using a 2-dimensional OAM subspace together with polarization) and, eventually, for higher values (using a larger OAM subspace). Initially, we will address the generation and manipulation of ququarts (qudits with d = 4) encoded in single photons. In this case, we will exploit only a 2-dimensional subspace of OAM in combination with polarization. Since we exploit two different degrees of freedom of the same particle, we refer to hybrid-ququart states. A complete characterization of arbitrary ququart states will be carried out by a quantum state tomography technique adapted to hybrid polarization-OAM spaces. The analysis in all possible mutually unbiased bases can be realized by appropriate combinations of q-plates, polarizing sets and single-mode fiber couplings. Another specific problem that we plan to address is the swapping of the two qubits that may respectively be encoded in the polarization space and a 2-dimensional OAM-subspace of the same photon. We will try to conceive and demonstrate a device capable of accomplishing this task, again exploiting the q-plate device presumably in combination with suitable interferometric layouts. The results of this part of the subtask will be assessed at milestone MS3.

Subtask T2.2.2 – OAM-polarization multi-photon couplers (plan for Months 1-12)

This subtask will start simultaneously with subtask 2.2.1 at the project beginning. The first part of the work of this subtask will be that of generating multi-photon quantum states exhibiting new

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[21] “How orbital angular momentum affects beam shifts in optical reflection”, M. Merano, N. Hermosa, J. P. Woerdman, A. Aiello, *Physical Review A* **82**, 023817 (2010).

[22] “Orbital angular momentum induced beam shifts”, N. Hermosa, M. Merano, A. Aiello, J. P. Woerdman, *Proceedings of SPIE* **7950**, 79500F (2011).

[23] “Role of spatial coherence in Goos-Hanchen and Imbert-Fedorov shifts”, A. Aiello, J. P. Woerdman, *Optics Letters* **36**, 3151-3153 (2011)

[24] E. Nagali et al., Optics Express 17, 18745 (2009).

forms of entanglement that involve both polarization and OAM of two or more photons. By adopting the deterministic polarisation-OAM transferrer schemes introduced in Ref. [E. Nagali et al., Optics Express 17, 18745 (2009)], the generation of polarisation-OAM hybrid entangled states of photon pairs can be achieved by starting with polarization-entangled pairs generated by SPDC. Apart from its fundamental interest, hybrid entanglement can be useful in quantum information processing, e.g. the quantum repeater. For instance the OAM features can be more appropriate for mapping single photon states in atomic systems, so as to create new forms of light-matter entanglement. The generation of hybrid entangled states can also be useful for asymmetric optical quantum network where the different communication channels adopted for transmitting quantum information exhibit different properties. In such a way one could adopt the degree of freedom with larger robustness along the channel. Therefore, a hybrid source can be advantageous as it enables a more flexible network with each photon being transmitted through the better suited channel. This work is planned to be completed by milestone MS3.

Subtask T2.2.1 – OAM-polarization single-photon couplers:

We have followed the plans with only minor deviations. In particular, we have successfully demonstrated the deterministic qubit transfer device (which is the deliverable D2.2) as planned, incorporating the electric-tunable q-plate technology developed within WP1, as well as the Sagnac interferometer scheme proposed in E. Nagali et al.[25]. The device is based on the design shown in Fig. 2.7.

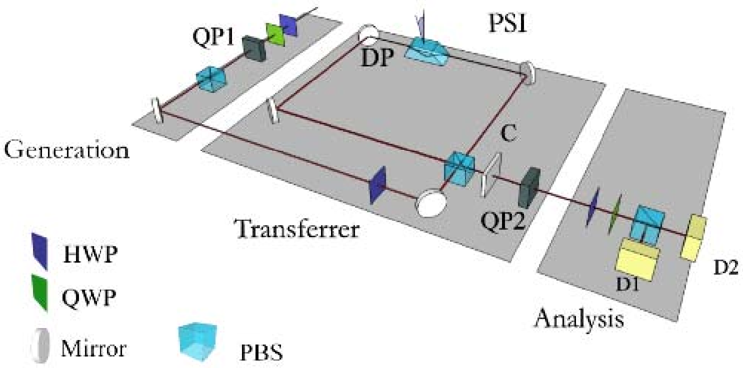

Figure 2.7 – Schematics of the qubit deterministic polarization-OAM transfer device. The sketch includes also the generation and analysis setups used for testing the device performances. Legend: PSI – polarized Sagnac interferometer; DP – Dove prism; QPn – q-plates; Dn – single photon detectors; HWP – half-wave plate; QWP – quarter-wave plate; PBS – polarizing beam splitter.

The device allows to transfer a generic qubit initially encoded in the orbital angular momentum of a single photon, to the polarization degree of freedom. The qubit coming out from the transferrer has been then analyzed by adopting an automatic setup for the polarization analysis, composed of two motorized waveplates and a polarizing beam splitter. Experimentally a mean fidelity of (0.989±0.002) has been observed. The transfer of information, completely reversible, turns out to offer clear advantages in terms of efficiency compared to the previous probabilistic implementation.

Aim of this task was also to generate and manipulate qudit states. In this framework, we have carried out the experimental generation of four-dimensional quantum states, or “ququarts”, encoded in the polarization and orbital angular momentum of a single photon, i.e. as spin-orbit photon states (this work was actually started before the formal beginning of the project; the first results have been published[26]). The adopted technique, based on the q-plate device, allows the ququart to be prepared and measured in all five mutually unbiased bases, thus allowing the reconstruction of the four-dimensional density matrix through the tomographic procedure for different ququart states with a mean fidelity value of 0.94 . The capacity to manipulate with high reliability all ququart states encoded in a single photon enforce the achievement of the quantum state

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[25] E. Nagali et al., Optics Express 17, 18745 (2009)

[26] E. Nagali, L. Sansoni, L. Marrucci, E. Santamato, F. Sciarrino, Phys. Rev. A 81, 052317 (2010)

engineering of ququart to direct towards the implementation of new quantum information protocols and more robust communication procedures.

And indeed, ahead of our schedule, we have already obtained some results on the experimental implementation of quantum information protocols based on polarization-OAM encoding (work which is planned mainly for the third project year). A first important result along this line was demonstrated in our paper in Phys. Rev. Lett.[27], in which we performed the optimal quantum cloning of spin-orbit ququarts. To our knowledge, this result is also the first experimental demonstration of quantum cloning in a Hilbert-space dimension higher than two. Optimal quantum cloning is the process of making one or more copies of an arbitrary unknown input quantum state with the highest possible fidelity. A quantum-cloning machine is an important multipurpose tool of the emerging quantum information technology. The demonstrated procedure, based on the symmetrization method, has been also proved theoretically to be generally applicable to quantum states of arbitrarily high dimension - or ``qudits'' - and to be scalable to an arbitrary number of copies, in all cases remaining optimal. In a recent paper, the implementation of a quantum cryptographic protocol has been proposed by the Rome Phorbitech group in collaboration with the University of Sevilla, adopting ququarts encoded in polarization and OAM.

As a slight deviation from plans, the work on the concept of "qubit swapping" between polarization and OAM, although started, is still at an early stage.

Subtask T2.2.2 – OAM-polarization multi-photon couplers:

Hybrid entangled states exhibit entanglement between different degrees of freedom of a particle pair and thus could be useful for asymmetric optical quantum network where the communication channels are characterized by different properties.

In this framework, we have reported the first experimental realization of hybrid polarization-orbital angular momentum (OAM) entangled states, adopting two complementary approaches, both based on combining a spontaneous parametric down conversion (SPDC) source of polarization entangled states with a q-plate based polarization-OAM qubit transfer device: (i) by generating polarization-entangled pairs with type-II SPDC and then transferring the qubit of one of the two photons into OAM[28]; (ii) by generating OAM-entangled pairs with type-I SPDC and the transferring the qubit of one of the two photons into polarization[29]. In both cases, we have shown that this approach provides quantum states with high fidelity and with a bright generation rate. Moreover by adopting several concatenated q-plates the generation of hybrid states with higher OAM value could be easily obtained. The generated quantum states have been characterized through quantum state tomography. In order to further characterize the state, a more quantitative parameter associated to the generated polarization-entangled states is given by the concurrence, which in the generated hybrid entangled state turned out to be $C=(0.957\pm0.002)$ (this value is for approach i). These values demonstrate the high degree of hybrid entanglement generation. Hybrid entangled states could be adopted to carry out quantum state teleportation between different degrees of freedom of light. Finally, the violation of Bell's inequalities with the hybrid two photon system has been observed, and the connection of this violation with issues of quantum contextuality have been discussed.

As second step, we have started to exploit hybrid-entangled states to investigate the resilience of OAM. In order to characterize the degradation undergone by the information content of qubits encoded in a bidimensional subspace of the OAM degree of freedom of photons, we investigated how the state fidelity is affected by a transverse obstruction placed along the propagation direction of the light beam. Emphasis has been placed on the effects of planar and radial hard-edged aperture functions on the state fidelity of Laguerre-Gaussian transverse modes and the entanglement properties of polarization-OAM hybrid-entangled photon pairs. In the classical case, we first demonstrated that the information encoded in a bidimensional subspace of OAM can be retrieved probabilistically in the same subspace even if the state is highly perturbed in such a way as to block a significant fraction of the transverse extension of the mode. The experimental

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[27] E. Nagali, D. Giovannini, L. Marrucci, S. Slussarenko, E. Santamato, F. Sciarrino, *Phys. Rev. Lett.* **105**, 073602 (2010)

[28] E. Nagali, F. Sciarrino, *Optics Express* **18**, 18243-18248 (2010).

[29] E. Karimi, J. Leach, S. Slussarenko, B. Piccirillo, L. Marrucci, L. Chen, W. She, S. Franke-Arnold, M. J. Padgett, E. Santamato, *Physical Review A* **82**, 022115 (2010)

results are in good agreement with the theoretical model. We then proceeded to demonstrate also in the single photon regime, by using polarization-OAM entangled photon pairs, the high resilience of single-photon bidimensional OAM states. We verified that hybrid entanglement correlations persist even in high-loss conditions, thus providing a useful and versatile quantum communication resource[30].

STATEMENT ON THE USE OF RESOURCES:

A total of 30 person-months (PM) have been used so far within this task, in line with the plans. In particular, a post-doc researcher (Dr. Eleonora Nagali) has been hired to work on this task (with a 24 PM contract) and on the other project activities involving UROM.

Task WP2.4: OAM waveguides & couplers

> Excerpt from Annex I: This task targets the development of specific waveguides for OAM transmission as well as coupling devices with free-space modes and mode multiplexing. Most optical quantum computing experiments to date have relied on polarization-encoded qubits, but unfortunately the majority of standard integrated-optic devices either do not preserve the phase between their polarization eigenmodes—they introduce phase decoherence—or they only efficiently transmit a single polarization—they introduce amplitude decoherence. One already demonstrated method to combat this is to use "dual rail" encoding, where a qubit is encoded by two spatial modes. OAM encoding, exploiting different transverse modes of waveguide may provide an interesting alternative that will be investigated in this task. OAM encoding within a single waveguide could possibly prove more stable than polarization, in particular if the waveguide profile is appropriately designed. This task is organized in three subtasks in series, [the first of which covers Months 1-12].
>
> Subtask T2.4.1 – Waveguide simulations and realization tests
>
> The work for this task will start with a preliminary study of different waveguide structures and materials for the transmission of photons in OAM maintaining waveguides, also based on appropriate numerical simulations of the light transmission, taking into account possible minor manufacturing imperfections. For the realization, we will benchmark several material systems (LiNbO3, SiOxNy, semiconductors), architectures (directional and MMI couplers, photonic crystal) and fabrication techniques (optical-, electron beam- and focussed ion beam-lithography, proton exchange, direct-write) to establish the best approaches for the project. In the direct-write approach, by engineering the beam-profile of the femtosecond laser adopted to inscribe the waveguide, different geometries of the waveguide cross-section can be implemented. In particular, the role of the waveguide transverse profile in determining the OAM preserving properties and the cross-talk, both in total-internal reflection and photonic-crystal bandgap confinement needs to be addressed in detail. The novel idea of a "negative wave-guiding", i.e., trapping the vortex dark core rather than the bright areas of the optical field will also be assessed, as it may provide a higher degree of robustness against phase perturbations. This subtask is planned to end at milestone MS3, at which its results will be assessed.

We have followed the plans with only minor deviations. We investigated different routes for OAM encoding in waveguides. One approach will utilise the recent results of Phorbitech task 3.1[31], demonstrating phase unfolding which projects the azimuthal phase dependence of OAM states onto a linear coordinate which can be injected into an array of single mode waveguides. We studied the evolution of large superposition states in waveguide array structures[32],[33] and conducted a theoretical study of mode coupling in single mode waveguides which is crucial for further applications of single mode as well as multimode waveguides (see Figure 2.8 and further details below). We show high control over single phonon and two-photon states in a

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[30] D. Giovannini, E. Nagali, L. Marrucci, F. Sciarrino, *Physical Review A* **83**, 042338 (2011).

[31] G. C. G. Berkhout, M. P. J. Lavery, J. Courtial, M. W. Beijersbergen, and M. J. Padgett, "Efficient Sorting of Orbital Angular Momentum States of Light", *Phys. Rev. Lett.* **105**, 153601 (2010)

[32] J. D. A. Meinecke, K. Poulios, A. Politi, J. C. F. Matthews, N. Ismail, K. Wörhoff, M. G. Thompson, and J L. O'Brien, "Coherent Time Evolution and Boundary Conditions of Two-Photon Quantum Walks", in preparation.

[33] K. Poulious, D. Fry, A. Politi, M. Thompson, J. L. O'Brien, "Two-photon quantum interference in integrated multi-mode interference devices", in preparation.

reconfigurable integrated quantum photonic circuit[34]. This opens the prospect to manipulate path encoded OAM states within the waveguide structure.

Besides encoding in single mode structures, multimode structures are an interesting approach for encoding. Light propagates in multimode devices as superpositions of Hermite-Gaussian modes and using the self-imaging principle provides prospect of transmitting OAM states.

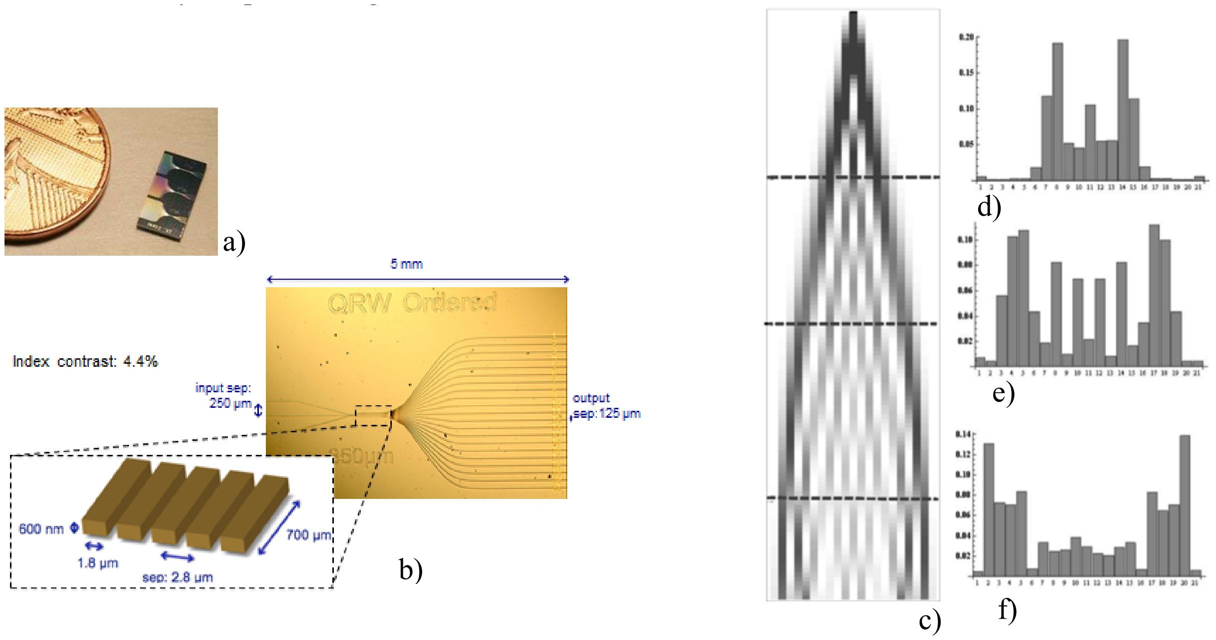

Figure 2.8 – a) shows SiON chip with three array structures of different length with waveguide dimensions stated in b). The simulated evolution of a single photon propagation in the array is shown in c) together with the measured time steps corresponding to the three different devices: d) array of 350 microns, e) array of 700 microns, f) array of 1050 microns.

We fabricated in cooperation with different partners (University of Twente, Jena University, TOSHIBA) waveguide structures in SiON[29,30], fused silica, and silicon-on-insulator (SOI) and characterised them with classical light as well as with correlated photons testing their stability concerning quantum interference effects.

Let us now discuss these results in more detail.

1. Single mode structures[33]

We theoretically studied mode coupling in arrays of single mode waveguides and experimentally measured the evolution of single photons as well as two indistinguishable photons in an array of 21 evanescently coupled waveguides in SiON (figure 2.8).

In cooperation with University of Jena we then measured a structure of 9 waveguides fabricated in fused silica by direct-write technique (figure 2.9). This technique allows three-dimensional waveguide structures, the refractive index contrast can be varied by changing the writing speed and by multiple writing processes.

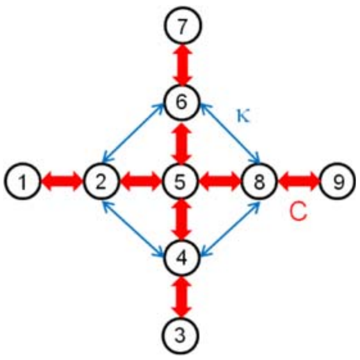

Figure 2.9 – Structure of 9 waveguides coupled horizontally and vertically (C) as well as diagonally (k).

We measured single photon propagation as well as two-photon

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[34] P. J. Shadbolt, M. R. Verde, A. Peruzzo, A. Politi, A. Laing, M. Lobino, J. C. F. Matthews, J. L. O'Brien, “Generating, manipulating and measuring entanglement and mixture with a reconfigurable photonic circuit”, arXiv:1108.3309v1.

correlations as shown in figure 2.10.

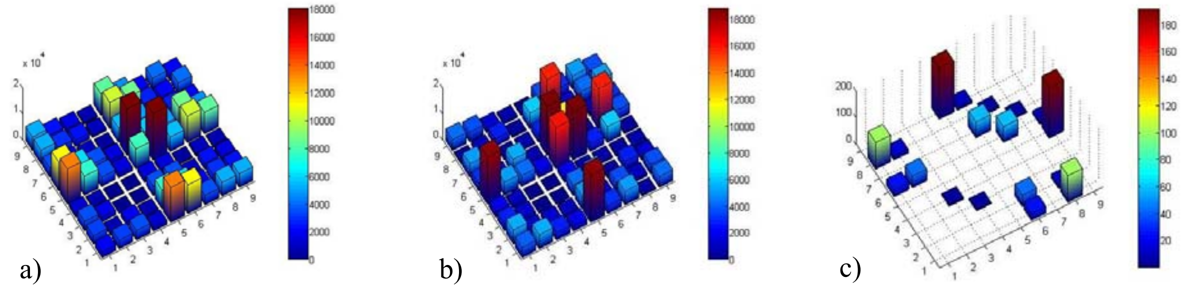

Figure 2.10 – Measured corretation function a) for input of two distinguisable photons in waveguides number 1 and 7, b) indistinguishable photons and the violations of a classical inequality in standard deviations c).

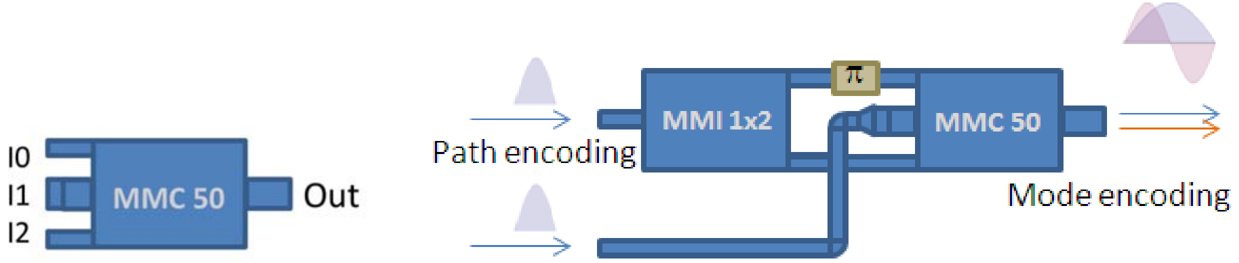

Figure 2.11 – Left: 50% efficiency path to mode converter. Right: 100% efficiency path to mode converter. The MMC 50 component maps the side inputs (I0 and I2) into the 1st order mode of the output. But if the light is launched only from one side, then the conversion efficiency into the first order mode is only 50%. The remaining power is lost. To get 100% efficiency, the light has to be launched from both sides. We therefore use a 1x2 MMI splitter with a phase correction on one arm before. If the mode at the input I1 is the 0 order mode, this mode is self imaged at the output. The 0 order mode is launched by adiabatically tapering the standard waveguide used in path encoding to match the size of I1.[31]

2. Multimode encoding

We designed multimode mode encoding devices (MME) (Fig. 2.11) adapting existing designs[35] to the technology that we used. In order to test those structures we have made two types of circuits:

- An MME followed by an adiabatic output taper with seven waveguides acting like a 7 pixel one dimensional CCD. This circuit should allow us to check the behaviour of the designed MMC.
- An encoding/decoding circuit (Fig. 2.12) with a first MMC to convert from path to mode encoding, a straight line which propagates the two modes together, ad finally another MMC circuit which converts back from mode to path.

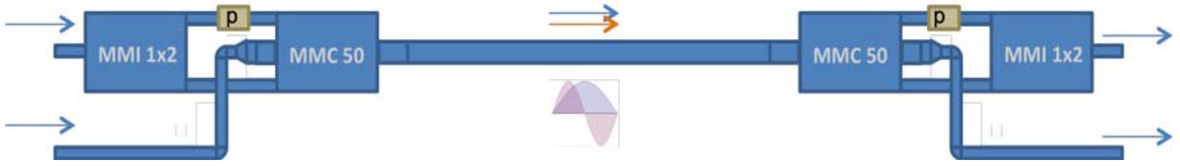

Figure 2.12 – Mode encoding/decoding circuit.

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[35] Leuthold et al., “Multimode interference couplers for the conversion and combining of zero-and first-order modes”, *Journal of Lightwave Technology* (2002) vol. **16** (7) pp. 1228-1239.

The devices were fabricated by TOSHIBA in a silicon-on-insulator (SOI) chip with an index contrast of ~2.0. Some processing issues induced large losses which prevented us to test those devices. This batch will be rerun and we expect to get new devices.

3. Multimode Interference devices[36]

We fabricated MMI devices in silicon oxynitride (SiON) with a high refractive index contrast providing a compact and highly stable platform for interference of multiple modes (see figure 2.13). We achieve in this structure non-classical interference with a visibility of up to 99% of the theoretical maximum for a range of splitting rations (figure 2.14).

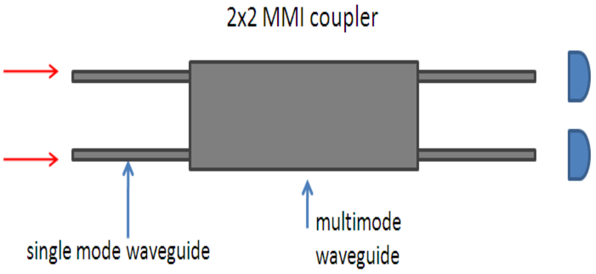

Figure 2.13 – Schematic view of a 2x2 MMI device, mapping two input modes onto two output modes.

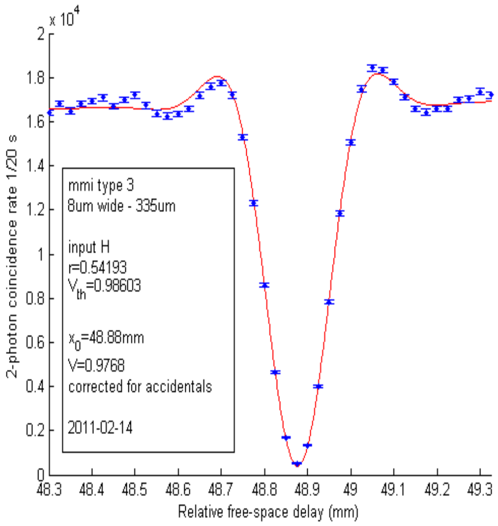

Figure 2.14 – Measured Hong-Ou-Mandel dip showing high visibility non-classical interference of two indistinguishable photons in a 2x2 MMI

4. Negative wave-guiding

This idea is still under investigation. We are currently performing beam-propagation-method (BPM) simulations in order to assess the potential validity of this idea.

STATEMENT ON THE USE OF RESOURCES:

For this task, we used 29 PM as planned.

3.2.2.3. Work-package WP3

Task WP3.1: OAM phase unfolding

Excerpt from Annex I: This task targets the development of a novel OAM detection method, suitable both for the quantum and classical regime, based on "unfolding" the angular phase profile typical of OAM modes via a suitable fish-eye lens. The resulting linear phase profile will then be focused to different detector positions. This task is divided into two subtasks in series, [the first covering Months 1-12].

Subtask T3.1.1 – OAM-phase-unfolding preliminary study

UGLAS, with the help of ULEID, will undertake both theoretical and experimental investigations of the lens system consisting of a fish-eye lens and a cylindrical lens. We will model the required

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[36] J. D. A. Meinecke, K. Poulios, A. Politi, J. C. F. Matthews, N. Ismail, K. Wörhoff, M. G. Thompson, and J L. O'Brien, *Coherent Time Evolution and Boundary Conditions of Two-Photon Quantum Walks,* in preparation.

> lens system with our ray tracing software and study the propagation of various OAM states to optimize the required orientation and focal length of the fish-eye lens. At the same time we will perform first experiments with our available fish-eye lenses, again monitoring the propagation of OAM light modes, initially using classical light sources and detection via CCD cameras. The results of this subtask will be assessed at milestone MS4.

Our progress regarding the idea of OAM-phase unfolding has advanced beyond the tasks set out for subtask T3.1.1 and in fact encompasses already various aims set for subtask T3.1.2 as discussed below. Our approach for separating OAM states was to transform azimuthal position in the input beam into linear position in the output beam, i.e. finding an optical element that transforms a helically phased beam into a transverse phase gradient.

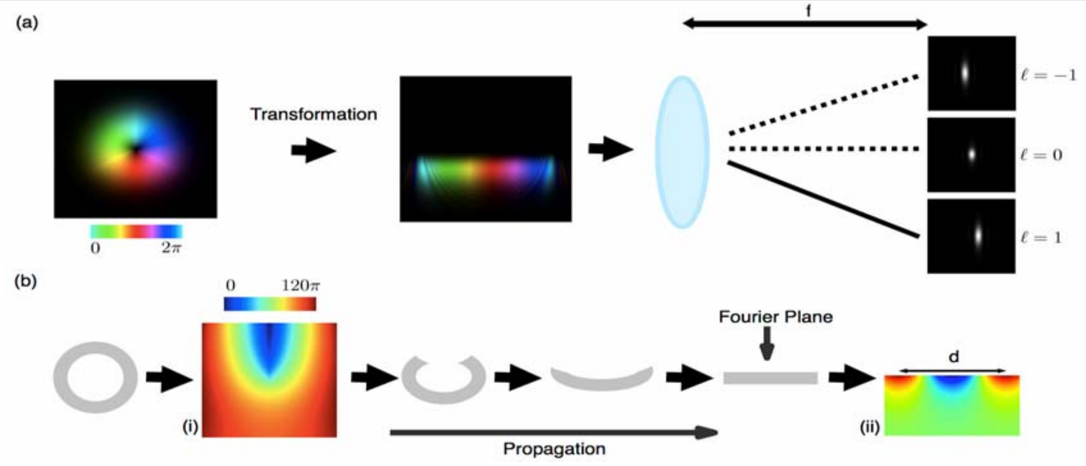

Figure 2.15 – Transformation of beams with a helical-phase into a linear phase gradient for the example of $l = 1$. (a) The cross section of a pure OAM mode is re-shaped such that azimuthal angle is transformed into a Cartesian coordinate, here horizontal. Intensity is represented as brightness and phase by colour. The resulting beam cross-section has a uniform phase gradient in the horizontal direction which is directly proportional to l. When passed through a lens it gets focussed to a horizontal position that depends on this phase gradient, and therefore on l. (b) Colour representation of the spatially-varying phase added by the phase holograms used in the experiment. Hologram (i) initiates the Cartesian-to-polar geometric transformation, which is complete by the time light has reached the hologram's Fourier plane. Hologram (ii) corrects for the differences in optical path length between different parts of the beam.

The first intention was to construct a system consisting of a fish eye lens and a cylindrical lens. In our investigation we discovered that the required transformation was an example of an optical geometric transformation[37]. We implemented this transformation through the use of a pair of optical elements separated by a transform lens. The combined system performs a conformal mapping of a position in the input plane to a position in the output plane, effectively mapping phase and radial coordinate of the input mode onto linear coordinates φ and $\ln(r/b)$, shown in Figure 2.15.

We have described a novel system comprising of two bespoke optical elements that can be used to efficiently measure the OAM state of light. We have shown numerical and observed data to support our method.

Our ideas on the efficient sorting of OAM modes and subsequent experiments performed with our proof-of-principle system based on SLMs have been reported in three publications.[38,39,40]

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[37] Bryngdahl, *J. Opt. Soc. Am*. **64**, 1092 (1974)

[38] G. C. G. Berkhout, M. P. J. Lavery, J. Courtial, M. W. Beijersbergen, and M. J. Padgett, "Efficient Sorting of Orbital Angular Momentum States of Light", *Phys. Rev. Lett*. **105**, 153601 (2010)

[39] G. C. G. Berkhout, M. P. J. Lavery, M. J. Padgett, and M. W. Beijersbergen, "Measuring orbital angular momentum superpositions of light by mode transformation", *Opt. Lett*. **36**, 1863-1865 (2011)

[40] M. P. J. Lavery, G. C. G. Berkhout, J. Courtial, and M. J. Padgett, "Measurement of the light orbital angular momentum spectrum using an optical geometric transformation", *J. Opt*. **13**, 064006 (2011) [special issue on OAM]

As an alternative approach, extending on earlier work,[41] we have also developed a compact interferometric sorter based on Dove prisms, see photograph in Figure 1.4. The work has been published[42] with the following abstract:

<<We have developed an interferometer requiring only minimal angular alignment for the routing of beams carrying orbital angular momentum. The Mach-Zehnder interferometer contains a Dove prism in each arm where each has a mirror plane around which the transverse phase profile is inverted. One consequence of the inversions is that the interferometer needs no alignment. Instead the interferometer defines a unique axis about which the input beam must be coupled. Experimental results are presented for the fringe contrast, reaching a maximum value of 93% ± 1%.>>

Our work on the efficient sorting of OAM modes, outlined above, was initially published in Physical Review Letters at the end of 2010,[38] and at the time of writing this report has already gained 14 citations. This work was actually undertaken before the official start date of Phorbitech but originates from the collaboration with Leiden that was established when writing the proposal. Our proof-of-principle system based on SLMs allowed us to publish two further papers.[39,40] The first is an experimental study into the modal content of non-integer OAM states concerning the measurement of superpositions, and the second considers the effects of misalignment when used as an OAM mode analyser.

STATEMENT ON THE USE OF RESOURCES:

The actual effort in this task was 6 PM as planned (excluding the effort put before the project formal start date).

Task WP3.2: OAM chiral media detection

Excerpt from Annex I: In this task, we will investigate the scattering of OAM light by a chiral-structured medium. The purpose is twofold: to realize novel optical media suitable for the OAM manipulation and analysis and to test the possible use of OAM in probing applications, particularly for biomedical applications. This task is structured in two subtasks in series, [the first of which encompassing Months 1-18].

Subtask T3.2.1 – OAM chiral structure generation and scattering

We will start our study using as model system a single mesoscopic spiral particle which is positioned in the focus of an OAM light beam. The spiral particle will be made out of photo-resist by means of holographic lithography using two counter-propagating Laguerre-Gauss (LG) beams (Philips Research will supply the technical know-how for this). The LG beams are to be normal to the substrate and have overlapping foci in the resist layer. If a l=±1 beam interferes with a l=0 beam the resulting standing-wave pattern is a single spiral, whereas interference of l=±1 with l=±1 results in a double spiral; for symmetry reasons only the latter one leads to circular birefringence and is thus the only useful version. After photo-polymerization the unexposed resist is rinsed away so that a substrate with a free-standing spiral results. We plan to use a Fianium laser (a spectroscopically filtered white-light fiber laser) to study the OAM dependence of light scattering by the spiral. This source is tunable in the range 400-1000 nm. For variation of the OAM of the input beam (say l = -1, 0, +1) we use a computer-generated fork hologram; we analyze in each case the OAM contents of the output beam and obtain thus the effect of the spiral-induced scattering on the output OAM intensity spectrum. We can also map the effect of this scattering on the phase relations between the OAM amplitude components, namely by using a superposition of OAM states as input beam. In this way we obtain the complete complex-valued scattering matrix. As an example of an OAM superposition, a HG01 beam is a phased superposition of LG01 and LG10 donut modes that travel with slightly different phase velocity along the spiral. As a result the nodal line of the HG01 mode is rotated. One may call this: OAM-type optical activity, as opposed to conventional optical activity which corresponds to rotation of linear polarization by

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[41] J. Leach, M. J. Padgett, S. M. Barnett, S. Franke-Arnold and J. Courtial, "Measuring the orbital angular momentum of a single photon", *Phys. Rev. Lett.* **88**, 257901 (2002).

[42] M. P. J. Lavery, A. Dudley, A. Forbes, J. Courtial and M. J. Padgett, "Robust interferometer for the routing of light beams carrying orbital angular momentum", *New J. Phys.* **13** 093014 (2011).

> passage through a circularly birefringent medium. This subtask is planned to be completed by milestone MS7, at mid-project time.

This task is planned to last until Month 18, so it is still undergoing. The work is proceeding according to plans.

The objective is to fabricate micrometer-scale helical dielectric particles by photolithography with a pitch of half the optical wavelength. This effort can be split in 3 parts: Evaluation of the photo resist, development of the lithography setup and implementation of efficient means of characterization.

We have tested and compared various photo resists, and the well-known SU-8 (Microchem) for fabrication of micro mechanical systems turned out to be superior. Spatial resolution is high enough (around 50nm) and processing conditions suitable for our facilities at Leiden.

The lithographic setup has been designed, built and characterized.

A single-mode fiber-coupled laser, operating at around 400 nm, is divided at a beam splitter, then both beams are spatially modulated and then focused in a counter-propagating geometry onto the photo resist layer. The spatial modulation is done using a spatial light modulator: We use a device from Hamamatsu (model X10468) to perform the mode conversion from the fundamental fiber mode into the desired Laguerre-Gauss mode. The two beams are focused onto the substrate using long working distance, NA=0.55 objectives. For this type of counter-propagating interference lithography, optical path-length stability is of uttermost concern. Therefore, vibrations must be minimized in the relevant frequency range (down to 30 Hz). To accomplish this, we use a large, undamped optical table, on which we place a smaller 1.5x1.5 m breadboard, which is vibration isolated by automated pneumatic isolators. Interferometric measurements show that further active stabilization of the lithography setup is not required; this is essential because no working solution is known for counter-propagating lithography schemes.

Currently, we are in the process of optimizing the optical quality of the Laguerre-Gaussian beams: From our simulations this turned out to be the key point. We evaluate the capability of the SLMs to correct for unavoidable wavefront errors induced by other optical components.

Since the helical particles will have only a few micrometer in external dimensions and the pitch is of the order of 100 nm, electron-beam microscopy (SEM) is needed to assess the quality of the lithographic fabrication process. We therefore set up a Platinum sputtering system to deposit ultra-thin metallization layers which is required for SEM. We are currently evaluating the test samples produced so far.

STATEMENT ON THE USE OF RESOURCES:

The actual effort in this task over the first year was 5 PM as planned.

Task WP3.3: OAM material storing

> Excerpt from Annex I: In this task we will develop a robust method to inscribe OAM information onto the spatial profile of atomic populations of a cold Rubidium gas. The technique will rely on phase-dependent atomic transitions that make the atom-light interaction sensitive to the optical phase as well as intensity. This task is structured in two subtasks in series, [the first of which encompassing Months 1-24].
>
> Subtask T3.3.1 – OAM-driven atomic populations
>
> Experiments will be performed on an ensemble of cold 87Rb atoms, trapped and cooled in a magneto-optical trap, using the usual trapping and re-pumping transitions at 780nm. The first part of the work will be to develop a laser system driving the required closed loop transitions that will be used for imprinting OAM information from light to atoms. For this, a transition at 795nm, coupling 5s1/2 and 5p1/2 will be used, offering a closed loop transition encompassing the two lower levels (5s1/2, F=1, mF=0) and (5s1/2, F=2, mF=0) separated by 6.8GHz, and the two upper state Zeeman levels (5p1/2, F=1, mF=-1), (5p1/2, F=1, mF=+1). The required laser light will be generated via two external cavity diode lasers stabilised by saturated absorption spectroscopy. The left- and right-handed polarised light components can then address transitions to the different Zeeman levels. The spatial phase profile of one of the driving transitions will be adjusted via

> SLM, generating an arbitrary OAM mode. For the observation of phase-dependent effects it is important to exclude any distortions of the wavefront either imposed by the SLM itself or by the glass cell. This will be achieved using a Gerchberg-Saxton algorithm on the SLM that iteratively corrects for wavefront distortions. UGLAS has already developed and implemented such systems [Sincl04]. We will then characterise the quality of the wavefronts, both in order to evaluate the effectiveness of the aberration corrections and, of course, to identify the imprinted phase pattern. This will be achieved by the observation of an interference pattern with a well-known beam profile, e.g. a beam emerging from a single mode fiber, and numerical comparison with mode profiles. This subtask is planned to end at milestone MS11. Owing to the need for setting up a new rather complex apparatus for atom trapping and cooling, this subtask is planned to last two years.

The first objective of this task is to develop an apparatus suitable to investigate interaction between cold atoms and OAM carrying light.

A standard magneto-optical trap (MOT) for Rb^{87} atoms, already built before the beginning of the project, has been significantly improved and is now fully functional. The atom number has been increased by almost 2 orders of magnitude to about $5x10^{8}$ and the temperature has been measured to be in the range of some 100 micro Kelvin. The trap stability has been increased from some minutes to hours.

We can monitor the atomic sample via absorption or fluorescense imaging. A LabVIEW routine with controllable timing sequence has been developed to measure atom number, density and temperature. The time resolution is limited by the internal clock rate of the data acquisition (DAQ) board to 2 microseconds. A LabVIEW interface also controls the required quadrupole field and compensation coils that eliminate stray magnetic fields, the latter can also provide a bias field that provides a reference quantisation axis during measuring/pumping schemes. Frequency and power of the trapping, repumping and probe lasers are determined by LabVIEW-controlled AOMs. Additionally, the frequency of the trapping laser can be jumped by up to hundreds of KHz, which effectively allows driving two separate transitions.

The various trapping parameters have been optimised to produce the maximum number of atoms, including beam power, magnetic field gradient, laser beam alignment, laser beam size and trap beam detuning. The diode lasers produce at an acceptable current level of 150 mA around 100 mW. For experiments which are particularly sensitive to atom number it will be possible to turn the laser power up to 200mA/150mW for short bursts. The measured dependence of atom number on detuning and field gradient is shown in Figure 2.16a, indicating an ideal detuning of -17 MHz. At this detuning we find trap temperatures of around 450 µK, which drop further in molasses.

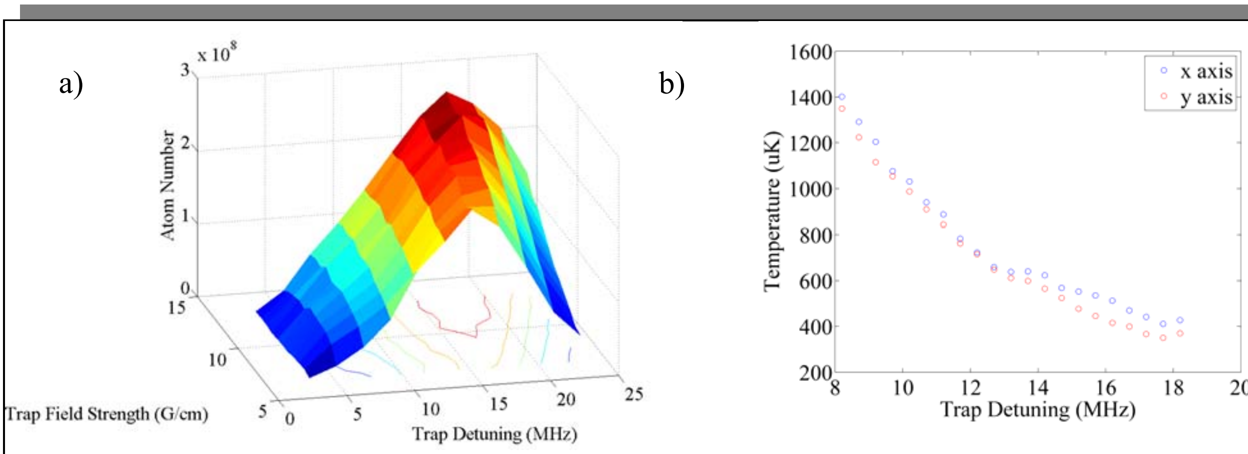

Figure 2.16 – a) Measurements of atom number as a function of field strength (in axial direction) and trap detuning. b) Measurements of temperature as a function of trap detuning.

A Hamamatsu Spatial Light Modulator has been purchased and tested to allow future beam shaping. First experiments in a Rb vapour cell at room temperature have been performed to show the frequency translation of OAM from 2 pumping lasers at 780nm and 776nm onto blue light at 420nm generated by four-wave mixing in an atomic cascade, see Figure 2.17.

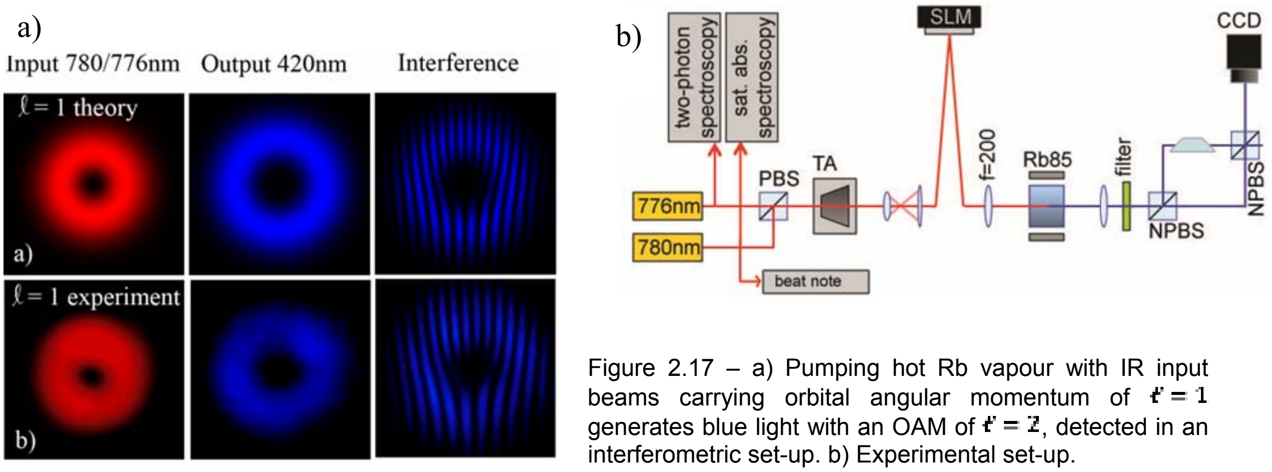

Figure 2.17 – a) Pumping hot Rb vapour with IR input beams carrying orbital angular momentum of $\ell = 1$ generates blue light with an OAM of $\ell = 2$, detected in an interferometric set-up. b) Experimental set-up.

Beyond the tasks originally planned for this work-package, but consistent with its general goal of advancing the scientific knowledge in the fundamental area of light-matter interaction involving angular momentum, we have observed for the first time a macroscopic rotary photon drag as predicted by Fresnel 200 years ago, which we reported in Science.[43] Similarly to the Faraday Effect, where a phase shift between right and left polarised light leads to a rotation of the polarisation axis, a phase shift between the components with positive and negative OAM corresponds to a rotation of the transmitted intensity profile. A mechanical rotation of a medium is predicted to induce a rotational photon drag, effecting polarisation state and image in the same way. As the rotation angle has a component that is inversely proportional to the group velocity, the angle gets significantly magnified in a slow light medium. Using a ruby window under conditions for coherent population oscillations, we induced an effective group index of about 1 million, so that the rotation angle was large enough to be observed by the eye (see figure 2.18).

Figure 2.18 – Rotary photon drag induced by a spinning ruby rod. a) Image rotation for clockwise and anti-clockwise spinning of the ruby crystal. b) Exit surface of the ruby crystal.

This work on the rotary photon drag was covered in national newspapers (e.g., The Scottish Herald), as well as in physorg.com, Physics World, the Engineer and various others.

In conclusion, the task is proceeding well and according to plans. The atom trap is fully functional and first experiments are under way aiming at increasing the atom density by implementing a novel dark spot trap using LG beams in the repumping laser. Experiments in a vapour cell are promising for the interaction of OAM between light and atoms and are currently being written up for publication.

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[43] S. Franke-Arnold , G. Gibson, R. W. Boyd[2], M. J. Padgett, *Rotary Photon Drag Enhanced by a Slow-Light Medium*, Science 333, no. 6038 pp. 65-67, DOI: 10.1126/science.1203984

STATEMENT ON THE USE OF RESOURCES:

The amount of resources used in this task, especially the person-months, is as planned (about 11 PM in the first 12 months). In particular, a post-doc has been hired from the 1st of October 2010 for the whole duration of PHORBITECH project to work on this and the other tasks involving UGLAS (Dr. Neal Radwell).

2.2.4 WP5: Dissemination activities

Scientific dissemination

The scientific dissemination activity consisted of scientific publication on high impact scientific journals and of communication to conferences and workshops. The research groups working in PHORBITECH have published during the first year a total of 28 project-related scientific publications in high-profile journals. Below the full list of publications resulting from the first year work:[44]

PHORBITECH full publication list:

1. "Hybrid ququart-encoded quantum cryptography protected by Kochen-Specker contextuality", A. Cabello, V. D'Ambrosio, E. Nagali, F. Sciarrino, *Physical Review A* **84**, 030302 (2011).
2. "Robust interferometer for the routing of light beams carrying orbital angular momentum", M. P. J. Lavery, A. Dudley, A. Forbes, J. Courtial, M. J. Padgett, *New Journal of Physics* **13**, 093014 (2011).
3. "Correlated photon-pair generation in a periodically poled MgO doped stoichiometric lithium tantalate reverse proton exchanged waveguide", M. Lobino, G. D. Marshall, C. Xiong, A. S. Clark, D. Bonneau, C. M. Natarajan, M. G. Tanner, R. H. Hadfield, S. N. Dorenbos, T. Zijlstra, V. Zwiller, M. Marangoni, R. Ramponi, M. G. Thompson, B. J. Eggleton, J. L. O'Brien, *Applied Physics Letters* **99**, 081110 (2011).
4. "Role of spatial coherence in Goos-Hanchen and Imbert-Fedorov shifts", A. Aiello, J. P. Woerdman, *Optics Letters* **36**, 3151-3153 (2011).
5. "Spin Hall effect of light in metallic reflection", N. Hermosa, A. M. Nugrowati, A. Aiello, J. P. Woerdman, *Optics Letters* **36**, 3200-3202 (2011).
6. "Adding control to arbitrary unknown quantum operations", X.-Q. Zhou, T. C. Ralph, P. Kalasuwan, M. Zhang, A. Peruzzo, B. P. Lanyon, J. L. O'Brien, *Nature Communications* **2**, 413 (2011).
7. "Flux enhancement of photons entangled in orbital angular momentum", S. Palacios, R. D. Leon-Montiel, M. Hendrych, A. Valencia, J. P. Torres, *Optics Express* **19**, 14108-14120 (2011).
8. "Search for Hermite-Gauss mode rotation in cholesteric liquid crystals", W. Loffler, M. P. van Exter, G. W. 't Hooft, G. Nienhuis, D. J. Broer, J. P. Wordman, *Optics Express* **19**, 12978-12983 (2011).
9. "Laser-induced radial birefringence and spin-to-orbital optical angular momentum conversion in silver-doped glasses", J. M. Amjad, H. R. Khalesifard, S. Slussarenko, E. Karimi, L. Marrucci, E. Santamato, *Applied Physics Letters* **99**, 011113 (2011).
10. "Rotary Photon Drag Enhanced by a Slow-Light Medium", S. Franke-Arnold, G. Gibson, R. W. Boyd, M. J. Padgett, *Science* **333**, 65-67 (2011).
11. "Circular dichroism of cholesteric polymers and the orbital angular momentum of light", W. Loffler, D. J. Broer, J. P. Woerdman, *Physical Review A* **83**, 065801 (2011).
12. "Demonstration of the angular uncertainty principle for single photons", B. Jack, P. Aursand, S. Franke-Arnold, D. G. Ireland, J. Leach, S. M. Barnett, M. J. Padgett, *Journal of Optics* **13**, 064017 (2011).

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[44] Some of the listed publications actually result from work started few months before the official start of the project, as of course the consortium started working on the ideas proposed in the project as soon as the project approval was known and particularly after the end of the negotiation stage.

13. “Measurement of the light orbital angular momentum spectrum using an optical geometric transformation”, M. P. J. Lavery, G. C. G. Berkhout, J. Courtial, M. J. Padgett, *Journal of Optics* **13**, 064006 (2011).
14. “Spin-to-orbital conversion of the angular momentum of light and its classical and quantum applications”, L. Marrucci, E. Karimi, S. Slussarenko, B. Piccirillo, E. Santamato, E. Nagali, F. Sciarrino, *Journal of Optics* **13**, 064001 (2011).
15. “Measuring orbital angular momentum superpositions of light by mode transformation”, G. C. G. Berkhout, M. P. J. Lavery, M. J. Padgett, M. W. Beijersbergen, *Optics Letters* **36**, 1863-1865 (2011).
16. “Resilience of orbital-angular-momentum photonic qubits and effects on hybrid entanglement”, D. Giovannini, E. Nagali, L. Marrucci, F. Sciarrino, *Physical Review A* **83**, 042338 (2011).
17. “Tunable liquid crystal q-plates with arbitrary topological charge”, S. Slussarenko, A. Murauski, T. Du, V. Chigrinov, L. Marrucci, E. Santamato, *Optics Express* **19**, 4085-4090 (2011).
18. “Cancellation of dispersion and temporal modulation with nonentangled frequency-correlated photons”, V. Torres-Company, A. Valencia, M. Hendrych, J. P. Torres, *Physical Review A* **83**, 023824 (2011).
19. “Quadrant detector calibration for vortex beams”, N. Hermosa, A. Aiello, J. P. Woerdman, *Optics Letters* **36**, 409-411 (2011).
20. “Orbital angular momentum induced beam shifts”, N. Hermosa, M. Merano, A. Aiello, J. P. Woerdman, *Proceedings of SPIE* **7950**, 79500F (2011).
21. “Efficient generation and control of different-order orbital angular momentum states for communication links”, S. Slussarenko, E. Karimi, B. Piccirillo, L. Marrucci, E. Santamato, *Journal of the Optical Society of America A* **28**, 61-65 (2011).
22. “The Polarizing Sagnac Interferometer: a tool for light orbital angular momentum sorting and spin-orbit photon processing”, S. Slussarenko, V. D’Ambrosio, B. Piccirillo, L. Marrucci, E. Santamato, *Optics Express* **18**, 27205-27216 (2010).
23. “Photon spin-to-orbital angular momentum conversion via an electrically tunable q-plate”, B. Piccirillo, V. D’Ambrosio, S. Slussarenko, L. Marrucci, E. Santamato, *Applied Physics Letters* **97**, 241104 (2010).
24. “Demonstration of a quasi-scalar angular Goos-Hanchen effect”, M. Merano, N. Hermosa, A. Aiello, J. P. Woerdman, *Optics Letters* **35**, 3562-3564 (2010).
25. “Efficient Sorting of Orbital Angular Momentum States of Light”, G. C. G. Berkhout, M. P. J. Lavery, J. Courtial, M. W. Beijersbergen, M. J. Padgett, *Physical Review Letters* **105**, 153601 (2010).
26. “Spin-orbit hybrid entanglement of photons and quantum contextuality”, E. Karimi, J. Leach, S. Slussarenko, B. Piccirillo, L. Marrucci, L. Chen, W. She, S. Franke-Arnold, M. J. Padgett, E. Santamato, *Physical Review A* **82**, 022115 (2010).
27. “How orbital angular momentum affects beam shifts in optical reflection”, M. Merano, N. Hermosa, J. P. Woerdman, A. Aiello, *Physical Review A* **82**, 023817 (2010).
28. “Generation of hybrid polarization-orbital angular momentum entangled states”, E. Nagali, F. Sciarrino, *Optics Express* **18**, 18243-18248 (2010).
29. “Experimental Optimal Cloning of Four-Dimensional Quantum States of Photons”, E. Nagali, D. Giovannini, L. Marrucci, S. Slussarenko, E. Santamato, F. Sciarrino, *Physical Review Letters* **105**, 073602 (2010).

PHORBITECH list of communications to conferences and workshops:

1. L. Marrucci, invited talk, “Spin-to-Orbital Optical Angular Momentum Conversion in Liquid Crystal "q-Plates": Classical and Quantum Applications”, 14th International Topical Meeting on Optics of Liquid Crystals (OLC 2011), Yerevan (Armenia), September 25 – October 1, 2011
2. E. Karimi, invited talk, “Photon Angular Momentum”, The International Symposium “OPTICS and its applications”, The institute of Physical Research, in Ashtarak, Yerevan, Armenia, September 5–September 9, 2011.

3. E. Karimi, invited talk, “Quantum Optics: Photon Behaviour”, The International Symposium “OPTICS and its applications”, The institute of Physical Research, in Ashtarak, Yerevan, Armenia, September 5–September 9, 2011.
4. L. Marrucci, invited talk, “Singular-pattern liquid crystal cells for controlling the topological charge and the angular momentum of optical waves and photons”, 7th International Congress on Industrial and Applied Mathematics (ICIAM 2011), mini-symposium “Advances in liquid crystals”, Vancouver (BC, Canada), July 18-22, 2011.
5. L. Marrucci, invited talk, “Singular-pattern liquid crystal cells: applications in the quantum information field”, 7th International Congress on Industrial and Applied Mathematics (ICIAM 2011), mini-symposium “Advances in liquid crystals”, Vancouver (BC, Canada), July 18-22, 2011.
6. L. Marrucci, invited talk, “Spin-to-orbital conversion of the angular momentum of light”, Workshop on singular optics and its applications to modern physics, The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, May 30– June 3, 2011.
7. L. Marrucci, invited talk, “q-plates: some classical and quantum applications”, Workshop on singular optics and its applications to modern physics, The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, May 30– June 3, 2011.
8. E. Santamato, invited talk, “Mechanical effects of light spin and orbital angular momentum in liquid crystals”, Workshop on singular optics and its applications to modern physics, The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, May 30– June 3, 2011.
9. E. Santamato, invited talk, “Manipulation of the OAM of a paraxial optical beam with linear optics devices”, Workshop on singular optics and its applications to modern physics, The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, May 30– June 3, 2011.
10. J.P. Woerdman, *Beam Shifts for Pedestrians*, Keynote Lecture at “Beam Shifts: Analogies between Light and Matter Waves”, Lorentz Centre, 28 March-1 April 2011, Leiden.
11. J.P. Woerdman, Optical *Beam Shifts and Orbital Angular Momentum*, invited talk at “Singular Optics and its Applications in Modern Physics”, International Centre for Theoretical Physics, Trieste, 30 May-3 June 2011..
12. N. Hermosa, *Spin Hall Effect of Light in Metallic Reflection*, “Singular Optics and its Applications in Modern Physics”, International Centre for Theoretical Physics, 30 May-3 June 2011, Trieste.
13. N. Hermosa, *Orbital Angular Momentum Induced Beam Shifts*, Photonics West, 22-27 January 2011, San Francisco.
14. J.P. Woerdman, *Beam Shifts for Pedestrians*, Kavli Colloquium, Delft University, 13 April 2011.
15. F. Sciarrino, “New optical technologies for quantum information processing”, Invited Plenary talk, Bienal de Fisica, Santander, Spain (19-23 September 2011)
16. 16, F. Sciarrino, “High quantum dimensionality by exploiting the photonic orbital angular momentum” Invited talk, Laser Physics, Sarajevo, Bosnia (11 – 15 July 2011)
17. F. Sciarrino, ”High-dimensional quantum states encoded in photonic orbital angular momentum and polarization”, Contributed talk, Workshop on High Dimensioanl Entanglement, Como, Italy, (21-24 June 2011).
18. F. Sciarrino, “Fundamental tests on higher dimensionality by exploiting the photonic orbital angular momentum”, Invited Plenary talk, Vaxjo, Sweden (13-13 June 2011)
19. F. Sciarrino, “New optical devices for quantum information processing”, Invited seminar, Università dell'Insubria, Como, (9 June 2011)
20. F. Sciarrino, “Photonic optimal quantum cloning”, Invited talk, Workshop on singular optics and its applications to modern physics, The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, (30 May 30– 3 June , 2011).
21. F. Sciarrino, “From qubit to qudit with hybrid OAM-polarization quantum state”, Invited talk, Workshop on singular optics and its applications to modern physics, The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, (30 May 30– 3 June , 2011).

22. F. Sciarrino, “New optical technologies for quantum information processing”, Invited talk, IV Italian Quantum Information Conference, Vietri sul Mare (18-20 April 2011)
23. F. Sciarrino, “Higher quantum dimensionality by exploiting the photonic orbital angular momentum”, Invited talk, The 13th Meeting on Optical Engineering and Science in Israel, Tel Aviv, Israel (7-9 March 2011)
24. F. Sciarrino, “New optical technologies for quantum information processing”, Invited seminar, Hebrew University, Jerusalem (6 March 2011)
25. F. Sciarrino, “Quantum information processing by exploiting the photonic orbital angular momentum”, Contributed talk, International Conference on Quantum Information and Computation, Stockholm (4-8 October 2010)
26. E. Nagali, « Exploiting the photonic orbital angular momentum for quantum information processing Workshop on New Trends in Quantum Dynamics and Quantum Entanglement », Poster presentation, ICTP - Trieste, Italy (21-25 February 2011).
27. E. Nagali, « Manipulation of photonic orbital angular momentum for higher-dimensional quantum information processes » , Contributed talk, Convegno Nazionale delle tecnologie Fotoniche - Fotonica 2011, Genova, Italy.(9-11 May 2011).
28. E. Nagali, « Engineering of photonic orbital angular momentum quantum states for quantum information processing » CLEO Europe - EQUEC 2011, Munich, Germany (22-26 May 2011).

Press

On PHORBITECH scientific publication: “Rotary Photon Drag Enhanced by a Slow-Light Medium”, S. Franke-Arnold, G. Gibson, R. W. Boyd, M. J. Padgett, *Science* **333**, 65-67 (2011).

Press release: University of Glasgow: Scientists drag light by slowing it to speed of sound
http://www.gla.ac.uk/news/headline_204211_en.html

Press articles

1. Rotating cylinder puts a new spin on slow light, physicsworld.com
http://physicsworld.com/cws/article/news/46445
2. Scientists drag light by 5¡ by slowing to the speed of sound, The Engineer
http://www.theengineer.co.uk/sectors/electronics/news/scientists-drag-light-by-5%C2%A1-by-slowing-to-the-speed-of-sound/1009306.article
3. Slowing the Speed of Light to a Crawl, Forbes
http://www.forbes.com/sites/alexknapp/2011/07/07/slowing-the-speed-of-light-to-a-crawl/?partner=yahoofeed
Also appeared in Yahoo! News http://news.yahoo.com/slowing-speed-light-crawl-140902305.html
4. Scientists drag light by slowing it to speed of sound, physorg.com
http://www.physorg.com/news/2011-07-scientists.html
Also appeared in http://scienceresearchprojects.com/2011/07/scientists-drag-light-by-slowing-it-to-speed-of-sound-2/
5. Scientists drag light by slowing it to the speed of sound, EarthSky
http://earthsky.org/energy/scientists-drag-light-by-slowing-it-to-the-speed-of-sound
6. Rotary Photon Drag Enhanced by a Slow-Light Medium. Right? Right, Jim on Light
http://www.jimonlight.com/2011/07/07/rotary-photon-drag-enhanced-by-a-slow-light-medium-right-right/
7. Crazy Friday Science: Mini-Interview with Sonja Franke-Arnold on Rotary Photon Drag, Jim on Light
http://www.jimonlight.com/2011/08/12/crazy-friday-science-mini-interview-with-sonja-franke-arnold-on-rotary-photon-drag/
8. Changing Speed Of Light: Scientists drag light by slowing it to speed of sound, Science Debate
http://www.sciencedebate.com/science-blog/changing-speed-light-scientists-drag-light-slowing-it-speed-sound

Wikipedia webpages (deliverable D5.2)

> Excerpt from Annex I: New wikipedia webpages on the orbital angular momentum of light developed by the project beneficiaries.

A search on the Wikipedia website revealed there were no pages on orbital angular momentum (OAM). We have therefore created three new wikipedia pages: (i) OAM (ii) light spin angular momentum (SAM) and (iii) angular momentum of light. The links are the following ones:

- Angular momentum of light: http://en.wikipedia.org/wiki/Angular_momentum_of_light

- Light orbital angular momentum: http://en.wikipedia.org/wiki/Light_orbital_angular_momentum

- Light spin angular momentum: http://en.wikipedia.org/wiki/Light_spin_angular_momentum

Given the diverse scientific backgrounds of the audience that access Wikipedia, the web-pages have different levels of specificity (an introduction aimed at a broader audience and following sections with a higher degree of technicalities). We included the PHORBITECH webpage as external link in the OAM Wikipedia page.

Other related-project dissemination initiatives

- Organization of the Workshop on "Singular optics and its applications to modern physics" at The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, May 30– June 3, 2011 (Ebrahim Karimi).

- Organization of the Workshop on « ENTANGLEMENT, QUANTUM INFORMATION and the QUANTUM – to – CLASSICAL TRANSITION », Accademia Nazionale dei Lincei, 5-7 May, 2011 (Fabio Sciarrino)

- Three lectures of two hours given to the Institute for Advanced Studies in Basic Sciences (Ebrahim Karimi, IASBS, Zanjan, Iran).

Technical support to dissemination activities

Logo and web (deliverable D5.1)

A Phorbitech logo has been designed to be graphically appealing and include a reference to the project acronym. The logo is intended to be the key of the visual identity of the project and will be used on the website, in all publicity material, presentations, letter heads, etc.

A PHORBITECH website has been developed: www.phorbitech.eu (see also section 2.3 below)

Leaflets on project goals (deliverable D5.3)

Leaflets and/or brochures on the project targets and first results, for distribution at events. Posting on project website. *[Excerpt from GA-Annex I DoW]*

A leaflet describing PHORBITECH's main concepts has been developed. It was designed to be graphically appealing and includes brief information about the project (name, funding scheme and list of participating institutions) and aims. To ensure effective dissemination to experts and non-experts, a few basic concepts have been included explained in an easy-to-understand, attractive fashion, and illustrated with images related to the results obtained within the project by consortium partners. The leaflet is targeted to a technical and non-technical audience and is intended for distribution at medium/large scientific events and/or public-at-large events. A copy of the leaflet has been posted on the PHORBITECH website in the "Dissemination to the General Public" webpage.

2.3 Project management during the period

The management of the project is described in WP4.

Governing bodies

Project Coordinator: Prof. Lorenzo Marrucci

Project management team (MT): Project coordinator: Prof. Lorenzo Marrucci; WP1 manager: Prof. Juan Perez; WP2 manager: Prof. Eric Eliel; WP3 manager: Dr. Sonja Franke-Arnold; WP4 manager: Giuliana Pensa; WP5 dissemination leader: Dr. Fabio Sciarrino

Steering Committee (SC), composed by the project coordinator, also acting as representative of UNAP, and one member from each other partner: UNAP & SC chairman: Prof. Lorenzo Marrucci (project coordinator); UROM: Dr. Fabio Sciarrino; ICFO: Prof. Juan Perez; UGLAS: Prof. Miles Padgett; UNIVBRIS: Prof. Jeremy L. O'Brien; ULEID: Prof. Han Woerdman.

Management of the financial contribution

UNAP has fully distributed among the partners the prefinancing amount before the beginning of the project, as follows:

Date	Beneficiary	Amount (EUR)
22/09/2010	UNIVERSITA' DI ROMA "LA SAPIENZA"	146.450,00
22/09/2010	ICFO - The Institute of Photonic Sciences	119.770,00
22/09/2010	UNIVERSITY OF GLASGOW	214.890,00
22/09/2010	UNIVERSITY OF BRISTOL	127.020,00
22/09/2010	UNIVERSITEIT LEIDEN	185.793,00

Consortium agreement

A consortium agreement between PHORBITECH partners has been circulated and comments from partners have been incorporated and final approval from all partners is expected at month 14.

Project management

In order to carry out the management of the consortium activities, a project manager has been hired with a competitive call, according to Italian University legislations. The project manager Giuliana Pensa has been hired, with a 30-month part-time contract lasting until the end of the project (for a total 14 PM).

The project management is carried out by the project manager in strict coordination with the coordinator. Appropriate procedures have been set up in order to ensure timely and efficient running of the project. In particular for what concerns:

- communication within the consortium and with the EC
- periodic administrative monitoring of the expenditure
- continuous monitoring and collection of the research outcomes in the form of scientific publications
- maintenance of internal and external communication through the project website and ensure timely updated by the partners

Scientific coordination and monitoring

The aim of this task is to organize and manage the assessment of the relevance and quality of scientific intermediate results, also based on deliverables and performance indicators.

The reporting process is managed with the same organizational structure described above for the whole project, with task responsible persons providing the first level, WP manager the second and the project coordinator the third level. All reports will be provided to the SC for evaluation and final approval, before delivery to EC. According to the procedures set up, all task managers were requested to uniform deliverables to the template prepared by the management team. Draft deliverables were collected and circulated before the annual project meeting. Each responsible presented the relative research activity and the deliverables were collectively discussed. According to the internal procedures indicated in Annex I DoW, the Steering Committee (SC) performed a scientific and technical analysis of the deliverables based on deliverables and performance indicators, such as publications, leading to their formal validation. After approval by the EC, the deliverables will be posted on the project website.

Interim report. After evaluation by the SC of the results achieved during year 1, interim scientific reports were collected and assembled through WP managers and task leaders. Draft WP reports were circulated among the partners.

The scientific management of the project involved all WP managers as members of the Project management team (MT) and was supported by the managing assistant to ensure timely and effective exchange of information.

Organization of project meetings

The aim of the project meetings is to guarantee horizontal flow of information within the consortium. As planned, two project meetings organized by Phorbitech took place during year one.

PHORBITECH Kick–off meeting. 11-12 October 2010, Rome (Italy)

Attending:

P1. NAPLES: Lorenzo Marrucci (PHORBITECH Coordinator), Giuliana Pensa (PHORBITECH Project Manager), Bruno Piccirillo, Ebrahim Karim, Sergei Slussarenko

P2. ROME: Fabio Sciarrino (WP5 manager), Paolo Mataloni, Eleonora Nagali

P3. ICFO: Juan Pérez (WP1 manager)

P4. GLASGOW: Sonja Franke-Arnold (WP3 manager)

P5. BRISTOL: Mirko Lobino, Jasmin Meinecke, Mark Thompson

P6. LEIDEN: Eric Eliel (WP2 manager), Han Woerdman

EU COMMISSION: Teresa De Martino (Project Officer)

The kick-off meeting was dedicated to clarify how the project will be managed and how each partner would have carried out his task in order to reach year 1 objectives. Task teams and responsible persons were defined. Work package organizational and planning meetings also took place.

Informal Phorbitech meeting during the “Workshop on singular optics and its applications to modern physics”, *May 30 – June 3 2011, Trieste (Italy)*

Attending:

P1. NAPLES: Lorenzo Marrucci, Enrico Santamato, Ebrahim Karim (co-organizer of the workshop), Sergei Slussarenko

P2. ROME: Fabio Sciarrino, Eleonora Nagali, Vincenzo D’Ambrosio

P4. GLASGOW: Sonja Franke-Arnold, Miles J. Padgett

P6. LEIDEN: Han Woerdman

A scientific meeting of some groups of PHORBITECH took place during the “Workshop on singular optics and its applications to modern physics”, co-organized by Dr. Ebrahim Karimi (Phorbitech member), and held at *The Abdus Salam International Centre for Theoretical Physics* (ICTP), Trieste, Italy, from May 30 to June 3, 2011. The status of ongoing tasks and prospects for some new experiments were discussed.

PHORBITECH First Annual meeting. 16-17 September 2011, Castelldefels, Barcelona (Spain)

Attending:

P1. NAPLES: Lorenzo Marrucci (PHORBITECH Coordinator), Giuliana Pensa (PHORBITECH Project Manager), Ebrahim Karim, Sergei Slussarenko

P2. ROME: Fabio Sciarrino (WP5 manager), Eleonora Nagali, Vincenzo D'Ambrosio

P3. ICFO: Juan Pérez (WP1 manager), Luis Alvarez, Martin Hendrych, Roberto Leon, Michal Micuda, Carmelo Rosales

P4. GLASGOW: Sonja Franke-Arnold (WP3 manager), Martin Lavery, Neal Radwell

P5. BRISTOL: Jasmin Meinecke

P6. LEIDEN: Eric Eliel (WP2 manager), Han Woerdman

Each task team has presented the work carried out during year 1, allowing an open discussion about the next steps. Brainstorm sessions have also been organized, crossing different teams. Work package organizational and planning meetings also took place.

Steering Committee meeting: Lorenzo Marrucci (UNAP), Fabio Sciarrino (UROM), Juan P. Torres (ICFO), Sonja Franke-Arnold (UGLAS), Jasmin Meinecke (as delegated UNIVBRIS representative), Han Woerdman (ULEID), Eric Eliel (ULEID, in a consultative capacity), Giuliana Pensa (UNAP, in a consultative capacity)

The SC has discussed the overall progress made and approved the global reports. No deviations from planned milestones and deliverables were found.

Management Board Meeting: Lorenzo Marrucci (UNAP), Fabio Sciarrino (UROM), Juan P. Torres (ICFO), Sonja Franke-Arnold (UGLAS), Eric Eliel (ULEID), Giuliana Pensa (UNAP)

MT discussed future project planning and reporting.

PHORBITECH group during the First Annual Meeting
ICFO, Castelldefels (Barcelona)
16-17 September 2011

Development of PHORBITECH website

To develop the website, we have analyzed the needs of the consortium and similar websites. A first demo was circulated among the consortium partners and their comments were collected. The website was developed according to all comments received and according to the most recent standards, and it is optimized for search engines. A content management system is used to allow timely updates.

The website is the project's key communication tool. The website is intended to be a mean of public dissemination of the project results and an effective way to share information among the project participants. It includes public pages with information on the project and its results, and a restricted access area for internal information exchanges. It also includes a project calendar with all the important dates (meetings, etc.). The aim is to post the project results, including videos and non-technical descriptions of scientific results in appropriate sections.

Website updating and management will be a task of the Management Team, but all project members can post relevant information in the appropriate areas. To ensure an effective dissemination to experts and non-experts, there is a specific section where the science and technology of the project is explained to non-experts in an easy-to-understand and attractive fashion, which includes the use of short videos, interviews, recordings of project meeting lectures, etc. A specific page is dedicated to all the scientific publications related to the project; this is regularly updated with links to open access articles when available, or to abstracts.

Collaborations with external groups

- Hong Kong University of Science and Technology (on photosensitive materials for q-plate manufacturing)

- Sevilla University (quantum cryptography and fundamental tests of quantum mechanics by exploiting higher-dimensional quantum states)

- Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan, Iran (on self-structured q-plates in silver-doped glasses)

3.3 Deliverables and milestones tables

All deliverables foreseen during year 1 have been submitted.

TABLE 1. DELIVERABLES

Del. no.	Deliverable name	Version	WP no.	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I (proj month)	Actual / Forecast delivery date Dd/mm/yyyy	Status No submitted/ Submitted	Contractual Yes/No	Comments
D1.1	Novel holograms		1	4	P	PU	12	30/09/2011	Yes	Yes	
D1.2	Intermediate QPM SPDC		1	3	R	PU	12	30/09/2011	Yes	Yes	
D1.3	Intermediate cavity-enhanced SPDC		1	3	R	PU	12	30/09/2011	Yes	Yes	
D2.1	OAM beam deviation matrix		2	6	R	PU	12	03/10/2011	Yes	Yes	
D2.2	Polarization-OAM deterministic transferrer		2	2	P	PU	12	03/10/2011	Yes	Yes	
D2.3	Hybrid polarization- OAM entanglement		2	2	R	PU	12	03/10/2011	Yes	Yes	
D2.4	OAM waveguides		2	5	P	PU	12	03/10/2011	Yes	Yes	
D3.1	OAM phase unfolding simulation		3	4	R	PU	12	30/09/2011	Yes	Yes	
D5.1	Logo and web		5	1	O	PU	6	06/06/2011	Yes	Yes	
D5.2	Wikipedia webpages		5	2	O	PU	12	30/09/2011	Yes	Yes	
D5.3	Leaflets on project goals		5	1	O	PU	12	30/09/2011	Yes	Yes	

TABLE 2. MILESTONES							
Milestone no.	Milestone name	Work package no	Lead beneficiary	Delivery date from Annex I dd/mm/yyyy	Achieved Yes/No	Actual / Forecast achievement date dd/mm/yyyy	Comments
MS1	Task-teams definition	WP1,WP2, WP3, WP4	1	31/12/2011	Yes	31/12/2011	All task responsible persons have been defined and most teams are defined, although some post-docs or student hires are still not completed (e.g. ICFO).
MS2	First evaluation of SPDC enhancement methods	WP1	3	30/09/2011	Yes	30/09/2011	The task reports suggest that a suitable combination of SPDC with q-plates can be indeed advantageous on specific tasks. However, the overall decision on the possible utilization of the two proposed enhancement methods will require further investigation and is postponed at the end of second year.
MS3	OAM transmission first check.	WP2	6	30/09/2011	Yes	30/09/2011	The work is progressing very well as far as free-space is concerned. Various wave-guiding approaches for OAM information are still under analysis and no definite decision can be taken at this stage.
MS4	First check of OAM unfolding concept	WP3	4	30/09/2011	Yes	30/09/2011	The new OAM unfolding concept is already proving to be a superior approach for OAM detection, as compared to other existing methods (holograms, interferometers). Its performances make it by far the most efficient approach, particularly when the input OAM is not confined to a small OAM subspace.
MS5	Management and dissemination 1st check point	WP4, WP5	1	30/09/2011	Yes	30/09/2011	A first analysis of management and dissemination actions has been performed. No corrective actions are deemed necessary at this stage.