PROJECT FINAL REPORT

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Final publishable summary report

PHORBITECH final report – Executive summary

PHORBITECH context and objectives. Although not many know it, a beam of light may have both a “spin” and a “twist”. These are two forms of rotation of the optical beam energy around the beam axis, the first associated with circular polarization, the second with a helical shape of the light wavefront. Scientists usually refer to the twist of light with the more technical expression of “*orbital angular momentum*” (OAM). Fully exploiting the OAM of light could benefit applications ranging from high-bandwidth optical communication, to quantum information processing, to photonic sensing, etc. PHORBITECH’s vision was to make the generation, manipulation, transmission and detection of the optical OAM as easy and commonplace as currently is the management of other degrees of freedom of light, such as polarization, both in the classical and in the quantum regimes. This vision has been pursued in the project three years (2010-2013) by developing a “*toolbox*” of innovative optical components and devices for the full and convenient control of OAM, as well as by advancing the *scientific knowledge* on the OAM of light and on its fundamental role in many physical phenomena.

PHORBITECH main results. The work carried out in these three years has been very exciting and productive. A number of new devices for OAM control and manipulation have been demonstrated and important scientific results were achieved as a consequence. The new OAM tools introduced within PHORBITECH include: (i) electric-field tunable *q-plates* with arbitrary topological charge *q* and associated devices based on sequential application of several q-plates; (ii) a high-brightness correlated *photon source, with OAM* entanglement; (iii) a very efficient *OAM sorter*, splitting the light into different paths depending on its OAM, for detection or further processing purposes; (iv) quantum setups for the *efficient transfer of quantum information* from polarization to OAM and vice versa; (v) tools for generating and detecting *rotation-invariant states of light*, suitable for quantum communication without need for alignment of the transmitting and receiving units; (vi) tools for generating and detecting highly rotation-variant states of light, suitable for *high-precision optical metrology of mechanical rotation angles*; (vii) an *integrated on-chip source of OAM*, for enhanced optical-data interconnects. The advance in scientific knowledge generated by PHORBITECH is demonstrated by the over 100 project-related scientific articles published in high-profile international journals, among which 27 appeared in the very top multidisciplinary and physics journals (more precisely, 3 in *Science*, 1 in *Nature Physics*, 4 in *Nature Photonics*, 4 in *Nature Communications*, and 15 in *Physical Review Letters*).

PHORBITECH potential impact. We identify three specific fields of science and technology in which the enhanced control of the OAM of light obtained thanks to PHORBITECH results has the highest potential for a future impact, in the medium or long term: (i) enhanced room for *multiplexing of the information* in classical communication, both in free-space and in optical fibers, which may help overcome the approaching bottleneck of communication bandwidth with current technology; (ii) implementation of *quantum information channels* with new capabilities and a higher dimensionality, which may help making the quantum information technology closer to real-world applications; (iii) new *high-sensitivity detection and measurement methods* in mechanical applications.

1.1 PHORBITECH: Summary description of project 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.

But 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. 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.

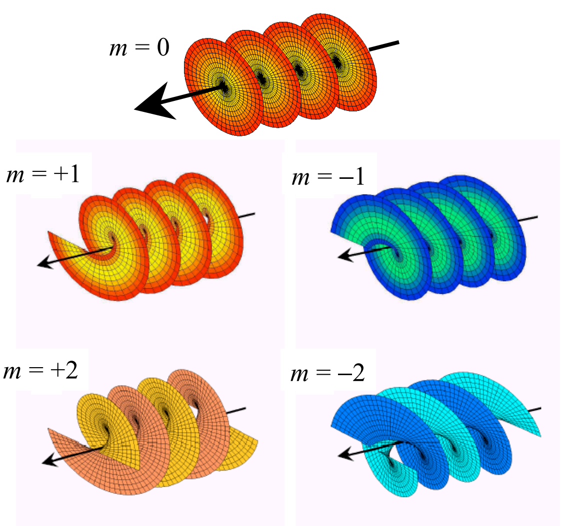

Fig. 1 – Wavefront shape of optical beams carrying orbital angular momentum (OAM).

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 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 were 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.

The first main objective of PHORBITECH was 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.

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

In order to pursue these general aims, PHORBITECH has been articulated into four main research (RTD) work-packages (WP), whose overall objectives are defined as follows:

WP1 – OAM generation. This work package was 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 included 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 included 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 was aimed at the development of optical devices for OAM manipulation and transmission, both in free space (including in air) and in waveguides. This WP included 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 included 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 was aimed at the development of optical devices for OAM detection and for its coherent storing/retrieval in material devices. This WP included 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 included the investigation of fundamental issues associated with the OAM-matter interaction.

WP6 – Misalignment-free quantum communication (started at mid-project). This work package was aimed at the development of a toolbox of devices for the misalignment-free quantum communication, exploiting hybrid polarization-OAM photonic states. The main steps of encoding, decoding, and manipulation of the rotation-invariant quantum states were all to be implemented, by separate devices. The developed scheme will be tested by physically rotating the measurement stages to verify that the communication capacity is not degraded by physical rotations. An investigation of the effect of atmospheric turbulence will also be carried out, in order to test the feasibility of implementing free-space communication through atmosphere.

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

These work-packages were carried out by the following consortium of 7 partners:

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/

Extra-European partner added with the FET INCO-extension program:

Brazil Universidade Federal do Rio de Janeiro, Quantum Optics Laboratory, Institute of Physics, Stephen Walborn, http://omnis.if.ufrj.br/~phsr/qopt/eng/overview.html

1.2 PHORBITECH: Description of the main S&T results/foregrounds

The work carried out in the three years of the project have been very exciting and productive ones. A number of new devices and tools for OAM control and manipulation have been demonstrated, contributing to the first general goal of PHORBITECH (the "toolbox"). In addition to this set of new 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, i.e. advancement of the scientific knowledge.

Overall, in the course of the three years, the PHORBITECH consortium has published about 120 project-related scientific articles in high-profile international journals, among which 3 in *Science*, 1 in *Nature Physics*, 4 in *Nature Photonics*, 4 in *Nature Communications*, and 15 in *Physical Review Letters*. Graphs showing the PHORBITECH publications indexed in Web of Science and their growing impact in terms of citations are shown in Fig. 2.

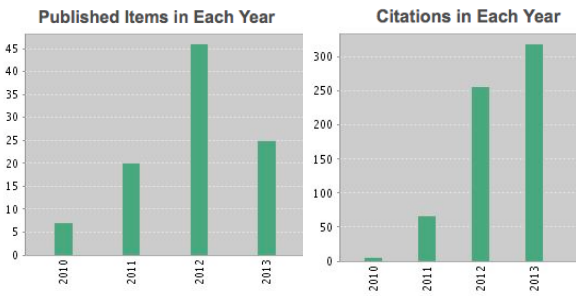

Fig. 2 – Graphs from Web of Science showing PHORBITECH publications and citations [Thomson-Reuters data-base, data extracted on 2013-10-31].

In the following pages, we summarize what we believe are the most interesting and representative results and foregrounds of PHORBITECH project, organized by work-package. We warn the readers that, in this summary, a number of additional results or variants of the main reported results will be omitted for brevity or just mentioned in passing. We refer the readers to the publications of the consortium for a full account of the obtained results.

WP1 – OAM generation

Holographic multiplexers. A new open-source software was developed in *LabVIEW*, which can be used for computing in real time the holographic pattern to be displayed on a computer-controlled spatial-light modulator (SLM) for the generation and multiplexing of a controlled superpositions of several OAM modes with prescribed orbital and radial profiles (technically, these are called Laguerre-Gaussian modes), and a given waist size of the beam. 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.

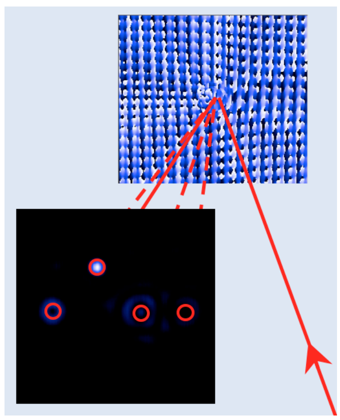

Fig. 3 – Holographic OAM multiplexer for computerized radial and azimuthal control of diffracted beam.

Q-plate technology. This technology, first introduced few years ago by one of the partners in PHORBITECH, has been greatly advanced during the project. The working principle of these devices is based on the spin-orbit coupling of the light crossing a suitably patterned liquid crystal cell, leading to an interaction between the light polarization and wavefront.

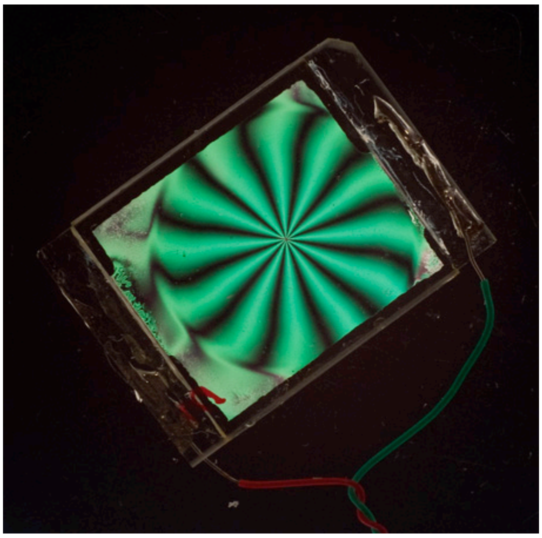

Fig. 4 – A q-plate prototype with q = 3 and electric tuning developed in PHORBITECH, as seen between crossed polarizers.

In particular, in PHORBITECH we have introduced for the first time the electric-field tuning of the q-plates, useful for various different purposes (wavelength selection, on/off switching of the device action, partial conversion of the transmitted light in order to obtain superpositions of different modes), and a photo-induced alignment process of the bounding surfaces so as to obtain any desired q-plate pattern (see Fig. 4). Several groups in the world are now using q-plates for generating OAM beams in a variety of applications. Recently, we have demonstrated q-plates with $q > 50$, enabling the generation of OAM with winding number $m > 100$ (see Fig. 5). These have been used in devices named "photonic polarization gears", which will be discussed in the frame of work-package 2.

Optical systems based on a sequence of q-plates have been demonstrated for various applications, ranging from fast multiplexing of generated OAM, to OAM-time information mapping, to simulating a quantum walk in OAM.

Tailored polarization-singular beams and multi-colored vector beams have been generated by exploiting partially tuned q-plates with electrical control. These results provide steps forward in the direction of future hybrid wavelength-space division multiplexing systems for ultra-broad band optical communication.

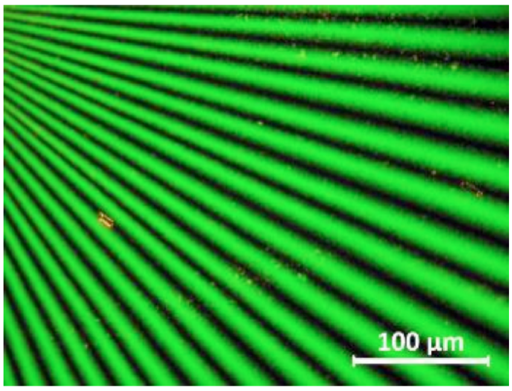

Fig. 5 – A section of a q-plate device with q = 25 developed in PHORBITECH, as seen in a polarizing microscope.

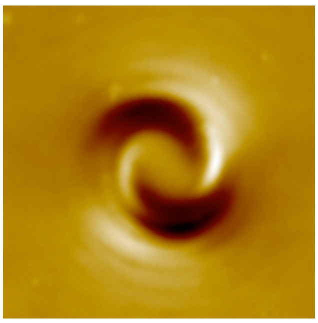

Fig. 6 – Spiral nano-relief structure induced by OAM light on the surface of an azopolymer thin film.

On a more purely scientific side, we have demonstrated the capability of highly-focused light carrying OAM to generate tiny spiral-shaped relief patterns on the surface of azo-polymer thin films, materials similar to those we use for the q-plate photoalignment, thus showing that the light-induced mass-transport phenomenon giving rise to these reliefs can be unexpectedly sensitive to the wavefront shape of the impinging light (Fig. 6). This result, published in Nature Communications in 2012, sheds light on the underlying molecular mechanism driving the mass transport and opens interesting new prospects for optical nano-lithography and near-field imaging.

Another potentially important scientific result has been the theoretical proposal of a q-plate analog for electron beams, a device based on suitably designed magnetic and electric fields within a multipolar Wien filter. This proposed device could be used in combination with electron-optical elements for the manipulation of the electron-beam OAM to obtain an efficient spin-polarization filter for electron beams, a tool that is presently lacking in the electron-optics technology.

OAM light generation in spontaneous parametric down conversion (SPDC). The SPDC process is particularly interesting for generating light with OAM, in particular when one is interested in single photons and quantum entanglement. A setup for a record-high-brightness (defined in terms of count rates) generation of entangled photon pairs based on spontaneous parametric down-conversion (SPDC) in a suitable periodically poled nonlinear crystal has been demonstrated in PHORBITECH (in collaboration with external researchers). Although this setup generates directly only polarization-entangled pairs with zero OAM, these can be then efficiently converted into OAM-entangled or hybrid polarization-OAM entangled pairs by exploiting the q-plate device in a suitable optical configuration, such as a quantum-state transfer device (see further below).

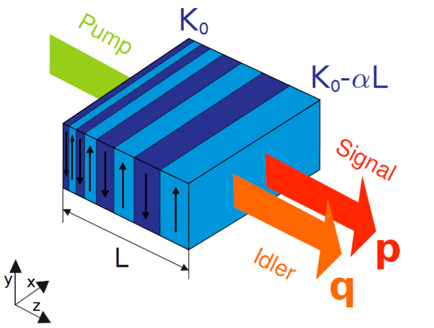

Fig. 7 – Scheme of SPDC in a linearly chirped quasi-phase-matched nonlinear crystal. The pump beam is a Gaussian beam, and p and q designate the photon transverse wave numbers. K_0 is the grating wave-vector at the input face of the crystal, and K_0-αL at its output face. The different colors (and arrow orientation) represent domains with different sign of the nonlinear coefficient.

Another interesting scientific result within this line of activity has been the theoretical investigation of the possible light-generation performances of the spontaneous parametric down conversion process in a chirped quasi-phase-matched crystal, which could be used in particular to obtain photon pairs having a higher-dimensional entanglement (see Fig. 7).

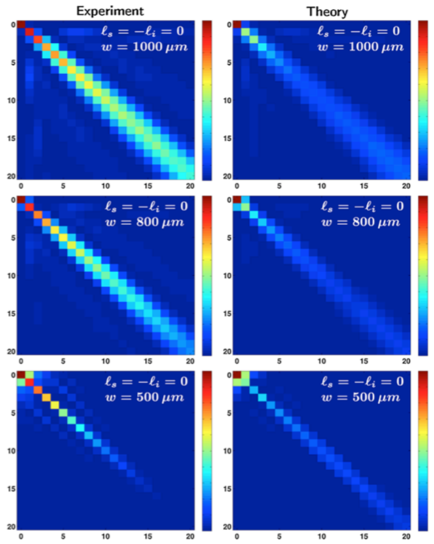

Fig. 8 – Experimental and theoretical correlations in the radial profile, as defined by the Laguerre-Gauss index p, in the twin photons generated in a SPDC process.

Finally, spatially entangled twin photons generated in spontaneous parametric down conversion can be used to directly generate very high-dimensional entanglement in the combined space of OAM (or azimuthal angle) and radial modes (see Fig. 8). By defining suitable radial detection modes with negligible cross correlations, we have demonstrated hybrid azimuthal-radial quantum correlations in a Hilbert space with more than 100 dimensions per photon[1]. This result represents a record in this specific figure of merit.

WP2 – OAM manipulation and transmission

OAM-related deviations from standard law of optics. Within this work-package, as a first task, we have investigated in detail the tiny deviations from the standard reflection and refraction laws that

[1] This result was actually obtained within WP2, but it is mentioned here because it is thematically closer to WP1.

occur when light carrying OAM impinges on an interface between two dielectric media and the resulting effects on the OAM spectrum of the reflected or transmitted light. These subtle optical phenomena provide important generalizations of the already known Goos-Hänchen and Imbert-Fedorov effects and can be relevant in any precision optical setup involving light carrying OAM. By way of example, we show in Fig. 9 the OAM sidebands appearing on reflection from a dielectric interface. The extension to fractional OAM has also been investigated.

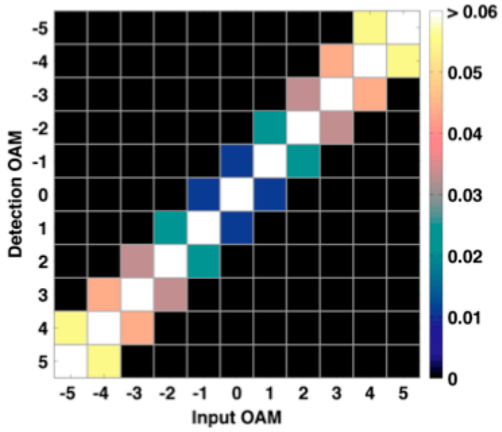

Fig. 9 – OAM sidebands appearing on reflection from a dielectric interface.

Polarization-OAM qubit transferrers. Next, by exploiting the q-plate technology in combination with a Sagnac interferometer containing a Dove prism, we have developed an optical system 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 (see Fig. 10). In terms of single photons, this tool can be considered as a new quantum interface device, for the deterministic transfer of a qubit of quantum information (qubits) from the polarization degree of freedom to the OAM, or vice versa.

By exploiting these devices in different ways, in combination with the more standard SLMs, we have carried out several fundamental studies involving the manipulation of higher-dimensional quantum states of photons defined within the polarization and OAM spaces. Among these, it is worth mentioning in particular the demonstration of a *dimension witness* capable of bounding the dimension of an unknown classical or quantum system only from measurement statistics (a result published in Nature Physics in 2012), the optimal quantum cloning of four-dimensional states of photons (ququarts), the experimental implementation of a Kochen-Specker set of quantum tests, the implementation of high-dimensional mutually-unbiased bases based on OAM, and a deterministic setup for encoding and decoding polarization-OAM hybrid qudits in photons.

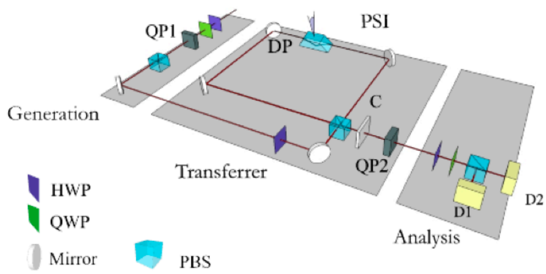

Fig. 10 – Layout of the polarization-OAM qubit deterministic transferrer based on q-plates (QPs) and a polarizing Sagnac interferometer (PSI). Legend: DP - Dove Prism, HWP - half-wave plate, QWP - quarter-wave plate, C - phase compensation crystal.

Still along this line of scientific work, an optical apparatus capable of “joining” the two-dimensional quantum states (qubits) carried by two separate input photons into a four-dimensional state (ququart) carried by a single output photon has been ideated and experimentally demonstrated. This result was published in Nature Photonics in 2013 (and also highlighted in a news appeared in Nature and Scientific American). A setup for the inverse operation, that is the quantum state “fission” of a single input photon into two output ones has been also proposed. These devices allow for a multiplexing of the quantum information across photons, with possible applications in future quantum information networks. The quantum space of the higher-dimensional photon can also be defined by combining polarization and OAM, although at present this requires an additional conversion stage.

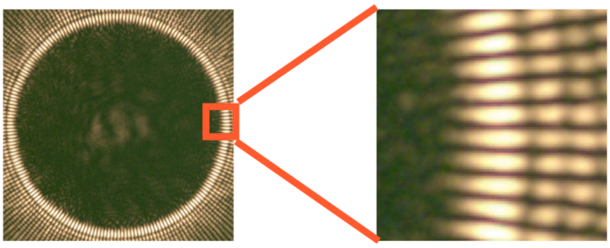

Fig. 11 – Highly space-variant light mode generated within a photonic gear device with q = 25 (OAM = 50) as visualized after filtering one linear polarization.

Photonic polarization gear. We have demonstrated a method for tailoring the rotational properties of the light, by a suitable combination of polarization and OAM, based again on the q-plate technology. Two opposite effects have been demonstrated, in particular: (i) rotation-invariant states of light, useful to carry out quantum communication independent of the relative alignment of the transmitting and receiving unit frames (see work-package 6); (ii) highly rotation-variant states of light (see Fig. 11). A device based on the latter idea was demonstrated in PHORBITECH and named "photonic polarization gear" and a patent application was filed on this concept. The results have also been published in Nature Communications in 2013. This tool can be used to detect and measure relative mechanical rotations with greatly enhanced sensitivity by a simple polarization measurement. In other words, beam of light passing through this device experiences of rotation of its (uniform) plane of linear polarization by an angle that is proportional to the mechanical rotation, with a proportionality constant ("gear ratio") that can be as high as one hundred.

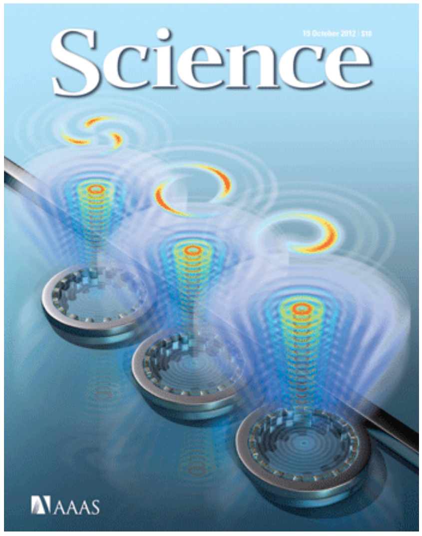

Fig. 12 – Cover of the journal Science with an artwork illustrating the main concept of the newly developed OAM source device based on integrated optical ring micro-resonators.

Finally, we have investigated the possible contact points between the OAM and integrated photonic technology, including waveguiding and optical processing on chip. In this area, the most significant result has been the developing of a new photonic technology for generating OAM light based on the fabrication of *integrated whispering-gallery ring micro-resonators*. The light is coupled out of the resonators transversely, with the help of an angular grating manufactured in the resonator internal side. A beautiful illustration of this result has been published on the cover of Science on October 19, 2012 (the PHORBITECH paper reporting this result was also published in this issue) and is copied here in Fig. 12. This result, obtained in a collaboration between PHORBITECH researchers and two groups external to the consortium, provides also an important step forward in the combination between OAM and integrated photonics technology, one of the most ambitious goals of the project.

WP3 – OAM detection and storing.

OAM sorting. One of the most successful devices developed in PHORBITECH is based on a novel approach to OAM sorting and measurement that has already affirmed itself as *the* most efficient existing method to this purpose. It is based on the concept of "*OAM phase unfolding*", as obtained by two specially designed optical phase transformations mapping different OAM states into different propagation directions of the outgoing light. A beautiful image of the developed device and of its optical action is shown in Fig. 13. Prototypes of this device have been already distributed to many groups worldwide. The main advantage of this technology compared to other methods is that it is ideally lossless and discriminates among all possible values of OAM in a single step. This makes it particularly convenient for quantum applications.

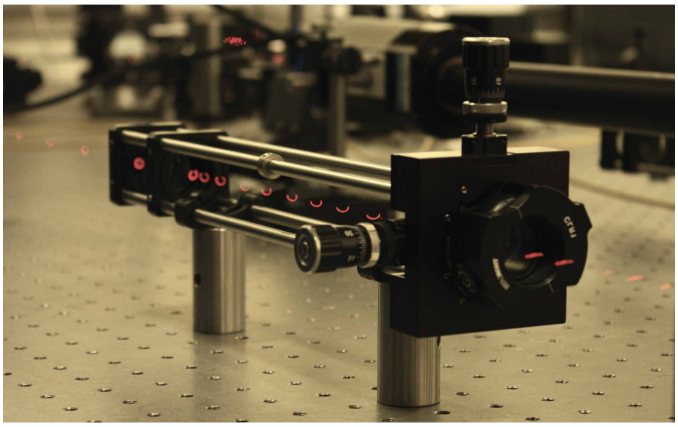

Fig. 13 – Photo of the phase-unfolding OAM sorter developed within PHORBITECH. A sequence of snapshots of the laser beam profile show how the OAM doughnut beam is first "cut" and then straightened out into a line carrying a phase gradient corresponding to the input OAM. Such line can then be focused to different spatial locations by a single lens, allowing direct detection of the OAM.

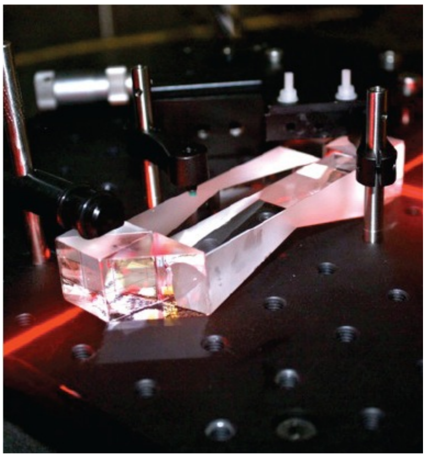

Fig. 14 – Robust OAM Dove-prism based sorting interferometer.

In addition, the PHORBITECH team has manufactured a robust "quasi-monolithic" interferometer device for the high-efficiency sorting of OAM, based on the principle of the Leach interferometer introduced several years ago by one of the PHORBITECH partners. This device hence 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. 14. Although less general than the phase-unfolding method, this sorter has its own advantages, among which in particular the full independence from the radial profile of the sorting direction.

An important scientific result obtained in PHORBITECH in connection with the interaction of OAM light with matter has been 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 global rotation of the optical image transmitted by the rotating medium. The result was published in Science, in 2011.

OAM atomic storage. A specific line of work concerned the interaction between light with OAM and trapped atoms, with the technological prospect of a coherent storage of quantum information. The transfer of OAM from a near-infrared pump light to the blue light generated in a four-wave-mixing process in a rubidium vapor was demonstrated (Fig. 15). The blue patterns obtained prove that the transfer is coherent.

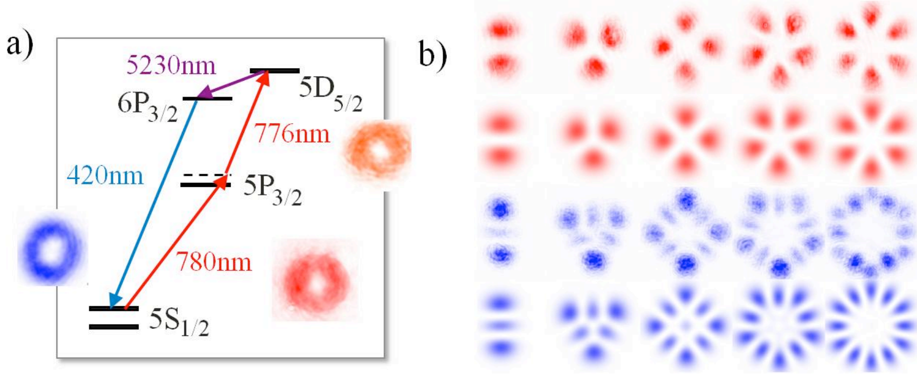

Fig. 15 – OAM color conversion mediated by the interaction with a rubidium vapor. a) Optical transitions and atomic levels. b) Pumping with complex light profiles obtained as superpositions of different OAM generates light modes that are determined by phase-matching in the four wave mixing process, and therefore show OAM conservation as well. The rows show measured and calculated input pump modes, measured and calculated blue light modes.

Next, in order to study OAM dependent interaction with cold atoms we have developed a holographically shaped atom trap, yielding atom densities of over 10^{12} atoms/cm^3, a record for a magneto-optical trap (see Fig. 16). In this trap the atoms can accumulate at higher densities than in standard magneto-optical (MOT) trap designs by sheltering the central atoms from the trapping light within the core of two overlapping light beams carrying OAM (dark SPOT geometry), and we

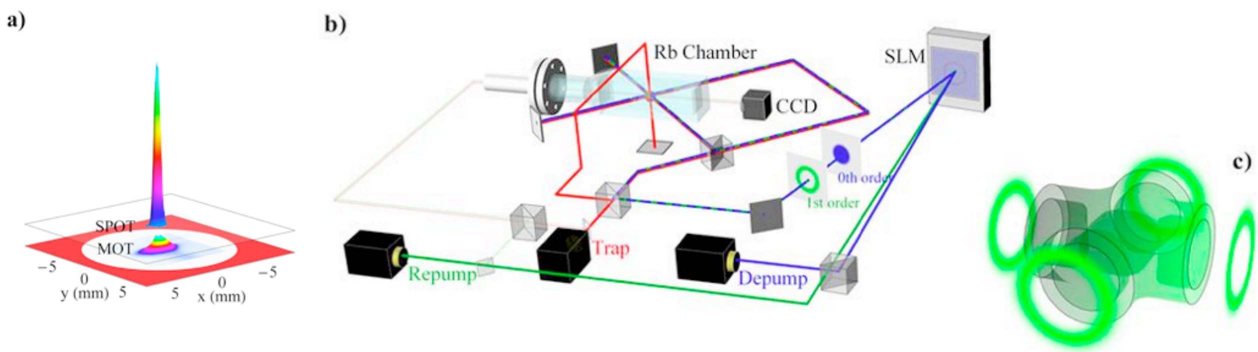

Fig. 16 – **a)** Atom density in the holographic SPT design compared to the MOT design. **b)** Simplified set-up. **c)** Trapping volume defined by the cross section of two crossing LG beams.

have seen an increase in atom density of two orders of magnitude, without heating the atoms and with a transfer of 75% of the atoms from the standard MOT.

This prototype system provides an ideal set-up for inscribing optical information into the atomic sample, due to the combination of high atom density, long lifetime of several 100ms and the fact that the atoms are not experiencing detrimental light shifts due to trapping light. We are currently testing our dense atom sample in processing of the optical OAM information. The phase structure of a shaped probe beam allows us to generate spatially dependent transparency of the atomic sample, thus converting the phase optical information into an intensity one.

WP6 – Misalignment-free quantum communication

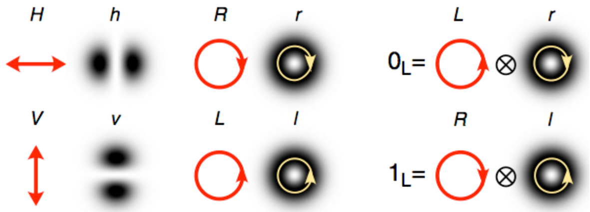

Fig. 17 – Polarization states and OAM modes having analogous rotational properties and combined polarization-OAM modes used to encode the quantum information in a rotation-invariant way.

Toolbox for alignment-free quantum communication. Within this more focused task, we have exploited the method for generating rotation-invariant states of single photons to carry out a demonstration of quantum communication independent of the relative alignment of the transmitting and receiving unit frames. In particular, we have developed and tested a convenient toolbox for encoding and decoding photonic qubits into these rotation-invariant states of light that are based on a suitable combination of polarization and OAM (Fig. 17).

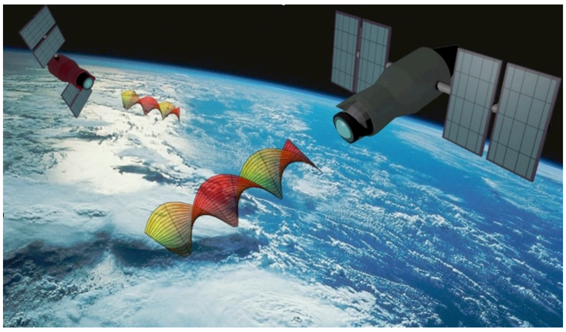
Fig. 18 – Artwork depicting a futuristic scenario in which satellites exchange photonic qubits encoded in rotation-invariant states of light based on OAM.

The experiments carried out in PHORBITECH have shown a successful transfer of quantum information and of entanglement, independent of the relative alignment of the transmitting and receiving stages. The results have been published in Nature Communications in 2012. The alignment problem is one of the outstanding problems on the way of implementing a satellite-based world-wide quantum communication technology, as illustrated in the artistic rendering of Fig. 18.

The main obstacle to a full exploitation of OAM in free-space communication is the strong sensitivity to turbulence. On a theoretical basis, we however expect that the rotation-invariant qubits encoded in polarization-OAM combined states should be more robust to turbulence-induced perturbations. This has been tested in experiments exploiting a machine for generating controlled turbulence, confirming the expected robustness.

1.3 PHORBITECH: potential impact and wider societal implications

In the words of the classic textbook “Fundamental of Photonics”, by B. E. A. Saleh and M. C. Teich, “an optical beam is characterized by several attributes. One of these attributes, e.g., intensity, can be modulated and used to transport a signal between two points. Another attribute, e.g., wavelength, may be used to mark different signals carried on the same beam, a process known as multiplexing.” The vision of PHORBITECH was that of placing orbital angular momentum (OAM) in the list of useful light attributes, on “equal foot” with the others. The development of an adequate toolbox of practical devices for the OAM generation, transmission, manipulation and detection, which has been the central goal of PHORBITECH, was the key pre-condition for this scenario. We can now safely claim that PHORBITECH has greatly contributed to the fulfillment of this key pre-condition. Its potential impact derives then from the technical uses that OAM may have as an additional attribute of light.

We identify three specific fields of science and technology in which the enhanced control of the OAM of light obtained thanks to PHORBITECH results has the highest potential for a future impact, in the medium or long term: (i) enhanced room for *multiplexing of the information* in classical communication, both in free-space and in optical fibers; (ii) implementation of *quantum information channels* with new capabilities and a higher dimensionality; (iii) new *high-sensitivity detection and measurement methods* in mechanical applications.

These future technological advances, if fully realized, will in turn have a very large socio-economical impact in terms of enhanced economical growth. The advantage will be worldwide, but of course the countries which will have contributed more to the technology progresses may benefit more, particularly if these technological advances will have been linked to a strengthening of the corresponding industrial sectors.

Let us now discuss each of these three fields in some more detail.

Technological potential impact

Multiplexing for classical communication.

“Optical communication technology has been advancing rapidly for several decades, supporting our increasingly information-driven society and economy. Much of this progress has been in finding innovative ways to increase the data-carrying capacity of a single optical fiber. To achieve this, researchers have explored and attempted to optimize multiplexing in time, wavelength, polarization and phase. Commercial systems now utilize all four dimensions to send more information through a single fiber than ever before. The spatial dimension has, however, remained untapped in single fibers, despite it being possible to manufacture fibers supporting hundreds of spatial modes or containing multiple cores, which could be exploited as parallel channels for independent signals.” [excerpt from the review article by D. J. Richardson, J. M. Fini and L. E. Nelson, “Space-division multiplexing in optical fibres”, appeared in *Nature Photonics* **7**, 354 (2013)].

The current technologies cannot sustain the current growth in data traffic without huge costs associated with lighting new fiber networks. This upcoming “capacity crunch” can be overcome by recurring to the emerging technology of space-division multiplexing. OAM-mode control in optical fibers is one of the main currently investigated possible approaches to this space-division multiplexing. PHORBITECH has contributed several important tools which may be essential to these developments. These include the q-plate technology, possibly useful as an input coupler or a switch from a single free-space mode to different guided OAM modes. The OAM efficient sorter can represent another important element, particularly as input/output coupler from different free-space modes to different free-space or guided OAM modes. The integrated vector beam coupler is another example of a device which can have a great impact in this area.

If these tools will be actually incorporated in the future optical-fiber commercial networks, given the enormous size of this market, the socio-economical impact of PHORBITECH might clearly become huge (in the scale of billions of euros or more). However, the uncertainties about what will be the actual future course of the fiber-optics network technology are presently still large, so this economical impact is subject to a similar large uncertainty.

Quantum information

Quantum information is presently one of the most attractive areas of future ICT technology. In particular, an application which is already a commercial reality is the secure communication or information exchange, i.e. cryptography, anonymous interrogation, etc., by quantum methods. But quantum technologies promise other impressive achievements, such as extremely fast methods based on *quantum computation* for solving problems such as factoring large integer numbers, searching huge data-bases, etc., that have extremely important applications in many areas of society.

The OAM degree of freedom can represent an extremely important enabling element of a future photonic quantum information technology. In particular, being a discrete but unbounded degree of freedom, OAM provides a very convenient choice to encode many qubits of quantum information, or alternatively a single high-dimensional *qudit* (multi-level quantum states for information encoding), into a single photon. In principle, OAM can allow an unlimited increase of the information content per photon (although this comes at the cost of an increasing transverse size of the optical beam), thus providing one promising practical approach to addressing the scalability problem of quantum technologies. The use of OAM will also enable the photonic implementation of qualitatively different quantum information protocols based on qudits, for which better theoretical performances than their qubit-based equivalents are predicted. All these advantages are now available for immediate application in further scientific work in the quantum information field, thanks to PHORBITECH-developed toolbox devices, such as the polarization-to-OAM transferrers (based on the q-plate technology), the OAM efficient sorter and the high-dimensional, high-brightness OAM-entangled sources based on spontaneous parametric down conversion. This, in turn, makes the quantum photonic technology one step closer to real-world applications.

In addition, a future complete quantum information technology will also require effective optical-matter interfaces, capable of coherently transferring quantum information from photons to matter degrees of freedom or vice versa. Atom trapping and coherent optical-field storage are important elements of a current effort to achieve practical quantum memories. Also here, PHORBITECH reported results can have an important impact.

Detection and measurement methods

The use of OAM to design optical tools for measurement and probing is the last area in which PHORBITECH impact can be expected. In particular, PHORBITECH invention of the photonics polarization gears might have a short-term impact in the technology for precision mechanical measurements of rotation, for example in high-precision stepping motors. Moreover, by exploiting the OAM it is possible to conceive new sensitive probes of material gradients and inhomogeneities which will benefit from the optical toolbox developed in PHORBITECH.

Advancement of scientific knowledge

In addition to this possible medium or long-term socio-economical impact, there is an evident and immediate impact of the PHORBITECH project in terms of advancement of human scientific knowledge. With about 120 scientific publications in international journals, among which 27 in top-level multidisciplinary or physics journals (more precisely, 3 in *Science*, plus a perspective piece, 1 in *Nature Physics*, 4 in *Nature Photonics*, plus a News & Views piece, 4 in *Nature Communications*, and 15 in *Physical Review Letters*), this scientific impact can be very significant indeed. The citation count, a direct measure of impact, is already adding up to significant values, given the very short time since the appearance of most publications (the current citation counts is already close to 700, with an h-index of 14, despite the fact that the average age of the publications is of about 1.5 years; diagrams were provided in Section 1.2).

Educational and scientific-career impact

As usual with the academic enterprise, the scientific work is also associated with an educational and dissemination activity, which has its own significant impact. As many as 19 graduate students (all enrolled in PhD programs) and 13 post-doctoral fellows have participated and contributed to PHORBITECH work (of whom, 3 PhD students and 10 post-doctoral fellows were specifically hired on the project funding) and have been hence educated and strengthened in their career prospects in the process. In some cases, these people have already secured permanent jobs or more senior post-doc positions (e.g., Eleonora Nagali, Ebrahim Karimi, Sergei Slussarenko, etc.). The senior personnel also has received a similar benefit in some cases, including improved promotion prospects and some career advancements.

Impact of public-at-large dissemination

Wider public dissemination activities such as those carried out in PHORBITECH (see Section 1.4) may also significantly impact the society by increasing the number of citizens appreciating the importance of science and technology, as well as the number of college students majoring in scientific and engineering subjects.

1.4 PHORBITECH: dissemination activities and exploitation of results

During the years of project PHORBITECH results have been disseminated through various means and at different level of audience.

Dissemination activities to the scientific community

PHORBITECH scientific dissemination activity consisted of scientific publications on high impact scientific journals, communications at conferences and workshops and organization of project-related events.

Scientific publications

PHORBITECH scientific results are of interest to a wide range of researchers, and we have published in the most outstanding international peer-review journals in physics and photonics, selected according to diffusion and impact factor. When appropriate, we have also published in the highest-ranking multi-disciplinary journals in order to reach the most varied audience.

The research groups working in PHORBITECH have published during the three years of project a total of 120 (29 in the 1st year, 49 in the 2nd year, and 43 in the 3rd) project-related scientific publications in high-profile journals. PHORBITECH members have made their best efforts to ensure that an electronic copy of the published version or the final manuscript accepted for publication of a project scientific publication becomes freely and electronically available to anyone:

- immediately if the scientific publication is published "open access", i.e. if an electronic version is also available free of charge via the publisher, or
- within 6 months of publication
- posted in the appropriate electronic preprint repositories

Communications to conferences and workshops (seminar, talks…)

We have reported our results at the relevant international conferences in our field by delivering a total of 156 communications.

Project-related events

PHORBITECH final Workshop

The aim of the final project workshop was to showcase the PHORBITECH achievements, disseminate the project results, and discuss these results in the wider community. In order to increase external exposure and attract a wider international audience, the workshop was held in conjunction with the international conference ICOAM 2013 (see below), which preceded the workshop (The Burrell Collection, Glasgow, UK, 3rd to 5th of June 2013). At the associated lab tour, the workshop participants were able to see the prototypes and experiments developed by the Glasgow partner.

PHORBITECH sessions in ICOAM 2013 Conference

On the occasion of the International Conference on the Optical Angular Momentum ICOAM 2013 (Glasgow, 3-5 June 2013), two conference sessions (an oral and a poster session) were explicitly devoted to the presentation of PHORBITECH-driven research, with contributions exclusively from PHORBITECH participants. Both sessions were titled "OAM toolbox," directly referring to the title of the PHORBITECH project. The oral and poster sessions were held at the second and first conference day respectively, with very high participant attendance.

Symposium for the 20th anniversary of OAM

On the occasion of PHORBITECH second annual meeting (September 11&13, 2012), a symposium was organized by the University of Leiden on the 12th of September to celebrate the 20th anniversary of OAM and the 70th birthday of Han Woerdman.

Workshop on Singular optics and its applications to modern physics

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 by Ebrahim Karimi.

Workshop on Entanglement, Quantum Information And The Quantum – To – Classical Transition

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

Dissemination activities to the public-at-large

We have made a conscious effort towards making our work available and accessible to the public at large through various media, as detailed in the following.

Logo

A Phorbitech logo has been designed to be graphically appealing and includes 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.

Project website

The website has been the project's key communication tool. The website was 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. All project results, including videos and non-technical descriptions of scientific results, were posted in appropriate sections.

Wikipedia pages

Three new pages of *Wikipedia* (the free online encyclopedia) on the angular momentum of light in general, its spin and its orbital component, have been developed and posted. Of course, as standard for Wikipedia, any user can now also modify the pages. However, in the following years we plan to periodically check these pages to ensure that its content stays correct and up to date.

Leaflets on project goals and on project results

Two leaflets, one describing PHORBITECH's main concepts and the other its main achievements, have been developed and distributed. The leaflet were targeted both to a technical and non-technical audience and were distributed at scientific events and/or public-at-large events. The leaflet on the project results (and a corresponding poster) were distributed during the ICOAM 2013 conference. In addition, each partner distributed some leaflets and poster at its institution.

Video on PHORBITECH highlights

A video on PHORBITECH main highlights has been developed. The video was targeted to a technical and non-technical audience and intended for a large distribution (on YouTube, the project website and other institutional websites). To ensure effective dissemination to experts and non-experts, the main basic concepts were explained in an easy-to-understand fashion, and illustrated with images related to the results obtained within the project by consortium partners. In particular, the video focuses on the q-plate technology and the experimental realization of alignment-free quantum communication and experiments involving the collaboration of three PHORBITECH partners (Rome, Naples and Rio de Janeiro).

The video is available on YouTube at the following link:
http://www.youtube.com/watch?v=JPmmEBntZBY

Press releases and press articles

Throughout the three years of the PHORBITECH project, we actively disseminated the best results achieved within the project through press releases issued by the partner press offices. In particular, the press interest rose towards some important PHORBITECH results that may have a greater impact on the society.

FET Newsletter

A brief article on the PHORBITECH project and its ongoing results was published in the FET newsletter (February 2013 issue).

Acknowledgment of the EC support

Appropriate acknowledgment of the EC support has been included in all PHORBITECH publications, conference slides, leaflets, website, video etc., using the standard form "The project PHORBITECH acknowledges the financial support of the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission, under FET-Open grant number: 255914.".

Exploitation of results

Some of PHORBITECH results have been protected with patent applications or were already protected with previously existent patents, whose potential value has been however increased by the results obtained within PHORBITECH. For such results, it is conceivable to set up a short-term exploitation directly by the PHORBITECH partners either by licensing the patents to interested companies or by setting up small start-up companies. These options are currently being explored by the partners owning the protected foreground.

In most cases, a full exploitation will however require additional research and development work. Members of the PHORBITECH consortium are currently planning or have already secured several follow-up projects on the OAM topic. As an outstanding example, Miles Padgett (University of Glasgow) has been recently awarded a prestigious advanced grant of the European Research Council on the OAM of light.

More details about the specific potential for commercial exploitation of the PHORBITECH foreground are reported in Table B2.

1.5 PHORBITECH: project website and contact details

http://www.phorbitech.eu/

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Plan for the use and dissemination of foreground

Table of contents

Section A –Table A1: List of all scientific (peer reviewed) publications relating to the foreground of the project

NO.	Title	Authors	Title of the periodical	Volume, issue nr. and relevant pages	Publisher	Place of publication	Year of pub-lica-tion	Perma-nent identifier (DOI)	Is/Will open Access be provided (**)
1	Rotary Photon Drag Enhanced by a Slow-Light Medium	S. Franke-Arnold, G. Gibson, R.W. Boyd, M.J. Padgett	Science	333, 65	American Association for the Advancement of Science	New York	2011	10.1126/science.1203984	No
2	Integrated Compact Optical Vortex Beam Emitters	X. Cai, J. Wang, M.J. Strain, B. Johnson-Morris, J. Zhu, M. Sorel, J.L. O'Brien, M.G. Thompson, S.T. Yu	Science	338(6105):363-6	American Association for the Advancement of Science	New York, USA	2012	10.1126/science.1226528	No
3	A Quantum Delayed-Choice Experiment	A. Peruzzo, P. Shadbolt, N. Brunner, S. Popescu, J.L. O'Brien	Science	338; 6107 :634-637	American Association for the Advancement of Science	New York, USA	2012	10.1126/science.1226719	No
4	Spinning the Doppler Effect	L. Marrucci	Science	341, 464-465	American Association for the Advancement of Science	New York, USA	2013	10.1126/science.1242097	No
5	Experimental estimation of the dimension of classical and quantum systems	M.Hendrych, R. Gallego, M. Micuda, N. Brunner, A. Acín, J.P. Torres	Nature Physics	8, 588–591	Nature Publishing Group	London,UK	2012	10.1038/NPHYS2334	No
6	Calculating unknown eigenvalues with a quantum algorithm	X.Q. Zhou, P. Kalasuwan, T.C. Ralph, J.L. O'Brien	Nature Photonics	7, 223–228	Nature Publishing Group	London, UK	2013	10.1038/nphoton.2012.360	No
7	Joining the quantum state of two photons into one	C. Vitelli, N. Spagnolo, L. Aparo, F. Sciarrino, E. Santamato, L. Marrucci	Nature Photonics	7, 521–526	Nature Publishing Group	London, UK	2013	10.1038/nphoton.2013.107	Yes
8	Generating, manipulating and measuring entanglement and mixture with a reconfigurable photonic circuit	P. J. Shadbolt, M. R. Verde, A. Peruzzo, A. Politi, A. Laing, M. Lobino, J. C. F. Matthews, and J. L. O'Brien	Nature Photonics	6, 45--49	Nature Publishing Group	London, UK	2012	10.1038/nphoton.2011.283	No

9	Experimental realization of Shor's quantum factoring algorithm using qubit recycling	E. Martin-Lopez, A. Laing, T. Lawson, R. Alvarez, X.Q. Zhou, J.L. O'Brien	Nature Photonics	6, 773–776	Nature Publishing Group	London, UK	2012	10.1038/nphoton.2012.259	No
10	Complete experimental toolbox for alignment-free quantum communication	V. D'Ambrosio, E. Nagali, S.P. Walborn, L. Aolita, S. Slussarenko, L. Marrucci, F. Sciarrino	Nature Communications	17;3:961	Nature Publishing Group	London, UK	2012	10.1038/ncomms1951	Yes
11	Light-induced spiral mass transport in azo-polymer films under vortex-beam illumination	A. Ambrosio, L. Marrucci, F. Borbone, A. Roviello, P. Maddalena	Nature Communications	7;3:989	Nature Publishing Group	London, UK	2012	10.1038/ncomms1996	Yes
12	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	Nature Publishing Group	London	2011	10.1038/ncomms1392	Yes
13	Photonic polarization gears for ultra-sensitive angular measurements	V. D'Ambrosio, N. Spagnolo, L. Del Re, S. Slussarenko, Y. Li, L. Chuan Kwek, L. Marrucci, S. P.Walborn, L. Aolita, F. Sciarrino	Nature Communications	4, 2432	Nature Publishing Group	London, UK	2013	10.1038/ncomms3432	Yes
14	Observing fermionic statistics with photons in arbitrary processes	J.C.F. Matthews, K. Poulios, J.D.A. Meinecke, A. Politi, A. Peruzzo, N. Ismail, K. Worhoff, M.G. Thompson, J.L. O'Brien	Scientific Reports	1,19375	Nature Publishing Group	London, UK	2013	10.1038/srep01539	Yes
15	Test of mutually unbiased bases for six-dimensional photonic quantum systems	V. D'Ambrosio, F. Cardano, E. Karimi, E. Nagali, E. Santamato, L. Marrucci, F. Sciarrino	Scientific Reports	3, 2726	Nature Publishing Group	London, UK	2013	10.1038/srep02726	Yes
16	Experimental Detection of transverse particle movement with structured light	C. Rosales-Guzman, N. Hermosa, A. Belmonte and J. P. Torres	Scientific Reports	3 2815	Nature Publishing Group	London, UK	2013	10.1038/srep02815	Yes
17	Guaranteed violation of a Bell inequality without aligned reference frames or calibrated devices	P. Shadbolt, T. Vertesi, Y.C. Liang, C.Branciard, N. Brunner and J. L. O'Brien	Scientific Reports	2012;2:470	Nature Publishing Group	London	2012	10.1038/srep00470	Yes

18	Testing sequential quantum measurements: how can maximal knowledge be extracted?	E. Nagali, S. Felicetti, P.-L. de Assis, V. D'Ambrosio, R. Filip, F. Sciarrino	Scientific Reports	2, 443	Nature Publishing Group	London	2012	10.1038/srep00443	Yes
19	Highly Efficient Noise-Assisted Energy Transport in Classical Oscillator Systems	R. de J. Leon-Montiel, J.P.Torres	Physical Review Letters	110;21: 218101	American Physical Society	New York, USA	2013	10.1103/PhysRevLett.110.218101	No
20	Molecular Model for Light-Driven Spiral Mass Transport in Azopolymer Films	A. Ambrosio, P. Maddalena, L. Marrucci	Physical Review Letters	110, 146102	American Physical Society	New York, USA	2013	10.1103/PhysRevLett.110.146102	Yes*
21	Weak measurements with orbital-angular-momentum pointer states	G. Puentes, N. Hermosa, J. P. Torres	Physical Review Letters	109, 040401	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.109.040401	Yes*
22	Shaping the Ultrafast Temporal Correlations of Thermal-Like Photons	V. Torres-Company, J.P. Torres, A.T. Friberg	Physical Review Letters	14;109:243905	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.109.243905	No
23	Spatial Coherence and Optical Beam Shifts	W. Loffler, A. Aiello, J.P.Woerdman	Physical Review Letters	109:213901	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.109.213901	No
24	Experimental Observation of Impossible-to-Beat Quantum Advantage on a Hybrid Photonic System	E. Nagali, V. D'Ambrosio, F. Sciarrino, A. Cabello	Physical Review Letters	108, 090501	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.108.090501	Yes*
25	Fast Path and Polarization Manipulation of Telecom Wavelength Single Photons in Lithium Niobate Waveguide Devices	D. Bonneau, M. Lobino, P. Jiang, C.M. Natarajan, M.G. Tanner, R.H. Hadfield, S.N. Dorenbos, V. Zwille, M.G. Thompson, J.L. O'Brien	Physical Review Letters	108, 053601	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.108.053601	Yes*
26	Full-Field Quantum Correlations of Spatially Entangled Photons	V. D. Salakhutdinov, E. R. Eliel, W. Löffler	Physical Review Letters	108, 173604	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.108.173604	No

27	Trans-spectral orbital angular momentum transfer via four wave mixing in Rb vapor	G. Walker, A. S. Arnold, S. Franke-Arnold	Physical Review Letters	108, 243601	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.108.243601	Yes*
28	Observation of Quantum Interference as a Function of Berry's Phase in a Complex Hadamard Optical Network	A. Laing, T. Lawson, E. M. Lopez, and J. L. O'Brien	Physical Review Letters	108.26.00	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.108.260505	Yes*
29	Observation of orbital angular momentum sidebands due to optical reflection	W. Loeffler, A. Aiello, J. P. Woerdman	Physical Review Letters	109, 113602 .	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.109.113602	Yes*
30	Spin-to-orbital angular momentum conversion and spin-polarization filtering in electron beams	E. Karimi, L. Marrucci, V. Grillo, E. Santamato	Physical Review Letters	108, 044801	American Physical Society	New York, USA	2012	10.1103/PhysRevLett.108.044801	Yes*
31	Fiber transport of spatially entangled photons	W. Loeffler, T.G.Euser, E.R. Eliel, M. Scharrer, P. St. Russell and J.P. Woerdman	Physical Review Letters	106, 240505	American Physical Society	New York, USA	2011	10.1103/PhysRevLett.106.240505	Yes*
32	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	American Physical Society	New York, USA	2010	10.1103/PhysRevLett.105.153601	Yes*
33	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	American Physical Society	New York, USA	2010	10.1103/PhysRevLett.105.073602	Yes*
34	Experimental implementation of a Kochen-Specker set of quantum tests	V. D'Ambrosio, I. Herbauts, E. Amselem, E. Nagali, M. Bourennane, F. Sciarrino, A. Cabello	Physical Review X	3, 011012	American Physical Society	New York, USA	2013	10.1103/PhysRevX.3.011012	Yes
35	Cold-atom densities of over 1012 cm^3 in a holographically shaped dark spontaneous-force optical trap	N. Radwell, G.Walker, S. Franke-Arnold	Physical Review A	88, 043409	American Physical Society	New York, USA	2013	10.1103/PhysRevA.88.043409	No

36	Einstein-Podolsky-Rosen steering inequalities from entropic uncertainty relations	J. Schneeloch, C.J. Broadbent, S.P. Walborn, E. G. Cavalcanti, and J. C. Howell	Physical Review A	87;6:062103	American Physical Society	New York, USA	2013	10.1103/PhysRevA.87.062103	Yes*
37	Coherent Time Evolution and Boundary Conditions of Two-Photon Quantum Walks	J. D. A. Meinecke, K. Poulios, A. Politi, J. C. F. Matthews, A. Peruzzo, N. Ismail, K. Wörhoff, J. L. O'Brien, M.G. Thompson	Physical Review A	88, 012308	American Physical Society	New York, USA	2013	10.1103/PhysRevA.88.012308	Yes*
38	Violation of Leggett-type inequalities in the spin-orbit degrees of freedom of a single photon	F. Cardano, E. Karimi, L. Marrucci, C. de Lisio, E. Santamato	Physical Review A	88, 032101	American Physical Society	New York, USA	2013	10.1103/PhysRevA.88.032101	Yes*
39	Detection efficiency for loophole-free Bell tests with entangled states affected by colored noise	G. Canas, J.F. Barra, E.S. Gomez, G. Lima, F. Sciarrino, A. Cabello	Physical Review A	87, 012113	American Physical Society	New York, USA	2013	10.1103/PhysRevA.87.012113	No
40	Experimental implementation of a Kochen-Specker set of quantum tests	V. D'Ambrosio, I.Herbauts, E. Amselem, E. Nagali, M. Bourennane, F. Sciarrino, A. Cabello	Physical Review X	3;1:011012	American Physical Society	New York, USA	2013	10.1103/PhysRevX.3.011012	Yes
41	Loophole-Free Bell Test Based on Local Precertification of Photon's Presence	A. Cabello, F. Sciarrino	Physical Review X	2, 021010	American Physical Society	New York, USA	2012	10.1103/PhysRevX.2.021010	Yes
42	Measurement of the temperature of atomic ensembles via which-way information	R. de J. León-Montiel, J. P. Torres	Physical Review A	85, 033801	American Physical Society	New York, USA	2012	10.1103/PhysRevA.85.033801	Yes*
43	Experimental observation of quantum correlations in modular variables	M.A.D. Carvalho, J. Ferraz, G.F. Borges, P.L. de Assis Padua, S. Walborn	Physical Review A	86, 032332	American Physical Society	New York, USA	2012	10.1103/PhysRevA.86.032332	Yes
44	Implementation of a spatial two-dimensional quantum random walk with tunable decoherence	J. Svozilik, J.D. Leon-Montiel, J.P. Torres	Physical Review A	86, 052327	American Physical Society	New York, USA	2012	10.1103/PhysRevA.86.052327	Yes

45	High spatial entanglement via chirped quasi-phase-matched optical parametric down-conversion	J. Svozilik, J.J. Perina, J.P. Torres	Physical Review A	86, 052318	American Physical Society	New York, USA	2012	10.1103/PhysRevA.86.052318	Yes
46	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	American Physical Society	New York, USA	2011	10.1103/PhysRevA.83.065801	Yes*
47	Hybrid ququart-encoded quantum cryptography protected by Kochen-Specker contextuality	A. Cabello, V. D'Ambrosio, E. Nagali, F. Sciarrino	Physical Review A	84, 030302	American Physical Society	New York, USA	2011	10.1103/PhysRevA.84.030302	No
48	Cancellation of dispersion and temporal modulation with nonentangled frequency-correlated photons	V. Torres-Company, A. Valencia, M. Hendrych, J.P. Torres	Physical Review A	A 83, 023824	American Physical Society	New York, USA	2011	10.1103/PhysRevA.83.023824	Yes*
49	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	American Physical Society	New York, USA	2011	10.1103/PhysRevA.83.042338	Yes*
50	How orbital angular momentum affects beam shifts in optical reflection	M. Merano, N. Hermosa, J. P. Woerdman	Physical Review A	82, 023817	American Physical Society	New York, USA	2010	10.1103/PhysRevA.82.023817	Yes*
51	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	American Physical Society	New York, USA	2010	10.1103/PhysRevA.82.022115	Yes*
52	The q-plate and its future	L. Marrucci	Journal of Nanophotonics	7, 078598	SPIE	Bellingham, USA	2013	10.1117/1.JNP.7.078598	Yes
53	Total internal reflection of orbital angular momentum beams	W. Loffler, N. Hermosa, A. Aiello, J.P. Woerdman	Journal of Optics	15; 014012	IOP publishing	Bristol, UK	2013	10.1088/2040-8978/15/1/014012	No

54	Liquid-crystal spatial-mode converters for the orbital angular momentum of light	S. Slussarenko, B. Piccirillo, V. Chigrinov, L. Marrucci, E. Santamato	Journal of Optics	15, 025406	IOP publishing	Bristol, UK	2013	doi:10.1088/2040-8978/15/2/025406	Yes*
55	Complementarity reveals bound entanglement of two twisted photons	B.C. Hiesmayr and W. Loeffler.	New Journal of Physics	15, 083036	IOP publishing	Bristol, UK	2013	10.1088/1367-2630/15/8/083036	Yes
56	Role of the spectral shape of quantum correlations in two-photon virtual-state spectroscopy	R. de J. Leon-Montiel, J. Svozilik, L.J. Salazar-Serrano, J.P.Torres	New Journal of Physics	15:053023	IOP publishing	Bristol, UK	2013	10.1088/1367-2630/15/5/053023	Yes
57	Light confinement via periodic modulation of the refractive index	A. Alberucci, L. Marrucci, G. Assanto	New Journal of Physics	15; 083013	IOP publishing	Bristol, UK	2013	10.1088/1367-2630/15/8/083013	Yes
58	Quantum simulation of a spin polarization device in an electron microscope	V. Grillo, L. Marrucci, E. Karimi, R. Zanella, E. Santamato	New Journal of Physics	15, 093026	IOP publishing	Bristol, UK	2013	10.1088/1367-2630/15/9/093026	Yes
59	Efficient measurement of an optical orbital-angular-momentum spectrum comprising more than 50 states	M.P.J. Lavery, D.J. Robertson, A. Sponselli; J. Courtial, N.K. Steinhoff, G.A. Tyler, A. E. Wilner, M. J. Padgett	New Journal of Physics	15; 013024	IOP publishing	Bristol, UK	2013	10.1088/1367-2630/15/1/013024	Yes
60	Generation and dynamics of optical beams with polarization singularities	F. Cardano, E. Karimi, L. Marrucci, C. de Lisio, and E. Santamato	Optics Express	21;7: 8815-8820	Optical Society of America	Washington, USA	2013	10.1364/OE.21.008815	Yes
61	Phase-stable source of polarization-entangled photons in a linear double-pass configuration	F. Steinlechner, S.Ramelow, M. Jofre, M. Gilaberte, T. Jennewein, J.. P. Torres, M. W. Mitchell, and V. Pruneri	Optics Express	21;10:11943-11951	Optical Society of America	Washington, USA	2013	10.1364/OE.21.011943	Yes
62	Generation of polarization-entangled photon pairs in a Bragg reflection waveguide	A. Valles, M. Hendrych, J. Svozilik, R. Machulka, P. Abolghasem, D. Kang, B. J. Bijlani, A. S. Helmy, and J. P. Torres	Optics Express	21;9:10841-10849	Optical Society of America	Washington, USA	2013	10.1364/OE.21.010841	Yes

63	Exact solution to simultaneous intensity and phase encryption with a single phase-only hologram	E. Bolduc, N. Bent, E. Santamato, E. Karimi, and R. W. Boyd	Optics Letters	38 ;18: 3546	Optical Society of America	Washington, USA	2013	10.1364/OL.38.003546	Yes
64	Walsh modes and radial quantum correlations of spatially entangled photons	D. Geelen and W. Loeffler	Optics Letters	38;20:4108-4111	Optical Society of America	Washington, USA	2013	10.1364/OL.38.004108	No
65	Optical vortices in antiguides	L. Marrucci, N.F. Smyth, G. Assanto	Optics Letters	38;10:1618-1620	Optical Society of America	Washington, USA	2013	10.1364/OL.38.001618	Yes*
66	Digital coherent receiver for orbital angular momentum demultiplexing	A. Belmonte, J.P. Torres	Optics Letters	38; 2: 241-243	Optical Society of America	Washington, USA	2013	10.1364/OL.38.000241	No
67	Helico-conical optical beams self-heal	N. Hermosa, C. Rosales-Guzmán, and J. P. Torres	Optics Letters	38;3:383-385	Optical Society of America	Washington, USA	2013	10.1364/OL.38.000383	No
68	Reconstructing the Poynting vector skew angle and wavefront of optical vortex beams via two-channel moire deflectometery	M. Yeganeh, S. Rasouli, M. Dashti, S. Slussarenko, E. Santamato, E. Karimi	Optics Letters	38;6:887-889	Optical Society of America	Washington, USA	2013	10.1364/OL.38.000887	No
69	Quantum multiplexing in single photons	L. Marrucci, C. Vitelli, N. Spagnolo, F. Sciarrino	SPIE Newsroom		SPIE	Bellingham, USA	2013	10.1117/2.1201308.005020	Yes
70	Photonic hybrid multidimensional systems and their application in quantum communication	V. D'Ambrosio, E. Nagali, L. Marrucci, F. Sciarrino	Proceedings of SPIE	8773, 87730P .	SPIE	Bellingham, USA	2013	10.1117/12.1518444	No
71	Orbital angular momentum of photons, atoms, and electrons	S.Franke-Arnold	Proceedings of SPIE	86370P	SPIE	Bellingham, USA	2013	10.1117/12.2002984	No
72	Non-integer OAM beam shifts of Hermite–Laguerre–Gaussian beams	A.M. Nugrowati, J.P. Woerdman	Optics communications	308, 253–255	Elsevier	Philadelphia, PA	2013	10.1016/j.optcom.2013.07.051	Yes*

73	Polarization pattern of vector vortex beams generated by q-plates with different topological charges	F. Cardano, E. Karimi, S. Slussarenko, L. Marrucci, C. de Lisio, E. Santamato	Applied Optics	51, C1-C6	Optical Society of America	Washington, USA	2012	10.1364/AO.51.0000C1	Yes*
74	Measuring protein concentration with entangled photons	A. Crespi, M. Lobino, J.C.F. Matthews, A. Politi,C.R. Neal, R. Ramponi, R. Osellame, J.L. O'Brien	Applied Physics Letters	100, 233704	AIP Publishing	Melville, NY, USA	2012	10.1063/1.4724105	Yes*
75	Unambiguous state discrimination in high dimensions	S. Franke-Arnold, J. Jeffers	European Physical Journal D	66:196	Springer	Heidelberg, Germany	2012	10.1140/epjd/e2012-30027-3	No
76	Spin-to-Orbital Optical Angular Momentum Conversion in Liquid Crystal "q-Plates": Classical and Quantum Applications	L. Marruccia, E. Karimi, S. Slussarenko, B. Piccirillo, E. Santamato, E. Nagali and F. Sciarrino	Molecular Crystals And Liquid Crystals	561	Taylor and Francis	Oxford,UK	2012	10.1080/15421406.2012.686710	No
77	Determining the dimensionality of bipartite orbital-angular-momentum entanglement using multi-sector phase masks	D. Giovannini, F. M. Miatto, J. Romero, S. M. Barnett, J. P. Woerdman, M. J. Padgett	New Journal of Physics	14; 073046	IOP publishing	Bristol, UK	2012	10.1088/1367-2630/14/7/073046	Yes
78	Enhancing the sensitivity and robustness of label-free imaging systems via stimulated Raman adiabatic passage	R. de J. Leòn-Montiel, J.P. Torres	New Journal of Physics	14 013018	IOP publishing	Bristol, UK	2012	10.1088/1367-2630/14/1/013018	Yes
79	Vacuum Faraday effect for electrons	C. Greenshields, R.L. Stamps, S. Franke-Arnold	New Journal of Physics	14; 103040	IOP publishing	Bristol, UK	2012	10.1088/1367-2630/14/10/103040	Yes
80	Quantum interference and manipulation of entanglement in silicon wire waveguide quantum circuits	D. Bonneau, E. Engin, K. Ohira, N. Suzuki, H. Yoshida, N. Iizuka, M. Ezaki, C. M. Natarajan, M. G. Tanner, R. H. Hadfield, S. N. Dorenbos, V. Zwiller, J L O'Brien and M G Thompson	New Journal of Physics	14: 045003	IOP publishing	Bristol, UK	2012	10.1088/1367-2630/14/4/045003	Yes

81	Influence of atmospheric turbulence on states of light carrying orbital angular momentum	B. Rodenburg, M.P. J. Lavery, M.Malik, M.N. O'Sullivan, M. Mirhosseini, D.J. Robertson, M. Padgett, R.W. Boyd	Optics Letters	37:3735-7.	Optical Society of America	Washington, USA	2012	10.1364/OL.37.003735.	Yes*
82	Bragg reflection waveguide as a source of wavelength-multiplexed polarization-entangled photon pairs	J. Svozilík, M. Hendrych and J. P. Torres	Optics Express	20, 15015	Optical Society of America	Washington, USA	2012	10.1364/OE.20.015015.	Yes
83	Light with enhanced optical chirality	C. Rosales-Guzmán, K. Volke-Sepulveda and J. P. Torres	Optics Letters	37, 3486	Optical Society of America	Washington, USA	2012	10.1364/OL.37.003486	No
84	A high-brightness source of polarization-entangled photons optimized for applications in free space	F. Steinlechner,P. Trojek, M. Jofre,H. Weier, D. Perez, T. Jennewein, R. Ursin, J. Rarity, M.W. Mitchell, J.P. Torres, H. Weinfurter, V. Pruneri	Optics Express	20, 9640-9649	Optical Society of America	Washington, USA	2012	10.1364/OE.20.009640	Yes
85	Fast beam steering with full polarization control using a galvanometric optical scanner and polarization controller	M. Jofre, G. Anzolin, F. Steinlechner, N. Oliverio, J.P. Torres, V. Pruneri, M.W. Mitchell	Optics Express	20, 12247-60	Optical Society of America	Washington, USA	2012	10.1364/OE.20.012247	Yes
86	Radial coherent and intelligent states of paraxial wave equation	E. Karimi, E. Santamato	Optics Letters	37, 2484-6	Optical Society of America	Washington, USA	2012	10.1364/OL.37.002484	Yes*
87	Radial mode dependence of optical beam shifts	N. Hermosa, A. Aiello, J. P. Woerdman	Optics Letters	37 , 1044-1046	Optical Society of America	Washington, USA	2012	10.1364/OL.37.001044	Yes*
88	Instability of higher-order optical vortices analyzed with a multi-pinhole interferometer	F. Ricci, W. Loffler, M.P. van Exter	Optics Express	20, 22961-75	Optical Society of America	Washington, USA	2012	10.1364/OE.20.022961	Yes
89	Refractive elements for the measurement of the orbital angular momentum of a single photon	M.P.J. Lavery, D.J. Robertson, G.C.G. Berkhout, G.D. Love, M.J. Padgett, J. Courtial	Optics Express	20, 2110-2115	Optical Society of America	Washington, USA	2012	10.1364/OE.20.002110	Yes
90	Self-homodyne detection of the light orbital angular momentum	A. Belmonte and J. P. Torres	Optics Express	37, 2940	Optical Society of America	Washington, USA	2012	10.1364/OL.37.002940	Yes

91	Weak interference in the high-signal regime	J. P. Torres, G. Puentes, N. Hermosa and L. J. Salazar-Serrano	Optics Express	20, 18869-18875	Optical Society of America	Washington, USA	2012	10.1364/OE.20.018869	Yes
92	Position measurement of non-integer OAM beams with structurally invariant propagation	A.M. Nugrowati, W.G. Stam and J.P. Woerdman	Optics Express	20, 27429	Optical Society of America	Washington, USA	2012		Yes
93	Deterministic qubit transfer between orbital and spin angular momentum of single photons	V. D'Ambrosio, E. Nagali, C. H. Monken, S. Slussarenko, L. Marrucci, F. Sciarrino	Optics Letters	37, 172-174	Optical Society of America	Washington, USA	2012	10.1364/OL.37.000172	Yes*
94	Time-division multiplexing of the orbital angular momentum of light	E. Karimi, L. Marrucci, C. de Lisio, E. Santamato	Optics Letters	37, 127-129	Optical Society of America	Washington, USA	2012	10.1364/OL.37.000127	Yes*
95	Optical angular momentum conversion in a nanoslit	P.F. Chimento, P.F.A. Alkemade, G.W. 't Hooft, E.R. Eliel	Optics Letters	37:4946-8	Optical Society of America	Washington, USA	2012	10.1364/OL.37.004946	Yes
96	Fundamental tests on higher quantum dimensionality by exploiting the photonic orbital angular momentum"	E. Nagali, V. D'Ambrosio, L. Marrucci, F. Sciarrino	AIP Conf. Proc.	1424, 324-334	AIP Publishing	Melville, NY	2012		No
97	Orbital angular momentum for quantum information processing	V. D'Ambrosio, E. Nagali, L. Marrucci, F. Sciarrino	Proceedings of SPIE	8440, 84400F	SPIE	Bellingham, USA	2012	10.1117/12.924842	No
98	GaN directional couplers for integrated quantum photonics	Y. Zhang, L. McKnight, E. Engin , I.M. Watson, M.J. Cryan , E. Gu , E.G. Thompson, S. Calvez, J.L. O'Brien, M.D. Dawson	Applied Physics Letters	99, 161119	AIP Publishing	Melville, NY	2011	10.1063/1.3656073	Yes*
99	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	AIP Publishing	Melville, NY	2011	10.1063/1.3610474	Yes*

100	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, 0811	AIP Publishing	Melville, NY	2011	10.1063/1.3628328	No
101	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	IOP publishing	Bristol, UK	2011	10.1088/2040-8978/13/6/064017	No
102	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	Optical Society of America	Washington, USA	2011	10.1364/JOSAA.28.000061	Yes*
103	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	64006	IOP publishing	Bristol, UK	2011	10.1088/2040-8978/13/6/064006	No
104	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	IOP publishing	Bristol, UK	2011	10.1088/2040-8978/13/6/064001	Yes*
105	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	IOP publishing	Bristol, UK	2011	10.1088/1367-2630/13/9/093014	Yes
106	Flux enhancement of photons entangled in orbital angular momentum	S. Palacios, R. de J. Leon-Montiel, M. Hendrych, A. Valencia, J.P. Torres	Optics Express	19, 14108	Optical Society of America	Washington, USA	2011	10.1364/OE.19.014108	Yes
107	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	Optical Society of America	Washington, USA	2011	10.1364/OE.19.004085	Yes
108	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 .	Optical Society of America	Washington, USA	2011	10.1364/OE.19.012978	Yes

109	Goos-Hänchen and Imbert-Fedorov shifts of a nondiffracting Bessel beam.	A. Aiello and J.P. Woerdman	Optics Letters	36, 543	Optical Society of America	Washington, USA	2011	10.1364/OL.36.000543	No
110	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	Optical Society of America	Washington, USA	2011	10.1364/OL.36.001863	Yes*
111	Optical Doppler shift with structured light.	Belmonte A, Torres JP	Optics Letters	15;36:4437-9	Optical Society of America	Washington, USA	2011	10.1364/OL.36.004437	No
112	Quadrant detector calibration for vortex beams	N. Hermosa, A. Aiello, J. P. Woerdman	Optics Letters	36, 3, 409-411	Optical Society of America	Washington, USA	2011	10.1364/OL.36.000409	Yes*
113	Spin Hall effect of light in metallic reflection	N. Hermosa, A.M. Nugrowati, A. Aiello, J.P. Woerdman	Optics Letters	36, 3200-3202	Optical Society of America	Washington, USA	2011	10.1364/OL.36.003200	Yes*
114	Role of spatial coherence in Goos-Hanchen and Imbert-Fedorov shifts	A. Aiello, J. P. Woerdman	Optics Letters	36, 3151-3153	Optical Society of America	Washington, USA	2011	10.1364/OL.36.003151	No
115	Orbital angular momentum induced beam shifts	N. Hermosa, M. Merano, A. Aiello, J.P. Woerdman	Proceedings of SPIE	7950, 79500F, 1-7	SPIE	Bellingham, USA	2011	10.1117/12.876253	Yes*
116	Engineering nonlinear optic sources of photonic entanglement	J. P. Torres, K. Banaszek, I. A. Walmsley	Progress in Optics	56, 227-331	Elsevier	Oxford, UK	2011	10.1016/B978-0-444-53886-4.00005-8	No
117	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	AIP Publishing	Melville, NY, USA	2010	10.1063/1.3527083	Yes*
118	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	Optical Society of America	Washington, USA	2010	10.1364/OE.18.027205	Yes

119	Generation of hybrid polarization-orbital angular momentum entangled states	E. Nagali, F. Sciarrino	Optics Express	18, 18243-18248	Optical Society of America	Washington, USA	2010	10.1364/OE.18.018243	Yes
120	Demonstration of a quasi-scalar angular Goos–Hänchen effect	M. Merano, N. Hermosa, A. Aiello, J. P. Woerdman	Optics Letters	35, 21, 3562-3564	AIP Publishing	Melville, NY	2010	10.1364/OL.35.003562	Yes*

*available on a institutional repository and on the PHORBITECH website
** for most papers for which there is no open access available, there still is an open preprint version on the arXiv data base (at http://arxiv.org)

Section A – Table A2: List of all dissemination activities

NO.	Type of activities	Main Leader	Title	Date / period	Place	Type of Audience	Size of Audience	Countries addressed
1	156 communications to conferences (seminar, talks…)	UROM, UNAP	(see project periodic reports for detailed list)			Scientific Community (higher education, Research), Civil Society		
2	120 of scientific publications on peer-reviewed journals	UROM, UNAP	(see Table A1 for detailed list)			Scientific Community (higher education, Research)		
3	Video	UROM, UNAP	PHORBITECH Highlights posted on you tube at http://www.youtube.com/watch?v=JPmmEBntZBY	October 2013		Scientific Community (higher education, Research), Civil Society, Media		
4	Workshop	UNAP, UGLAS	PHORBITECH Workshop	6 June 2013	Glasgow (UK)	Scientific Community (higher education, Research)	40	
5	Oral session in a scientific Conference	UGLAS, UNAP	PHORBITECH oral session “OAM toolbox” at ICOAM 2013 Conference	4 June 2013	Glasgow (UK)	Scientific Community (higher education, Research)	90	
6	Poster session in a scientific Conference	UGLAS, UNAP	PHORBITECH poster session “OAM toolbox” at ICOAM 2013 Conference	3 June 2013	Glasgow (UK)	Scientific Community (higher education, Research)	90	
7	Workshop	ULEID	20-Years Orbital Angular Momentum of Light Symposium	12 September 2012	Leiden (The Netherlands)	Scientific Community (higher education, Research)	40	

8	Workshop	UNAP	Singular optics and its applications to modern physics at The Abdus Salam International Centre for Theoretical Physics (ICTP)	May 30–June 3, 2011	Trieste (Italy)	Scientific Community (higher education, Research)		
9	Workshop	UROM	ENTANGLEMENT, QUANTUM INFORMATION and the QUANTUM – to – CLASSICAL TRANSITION at the Accademia Nazionale dei Lincei by Fabio Sciarrino	5-7 May, 2011	Rome (Italy)	Scientific Community (higher education, Research)		
11	Logo	UROM, UNAP	PHORBITECH logo	May 2011				
12	Website	UROM, UNAP	PHORBITECH website	May 2011				
13	Leaflet	UNAP, UROM	PHORBITECH Results	May 2013		Scientific Community (higher education, Research)		
14	Poster	UNAP, UROM	PHORBITECH Results	May 2013				
15	Leaflet	UNAP	PHORBITECH Project Aims	Septem ber 2011		Scientific Community (higher education, Research)		
16	Publication	UNAP	PHORBITECH On FET Newsletter			Scientific Community (higher education, Research)		
17	Web	UNAP, UROM	Wikipedia Page On Orbital Angular Momentum (OAM)			Scientific Community (higher education, Research), Civil Society, Media		
18	Web	UNAP, UROM	Wikipedia Page On Light Spin Angular Momentum (SAM)			Scientific Community (higher education, Research), Civil Society, Media		

19	Web	UNAP, UROM	Wikipedia Page On Angular Momentum Of Light			Scientific Community (higher education, Research), Civil Society, Media		
20	Video	UGLAS	Optical tweezers and twisted beams of light			Scientific Community (higher education, Research)		
21	Publication	ICFO	News & Views Article Optical communications: Multiplexing twisted light			Scientific Community (higher education, Research)), Civil Society, Media		
22	Press release and press articles	UROM, URIO	Related to Photonic polarization gears for ultra-sensitive angular measurements. V. D'Ambrosio, N Spagnolo, L Del Re, S. Slussarenko, Y. Li, L. Chuan Kwek, L. Marrucci, S. P. Walborn, L. Aolita and F. Sciarrino. Nature Communications 4: 2432 (2013) http://www.icfo.eu/newsroom/news2.php?id_news=2087&subsection=home http://www.sbfisica.org.br/v1/index.php?option=com_content&view=article&id=499	September 2013		Scientific Community (higher education, Research), Civil Society, Media		

23	Press articles	UROM	Related To: Experimental Implementation Of A Kochen-Specker Set Of Quantum Tests. V. D'Ambrosio, I. Herbauts, E. Amselem, E. Nagali, M. Bourennane, F. Sciarrino, A. Cabello. Phys. Rev. X 3, 011012 (2012)	April 2013		Scientific Community (higher education, Research)), Civil Society, Media		
24	Press release and press articles	UNAP	Related To: Joining The Quantum State Of Two Photons Into One. C. Vitelli, N. Spagnolo, L. Aparo, F. Sciarrino, E. Santamato, L. Marrucci. Nature Photonics 7, 521–526 (2013) http://www.news.unina.it/dettagli_area.jsp?area=IN%20ATENEO&ID=13605	May 2013		Scientific Community (higher education, Research), Civil Society, Media		
25	Press release and press articles	UNIVBRIS	Related To: Calculating Unknown Eigenvalues With A Quantum Algorithm. X.Q. Zhou, P. Kalasuwan, T.C. Ralph, J.L. O'Brien. Nature Photonics 7, 223–228 (2013) http://www.bris.ac.uk/news/2013/9162.html	February 2013		Scientific Community (higher education, Research), Civil Society, Media		
26	Press release and press articles	UNIVBRIS	Related To: A Quantum Delayed-Choice Experiment. A. Peruzzo, P. Shadbolt, N. Brunner, S. Popescu, J.L. O'Brien. Science 338; 6107 :634-637 (2012) http://www.bristol.ac.uk/news/2012/8889.html	November 2012		Scientific Community (higher education, Research), Civil Society, Media		

27	Press release and press articles	UNIVBRIS	Related To: Integrated Compact Optical Vortex Beam Emitters X. Cai, J. Wang, M.J. Strain, B. Johnson-Morris, J. Zhu, M. Sorel, J.L. O'Brien, M.G. Thompson, S.T. Yu. Science. 338(6105):363-6 (2012) http://www.bristol.ac.uk/news/2012/8870.html	October 2012		Scientific Community (higher education, Research), Civil Society, Media		
28	Press release and press articles	UNAP	Related To: Ambrosio Et Al. “Light-Induced Spiral Mass Transport In Azo-Polymer Films Under Vortex-Beam Illumination”, Nature Communication 3, Article No. 989, 2012 http://www.stampa.cnr.it/docUfficioStampa/comunicati/italiano/2012/Agosto/66_AGO_2012.HTM	August 2012		Scientific Community (higher education, Research), Civil Society, Media		
29	Press release and press articles	UROM	Related To: D'Ambrosio Et Al. “Complete Experimental Toolbox For Alignment-Free Quantum Communication”, Nature Communication 3, 961, 2012 http://www.phorbitech.eu/attache/file/0b_Bozza%20comunicato%20Stampa_LaSapienza.pdf	July 2012		Scientific Community (higher education, Research), Civil Society, Media		

30	Press articles	ICFO	Related To: Hendrych Et Al. “Experimental Estimation Of The Dimension Of Classical And Quantum Systems”, Nature Physics 8, 588–591 (2012)	July 2012		Scientific Community (higher education, Research), Civil Society, Media		
31	Press release and press articles	UNAP	Related To: Karimi Et Al.“Spin-To-Orbital Angular Momentum Conversion And Spin-Polarization Filtering In Electron Beams”, Phys. Rev. Lett.,(2012) http://www.stampa.cnr.it/documenti/comunicati/italiano/2012/febbraio/12_feb_2012.htm	February 2012		Scientific Community (higher education, Research), Civil Society, Media		
32	Press release and press articles	UGLAS	Related To: Franke-Arnold Et Al. “Rotary Photon Drag Enhanced By A Slow-Light Medium”, Science 333, 65-67, 1 July 2011 http://www.gla.ac.uk/colleges/scienceengineering/newsandevents/2011archive/june/headline_204252_en.html	July 2011		Scientific Community (higher education, Research), Civil Society, Media		

Section B – Table B1: List of applications for patents, trademarks, registered designs, etc.

B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights[1]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)
Patent	YES	Filed June 03, 2013		Ultra-sensible photonic tiltmeter utilizing the orbital angular momentum of the light, and relevant angular measurement method	Università Degli Studi Di Roma “La Sapienza”, Università Degli Studi Di Napoli “Federico II”, ICFO – Institut de Ciences Fotoniques, Universidade Federal do Rio de Janeiro, National University of Singapore

[1] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Section B – Table B2: List of exploitable foreground

Type of Exploitable Foreground[1]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[2]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	*Holographic multiplexers*	NO		*Software for SLM control*	*C26.7 - Manufacture of optical instruments and photographic equipment*			University of Glasgow
General advancement of knowledge	*OAM light generation in spontaneous parametric down conversion*	NO		*Optical technology for high-rate high-dimensionality entangled photon pair generation*	*C26.7 - Manufacture of optical instruments and photographic equipment* *M72 - Scientific research and development*			ICFO – Institut de Ciences Fotoniques, University of Leiden
Commercial exploitation of R&D results	*Upgraded q-plate devices and associated optical systems*	NO		*Optical elements for spatial mode profiling or multiplexing (input)*	*C26.7 - Manufacture of optical instruments and photographic equipment* *C26.3 - Manufacture of communication equipment*		*Original patent on q-plate (filed before PHORBITECH)*	Università di Napoli Federico II, Università di Roma La Sapienza
Commercial exploitation of R&D results	*Photonic polarization gear*	NO		*Remote, non-contact sensing of roll rotation angles*	*C28 - Manufacture of machinery and equipment n.e.c.*		*Italian Patent number RM2013A000318 filed on June 03,*	Università Degli Studi Di Roma "La Sapienza", Università Degli Studi Di Napoli "Federico II", ICFO

[1] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.
[2] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

Type of Exploitable Foreground[1]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[2]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
					C26.7 - Manufacture of optical instruments and photographic equipment		*2013*	– Institut de Ciences Fotoniques, Universidade Federal do Rio de Janeiro, National University of Singapore
Commercial exploitation of R&D results	*Free-space / guided-mode integrated optical coupler*	YES		*Optical technology for coupling guided modes in integrated optical system to different free-space spatial modes*	*C26.7 - Manufacture of optical instruments and photographic equipment* *C26.3 - Manufacture of communication equipment*			University of Bristol
Commercial exploitation of R&D results	*Spatial-mode efficient sorter*	NO		*Optical system for spatial mode multiplexing (output)*	*C26.7 - Manufacture of optical instruments and photographic equipment* *C26.3 - Manufacture of communication equipment*			University of Glasgow
General advancement of knowledge	*Atomic trapping and phase storage*	NO		*Improved magneto-optical trapping and system for optical phase storage*	*C26.7 - Manufacture of optical instruments and photographic equipment*			University of Glasgow

Type of Exploitable Foreground[1]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[2]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	*Toolbox for alignment-free quantum communication*	NO		*Optical system for quantum communication without need for alignment*	*C26.7 - Manufacture of optical instruments and photographic equipment* *C26.3 - Manufacture of communication equipment*			Università di Roma La Sapienza, Università di Napoli Federico II, Universidade Federal do Rio de Janeiro, ICFO – Institut de Ciences Fotoniques

Further details on the exploitable foreground:

Holographic multiplexers

- Its purpose: reshaping an incoming laser beam so as to obtain any desired Laguerre-Gaussian mode or superposition of modes at output
- How the foreground might be exploited, when and by whom: besides the academic/scientific sector (immediate use), the foreground may perhaps be exploited in a future communication technology using spatial-mode multiplexing to widen the channel bandwidth, or in a quantum communication technology, to prepare prescribed photonic states; the likely time-frame of these developments is 5-10 years (the multiplexing) and 10-20 years (the quantum communication); companies providing communication hardware (networks) would be interested in exploiting this foreground
- IPR exploitable measures taken or intended: no measures taken, the foreground has been made public;
- Potential/expected impact (quantify where possible): immediate impact in the further advancement of knowledge, possible medium-term impact in the communication industry sector, if fully realized it may be huge (billions of euros or even tens of billions) and would imply economical growth for the whole society

OAM light generation in spontaneous parametric down conversion

- Its purpose: generating photon pairs at high rate and with prescribed quantum properties (entanglement, or other) in polarization and spatial-mode spaces
- How the foreground might be exploited, when and by whom: as a standard light source for carrying out scientific experiments of quantum information technology, in the next 1-2 years, mainly the academic / scientific sector; possibly, this technology may become useful also for future quantum communication industries (possible commercial use in 10-20 years)
- Potential/expected impact (quantify where possible): impact in the further advancement of knowledge, possible long-term impact in future communication industry (hard to quantify)

Upgraded q-plate devices and associated optical systems

- Its purpose: reshaping an incoming laser beam so as to obtain a structured azimuthal mode or a vector beam (close to the true eigenstates of few-mode optical fibers) or superposition of these modes
- How the foreground might be exploited, when and by whom: besides the academic/scientific sector (immediate use), the foreground can be exploited in a future communication technology exploiting spatial-mode multiplexing to widen the channel bandwidth, particularly as input couplers for optical fibers, or in a quantum communication technology, to prepare or read photonic states; the likely time-frame of these developments is 5-10 years (the multiplexing) and 10-20 years (the quantum communication); companies providing communication hardware (networks) would be interested in exploiting this foreground
- IPR exploitable measures taken or intended: a patent is already present on the main q-plate concept, by one of the consortium partners
- Further research necessary, if any: device optimization
- Potential/expected impact (quantify where possible): immediate impact in the further advancement of knowledge; the impact in the communication industry sector is uncertain and medium-long term, but if fully realized it may be huge (billions of euros or even tens of billions per year) and would imply income for the patent owners and economical growth for the whole society

Photonic polarization gear

- Its purpose: traducing a mechanical rotation into an amplified rotation of the optical polarization of a light beam
- How the foreground might be exploited, when and by whom: besides the academic/scientific sector (immediate use), the foreground can be exploited for developing a tool providing high-precision non-contact, possibly long-distance, measurements of the rotation angle of a mechanical stage relative to a fixed reference; a product development and its commercialization may be expected within the next 5 years; this product may be of interest of companies specializing in automation
- IPR exploitable measures taken or intended: a patent has been filed by the reported organizations
- Further research necessary, if any: a technical development work may be needed to optimize the device for specific motorized stages
- Potential/expected impact (quantify where possible): immediate impact in the further advancement of knowledge; the impact in the precision automation industry is uncertain and medium-term, but if successful it can be significant (hundreds thousands or even millions of euros per year) and would imply possible income for the patent owner organizations, economic growth for the society at large

Free-space / guided-mode integrated optical coupler

- Its purpose: coupling guided modes in integrated optical systems into free-space azimuthally structured modes or vector beams
- How the foreground might be exploited, when and by whom: besides the academic/scientific sector (immediate use), the foreground can be exploited in a future communication technology exploiting spatial-mode multiplexing to widen the channel bandwidth and in the photonic/electronic industry to develop integrated optical or hybrid processors; the likely time-frame of these developments is 10-20 years; electronic companies and companies providing communication hardware (networks) would be interested in exploiting this foreground
- Further research necessary, if any: a full applicability will require additional research and development work (1-3 years)
- Potential/expected impact (quantify where possible): immediate impact in the further advancement of knowledge; the impact in the electronic and communication industry sectors is uncertain and medium-long term, but if fully realized it may be huge (billions of euros)

and would imply significant economical growth for the whole society

Spatial-mode efficient sorter

- Its purpose: splitting the incoming light into different spatial channels, depending on the input mode azimuthal structure, with minimal losses
- How the foreground might be exploited, when and by whom: besides the academic/scientific sector (immediate use), the foreground can be exploited in a future communication technology exploiting spatial-mode multiplexing to widen the channel bandwidth, particularly as output couplers for optical fibers, or in a quantum communication technology, to read photonic states; the likely time-frame of these developments is 5-10 years (the multiplexing) and 10-20 years (the quantum communication); companies providing communication hardware (networks) would be interested in exploiting this foreground
- Further research necessary, if any: device optimization for specific applications
- Potential/expected impact (quantify where possible): immediate impact in the further advancement of knowledge; the impact in the communication industry sector is uncertain and medium-long term, but if fully realized it may be huge (billions of euros or even tens of billions per year) and would imply significant economical growth for the whole society

Atomic trapping and phase storage

- Its purpose: high-density trapping of atoms and storage of optical-phase information
- How the foreground might be exploited, when and by whom: useful for carrying out scientific experiments of quantum information technology and atomic physics, mainly by the academic / scientific sector; possibly, this technology may become useful also for future quantum information industries (possible commercial use in 10-20 years)
- Further research necessary, if any: yes, depending on the specific application
- Potential/expected impact (quantify where possible): impact in the further advancement of knowledge, possible long-term impact in future

quantum-information industry (hard to quantify)

Toolbox for alignment-free quantum communication

- Its purpose: encoding/decoding the quantum information in rotation-invariant states, so as to make the process independent of the relative alignment of transmitting and receiving units
- How the foreground might be exploited, when and by whom: besides the academic/scientific sector (immediate use), the foreground can be exploited in a future quantum communication technology, in particular a possible satellite-based worldwide network; the likely time-frame of these developments is 15-30 years; companies providing communication hardware (networks) would be interested in exploiting this foreground
- IPR exploitable measures taken or intended: no measures taken
- Further research necessary, if any: yes, optimization for specific applications
- Potential/expected impact (quantify where possible): immediate impact in the further advancement of knowledge; the impact in the communication industry sector is uncertain and long term, but if fully realized it may be significant (tens of millions of euros) and would imply economical growth for the whole society

Report on societal implications

A General Information *(completed automatically when **Grant Agreement number** is entered.*

Grant Agreement Number:	255914
Title of Project:	A Toolbox for Photon Orbital Angular Momentum Technology
Name and Title of Coordinator:	Lorenzo Marrucci, Professor

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	NO
2. Please indicate whether your project involved any of the following issues (tick box) :	
RESEARCH ON HUMANS	
• Did the project involve children?	NO
• Did the project involve patients?	NO
• Did the project involve persons not able to give consent?	NO
• Did the project involve adult healthy volunteers?	NO
• Did the project involve Human genetic material?	NO
• Did the project involve Human biological samples?	NO
• Did the project involve Human data collection?	NO
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	NO
• Did the project involve Human Foetal Tissue / Cells?	NO
• Did the project involve Human Embryonic Stem Cells (hESCs)?	NO
• Did the project on human Embryonic Stem Cells involve cells in culture?	NO
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	NO
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	NO

• Did the project involve tracking the location or observation of people?	NO
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	NO
• Were those animals transgenic small laboratory animals?	NO
• Were those animals transgenic farm animals?	NO
• Were those animals cloned farm animals?	NO
• Were those animals non-human primates?	NO
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	NO
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	-
DUAL USE	
• Research having direct military use	NO
• Research having the potential for terrorist abuse	NO

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	1
Work package leaders	1	4
Experienced researchers (i.e. PhD holders)	0	11
PhD Students	2	17
Other	5	11

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	13
Of which, indicate the number of men:	9

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project? | | Yes

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective → Very effective
X	Design and implement an equal opportunity policy	○ ○ X ○ ○
X	Set targets to achieve a gender balance in the workforce	○ X ○ ○ ○
❑	Organise conferences and workshops on gender	○ ○ ○ ○ ○
X	Actions to improve work-life balance	○ ○ X ○ ○
○	Other:	

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

X No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

X Yes- please specify: PhD students

○ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

X Yes- please specify: website, Wikipedia pages, video, leaflets, FET newsletter, press articles

○ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

X Main discipline[1]: Physical sciences

X Associated discipline[1]: Electrical engineering, electronics

X Associated discipline[1]: Other engineering sciences

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*

○ Yes
X No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

○ No

○ Yes- in determining what research should be performed

○ Yes - in implementing the research

○ Yes, in communicating /disseminating / using the results of the project

[1] Insert number from list below (Frascati Manual).

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	O X	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

- O No
- O Yes- in framing the research agenda
- X Yes - in implementing the research agenda
- X Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- O Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- X Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- O No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights <u>Information Society</u> Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy <u>Research and Innovation</u> <u>Space</u> Taxation Transport	

13c If Yes, at which level? ○ Local / regional levels ○ National level X European level X International level	

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**120**
To how many of these is open access[1] provided?	**86**
How many of these are published in open access journals?	**46**
How many of these are published in open repositories?	**40**
To how many of these is open access not provided?	**34**
Please check all applicable reasons for not providing open access:	
X publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available X no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[2]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*		**1**
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**
17. How many spin-off companies were created / are planned as a direct result of the project?		**0**
Indicate the approximate number of additional jobs in these companies:		

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑	Increase in employment, or	❑	In small & medium-sized enterprises
❑	Safeguard employment, or	❑	In large companies
❑	Decrease in employment,	❑	None of the above / not relevant to the project
X	Difficult to estimate / not possible to quantify		

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:* **= 29**

[1] Open Access is defined as free of charge access for anyone via Internet.
[2] For instance: classification for security project.

Difficult to estimate / not possible to quantify	❑

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

O Yes X No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

X Yes O No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

X	Press Release	X	Coverage in specialist press
❑	Media briefing	X	Coverage in general (non-specialist) press
❑	TV coverage / report	X	Coverage in national press
❑	Radio coverage / report	X	Coverage in international press
X	Brochures /posters / flyers	X	Website for the general public / internet
X	DVD /Film /Multimedia	❑	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

❑	Language of the coordinator	X	English
❑	Other language(s)		

***Question F-10*:** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES
1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]
1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
1.3 Chemical sciences (chemistry, other allied subjects)
1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)
1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY
2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial

chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]