Sección Especial en Óptica Cuántica / Special Section on Quantum Optics

# Quantum engineering of light

## Ingeniería cuántica de la luz

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Recibido / Received: 30/10/2010. Aceptado / Accepted: 15/12/2010

**ABSTRACT:**

Our group, Quantum Engineering of Light is part of the ICFO-Institut de Ciencies Fotoniques, a research institute located nearby the city of Barcelona. The areas of work of the group are nonlinear and quantum optics. The group aims at generating, tailoring, using and detecting new types of classical and quantum light for (a) exploring fundamental aspects of quantum theory and (b) implementing new applications that might require light with specific features. We consider new ways of tailoring photonic entanglement, through the implementation of new configurations that make use of spontaneous parametric down-conversion (SPDC). Along these lines, we are especially interested in the orbital angular momentum of photons to encode quantum information in multidimensional Hilbert spaces.

**Keywords:** Quantum Optics, Nonlinear Optics, Entanglement, Orbital Angular Momentum, Coherence.

**RESUMEN:**

Nuestro grupo, Ingeniería Cuántica de Luz, forma parte del ICFO- Institut de Ciencies Fotoniques, instituto de investigación localizado cerca de la ciudad de Barcelona. Las áreas de trabajo del grupo están centradas en óptica cuántica y no lineal. El grupo persigue la generación, control, utilización y detección de luz clásica y cuántica para (a) explorar aspectos fundamentales de la teoría cuántica y (b) implementar nuevas aplicaciones que puedan requerir luz con características específicas. Consideramos dos tipos de producir atrapamiento fotónico a través de la implementación de nuevas configuraciones que emplean conversiones paramétricas espontáneas (SPDC). De entre estas líneas, estamos especialmente interesados en el uso del momento angular orbital de fotones para codificar información cuántica en espacios de Hilbert multidimensionales.

**Palabras clave:** Óptica Cuántica, Óptica no Lineal, Atrapamiento, Momento Angular Orbital, Coherencia.

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## 1. Introduction

### 1.1 The Institute: ICFO-Institut de Ciències Fotòniques

Our group develops its work in ICFO - The Institute of Photonic Sciences (http://www.icfo.es), a research institution founded in 2002 which is currently associated to the Universitat Politecnica de Catalunya.

ICFO is located in the Mediterranean Technology Park, in the Barcelona metropolitan area. Its aim is to become a leading, world-class, wide-scope research centre in optical sciences and technology. The double mission of the center is to push the frontiers of research and to train technologists by equipping them with unique technical and personal skills. ICFO hosts a variety of research groups working in a variety of fields that include quantum information technologies, health, environment, safety, energy, nano-photonic devices, remote sensors, optoelectronics, integrated optics, ultrafast optics, bio-photonics and biomedical optics. ICFO researchers participate very actively in research projects and networks funded by national and international funding agencies.

One of the main areas of activity in ICFO is Quantum Optics and Quantum Information. Along these lines, there are several groups that address different aspects of these areas: Quantum information theory, quantum memories, quantum computation, quantum communications, and the generation and distribution of entanglement.

### 1.2 The group: Quantum Engineering of Light

Our research can be included in that fuzzy area between nonlinear and quantum optics, where nonlinear optics provides most of the experimental tools that we use, while quantum theory provides the fundamental tools to describe main results. It is also a mix of fundamental physics and quantum photonic engineering.

Even though we address fundamental issues such as entanglement and coherence, we can say that we devote most efforts to engineer sources of light.

The three words that compose the name of the group succinctly summarize the main traits of our research. Light is the main tool of our research. We use streams of photons, even at the single photon level, (a) to explore quantum theory and (b) to implement applications that might require specific types of quantum or classical light. In other words, we aim at generating, tailoring, using and detecting (*quantum engineering*) new types of classical and quantum light.

 

The activities of the group combine theory and experiments. These activities are divided in three main areas of interest, which notwithstanding might often overlap:

1) The orbital angular momentum of light.
2) Quantum engineering of light.
3) From quantum optics to biology.

## 2. The orbital angular momentum of light

Light carries energy, and both linear and angular momenta. In most practical scenarios, the angular momentum can be decomposed into two independent contributions: the spin contribution associated with polarization, and the orbital contribution associated with the spatial shape of the light intensity and phase. Optical vortices, namely beams that exhibit a corkscrew-like phase spiraling around their axis, are the simplest kind of light patterns that carry orbital angular momentum (see Fig. 1). Optical vortices are given many different names: optical tornadoes, vortex beams, twisted light...

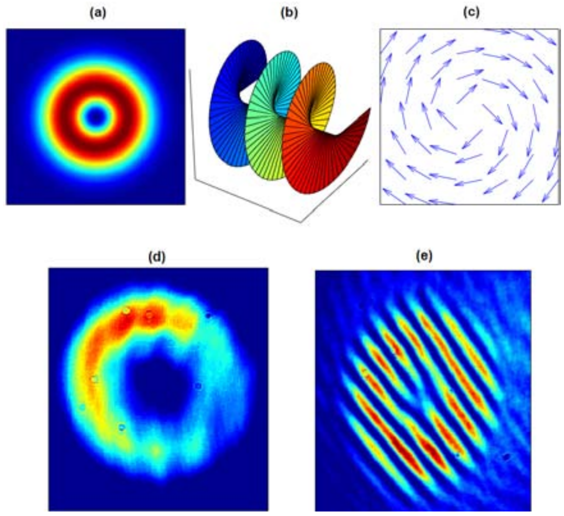


Fig. 1: Properties of the orbital angular momentum modes. Panels (a) and (d) display the typical transverse intensity pattern of a light beam with orbital angular momentum. (a) is a theoretical plot, while (d) corresponds to the experimentally obtained image of a light beam with OAM generated with a computer-generated hologram. The light beam exhibits a dark spot in the center, and a ring-like intensity profile. The phase of the beam twists around the central dark spot, producing an staircase-like phase wavefront, as depicted in (b). Such spiraling phase makes that the local momentum of the beam mimics the velocity pattern of a tornado vortex fluid, as shown in (c), a similarity that causes these singular spots to be named optical vortices. To visualize such a spiral phase, one can observe the interference of the light beam with OAM with a vorticityless plane wave propagating at a slightly different angle. Panel (e) show the typical interference pattern obtained for *m*=1, as revealed by the characteristic fork-like structure. From [1].

Orbital angular momentum represents a fundamentally new extra degree of freedom that researchers are exploring for a variety of novel natural phenomena as well as far-reaching applications. The orbital angular momentum concept holds also for single photons in the quantum world [1]. While the spin angular momentum is a workhorse of quantum information, the orbital part has been added to the toolkit only recently, affording a wealth of new opportunities.

In quantum optics, the orbital angular momentum has received a great deal of attention since 2001 [2,3]. The OAM of photons opens the use of multidimensional quantum states, which enables the exploration of deeper quantum features and might guide the elucidation of proof-of-principle capacity-increased quantum information processing schemes. The dimensionality of the quantum states generated is determined by its *spiral bandwidth* [4], and different techniques have been considered to control it [5].

Of particular interest is the generation of paired photons entangled in OAM. Entanglement is an inherently quantum mechanical phenomenon with no analogue in classical physics. Spontaneous parametric down-conversion (SPDC), the process by which two low-frequency photons (signal and idler) are generated from a single high-frequency photon that belongs to an intense pump laser, when it interacts with a non-linear crystal, is a reliable source for generating entangled pairs of photons. Such photon pairs not only can be polarization entangled, but can also exhibit OAM entanglement with specific measurable correlations [6].

The use of the OAM of photons turns out to be potentially advantageous also in different scenarios. A major application of optics is imaging all types of structural, physical, chemical and biological features of matter. Techniques based on most known properties of light have been developed over the years to remotely acquire information about such features. They include the spin angular momentum, encoded in the polarization, but not yet the orbital angular momentum encoded in its spiral spectrum. We are interested in showing how the orbital angular momentum spectra of a light beam can be used for retrieving specific properties of targets that might be difficult otherwise [7], to image a variety of intrinsic and extrinsic properties encoded, e.g., in phase and amplitude gradients, dislocations or delays.

The concept comprises illuminating the target with a light beam with a convenient spatial shape, expanding the reflected or transmitted signal into the spiral eigenstates of orbital angular momentum, and acquiring information of the target by analyzing the corresponding spiral spectrum. The shape of the spiral spectrum, its bandwidth, or the weights of prescribed eigenstates carry the sought after information. A principal difference between the spin angular momentum and the orbital angular momentum is that the former forms two-dimensional light states (e.g., vertical o horizontal polarization) while the latter encodes information in infinite-dimensional states, hence providing multi-dimensional acquisition alphabets.

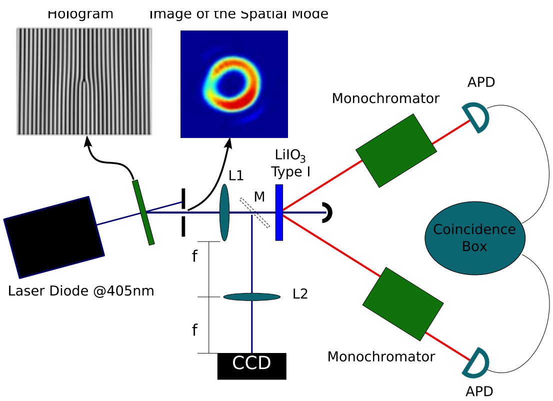


Fig. 2: Sketch of the experimental setup. The LG mode is produced by a computer generated hologram. Photos of the hologram and the diffracted beam are shown. The size of the beam impinging into the crystal is controlled via L1. The downconverted beams are collected into single mode optical fibers and sent through a pair of computer controlled monochromators and APD detectors. Single and coincidence counts are recorded with standard electronics. M is a flipping mirror used to switch from the frequency correlation measurement to the transverse momentum distribution measurement. From [8].

## 3. Quantum engineering of light

One of the goals of quantum optics is to implement new sources of quantum light that allow tunable control of the relevant photonic properties. The most appropriate type of frequency correlations between paired photons and bandwidth depends on the specific quantum information application under consideration. Heralded single photons with a high degree of quantum purity can be obtained by a generation of frequency-uncorrelated paired photons. The use of frequency-correlated (anticorrelated) photons allows the erasing of the distinguishing information coming from the spectra when considering polarization entanglement.

The development of methods for the generation of entangled photon pairs (biphotons) with a specfic band width is also of great interest. Narrow bandwidth is important for the design of efficient atom-photon interfaces in quantum networks, long-distance quantum communications, or to enable direct measurements of temporal correlations with current photodetectors. On the other hand, some applications such as quantum optical coherence tomography and nonlinear microscopy require wide bandwidths. Wide bandwidths are a requisite for the generation of biphotons with very short correlation times and when high fluxes of biphotons are desired. A bandwidth of hundreds of terahertz can generate biphotons with a few femtoseconds of correlation time.

These short temporal biphotons are of particular interest in the fields of quantum metrology and for some protocols for timing and positioning measurements. Thanks to the strong correlations of the entangled photons that allow remote compensation of chromatic dispersion, the narrow temporal correlation embedded in the biphoton can be transmitted over large distances.

Our group has implemented in the last few years some techniques to control the frequency correlations and bandwidth of entangled photon pairs. One method [8] to tailor the waveform of the down-converted photons is to make use of noncollinear SPDC configurations (see Fig. 2). Contrary to the case of collinear SPDC, where the transverse spatial shape of the pump beam translates into specific features of the spatial waveform of the two-photon state, in non-collinear SPDC, the phase matching conditions inside the nonlinear crystal mediate the mapping of spatial features of the pump beam into the joint spectrum of the down-converted photons (see Fig. 3). This spatial-to-spectral mapping allows one to tune independently frequency correlations and the waveform. Non-collinear configurations has also been implemented for generating with high efficiency fully uncorrelated pairs of photons in all degrees for freedom [9].

Another method, which comes from a fruitful exchange of ideas between nonlinear and quantum optics applications [10], is based on the proper tailoring of the group velocities of all interacting waves through the use of beams with angular dispersion, i.e., pulses with pulse-front tilt [11,12]. Importantly, this technique works independently of the working frequency band and the nonlinear crystal used, and therefore it can be implemented in materials and frequency bands where conventional solutions do not hold. The scheme allows one to easily tune the frequency correlations by changing only the amount of the angular dispersion of the pump beam, with no further changes of the SPDC source (see Fig. 4).

The method can also be employed to enhance the bandwidth of paired photons as well [13], reducing correspondingly the correlation time of the photons. Recently, a joint collaboration between groups at Boston University, Stanford University and ICFO has demonstrated an alternative technique to enhance the bandwidth of paired photons generated in SPDC. The technique makes use of properly tailored longitudinally chirped quasi-matched (QPM) gratings [14]. The QPM grating not only allows to fulfill phase mismatch conditions, but also helps tailoring the frequency shape of the photons generated.

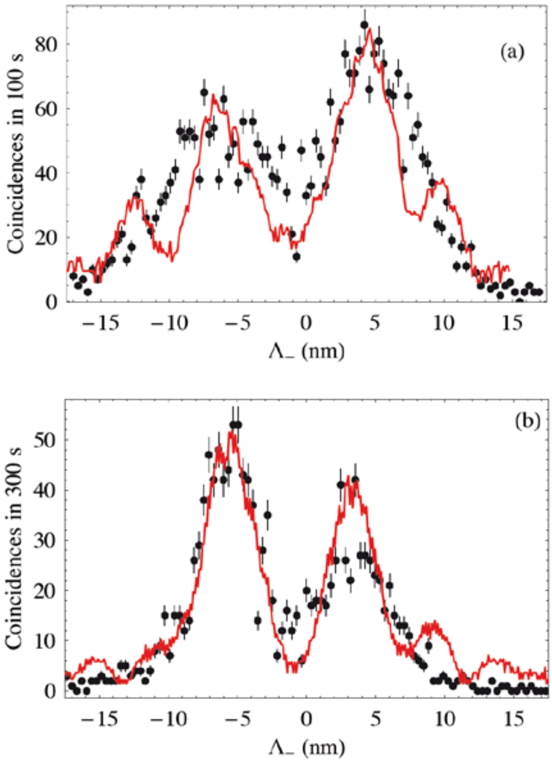


Fig. 3: Comparison of the measured spatial shape of the pump beam in the transverse wavevector domain (solid line), and the measured joint spectral intensity as a function of $\Lambda_-$ (dots). (a) The pump beam shape is modified with a hologram and, (b) The spatial shape is modified with a thin microscope slab. From [8].

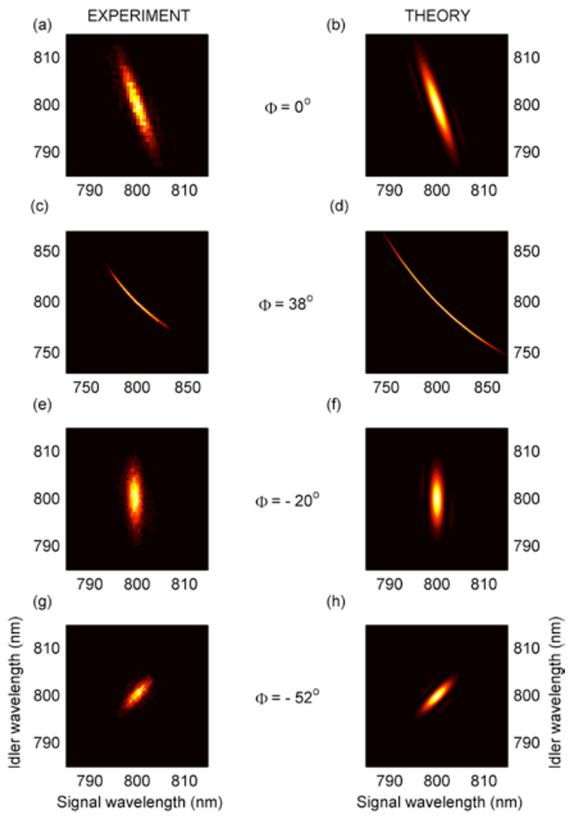


Fig. 4: Shape $S(\omega_s,\omega_i)$ of the frequency correlations measured experimentally (left column) and predicted theoretically (right column). (a) and (b): no tilt, $\Phi$=0º; (c) and (d): anticorrelated photons, $\Phi$=38º; (e) and (f): uncorrelated photons, $\Phi$=–20º; (g) and (h): correlated photons, $\Phi$=–52º. Pump-beam bandwidth: $\Delta\lambda_p$=2 nm. Non-linear crystal length: $L$=3.5 nm. From [10].

 

## 4. From quantum optics to biology

Light is routinely used to tailor atomic transitions to obtain full control of atoms and molecules. High resolution imaging of the chemical and physical properties of tissue is an area of interest that can benefit from all these techniques. Our interests are: (a) exploring how techniques routinely used in quantum optics to tailor the quantum state of atoms and molecules can be used as well for probing the presence of few molecules in situations of biological interest; (b) exploring if quantum coherence and entanglement play any significant role in the dynamics of certain biological processes, such as photosynthesis and the passive transport of ions through ion channels.

## 5. Conclusions

The group of ICFO - Institut de Ciencies Fotoniques *Quantum Engineering of Light*, led by Dr. Juan P. Torres (associate professor at the Universitat Politecnica de Catalunya since 1996) works in the area of nonlinear and quantum optics. It focus its research activities in three main areas: 1) Use of the orbital angular momentum of light, for encoding multidimensional quantum information and developing new techniques to probe substances of biological interest; 2) Quantum engineering of light, to explore fundamental aspects of quantum theory and implement new quantum optics applications that require specific types of light and 3) Translations of ideas from quantum optics to the realm of biology applications.

**Acknowledgements**

The work presented here is currently supported by the European Commission through the projects *Photon orbital angular momentum technologies* (PHORBITECH, FET-Open grant number 255914) and *Consortium Europe-Mexico for the development of applications in quantum information and communications* (FONCICYT, Project number 94142). It is also supported by the Government of Spain through the projects *Quantum optical information technology* (QOIT, Consolider Ingenio CSD2006-00019), and *Quantum optics technologies for enhancing the sensitivity of molecule detection systems* (QOTES, FIS2010-14831).

 