

Electro-optical photonic circuits for classical and quantum applications

Ph.D. Thesis Project

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At present there is growing scientific interest in the development of highly integrated photonic circuits [1]. This is motivated both by the ever-present need for faster and more functional optical devices for information networks and both by the need to miniaturize nonlinear optics and quantum optics apparatus. One important and open issue is how to achieve the miniaturization of functional optical circuits in full three-dimensional settings up to visible wavelengths. Controlling and guiding light deep in the volume requires strong nonlinear phenomena. In particular, electro-optic effects play a central role because they connect electrical and optical response, this paving the way to interfaced electronic and photonic hardware. Electro-optic effects in nature are commonly very weak, this makes the correct design of materials to use crucial. Photorefractive materials offer unique possibilities because in these the electro-optic response can be controlled optically.

My PhD research consists in the conception and realization of experiments that can allow us to explore opportunities provided by light matter interaction in the field of light modulation (section 1), illumination for imaging systems (section 2), simulation of nonlinear phenomena (section 3), application in quantum optics experiments (section 4 and 5) and the development of technologies to miniaturize and integrated these specific schemes. Following sections will briefly describe these aspects of my research, presenting some results obtained and issues that I am addressing.

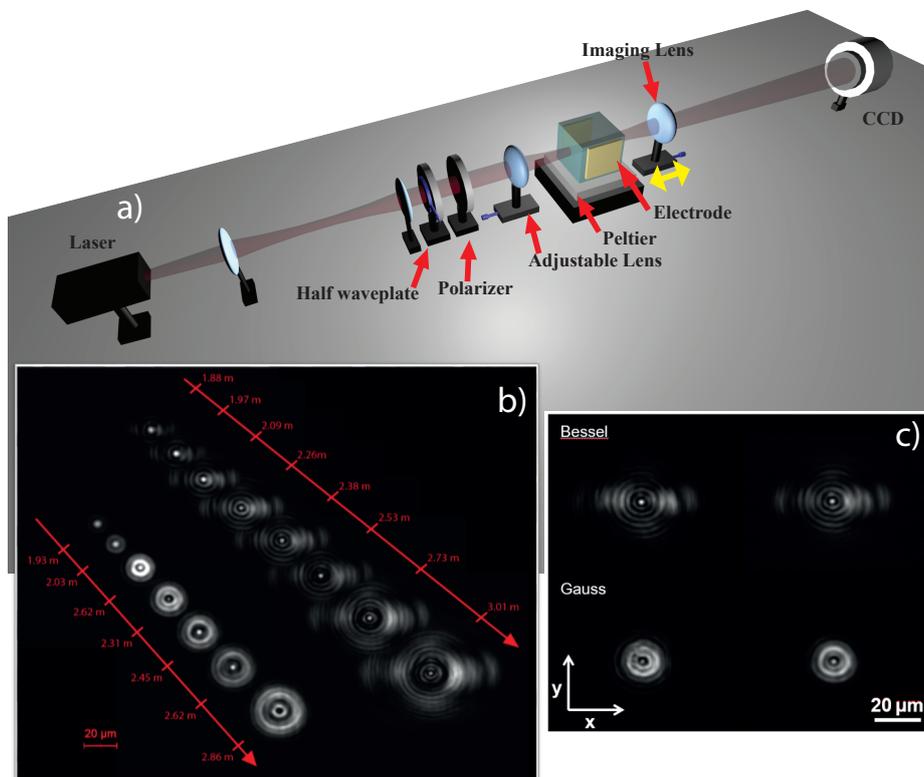


Figure 1: a) Scheme of experimental set-up. b) Comparison between propagation of a Gaussian beam in our inverted funnel waveguide with (top sequence) and without (bottom sequence) applied field for different propagation distances. c) Self reconstruction of beams after an obstacle (left column) compared with propagation in free space (right column).

1 Micrometric electro-optic Gaussian-to-Bessel beam converter

Photorefractive funnel waveguides [2] have proved capable of interesting properties: they are able to couple light beams irrespective of their wavelength, to act as tunable beam splitters and as a fast light shutter. In a recent experiment, we investigate a novel configuration of funnel waveguides, in which we are able to create a conical distributed index of diffraction that we term inverted funnel. The pattern acts as a miniaturized axicon lens that can be electrically activated, modulating the Gaussian beam passing through it, FIG.(1 a). In fact we have been able to generate Bessel beams from Gaussian beams simply by changing the bias electric field. Since the electro-optic effect can at once have nanosecond response times and furthermore be susceptible to miniaturization (we have proven a 30 x 30 microns transverse component with a millimetric propagation distance), the setup can in principle be miniaturized and integrated into optical circuits as a tunable light modulator. To prove the Bessel nature of those beams

we compare the diffraction properties of a free propagating Gaussian beam with those of the same beam modulated by the inverted funnel waveguide. FIG.(1 b) shows how when the beam is modulated it has an increased capacity to propagate without distortion. In the case reported, a Bessel beam with a $4.8\mu m$ central lobe suffers less distortion than a larger $7.5\mu m$ Gaussian beam. Further results are reported in FIG:(1 c) where we compare the self healing properties of a regular Gaussian beam and those of a Bessel beam by detecting the transmitted light with an obstacle along the path. The effect of the obstacle is negligible for the Bessel beam whereas it distorts the Gaussian beam. Our results demonstrate a novel technique for generating high quality Bessel beams with fast response, miniaturization and integrability.

2 Light Droplets

The ability of an optical system to image objects inside a full three-dimensional environment is ultimately dictated by diffraction and scattering, the latter being especially important in biological settings. At present, standard imaging methods in the visible can only penetrate a few hundreds of micrometers inside a biological tissue [3]. To overcome this, several modern techniques have been studied, infrared, ultrasound methods, optical coherence tomography and nonlinear optics. Bessel beams, in turn, provide a significant increase in the penetration depth without nonlinearity or wavelength depending effect. These are non-diffracting beams of light resulting from the interference of a set of plane waves. Ironically, it is this very non-diffracting nature with its enhanced penetration that makes them unsuitable for imaging in basic schemes, where an extended depth of focus naturally washes out axial resolution.

In our experiments, we achieve non-diffracting light fields with an effective finite depth of focus, comparable to that of a Gaussian beam that we term light droplets. A zeroth-order Bessel beam is formed by the monochromatic superposition of plane waves that propagate at a fixed angle θ with respect to a given axis z . Since the waves share the same wavevector component $k_z = k \cdot \cos(\theta)$, where $k = 2\pi/\lambda$ and λ is the wavelength, there are no phase shifts along the axis between the interfering plane waves. This gives the beams a z -invariant intensity distribution $I_1 = J_0(k_\perp \rho)^2$, where J_0 is the zeroth-order Bessel function and $\rho = \sqrt{x^2 + y^2}$ is the distance from the beam axis in the transverse x, y plane. To introduce z -dependence preserving the diffraction-free and self-healing properties, we superimpose n coaxial Bessel beams, each with a distinct value of θ_i ($i = 1, \dots, n$). The result is the light-droplet structure $I(z)_n = J_0(k_\perp \rho)^2 \left| \sum_{i=1}^n \exp(jk_z(\theta_i) \cdot z) \right|^2$ [5], an interference pattern with localized periodic light spots along the propagation.

The three-dimensional intensity distribution is investigated by imaging the beam profile for each plane along z axis. Results demonstrate that light droplets allow selective multi-point 3D localized illumination inside turbid volumes. Since the amplitude distribution in the Fourier space ultimately sets the location of the droplets, motionless scanning data acquisition of three dimensional images can be achieved streaming sequential annular patterns on a fast SLM.

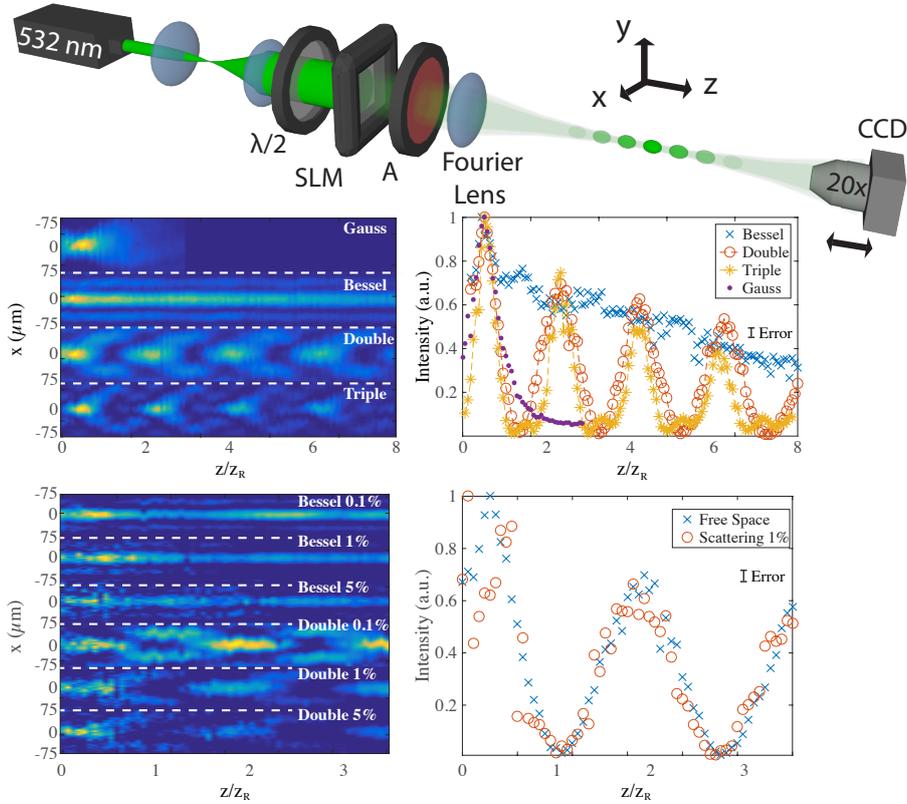


Figure 2: (top) Schematic of the optical setup. A Spatial-Light-Modulator (SLM) is used to modulate the amplitude of an expanded laser beam (532 nm) using a binary mask with multiple concentric annuli of different diameters, these determining the corresponding θ_i and the associated k -vectors. The droplet field is generated by a lens that performs a Fourier transform of the field distribution at the pupil plane where two co-propagating Bessel beams with $\theta_1 \neq \theta_2$ beat along the z axis. (center right) Beam intensity profiles along the z axis for a Gaussian beam, a Bessel beam and different light-droplet realizations, two and three annuli. (center left) reports the x - y integrated intensity distribution of the beams along the z axis. Light droplets in the $n = 3$ case show a more localized profile in z compared to the $n = 2$ case. (bottom) Data for propagation of Bessel and Double Bessel Beam in water-milk solution at different concentration as a demonstration of droplet self-healing in strongly scattering liquid volumes.

3 Artificial Non-Linearity

Funnel shaped index of refraction patterns in photorefractive crystals offer a versatile and multifunctional light manipulation technique [6, 7, 8]. Because of their ability to easily change diffraction with the applied voltage it is possible to create an artificial nonlinear effect. The idea is to collect the light from the funnel waveguide, analyze the image with a computer algorithm which produces a value of voltage to apply back to the funnel waveguide. Globally we have a

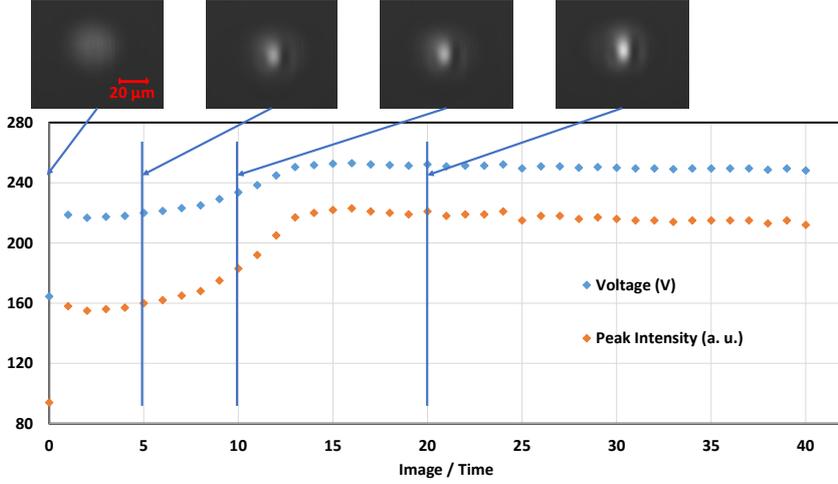


Figure 3: Observation of an artificial self focusing effect. (top) Beam profile of the first, fifth, tenth and twentieth image on the output facet of the crystal. (bottom) Peak intensity of images and corresponding applied voltage.

system able to forward feed forming an artificial nonlinearity with a programmable nonlinear response. A first observation of an artificial self focusing effect is shown in FIG: ([?]) were the system is programmed to apply a voltage according to:

$$\Delta V \sim K \cdot I_0 + H \cdot I_{-1} \quad (1)$$

Where I_0 and I_{-1} are the peak intensity of the current and previous image respectively while K and H are adjustable parameters we use for this test $K = H = 0.5$. In future steps, we will implement more complex non-linearity that not only depends on peak intensity but also on the shape of the beam, and we will exploit the property of funnel arrays. In fact, funnels can be grouped into clusters [8] and can be controlled independently so as to create a fully delocalized volume non-linearity.

4 Miniaturized electro-optic circuits for quantum optics applications

We are also interested in quantum optics experiments and in particular in how circuit reconfigurability and re-programmability using electro holography can be used to generate non classical state of light. Today there are accessible technologies for a wide range of coherent light sources, but good quality single photon sources like could atoms, ion in trap, quantum dot remain expensive and difficult to handle [?]. Common sources, such as lasers or diodes, give a Poissonian distribution of photons and must be strongly attenuated to reduce the probability of obtaining two or more photons at a time, the light remains in principle classical and the rate of emission of single photons is limited. To overcome these limitations an option is to use photon pairs from a parametric down conversion

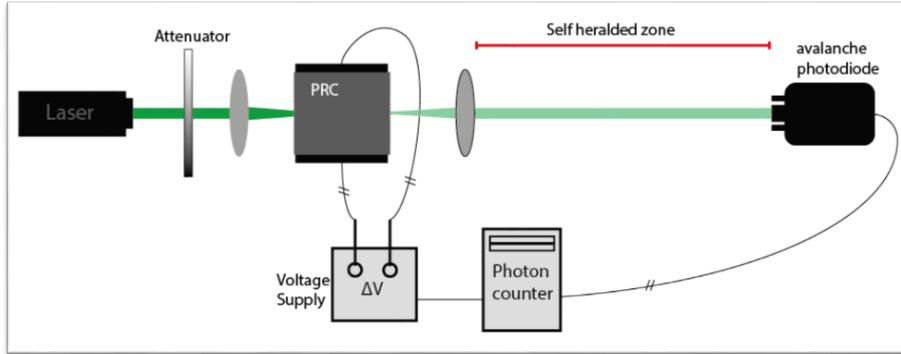


Figura 4: Set up for photon flux regularization using miniaturized electro-optic circuits

and use one photon of the correlated pair as a trigger for its companion (commonly called heralded single photons generation). Being able to electro-activate a funnel waveguide allows us to generate a very effective intensity modulation in conjunction with very short response time. These properties are interesting because they can be used to realise a fast electro-optic shutter to regularize a photon flux. So our aim is the use of funnel waveguides to modulate light at the single photon level, introducing artificially a dead time in the photo events so as to create a sub Poissonian distribution of photodetection. Specifically as shown in FIG.(4) we want to regularize a photon flux by interlocking in a funnel waveguide feedback loop, using a conventional dead time deletion process. The photon propagates through a funnel waveguide in a photo-refractive crystal (PRC in the figure) and enters in a regularized path where experiments can take place. The path ends in a photon counter that reveals the photon and sends a signal to the funnel waveguide to shut the light beam. Because of the fast response of electro-optic effect and of all the involved electronics, the whole loop is so fast that it is highly probable that just one photon at time is located inside the loop. Such a scheme would have the same features of the heralded generation scheme without the complications deriving by parametric down conversion. With the same set up it is also possible to demonstrate a non-linearity at single photon level, simply by programming a behavior of the funnel waveguide with the same principle used for artificial non-linearity experiments.

5 Entangle two system with a single particle

From a fundamental point of view we are interest in the nature of entanglement in single particle systems. Although a single particle cannot support two space-like measurements, it might interact with two distant systems, for example a photon with two atoms, and these could support a Bell-type experiment and hence be entangled [10]. This question is key both from a theoretical and practical perspective, since entanglement is at the basis of a wide range of state-of-the-art technological initiatives to realize quantum information devices. If a single particle could entangle two distant systems, this would allow quantum

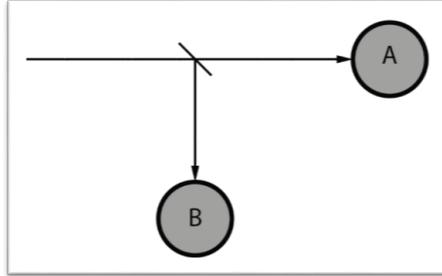


Figura 5: A photon split into two modes 1 and 2 supposedly entangling two distant atoms A and B within a cavities.

entanglement without the need for multi-particle interaction phenomena, such as parametric down-conversion in optics. We show that for reasons linked to reversibility of processes, single particle systems cannot show non local effects. The proof is not specific to photons and atoms. It holds equally well for any single particle and pair of distant microscopic bodies and it directly follows from first principles of quantum mechanics: the absence of entanglement between the internal degrees of freedom of two distant and initially uncorrelated systems persists, after interaction with a split single particle, as a consequence of the mere existence of translation motion, even if this is not observed. For the system shown in FIG. (5) the hidden variable is the momentum of the atom and the density matrix corresponds to a separable state (in its more general definition [11]), so the two atoms cannot be considered entangled. Our result corroborates the statement that there are only two ways to entangle A and B : I) Let A and B interact with one another and then we separate them. II) Swap the entanglement previously present in another two-particle system on the already remote A and B . All other experiments that involve correlations between the internal degrees of freedom of the particles are described by tracing over the translational degrees of freedom, leading to a disentangled mixed state.

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References

- [1] SPIE Optics + Optoelectronics 2015 conference. 13-16 April 2015. Prague, Czech Republic.
- [2] E. DelRe, B. Crosignani, P. Di Porto, E. Palange and A. J. Agranat Electro-optic beam manipulation through photorefractive needles. *Optics letters*, 27(24), 2188-2190 (2002).
- [3] P. J. Keller "Imaging Morphogenesis: Technological Advances and Biological Insights" *Science* 340, 6137 (2013).
- [4] J. Durnin, J.J. Miceli, and J. H. Eberly, "Diffraction-Free Beams", *Physical Review Letters* Vol 58, N 15 (1987).
- [5] F. Gori, G. Guattari, C. Padovani, "Bessel-Gauss beams." *Opt. Comm.* 64 (6), (1987).
- [6] E. DelRe, A. Pierangelo, E. Palange, A. Ciattoni, and A. J. Agranat, Beam shaping and effective guiding in the bulk of photorefractive crystals through linear beam dynamics, *Appl. Phys. Lett.* 91, 081105 (2007).
- [7] A. Pierangelo, E. DelRe, A. Ciattoni, E. Palange, A. J. Agranat, and B. Crosignani, Linear writing of waveguides in bulk photorefractive crystals through a two-step polarization sequence, *J. Opt. A. Pure Appl. Opt.* 10, 064005 (2008).
- [8] A. Pierangelo, A. Ciattoni, E. Palange, A. J. Agranat, and E. Del-Re, Electro-activation and electro-morphing of photorefractive funnel waveguides, *Opt. Express* 17, 2265922665 (2009).
- [9] B. Lounis and M. Orrit Single-photon sources. *Reports on Progress in Physics*, 68(5), 1129 (2005).
- [10] S. J. Van Enk, "Single-particle entanglement" *Phys. Rev. A* 72, 064306 (2005).
- [11] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, "Quantum entanglement" *Rev. Mod. Phys.* 81, 865 (2009).

Papers

- [1] D. Pierangeli, M. Ferraro, F. Di Mei, G. Di Domenico, C. E. M. de Oliveira, A. J. Agranat, and E. DelRe "Super-crystals in composite ferroelectrics" Nat. Comm. 7 (2016).
- [2] F. Di Mei, P. Caramazza, D. Pierangeli, G. Di Domenico, H. Ilan, A.J. Agranat, P. Di Porto, and E. DelRe "Observation of intrinsic negative-mass dynamics in guided light beams with a shape-sensitive nonlinearity" Accepted.
- [3] P. Di Porto, G. Di Domenico, F. Di Mei, B. Crosignani, and E. DelRe "Microscopic reversibility and no entanglement produced by a single particle" Phys. Rev. Lett. (2016). Submitted and Under Rieview.
- [4] G. Antonacci, G. Di Domenico, S. Silvestri, E. DelRe and G. Ruocco "Diraction-Free Light Droplets" Nat. Phot. (2016). Submitted and Under Rieview.
- [5] G. Di Domenico, J. Parravicini, G. Antonacci, E. DelRe "Demonstration of a miniaturized electro-optic Gaussian-to-Bessel beam converter" (2016). In preparation.