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Giuseppe Di Domenico

# Electro-optic Photonic Circuits

## From Linear and Nonlinear Waves in Nanodisordered Photorefractive Ferroelectrics

Doctoral Thesis accepted by
the University of Rome La Sapienza, Rome, Italy

Springer

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*This work is for Giulia,*
*who deserves a Ph.D. in being the best.*

# Supervisor's Foreword

An electrical circuit can be seen as a family of electric devices that act on flowing current; each device is based on different physical principles and realized in different materials; and all are integrated together on a single board. An optical circuit is exactly that a series of single optical devices pooled together to perform a given operation on propagating light. Giuseppe Di Domenico, in this present treatise, describes his exploration and development of a method to realize generic optical operations integrated and miniaturized inside one single bulk material. The starting point of his journey is a rather intriguing setting, a nanodisordered ferroelectric. While his final achievements, such as the ability to integrate an electro-optic Gaussian-to-Bessel beam converted into a miniscule slot of the, so to say, crystalline motherboard, are inspiring to an applicative eye, it is the journey itself that captures our attention. Choosing a material in an optical research initiative sometimes sets you along a wholly unexpected and adventurous path. This is certainly the case for potassium-lithium-tantalate-niobate and potassium-sodium-tantalate-niobate described here. The choice is generally between a well-known material with established industrial pedigree or a newly developed material with still unknown properties, but with the potential to make things work. To achieve a complete optical operation, you require an optical source, detection, guiding, fast modulation and steering, electronic control, polarization control, wavelength selectivity, and nonlinearity, all miniaturized in a full three-dimensional volume, where light has its edge on electronic circuits. Aside from light generation and detection, all the other ingredients are found in nanodisordered ferroelectrics, that is, ferroelectrics achieved by mixing different crystals into a single perovskite structure, a crystal that is actually a solid solution. A particularly enticing material has been developed by Aharon J. Agranat and his group at the Hebrew University of Jerusalem. This is a material that has a room-temperature phase transition and maintains its optical quality, so that it can be used in proximity of its dielectric anomaly at the Curie point. Here, the material manifests electro-holography, electro-optic waveguides, spatial solitons, scale-free optics, giant refraction, huge second-harmonic generation, and a hereto unknown ferroelectric phase, a ferroelectric supercrystal composed of hypervortices. While all these add up to a multifunctional material, a candidate to host generic optical operations, they also lead to a rich playground for the observation and discovery of new phenomena, such as the first observation of the supercrystal phase and the intriguing detection of a nonlinearity able to generate an intrinsic negative mass, that is, a Schroedinger wave equation with a negative mass term not in the delocalized Bloch modes, as occurs for holes in semiconductors, but in the actual localized optical wave.

Rome, Italy
June 2019

Prof. Eugenio Del Re

# Abstract

The work presented in this thesis addresses different aspects of three main physical issues belonging to the field of nonlinear optics, quantum optics, and optical microscopy. We analyze how photorefraction can be used to photoinduce a tapered fiber index of refraction patterns in the bulk of nanodisordered crystals, and we observe how these patterns are able to modulate the phase of Gaussian beams converting them to Bessel–Gauss beams, enhancing their depth of field and their ability to self-heal after an obstacle. These properties suggest the use of Bessel beam in microscopy. In our investigations, we proposed and experimentally demonstrated, in turbid media, the idea of using the interference between multiple Bessel beams to generate a light field that is non-diffracting and self-healing, but also localized along the propagation axis. Our study on superimposed Bessel beams reveals how the interference between their side lobes has the overall effect of reducing the amount of energy possessed by the beam outer structures, practically enhancing their localization in the radial direction as well as in the axial. At present, we are studying how to implement these findings in a light sheet microscope to improve optical sectioning. Also described in this thesis are a number of intriguing experiments carried out on disordered ferroelectrics and their giant response, including negative intrinsic mass dynamics, ferroelectric supercrystals, rogue wave dynamics driven by enhanced disorder, and the first evidence of spatial optical turbulence. Lastly, relying on the necessarily reversible nature of the microscopic process, we demonstrate how a single photon is not able to entangle two distant atoms because of conservation laws, clarifying the long-standing debate on the nature of single-photon non-locality and introducing fundamental limitation, in the use of linear optics for quantum technology.

The thesis is organized as follows: In Chap. 1 we present the basic mechanism of photorefractive spatial solitons and the phenomena involved in soliton formation, whereas in Chap. 2 we describe the basic concept of optical microscopy. Chapter 3 is dedicated to the experimental observation of a miniaturized device that can convert a Gaussian beam into a Bessel beam with low response time and using volume integrable techniques. Chapter 4 reports the experimental investigation of a new non-diffracting light-field-generated superposing multiple Bessel Beams, what we term “light droplet.” Further experiments demonstrate that the droplets are self-healing in turbid media, a feature that can potentially allow in vivo imaging of thick specimens in a backscattering microscope configuration. In Chap. 5, we continue the experiments on “light droplets” and Bessel beam superposition by showing how the interference of their side lobe leads to a reduction of the off-axial intensity. In Chap. 6, we discuss theoretically the idea of entangling two distant systems by means of a single particle. Our findings show how, from first principles, quantum mechanics prevents the possibility of entangling the two systems in any useful way. In Chap. 7, the discovery of a spontaneous polarization supercrystals in microstructured samples of potassium-lithium-tantalate-niobate (KLTN) is described. This polarization domain structure is three-dimensional, has a micrometric period, and affects the light propagating through it by spatially separating its polarization components. In Chap. 8, we describe experiments, theory, and numerics that show how anti-diffracting nonlinear waves evolving into an optical potential made by an integrated slab waveguide give rise to the dynamics of a negative mass quantum particle. Chapter 9 reports direct evidence of turbulent transitions in optical wave propagation. The transition occurs as the disordered hosting material passes from being linear to being extremely nonlinear, a regime that unveils the emergence of concomitant rogue waves. The control of these extreme events through spatial incoherence is also experimentally demonstrated.

# Preface

The research contained in this thesis was carried out under the supervision of Eugenio Del Re, in collaboration with Fabrizio Di Mei, Davide Pierangeli, Giuseppe Antonacci, Paolo Di Porto, Salvatore Silvestri, Jacopo Parravicini, and Aharon J. Agranat. The experimental activity has been implemented in the laboratory of the Physics Department of the University of Rome "La Sapienza" (S005-S008, Fermi building) thanks to funding from the FIRB Futuro in Ricerca project grants PHOCOSRBFR08E7VA, the PRIN project 2012BFNWZ2, and Sapienza 2014–2015 Awards projects. The support from the Italian Institute of Technology IIT@Sapienza (Center for Life Nano Science) is also acknowledged.

Tel Aviv, Israel | Dr. Giuseppe Di Domenico

## Publications Related to This Thesis

**Papers published by the candidate during the three-year Ph.D. course:**

Davide Pierangeli, Mario Ferraro, Fabrizio Di Mei, Giuseppe Di Domenico, C.E.M. de Oliveira, Aharon J. Agranat, Eugenio Del Re. *Super-crystals in composite ferroelectrics*. Nat. Comm. **7**, 10674 (2016).

Fabrizio Di Mei, Piergiorgio Caramazza, Davide Pierangeli, Giuseppe Di Domenico, H. Ilan, Aharon J. Agranat, Paolo Di Porto, Eugenio DelRe. *Intrinsic negative mass from nonlinearity*. Phys. Rev. Lett. **116**, 153902 (2016).

Davide Pierangeli, Fabrizio Di Mei, Giuseppe Di Domenico, Aharon J. Agranat, Claudio Conti, Eugenio DelRe. *Turbulent transitions in optical wave propagation*. Phys. Rev. Lett. **117**, 183902 (2016).

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Giuseppe Antonacci, Simone De Panfilis Giuseppe Di Domenico, Eugenio DelRe, Giancarlo Ruocco. *Breaking the Contrast Limit in Single-Pass Fabry-Pérot Spectrometers*. Phys. Rev. App. **6**, 054020 (2016).

Giuseppe Antonacci, Giuseppe Di Domenico, Salvatore Silvestri, Eugenio DelRe, Giancarlo Ruocco. *Diffraction-free light droplets for axially-resolved volume imaging*. Sci. Rep. **7**, 17 (2017).

Giuseppe Di Domenico, Jacopo Parravicini, Giuseppe Antonacci, Salvatore Silvestri, Aharon J. Agranat, Eugenio DelRe. *Miniaturized photogenerated electro-optic axicon lens Gaussian-to-Bessel beam conversion*. Appl. Opt. **56**, 2908 (2017).

Mario Ferraro, Davide Pierangeli, Mariano Flammini, Giuseppe Di Domenico, Ludovica Falsi, Fabrizio Di Mei, Aharon J. Agranat, Eugenio DelRe. *Observation of polarization-maintaining light propagation in depoled compositionally disordered ferroelectrics*. Opt. Lett. **42**, 3856 (2017).

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Mariano Flammini, Giuseppe Di Domenico, Davide Pierangeli, Fabrizio Di Mei, Aharon J. Agranat and Eugenio DelRe. *Observation of Bessel-beam self-trapping*. Phys. Rev. A. **98**, 3 (2018).

**Papers presented by the candidate at international conferences:**

Davide Pierangeli, Mario Ferraro, Fabrizio Di Mei, Giuseppe Di Domenico, C.E.M. de Oliveira, Aharon J. Agranat, Eugenio DelRe. *Spontaneous photonic super-crystals in composite ferroelectrics*. Conference on Lasers and Electro-Optics (CLEO), San Francisco CA, USA (2016).

**Papers prepared by the candidate and currently under review process in journals:**

Paolo Di Porto, Giuseppe Di Domenico, Fabrizio Di Mei, Bruno Crosignani, Eugenio DelRe. *Microscopic reversibility and no entanglement produced by a single particle on distant systems*. Submitted to Physical Review Letters.

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Thank you.

April 2019

Dr. Giuseppe Di Domenico
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