THEORETICAL QUANTUM OPTICS

Quantum entanglement is a fundamental resource at the core of modern quantum technologies, such as quantum communication, information, and metrology. In these contexts, light represents a natural carrier of information and a widely used metrological sensor. The specific expertise of our group is the study and realization of entangled and squeezed states of light in high dimensional Hilbert spaces. The interest towards multimode quantum optical sources dates back to the beginning of the 90's, when the quantum optics community started to investigate the spatial correlation of quantum fluctuations of light, arising in the plane transverse to the mean direction of propagation, and recognized their potential for high precision measurements in the spatial domain, in particular for the so called *quantum imaging*. In later years, the multimode approach introduced by quantum imaging revealed to be useful also for the fields of quantum communication and information, where the multimode nature (in space, time and polarization) of light can be e.g. exploited to increment the amount of information in a quantum channel, or its security, or to devise novel communication protocols. Our group was among the ones in Europe to pioneer this field of research, and participated to three consecutive European projects which brought embryonal ideas to several successful realizations.

Our current research activity focuses on the *twin photons* generated by the process of parametric down-conversion (PDC), occurring in media exhibiting a second order optical response ($\chi^{(2)}$ nonlinearity). Microscopically, the process corresponds to the destruction of a high energy photon from a pump laser illuminating the medium, and the creation of a pair of photons at lower energy. Twin photons generated in this way are naturally entangled in various degrees of freedom (polarization, time-energy, position-momentum). We investigate the spontaneous regime, where photon pairs are generated and detected, and the stimulated regime where multiple photon pairs contribute to macroscopic twin beams, and explore the possibility of manipulating their entanglement properties by properly engineering the source. The goal is realizing novel states of light, useful for quantum technological applications. To this end, in collaboration with the Ultra-fast Nonlinear Optics group (CNR, Ottavia Jedrkiewicz), we focus on two methods:

- The use of built ad hoc structured materials, such as periodically poled nonlinear crystals with a submicron poling, which allow the generation of **counter-propagating twin photons**, or **nonlinear photonic crystals**, with a two-dimensional periodic modulation of the $\chi^{(2)}$ nonlinearity (a 2D poling pattern). In the first case, the device has the potentiality of generating narrowband heralded photons in pure quantum states, and from a more fundamental point of view, exhibits a critical behaviour of the quantum correlation of twin beams. In the second case, the research, performed in collaboration with the Royal Institute of Technology (Sweden), has revealed that three and four-mode coupling processes with enhanced gain may arise under particular conditions, leading to a peculiar multipartite entanglement, absent in standard 2-mode PDC sources [1,2] (see Fig.1).
- The use of structured pump fields, e.g. Bessel beams, or in general beams with a proper spatial modulation in the transverse plane.

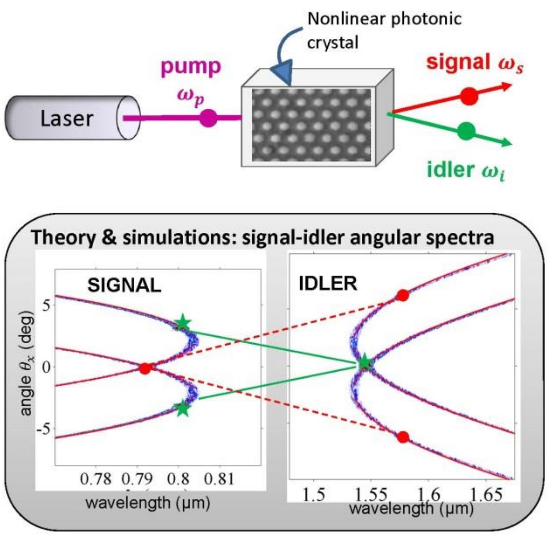

Fig.1. *Example of 3-mode entanglement with enhanced gain from a hexagonally poled nonlinear photonics crystal as predicted in [1,2].*

Recent publications:

[1] A. Gatti, E. Brambilla, K. Gallo, and O. Jedrkiewicz, *Golden ratio entanglement in hexagonally poled nonlinear crystals*, Physical Review A **98** (2018)

[2] O. Jedrkiewicz, A. Gatti, E. Brambilla, M. Levenius, G. Tamoˇsauskas, and K. Gallo, *Golden Ratio Gain Enhancement in Coherently Coupled Parametric Processes*, Scientific Reports 8, 11616 (2018)

[4] D. C. Cole, Alessandra Gatti, S. B. Papp, F. Prati, and L. Lugiato, *Theory of Kerr frequency combs in Fabry-Perot resonators*, Phys. Rev. A **98**, 013831 (2018)

[5] A. Gatti and E. Brambilla, *Heralding pure single photons: A comparison between counterpropagating and copropagating twin photons*, Phys. Rev. A **97**,013838 (2018)

[6] A. Gatti and E. Brambilla, *Continuous variable entanglement of counter-propagating twin beams*, Int. J. of Quant. Inf. **15**, 1740017 (2017).

[7] A. Gatti, T. Corti and E. Brambilla, *Squeezing and Einstein-Podolsky-Rosen correlation in the mirrorless optical parametric oscillator*, Phys. Rev. A **96** ,013820 (2017).

[8] T. Corti, E. Brambilla, A. Gatti, *Critical behaviour of coherence and correlation of counterpropagating twin beams*, Phys. Rev. A **93**, 023837 (2016),

[9] A. Gatti, T.Corti, and E. Brambilla, *Temporal coherence and correlation of counterpropagating twin photons*, Phys. Rev. A **92**,053809 (2015).

[10] A. Allevi, O. Jedrkiewicz, E. Brambilla, A. Gatti,J. Perina Jr., O. Haderka, and M. Bondani, *Coherence properties of high-gain twin beams generated in pump-depletion regime*, Phys. Rev.A **90**, 063812 (2014)

[11] E. Brambilla, O. Jedrkiewicz, P. Ditrapani and A. Gatti, *Space-time coupling in upconversion of broadband downconverted light*, J. Opt. Soc. Am. B **31**, 1383 (2014).

[12] A. Gatti, L. Caspani, T. Corti, E. Brambilla, O. Jedrkiewicz, *Spatio-temporal entanglement of twin photons: an intuitive picture*, International J. of Quantum Information, **12,** 1461016 (2014).

The theoretical group in Como

Alessandra Gatti (alessandra.gatti@ifn.cnr.it)

Alessandra Gatti is a senior researcher (Primo Ricercatore) of the Institute of Photonics and Nanotechnologies of the Italian National Research Council (CNR), and contract professor at Insubria University, where she teaches quantum optics. She received in 1997 the PhD in Physics from Milano University, and qualified in 2013 as full professor in the area of theoretical physics of matter. Internationally known for her contributions to the fields of quantum imaging and high dimensional entanglement of light, she co-authored 120 scientific works (85 in peers reviewed journals), receiving more than 4500 citations, with a h-index of 33 (Scopus). She participated to several European projects, and was the Scientific Coordinator of the FP7project **HIDEAS,** *High Dimensional Entangled Systems* (grant 221906 of the FET OPEN program, 2008-2012). Since 2014 she is **Fellow of the Optical Society of America**, and in 2013 she received from the European Physical Society the **Emmy Noether distinction for Women in Physics** « for pioneering contributions to the field of quantum imaging ».

Enrico Brambilla (enrico.brambilla@uninsubria.it)

Enrico Brambilla is a researcher at the University of Insubria where he teaches "Theory of semiclassical optical systems" for the Laurea Magistrate in Physics. He received his PhD in Physics at the University of Milan in 2000. He is co-authors of more than 40 scientific publications in peer review journals (current h-index 20, Scopus)