Project title: Non-Hermitian Quantum Photonics

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Current state of the art

As a complex extension of the conventional Hermitian regime, parity–time (PT)-symmetric quantum mechanics has garnered substantial interest in recent years [1]. PT-symmetric systems may possess an entirely real eigenvalue spectrum despite violating Hermiticity, giving rise to hallmark features such as non-orthogonal eigenmodes, exceptional points, and diffusive coherent transport [2]. Moreover, PT symmetry has profound implications regarding nonlinearity, lasing, and non-trivial topologies [3, 4]. Although PT symmetry is mostly being explored using photonic platforms, its implications have enriched other fields of research ranging from atomic diffusion to superconducting wires and electronic circuits. Despite its general formulation, the vast majority of experimental demonstrations so far have focused on single-particle phenomena, that is, on first-quantization quantum mechanics using wavefunctions and their analogies, in either the classical regime or the single-photon realm. Yet, only in second quantization, where the wavefunction itself is quantized, does the true nature of quantum physics make its full appearance. Recently, our team provided the first experimental demonstration of PT-symmetric quantum optics [5], using integrated quantum waveguide circuits fabricated with the laser direct-write approach [6]. When ultrashort laser pulses are tightly focused into transparent bulk material, nonlinear absorption takes place leading to optical breakdown and the formation of a micro plasma, which induces a permanent change in the material's molecular structure. In the particular case of fused silica as the processed material, the density is locally increased, yielding an increase of the refractive index. The dimensions of these changes are approximately the same as the size of the focal region. By moving the sample with respect to the beam, permanent waveguides can be created (see Fig. 1a) along three-dimensional free-form paths in virtually arbitrary arrangements, since the only limiting factor in the placement of the focus is the focal length of the writing objective. In our work on PT-symmetric quantum optics, we implemented non-Hermiticity by imposing radiation losses facilitated by sinusoidally modulated waveguides (see Fig. 1b). This approach allows the fabrication of integrated beam splitters respecting PT-symmetry (see Fig. 1c), to study fundamental quantum effects such as Hong-Ou-Mandel interference. Along these lines, we found that the position where the single photons are equally distributed among the waveguides is systematically displaced with respect to the Hermitian case (see Fig. 1d).

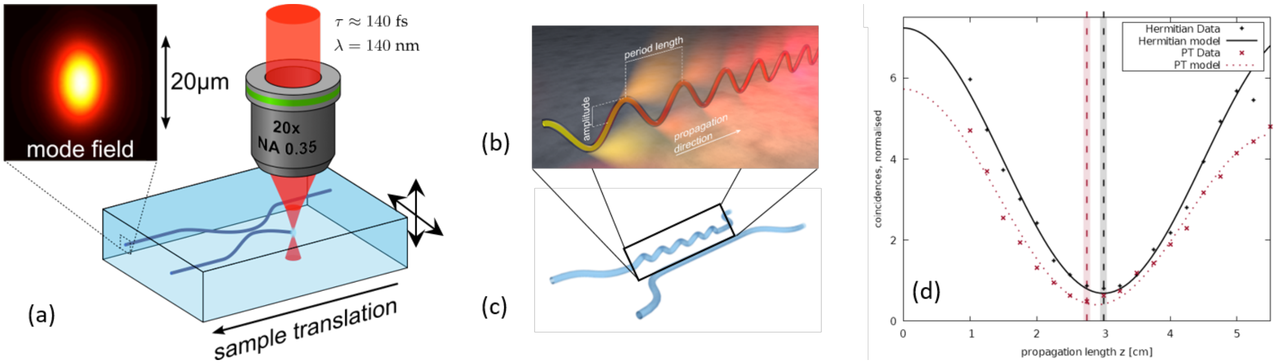

Figure 1: (a) Setup for writing waveguides using ultrashort laser pulses. The inset shows a typical waveguide mode. (b) In order to imlement PT-symmetry, radiation losses are imposed onto a waveguides using a sinusoidal modulation. (c) Sketch of an integrated PT-symmetric beam splitter. (d) The measurements reveal that the position of equal distribution of the single photons among the waveguides significantly differs in the PT-symmetric and the Hermitian case.

Research goals and working program

Despite significant interest, the field of PT-symmetric quantum optics is still in its infancy. To date, only a small number experimental implementations are at hand, leaving numerous scientific surprises to be discovered and potential technological applications to be developed. Within this PhD project, **we will explore the impact of non-Hermiticity and particularly PT-symmetry on the evolution of single-photon quantum light.**

Based on our expertise in fabricating extended non-Hermitian waveguide circuits for the exploration of, e.g., non-Hermitian transport transitions [7] and non-Hermitian flat bands [7], we will explore two fundamental settings for non-Hermitian dynamics of quantum light: One focus of our efforts are waveguide lattices in which continuous-time quantum walks can be implemented (see Fig 2a). This will allow us to systematically study the transition from broken to unbroken PT-symmetry. The other type of structure in which non-Hermitian quantum optics will be realized are sequences of PT-symmetric waveguides couplers that were implemented in [5] (see Fig. 2b). The latter are the basis for discrete-time quantum walks that are inherently periodic in time and, hence, are able to simulate Floquet physics. Moreover, they are the basis for the implementation of the Boson sampling protocol [9], which in turn allows us to explore its non-Hermitian counterpart with - so far unknown - implications.

Within this PhD thesis project, the doctoral candidate will be responsible for the entire process of designing and modelling the integrated circuits, their fabrication with the laser direct-write approach, and their characterization using quantum light.

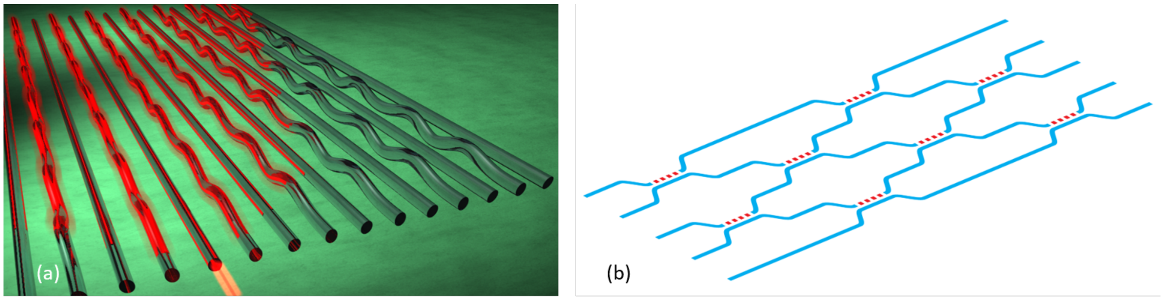

Figure 2: (a) Schematic of a continuous-time photonic quantum walk in a non-Hermitian waveguide array, where the losses are facilitated by enhanced radiation in undulating waveguides. (b) Sketch of a photonic circuit that implementing the Boson sampling protocol [9], under PT-symmetric conditions, as indicated by lossy sections (red dots).

[1] Nature Physics. 14, 11 (2018).

[2] Science 363, eaar7709 (2019).

[3] Science 368, 311 (2020).

[4] Nature 601, 354 (2022).

[5] Nature Photonics 13, 883 (2019).

[6] Phys. B 43, 163001 (2010).

[7] Nature Commun. 4, 2533 (2013).

[8] Phys. Rev. Lett. 123, 183601 (2019).

[9] Nature Photon. 7, 540 (2013).