# Project title: Holonomic quantum gates in integrated waveguides

## Supervisors: Stefan Scheel, Alexander Szameit (UROS), Jeff Lundeen (uOttawa)

### Current state of the art

When a quantum system undergoes slow changes, its evolution solely depends on the corresponding trajectory in Hilbert space, the so-called quantum holonomy. This geometric concept of quantum theory can be very usefully exploited for quantum computation [1]. These transformations arise when a state vector is undergoes parallel transport along a closed loop in a suitable subspace (see Fig. 1). For an adiabatic holonomy, this subspace is usually some (non)degenerate ground-state subspace [2]. In contrast, in the case of nonadiabatic quantum holonomies, evolution takes place in a subspace with vanishing mean energy, thus rendering the evolution purely geometric. Perhaps the most well-known incarnation of a geometric evolution is the Abelian Berry phase [3]. However, evolution in degenerate subspaces typically result in matrix-valued (non-Abelian) phases that imprint a unitary evolution on a quantum state upon traversing a loop in parameter space (see Fig. 1).

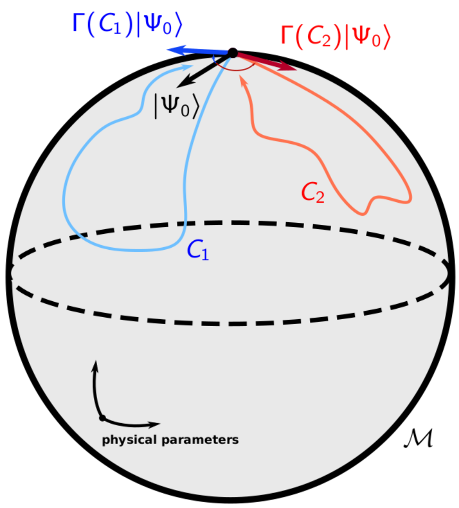


Figure 1: A quantum state $|\Psi_0\rangle$ is moved adiabatically through a parameter space $\mathcal{M}$ along different paths $C_{1,2}$. Depending on the chosen path, a holonomy $\Gamma(C_{1,2})$ acts on the state, thus representing a geometric evolution.

One of the most promising experimental architectures for implementing such non-Abelian holonomic quantum evolutions are integrated photonic waveguide circuits (see Fig. 2). Femtosecond laser-writing provides a versatile platform that enables full control over the relative position of the waveguides, and thus spatiotemporal control over the coupling strength between modes supported by them. The flexibility of this platform has been successfully exploited for the generation of U(2)- [4] and U(3)-valued [5] geometric phases. It has also been shown that even strongly coupled waveguides, in which individual waveguide modes are no longer mutually orthogonal, can be used to implement non-Abelian geometric phases [6], and general schemes for constructing robust linear optics from non-Abelian geometric phases have been developed [7].

Despite recent advances, several obstacles have to be overcome before holonomic quantum computation using photons can become reality. In particular, any adiabatic (or even cyclic nonadiabatic) evolution imposes constraints on how rapid the quantum state evolution can be made. This limit crucially depends on the available coupling strength between waveguides, and hence most notably the refractive index contrast between waveguide and surrounding material. Integrated silicon photonics would provide an answer to this problem, but comes with its own set of challenges as fully three-dimensional structuring of waveguides is beyond the current reach of this platform.

Moreover, some of the more involved quantum architectures using linear optics requires post-selection of measurement results as well as conditional feed-forward. However, integrating detectors into waveguides also seems to pose severe challenges. Non-Hermitian quantum evolution [8] could serve to avoid the need for on-chip photodetection by damping away unwanted evolution outcomes, and amplifying the wanted result in turn. This way, conditional evolution is replaced by non-Hermitian yet deterministic evolution.

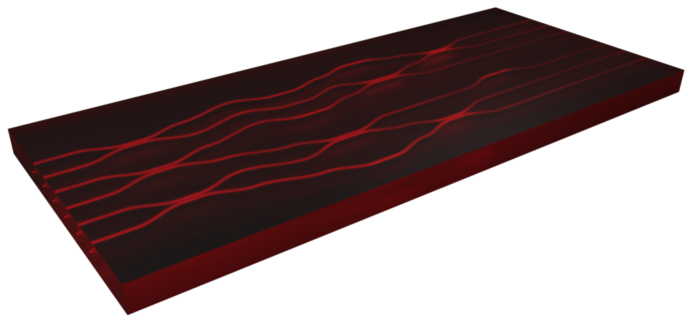

Figure 2: Femtosecond laser-written integrated photonic waveguides in silica glass. Accurate positioning of the waveguides provides full control over spatialtemporal mode coupling.

### Research goals and working program

The research goals of this project are thus 1) to investigate holonomic quantum evolution in high-index contrast platforms such as silicon photonics, and 2) to develop concepts for non-Hermitian quantum evolution to effectively replace conditional measurements on-chip. As mentioned above, silicon photonics suffers from the manufacturing restriction to two dimensions, i.e. waveguides can only be grown in a two-dimensional layer. However, different layers can be grown on top of one another, resulting in an effectively 2.5-dimensional structure. The project will first be concerned with the restriction of waveguides to strictly two dimensions, and with investigating what types of quantum holonomies can be generated in this restricted geometry. Further, as silicon photonics provides a large index contrast between waveguides and surrounding material, the project will be concerned with the non-orthogonal mode structure and its impact on geometric quantum evolution.

In the second part of the project, the focus will be on non-Hermitian quantum evolution. Within the framework of open quantum systems, structured reservoirs for the guided photons that are, e.g. themselves implemented by additional sets of waveguides, can induce an effectively non-Hermitian evolution. The task here is to reverse-engineer a reservoir in order to generate a particular sought non-Hermitian evolution. This means in particular to develop a theoretical toolbox that maps the set of Lindblad operators relevant for the non-Hermitian evolution onto the coupling constants of a waveguide array modelling the dissipative reservoir.

The project supervisors in Rostock, Prof. Stefan Scheel and Prof. Alexander Szameit, have a long-standing expertise in theoretical quantum optics and experimental integrated waveguide photonics, respectively. The Canadian partner, Prof. Jeff Lundeen in Ottawa, complements that with his expertise in silicon photonics and experimental quantum optics. While the project is anchored in Rostock, the successful applicant is expected to spend between 6-12 months at the University of Ottawa.

[1] P. Zanardi and M. Rasetti, *Holonomic quantum computation*, Phys. Lett. A **264**, 94 (1999).

[2] F. Wilczek and A. Zee, *Appearance of Gauge Structure in Simple Dynamical Systems*, Phys. Rev. Lett. **52**, 2111 (1984).

[3] M. V. Berry, *Quantal phase factors accompanying adiabatic changes*, Proc. R. Soc. London A **392**, 45 (1984).

[4] M. Kremer, L. Teuber, A. Szameit, and S. Scheel, *Optimal design strategy for non-Abelian geometric phases using Abelian gauge fields based on quantum metric*, Phys. Rev. Research **1**, 033117 (2019).

[5] V. Neef, J. Pinske, F. Klauck, L. Teuber, M. Kremer, M. Ehrhardt, M. Heinrich, S. Scheel, and A. Szameit, *Three-dimensional non-Abelian Quantum Holonomy*, Nature Physics (2022).

[6] J. Pinske and S. Scheel, *Symmetry-protected non-Abelian geometric phases in optical waveguides with nonorthogonal modes*, Phys. Rev. A **105**, 013507 (2022).

[7] J. Pinske and S. Scheel, *Geometrically robust linear optics from non-Abelian geometric phases*, Phys. Rev. Research **4**, 023086 (2022).

[8] F. Klauck, L. Teuber, M. Ornigotti, M. Heinrich, S. Scheel, and A. Szameit, *Observation of PT-symmetric quantum interference*, Nat. Photonics **13**, 883 (2019).