Topologically protected states in active photonic metamaterials
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Background: A topologist is sometimes described as a mathematician who cannot discriminate between a tea cup and a doughnut. This means that topology focuses on global properties such as connectedness instead of geometrical detail, thereby paving the road for a new level of understanding. Topological invariants such as the Euler characteristic for surfaces in $\mathbb{R}^3$ are naturally quantized and do not change their value upon smooth deformations.

Topological states in physical systems have a similar characteristics and are largely insensitive to perturbations. The discovery of topological phases in quantum matter [1] that stands in direct connection to the quantum Hall effect [2] led to a new class of superconducting and insulating materials with unique properties, and sparked a wave of research that culminated in the 2016 Nobel Prize in Physics “for theoretical discoveries of topological phase transitions and topological phases of matter”. Crucially, topological effects are not restricted to quantum systems. In fact, the change of the polarisation state of classical light when passing through a twisted optical fibre was described on a topological basis long before the discovery of the quantum Hall effect [3]. In 2008, Raghu and Haldane introduced the idea of a classical topological insulator on the basis of a photonic crystal (i.e. a periodic structure of dielectrics that is fully understood in terms of classical electrodynamics, despite its name) [4].

Objective: Investigate topological states in nanoplasmonic arrays and photonic crystals: We recently proposed a system of spherical nanoparticles on a 2D honeycomb lattice as a system that gives rise to plasmonic Dirac dispersion [5] with non-trivial topology, analogous to the massless electron dispersion in graphene. Now, using group theory [6], we can build on this idea to identify 3D geometries with similar properties, that can lead to unique physical behaviour such as zero refractive index materials [7]. The aim of this project is thus to find and study plasmonic and photonic metamaterials with topologically protected states at the surface and in the bulk, and to explore possible applications of these states.

Methods & Programme: The following is an incomplete list of available methods to study topological effects in photonic structures. Depending on the direction, not all of these might be exploited. There is also an opportunity to develop own numerical tools, to expand the scope of the planewave solver below, and to collaborate with experimental groups to realise the designs in practice.

- **Simulation of eigenmodes:** compute the topological modes of periodic assemblies with a Maxwell solver. Specifically, an FEM solver such as Comsol works best for metallic constituent materials, while homegrown code [8] based on a planewave expansion computes bulk and surface states of non-metallic structures.

- **Simulation of optical response:** Finite Difference Time Domain, as implemented in Lumerical, is a direct simulation technique that is best suited to run numerical experiments. We can thereby test the metamaterials response under external illumination, or internal stimulation by for example a quantum dot emitter.

- **Group theory:** the existence, level of degeneracy and the algebraic structure of exceptional points (where two bands meet) in the dispersion relation can be predicted from a system’s symmetry. As a result, the bandstructure in the vicinity of these points is characterized by a low-dimensional ‘Hamiltonian’, similar to that of the Dirac equation, with an analytical solution. The physical interpretation and topological characterisation of the solutions will yield additional insight into the nature of the modes, and pave the road for new applications in nano-optics and photonics.

- **Topological characterisation:** the topological analogue of the Euler number for vector fields is the Chern number. It can be calculated numerically and analytically on the basis of the simulated eigenmodes or the model Hamiltonian, respectively. The Chern characteristics of a structure is directly correlated with its unique topological properties.