Gyroid Photonics – From Chiral Beamsplitters and Active Materials to Topological Physics and Bound States in the Continuum

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In this lecture, I will explore the breadth of photonic effects associated with nano-structured gyroid materials. I will focus on optical composites, where one (chiral single gyroid) or two (achiral double gyroid) of the gyroid's network channels are filled with constituent optical materials [1]. As a common theme, we will find that the network topology and material fill fraction govern the light-matter interaction. On the other hand, the specific geometrical realisation – for example, constant mean curvature domains or rod-connected networks – only weakly affects the photonic response.

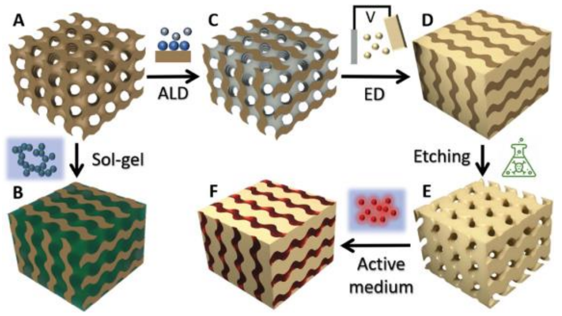

Figure 1 Towards active gyroid media. A biotemplate (A) is infiltrated with a barium-titanate sol-gel (B) to obtain a non-linear PhC, or cast into an active metamaterial through (C) atomic layer deposition, (D) electrodeposition, (E) etching of the biotemplate, and (F) infiltrating with a dye or quantum dot solution. Reproduced from [2].

Most photonic nano-composites are classified as *photonic crystals* (PhCs) or *metamaterials* (MMs). PhCs are dielectric structures whose optical properties are primarily obtained from an interference effect caused by a refractive index variation on the order of the wavelength of the light. PhCs started to attract attention after two seminal papers appeared in the same issue of Physical Review Letters in 1987, describing strong Anderson localisation of light (S. John) and completely suppressed spontaneous emission (E. Yablanovitch). Both effects have not been experimentally demonstrated to date. I will explain why a gyroid PhC infiltrated with an active photonic component, illustrated in Figure 1, is an excellent candidate to test and exploit Yablanovitch's hypothesis. But even without an active component, gyroid PhCs offer many exciting phenomena. For example, the single gyroid's 3D chirality has been exploited to design a circular polarisation beamsplitter, as shown in Figure 2. On the other hand, a double gyroid PhC with broken parity symmetry was the first practical physical system in which the Weyl equation could be demonstrated 85 years after its derivation by Ling Lu and coworkers at MIT.

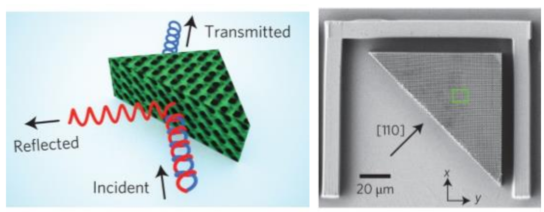

Figure 2 Gyroid circular polarisation beamsplitter. Left: Illustration of the functionality. Right: SEM micrograph of the fabricated device. Reproduced from [3].

Gyroid MMs are metallic composites typically structured on a sub-wavelength scale. They obtain their optical properties from how the 3D gyroid topology restricts the plasmonic excitations of the free electrons in the constituent metal. Gyroid MMs based on block-copolymer self-assembly have long been considered an ideal candidate to achieve 3D negative refraction and build Pendry's *perfect lens*, with a resolution not limited by diffraction. I will explain the failure of attaining negative refraction in single gyroids and highlight the potential of double gyroids MMs as a 3D lasing cavity through a bound state in the continuum mechanism.

[1] J. A. Dolan et al., Advanced Optical Materials, 3, 12 (2014).
[2] V. V. Vogler-Neuling et al., Advanced Functional Materials 34, 2306528 (2024).
[3] M. Turner et al., Nature Photonics 7, 801 (2013).