Semi-Analytic Approaches to Photonic Crystal Device Modelling

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Photonic crystals (PC), which are at the forefront of theoretical and experimental research in optics, are amongst the most exciting of optical structures due to their ability to manipulate (and confine) light on the wavelength scale and also their remarkable dispersion properties. In order to exploit their technological potential, through the development of devices that underpin the integrated "photonic chip" – an all optical signal processor – a thorough understanding of the mechanisms by which light is coupled into, and guided through, such structures is needed. Device design is dependent on extensive modelling which, for the most part, is undertaken using purely computational techniques such as finite-difference time domain (FDTD) methods. While this is an important, omnibus tool, it neither provides physical insight into the underlying scattering processes, nor takes advantage of the structure and geometry of the problem to deliver computational advantages. The purpose of this talk is outline semi-analytical approaches to the modelling of PC devices, highlighting their advantages, the situations in which there are best applied, and survey a range of applications including device design, and their role in answering theoretical questions that cannot be tackled using alternative approaches.

Underpinning these techniques is the Bloch mode basis that characterises the structure, or each layer of the structure, the calculation of which requires the solution of a linear (transfer matrix) or nonlinear eigenvalue problem. In the case of layered structures, the analysis proceeds in a manner that mirrors and generalises the techniques of thin film optics, with propagation in any particular layer determined by the layers Bloch factors, and with the scattering/diffraction that occurs at interfaces being handled with generalised Fresnel "coefficients" (matrices). These Fresnel matrices structurally resemble their familiar scalar counterparts and we will demonstrate how the familiar concept of impedance can be defined rigorously for a photonic crystal directly from the Bloch modes. This, we exemplify by showing how optimal coupling efficiency can be achieved through the design of PC anti-reflection coatings.

In the final part of the talk, we consider two theoretical questions that cannot be handled numerically: the first providing a definitive proof that the fundamental mode of a photonic crystal fibre (PCF) is never cut-off, and the second outlining a general asymptotic formulation of the evolution of defect modes from cut-off at the edge of a band gap. The demonstration of the former necessitated the development of a new technique, the fictitious source superposition (FSS) method that models defects in genuinely infinite claddings, and which is required to handle the highly extended modes that occur near cut-off. Our final example develops a first order perturbation analysis of the Green's function from which we may infer the structure of the defect mode and devise an elegant exponential law which relates the difference in frequency of the mode and band edge to the relative change in the energy caused by the defect.