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COMMENT

Photonic crystals and topological photonics

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The idea of photonic crystals and photonic band gap was first introduced by both Yablonovitch [1] and John in 1987 [2]. Photonic crystals are man-made periodic optical media in which the dispersion of light is strongly modified due to the scattering of periodically arranged dielectric or metal inclusions in the unit cell. Photonic band gaps, a frequency range in which light cannot propagate, can form as a consequence of Bragg scattering or the resonance of the inclusions in the unit cell. The existence of band gaps means that photonic crystals can serve as low-loss distributed feedback mirrors and as such, they can confine light and can be used to realize high fidelity resonant cavities that can facilitate the observation of quantum electronics phenomena. The application of such ideas to realize strong coupling between photon and exciton is achieved using planar dielectric Si periodic structures [3]. When combined with a gain material, photonic crystals are obviously good platforms to realize lasing and indeed photonic crystal based lasers have attracted great interest in past three decades. The technical challenges and progress in distributed feedback organic lasers based on photonic crystals are discussed and reviewed by Fu and Zhai [4]. For practical applications, nonlinear photonic crystals with different superlattices has been successfully used in quasi-phase matching and nonlinear diffraction harmonic generation. This is reviewed by Li and Ma [5].

Artificial materials that have superior optical properties usually have complex structures and photonic crystals are no exception. Potonic crystals that operate at optical frequencies have complex nano-scale features which can be made by bottom-up or top-down approaches. Top-down fabrication processes are suitable for a precise control of shape and size down to the nano-scale, and multi-beam interference lithography is a particularly versatile method. The holographic fabrication method is reviewed and illustrated by Lin et al. using graded photonic crystal as an example [6].

In recent years, the discovery of topological materials is one of the most exciting advances that captured the attention of scientists in the field of material science and condensed matter physics. Topological materials are characterized by topological invariants that depend on the global properties of the wave functions in the bulk. As photonic crystals are periodic systems that have band structures, they are natural candidates for extending the notion of topological materials to photonics; and in the past few years, many exciting results have emerged in the new field of “topological photonics”. The study of topological consequence in photonics can give us a deeper and better understanding of topological material for many reasons. First of all, many topological invariants such as the Chern numbers are defined using the Bloch wave functions. In electronic materials, the band structures that are calculated using methods such as the density functional approach are in fact one-body (mean-field) description of a complicated many body problem. In contrast, the band structures of linear photonic crystals have no such complication and are much easier to understand and comparison with experiment is more straightforward and direct. Another advantage of a photonic system is the ease to design a real material that is topologically non-trivial. Photonic crystals are man-made and their building blocks (the “meta-atoms”) can be of different shapes and material content, and are hence more designable. With advances in fabrication technologies down to the nano-scale, almost any structure that is designed in photonics can be made in practice. This is not in case in electronic systems, as a computer designed topological electronic material may not be chemically stable. Even if the band structure has interesting topological features, those features are not interesting in electronic systems unless they are at or near the Fermi level. For classical wave systems, the structure can be scaled in size so that the interesting topological features, such as non-trivial band gaps or nodal points, can be aligned with the operating frequency. Another advantage of

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classical wave is that doing optical experiments to characterize photonic crystals is usually easier than characterizing electronic materials. Almost any type of electronic topological materials have photonic crystal counterparts that have been designed, fabricated and characterized. The rapid development in the field of topological photonic crystals is reviewed by Lu et al. [7]. It is worth noting that topological photonic crystals are not merely counterparts that mirror electronic topological materials. They can manifest topological phenomena unique to photonics and electromagnetics. Examples such as topological non-Hermitian photonic crystals and nonlinear photonic crystals are discussed in Lu's review.

In some cases, simple model Hamiltonians offer a good qualitative description for topological photonic crystals, and calculating the bulk topological invariants such as Chern numbers is relatively straightforward for Hamiltonians whose eigenfuctions have analytical expressions. However, simple Hamiltonians usually provide a quantitative description only in a small part of the Brillouin zone and as topological invariants are global properties, it is important to calculate the invariants using the true eigenfields in the entire Brillouin Zone of the real systems. These eigenfields are typically obtained numerically using full wave packages in photonics research, and the integration in the Brillouin zone can be tedious and tricky. Lu et al. [8] developed a direct and universal numerical method that can calculate Chern numbers using the output of commercial finite-element packages. This is particularly useful for experimental groups that are working with real materials.

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