Early lights

This year marks a quarter of a century since the birth of photonic crystals. Overcoming early difficulties, the field has made a range of technological developments possible as well as the emergence of new science at the interface between condensed-matter physics and photonics.

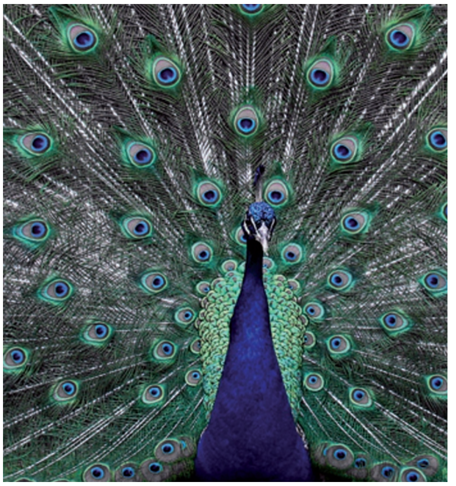
Sometimes unexpected breakthroughs can emerge when scientists try to address deceptively simple questions. This is how the field of photonic crystals was born 25 years ago, largely as a consequence of the creative works[1,2] of two scientists, Eli Yablonovitch and Sajeev John. Both are now considered to be the founders of a field that has become a staple of contemporary condensed-matter physics and photonics.

The problems that initially motivated the two scientists were inherently different. Yablonovitch, then working at Bell Communications, was investigating whether the spontaneous emission of excited atoms placed inside dielectric cavities could rigorously be suppressed[1]. At Princeton University, John was instead occupied with a more fundamental challenge: whether systematic observation of Anderson localization — the absence of wave transport in a disordered medium — could be achieved by using classical electromagnetic waves in non-dissipative systems[2]. They both realized that a solution to their problems could be reached if a suitably designed dielectric structure, periodic in all three spatial dimensions, were to be used, such that a full electromagnetic bandgap (a frequency region where no modes, regardless of their polarization, are allowed) opens up in the photon dispersion relation.

The fact that spontaneous emission is not an immutable property of atoms but can be affected and controlled by the electromagnetic environment was already well appreciated from the 1940s as a result of the pioneering work of Edward Purcell[3]. Later studies reported that, for instance, a simple one-dimensional (1D) metallic configuration, such as two conducting plates separated by a distance smaller than the cutoff wavelength of the structure's fundamental mode, could suppress the density of electromagnetic states for one polarization at the transition frequency of the atoms[4]. Reduction of the spontaneous emission rate in Rydberg excited atoms or electrons in Penning magnetoelectric traps by means of similar 1D microwave cavities had thus been achieved before 1987. In this issue, Yablonovitch mentions in an Interview[5] that, unconvinced about the effectiveness of those approaches, he realized that to obtain a complete inhibition of spontaneous emission a full bandgap was needed, suppressing rigorously the density of states for both polarizations. To achieve this goal, Yablonovitch had to extend preceding work on the optics of (mainly 1D) periodic layered structures[6] to 3D periodic media, which can provide control of the optical properties in all directions.

On the other hand, John was motivated by the fact that experimental observations of Anderson localization of electrons were exceedingly difficult, hampered by the presence of electron–electron interactions that can lead to Mott localization. The best experimental evidences before 1987 had been the observation of variable-range hopping — a characteristic temperature dependence of the conductivity in semiconductors that arises from thermally activated localized electrons — or of the integer quantum Hall effect. Also in this issue, John explains in a Commentary[7] he realized that the tendency of electrons in semiconductors to localize at small energies, close to a band edge, also appears for photons in 3D periodic structures possessing a certain degree of disorder[2].

It is forgotten that this early work of Yablonovitch and John, theoretical in nature, passed unnoticed for a few years. It was only after preliminary experimental attempts to attain 3D photonic bandgaps[8] that the photonics and condensed-matter communities began to pay attention to the early papers and realized their implications. This led to the flurry of activity that gave birth to exciting scientific results and tangible technological output. Examples of commercially available applications include ultra-broadband, high-brightness spectra via supercontinuum generation in photonic crystal fibres, light coupling to silicon photonic chips, enhanced light extraction from light-emitting diodes and laser-light guiding for cancer surgery. Furthermore, it has been recognized that periodic nanostructures are abundant in the animal world, where they are responsible for the bright, iridescent colours (particularly blue) found on the skin, wings or feathers of tropical fishes, hummingbirds, moths, beetles, butterflies and peacocks, among other species (see image).



The vivid colours in the feathers of male peacocks arise from natural photonic crystals.

Equally important has been the influence that the field of photonic crystals has had on a broad community of scientists, with many of them joining the field and, along the way, fusing concepts from photonics, plasmonics and condensed matter. Entire new scientific areas, such as metamaterials, have been born out of this synergy, striking out in new directions and flourishing in their own right.

That said, the realization of truly 3D photonic crystals, particularly at optical wavelengths, has proved persistently challenging owing to the intricacy of periodically nanosculpturing a material in all three spatial dimensions, and at the moment this limits the technological impact of these structures. With continuous advances in the synthesis, fabrication and self-assembly of photonic nanomaterials we can be hopeful that those challenges will eventually be overcome, closing another chapter in what has until now been a success story. ❐

References

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