Why trap light?

Sajeev John

The field of photonic crystals has become one of the most influential and wide-ranging realms of contemporary electromagnetics and optics, with numerous more opportunities on the horizon.

In 1865 James Clerk Maxwell showed how light propagates as electromagnetic waves. In 1984 it was realized that light can also be trapped[1]. My journey into this subject began as a PhD student at Harvard University, focusing on the possibility to trap or localize any classical wave in a suitable material[2]. This was not one of the 'big questions of science' at the time, but my supervisor Michael J. Stephen encouraged me to pursue it. Electrons can easily be trapped in atoms, but classical waves such as light have the disadvantage of being restricted to positive energy states. Maxwell's equations require that in any non-absorbing dielectric material, the energy of photons surpasses all potential barriers. This made trapping of light seemingly impossible.

Signatures of light localization occur in strong randomly scattering media[1,3]. However, it would require a fundamentally new class of materials to achieve the goal of systematic light trapping. Photonic crystals are artificial periodic dielectrics that trap light with manifold consequences. In basic science, they provide a way to engineer light–matter interactions at will. Light trapping in photonic crystals allows tailoring of the fundamental electromagnetic force. For practical applications, they enable processing of laser light on microchips for information technology, trapping of sunlight in thin films for energy conversion, and ways of guiding laser light for medical diagnostics and therapy.

After completing my thesis on wave localization, I investigated a seemingly unrelated question of electronic band tails in disordered semiconductors[4]. Band tails arise from localized electronic states below the band edge within the bandgap of the semiconductor. It was my hunch that creating a photonic band edge was the key to strong localization of light. Previously, in optics, only 'stop-gaps' in one-dimensional (1D) periodic dielectrics that could trap light in one dimension had been considered. Light was still free to escape in the other two dimensions. To completely trap light in three dimensions it would be necessary to create a spectral gap for light that persisted in all directions in 3D space.

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I considered whether a complete 3D bandgap for light could be created using non-absorbing periodic dielectrics. This is more difficult for photons than electrons due to the vector nature of the electromagnetic field. Nevertheless, I discovered[5] that it was feasible to create a 3D bandgap with available materials of reasonable refractive index, sculpted into the form of a periodic face-centred cubic lattice. After my paper was accepted for publication, I was informed of an independent paper submitted to the same journal[6] suggesting a 3D gap in the electromagnetic spectrum for the inhibition of spontaneous emission of light from atoms. The phrase 'photonic bandgap (PBG) material' was soon coined, framing the related goals of light trapping and inhibited spontaneous emission as a new challenge in materials science. (More details can be found in ref. 7.) The demonstration that the diamond lattice was the best candidate for realizing a PBG[8] was crucial to the ensuing materials fabrication efforts[9–11], allaying some fears that early efforts would "bite the dust"[12].

Optical microchips

Sometimes 'small questions of science' when investigated thoroughly lead to extraordinary answers. The PBG concept has implications that go far beyond the original motivations. Trapping light implies that light can also be guided in ways never before possible. Traditional guiding of light is based on total internal reflection. This is how optical fibres convey information over long distances. This type of guiding cannot rigorously be applied to light on a small microchip with optical circuit paths that bend on the wavelength scale, as light will simply diffract out of the circuit path and escape into free space. Optical waveguides in a PBG material do not suffer from this problem because whatever modes that light could diffract into are removed by the PBG. Backscattering along the circuit path can also be minimized by suitable design considerations[13]. Strikingly, each guiding path can convey hundreds of independent wavelength channels of optical information simultaneously. Because PBG-based guiding does not require total internal reflection, the circuit paths can consist of air rather than high-refractive-index material (Fig. 1a).

Unlike the situation in 2D electronic chips, heat generation and dissipation are not issues for a densely integrated 3D optical microchip[14,15]. This third (geometrical) dimension and the fourth (frequency-channel) dimension of integration are generally unavailable in microelectronics. These two additional dimensions of optical integration, unrestricted by heating issues, and conveying streams of data at the speed of light may offer important advantages over present-day electronic chips.

The ability of PBG materials to guide light without total internal reflection has also been successfully applied to a class of optical fibres known as photonic crystal fibres[16]. They can guide light in a hollow rather than solid core. Start-up companies including NKT Photonics and OmniGuide now exploit this technology. Although this offers opportunities for dispersion management and new low-loss wavelength windows in optical telecommunications, a striking life-saving application of a hollow-core photonic bandgap fibre has appeared in the field of medicine.

Non-invasive surgery

Laser surgery usually requires line-of-sight propagation of an intense laser beam to the location of a tumour. This typically requires incision and trauma to the patient. On the other hand, high-intensity laser beams cannot always be handled by solid-

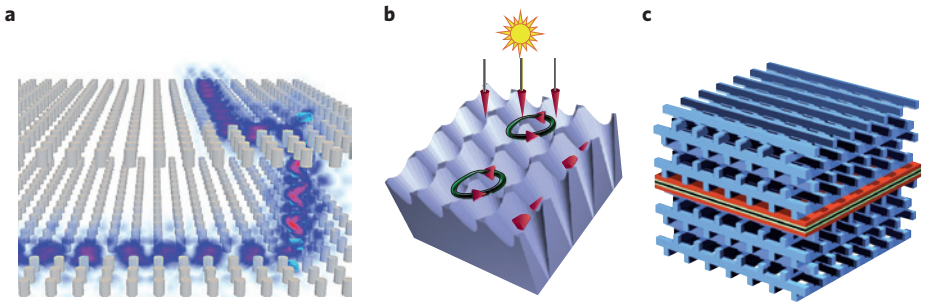

Figure 1 | Photonic crystal light-trapping takes numerous forms. **a**, A 3D optical microchip (showing two embedded planar microchip layers) guides light through air regions (intensity pattern shown in colour where red represents high intensity and blue represents low intensity) in a 3D circuit path with sharp bends on subwavelength scales. Here centre-to-centre distance between silicon rods (grey) is 600 nm for light with 1,500 nm wavelength. **b**, Solar-light-trapping architecture consists of a photonic crystal of slanted conical pores in silicon. Eighty-five per cent of sunlight in the wavelength range of 300–1,100 nm is trapped and absorbed in the thin film (1 μm of silicon) as it flows in circulating patterns (green circles) and parallel-to-interface resonances (red arrows). **c**, A semiconductor multiple quantum-well region (red-yellow-black) is sandwiched between two 3D PBG materials (blue). Excitons in the quantum well are prevented from radiative decay due to the PBG but experience ultrastrong coupling to a photonic band edge mode, facilitating exciton Bose–Einstein condensation at high temperatures. Panel **c** reproduced with permission from ref. 28, © 2007 APS.

core fibres (that could guide light without recourse to incision) without the fibre itself being damaged by the light. In 2004, when a particular patient with a recurrent life-threatening, respiratory tract cancer, was faced with unacceptable trauma from repetitive line-of-sight surgery, approval was obtained to use a hollow-core PBG fibre[17]. This fibre guided intense laser light non-invasively through a flexible endoscope inserted through the mouth, to remove and manage the cancer. This was perhaps the first human life directly saved by the science of photonic crystals.

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Photonic crystals perform novel functions in conditions common to human experience, allowing for broader applications. Light trapping is enabling not only for information and medical technologies, but also for energy technology. The efficiency of photovoltaic solar-energy conversion depends on the ability to trap and absorb light and then collect the photogenerated charge carriers before they recombine or lose their energy. Remarkably, photonic crystals provide a distinct type of light trapping suitable for absorbing broadband sunlight in a solar cell. This does not utilize a PBG but occurs in a spectral range where the engineered electromagnetic density of states is much larger than in an unstructured material[18]. This corresponds to a large density of high-quality optical resonances into which sunlight from a broad range of incident angles and over a broad spectrum can be trapped and absorbed.

Photovoltaics

Thin-film silicon solar cells are usually unable to absorb much sunlight in the near-infrared range of 800 to 1,100 nm due to the indirect nature of the silicon electronic bandgap. An unstructured 1-μm-thick slab of crystalline silicon, resting on a silica substrate, can produce a maximum achievable photocurrent density of no more than 8 mA cm^{-2}. This occurs if all absorbed solar photons (400–1,100 nm) are converted to electricity without carrier recombination losses. Carefully designed photonic crystals (Fig. 1b) consisting of the same amount of silicon and a back-reflector can yield more than four times this photocurrent[19,20] (S. Eiderman, S. John and A. Deinega, submitted for publication). This photonic crystal absorption exceeds the long-standing (hypothetical) statistical ray-trapping limits[21,22] of solar absorption. When losses are included, the overall power-conversion efficiency is about 20% for the 1-μm-thick silicon photonic crystal solar cell (A. Deinega, S. John and S. Eiderman, unpublished observations) compared with 5% efficiency for its unstructured counterpart. In other words, an efficiency that would normally require up to 300 μm thickness of very high-quality solid silicon can be realized using 1 μm of lower quality silicon sculpted into the form of a light-trapping photonic crystal. This reduces a crucial cost factor of converting solar energy to electricity.

Light trapping is also accompanied by intense light concentration in certain spatial regions. Such high intensities can be used to drive nonlinear optical effects that either up-convert[23,24] photons that are below the electronic bandgap of silicon or down-convert[25] photons that are too far above it. At present, more than 50% of incoming solar power is lost to either low-energy photons that cannot be absorbed in silicon or high-energy photons producing charge carriers that simply generate heat as the carriers thermalize and fall in energy to the electronic band edge. The photonic-crystal light-trap may help nonlinearly compress the broad solar spectrum, avoiding this wastage of solar power. If in this way photonic crystal photovoltaics can deliver power-conversion efficiencies surpassing 30%, it would be an industry game changer.

Bose–Einstein condensation

As a final illustration of why trap light, I return to fundamental science. One of the holy grails of quantum physics is the realization of macroscopic quantum coherence at room temperature. Cold-trapped atoms and 'high-temperature superconductors' are examples of such Bose–Einstein condensation (BEC), but even the latter have not been attained at room temperature. Optically excited charge carriers in a semiconductor such as GaAs are also candidates for BEC. An appealing aspect of excitons (bound electron–hole pairs) in a semiconductor quantum well, strongly coupled to a suitable optical mode, is that their effective mass can be made nearly five orders of magnitude smaller than in an unstructured, bulk semiconductor[26]. Essentially, the exciton inherits certain properties of the photon to which it is strongly coupled. The smaller the effective mass of the exciton, the longer its quantum mechanical de Broglie wavelength and the more likely BEC can occur at elevated temperatures. The exciton–photon coupling strength ultimately limits the temperature range over which BEC can occur.

In past experiments[27], GaAs quantum wells sandwiched between 1D photonic crystals (Bragg mirrors) have shown non-equilibrium signatures of trapped exciton BEC below 100 K. While strong coupling occurs between excitons and a desired optical cavity mode of the 1D photonic crystal, the excitons also couple

to extraneous optical modes into which they decay in picoseconds. This is not enough time to establish thermodynamic equilibrium and true BEC. On the other hand, by sandwiching quantum wells between a pair of 3D PBG materials (Fig. 1c), the unwanted radiative decay channels are removed. Essentially the photon that the exciton would normally emit forms a bound state to the exciton[28]. The coupling of the exciton to a 2D or 3D photonic band edge mode is many times stronger than for the 1D Bragg mirror. This offers the tantalizing possibility of long-lived exciton condensates[29], bringing the magic of macroscopic quantum mechanics to room temperature.

The greatest challenge to realizing the myriad of opportunities for photonic crystals lies in the realm of materials science. Inexpensive, precise and stable materials need to be synthesized with a route to mass production. Important recent strides have been achieved through techniques such as self-assembly[30], template inversion[31], optical phase mask lithography[32] and epitaxial growth of semiconductors through a template structure[33]. Greater perfection and economies of scale are needed. When confronted by candle-carrying critics of his ambition to commercialize the emerging technology of light bulbs, Thomas Edison once retorted "I will make the light bulb so cheap that only the rich can afford to burn candles!" The immense consequences of light-trapping photonic crystals should likewise invigorate the challenging and equally rewarding photonic crystal synthesis endeavour. ❐

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