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OPTICAL PHYSICS

Trapping the light fantastic

Using a material called a photonic crystal, researchers have designed a mirror that is, in a certain sense, perfect — there is in principle no light transmitted through it nor absorbed by it. SEE LETTER P.188

A. DOUGLAS STONE

Storing or confining light without absorbing it is of great importance for both science and technology. A device or system for trapping light is known as an optical resonator, and its most basic component is some kind of reflecting surface or region — a mirror in the general sense of the word. The most common type of mirror, a glass surface covered with a thin metal layer, has been around for two millennia, and mirrors of this type are crucial components of many optical systems. However, metal-based mirrors do absorb light to some degree. So, in modern optics research, scientists have developed many types of reflecting surfaces and resonators based on other principles. Given the tremendous and long-standing emphasis that optics places on trapping light, it is surprising that a substantially new type of mirror could still be discovered, but that is precisely what Hsu *et al.* have done[1] (page 188 of this issue).

The authors have designed a mirror based on a well-established system in modern optical physics known as a photonic crystal[2]. This is a dielectric (non-conducting) material that is patterned, often simply by drilling or cutting out a series of air holes, so as to leave a spatially varying but three-dimensional, periodic structure (Fig. 1). The system can trap, guide and control light using optical interference in a similar manner to the familiar one-dimensional grating, but with much greater design flexibility.

For example, one can make photonic-crystal waveguides that can confine or steer light just below the surface of the crystal. But just as for conventional waveguides, the light is totally internally reflected and thus fully confined only if it hits the surface at a sufficiently shallow angle. If it hits the surface at a steeper angle, it partially refracts out into the air and travels off to infinity. Such a partially trapped light wave is called a resonance; it can be observed by the strong reflection of an incident light wave, at the corresponding (steeper) angle, that penetrates into the crystal before reflecting back out.

However, Hsu *et al.* have discovered theoretically, and demonstrated experimentally, a photonic crystal that can violate this conventional behaviour at its surface: at a specific angle and frequency, the expected strong reflection resonance disappears. This implies that light cannot escape from inside at all, even though at this angle it is not totally internally reflected. Hence, at this angle and frequency, the system acts as a new kind of perfect mirror for a light wave approaching the surface of the crystal from inside. As a result of this behaviour, light can be trapped in the crystal indefinitely at a specific frequency and angle. Its lifetime, or '*Q* value' in the language of resonance theory, is infinite.

The authors show that this effect is due to a subtle kind of coincidence, similar to a phenomenon in quantum theory known as accidental degeneracy, in which the coupling between light waves inside and outside the photonic crystal vanishes simultaneously for both possible polarization states of light, even though there is no symmetry principle that demands that this happen (cases in which symmetry prevents coupling were previously known). In their system, the designers can vary three parameters (the frequency and the tilt angle of the incident light in both directions perpendicular to the crystal surface), which are enough to ensure that this 'coincidence' always occurs. Hence, their effect is robust against many types of small imperfections, such as those that actually exist in their, and any, experiment. Such imperfections slightly perturb the angle at which the light is perfectly trapped, but they do not eliminate the effect. The ultimate source of the perfect trapping, the authors show, can be traced back to destructive interference between different escape channels.

In fact, this work relates to a long-standing question in wave physics, which was famously addressed by two giants of quantum theory, John von Neumann and Eugene Wigner, in 1929. They asked if the Schrödinger equation of quantum mechanics allows 'bound states' (in their case, localized, trapped electron states) in the continuum — that is, if a perfect potential-energy trap could exist for an electron at the same energy at which a free electron could exist at infinity[3]. Although conventional wisdom held that this was

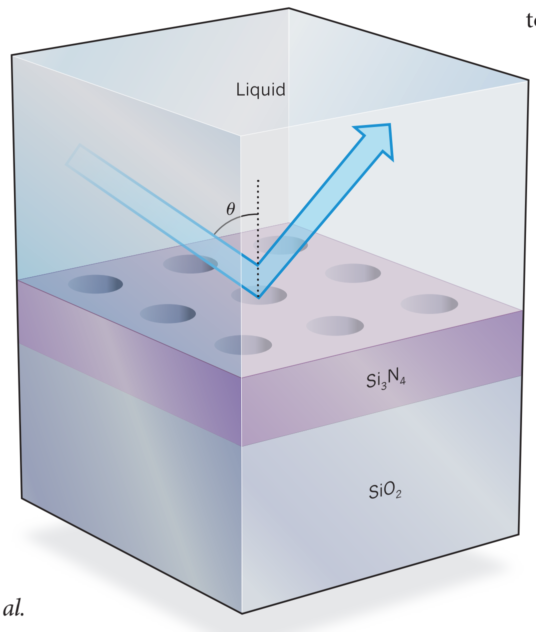

Figure 1 | A perfect mirror. Hsu and colleagues[1] have designed a photonic-crystal system that acts as a perfect mirror. The system consists of a silicon nitride (Si_3N_4) layer patterned periodically with holes, submerged in a liquid and mounted on a silicon dioxide (SiO_2) substrate. The liquid has the same index of refraction as the SiO_2 substrate, so that it gives the system up–down symmetry for light propagation. At one specific angle of incidence, θ, light of a certain frequency is perfectly reflected, with no absorption or transmission through the Si_3N_4 layer owing to a subtle interference effect. This indicates that a perfectly trapped state of light exists within the medium.

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impossible, von Neumann and Wigner showed that it can indeed be done in principle, and they constructed mathematically the special type of potential-energy function (analogous to the photonic-crystal structure in the current work) that would allow this to happen, at one specific energy. However, such a potential-energy trap was impractical to realize, because it extended out an infinite distance from its centre. Since that time, there have been several proposals for creating bound states in the continuum, and a few[4–6] were quite similar to Hsu and colleagues' realization. But none have been demonstrated experimentally, nor do they have the robustness and ease of implementation of the current work.

Hsu and co-authors' mirror presents a promising optical element for applications. Although in theory the mirror is perfect, and the current experiment indicates that it is extremely good, there are some imperfections that allow light to escape. The goal will be to tailor the leakage to be just right for proposed applications. A unique property of resonances of this type is that, although very little light will leak out to infinity, the electric field of the trapped light does extend outwards some distance across the entire surface. Resonances with such large surface area and high Q are just what are needed to make more powerful, highly directional, 'single-mode' lasers, as well as efficient surface sensors for biological and chemical applications. ■

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EARTH SCIENCE

A holistic approach to climate targets

An assessment of allowable carbon emissions that factors in multiple climate targets finds smaller permissible emission budgets than those inferred from studies that focus on temperature change alone. **SEE LETTER P.197**

JOERI ROGELJ

Ensuring sustainable human development for future generations will involve putting limits on the pressures that global society exerts on our planet[1]. Global warming is only one of those pressures; ocean acidification, chemical pollution and the rate of biodiversity loss are examples of others. These impacts do not occur in isolation. Many are intertwined and thus call for an integrated approach that explicitly accounts for possible interactions. A study by Steinacher *et al.*[2] in this issue (page 197) shows the importance of such an integrated-systems perspective, and provides valuable insight into what could form part of a "safe operating space for humanity"[1]. The authors quantify the ways in which simultaneously achieving multiple sustainability objectives influences the amount of carbon emissions we are allowed to emit. Their most striking finding is that when multiple limits are not allowed to be exceeded, permissible carbon emissions are generally lower than for the most restrictive single limit — a direct result of this holistic approach*.

Steinacher and colleagues' study focuses mainly on the climate system, but is not restricted to warming alone. Consistent with how the climate system is being defined in the international policy arena[3], the authors include aspects and interactions of the atmosphere, hydrosphere and biosphere in their analysis. By doing so, they go the crucial extra mile beyond previous studies that focused on temperature[4,5] or other effects in isolation. They impose limits on six target variables of the climate system that are related to one or more of the above-mentioned 'spheres': global-mean warming; sea-level rise from thermal expansion; ocean-acidification indicators both in the Southern Ocean and in locations that are common coral-reef habitats; changes in the net primary production of the terrestrial biosphere; and the loss of carbon from cropland soils.

How do Steinacher *et al.* explain their finding that allowable carbon emissions under multiple climate objectives turn out to be lower than for the most restrictive single limit? They explored this question using a global climate model of intermediate complexity in a probabilistic set-up. Such an approach provided them with a fully interactive representation of the geophysical processes of interest at manageable computational cost. They observed many cases in which meeting one objective in isolation simultaneously leaves open the possibility that other objectives are pushed beyond their allowed values. Combining emission constraints for all objectives then results in an overall smaller allowable carbon budget.

As is the case for most modelling studies, the true value of Steinacher and colleagues' work lies in its insights, not in its numbers[6]. The study is instructive because the authors point out its limitations, and caution against reading too much into its results. The target variables that they assessed are illustrative and will need further elaboration. For instance, their choice of objectives was limited to processes actually represented in their model. Therefore, targets on regional sea-level rise, for example, or interactions between human health and air pollution, could not be evaluated. Stakeholders might also need to evaluate trade-offs and set priorities with regard to the stringency of the respective limits. Furthermore, because the authors could not account for uncertainties in the model's structure, the assessment remains dependent on the model used[7]. Finally, the analysis uses a set of emissions scenarios from the literature that were not explicitly developed to span the entire range of possible future outcomes, and can therefore be at best informative.

The study's results clearly demonstrate the importance of holistic and integrated assessments of sustainable human development. The conventional focus on temperature change alone should move towards a more comprehensive accounting of multiple objectives and their interactions, from the global to the local scale. It calls not only for fuller integration of geophysical processes and biogeochemical cycles, but also for approaches that explore integrated policy answers to those challenges.

"The results clearly demonstrate the importance of holistic and integrated assessments of sustainable human development."

The relevance of such assessments for policy-making cannot be overemphasized. Nowadays, policy-makers need to carry out the often difficult task of linking global objectives to a variety of local effects. Approaches that follow Steinacher and colleagues' study could allow them to define explicit sustainability limits for a range of effects that directly influence the well-being of the populations involved. This will result in a better understanding of trade-offs and synergies between objectives, allowing them to be prioritized more effectively. To be sure, no modelling framework can by itself objectively

*This article and the paper under discussion[2] were published online on 3 July 2013.

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