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OPTICS

Gain and loss mixed in the same cauldron

The mathematical concept of parity–time symmetry, which was first introduced in field theories of quantum mechanics, has been demonstrated experimentally in a large-scale optical system. **SEE ARTICLE P.167**

LUCA RAZZARI & ROBERTO MORANDOTTI

The search for artificial structures exhibiting optical properties not found in nature is a major scientific endeavour. This effort has led, for example, to the development of photonic crystals[1] for controlling the propagation of electromagnetic waves by creating allowed and forbidden energy bands. It has also led to the design of metamaterials aimed at rendering objects invisible or at allowing super-resolution imaging[2,3]. Yet, irrespective of the specific system involved, most of these advances have so far been based on a judicious crafting of the spatial distribution of the refractive index across passive optical components, which require no input power to function. Indeed, refractive-index engineering is considered today to be one of the cornerstones of modern photonics. On page 167 of this issue, Regensburger and co-workers[4] herald the next frontier in this research field.

The authors' proposal is based on the fact that the refractive index is, in the most general case, a complex quantity. Whereas the real part of the index is responsible for the bending and slowing down of light, the imaginary part can lead to either amplification (gain) or absorption (loss) of light within a material. By modulating both the real and the imaginary part of the index, the authors were able to produce the first example of a new class of optical structure. The structure displays the recently developed concept of parity–time (PT) symmetry — a property of physical systems that are invariant under time inversion and mirror reflection. Key to achieving this symmetry was the authors' deliberate use of both gain and loss. Interestingly, PT symmetry was originally introduced in field theories of quantum mechanics[5].

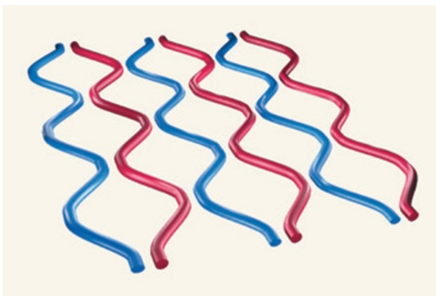

Figure 1 | A parity–time optical network. Regensburger *et al.*[4] have designed an optical system that displays parity–time symmetry. The system is analogous to a spatially periodic network of channels that either amplify (red channels) or absorb (blue channels) light.

Although the impact of PT symmetry in quantum mechanics is still open to debate, it has been recognized[6] that this concept could flourish in the field of optics if gain, loss and refractive index are manipulated. For an extended optical system to be PT symmetric, the refractive-index profile needs to be symmetric in its real part and anti-symmetric in the imaginary one. So far, the implementation of such PT-symmetric devices has been hampered by technical difficulties, and has thus been limited to simplified proof-of-principle structures involving only two components[7,8]. Regensburger and colleagues' work represents the first experimental demonstration of a large-scale PT-symmetric lattice, which introduces PT synthetic devices into the larger family of artificial optical systems.

To realize their artificial structure, and

50 Years Ago

The first practical research tool based on solid state lasers to be made available in the United Kingdom is announced by Kollsman Instrument, Ltd. The 'Pisto Laser', so called because of its double pistol-grip triggering, was designed and developed by the Company's associate in the United States of America, the Kollsman Instrument Corporation. It emits a beam of intense, coherent red light of wavelength 6929 Å., with a beam divergence of less than 0.3 degree … The radiation output of the pulsed, ruby, laser beam is more than 10^9 times the corresponding output of the Sun within the same frequency band … In communications research the 'Pisto Laser' can be used to study the characteristics of very narrow beam-width transmission of optical data; in medical research, high-intensity cauterization; in crystallography, crystal structures using non-linear light transmission; in photography, pictures of extreme clarity; and in biology, biological responses to high-intensity monochromatic stimulation.
From *Nature* 11 August 1962

100 Years Ago

A good deal has been recently heard about "holes in the air" in connection with sudden collapses of flying machines. Prof. W. J. Humphreys, of the Washington Weather Bureau, writing in *The Popular Science Monthly* for July, classifies the eight different types of atmospheric disturbance as follows:— A vertical group, including aërial fountains, aërial cataracts, aërial cascades, and aërial breakers, and a horizontal group, including wind layers, wind billows, and aërial torrents; in addition wind eddies fall under both groups. Holes in the sense of vacuous regions do not exist.
From *Nature* 8 August 1912

to study the transport of light therein, Regensburger *et al.* used an elegant experimental arrangement that operates in the temporal domain. The authors injected a sequence of light pulses into two connected optical-fibre loops that were designed to exhibit PT symmetry: the required anti-symmetry of the imaginary part of the refractive-index profile was attained by alternating gain and loss in the two loops using optical amplifiers and amplitude modulators; and the symmetry of the real component of the profile was introduced using phase modulators (devices that control where a light wave's peaks and troughs lie). Figure 1 shows a network that is a spatial equivalent of the authors' structure; each node of this spatial network corresponds to a specific 'time slot' of the temporal lattice.

Using this set-up, Regensburger *et al.* have observed unusual optical behaviour such as unidirectional invisibility. They demonstrate that their system can become totally invisible when light traverses it from one side, whereas it can still be seen when it is illuminated from the other. What's more, the authors suggest that the device could find interesting applications in laser science, in particular in the dynamical control of light power in laser cavities. Indeed, their set-up shares several similarities with a laser cavity known as an active mode-locking cavity, which produces a train of ultrashort optical pulses on the basis of active phase modulation and balance between gain and loss.

The demonstration of a large-scale PT-symmetric optical network in the temporal domain is undoubtedly of great importance. Yet the realization of a spatial analogue, such as a waveguide array or crystal, remains a challenge. Transferring PT-related concepts to the spatial domain would allow the implementation of new optical devices that could in principle be scaled down and arranged on a chip. In particular, we can envisage the use of PT symmetry in the next generation of metamaterials and plasmonic devices, which work by manipulating surface plasmons — collective, wave-like motions of free electrons on a metal surface. PT symmetry can put to good use these systems' light losses, which have always been considered problematic. Similarly, we can imagine devices that combine PT symmetry and nonlinear optical properties. Such composite systems could permit the exploration of unprecedented optical functions, further improving our ability to artificially manipulate light. ■

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ATMOSPHERIC CHEMISTRY

The X factor

Measurements in a forest reveal a previously unknown atmospheric oxidant that acts as a source of sulphuric acid — one of the main precursors for the formation and growth of aerosol particles and clouds. **SEE LETTER P. 193**

DWAYNE HEARD

Background signals are a nuisance for atmospheric scientists doing fieldwork, because they limit the sensitivity and precision of the instruments used to measure atmospheric composition. But it pays to inspect background signals carefully, particularly if the molecule under study is the hydroxyl radical ($OH^{\bullet}$, referred to here as OH for simplicity), the most important oxidant in the atmosphere. Just such an inspection led Mauldin *et al.*[1] to discover a previously unknown atmospheric oxidant, as they report on page 193 of this issue. Their findings should help to refine models of atmospheric oxidation processes.

The story begins in a Finnish forest (Fig. 1), where the authors were indeed measuring OH. Their method involved adding sulphur dioxide (SO_2) to airstream samples so that it reacts with OH to form sulphuric acid (H_2SO_4), which is then detected by a mass spectrometer. When they deliberately removed OH from their samples using a chemical scavenger, however, they noticed that the background signal was actually larger than the OH signal. In other words, something in the forest other than OH was converting sulphur dioxide into sulphuric acid in their analyses, and so must also have been doing so in the atmosphere above the forest.

The atmospheric concentration of the unknown oxidant — which Mauldin *et al.* dubbed 'X' — was found to exceed that of OH, most noticeably in the evenings and at night. The concentration of X showed no clear daily cycle, however, suggesting that it forms from the reaction of surface emissions, such as naturally produced hydrocarbons, with ozone (O_3).

To test this hypothesis, the authors performed laboratory experiments in which they exposed sulphur dioxide to mixtures of ozone and various unsaturated hydrocarbons (alkenes). The reactions of alkenes with ozone are known to produce OH, but the levels of sulphuric acid observed in the experiments were well above those that would have been expected from the reaction of OH with sulphur dioxide alone. This was especially true when the authors reacted ozone with limonene and α-pinene, two alkenes emitted by trees[2]. To prove beyond reasonable doubt that plant emissions are linked to X, Mauldin *et al.* went back to the forest and placed cut tree branches close to the inlet of their oxidant-measuring instrument. Sure enough, they observed substantial levels of X.

The authors propose that X is probably a stabilized Criegee intermediate[3]; such molecules are free radicals that form from the reaction of ozone with alkenes, and are known to react with sulphur dioxide[4]. But the rates of the reactions of Criegee intermediates with sulphur dioxide were thought to be too slow to have any atmospheric relevance to the formation of sulphuric acid[5]. So is the authors' interpretation correct?

Support comes from a paper published earlier this year[6], in which the simplest Criegee intermediate, CH_2OO, was detected directly for the first time, and was shown to be much more reactive towards sulphur dioxide than previously thought. When Mauldin *et al.*[1] estimated the rate constants — measures of reaction rates — for reactions of sulphur dioxide with the Criegee intermediates generated from α-pinene and limonene, they found that these reactions, too, were faster than previously assumed.

In their field experiments, the authors were able to measure atmospheric concentrations of sulphuric acid at the same time as they detected OH. They therefore compared the concentration of atmospheric sulphuric acid in the Finnish forest with the concentration that would have been produced by the oxidation of sulphur dioxide by OH alone, which they calculated from the measured concentrations of atmospheric OH and sulphur dioxide. They observed a difference at all times of the day, with the difference scaling with the concentration of X, clearly connecting X to the formation of the acid.

By determining the rate constant for the reaction of X with sulphur dioxide in their laboratory experiments, Mauldin *et al.* calculated the concentration of sulphuric acid in