NONLINEAR OPTICS

Asymmetry from symmetry

An unusual form of symmetry breaking in coupled microresonators with balanced optical gain and loss is now exploited to realize a novel type of optical isolator.

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Each mode of an optical resonator has a finite lifetime: the confined light eventually leaks away either through radiation loss or intrinsic material absorption. The properties of a long-lifetime mode — particularly its frequency and spatial profile — are typically almost exactly the same as in the lossless case. However, this seemingly self-evident behaviour can break down if optical gain is also present. An example of this situation that has been of particular recent interest is the 'PT-symmetric' structure. These structures feature spatially balanced regions containing equal and opposite amounts of gain and loss — PT refers to the combination of spatial-parity (P) and time-reversal (T) symmetry operations, where the latter swaps gain and loss processes[1,2]. The simultaneous presence of gain and loss in a PT-symmetric structure can alter both the frequencies and spatial profiles of the optical modes. This occurs through an unusual version of spontaneous symmetry breaking: modes with unbroken PT symmetry are distributed evenly across both halves of the structure in such a way that the gain and loss compensate for each other; PT-broken modes, on the other hand, become spontaneously concentrated in either the amplifying or lossy half and undergo either net gain or loss.

PT symmetry was originally proposed as a speculative extension of fundamental quantum mechanics[1]. But research from 2008 revealed that studying the concept was feasible using coupled optical waveguides[2]. This ignited a flurry of research into PT-symmetric optics, including recent experimental demonstrations in silicon-on-insulator waveguides[3] and optical-fibre loops[4]. As they now describe in *Nature Physics*, Bo Peng and colleagues[5] have taken an important step in the practical exploitation of PT symmetry for device applications by realizing the first resonant on-chip optical device exhibiting PT-symmetry breaking and showing that it can act as an efficient nonlinear optical isolator.

Their device consisted of two coupled silica microtoroid resonators (Fig. 1). The resonators were spatially symmetric and subject to similar losses, but one was doped with erbium (a gain medium). Tapered fibres coupled to each resonator probed the system's resonances and provided optical pumping of the gain medium. By varying the inter-resonator coupling at fixed levels of gain and loss, Peng *et al.* observed a pair of resonances undergoing a characteristic PT-symmetry-breaking 'bifurcation': the two resonance frequencies coalesced, and the difference between the lifetimes diverged as one mode became increasingly concentrated in the amplifying resonator and the other in the lossy resonator.

The team also explored their device's utility as a nonlinear optical isolator. The development of on-chip optical isolators is one of the key challenges in integrated optics — one that arises from the difficulty of miniaturizing traditional Faraday isolators based on magneto-optic materials[6]. It is known that, as an alternative to magneto-optic materials, nonlinear media can achieve optical isolation, and in 2010 it was proposed theoretically that PT-symmetry breaking could be useful for designing

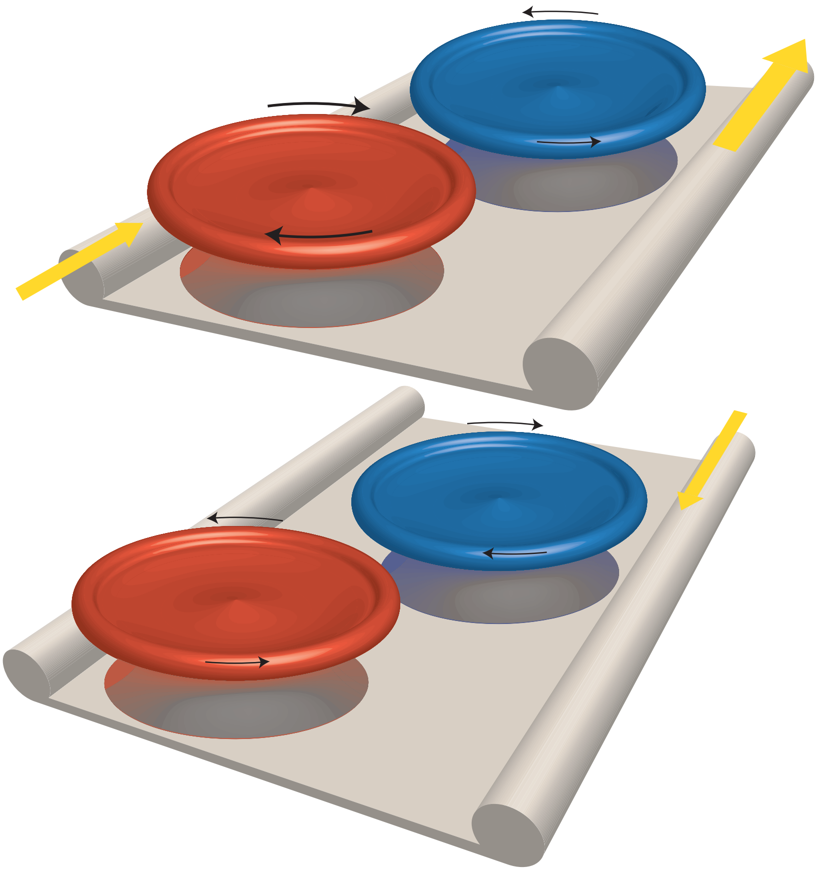

Figure 1 | A nonlinear optical isolator based on parity–time symmetry. Peng *et al.* create a pair of coupled microtoroid resonators, one providing gain (red) and the other loss (blue). With optical nonlinearity present, light (yellow arrows), passing through the resonators from optical fibres, is amplified in one direction (top) and is attenuated in the opposite direction (bottom). Figure reproduced from ref. 5.

such devices[7,8]. The trick is to ensure that ‘forward’ transmission occurs via an amplified PT-broken mode and ‘backward’ transmission via its dissipative counterpart.

Peng *et al.* accomplished this by attaching the input fibre to the resonator containing gain, and the output fibre to the lossy resonator. In the linear regime, such a set-up cannot produce optical isolation owing to a fundamental principle called optical reciprocity, which holds even in the presence of (linear) gain and loss. This states that light propagating from one port to another necessarily receives the same net gain or loss as it would if the input and output ports were reversed[9]. Optical nonlinearity, however, breaks reciprocity and allows for the possibility of optical isolation. Based on these ideas, non-reciprocal propagation (without isolation) has previously been demonstrated in PT-symmetric optical waveguides[3], and the realization of optical isolation using PT-symmetric resonators has been theoretically proposed and studied in an electric-circuit analog[8]. The work of Peng *et al.* is the first experimental realization of this type of optical isolator.

It is worth noting that exact PT symmetry is not required for the isolator to function; indeed, PT symmetry generally breaks down when optical nonlinearity is present. Rather, approximate PT symmetry serves as a convenient way to produce pairs of modes with closely matched frequencies, but very different spatial characteristics and gain/loss rates. The resulting device performs remarkably well: Peng *et al.* note that it has a lower minimum operating power and better contrast between forward and backward transmission than many of the nonlinear optical isolators thus far studied in the literature. A future version of this isolator, in which the resonators are coupled to integrated optical waveguides, could serve as a vital component in an integrated optical circuit. Even in the linear regime, this work could be developed into a platform for the exploration of exotic optics, such as the effects of gain and loss in coupled resonator lattices. ❐

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