Nonlinear optics : asymmetry from symmetry

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2014

Yidong, C. (2014). Nonlinear optics : asymmetry from symmetry. Nature physics, 10(5), 336-337.

https://hdl.handle.net/10356/79403

https://doi.org/10.1038/nphys2941

Title: Asymmetry from symmetry

Abstract: An unusual form of symmetry breaking, in coupled microresonators with balanced optical gain and loss, has been exploited to realize a new type of optical isolator.

In an optical resonator, each mode has a finite "lifetime" that describes how long it takes to leak away, through radiation loss as well as intrinsic material absorption. Typically, if a mode's lifetime is long, its other properties---particularly its frequency and spatial profile---will be almost exactly the same as in the lossless case. However, this seemingly self-evident behavior can break down if optical gain is also present. Of particular recent interest are "PT-symmetric" structures, which 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]. In a PT-symmetric structure, the simultaneous presence of gain and loss can alter both the frequencies and spatial profiles of the optical modes. This occurs through an unusual version of spontaneous symmetry breaking: some modes, called "PT-symmetric", are distributed evenly across both halves of the structure, in such a way that the gain and loss compensate for each other, whereas other "PT-broken" modes become spontaneously concentrated in either the amplifying or lossy half, hence undergoing either net gain or loss.

PT symmetry was originally proposed as a speculative extension of fundamental quantum mechanics [1], but in 2008 it was pointed out that the concept could be feasibly studied 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 fiber loops [4]. On page ??? of this issue, Peng et al. have taken an important step in the exploitation of PT symmetry for device applications. They have realized the first resonant on-chip optical device exhibiting PT symmetry breaking, and shown that it can be used as an efficient nonlinear optical isolator.

Their device consists of two coupled silica microtoroid resonators. The resonators are spatially symmetric and subject to similar losses, but one is also doped with erbium (a gain medium). Tapered fibers, coupled to each resonator, are used to probe the system's resonances and for optical pumping of the gain medium. By varying the inter-resonator coupling at fixed levels of gain and loss, the authors were able to observe a pair of resonances undergoing a characteristic PT symmetry-breaking "bifurcation": the two resonance frequencies coalesce, and the difference between the lifetimes diverges as one mode becomes increasingly concentrated in the amplifying resonator and the other in the lossy resonator.

The authors have also explored the device's utility as a nonlinear optical isolator. The development of on-chip optical isolators is one of the key challenges in the field of integrated optics, arising from the difficulty of miniaturizing traditional Faraday isolators based on magneto-optic materials [5]. It is known that, as an alternative to magneto-optic materials, nonlinear media can be used to achieve optical isolation, and in 2010 it was proposed theoretically that PT symmetry breaking could be useful for designing such devices [6,7]. The trick is to ensure that "forward" transmission occurs via an amplified PT-broken mode, and "backward" transmission via its dissipative counterpart. In the present device, this is accomplished by attaching the input port to the resonator containing gain, and the output port to the lossy resonator. In the linear regime, such a setup cannot produce optical isolation, due to a fundamental principle called "optical reciprocity", which holds even in the presence of (linear) gain and loss, and states that light propagating from one port to another necessarily receives the same net gain or loss as if the input and output ports were reversed [8]. Optical nonlinearity, however, breaks reciprocity, and this allows for the possibility of optical isolation. Based on these ideas, nonreciprocal 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 [7]. The work of Peng et al. is the first experimental realization of this type of novel 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: the authors note that it has a lower minimum operating power, and better con trast 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 of 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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