Observation of Parity-Time Symmetry in Optical Systems

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Quantum mechanics demands that each physical observable must be hermitian. In the case of the Hamiltonian operator, this axiom not only implies real eigen-energies but also guarantees probability conservation. Hermiticity is believed to be an absolute must in order to have real eigenvalues. Interestingly, however, a wide class of non-hermitian Hamiltonians can still exhibit entirely real spectra. Among these, are Hamiltonians respecting parity-time (PT) symmetry.[1]

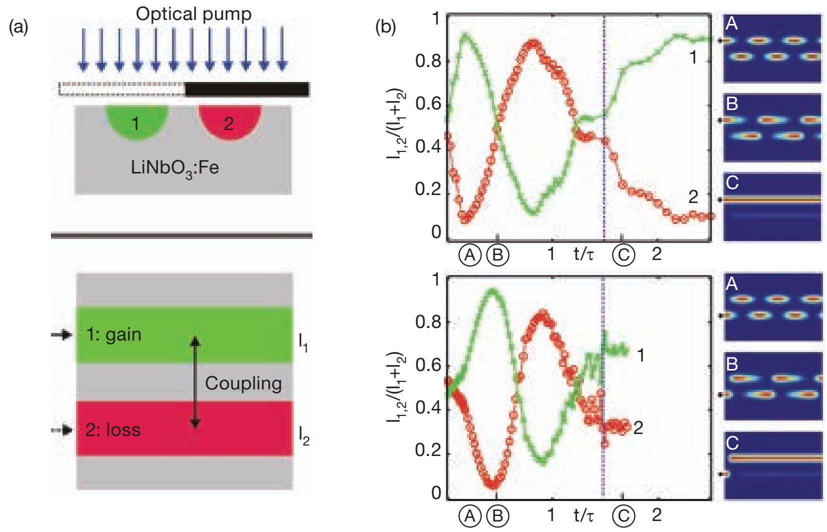
In general, such PT reflection requires that the associated complex potentials obey the condition $V(x)=V^{*}(-x)$. Even though the hermiticity of quantum observables was never in doubt, such concepts have motivated discussion in theoretical physics. They have led to a critical re-examination of hermiticity in many disciplines, including quantum field theories, non-hermitian Anderson models, and open quantum systems. While the impact of PT symmetry is still debated, optics provides a fertile ground for PT-related notions to be investigated.[2-4]

Early this year, we reported observation of PT symmetry in an optical coupled system.[5] Such PT "optical potentials" can be realized through a judicious inclusion of index guiding and gain/loss regions. Given that the complex refractive index distribution $n(x)=n_R(x)+in_I(x)$ plays the role of an optical potential, one can then design a PT-symmetric system where the refractive index profile must be an even function of position x while the gain/loss distribution should be odd.

In our experiments, we used two Ti in-diffused parallel waveguide channels in Fe-doped $LiNbO_3$. One of the channels was optically pumped from the top via photorefractive two-wave mixing to provide the necessary gain for the guided light, while the neighboring arm experienced loss. In this single-cell PT system, we observed both spontaneous PT symmetry breaking and power oscillations violating left-right symmetry. The experimental response (intensities $I_{1,2}$ of channels 1 and 2, as well as their phase relation) of our optical system, when exciting either the gain or loss channel, is in excellent agreement with solutions of the corresponding wave equations.[5]

At $t = 0$, the system evolves from zero gain and shows a reciprocal response. However, as the photorefractive gain builds up for recording times $t > 0$, optical wave propagation becomes strongly nonreciprocal. At threshold, the system's supermodes become degenerate. From there on, power in the gain channel monotonically increases, while power in the loss channels decays.

Our results, when extended to transversely periodic media (photonic lattices, waveguide arrays), pave the way toward a new class of PT-synthetic optical materials with intriguing properties that rely on nonreciprocal light propagation and tailored transverse energy flow. Nonlinearities can be used to fabricate novel functional systems like PT lattices. This may provide a platform to investigate, for example, the fascinating behavior of phase transition.



(a) Front (top) and top (bottom) view of the PT-symmetric coupled system fabricated in $LiNbO_3$. (b) Measured (normalized) intensities $I_{1,2}$ at the output facet during optical pumping as a function of time t (normalized by the time constant τ for build-up of gain). The upper/lower panel shows the situation when light is coupled into channel 1 and 2, respectively. Clearly, with increasing gain, the system behaves in a nonreciprocal manner. Blue dashed lines mark the symmetry-breaking threshold. Above that, light is predominantly guided in channel 1—thus experiencing gain—and the intensity in both channels depends solely on the magnitude of the gain. The power evolution is also depicted (last column) at various times.

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