Nonreciprocal phase transitions and time-space crystals

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Abstract: Using nano-opto-mechanical platform we demonstrate a new class of photonic materials in which illumination with light creates nonreciprocal interactions that spontaneously breaks continuous space and time translation symmetries into discrete translation symmetries.

Time crystals are a keenly-sought, non-equilibrium state of matter (predicted by Frank Wilczek in 2012) with properties periodic in time, rather than in space. Following Wilczek's work, it was quickly understood that the envisioned spontaneous transition to such a state, breaking continuous time translation symmetry, is only possible in an open system. Discrete time-translation symmetry breaking has been demonstrated in systems including trapped ions, atoms, and spins, where an external periodic force initiates oscillation at sub-harmonic frequencies. But experimental systems realizing the spirit of the original proposal – spontaneous breaking of continuous time translation symmetry in response to an arbitrarily weak perturbation – have remained elusive, until recently.

We have now observed the continuous time/space crystal state in a classical nano-mechanical photonic metamaterial – an array of dielectric nanowires decorated with π-shaped plasmonic metamolecules [1]. Under illumination resonant with the metamolecules' plasmonic mode, electromagnetic interactions among the nanowires control a transition from incoherent motion to synchronized periodic oscillation. At a ($\mu W/\mu m^2$) threshold level of continuous light intensity, the system "crystallizes in time," switching from a regime of low-amplitude (picometric) thermomechanical fluctuation to one of robust, synchronized oscillation. With subsequent reduction of the incident light intensity the time crystal "melts," but at a lower intensity level than the synchronization threshold, thereby yielding a hysteresis in properties (Fig. 1).

The phenomenon illustrates a novel mechanism of spontaneous synchronization among noise-driven, linear oscillators. It belongs to a recently identified class of 'nonreciprocal phase transitions' [2]: Synchronization occurs not because of nonlinearity (e.g. as in the Kuramoto model) but via nonreciprocal interactions (non-Hamiltonian optical forces) between plasmonic metamolecules, which emerge from the radiation pressure of scattered fields constantly pumping energy into the system.

The simplicity of control achievable in the nano-opto-mechanical metamaterial platform offers a path towards applications in all-optical modulation, frequency conversion and timing, and for the study of dynamic classical many-body states in the strongly correlated regime.

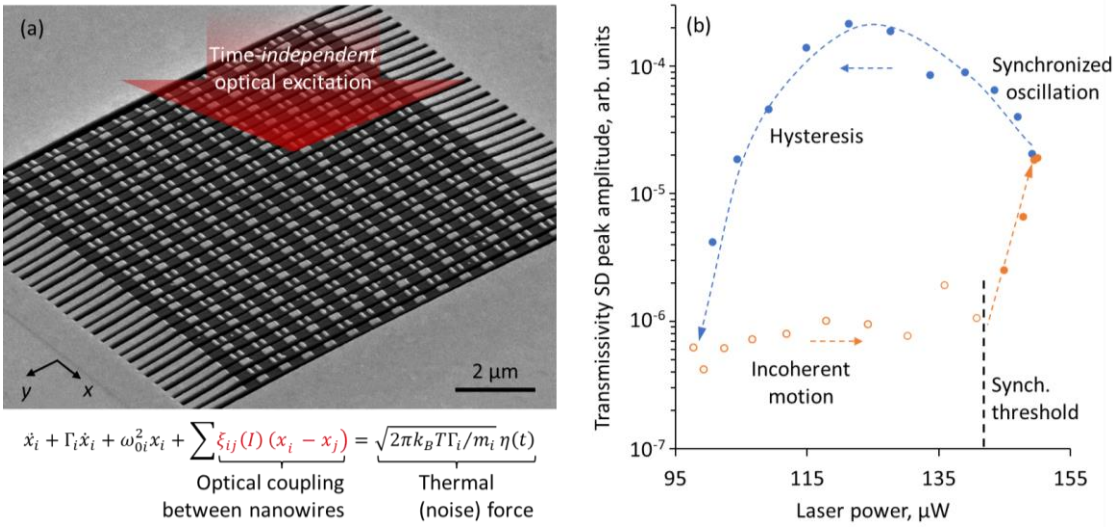

Fig. 1. (a) Metamaterial continuous time crystal constructed as an array of nanowires decorated with plasmonic metamolecules. (b) Light-induced interactions among metamolecules lead to synchronized motion of the nanowires via a 1st-order, non-reciprocal phase transition, resulting in a manifold increase of transmissivity modulation.

References

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[2] M. Fruchart, R. Hanai, P. B. Littlewood, and V. Vitelli, "Non-reciprocal phase transitions," Nature **592**, 363 (2021).