Wilczek's Time Crystals on Photonic Metamaterial Platforms

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Time crystals, first discussed by Frank Wilczek in 2012 [1], are many-body interacting systems exhibiting a spontaneous transition to a robust oscillatory state, breaking continuous time translation symmetry in response to an arbitrarily small change in an external driving force. Here, we present time crystals driven by predator-prey-like, nonreciprocal optical interaction forces in metamaterial arrays, arising between alternately dissimilar nanowire oscillators decorated with plasmonic or dielectric nanoparticles (Fig.1a): Above a threshold incident light intensity level, these forces trigger a spontaneous transition in the nanowire array, from a state of uncorrelated stochastic thermal fluctuation to one of synchronized, high amplitude periodic motion [2,3].

Experimental and computational studies of the transient dynamics of this 'mobilization' transition, mapping the phase trajectories of the nanowire system (Fig. 1b-e), demonstrate that it is characterized by ergodicity-breaking and a local decrease in the entropy of the nanowires' motion. The breaking of continuous (as opposed to discrete) time translation symmetry is confirmed by the random phase of mobilized oscillation with respect to the triggering event.

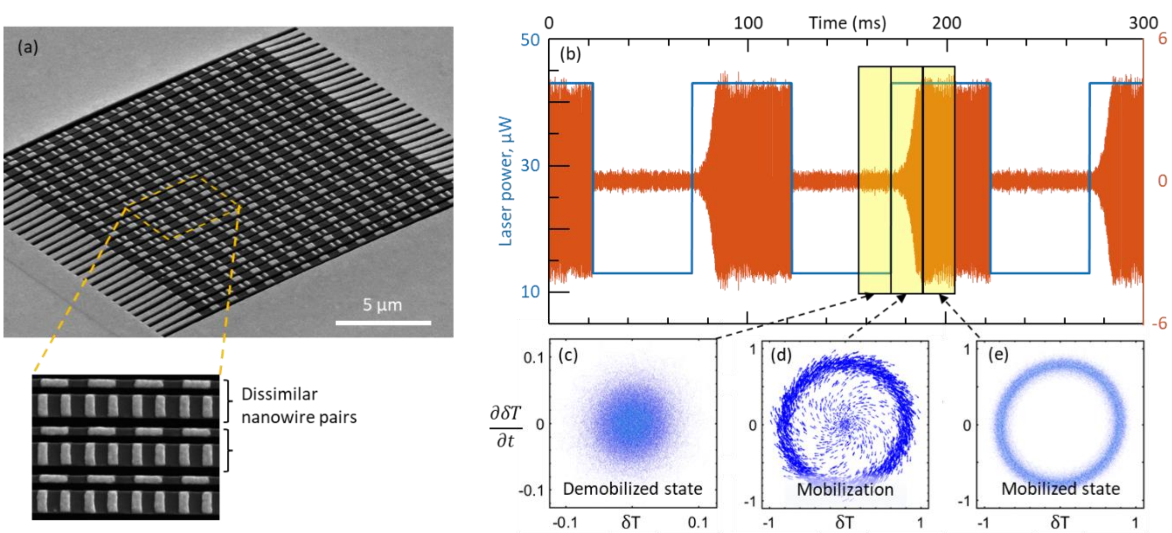

Fig. 1. (a) Plasmonic metamaterial time crystal array comprising alternately dissimilar free-standing silicon nitride nanowires decorated with gold nanorods. Light at a wavelength of 1.55 µm induces nonreciprocal out-of-plane interaction forces between the two parts of the π-shaped metamolecules supported on neighbouring nanowires, triggering spontaneous synchronization of nanowire oscillation across the array above a certain threshold intensity. (b) Metamaterial transmissivity oscillation dynamics during mobilization and demobilization. (c-e) Transmissivity phase diagrams: (c) of the disordered state; (d) during mobilization; (e) of the mobilized time crystal state. Phase diagrams are derived from analysis of the segments indicated by the yellow shaded boxes in (b) over hundreds of repeated mobilization cycles.

Nano-opto-mechanical metamaterial time crystals provide insight, and a platform to study the classical dynamics of many-body systems in the strongly correlated regime, complementing cold atom and spin quantum platforms. They present opportunity for implementing all-optical neural networks and reservoir computing architectures, and for developing optical 'timetronic' functionalities [4], based upon spontaneous symmetry and ergodicity breaking.

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[4] N. I. Zheludev, "Time crystals for photonics and timetronics," Nat. Photon., **18**, 1123 (2024).