Transition Dynamics of Photonic Metamaterial Continuous Time Crystals

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The transition dynamics of metamaterial time crystals driven by nonreciprocal optical forces reveal their stability and rigidity, establishing them as a platform for timetronics – an emerging information technology leveraging unique functionalities of time crystal states.

Time crystals, first discussed by Frank Wilczek in 2012, are many-body interacting systems that exhibit a spontaneous transition to a robust synchronized oscillatory state, breaking time translation symmetry under an arbitrarily small change in the external driving force. Here, we examine the transition dynamics of a new type of time crystal driven by nonreciprocal, predator-prey-like, optical interaction forces in a metamaterial array, which arise between nanowire oscillators alternately decorated with dissimilar nanoparticles. Above a certain threshold of incident light intensity, they trigger a transition in the nanowire ensemble, from a state of uncorrelated stochastic thermal motion to one of synchronized, high amplitude oscillation. This transition, and the reverse - back to the thermal fluctuational state, are known as mobilization and demobilization, respectively.

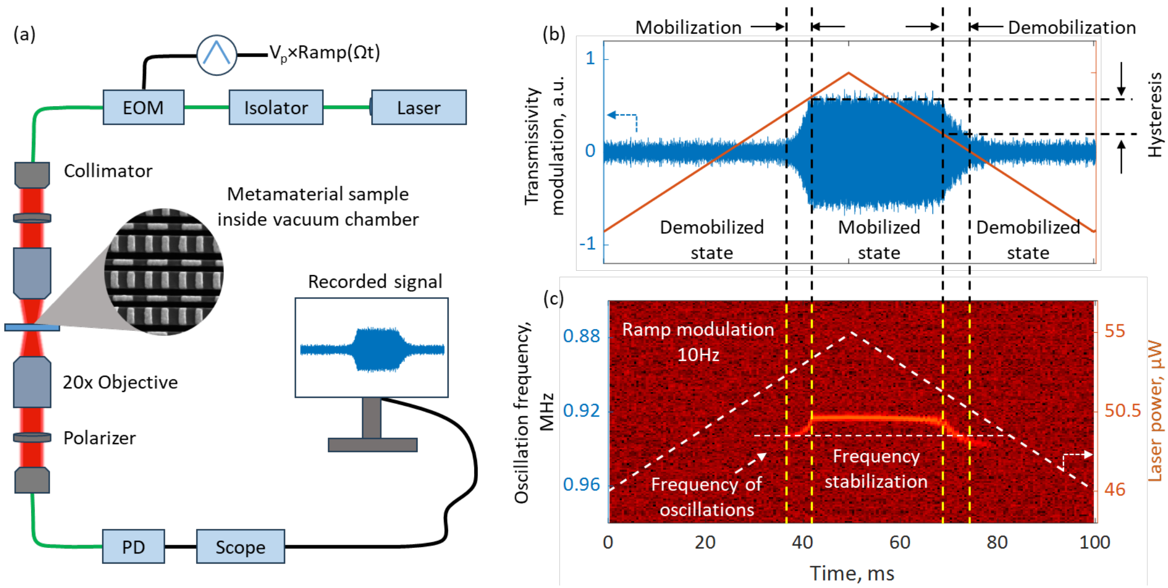

Fig. 1. (a) Schematic of the experimental arrangement for observing transition dynamics of a metamaterial time crystal - comprising a 2D (12 µm × 28 µm) array of π-shaped plasmonic metamolecules supported on flexible silicon nitride nanowires [as shown in the inset electron microscope image]. (b) Incident laser power [orange line] and corresponding metamaterial transmissivity change [blue] as a function of time over one cycle of adiabatic incident power modulation. (c) Corresponding dependence of transmissivity frequency spectrum on time [i.e. laser power].

The metamaterial nanowire array is mounted inside a low vacuum (~10^{-3} mbar) chamber in a transmission microscope and illuminated with linearly polarized laser light at 1550 nm, modulated adiabatically around the few tens of µW transition threshold for realization of the time crystal state (Fig. 1a). Changes in the mutual displacement of nanowires change the transmissivity of the array, as illustrated in Fig. 1b for one cycle of incident laser power modulation: Below the mobilization threshold, the nanowires exhibit independent stochastic thermomechanical fluctuations driven by momentum transfer from flexural phonon creation and annihilation, yielding low amplitude transmissivity fluctuations. Above threshold, the array spontaneously transitions to a synchronized oscillatory state characterized by high amplitude transmissivity oscillation. The nanowire ensemble's frequency spectrum (Fig. 1c) narrows through the mobilization transition to a single synchronized oscillation frequency (~922 kHz in the present case). Both the amplitude and frequency of oscillation remain stable until the demobilization threshold is crossed, upon decreasing incident laser power. This, and the hysteretic nature of the mobilization-demobilization cycle, are clearly seen in a plot of transmissivity oscillation.

Figure 1 presents data for a plasmonic metamaterial time crystal. Similar dynamics are observed in all-dielectric systems (silicon nitride nanowires decorated with Mie resonant amorphous silicon nanoparticles). We study both under varying conditions of incident power threshold crossing and in the presence of noise to probe the rigidity and criticality of the time crystal state.