Metamaterial Continuous Time Crystal - A New State of Photonic Matter

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We report that a classical metamaterial nanostructure, a two-dimensional array of plasmonic metamolecules supported on flexible nanowires, can be driven to a state possessing all key features of a continuous time crystal: continuous coherent illumination by light resonant with the metamolecules' plasmonic mode triggers a spontaneous phase transition to a superradiant-like state of transmissivity oscillations resulting from many-body interactions among the metamolecules, characterized by long-range order in space and time.

Time crystals are an eagerly sought new phase of matter in which time-translation (TT) symmetry is broken and are of particular interest in photonics for their promise to support a variety of new wave propagation phenomena. As originally proposed [1], a time crystal is a quantum many-body system whose lowest-energy state is one in which the particles are in continuous oscillatory motion. Although it has subsequently been shown that such systems, breaking *continuous* TT symmetry, are prohibited in nature, several systems manifesting *discrete* TT symmetry-breaking imposed by an external modulated parametric drive have been realized on various platforms, including trapped atomic ions, spin impurities, ultracold atoms, condensates of magnons and quantum computers. A quantum time crystal that breaks TT symmetry continuously has also been observed recently in a Bose-Einstein condensate within an optical cavity.

Here, we show that a 2D lattice of plasmonic metamolecules supported on doubly-clamped nanowires cut from a semiconductor membrane (Fig. 1a) spontaneously transitions, at room temperature, to a continuous time crystal analogue state characterized by persistent transmissivity oscillations when illuminated by coherent light that stimulates interaction among the metamolecules. Above a threshold of incident optical power, the spectrally dispersed thermal fluctuations of the individual nanowires become spatially coherent synchronous oscillations over the illuminated ensemble (Fig. 1b).

The metamaterial is illuminated with a single continuous beam of laser light at a wavelength of 1550 nm. At low power (≤tens of μW), the transmissivity spectrum contains several small amplitude peaks, at ~1 MHz, derived from the thermomechanical oscillation of individual nanowires (with characteristic amplitude ~250 pm). With adiabatically increasing laser power, at ~130 μW, the onset of synchronization is observed first in a narrowing of the spectrum. Further increasing power leads to spontaneous synchronization of the nanowires' oscillation, and the emergence of a single narrow peak in the transmissivity spectrum, with an amplitude four orders of magnitude larger than the peaks associated with the individual nanowires' uncorrelated fluctuations. With decreasing laser power, hysteretic loss of synchronization is observed, demonstrating the first order nature of the synchronization phase transition.

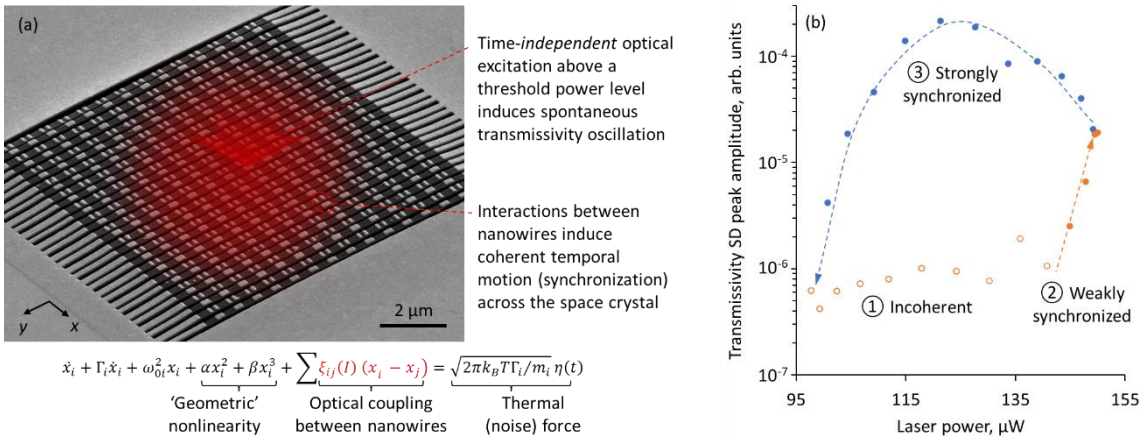

Fig. 1 Metamaterial analogue of a continuous time crystal: (a) plasmonic metamolecules - Π-shaped arrangements of three Au nanorods - are supported on adjacent pairs of dielectric nanowires such that the wires' mutual displacement strongly affects the metamolecules' resonant optical properties. (b) Synchronization as a 1st-order phase transition: Peak amplitude of transmissivity oscillation spectral density against increasing [orange symbols] and decreasing [blue] incident laser power.

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

[1] F. Wilczek, "Quantum Time Crystals," Phys. Rev. Lett. **109**, 160401 (2012).