

Time Translation Symmetry Breaking and Random Number Generation in a Metamaterial Time Crystal

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The inherent unpredictability of oscillation phase in the continuous time crystal state on a nano-opto-mechanical platform, experimentally validated by statistical analysis, offers a novel, on-demand source for true random number generation.

Time crystals are an exotic non-equilibrium state of matter exhibiting spontaneous time translation symmetry breaking (S τ B) in the transition to a state of robust periodic motion [1]. Here, we provide experimental evidence, and corresponding statistical analysis, of light-induced S τ B in an ensemble of nonreciprocally interacting nano-opto-mechanical oscillators. S τ B is manifested in the randomness synchronized oscillation phase in the time crystal state. The null-hypothesis of randomness in the uniformity, and unpredictability of oscillation phase in time crystal state is firmly supported by Kolmogorov–Smirnov (K-S), and autocorrelation tests respectively. Other entropy and spectral tests confirm the absence of any underlying pattern or regularity over repeated realizations. While evidencing nonreciprocal coupling as a mechanism for S τ B, our results also have immediate practical implications as they demonstrate a new physical means of generating random numbers on demand (Fig. 1).

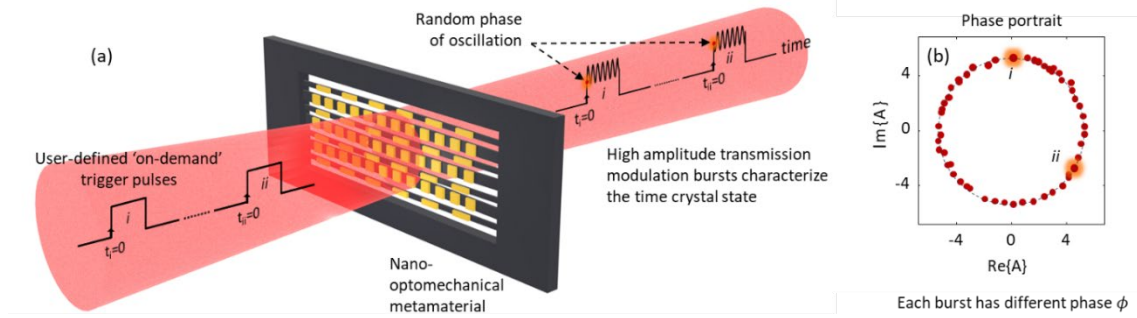


Fig. 1. Schematic illustration of on-demand random number generation based on a nano-opto-mechanical metamaterial time crystal. (a) Using a series of user-controlled, arbitrarily timed optical trigger pulses, the nanowire ensemble can be repeatedly driven to the time crystal state, yielding a sequence of synchronized transmissivity oscillation bursts with random phases, but consistent frequency and amplitude. (b) Typical phase portrait of a burst sequence, plotted as the imaginary vs. real part of the amplitude spectral density at the synchronized frequency.

The device consists of a 2D array ($12\ \mu\text{m} \times 28\ \mu\text{m}$) of π -shaped plasmonic metamolecules supported on flexible dielectric nanowires, mounted in a low-vacuum ($\sim 10^{-3}$ mbar) chamber in a transmission microscope. In the absence of illumination, the nanowires exhibit low-amplitude, incoherent motion driven by stochastic thermal forces. Linearly polarized continuous laser light at 1550 nm (resonant with the plasmonic metamolecules), above a certain threshold intensity, triggers spontaneous, high-amplitude coherent oscillation across the array. In successive realizations of the time crystal state, triggered by square wave laser power modulation around the transition threshold ($\sim 40\ \mu\text{W}$), the nanowires oscillate at the same frequency but with random phase. We analyse phase randomness over 200 cycles using statistical tests for specific relationships within the sequence, including the χ^2 and Kolmogorov–Smirnov (K-S) tests for goodness of fit, the autocorrelation test for independence of phase from cycle to cycle, and spectral and entropy tests for hidden periodic patterns or regularities in the sequence.

The sequence of oscillation phases generated through repetitive realizations of the time crystal state passes all of these statistical tests: they are uniformly distributed at a significance level of 5%, independent from cycle to cycle, and do not depend on prior oscillation states with 95% confidence. The phase of time crystal state oscillation thus serves as a novel and reliable source for true random number generation. The timing of trigger pulses is user-defined, so a random number sequence can be generated on demand. This stands in contrast to other generators based on physical phenomena, such as radioactive decay, which cannot be controlled by the user.

We argue therefore, that optically controlled time crystals driven by nonreciprocal forces represent a potentially important platform for random number generation as they are easy to fabricate and to integrate with other photonic devices at the nanoscale. More broadly, the nano-opto-mechanical metamaterial platform is suitable for developing various components for optical ‘timetronics’ – a technology relying on the unique functionalities of time crystals, derived from their spontaneous breaking of time translation symmetry and ergodicity [2].

[1] M. P. Zaletel, et al., "Colloquium: Quantum and classical discrete time crystals". *Rev. Mod. Phys.*, **95**, 031001 (2023).

[2] N. I. Zheludev, "Time crystals for photonics and timetronics," *Nat. Photon.*, **18**, 1123-1125 (2024).