Blurring the boundary between Floquet matter and metamaterials

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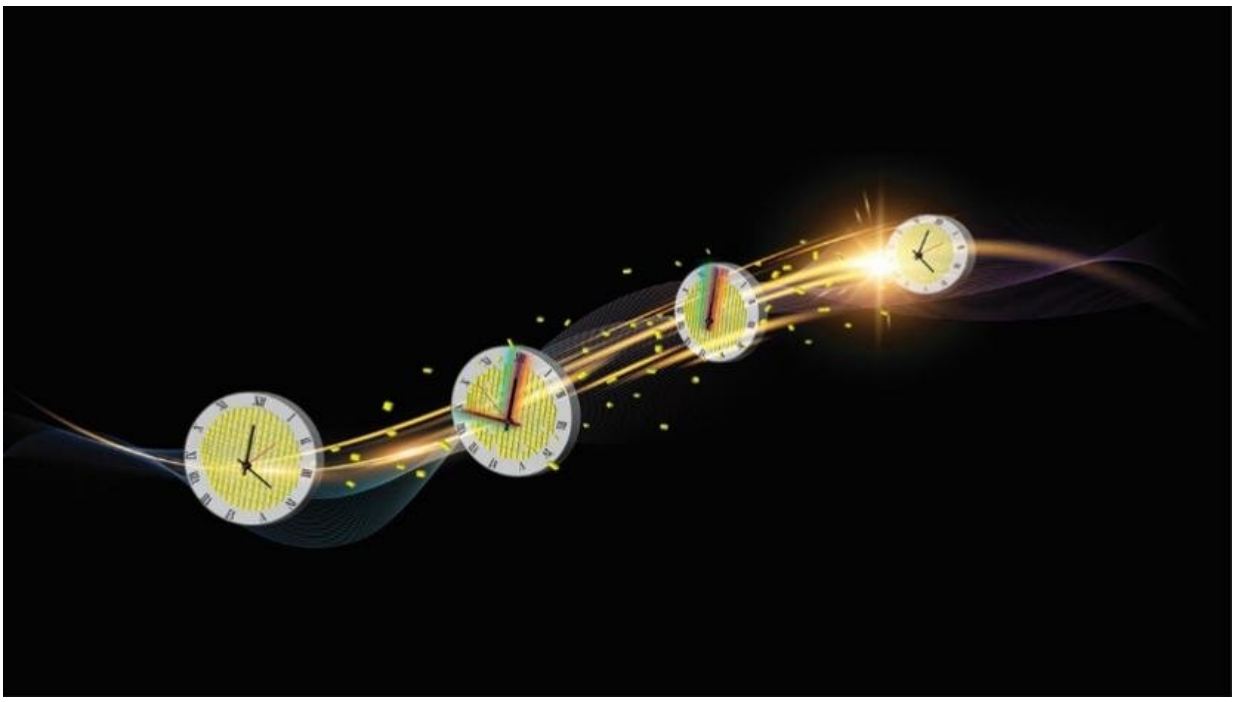

Credit: Shixiong Yin, Emanuele Galiffi, and Andrea Alù

Metamaterials—artificial media with tailored subwavelength structures—have now encompassed a broad range of novel properties that are unavailable in nature. This field of research has stretched across different wave platforms, leading to the discovery and demonstration of a wealth of exotic wave phenomena. Most recently, metamaterial concepts have been extended to the temporal domain, paving the way to

completely new concepts for wave control, such as nonreciprocal propagation, time-reversal, new forms of optical gain and drag.

Meanwhile, the concept of designer matter has also inspired significant research efforts in condensed matter physics, broadening the horizon of known phases of matter. Of particular interest has been the recent activity in Floquet matter, characterized by periodic modulations imposed, e.g. via a strong optical pulse, on the energy landscape experienced by the electrons in a system, thereby altering their steady-state dynamics dramatically.

In a new Perspective paper published in *eLight*, a team of scientists led by Professor Andrea Alù of the City University of New York (CUNY) points out the window of opportunity offered at the confluence between Floquet matter and metamaterials. Their Perspective paper highlights the exciting opportunities emerging from their synergies.

One realm where Floquet physics has recently found fertile ground is that of topological insulators, materials that host waves immune from scattering off impurities or disorder in a material, and whose discovery led to the 2016 Nobel Prize in Physics. Static topological insulators typically draw their exotic properties from their specific spatial crystalline arrangement, or on the application of a magnetic field. However, the periodic temporal modulation in a Floquet systems can also produce a synthetic effective magnetic field, which is not unique to electrons, but can thus be realized for electromagnetic waves (photons), elastic vibrations in a solid material or air (phonons), or even water waves, which do not normally experience the effects of a physical magnetic field.

Optical implementations of Floquet systems have traditionally been realized by replacing the temporal direction with a spatial one. However, according to Noether's theorem, temporal inhomogeneities intrinsically

imply the presence of gain and loss in a system: The common assumption of energy conservation does not generally hold in such a scenario, whereby energy is exchanged with the external mechanism (which acts like an energy bath) exerting the time-modulation. Owing to their intrinsic non-equilibrium dynamics, Floquet topological systems can host unique features not available within their static counterparts.

In parallel, metamaterials enable the tailoring of extreme wave-matter interactions, and the temporal dimension has recently emerged as a new degree of freedom to engineer exotic wave dynamics. This has included time-reversal (namely the temporal analog of reflection at a boundary between two media), nonreciprocity (direction-dependent wave propagation in a material) and many other effects. Importantly, the metamaterial concept has now expanded across most wave realms, offering an ideal platform where concepts which originated in the Floquet physics community may flourish and find a rich experimental playground.

However, the breadth of wave physics encompassed by metamaterial concepts also brings its own exotic intricacies and wealth of physical sophistication. For instance, most photonic systems feature an intrinsic temporal retardation in their response to an impinging wave, which is typically absent when solving the Schrodinger equation for matter waves such as electrons. This effect, called dispersion (which lies behind the splitting of white light into the rainbow colors by a prism, for example), introduces a rich playground for designing new forms of material responses when the material properties are switched in time at ultrafast speeds. These ultrafast (faster than the wave period) changes in material properties mimic, in the temporal domain, what in the metamaterials field are called meta-atoms: these are the fundamental building blocks whose individual response and periodic arrangement, give rise to the emergent properties of a metamaterial.

Hence, tailoring the specific temporal switching applied to a meta-structure opens an unexplored avenue for the design of Floquet metamaterials, structures where the synergy between the response of single temporal meta-atoms and their emergent Floquet behavior can be leveraged for the design of completely new forms of wave-matter interactions. Thus, this confluence promises to enrich both fields with the development of novel fundamental concepts, as well as a wealth of opportunities for experimental implementations across all (classical) wave realms.

More information: Shixiong Yin et al, Floquet metamaterials, *eLight* (2022). DOI: 10.1186/s43593-022-00015-1

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