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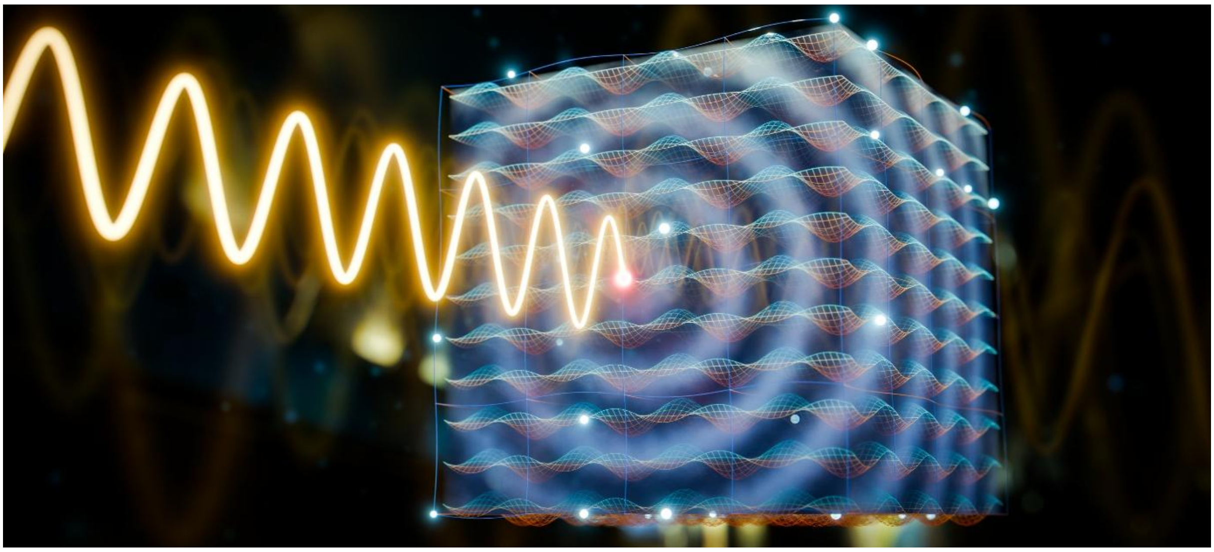
Shaping light like never before – with photonic time crystals



A THz electromagnetic wave induces strong, fast temporal modulations that realize a photonic time crystal: a crystal lattice in time for photon © B. Schröder/HZDR

France, July 29, 2026 - An international team of researchers from École Polytechnique, Collège de France, and Helmholtz-Zentrum Dresden-Rossendorf (HZDR) has achieved a world first: the experimental realization of an all-optical photonic time crystal (PTC), a material whose optical properties can be strongly and periodically modulated in time at ultrafast scales. Published in Nature, this breakthrough leverages HZDR's TELBE superradiant terahertz source to drive the system into a new regime of light-matter interaction in the terahertz range. This discovery paves the way for ultrafast optical computing, new telecommunication systems and eventually new types of terahertz lasers.

Shaping the properties of light as it interacts with materials is the foundation of many discoveries and technological advances, whether optical fibers in telecommunications, lasers as light sources, or sensors for chemistry and biology.

At École Polytechnique, scientists are setting the groundwork for a technology that has yet to be widely exploited: Yannis Laplace, assistant professor at École Polytechnique and his team at the Laboratory of Irradiated Solids (LSI[1]) are developing new photonic devices to control light in the terahertz (THz) frequency range. Research into this frequency band, 1,000 times faster than used for electronic components, is rapidly progressing and could unlock up new insights for observing and manipulating matter. "*The THz range represents the frontier between electronic and photonic technologies,*" explains Laplace. "*It is a range full of opportunities both for science and for the society, yet is still under-developed technologically*

[1] LSI: a joint research unit CEA, CNRS, École Polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France

compared to its electrical and photonic counterparts. Creating photonic crystals could lead the way to the closing of this gap."

The Breakthrough: From Spatial to Temporal Control

Those photonic crystals are nanostructured materials with a periodic optical pattern (like a lattice) that controls the flow of photons. By cleverly adjusting the refractive index and the shapes of different materials, they can block, guide, or enhance specific wavelengths, similar to how semiconductors control electrons.

In previous studies, this research team had demonstrated how manipulating temperature or magnetic fields could alter the light-capturing properties of photonic crystals, but until now their control was static in time.

This new work introduces the very first photonic time crystals, where the material's optical properties (e.g., reflectivity, resonance frequency) are dynamically modulated on picosecond timescales, comparable to the light's own oscillation cycle.

"*By extending photonic crystals from space to time, we open a new dimension for light control—and a novel path toward amplification and lasing. That could be a game-changer for optical technologies at terahertz frequencies and beyond,*" explains Tingwen Guo, PhD student at École Polytechnique and lead author on the publication.

Overcoming the arduous technical challenge

To unlock the ability to alter photon properties over time, scientists had to build a one-of-a-kind, complex device. Enrolling the help of Laboratoire Albert Fert[2] and Polytechnique's Physics of Interfaces (LPICM[3]) laboratory, they created a special kind of photonic crystal, called "plasmonic metamaterial".

They consist of micrometer-scale gold crenellated structures, beneath which lies an insulating layer and, finally, a semiconductor material made of mixture of indium and antimony. These crenellations act as cavities that trap photons of light between the gold layer and the semiconductor layer; the excitation of the surface of this semiconductor leads to "surface plasmons", where the electrons behave as a kind of collective wave able to capture light and sustain its oscillations.

By sending terahertz laser pulses to this device, thanks to the intense and frequency-tunable terahertz source TELBE at HZDR's ELBE accelerator, the researchers demonstrated that the material's optical properties, particularly its ability to reflect light, were modulated very strongly over very short timescales. This is an experimental feat, as achieving modulation that is both very strong (like forcing an object to emit a whole different color) and very rapid (on the picosecond scale—one billionth of a billionth of a second) was extremely difficult.

"*TELBE's unique ability to generate high-field, phase-stable terahertz pulses was critical,*" confirmed Jan-Christoph Deinert, the coordinator of the TELBE facility. "*Without this infrastructure, achieving the coherent, ultrafast modulation needed for the PTC regime would have been impossible.*"

Beyond the experimental observations, a theoretical model developed by Marco Schiró's, CNRS Research Scientist at Collège de France[4], and his team confirmed the experimental results, providing an explanation for the behavior of the photons within the device. The

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[2] Laboratoire Albert Fert: LAF, CNRS / Thales
[3] LPICM: a joint research unit CNRS, École Polytechnique - Institut Polytechnique de Paris
[4] Collège de France: CNRS / Collège de France

temporal modulation was also shown to reduce dissipation of photons within the metamaterial, i.e. the proportion of photons not reflected but passing through the surface of the material, by half.

"*The theory not only reproduces the experiment but also provides the basis for guiding future discoveries in this system,*" rejoiced Schiró.

Enabling Futures Optical Applications

The next step will be to figure out how to further prevent the dissipation of photons through the crystals, then amplifying the number of photons trapped within the device. At high level of amplification, they could be the source of new lasers with unparalleled modularity.

This breakthrough could transform how we use light in technology, particularly in the terahertz range. By enabling the modulation of light over such short timescales, these photonic time crystals bring us closer to new types of ultrafast lasers for medical imaging and communications, and enables on-demand tuning of light's properties, like changing its "color" or intensity instantly, for smarter, more adaptable optical systems.

Read the full publication **here**.

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