# Using 'Kerr solitons' to boost the power of transmission electron microscopes

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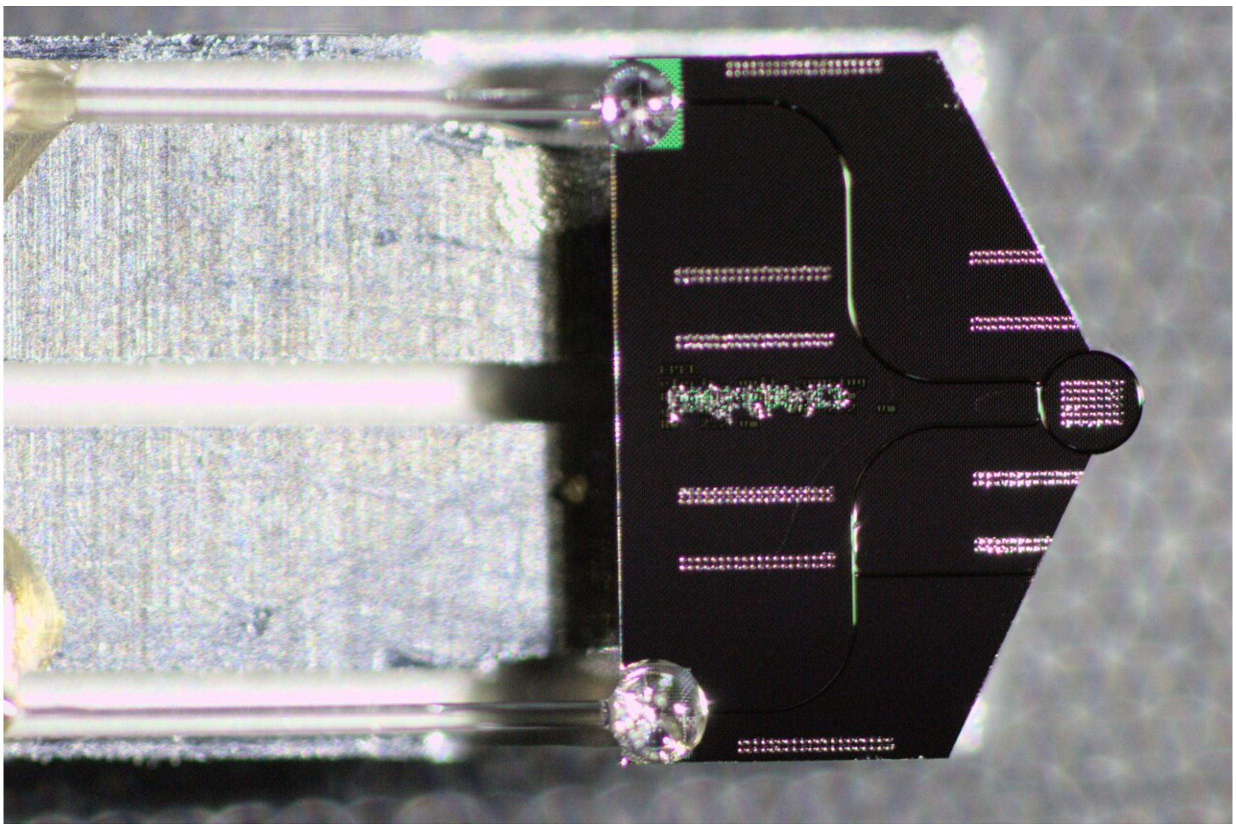


Photonic chip used in this study, mounted on a transmission electron microscope sample holder and packaged with optical fibers. Credit: Yang et al. DOI: 10.1126/science.adk2489

When light goes through a material, it often behaves in unpredictable ways. This phenomenon is the subject of an entire field of study called "nonlinear optics," which is now integral to technological and scientific advances from laser development and optical frequency metrology, to gravitational wave astronomy and quantum information science.

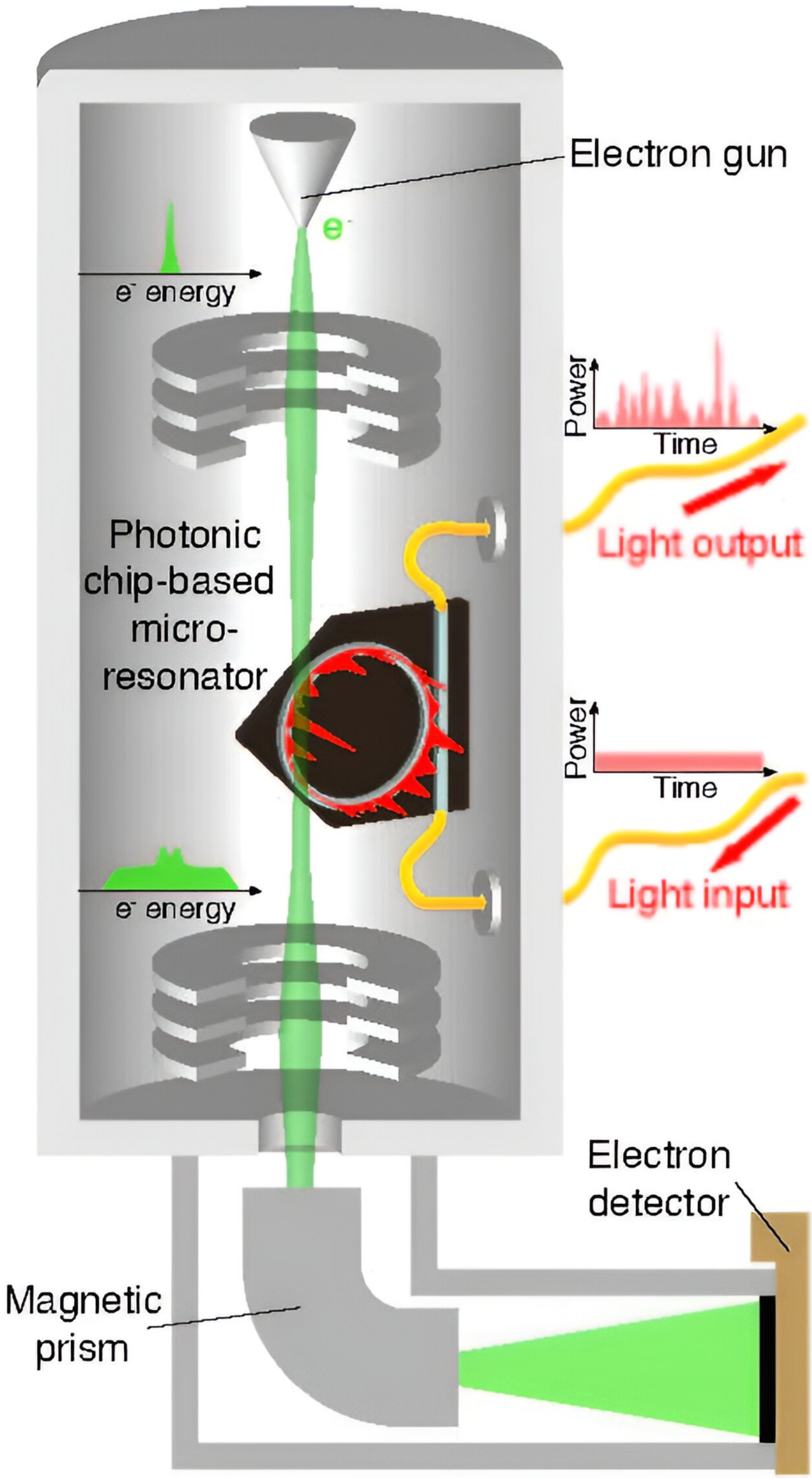
In addition, recent years have seen nonlinear optics applied in optical signal processing, telecommunications, sensing, spectroscopy, light detection and ranging. All these applications involve the miniaturization of devices that manipulate light in nonlinear ways onto a small chip, enabling complex light interactions on a chip scale.

Now, a team of scientists at EPFL and the Max Planck Institute has brought nonlinear optical phenomena into a transmission electron microscope (TEM), a type of microscope that uses electrons for imaging instead of light. The study was led by Professor Tobias J. Kippenberg at EPFL and Professor Claus Ropers, Director of the Max Planck Institute for Multidisciplinary Sciences. It is now published in *Science*.

At the heart of the study are "Kerr solitons," waves of light that hold their shape and energy as they move through a material, like a perfectly formed surf wave traveling across the ocean. This study used a particular type of Kerr solitons called "dissipative," which are stable, localized pulses of light that last tens of femtoseconds (a quadrillionth of a second) and form spontaneously in the microresonator. Dissipative Kerr solitons can also interact with electrons, which made them crucial for this study.

The researchers formed dissipative Kerr solitons inside a photonic microresonator, a tiny chip that traps and circulates light inside a reflective cavity, creating the perfect conditions for these waves. "We generated various nonlinear spatiotemporal light patterns in the microresonator driven by a continuous-wave laser," explains EPFL researcher Yujia Yang, who led the study. "These light patterns interacted with a beam of electrons passing by the photonic chip, and left fingerprints in the electron spectrum."

Specifically, the approach demonstrated the coupling between free electrons and dissipative Kerr solitons, which allowed the researchers to probe soliton dynamics in the microresonator cavity and perform ultrafast modulation of electron beams.


Electron gun
e-
e- energy
Power
Time
Light output
Photonic
chip-based
micro-
resonator
Power
Time
Light input
e- energy
Electron
detector
Magnetic
prism

Schematic of the experiment. Nonlinear spatiotemporal light patterns in a photonic chip-based microresonator modulate the spectrum of a beam of free electrons in a transmission electron microscope. Credit: Yang et al. DOI: 10.1126/science.adk2489

"Our ability to generate dissipative Kerr solitons [DKS] in a TEM extends the use of microresonator-base frequency combs to unexplored territories," says Kippenberg. "The electron-DKS interaction could enable high repetition-rate ultrafast electron microscopy and particle accelerators empowered by a small photonic chip."

Ropers adds, "Our results show electron microscopy could be a powerful technique for probing nonlinear optical dynamics at the nanoscale. This technique is non-invasive and able to directly access the intracavity field, key to understanding nonlinear optical physics and developing nonlinear photonic devices."

The photonic chips were fabricated in the Center of MicroNanoTechnology (CMi) and the Institute of Physics cleanroom at EPFL. The experiments were conducted at the Göttingen Ultrafast Transmission Electron Microscopy (UTEM) Lab.

**More information:** Yujia Yang et al, Free-electron interaction with nonlinear optical states in microresonators, *Science* (2024). DOI: 10.1126/science.adk2489.
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