'Ruler for light' could enable detailed measurement in personal devices

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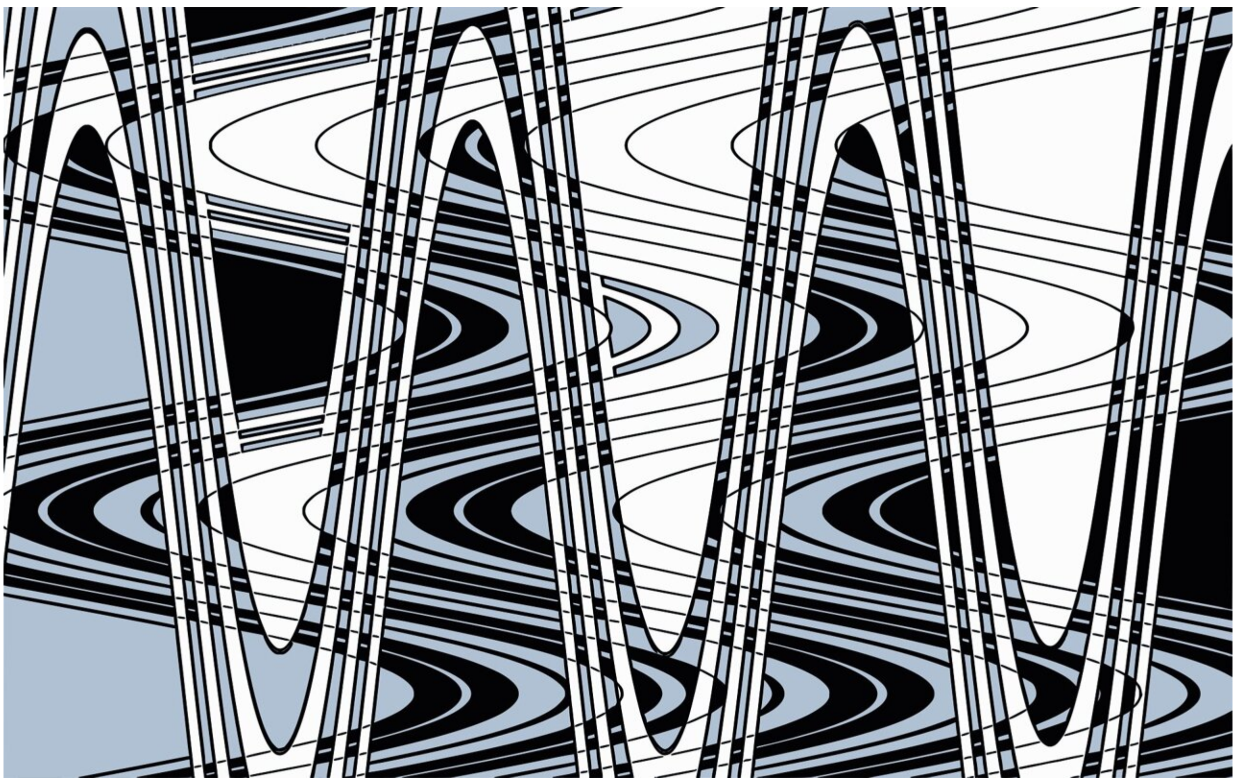

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Stanford researchers have unveiled a new type of frequency comb, a high-precision measurement device, that is innovatively small, ultra-energy efficient, and exceptionally accurate. With continued development, this breakthrough "microcomb"—which is detailed in a study published March 7 in *Nature*—could be the basis for mass-market adoption of the devices in everyday electronics.

Frequency combs are specialized lasers that generate evenly spaced-out lines of light akin to the teeth of a comb or, more aptly, the tick marks on a ruler. In the roughly quarter-century of their development, these "rulers for light" have revolutionized many kinds of high-precision measurement, from timekeeping to molecular detection via spectroscopy. Yet because frequency combs require bulky, costly, and power-hungry equipment, their deployment has been largely limited to laboratory settings.

The researchers discovered a workaround for these issues by integrating two different approaches for miniaturizing frequency combs into one straightforward, easily producible, microchip-style platform. Among the many applications the researchers envision for their versatile technology are powerful handheld medical diagnostic devices and widespread greenhouse gas monitoring sensors.

"The structure for our frequency comb brings the best elements of emerging microcomb technology together into one device," said Hubert Stokowski, a postdoctoral scholar in the lab of Amir Safavi-Naeini, and lead author of the study. "We can potentially scale our new frequency microcomb for compact, low-power, and inexpensive devices that can be deployed almost anywhere."

"We're very excited about this new microcomb technology that we've demonstrated for novel types of precision sensors that are both small and efficient enough to be in someone's phone someday," said Safavi-Naeini, associate professor in the Department of Applied Physics at Stanford's School of Humanities and Sciences and senior author of the study.

Wrangling light

This new device is called an Integrated Frequency-Modulated Optical Parametric Oscillator, or FM-OPO.

The tool's complex name indicates that it combines two strategies for creating the range of distinct frequencies, or colors of light, that constitute a frequency comb. One strategy, called optical parametric oscillation, involves bouncing beams of laser light within a crystal medium, wherein the generated light organizes itself into pulses of coherent, stable waves.

The second strategy centers on sending laser light into a cavity and then modulating the phase of the light—achieved by applying radio-frequency signals to the device—to ultimately produce frequency repetitions that similarly act as light pulses.

These two strategies for microcombs have not been used widely because both come with drawbacks. These issues include energy inefficiency, limited ability to adjust optical parameters, and suboptimal comb "optical bandwidth" where the comb-like lines fade as the distance from the center of the comb increases.

The researchers approached the challenge anew through their work on highly promising optical circuit platform based on a material called thin film lithium niobate. The material has advantageous properties compared to silicon, the industry standard material. Two of these helpful properties are "nonlinearity" (it allows light beams of different colors to interact with each other to generate new colors or wavelengths) and a broad range of light wavelengths can pass through it.

The researchers fashioned the components at the heart of the new frequency comb using integrated lithium niobate photonics. These light-manipulating technologies build upon advances in the related, more established field of silicon photonics, which involves fabricating optical and electronic integrated circuits on silicon microchips. In this way, lithium niobate and silicon photonics have both expanded upon the semiconductors in conventional computer chips, the roots of which reach back to the 1950s.

"Lithium niobate has certain properties that silicon doesn't, and we couldn't have made our microcomb device without it," said Safavi-Naeini.

Surprisingly excellent performance

Next, the researchers brought together elements of both optical parametric amplification and phase modulation strategies. The team expected certain performance characteristics from the new frequency comb system on lithium niobate chips—but what they saw proved far better than they anticipated.

Overall, the comb produced a continuous output rather than light pulses, which enabled the researchers to reduce the required input power by approximately an order of magnitude. The device also yielded a conveniently "flat" comb, meaning the comb lines farther in wavelength from the center of the spectrum did not fade in intensity, thus offering greater accuracy and broader utility in measurement applications.

"We were really surprised by this comb," said Safavi-Naeini. "Although we had some intuition that we would get comb-like behaviors, we weren't really trying to make exactly this type of comb, and it took us a few months to develop the simulations and theory that explained its main properties."

For further insight into their overperforming device, the researchers turned to Martin Fejer, the J. G. Jackson and C. J. Wood Professor of Physics and a professor of applied physics at Stanford. Along with other peers at Stanford, Fejer has helped advance modern thin film lithium niobate photonics technologies and the understanding of the material's crystal properties.

Fejer, who is also a study co-author, made the key connection between the physical principles underlying the microcomb and ideas discussed in scientific literature from the 1970s, particularly concepts pioneered by Stephen Harris, emeritus professor of applied physics and electrical engineering at Stanford.

The new microcombs, with further honing, should be readily manufacturable at conventional microchip foundries with many practical applications such as sensing, spectroscopy, medical diagnostics, fiber-optic communications, and wearable health-monitoring devices.

"Our microcomb chip could be put into anything, with the size of the overall device depending on the size of the battery," said Stokowski. "The technology we've demonstrated could go inside a low-powered personal device, the size of a phone or even smaller, and serve all kinds of useful purposes."

More information: Amir Safavi-Naeini, Integrated frequency-modulated optical parametric oscillator, *Nature* (2024). DOI: 10.1038/s41586-024-07071-2. www.nature.com/articles/s41586-024-07071-2

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