Coupled semiconductor lasers generate novel optical patterns, enabling new spectroscopy techniques

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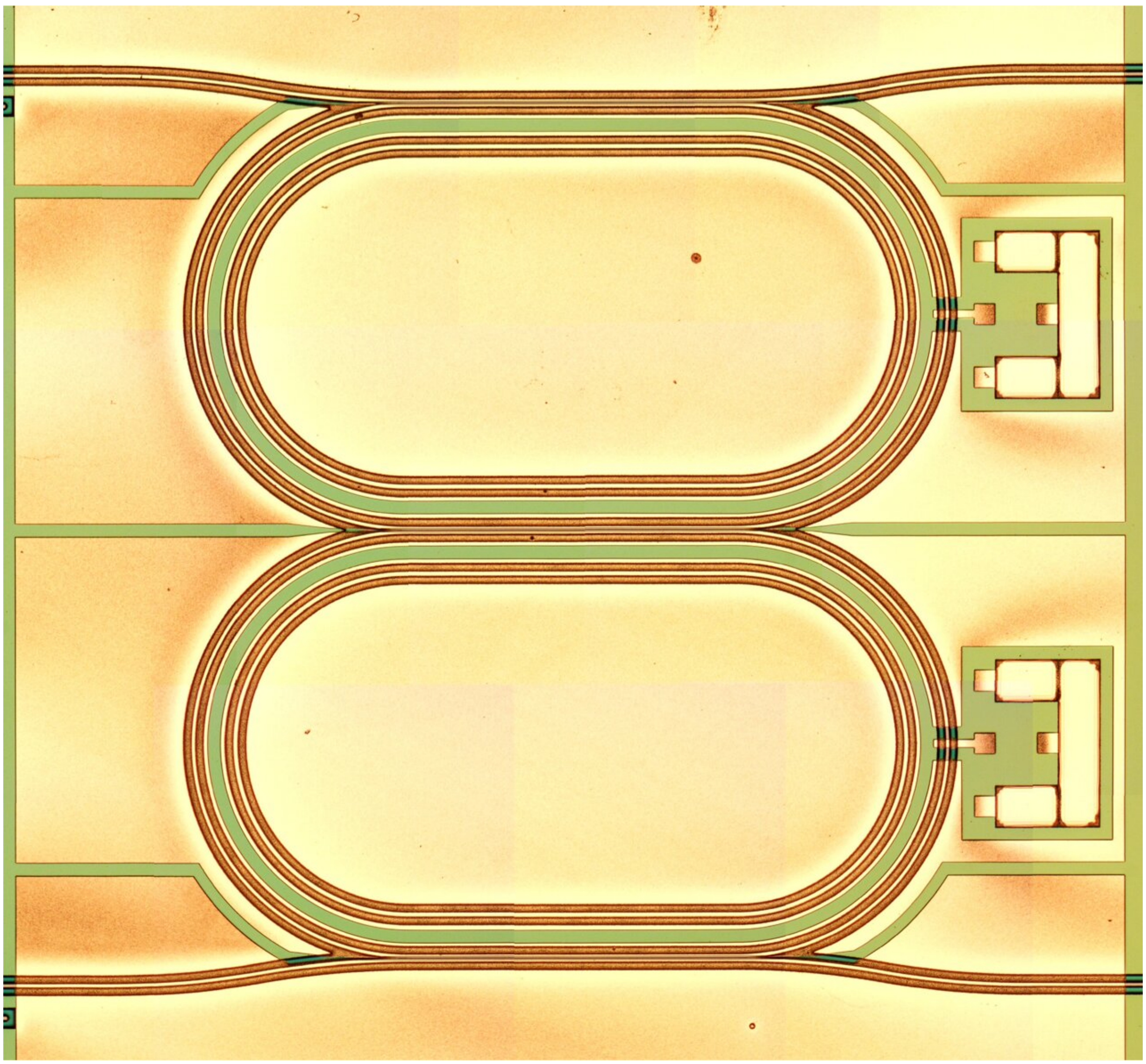

Image showing gold contacts where we bias each laser with DC current. Light is out-coupled from the racetracks using the directional-coupler waveguides along the straight section of either racetrack. Credit: *Physical Review Letters* (2025). DOI: 10.1103/PhysRevLett.134.023802

The physical interaction between two or more systems, also known as coupling, can give rise to unique and unexpected effects. In the field of optics, coupled light sources (e.g., lasers) can influence each other, producing complex light patterns that cannot be emitted by individual light-emitting systems.

Researchers at Harvard University, Politecnico di Torino and TU Wien have recently shown that a set of coupled semiconductor-based ring lasers can generate unique and interesting optical patterns that would be impossible to produce for a single laser. Their paper, published in *Physical Review Letters*, could open new possibilities for the development of spectroscopy techniques and on-chip laser systems.

"Our work on coupled racetrack quantum cascade lasers (QCLs) builds on previous experiments with single racetrack QCLs, where we discovered intriguing coherent states," Theodore P. Letsou, first author of the paper, told Phys.org.

"Notably, upon turning a single racetrack laser on, we observed spontaneous emission of 'dark' pulses of light, known as Nozaki-Bekki solitons. Motivated by these findings, we sought to uncover new states of light by strongly coupling multiple racetrack lasers, effectively combining the fast nonlinear dynamics of QCLs with multi-resonator systems."

To conduct their experiments, Letsou and his colleagues employed coupled semiconductor ring lasers, miniature ring-shaped lasers. The system they used includes a pair of QCLs shaped like racetrack resonators, which are coupled to each other along their straight sections.

"Light can circulate in each racetrack in either a clockwise or counterclockwise direction, exchanging light between them," explained Letsou. "When two oscillators—regardless of their composition—are strongly coupled, their resonant frequencies split or 'hybridize,' moving further apart as the coupling strength increases. We observed this splitting in our coupled lasers by injecting light into one racetrack through its bus waveguide and measuring the output from the other racetrack."

In contrast with the conventional coupling achieved between oscillators, the methods used by Letsou and colleagues allowed them to simultaneously bias both coupled lasers in their system above threshold. Under these conditions, the frequencies emitted by the lasers were found to lock together, forming two distinct frequency combs (i.e., one for each set of hybridized modes).

"The two combs lock to the same repetition rate while repelling each other because of strong coupling," said Letsou. "Remarkably, one set of frequencies corresponds to a 'dark' pulse of light, while the other set corresponds to a 'bright' pulse—a phenomenon observed for the first time in a free-running semiconductor laser."

Using their experimental setup, the researchers were able to produce ultra-short and bright pulses of light simply by biasing each laser in their system, as well as the emission of dark pulses. The system they devised and the unique light patterns it produced could serve as an inspiration for future studies.

"These pulses could, in principle, be extracted and amplified for a wide range of nonlinear optical experiments," said Letsou. "In addition, this device platform could enable powerful spectroscopy techniques, such as dual-comb spectroscopy. Both frequency combs emitted from the coupled lasers can probe gas absorption lines, and by mixing the resulting signals onto a detector, the optical absorption is effectively converted into an electrical signal."

This recent work by Letsou and his colleagues highlights the possibility of leveraging the coupling between lasers to produce different light patterns. Their findings could eventually contribute to the development of various optical technologies, including communication techniques, spectroscopic tools and photonic chips.

"Future research directions include going beyond two racetracks," added Letsou. "In other words: What happens if we couple three or four racetracks together, and what about a matrix of rings? We hope this work will lay the groundwork for future investigations into coherent states of light in multi-resonator systems."

More information: Theodore P. Letsou et al, Hybridized Soliton Lasing in Coupled Semiconductor Lasers, *Physical Review Letters* (2025). DOI: 10.1103/PhysRevLett.134.023802.

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