New device modulates visible light—without dimming it—with the smallest footprint and lowest power consumption

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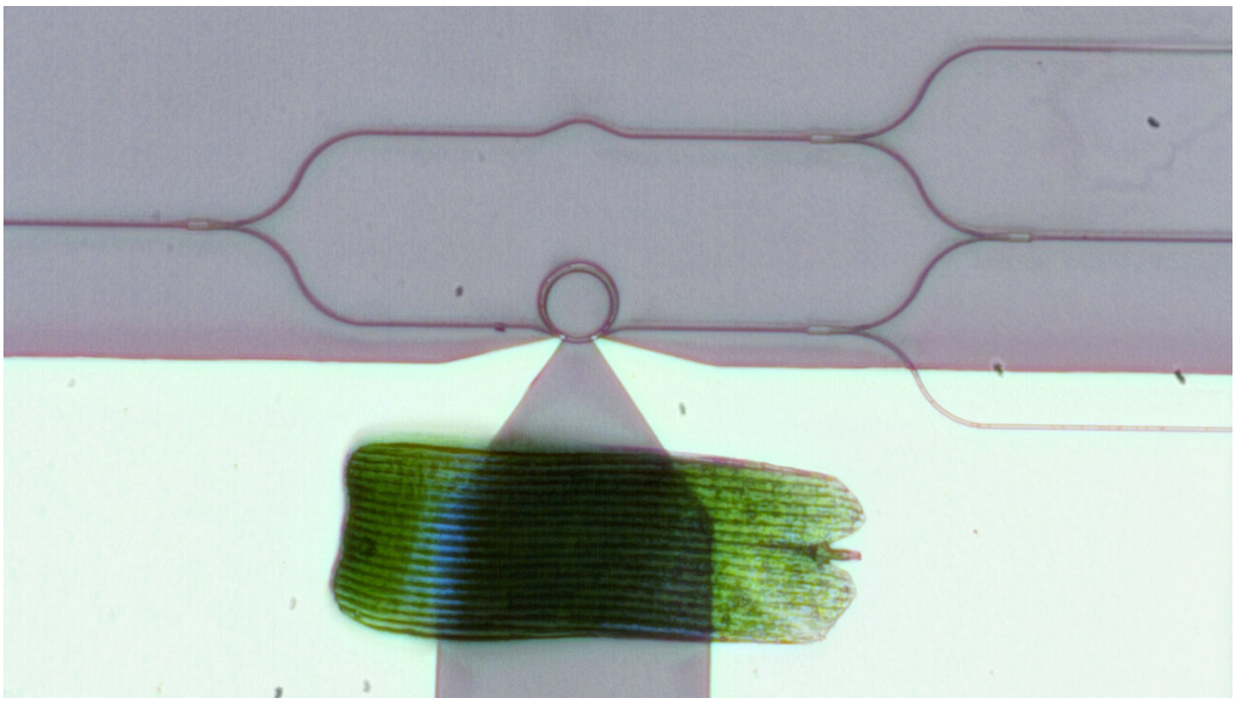


A visible-spectrum phase modulator (the ring at the center of a radius of 10 microns) is tinier than a butterfly wing scale. Credit: Heqing Huang and Cheng-Chia Tsai/Columbia Engineering

Over the past several decades, researchers have moved from using electric currents to manipulating light waves in the near-infrared range for telecommunications applications such as high-speed 5G networks, biosensors on a chip, and driverless cars. This research area, known as integrated photonics, is fast evolving and investigators are now exploring the shorter—visible—wavelength range to develop a broad variety of emerging applications. These include chip-scale LIDAR (light detection and ranging), AR/VR/MR (augmented/virtual/mixed reality) goggles, holographic displays, quantum information processing chips, and implantable optogenetic probes in the brain.

The one device critical to all these applications in the visible range is an optical phase modulator, which controls the phase of a light wave, similar to how the phase of radio waves is modulated in wireless computer networks. With a phase modulator, researchers can build an on-chip optical switch that channels light into different waveguide ports. With a large network of these optical switches, researchers could create sophisticated integrated optical systems that could control light propagating on a tiny chip or light emission from the chip.

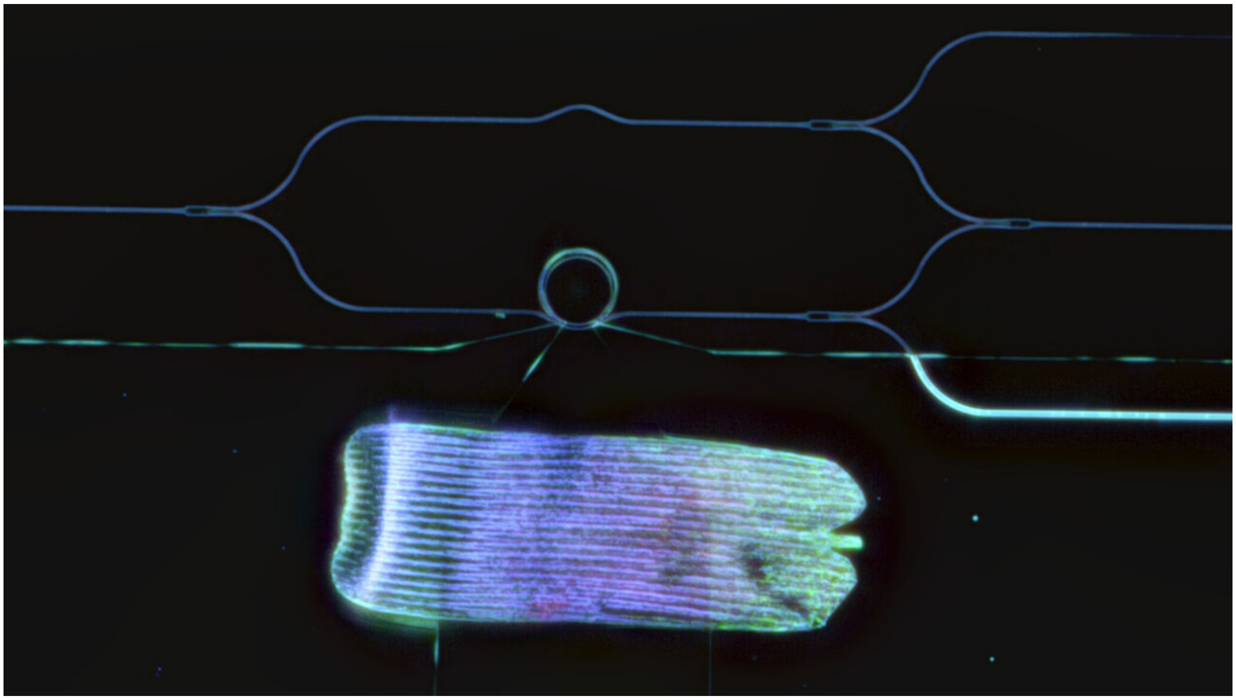
But phase modulators in the visible range are very hard to make: there are no materials that are transparent enough in the visible spectrum while also providing large tunability, either through thermo-optical or electro-optical effects. Currently, the two most suitable materials are silicon nitride and lithium niobate. While both are highly transparent in the visible range, neither one provides very much tunability. Visible-spectrum phase modulators based on these materials are thus not only large but also power-hungry: the length of individual waveguide-based modulators ranges from hundreds of microns to several mm and a single modulator consumes tens of mW for phase tuning. Researchers trying to achieve large-scale integration—embedding thousands of devices on a single microchip—have, up to now, been stymied by these bulky, energy-consuming devices.

Today, Columbia Engineering researchers announced that they have found a solution to this problem—they've developed a way based on micro-ring resonators to dramatically reduce both the size and the power consumption of a visible-spectrum phase modulator, from 1 mm to 10 microns and from tens of mW for π phase tuning to below 1 mW. The study was published today by *Nature Photonics*.

"Usually the bigger something is, the better. But integrated devices are a notable exception," said Nanfang Yu, associate professor of applied physics, co-principal investigator (PI) on the team, and an expert in nanophotonics. "It's really hard to confine light to a spot and manipulate it without losing much of its power. We are excited that in this work we've made a breakthrough that will greatly expand the horizon of large-scale visible-spectrum integrated photonics."

Conventional optical phase modulators operating at visible wavelengths are based on light propagation in waveguides. Yu worked with his colleague Michal Lipson, who is the leading expert on integrated photonics based on silicon nitride, to develop a very different approach.

"The key to our solution was to use an optical resonator and to operate it in the so-called strongly over-coupled regime," said Lipson, co-PI on the team and Eugene Higgins Professor of Electrical Engineering and professor of applied physics.



A visible-spectrum phase modulator (the ring at the center of a radius of 10 microns) is tinier than a butterfly wing scale. Credit: Heqing Huang and Cheng-Chia Tsai/Columbia Engineering

Optical resonators are structures with a high degree of symmetry, such as rings that can cycle a beam of light many times and translate tiny refractive index changes to a large phase modulation. Resonators can operate under several different conditions and so need to be used carefully. For example, if operating in the "under coupled" or "critical coupled" regimes, a resonator will only provide a limited phase modulation and, more problematically, introduce a large amplitude variation to the optical signal. The latter is a highly undesirable optical loss because accumulation of even moderate losses from individual phase modulators will prevent cascading them to form a circuit that has a sufficiently large output signal.

To achieve a complete 2π phase tuning and minimal amplitude variation, the Yu-Lipson team chose to operate a micro-ring in the "strongly over-coupled" regime, a condition where the coupling strength between the micro-ring and the "bus" waveguide that feeds light into the ring is at least 10 times stronger than the loss of the micro-ring. "The latter is primarily due to optical scattering at the nanoscale roughness on the device sidewalls," Lipson explained. "You can never fabricate photonic devices with perfectly smooth surfaces."

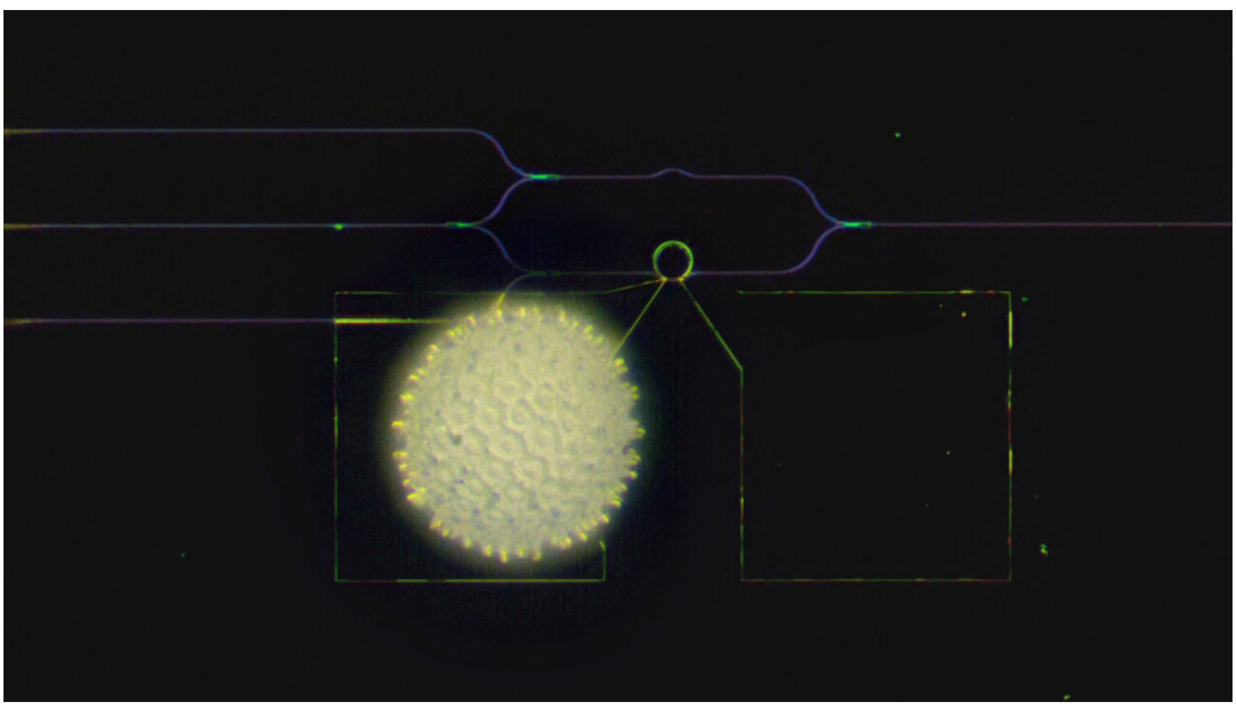
The team developed several strategies to push the devices into the strongly over-coupled regime. The most crucial one was their invention of an adiabatic micro-ring geometry, where the ring smoothly transitions between a narrow neck and a wide belly, which are at the opposite edges of the ring. The narrow neck of the ring facilitates the exchange of light between the bus waveguide and the micro-ring, thus enhancing the coupling strength. The ring's wide belly reduces optical loss because the guided light interacts only with the outer sidewall, not the inner sidewall, of the widened portion of the adiabatic micro-ring, substantially reducing optical scattering at the sidewall roughness.

In a comparative study of adiabatic micro-rings and conventional micro-rings with uniform width fabricated side by side on the same chip, the team found that none of the conventional micro-rings satisfied the strong over-coupling condition—in fact, they suffered very bad optical losses—while 63% of the adiabatic micro-rings kept operating in the strongly over-coupled regime.

"Our best phase modulators operating at the blue and green colors, which are the most difficult portion of the visible spectrum, have a radius of only 5 microns, consume power of 0.8 mW for π phase tuning, and introduce an amplitude variation of less than 10%," said Heqing Huang, a graduate student in Yu's lab and first author of the paper. "No prior work has demonstrated such compact, power-efficient, and low-loss phase modulators at visible wavelengths."

The devices were designed in Yu's lab and fabricated in the Columbia Nano Initiative cleanroom, at the Advanced Science Research Center NanoFabrication Facility at the Graduate Center of the City University of New York, and at the Cornell NanoScale Science and Technology Facility. Device characterization was conducted in Lipson's and Yu's labs.

The researchers note that while they are nowhere near the degree of integration of electronics, their work shrinks the gap between photonic and electronic switches substantially. "If previous modulator technologies only allow for integration of 100 waveguide phase modulators given a certain chip footprint and power budget, now we can do that 100 times better and integrate 10,000 phase shifters on chip to realize much more sophisticated functions," said Yu.



A visible-spectrum phase modulator (the ring at the center of a radius of 10 microns) is much smaller than a grain of pollen of the morning glory. Credit: Heqing Huang and Cheng-Chia Tsai/Columbia Engineering

The Lipson and Yu labs are now collaborating to demonstrate visible-spectrum LIDAR consisting of large 2D arrays of phase shifters based on adiabatic micro-rings. The design strategies employed for their visible-spectrum thermo-optical devices can be applied to electro-optical modulators to reduce their footprints and drive voltages, and can be adapted in other spectral ranges (e.g., ultraviolet, telecom, mid-infrared, and THz) and in other resonator designs beyond micro-rings.

"Thus, our work can inspire future effort where people can implement strong over-coupling in a wide range of resonator-based devices to enhance light-matter interactions, for example, for enhancing optical nonlinearity, for making novel lasers, for observing novel quantum optical effects, while suppressing optical losses at the same time," Lipson said.

More information: Guozhen Liang et al, Robust, efficient, micrometre-scale phase modulators at visible wavelengths, *Nature Photonics* (2021). DOI: 10.1038/s41566-021-00891-y

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