Sub-wavelength confinement of light demonstrated in indium phosphide nanocavity

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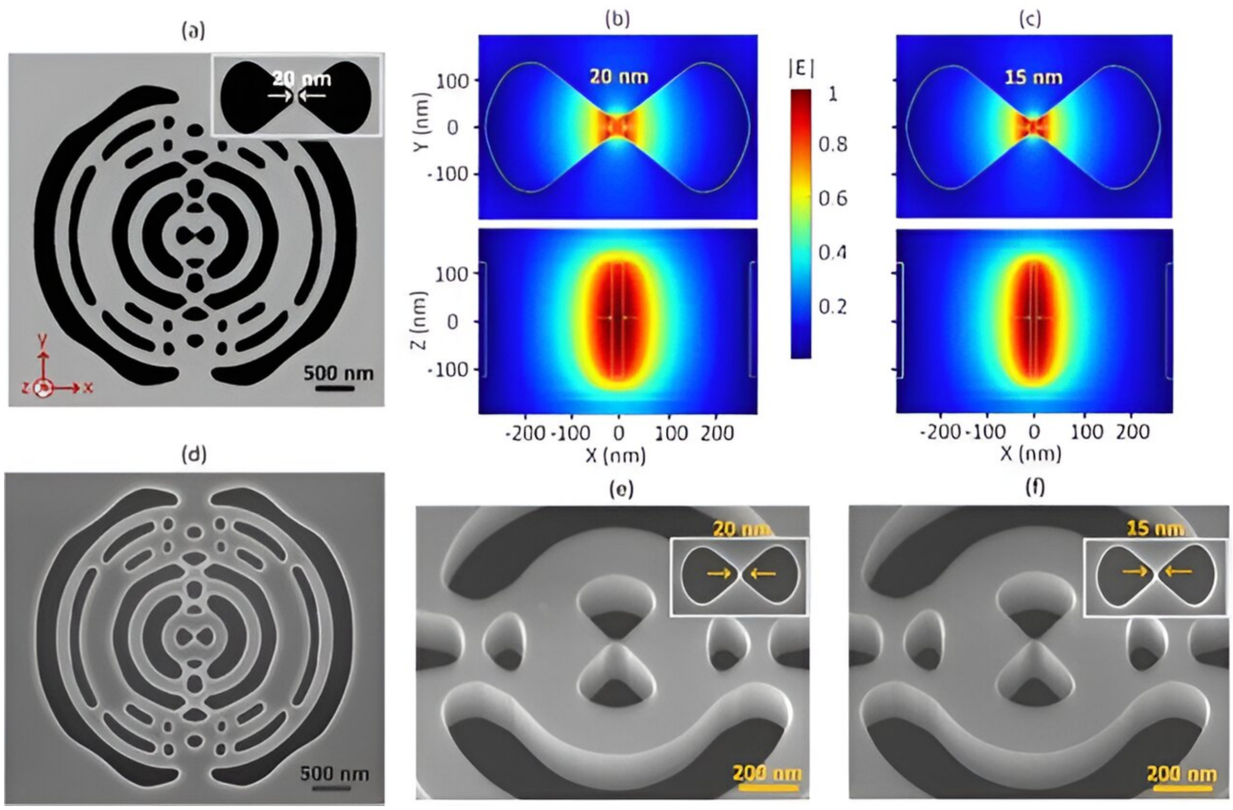

Researchers developed a new III-V semiconductor nanocavity that confines light at levels below the diffraction limit. The design of the cavity is shown in a, the calculated electric field distribution in b and c, and scanning electron microscopy images in d-f. Credit: Meng Xiong, Technical University of Denmark

As we transition to a new era in computing, there is a need for new devices that integrate electronic and photonic functionalities at the nanoscale while enhancing the interaction between photons and electrons. In an important step toward fulfilling this need, researchers have developed a new III-V semiconductor nanocavity that confines light at levels below the so-called diffraction limit.

"Nanocavities with ultrasmall mode volumes hold great promise for improving a wide range of photonic devices and technologies, from lasers and LEDs to quantum communication and sensing, while also opening up possibilities in emerging fields such as quantum computing," said the leading author Meng Xiong from the Technical University of Denmark. "For example, light sources based on these nanocavities could significantly improve communication by enabling faster data transmission and strongly reduced energy consumption."

In the journal *Optical Materials Express*, the researchers show that their new nanocavity exhibits a mode volume an order of magnitude smaller than previously demonstrated in III-V materials. III-V semiconductors have unique properties that make them ideal for optoelectronic devices. The strong spatial confinement of light demonstrated in this work helps enhance light-matter interaction, which allows higher LED powers, smaller laser thresholds and higher single-photon efficiencies.

"Light sources based on these new nanocavities could have a major impact on data centers and computers, where ohmic and power-hungry connections could be replaced by high-speed and low-energy optical links," said Xiong. "They could also be used in advanced imaging techniques such as super-resolution microscopy to enable better disease detection and treatment monitoring or to improve sensors for various applications, including environmental monitoring, food safety and security."

Boosting light interaction

The work is part of an effort by researchers at the Technical University of Denmark's NanoPhoton-Center for Nanophotonics, who are exploring a new class of dielectric optical cavities that enable deep subwavelength confinement of light through a principle the researchers have coined extreme dielectric confinement (EDC). By enhancing the interaction between light and matter, EDC cavities could lead to highly efficient computers with deep-subwavelength lasers and photodetectors that are integrated into transistors for reduced energy consumption.

In the new work, the researchers first designed an EDC cavity in the III-V semiconductor indium phosphide (InP) using a systematic mathematical approach that optimized the topology while relaxing geometric constraints. They then fabricated the structure using electron beam lithography and dry etching.

"EDC nanocavities have feature sizes down to a few nanometers, which is crucial for achieving extreme light concentration, but they also come with a significant sensitivity to fabrication variations," said Xiong. "We attribute successful realization of the cavity to the improved accuracy of the InP fabrication platform, which is based on electron beam lithography followed by dry etching."

Meng Xiong and Frederik Schröder of the research team are shown with the scattering scanning near-field optical microscope used to demonstrate the spatial light confinement of the new nanocavities. Nanocavities with ultrasmall mode volumes could help improve a wide range of photonic devices and technologies. Credit: Meng Xiong, Technical University of Denmark

Making a smaller nanocavity

After refining the fabrication process, the researchers achieved a remarkably small dielectric feature size of 20 nm, which became the basis for the second round of topological optimization. This last round of optimization produced a nanocavity with a mode volume of just 0.26 $(\lambda/2n)^3$, where λ represents the wavelength of light and n its refractive index. This achievement is four times smaller than what is often termed the diffraction-limited volume for a nanocavity, which corresponds to a box of light with a side-length of half the wavelength.

The researchers point out that although similar cavities with these characteristics were recently achieved in silicon, silicon lacks the direct band-to-band transitions found in III-V semiconductors, which are essential for harnessing the Purcell enhancement provided by nanocavities.

"Prior to our work, it was uncertain whether similar outcomes could be achieved in III-V semiconductors because they don't benefit from the advanced fabrication techniques developed for the silicon electronics industry," said Xiong.

The researchers are now working to improve the fabrication precision to further reduce the mode volume. They also want to use the EDC cavities to achieve a practical nanolaser or nanoLED.

More information: Meng Xiong et al, Experimental realization of deep sub-wavelength confinement of light in a topology-optimized InP nanocavity, *Optical Materials Express* (2023). DOI: 10.1364/OME.513625

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