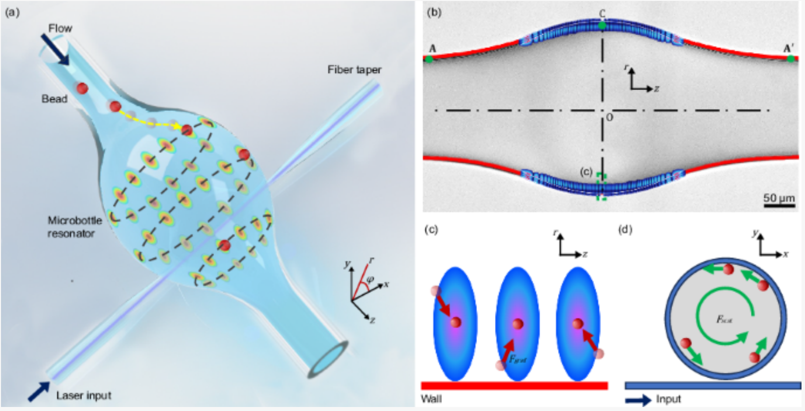
When geometry matters: Gradient-wall microresonators enable large-scale optical trapping



Gradient-thickness-protected WGM microbottle resonator for large-scale particle trapping.

GA, UNITED STATES, March 10, 2026 /EINPresswire.com/ -- Optical trapping is a powerful tool for manipulating microscopic particles, but conventional approaches often suffer from limited trapping range and poor stability when particles disturb the optical field. A new resonator design overcomes these constraints by reshaping how light interacts with matter. By using a hollow microbottle structure with a gradient wall thickness, the system enables particles to be trapped directly by strong optical-field antinodes rather than by weak surface-bound evanescent fields. This strategy allows stable, large-scale trapping over an extended axial distance while maintaining low power consumption. The work demonstrates that carefully engineered geometry can dramatically enhance both the robustness and scalability of optical manipulation.

Near-field optical trapping has transformed particle manipulation in biology, chemistry, and nanotechnology, enabling contact-free control of objects ranging from nanoparticles to living cells. However, most existing whispering-gallery-mode and waveguide-based platforms rely on evanescent fields that penetrate only about 100 nanometers into the surrounding medium. This shallow interaction region restricts trapping efficiency and makes the system highly sensitive to perturbations caused by trapped particles themselves. Such instability limits practical applications requiring dense, large-area, or long-term manipulation. Given these challenges, it is necessary to develop optical trapping strategies that achieve deeper field penetration, stronger light–matter interaction, and greater robustness against particle-induced disturbances.

Researchers from Fudan University and The Hong Kong Polytechnic University report a new optical trapping platform in Microsystems & Nanoengineering, published in January 2026. The team demonstrates a gradient-thickness-protected microbottle resonator that enables large-scale, stable optical trapping via whispering-gallery modes. By introducing a controlled wall-thickness gradient into a hollow microbottle geometry, the device supports high-order axial modes that generate multiple optical trapping sites along its length. This design allows particles to be trapped efficiently over nearly 200 micrometers with ultralow optical power.

The core innovation lies in the microbottle resonator's gradient wall thickness, which is thinnest at the equator and gradually thickens toward both ends. This geometry fundamentally changes how optical fields are distributed inside the resonator. Instead of confining particles to weak evanescent fields near the surface, the device generates strong optical-field antinodes that extend several micrometers into the liquid core, creating deep, stable trapping potentials.

The researchers show that this configuration supports high-order axial whispering-gallery modes, forming dozens of discrete trapping "orbits" along the resonator axis. Experiments demonstrate stable trapping of 500-nanometer-radius polystyrene particles across an axial span exceeding 195 micrometers, far larger than that of most near-field platforms. Remarkably, the trapping threshold power is only 0.198 milliwatts, highlighting the system's energy efficiency.

Equally important, the gradient-thickness design protects the strongest optical fields by confining them within the silica wall at the resonator ends. This minimizes degradation of the optical quality factor when particles are trapped, ensuring consistent performance even during large-scale, multi-particle manipulation. The platform also supports localized, tunable trapping via standing-wave excitation, enabling precise repositioning of individual particles.

"This work shows that optical trapping performance is not only about stronger lasers, but about smarter structures," the researchers note. "By engineering the resonator geometry, we can control where optical energy resides and how it interacts with particles." They emphasize that isolating the peak optical fields from particle-induced perturbations is key to achieving robust and scalable trapping. The approach, they suggest, bridges the gap between laboratory demonstrations and practical optofluidic systems capable of handling complex, real-world samples.

The gradient-thickness microbottle resonator opens new possibilities for high-throughput and label-free particle manipulation. Its extended trapping range and multiple stable orbits make it suitable for parallel single-cell analysis, bioparticle sorting, and real-time monitoring of microbial dynamics. The rapid orbital motion of trapped particles can also enhance micromixing, potentially accelerating biochemical reactions in microfluidic environments. Beyond biology, the platform may enable advanced sensing, targeted drug delivery, and reconfigurable optofluidic devices. More broadly, the study highlights how geometric design can unlock new regimes of light–matter interaction, offering a versatile blueprint for next-generation optical manipulation technologies.

References

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Lucy Wang
BioDesign Research
email us here
