First device based on 'optical thermodynamics' can route light without switches

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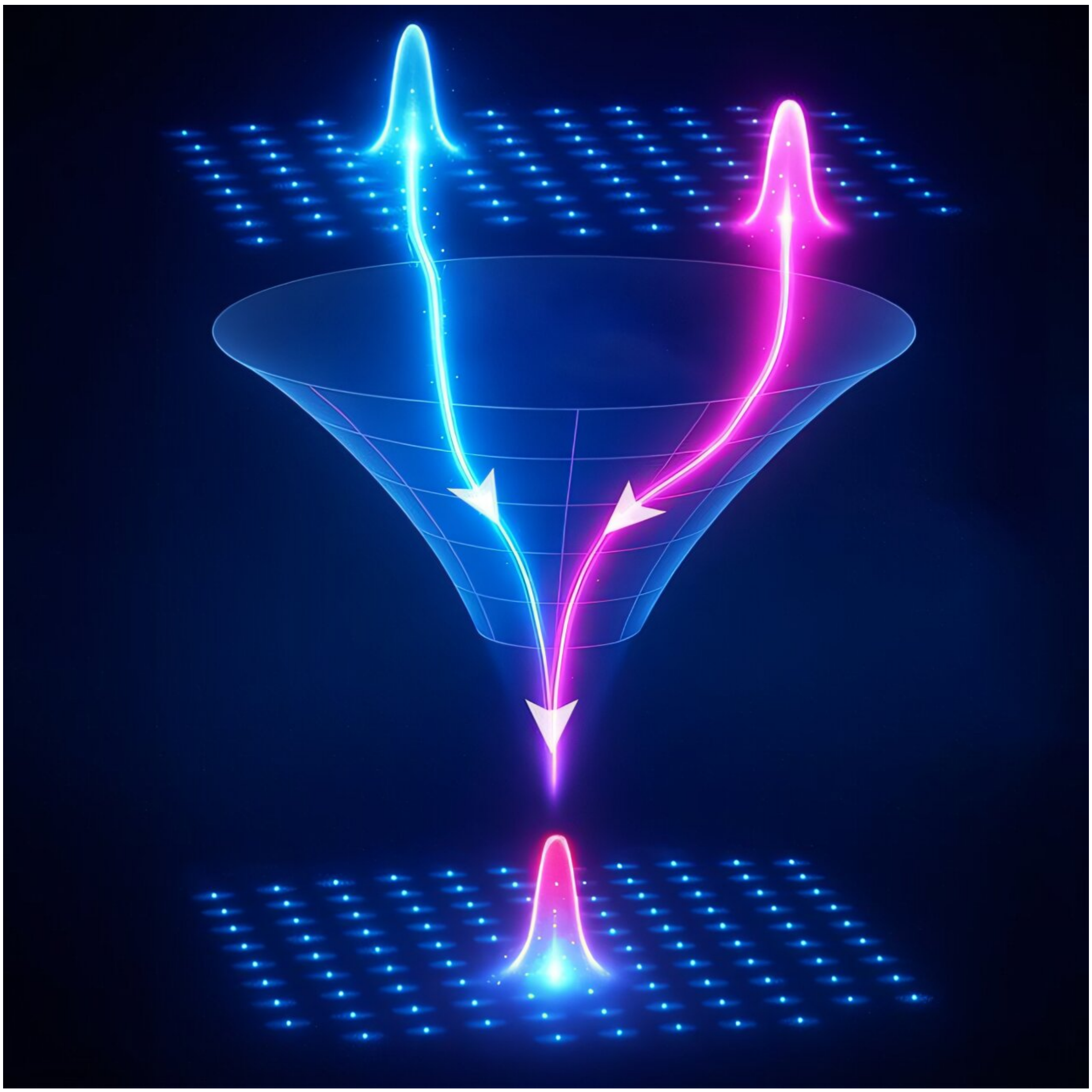

Credit: Yunxuan Wei at USC.

A team of researchers at the Ming Hsieh Department of Electrical and Computer Engineering has created a new breakthrough in photonics: the design of the first optical device that follows the emerging framework of optical thermodynamics.

The work, reported in *Nature Photonics,* introduces a fundamentally new way of routing light in nonlinear systems—meaning systems that do not require switches, external control, or digital addressing. Instead, light naturally finds its way through the device, guided by simple thermodynamic principles.

From valves to routers to light

Universal routing is a familiar engineering concept. In mechanics, a manifold valve directs inputs to a chosen outlet. In digital electronics, a Wi-Fi router at home or an Ethernet switch in a data center directs information from many input channels to the correct output port, ensuring that each stream of data reaches its intended destination.

When it comes to light, the same problem is far more challenging, however. Conventional optical routers rely on complex arrays of switches and electronic control to toggle pathways. These approaches add technical difficulty, while limiting speed and performance.

The photonics team at the USC Viterbi School of Engineering has now shown that there is another way. The idea can be likened to a marble maze that arranges itself.

Normally, you'd have to lift barriers and guide a marble step-by-step to make sure it reaches its destination—the right hole. In the USC team's device, however, the maze is built so that no matter where you drop the marble, it will roll on its own toward the right place—no guiding hands needed. And this is exactly how light behaves: it finds the correct path naturally, by following the principles of thermodynamics.

Potential industry impact

The implications of the new approach extend far beyond the laboratory. As computing and data processing continue to push the limits of traditional electronics, various companies—including chip designers such as NVIDIA and others—are exploring optical interconnects as a way to move information faster and more efficiently.

By providing a natural, self-organizing way to direct light signals, however, optical thermodynamics could accelerate the development of such technologies. Beyond chip-scale data routing, the framework may also influence telecommunications, high-performance computing, and even secure information processing, offering a path toward devices that are both simpler and more powerful.

How it works: Chaos tamed by thermodynamics

Nonlinear multimode optical systems are often dismissed as chaotic and unpredictable. Their intricate interplay of modes has made them among the hardest systems to simulate—let alone design for practical use. Yet, precisely because they are not constrained by the rules of linear optics, they harbor rich and unexplored physical phenomena.

Recognizing that light in these systems undergoes a process akin to reaching thermal equilibrium—similar to how gases reach equilibrium through molecular collisions—the USC researchers developed a comprehensive theory of "optical thermodynamics." This framework captures how light behaves in nonlinear lattices using analogs of familiar thermodynamic processes such as expansion, compression, and even phase transitions.

A device that routes light by itself

The team's demonstration in *Nature Photonics* marks the first device designed with this new theory. Rather than actively steering the signal, the system is engineered so that the light routes itself.

The principle is directly inspired by thermodynamics. Just as a gas undergoing what's known as a Joule-Thomson expansion redistributes its pressure and temperature before naturally reaching thermal equilibrium, light in the USC device experiences a two-step process: first an optical analog of expansion, then thermal equilibrium. The result is a self-organized flow of photons into the designated output channel—without any need for external switches.

Opening a new frontier

By effectively turning chaos into predictability, optical thermodynamics opens the door to the creation of a new class of photonic devices that harness, rather than fight against, the complexity of nonlinear systems.

"Beyond routing, this framework could also enable entirely new approaches to light management, with implications for information processing, communications, and the exploration of fundamental physics," said the study's lead author, Hediyeh M. Dinani, a Ph.D. student in the Optics and Photonics Group lab at USC Viterbi.

The Steven and Kathryn Sample Chair in Engineering, and Professor of Electrical and Computer Engineering at USC Viterbi Demetrios Christodoulides added, "What was once viewed as an intractable challenge in optics has been reframed as a natural physical process—one that may redefine how engineers approach the control of light and other electromagnetic signals."

More information: Hediyeh M. Dinani et al, Universal routing of light via optical thermodynamics, *Nature Photonics* (2025). DOI: 10.1038/s41566-025-01756-4

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