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Digital Twin Optical Computing System

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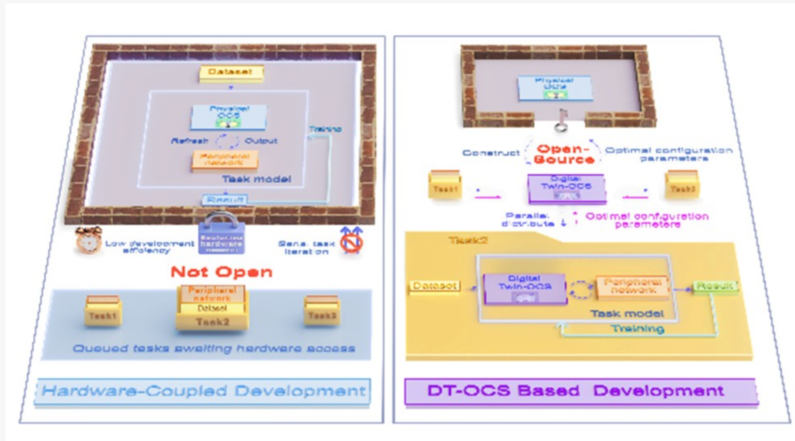
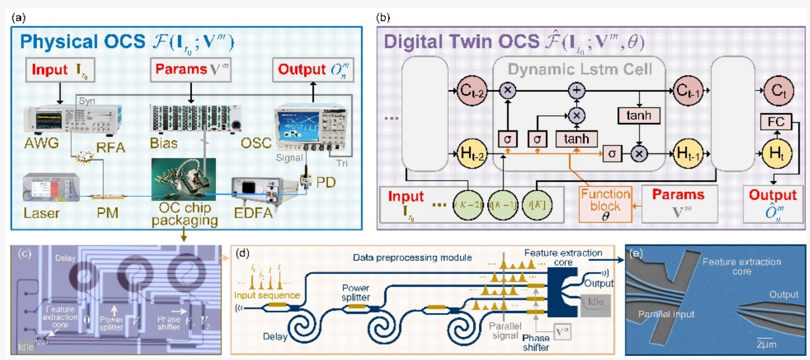


Researchers compare hardware-coupled and DT-OCS-based development workflows for optical computing systems.

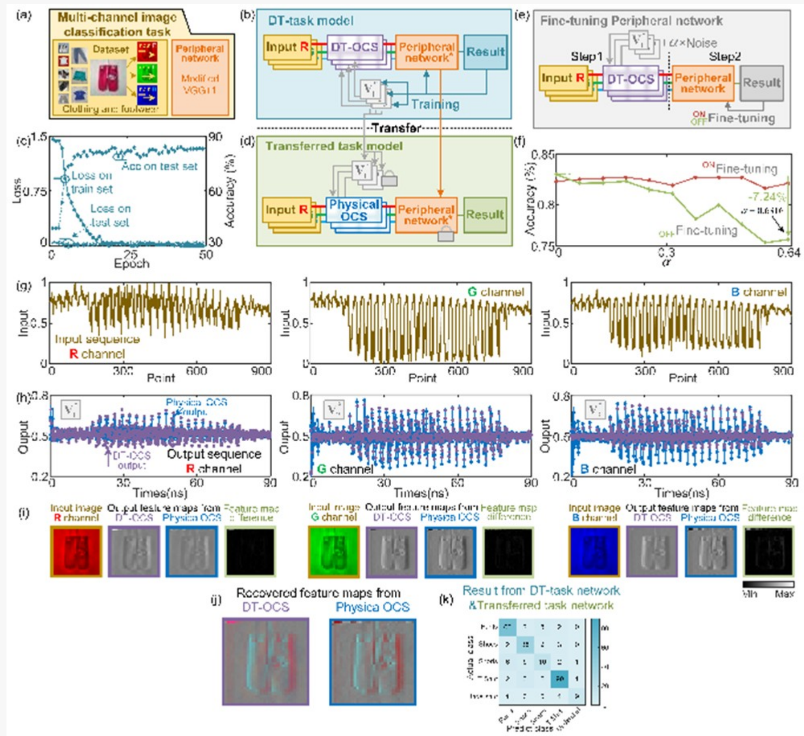


Researchers propose a DT-OCS that reproduces the input-output responses of the physical system under different configuration parameters on a digital platform, thereby enabling offline simulation, training and optimization of computational tasks in the digital domain.

CHINA, June 16, 2026 /EINPresswire.com/ -- While optical computing systems (OCS) with high bandwidth, low latency, and inherent parallelism are promising accelerators for artificial intelligence, the existing OCS implementations require direct participation of physical hardware, tightly coupling development workflows to device access and limiting offline design. Now, researchers have developed a Digital Twin OCS, a system-level, measurement-driven digital surrogate that enables a hardware-decoupled and fully offline development paradigm for OCS.

With the rapid advancement of artificial intelligence and deep learning, traditional electronic computing systems are facing significant bottlenecks in handling large-scale data and complex computational tasks. To overcome these limitations, optical computing has gradually emerged as an important development direction. By leveraging the physical properties of light, such as interference and diffraction, optical computing enables data processing in a fundamentally different way. Compared with electronic computing, it offers higher speed, better energy efficiency, and stronger parallel processing capabilities. Especially in fields such as image processing, machine learning, and big data analytics, optical computing demonstrates broad application prospects.

However, existing optical computing systems (OCS) still face a prominent challenge: the development of computational tasks relies heavily on physical hardware platforms. Under conventional optical computing frameworks, when multiple users need to conduct research using the same OCS, they often have to wait in line for access. Each user must first occupy the device to load parameters, then repeatedly tune the system based on experimental outputs and perform online error calibration before formal computation can begin. After one user completes debugging and computation, the next user often has to readjust the system state, making it difficult to continue directly with a new task. Over time, the entire platform can easily fall into a cycle of "waiting in line, repeated tuning, and repeated calibration." This not only leads to long equipment occupation times and high trial-and-error costs, but also makes it difficult for different tasks to proceed in parallel, thereby severely limiting research efficiency and the flexibility of system applications.



Researchers propose a Digital Twin Optical Computing System, a system-level, measurement-driven digital surrogate that emulates the end-to-end input-output behavior of a specific physical Optical Computing System under different operating configurations.

To overcome the above challenges, the Digital Twin OCS (DT-OCS) has been proposed. By constructing a digital twin model corresponding to the physical OCS, DT-OCS reproduces the input-output responses of the physical system under different configuration parameters on a digital platform, thereby enabling offline simulation, training, and optimization of computational tasks in the digital domain. If the physical OCS can be compared to an expensive and heavily occupied "real machine," then DT-OCS can be seen as its high-fidelity simulator. Instead of relying on real hardware for trial and error every time, researchers can first complete task training, parameter optimization, and performance verification in the digital environment, and then deploy the optimized results to the physical system. In this way, the dependence of task development on hardware during the training and optimization stages is greatly reduced, avoiding the limitations of long-term hardware occupation, online optimization, and repeated debugging in conventional optical computing. DT-OCS not only improves the efficiency of task development but also makes the parallel design and validation of multiple tasks possible, thereby enhancing the flexibility of optical computing research and helping accelerate its practical application and technological advancement. The study was published online in the journal of Opto-Electronic Advances on April 21, 2026.

The significance of this work lies not only in proposing a new model but also in establishing a shareable and reusable digital development paradigm for OCS. It is equivalent to equipping traditional optical computing platforms, which have long relied on physical hardware, with a "digital development kit," enabling researchers to carry out task training, performance validation, and method comparison within a unified digital environment, without repeatedly starting from real hardware for trial and error.

From a longer-term perspective, a mature optical computing platform should not consist of physical hardware alone, but should also provide a digital model corresponding to its computational behavior. Just as modern transportation relies not only on physical road networks but also on continuously updated digital maps, future OCS should likewise adopt a dual form of "hardware platform + digital twin model." Only in this way can more researchers collaborate on the same platform, conduct unified validation, and make fair comparisons, thereby promoting optical computing from a standalone experimental system to a shareable, scalable, and general-purpose research platform.

The DT-OCS framework adopts digital twin technology to construct a high-fidelity digital twin model corresponding to the physical OCS, significantly reducing the dependence of task training, optimization, and development on physical hardware. Based on this framework, researchers are able to carry out task training and parameter optimization independently in an offline environment, while also supporting the parallel development of multiple tasks. As a result, the DT-OCS framework effectively improves the research efficiency and application flexibility of OCS.

The core advantage of the DT-OCS framework lies in decoupling the task development process from physical hardware. In traditional OCS, task training and parameter optimization often require repeated use of physical devices for configuration, measurement, and adjustment, resulting in long development cycles, low efficiency, and limited support for the simultaneous development of multiple tasks. To address this issue, DT-OCS constructs a digital twin model of the physical OCS, which can faithfully reproduce the input-output responses of the system under different configuration parameters in the digital domain. This enables task training and optimization to be carried out mainly in an offline environment. Researchers can therefore perform task training, parameter optimization, and scheme validation without continuously occupying physical hardware, while also supporting the parallel advancement of multiple tasks, thereby significantly improving the development efficiency and application flexibility of OCS.

This study experimentally verifies the effectiveness of the DT-OCS application framework. Using a high-speed OCS integrated with a silicon photonic feature-computing chip as the experimental platform, the research team demonstrated the application of DT-OCS in image classification and sequential decision-making tasks. The experimental results show that after task training and optimization are completed based on DT-OCS, the resulting configuration parameters can be directly transferred to the physical system for use. Moreover, the task performance of the physical system is highly consistent with the predictions of the digital model, validating the high fidelity and strong transferability of DT-OCS at the task-application level. At the same time, since task training and optimization are carried out mainly in the digital domain, different tasks can be developed in parallel, thereby effectively shortening the overall development cycle and improving research efficiency.

The digital twin system supports offline training and final deployment for the Fashion-MNIST classification task. The significance of the DT-OCS framework lies not only in improving the efficiency of task development, but more importantly in promoting the separation of task design from computing system design. In traditional optical computing research, task validation usually depends on specific hardware platforms, and the research process is often constrained by device availability and experimental conditions. This also makes it difficult to conduct broad and reproducible comparisons across different tasks. The open-source nature of the DT-OCS framework further strengthens its methodological value and broader impact. This work not only proposes a digital twin modeling approach but also makes the DT-OCS framework and related task datasets openly available to the research community. As a result, DT-OCS is no longer confined to use within a single experimental platform, but can instead serve as a reproducible, accessible, and scalable software resource for wider sharing and validation. This enables researchers to carry out task design, training, and validation without relying on physical hardware, thereby creating opportunities for broader task exploration and application testing. At the same time, this work also proposes a new application paradigm for optical computing: future OCS should not only provide physical hardware capabilities but also offer open-source digital models that are equivalent at the computational level. Only in this way can optical computing platforms truly evolve from specialized devices dependent on experimental conditions into a new type of computing resource that is shareable, reproducible, and scalable.

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