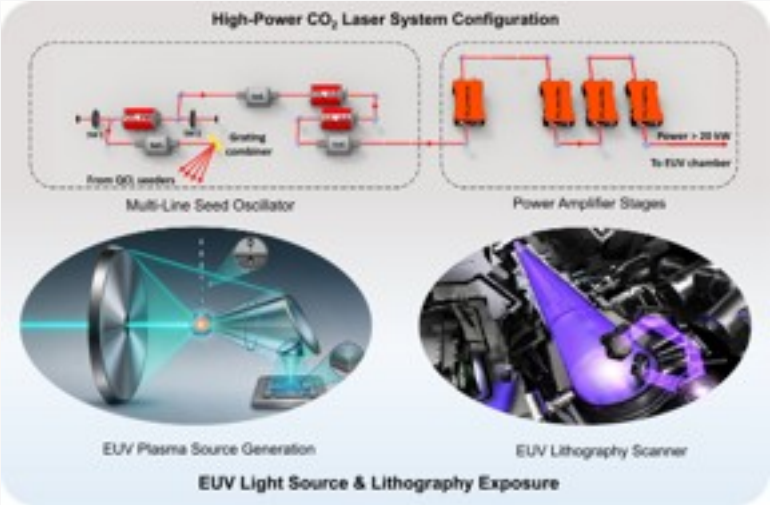
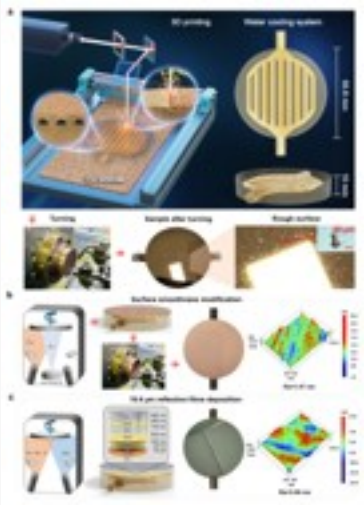
3D-printed copper water cooling system assisted fabrication of 10.6-μm high-power CO2 laser resistance reflectors

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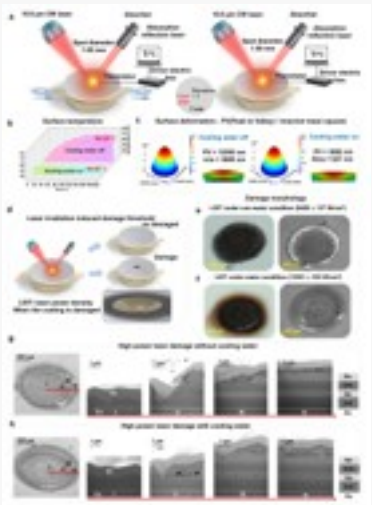
Schematic of a high-power CO2 laser system for EUV lithography.


Integrated fabrication process for the 10.6-μm reflector

Researchers at Tongji University have developed a 3D-printed copper mirror with built-in water-cooling channels for high-power 10.6-μm CO2 lasers. By combining additive manufacturing, a highly conductive copper modification layer, ultra-precision machining and multilayer optical coatings, the integrated mirror reduces heat buildup and deformation while improving laser-damage resistance. The approach offers a compact thermal-management solution for EUV lithography laser chains and other high-power continuous-wave mid-infrared systems. It also supports more compact high-power optical architectures.

As a core driving source for advanced optical manufacturing systems such as extreme ultraviolet (EUV) lithography, the performance of high-power CO2 lasers directly influences the achievable throughput and precision of semiconductor manufacturing. During the multistage amplification, beam expansion, shaping, and focusing of high-power CO2 laser systems, 10.6 μm reflectors are key optical components for ensuring stable energy delivery. As the laser power density continues to increase, photothermal loading caused by absorption in the reflective coating becomes

increasingly severe, leading to heat accumulation at the mirror surface, surface-figure distortion, and coating damage. These effects degrade beam quality and focusing stability and have become a major bottleneck limiting the reliable operation of the overall system. Developing a new generation of reflectors that combines high reflectivity with strong resistance to laser-induced damage is therefore a critical challenge in extreme optical manufacturing.



Comparison of temperature rise, thermal deformation, and laser-damage performance with and without water cooling.

Conventional approaches typically enhance heat dissipation by attaching a water-cooling system to the back surface of the reflector, which can mitigate laser-induced thermal effects to some extent. In recent years, 3D printing has overcome structural constraints associated with conventional manufacturing through its high degree of design freedom and ability to integrally fabricate complex geometries, enabling the widespread use of additively manufactured aluminum-based mirrors in multiwavelength space optical imaging. However, the relatively low thermal conductivity of aluminum makes it difficult to meet the extreme heat-dissipation requirements of ultrahigh-power lasers. By contrast, copper-based materials offer excellent thermal conductivity and have become key materials for advanced thermal-management applications. At present, 3D-printed copper-based liquid-cooling plates are emerging as a major technological route for thermal management in next-generation high-end equipment. Nevertheless, the conventional separated architecture of an optical substrate combined with an externally mounted rear-cooling system inherently suffers from high interfacial thermal resistance, limited heat-dissipation efficiency, and low integration. As laser power density continues to rise, this architecture is increasingly approaching its performance limit.

To address these challenges, a research team at Tongji University departed from the conventional separated cooling strategy and proposed an integrated optical-thermal-structural design that combines four key technologies: 3D printing, surface modification, ultraprecision machining, and optical coating. Using laser powder bed fusion (LPBF), the team directly printed high-precision, complex cooling channels inside the copper-based mirror body, seamlessly integrating the heat-dissipation structure with the optical substrate. This design fundamentally eliminates the thermal resistance associated with an external interface while reducing the overall system volume. A highly thermally conductive copper modification layer was then prepared by electron-beam evaporation with ion-beam-assisted deposition, followed by ultraprecision single-point diamond turning to obtain an ultrasmooth mirror substrate. Finally, a multilayer reflective coating was deposited to form an integrated high-power reflector consisting of a high-reflectivity coating, a highly thermally conductive copper modification layer, and 3D-printed copper-based water-cooling channels.

The central innovation of this study is the development and implementation of an integrated

optothermal management scheme combining a high-reflectivity coating, a highly thermally conductive copper modification layer, and embedded water-cooling channels. By integrating the water-cooling system directly into the 3D-printed copper-based reflector, the design overcomes the conventional separated architecture based on externally mounted rear cooling. The copper-based reflector substrate was fabricated by LPBF, and parallel straight-through water-cooling channels were optimized through multi-physics simulations to balance heat-dissipation efficiency, flow resistance, and manufacturability. To address the high porosity and surface roughness of 3D-printed copper components, a process sequence of ultraprecision turning, copper modification, and secondary single-point diamond turning was employed to fill surface pores and achieve ultrasmooth planarization. Combined with the deposition of a multilayer high-reflectivity coating, the reflector achieved a reflectivity exceeding 99.50% at 10.6 μm under 45° incidence. Experimental results demonstrated that, at a laser power density of 5093 W/cm2, the integrated design reduced the maximum mirror-surface temperature by 53%, decreased the peak-to-valley thermal deformation by approximately 75%, and increased the laser-induced damage threshold by 60%. A comparison between copper and nickel modification layers further confirmed the critical role of highly thermally conductive materials near the coating interface in efficiently extracting heat.

Overall, this work integrates additive manufacturing, ultraprecision machining, optical coatings, and active liquid cooling within a single optical component. It provides a new engineering solution that simultaneously addresses optical performance, thermal stability, and manufacturability for EUV-lithography drive-laser beamlines and other high-power continuous-wave mid-infrared laser systems.

Keywords: 3D printing cooling system, surface modification, 10.6 μm reflective coating, thermal control, laser-induced damage threshold
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papers and holds more than 20 granted patents. His honors include the First Prize of the 2015 Ministry of Education Technological Invention Award (fourth contributor), the Second Prize of the 2019 State Technological Invention Award (third contributor), the Second Prize of the 2019 Ministry of Education Science and Technology Progress Award (second contributor), and the First Prize of the 2024 Science and Technology Progress Award of the Chinese Society for Optical Engineering (third contributor).

This work was completed at the Institute of Precision Optical Engineering, Tongji University. Led by Prof. Zhanshan Wang, a recipient of the National Science Fund for Distinguished Young Scholars and a Changjiang Scholar, and Prof. Xinbin Cheng, a recipient of the National Science Fund for Distinguished Young Scholars, the Institute supports the first-level discipline of Optoelectronic Science and Technology, the second-level discipline of Optics, and the undergraduate program in Optoelectronic Information Science and Engineering. The Institute currently operates on the basis of one national-level and three provincial/ministerial-level platforms: the National Industrial Metrology and Testing Center for Integrated-Circuit Micro/Nano Inspection Equipment (Shanghai), the Key Laboratory of Advanced Micro-Structured Materials of the Ministry of Education, the Shanghai Frontier Science Research Base of Digital Optics, and the Shanghai Professional Technical Service Platform for Full-Spectrum High-Performance Optical Thin-Film Devices and Applications. It has long been engaged in education and training, fundamental science, key technologies, and engineering applications in precision optical engineering. With a mission to address frontier scientific questions and achieve breakthroughs in core technologies, the Institute has undertaken multiple major national research projects in recent years. It has received one First Prize of the State Scientific and Technological Progress Award, two State Technological Invention Awards, one China Patent Gold Award, and more than ten provincial- and ministerial-level awards, and has become an important base for cultivating high-level talent and conducting high-quality scientific research.
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