

Researchers Develop Next-Generation Encryption Metasurface Using Femtosecond Laser Technique

Announcing a new publication from *Opto-Electronic Advances*; DOI 10.29026/oea.2026.250303.

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In the digital age, information security has become the "lifeline" for safeguarding personal privacy, corporate secrets, and national information. For instance, reliable encryption methods are indispensable for mobile payment digital signatures, security authentication, anti-counterfeiting technologies, and sensitive data encryption protection. The complexity and insecurity of the network environment will inevitably promote the popularization and application of physical encryption methods. Optical encryption, with its advantages of high efficiency and high speed, has become a research hotspot in the field of information security. The emergence of metasurface technology has led us into a new era of multi-channel high-security encryption. Through combination with external stimuli such as light, heat, electric fields, and phase change materials (PCMs) systems, flexible encryption upgrades can also be achieved. However, the practical application of this technology is still limited by two major constraints: significant reliance on complex optical decryption systems and high-precision nanofabrication technologies (especially electron beam lithography). The emergence of the concepts of "quasi-ordered" and "disordered" metasurfaces provides new feasibility for expanding the technical boundaries of optical encryption, and further catalyzes the innovation of high-efficiency manufacturing technologies to reduce dependence on traditional lithography technologies.

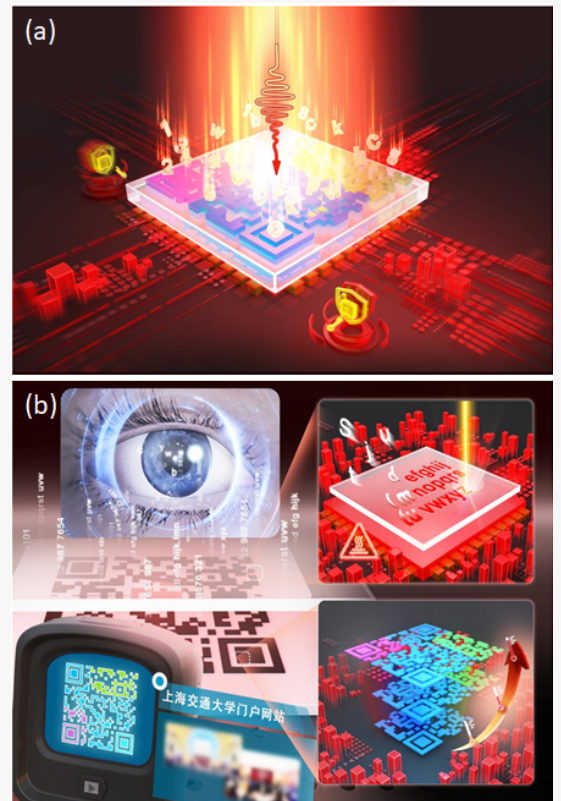


Figure 1. (a) Concept diagram of integrated laser information writing and multi-dimensional information matrix display encryption. (b) Conceptual diagram of visible light infrared crosstalk free information reading, visible light information high-tempera

Femtosecond laser maskless direct writing (fs-LMDW) technology has gradually become a new method of concern in the field of metasurface engineering. Its core advantages are manifested in: simple and fast operation, no environmental dependence, strong cross-scale processing capability, which can realize customized patterning processing from micron to nanometer scale, excellent structural reconfigurability, material universality, especially obvious advantages in micro-nano processing of difficult-to-process materials such as refractory metals, and wide compatibility with other processing techniques. In addition, its unique chemical-physical synergistic modification capability is particularly prominent, which is expected to achieve a multi-dimensional balance of efficiency, precision, and manufacturability, providing strong support for the development of optical metasurfaces. However, the information writing capability of this technology on non-transparent materials is usually in a single band, either visible light or infrared. It has become an urgent challenge to encode and write visible light band information and infrared information into a single entity without crosstalk, perform matrix-based regulation of multi-band information (Figure 1 (a)), and simultaneously exert the high-temperature resistance advantage of refractory metals to achieve high-security and high-selectivity information decryption regulation.

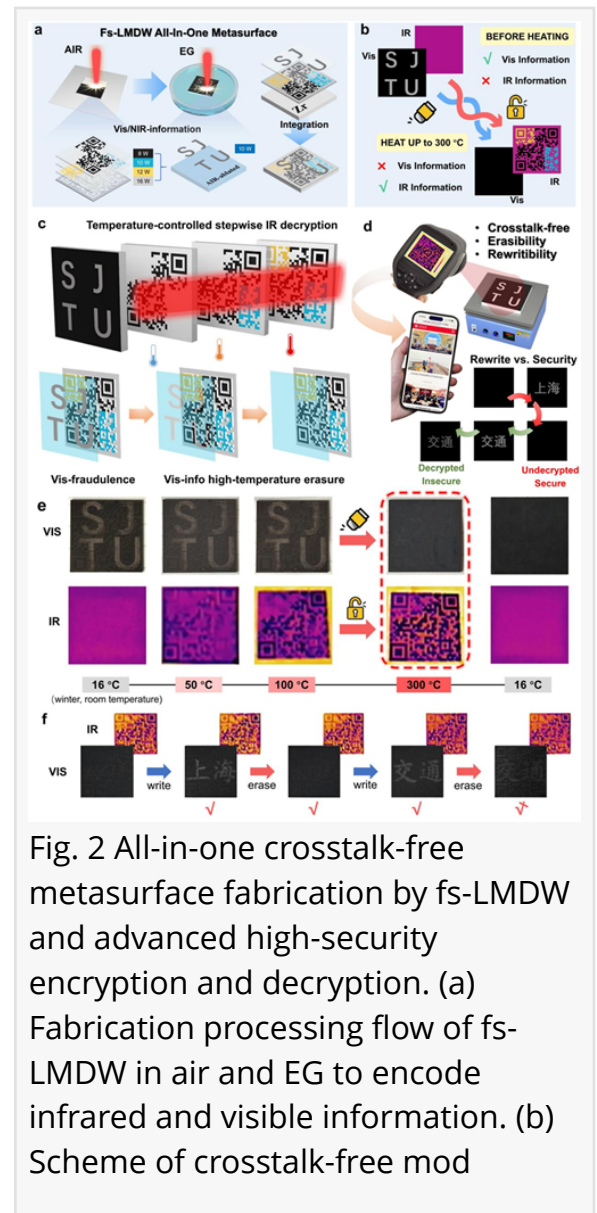


Fig. 2 All-in-one crosstalk-free metasurface fabrication by fs-LMDW and advanced high-security encryption and decryption. (a) Fabrication processing flow of fs-LMDW in air and EG to encode infrared and visible information. (b) Scheme of crosstalk-free mod

The femtosecond laser micro-nano processing team from the School of Materials Science and Engineering, Shanghai Jiao Tong University, proposed a potential solution. They can integrally write visible/infrared dual-band information on pure zirconium refractory metal substrates through femtosecond laser maskless direct writing technology, realize crosstalk-free hierarchical regulation of visible light information and infrared information, and endow encrypted information with a high-temperature key, as shown in Figure 1 (b). This work was published in the journal Opto-Electronic Advances under the title "Femtosecond Laser Maskless Direct Writing of Dual-Band Crosstalk-Free Information for All-In-One High-Security Encryption Metasurface".

Figure 2 shows the preparation process and actual test results of the metasurface. First, in an air environment, femtosecond laser is used to engrave infrared information with gradient micro-nano structures (such as the QR code of Shanghai Jiao Tong University's official website) on the zirconium substrate. This structure presents a uniform black color due to the rich oxygen vacancies, which can effectively hide the infrared information; subsequently, the substrate is

placed in an ethylene glycol (EG) environment, and gray visible light information (such as patterns of "SJTU", "Shanghai", "Jiaotong", etc.) is written by femtosecond laser. Since the modified structure is limited to the nanometer scale, it will not damage the micro-scale structure related to infrared information. The spatial structure and spectrum are synergistically regulated to complete the crosstalk-free writing of dual-band information. The visible light information has high-temperature erasability and laser rewritability. The SJTU and "Shanghai" patterns disappear at 300°C, and the "Jiaotong" pattern rewritten by femtosecond laser is also clearly visible, which cannot be completely erased at 300°C, demonstrating the one-time complete erasure capability of the sample, which can effectively verify whether the information has been maliciously read and rewritten. The infrared band information can be displayed in a temperature gradient. With the increase of temperature, the QR code information written at different powers will be displayed in a graded manner. At 300°C, the QR code is completely clearly displayed, and the relevant content of Shanghai Jiao Tong University's homepage can be read by mobile phone scanning. The proposal and verification of the "temperature-controlled key" encryption metasurface fully exert the characteristics of refractory metals. Compared with phase change materials, the decryption temperature is greatly increased, and the unique advantages of femtosecond laser micro-nano processing of refractory metals are also fully exerted.

To verify the internal mechanism of visible light information writing and high-temperature erasure, the researchers conducted various comparative characterizations on the structural details (Figure 3). It was found that LIPSS structuring along with the reducing ability and low oxygen defect oxidation ability in the ethylene glycol liquid phase environment are the main reasons for the differential color development, and the oxidation in the high-temperature environment is the internal mechanism for the erasability of visible light information.

Keywords: all-in-one metasurface, femtosecond laser maskless direct writing, high-security encryption temperature-controlled decryption, erasability and rewritability

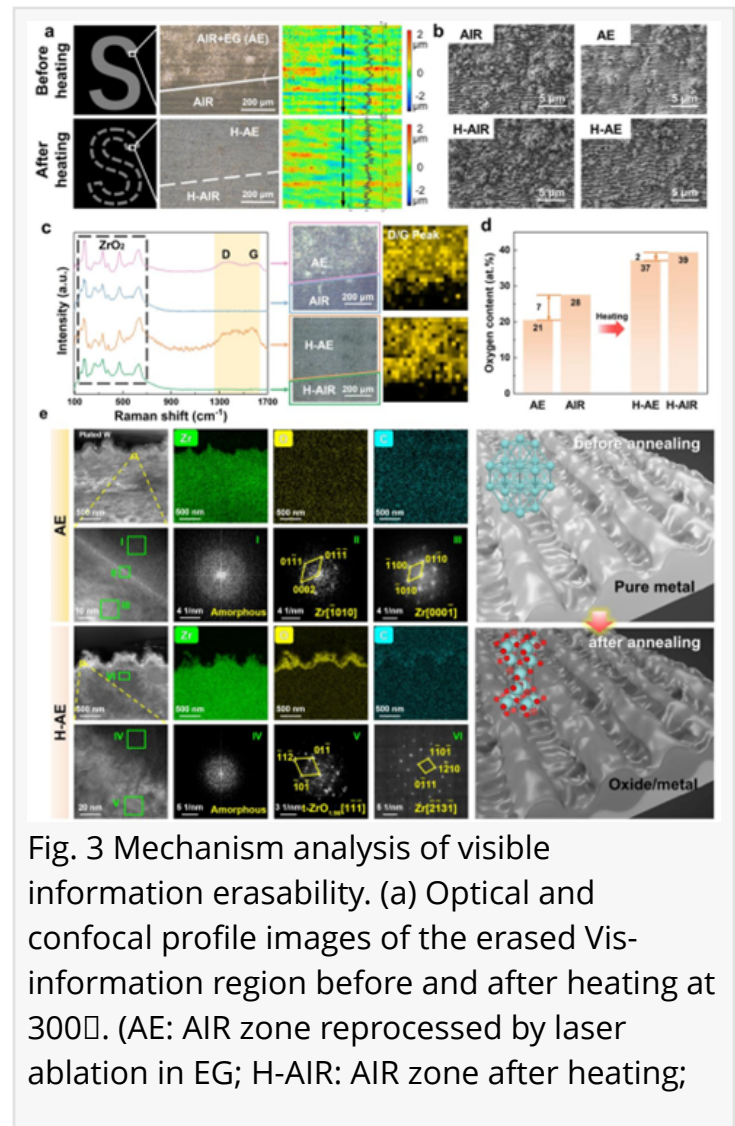


Fig. 3 Mechanism analysis of visible information erasability. (a) Optical and confocal profile images of the erased Vis-information region before and after heating at 300°C. (AE: AIR zone reprocessed by laser ablation in EG; H-AIR: AIR zone after heating;

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This research was carried out under the guidance of Associate Professor Dongshi Zhang and Professor Zhuguo Li, relying on the Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiao Tong University. The first author is Master's student Hanmian Jiang. The team has long been committed to the research of femtosecond laser processing and material interface modification, focusing on the development of laser direct writing multi-functional metasurfaces, and exploring the development potential of femtosecond laser micro-nano processing in fields such as information encryption and infrared camouflage. Relevant achievements have been published in journals such as Engineering, Opto-Electronic Advances, and International Journal of Extreme Manufacturing.

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