

Article

Optical Performance Analysis of Anti-Reflective Microholes with Different Arrangements Fabricated by Femtosecond Laser Zigzag Scanning

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Abstract

A femtosecond laser serves as an excellent tool for efficiently fabricating large-area anti-reflective microhole arrays on infrared windows. The impact of the arrangement of the microholes during processing on final performance, however, remains unclear. Here, microhole arrays were fabricated on MgF_2 windows using a femtosecond laser. The optical performance was analyzed by the finite-difference time-domain method, focusing on the effects of in-plane arrangement deviation and double-sided alignment error. Simulation results indicate that the arrangement variations alter the average transmittance by less than 0.02%. Analysis via effective medium theory revealed that, within the target band, the microstructure array collectively functions as a thin film with a gradient refractive index. Its macroscopic properties show little sensitivity to minor misalignments at the microscopic scale. As a proof of concept, a large-area (20 mm $\times$ 20 mm) double-sided antireflection window was rapidly fabricated by employing a zigzag scanning strategy, which achieved an average transmittance exceeding 97.5% and exhibited a high degree of consistency between the simulated and experimental results. Upon final integration into the infrared thermal imaging system, this window not only enhanced the richness of detail in captured images but also improved target contrast.

Keywords: femtosecond laser; zigzag scanning; anti-reflective microhole; arrangement deviation; optical performance

1. Introduction

Over long periods of evolution, numerous organisms have developed refined structural features [1]. Examples include plant stems and leaves [2], insect compound eyes [3], reptile footpads [4], etc. These features support survival, foraging, and reproduction in extreme environments. Recently, the exceptional visual capability of insect compound eyes has drawn considerable research attention [5–9]. Studies show that the compound eyes of moths, stink bugs, and dragonflies possess surfaces with micro–nano structural arrays [10]. These arrays are crucial for achieving wide-angle, high-sensitivity vision [11]. Inspired by such biological microstructures, researchers have attempted to fabricate sub-wavelength anti-reflection microstructure arrays on infrared window surfaces [12]. These arrays establish a gradient refractive index at the surface, which significantly reduces Fresnel reflection loss [13]. The infrared window is a key optical component in thermal imaging



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systems [14]. Its main functions are transmitting infrared signals and protecting internal detectors. Minimizing signal loss at the surface helps obtain clearer infrared images. These subwavelength structures maintain material consistency with the substrate. They not only improve infrared transmittance but also avoid the drawbacks of traditional anti-reflection coatings, such as poor mechanical strength and thermal expansion [15]. Consequently, they are particularly suitable for infrared imaging applications in complex environments [16].

Femtosecond laser processing, a maskless technique offering adjustable dimensions and single-step fabrication, has emerged as a promising solution for creating large-area microstructures [17–26]. For instance, Zhang et al. employed a point-by-point fs-laser strategy to fabricate periodic microhole arrays with square and hexagonal lattices [27]. Tests on a small area showed that this structure increased the transmittance of zinc sulfide from 73% to 82%. Practical applications, however, require millions to billions of microstructures on a window surface, demanding much higher processing speeds. Systems combining high-repetition-rate fs-lasers with precision three-axis motion platforms have proven effective for large-area fabrication [28]. Li et al. mounted a zinc sulfide window on such a platform, using a laser scan at 10 mm/s to create microgrooves [29]. Two cross-hatched zigzag scans then produced a microcone array across a 76.2 mm × 76.2 mm area. The platform's relatively low translation speed here limited processing efficiency. Employing high-repetition-rate pulse bursts to form microholes in a single step can enhance efficiency. Ding et al. used 20 kHz fs-laser pulse bursts with a 36 mm/s zigzag scan to fabricate approximately 7 billion microholes on both sides of a 100 mm diameter zinc sulfide window, achieving a rate near 20,000 holes per second [30]. This method, however, results in varied hole arrangements. Furthermore, the minute feature sizes make precise alignment between double-sided microstructures difficult to guarantee [31,32]. Investigating the influence of antireflective microstructure arrangement on transmittance, some studies have analyzed samples fabricated by point-by-point engraving [27,33]. However, due to limitations in processing efficiency, measurement inaccuracies, and manufacturing tolerances, accurately determining the relationship between the arrangement of antireflective microholes and their transmittance performance remains challenging. So far, systematic studies are lacking on whether the inherent variations in microhole arrangement and unavoidable double-sided alignment errors significantly degrade anti-reflective performance.

In this study, anti-reflective microhole arrays were fabricated on MgF₂ windows using a femtosecond laser zigzag scanning strategy. By integrating simulation and experimental approaches, the influence of fabrication deviations on window transmittance was systematically quantified. The results show that these deviations cause fluctuations in the average transmittance of less than 0.02%, demonstrating excellent performance robustness. Furthermore, a double-sided anti-reflection window was successfully prepared, achieving an average transmittance exceeding 97.5%. When integrated into an infrared thermal imaging system, the window enhanced both the local entropy and contrast of the captured images, thereby confirming its practical application value.

2. Simulation and Experiment

To investigate the influence of anti-reflection microstructure arrangement on optical performance, simulations of transmission spectra, reflection spectra, and energy flux density distributions near the structures were conducted using the finite-difference time-domain (FDTD) method [34]. The simulation model was constructed using the commercial software Ansys Lumerical FDTD Solutions, version 2022 R2. The simulation setup, shown in Figure 1a, primarily included boundary conditions, a light source, substrate material, and monitors [35]. A perfectly matched layer (PML) boundary condition was applied in the z-direction to eliminate reflections of plane waves at the computational boundaries [36].

Periodic boundary conditions were used in the x- and y-directions, which allowed for modeling the periodic arrangement of microstructures while effectively reducing computation time. The excitation source was a plane wave ($3\text{--}5\text{ }\mu\text{m}$), the substrate material was an MgF_2 window, and field distribution monitors were set to record the results. At three distinct locations, field distribution monitors were placed to record the transmittance, reflectance, and energy flux distribution, respectively (Figure 1a). The mesh accuracy was set to 20 nanometers, and the simulation time was uniformly set to 5000 fs to ensure the stability of the transmission spectra, reflection spectra, and energy flux distribution results.

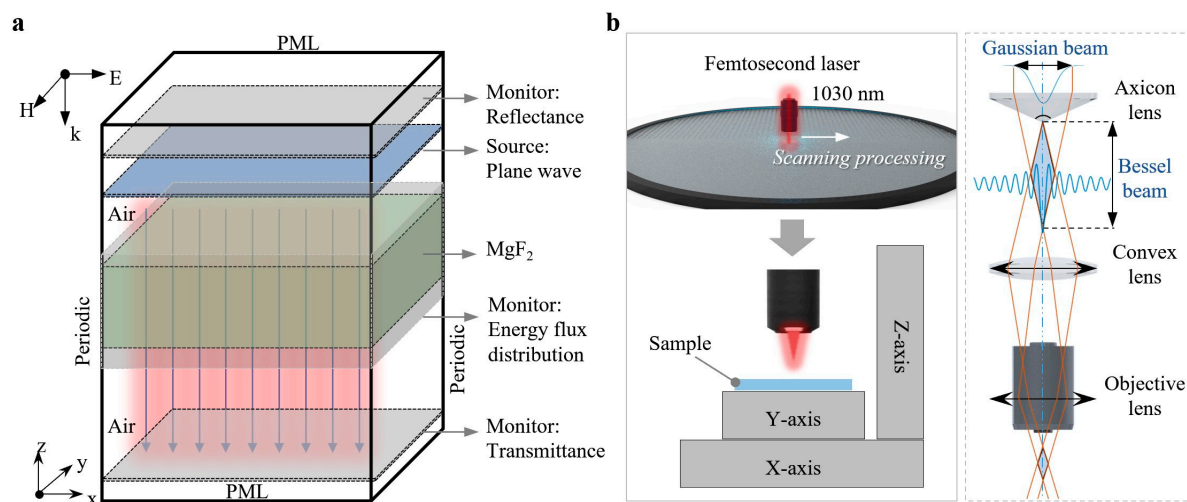


Figure 1. (a) Schematic of the FDTD modeling for the anti-reflective microstructure; (b) illustration of the femtosecond laser processing system.

For the experiments, a processing system combining a high-repetition-rate femtosecond laser and a precision three-axis motion platform was employed (Figure 1b). The processed samples were double-sided polished MgF_2 windows. The femtosecond laser (HR-300-1, Ultron Photonics, Hangzhou, China) emitted pulses with a repetition rate of 10 kHz, a pulse width of 844 fs, and a wavelength of 1030 nm. The Gaussian beam emitted by the laser has a diameter of 4 mm. To enhance the Rayleigh length of the laser focus for fabricating large-area microholes with high consistency, the Gaussian beam from the femtosecond laser was transformed into a Bessel beam using an axicon with a cone angle of 175° , and a convex lens (150 mm focal length) was employed to compress the Bessel beam diameter to match the entrance pupil size of the objective lens. The laser beam was focused to the required size using a $40\times$ objective lens with a numerical aperture of 0.6. The platform performed a zigzag scan at a speed of 20 mm/s and a period of $2\text{ }\mu\text{m}$, enabling the efficient fabrication of large-area anti-reflection microhole arrays (using a single pulse). The morphology and three-dimensional profiles of the microholes were characterized using field emission scanning electron microscopy (SEM, JSM-7900F, JEOL, Tokyo, Japan) and atomic force microscopy (AFM, Dimension Icon, Bruker, Karlsruhe, Germany), respectively. Microhole diameter and depth data were extracted from cross-sectional profile images using ImageJ software, version 1.52. Each set of parameters was measured 10 times, and the results are expressed as mean $\pm$ standard deviation. Transmittance was tested using a Fourier transform infrared spectrometer (IS50, Thermo Fisher, Waltham, MA, USA). The measurements were conducted in transmission mode with the following parameters, a spectral resolution of 4 cm^{-1} over the wavenumber range of $4000\text{--}400\text{ cm}^{-1}$, and 32 scans were accumulated and averaged for both the background (open beam) and the sample to ensure a high signal-to-noise ratio. The incident beam spot size on the sample was approximately 10 mm in diameter. The transmittance spectrum was automatically calculated by

the instrument's software (OMNIC, Thermo Scientific, USA), version 9.2. Infrared imaging performance was evaluated with an infrared thermal imager (ImageIR 8300, InfraTec GmbH, Dresden, Germany).

3. Results and Discussion

Figure 2a presents two typical microstructures fabricated by a femtosecond laser. The microcones were produced through two overlapping zigzag scans. This process requires a lower scanning speed to ensure sufficient overlap between the laser-affected zones of adjacent pulses [37]. In contrast, microholes are created with just a single zigzag scan, which permits a higher processing speed [38–42]. This characteristic gives microhole fabrication a distinct efficiency advantage for producing large-area anti-reflective surfaces. The anti-reflective microhole array obtained via the zigzag scanning method is shown in Figure 2b. Here, the laser operated at a fixed repetition rate of 10 kHz, while the three-axis platform moved at 20 mm/s with a 2 μm interval. This setup resulted in a periodic 2 μm spacing for the microholes, both along the scanning direction and between rows. It is important to note that the abrupt deceleration and acceleration of the scanning path at its ends can lead to variations in the microhole arrangement. These include square, hexagonal, and other irregular lattice patterns, as illustrated in Figure 2c.

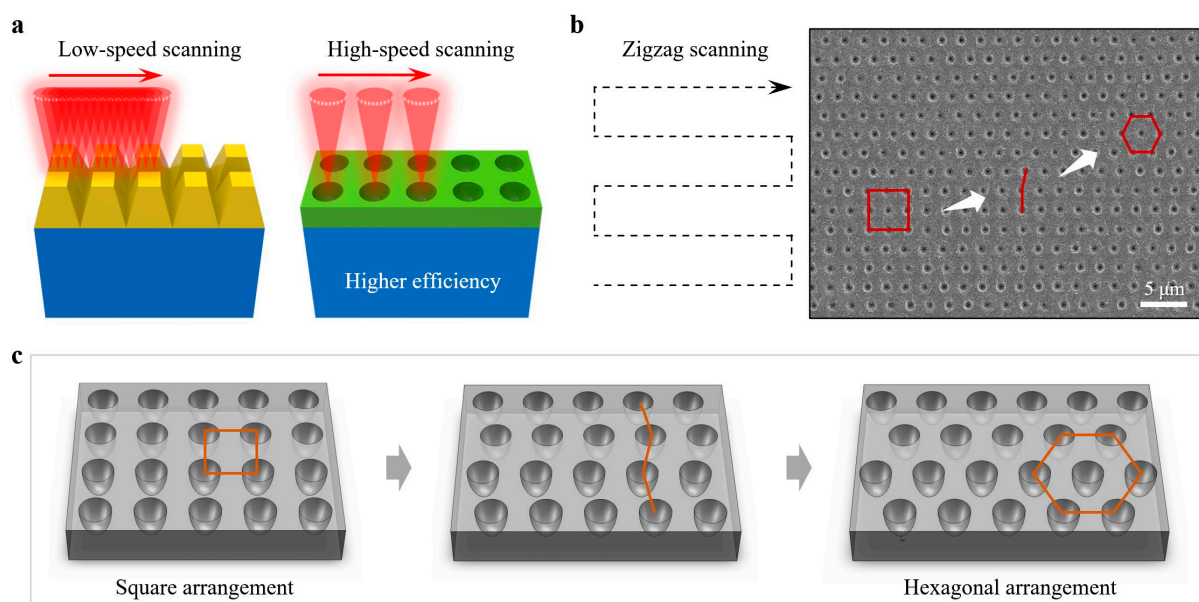


Figure 2. (a) Morphologies of two typical microstructures fabricated by femtosecond laser; (b) anti-reflective microhole array processed under a zigzag scanning path; and (c) observed square, hexagonal, and other irregular arrangements within the microhole array.

To investigate how the arrangement of microholes affects anti-reflective performance, we developed a series of FDTD simulation models representing different offset conditions. The deviation between the centers of microholes in adjacent rows was defined as δ , as illustrated in Figure 3a. A δ value of 0 μm corresponds to a square lattice arrangement, while $\delta = 1 \mu\text{m}$ results in a hexagonal lattice. Figure 3b shows that under different δ values, the transmission and reflection spectra of the microhole array in the 3–5 μm band are nearly identical. Calculating the average transmittance across this band reveals that variations caused by different offsets are below 0.02% (Figure 3c). This indicates that the specific arrangement has a negligible impact on anti-reflective performance. This observed robustness can be explained by the effective medium theory [34]. Given a structural period of 2 μm , the microstructure array effectively functions as a homogeneous layer with a

gradient refractive index for the 3–5 μm infrared band (Figure 4a). Simulations of the energy flux density distribution confirm a localized field enhancement within the microstructure region [43], which aids in improving light transmission efficiency (Figure 4b). Furthermore, the modulated beam maintains its original propagation direction (Figure 4c). Consequently, variations in arrangement do not alter the fundamental nature of the structure as a gradient-index layer [44,45]. From a microscopic perspective, whether the columns of microholes are perfectly aligned has little effect on the macroscopic optical behavior. As long as each row maintains a periodic arrangement, the structure achieves the desired equivalent gradient-index effect.

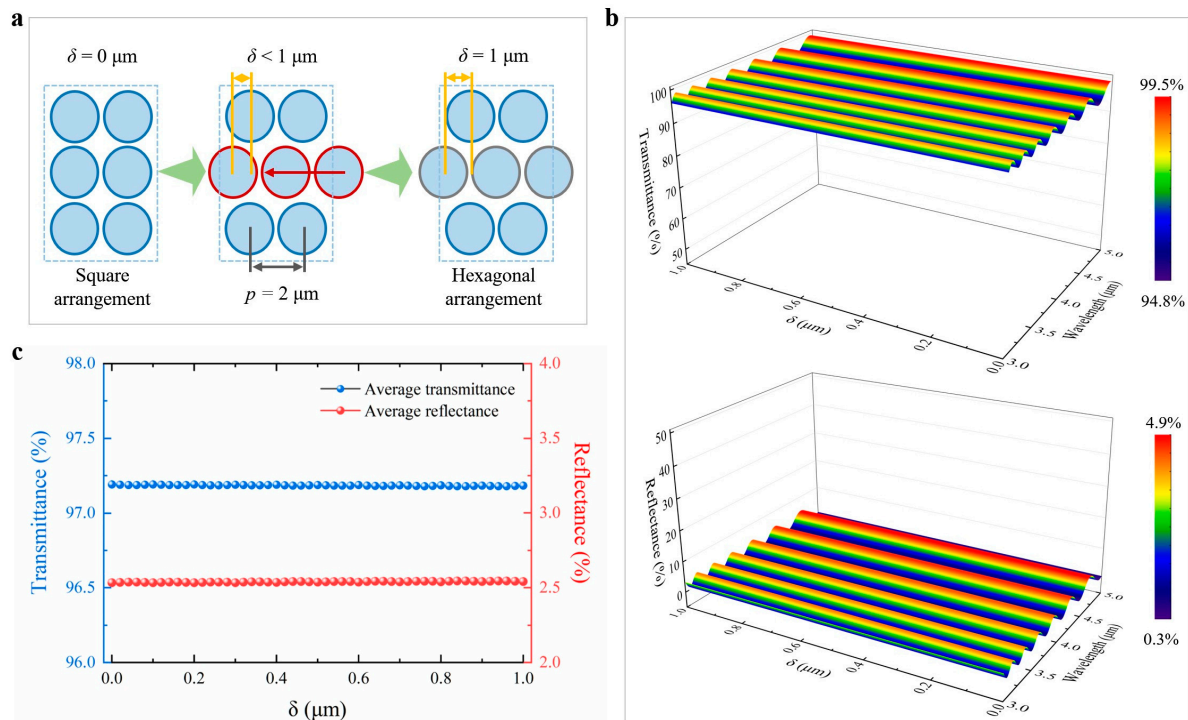


Figure 3. (a) Schematic of the center deviation δ between microholes in adjacent rows; (b) transmission and reflection spectra of the microhole array in the 3–5 μm band under different δ conditions; and (c) statistical averages of transmittance and reflectance under the corresponding conditions.

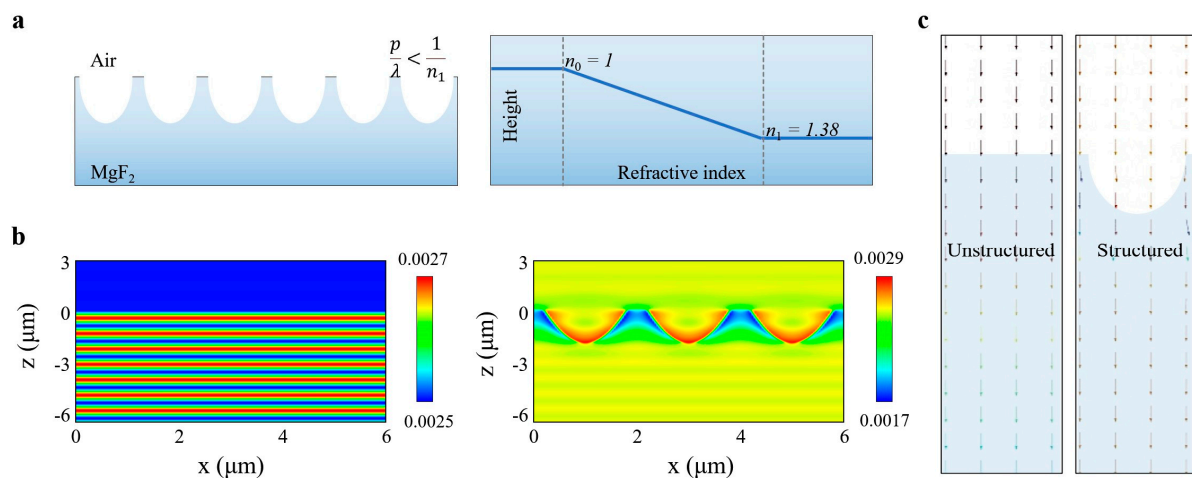


Figure 4. (a) Schematic illustrating the equivalence of the anti-reflective microstructure array to a gradient-index medium layer; (b,c) simulation results of the energy flux density distribution and beam propagation on window surfaces without and with the microstructure.

To further reduce the reflection loss of infrared signals at both the front and rear surfaces, anti-reflective microhole arrays need to be fabricated on both sides of the optical window [30]. However, with a microhole period of only $2\ \mu\text{m}$, achieving precise alignment for the second side after processing the first is challenging. To address this, we established a simulation model for the double-sided microstructure, defining the deviation between the centers of the inner and outer microholes as Δ (Figure 5a). Figure 5b compares the simulated transmission spectra of single-sided and double-sided microstructures. The double-sided structure suppresses reflection from both surfaces simultaneously, leading to a further increase in transmittance. Within the $3\text{--}5\ \mu\text{m}$ band, the transmission and reflection spectra under different Δ conditions, along with their statistical averages, are essentially consistent. The maximum discrepancy does not exceed 0.02% , indicating that the alignment deviation between the two sides has no significant impact on the anti-reflective performance (Figure 5c,d). This phenomenon is similar to the case of in-plane arrangement deviation δ . In the macroscopic effective model, the microstructure array is treated as a continuous medium layer. Therefore, alignment errors at the microscopic scale do not alter its gradient refractive index characteristic. The highly consistent energy flux density distributions of the double-sided structure under different Δ conditions, shown in Figure 6, confirm this conclusion.

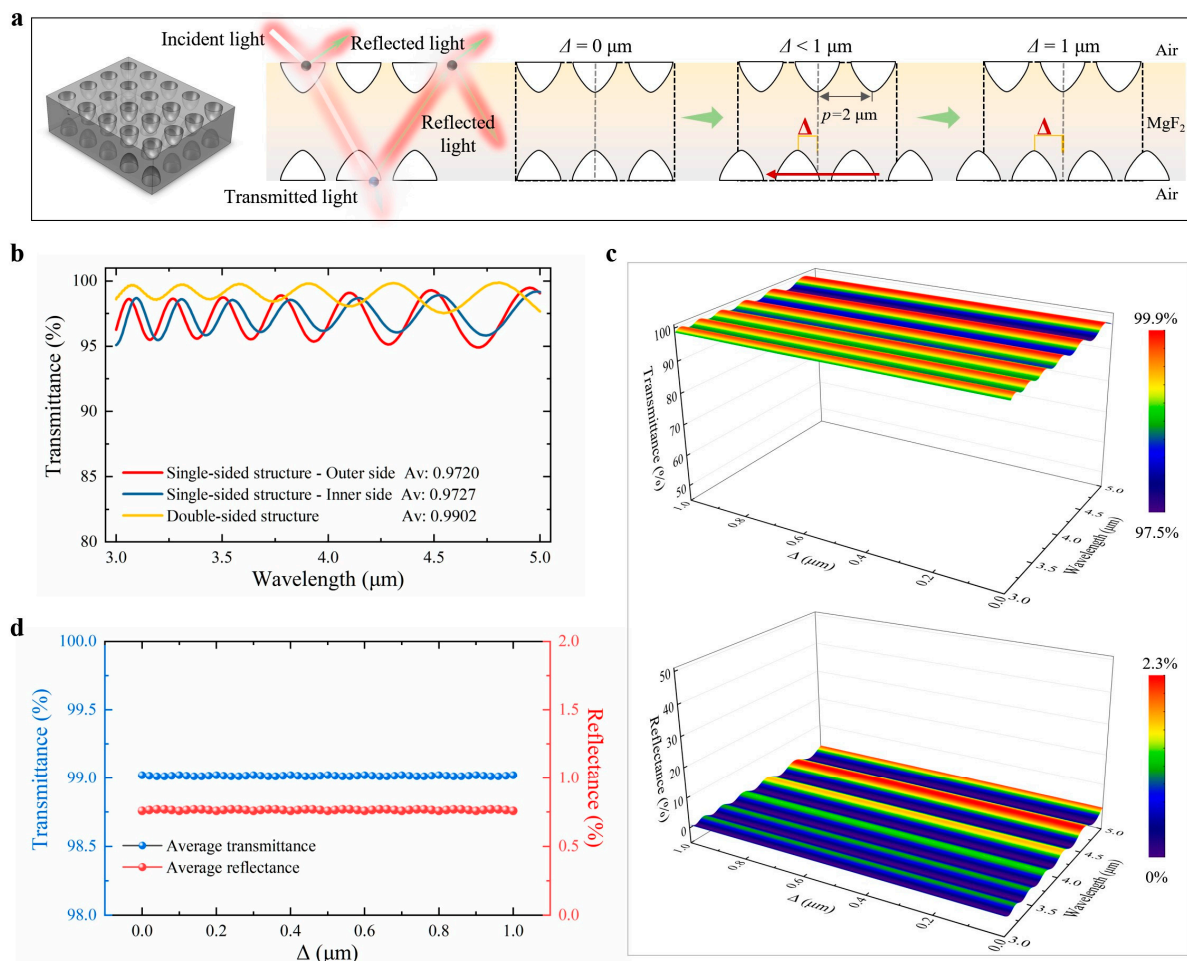


Figure 5. (a) Schematic of the center position deviation Δ for double-sided microholes; (b) simulated transmission spectra for single-sided and double-sided anti-reflective structures; and (c,d) simulated results of average transmittance and reflectance in the $3\text{--}5\ \mu\text{m}$ band under different Δ conditions.

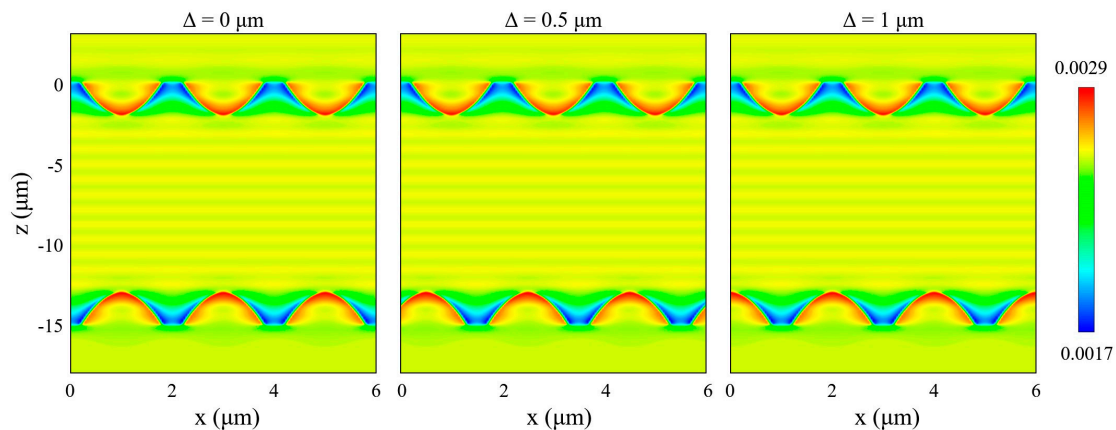


Figure 6. Energy flux density distributions of the double-sided anti-reflective microhole array with Δ values of 0, 0.5, and 1.0 μm .

To validate the method, a large-area anti-reflective microhole array measuring 20 mm $\times$ 20 mm was fabricated using zigzag scanning with a pulse energy of 56 μJ (Figure 7a). The AFM three-dimensional topography and cross-sectional profile reveal microholes with a diameter of approximately $1.51 \pm 0.11 \mu\text{m}$ and a depth of about $0.43 \pm 0.05 \mu\text{m}$ (Figure 7b). Fourier transform infrared spectroscopy tests demonstrate that the MgF_2 window with double-sided microstructures achieves an average transmittance exceeding 97.5% in the mid-wave infrared (3–5 μm) band (Figure 7c). The simulated transmittance under different Δ conditions is shown in Figure 7d,e. It should be noted that the simulated transmittance spectrum exhibits a periodic, cosine-like oscillatory curve. This is due to the oscillation of the incident light between the upper and lower surfaces of the window medium in the simulation [27,35]. Nevertheless, this oscillation does not affect the overall trend of the transmittance. The increase in its average value reflects the antireflection performance of the microhole array. A comparison between the oscillatory curve and the experimental results reveals close alignment of its median with the measured data, confirming the reliability of the simulation model.

The infrared window is typically positioned at the front end of a thermal imager [16,46,47]. Its role is to receive infrared signals while protecting the internal optical system. After passing through the window, infrared light is converted into an image by the detector (Figure 8a). The strength of this signal directly affects final image quality [48]. For a comparative imaging test, a standard MgF_2 window and the anti-reflective MgF_2 window were mounted separately on the same infrared thermal imager (Figure 8b). Analysis of two key image features—local entropy and contrast—revealed clear improvements [49]. The images obtained with the anti-reflective window showed an increase in local entropy from 5.43 to 5.52 bit and in contrast from 32.28 to 32.74 a.u. (Figure 8c). Local entropy quantifies the richness of detail within local image regions, while contrast characterizes the distinction between the target and its background. The enhancement of both metrics demonstrates that the anti-reflective window effectively improves the detection performance of the infrared thermal imaging system.

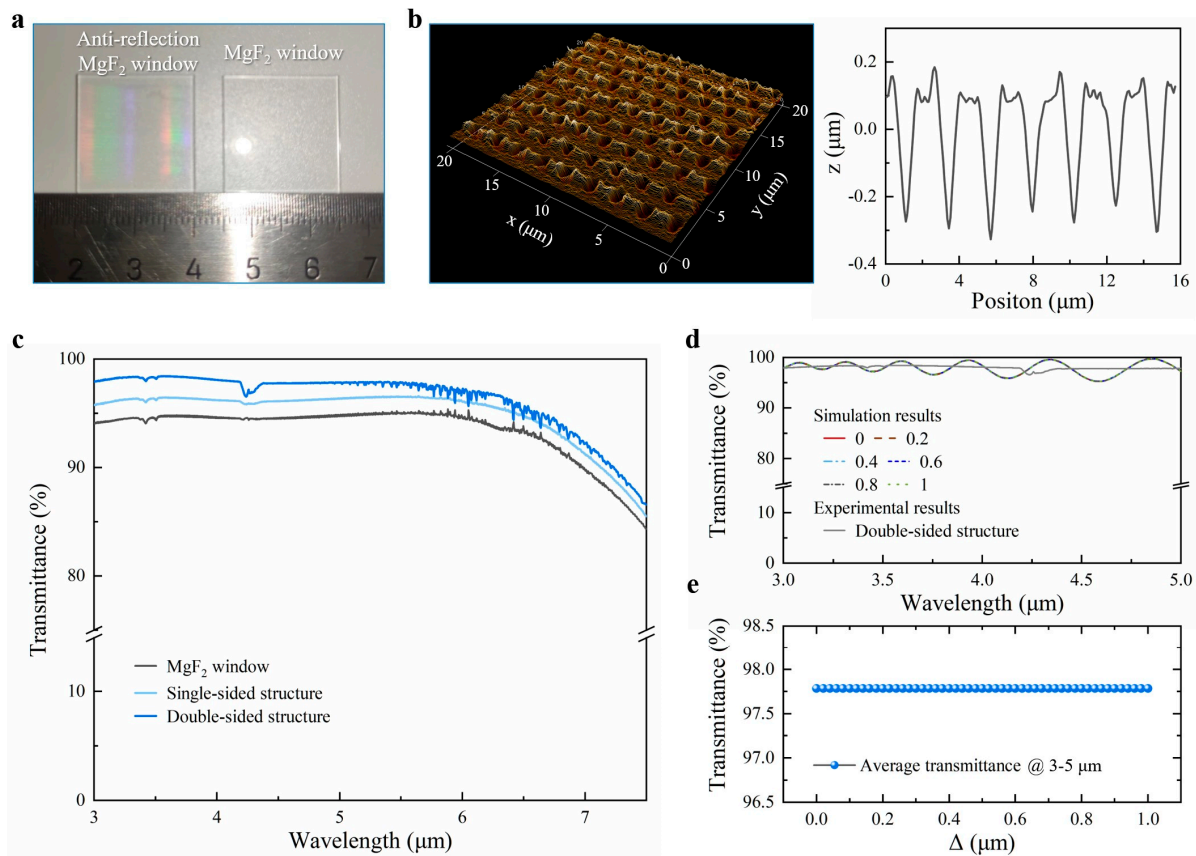


Figure 7. (a) Photographs of a standard MgF₂ window and an anti-reflective MgF₂ window; (b) AFM three-dimensional morphology and cross-sectional profile of the anti-reflective microhole array; (c) measured transmittance results for the two types of windows; and (d,e) simulated transmittance spectrum and average transmittance in the 3–5 μm band under different Δ conditions, based on the fabricated microhole parameters.

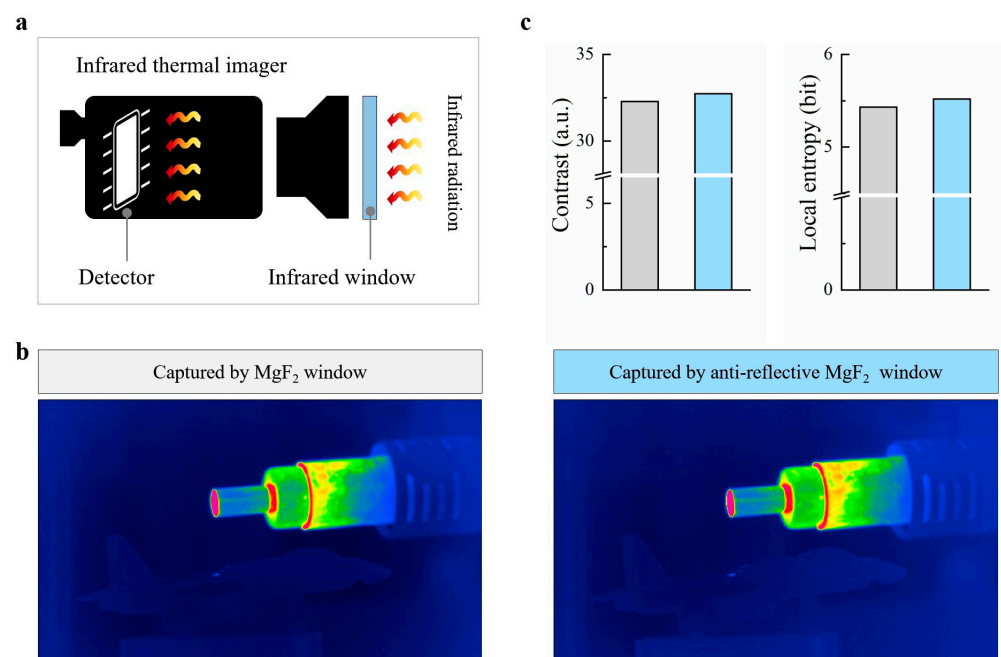


Figure 8. (a) Schematic of the infrared thermal imaging system; (b) infrared images captured with the MgF₂ window and anti-reflective MgF₂ window installed; and (c) comparison of the two sets of images in terms of local entropy and contrast metrics.

4. Conclusions

This study combined simulation and experiment to analyze the influence of arrangement on the optical performance of large-area anti-reflective microhole arrays fabricated by a femtosecond laser. The findings demonstrate that for infrared light in the 3–5 μm band with a microhole period of 2 μm , variations in average window transmittance remain below 0.02%. This holds true for both in-plane arrangement deviations and double-sided alignment errors. The fundamental reason is that across this band, the microstructure array can be regarded as an equivalent layer with a gradient refractive index. Minor differences in microscopic arrangement are insufficient to alter this macroscopic optical property. Guided by this understanding, a high-repetition-rate femtosecond laser employing a zigzag scanning strategy was used to successfully fabricate a large-area (20 mm $\times$ 20 mm) double-sided microhole array on an MgF_2 window. This process elevated the average mid-wave infrared transmittance to over 97.5%. The average transmittance values from the simulation and experimental results closely match. Imaging tests confirmed that windows prepared with this method yield infrared images with richer detail and clearer contrast. This work explains the mechanism behind the stable performance of large-area anti-reflective microstructures and provides a practical solution for the rapid fabrication of high-performance infrared windows.

Author Contributions: Y.D.: conceptualization, data curation, investigation, methodology, and writing—original draft; C.W.: project administration, supervision, and writing—review and editing; Z.G.: data curation and investigation; X.J. (Xiang Jiang): data curation and investigation; S.W.: data curation and investigation; X.J. (Xianshi Jia): conceptualization and methodology; L.L.: conceptualization and methodology; J.D.: project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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References

1. Sarededdine, R.; Kadiri, H.; Guelorget, B.; Le Cunff, L.; Alhussein, A.; Habchi, R.; Léronel, G. A Review on Potential Mechanically Resistant Materials for Optical Multifunctional Surfaces: Bioinspired Surfaces with Advanced Properties. *Adv. Mater. Interfaces* **2024**, *11*, 2300793. [[CrossRef](#)]
2. Neinhuis, C.; Barthlott, W. Characterization and Distribution of Water-Repellent, Self-Cleaning Plant Surfaces. *Ann. Bot.* **1997**, *79*, 667–677. [[CrossRef](#)]
3. Tadepalli, S.; Slocik, J.M.; Gupta, M.K.; Naik, R.R.; Singamaneni, S. Bio-Optics and Bio-Inspired Optical Materials. *Chem. Rev.* **2017**, *117*, 12705–12763. [[CrossRef](#)]
4. Comanns, P.; Effertz, C.; Hischen, F.; Staudt, K.; Böhme, W.; Baumgartner, W. Moisture Harvesting and Water Transport through Specialized Micro-Structures on the Integument of Lizards. *Beilstein J. Nanotechnol.* **2011**, *2*, 204–214. [[CrossRef](#)] [[PubMed](#)]
5. Yun, B.; Chen, Z.; Wu, Z.; Leng, R.; Zhao, X.; Liu, X.; Chen, Q.; Wang, L. Foci-Multiplexed Optical Printing of High-Transmittance Infrared Subwavelength-Structured Surface. *Opt. Express* **2025**, *33*, 8738. [[CrossRef](#)]
6. Yue, Z.; He, L.; Cui, Q.; Gao, W.; Yin, Y.; Meng, L.; Chen, C.; Liao, Y.; Leng, Y.; Wang, Z.; et al. Fabrication of Sapphire Optical Windows with Infrared Transmittance Enhancement and Visible Transmittance Reduction by Femtosecond Laser Direct Writing. *Opt. Laser Technol.* **2025**, *188*, 112989. [[CrossRef](#)]
7. Yang, J.; Zhou, S.; Yang, M.; Zhao, S.; Wang, S.; Deng, G. Antireflection Microstructures on a ZnS Surface Fabricated by Femtosecond Laser Direct Writing Assisted with Wet Etching. *Opt. Mater.* **2025**, *159*, 116597. [[CrossRef](#)]

8. Xu, K.; Zheng, M.; Huang, L.; Yao, L.; Chen, J.; Xu, S. All-glass Nanohole Metalens by Non-diffracting Laser Lithography. *Laser Photonics Rev.* **2025**, *19*, 2402006. [[CrossRef](#)]
9. Chien, K.-C.; Kepenekci, M.; Tunell, A.; Chang, C.-H. Scratch-Resistant Sapphire Nanostructures with Anti-Glare, Anti-Fogging, and Anti-Dust Properties. *Mater. Horiz.* **2025**, *12*, 1796–1807. [[CrossRef](#)] [[PubMed](#)]
10. Liu, R.; Zhang, D.; Li, Z. Femtosecond Laser Subtractive/Additive-Integrated Biomimetic Manufacturing for Visible/Infrared Encryption and Stimuli-Responsive Infrared Decryption. *Int. J. Extreme Manuf.* **2025**, *7*, 045009. [[CrossRef](#)]
11. Bushunov, A.A.; Tarabrin, M.K.; Lazarev, V.A. Review of Surface Modification Technologies for Mid-infrared Antireflection Microstructures Fabrication. *Laser Photonics Rev.* **2021**, *15*, 2000202. [[CrossRef](#)]
12. Liu, X.; Zhang, Y.; Li, Q.; Zheng, J.; Lu, Y.; Juodkakis, S.; Chen, Q.; Sun, H. Biomimetic Sapphire Windows Enabled by Inside-out Femtosecond Laser Deep-Scribing. *Photonix* **2022**, *3*, 1. [[CrossRef](#)]
13. Raut, H.K.; Ganesh, V.A.; Nair, A.S.; Ramakrishna, S. Anti-Reflective Coatings: A Critical, in-Depth Review. *Energy Environ. Sci.* **2011**, *4*, 3779. [[CrossRef](#)]
14. Song, Y.M.; Choi, H.J.; Yu, J.S.; Lee, Y.T. Design of Highly Transparent Glasses with Broadband Antireflective Subwavelength Structures. *Opt. Express* **2010**, *18*, 13063–13071. [[CrossRef](#)]
15. Li, Y.; Zhang, T.; Fan, S.; Cheng, G. Fabrication of Micro Hole Array on the Surface of CVD ZnS by Scanning Ultrafast Pulse Laser for Antireflection. *Opt. Mater.* **2017**, *66*, 356–360. [[CrossRef](#)]
16. Ding, Y.; Liu, L.; Wang, C.; Li, C.; Lin, N.; Niu, S.; Han, Z.; Duan, J. Bioinspired Near-Full Transmittance MgF₂ Window for Infrared Detection in Extremely Complex Environments. *ACS Appl. Mater. Interfaces* **2023**, *15*, 30985–30997. [[CrossRef](#)]
17. Qiu, P.; Li, J.; Yuan, D.; Xin, Z.; Huang, J.; Xu, S. Adaptive Beam-Shaping Enabled High-Precision Patterned Laser Micro-Grooving. *Int. J. Extreme Manuf.* **2025**, *7*, 065002. [[CrossRef](#)]
18. Gao, L.; Zhang, Q.; Gu, M. Femtosecond Laser Micro/Nano Processing: From Fundamental to Applications. *Int. J. Extreme Manuf.* **2025**, *7*, 022010. [[CrossRef](#)]
19. Han, J.; Xin, D.; Pang, J.; Zhao, L.; Sun, D.; Zheng, Y.; Liu, X.; Zhao, Z.; Zhang, X.; Sun, Q.; et al. Laser-Assisted Manufacturing for Sensors. *Int. J. Extreme Manuf.* **2025**, *7*, 042008. [[CrossRef](#)]
20. Xu, L.; Tao, J.; Li, Z.; He, G.; Zhang, D. Femtosecond Laser Ultrafast Photothermal Exsolution. *Int. J. Extreme Manuf.* **2024**, *6*, 055002. [[CrossRef](#)]
21. Tan, Y.; Mou, Z.; Xu, J.; Luo, H.; Jiang, G.; Qi, J.; Liang, Y.; Chong, H.; Cai, Y.; Cheng, Y. Femtosecond Laser Three-Dimensional Isotropic Inscription in Glass Enabled by High-Speed Rotating Slit Beam Shaping. *Int. J. Extreme Manuf.* **2026**, *8*, 015001. [[CrossRef](#)]
22. Liao, J.; Li, Z.; Zhang, D. Bionic Femtosecond Laser Manufacturing for Impressionistic Camouflage Infrared Display. *Int. J. Extreme Manuf.* **2026**, *8*, 015010. [[CrossRef](#)]
23. Li, Q.; Zhou, F.; Huang, M. Femtosecond Laser-Induced Sub-50-Nm Period Nanogratings with Ultrahigh Uniformity on Graphite under Water Immersion. *Int. J. Extreme Manuf.* **2026**, *8*, 015007. [[CrossRef](#)]
24. Zhang, J.; Ren, F.; Yang, Q.; Ma, Q.; Liang, J.; Meng, Y.; Gou, X.; Xia, C.; Chen, F. Glass Catfish Inspired Subaquatic Abrasion-Resistant Anti-Fouling Window Fabricated by Femtosecond Laser Electrodeposition. *Int. J. Extreme Manuf.* **2025**, *7*, 015004. [[CrossRef](#)]
25. Yang, Q.; Yu, M.; Chen, Z.; Ai, S.; Kentsch, U.; Zhou, S.; Jia, Y.; Chen, F.; Liu, H. A Novel Approach towards Robust Construction of Physical Colors on Lithium Niobate Crystal. *Opto-Electron. Adv.* **2025**, *8*, 240193. [[CrossRef](#)]
26. Zhang, S.; Fan, M.; Niu, P.; Geng, J.; Jiang, J.; Shi, L. Modulating the Periodicity of Plasmonic Lithography by High-Repetition-Rate Laser-Driven Heat Accumulation. *Opt. Lett.* **2025**, *50*, 5242–5245. [[CrossRef](#)] [[PubMed](#)]
27. Zhang, F.; Wang, H.; Wang, C.; Zhao, Y.; Duan, J. Direct Femtosecond Laser Writing of Inverted Array for Broadband Antireflection in the Far-Infrared. *Opt. Laser Eng.* **2020**, *129*, 106062. [[CrossRef](#)]
28. Jia, X.; Chen, Y.; Yi, Z.; Lin, J.; Luo, J.; Li, K.; Wang, C.; Duan, J.; Polyakov, D.S.; Veiko, V.P. Tailoring Sapphire-Invar Welds Using Burst Femtosecond Laser. *Light Adv. Manuf.* **2026**, *6*, 1. [[CrossRef](#)]
29. Li, X.; Shan, C.; Chen, K.; Li, C.C.; Wang, L.F.; Wang, Y.N.; Tan, Y.; Li, M. Bioinspired ZnS Infrared Detection Window with Enhanced Broadband Transmittance via Green Picosecond Laser Assisted with Chemical Etching. *ACS Appl. Opt. Mater.* **2025**, *3*, 1618–1627. [[CrossRef](#)]
30. Ding, Y.; Wang, C.; Jia, X.; Liu, L.; Gao, Z.; Jiang, X.; Wang, S.; Yan, D.; Lin, N.; Li, Z.; et al. Laser-Optical-Field-Modulation Fabricating Large-Aperture Dual-Band Antireflection Windows for MWIR and LWIR Imaging. *Int. J. Extreme Manuf.* **2026**, *8*, 025004. [[CrossRef](#)]
31. Ding, Y.; Wang, C.; Jia, X.; Liu, L.; Gao, Z.; Jiang, X.; Wang, S.; Yan, D.; Lin, N.; Li, Z.; et al. Machine Learning-Driven Optimization of Burst Femtosecond Laser Processing for High-Performance Anti-Reflective Windows. *ACS Appl. Mater. Interfaces* **2025**, *17*, 65300–65309. [[CrossRef](#)]
32. Ding, Y.; Wang, C.; Jia, X.; Liu, L.; Gao, Z.; Jiang, X.; Wang, S.; Yan, D.; Lin, N.; Duan, J. Biomimetic ZnS Windows Fabricated by Femtosecond Laser Optical Field Modulation Assisted with Wet Etching for High-Performance Infrared Monitoring of EV Charging. *ACS Appl. Mater. Interfaces* **2025**, *17*, 42462–42473. [[CrossRef](#)]

33. Zhou, S.; Yang, J.; Wang, S.; Wang, S.; Deng, G.; Zhou, S. Preparation of Antireflection Microstructures on ZnSe Crystal by Femtosecond Burst Bessel Direct Laser Writing. *Photonics* **2023**, *10*, 479. [\[CrossRef\]](#)
34. Jing, X.; Ma, J.; Liu, S.; Jin, Y.; He, H.; Shao, J.; Fan, Z. Analysis and Design of Transmittance for an Antireflective Surface Microstructure. *Opt. Express* **2009**, *17*, 16119–16134. [\[CrossRef\]](#)
35. Cao, H.; Li, Y.; Wang, G.; Li, H.; Sun, D.; Tang, Z.; Li, L.; Jin, Z.; Yu, Y.; Liu, X.; et al. Laser Cleaning-Assisted Femtosecond Laser Direct Writing of Diamond Antireflective Microstructures with Superhigh Transmittance of 94.5% at 10.6 Mm. *Small Struct.* **2025**, *6*, 2400590. [\[CrossRef\]](#)
36. Zheng, J.-X.; Liu, X.-Q.; Tian, K.-S.; Li, H.-Y.; Zhang, X.; Tian, Z.-N.; Qian, M.-D.; Wang, L.; Chen, Q.-D. Nanofabrication of Lithium Niobate Anti-Reflective Subwavelength Structures for High Power Mid-Infrared Lasers. *Laser Photonics Rev.* **2024**, *18*, 2400546. [\[CrossRef\]](#)
37. Syubaev, S.; Modin, E.; Gurbatov, S.; Cherepakhin, A.; Dostovalov, A.; Tarasova, A.; Krinitsin, P.; Yelisseyev, A.; Isaenko, L.; Kuchmizhak, A. SWIR Anti-Reflective Nanostructures on Nonlinear Crystals by Direct UV Femtosecond Laser Printing. *Appl. Phys. Lett.* **2023**, *123*, 061108. [\[CrossRef\]](#)
38. Teslenko, A.; Konstantinova, T.; Bushunov, A.; Ibragimov, A.; Rodionov, I.; Tarabrin, M. Antireflection Microstructures on ZnSe for Mid- and Far-IR Fabricated by Femtosecond Laser Ablation Assisted with Wet Chemical Etching. *Sci. Rep.* **2024**, *14*, 10743. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Yin, J.; Zhao, Y.; Hong, M. High Performance Laser Induced Plasma Assisted Ablation by GHz Burst Mode Femtosecond Pulses. *Opto-Electron. Adv.* **2024**, *7*, 240222. [\[CrossRef\]](#)
40. Zhang, Y.; Koike, T.; Yoshizaki, R.; Ren, G.; Shibata, A.; Kiriake, S.; Hasegawa, R.; Nagasawa, I.; Nagato, K.; Sugita, N. Ultrahigh-Speed Laser Drilling of Transparent Materials via Transient Electronic Excitation. *Sci. Adv.* **2025**, *11*, eadv4436. [\[CrossRef\]](#)
41. Fraggelakis, F.; Lingos, P.; Tsibidis, G.D.; Cusworth, E.; Kay, N.; Fumagalli, L.; Kravets, V.G.; Grigorenko, A.N.; Kabashin, A.V.; Stratakis, E. Double-Pulse Femtosecond Laser Fabrication of Highly Ordered Periodic Structures on Au Thin Films Enabling Low-Cost Plasmonic Applications. *ACS Nano* **2025**, *19*, 23258–23275. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Park, M.; Gu, Y.; Mao, X.; Grigoropoulos, C.P.; Zorba, V. Mechanisms of Ultrafast GHz Burst Fs Laser Ablation. *Sci. Adv.* **2023**, *9*, eadf6397. [\[CrossRef\]](#)
43. Münzer, H.-J.; Mosbacher, M.; Bertsch, M.; Zimmermann, J.; Leiderer, P.; Boneberg, J. Local Field Enhancement Effects for Nanostructuring of Surfaces. *J. Microsc.* **2001**, *202*, 129–135. [\[CrossRef\]](#)
44. Nishijima, Y.; Komatsu, R.; Ota, S.; Seniutinas, G.; Balčytis, A.; Juodkakis, S. Anti-Reflective Surfaces: Cascading Nano/Microstructuring. *APL Photonics* **2016**, *1*, 076104. [\[CrossRef\]](#)
45. Papadopoulos, A.; Skoulas, E.; Mimidis, A.; Perrakis, G.; Kenanakis, G.; Tsibidis, G.D.; Stratakis, E. Biomimetic Omnidirectional Antireflective Glass via Direct Ultrafast Laser Nanostructuring. *Adv. Mater.* **2019**, *31*, 1901123. [\[CrossRef\]](#)
46. Fang, Z.; Yi, X.; Liu, X.; Zhang, W.; Zhang, T. Dual-Band Infrared Remote Sensing System with Combined Long-Wave Infrared Imaging and Mid-Wave Infrared Spectral Analysis. *Rev. Sci. Instrum.* **2013**, *84*, 083106. [\[CrossRef\]](#)
47. Huang, L.; Han, Z.; Wirth-Singh, A.; Saragadam, V.; Mukherjee, S.; Fröch, J.E.; Tanguy, Q.A.A.; Rollag, J.; Gibson, R.; Hendrickson, J.R.; et al. Broadband Thermal Imaging Using Meta-Optics. *Nat. Commun.* **2024**, *15*, 1662. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Boyer, T.H. Blackbody Radiation in Classical Physics: A Historical Perspective. *Am. J. Phys.* **2018**, *86*, 495–509. [\[CrossRef\]](#)
49. Wan, M.; Gu, G.; Qian, W.; Ren, K.; Chen, Q.; Maldague, X. Particle Swarm Optimization-Based Local Entropy Weighted Histogram Equalization for Infrared Image Enhancement. *Infrared Phys. Technol.* **2018**, *91*, 164–181. [\[CrossRef\]](#)

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