

Optics Letters

Efficient femtosecond laser fabrication of ultra-large-area Dammann gratings via line-field shaping

HAI HU,¹ YIHANG YIN,¹ WENLIANG LIANG,¹ JINGJING ZHANG,^{1,4} JINCHENG NI,² ZHAOXIN LAO,³ SHENGLAI ZHEN,¹ ZHIQIANG WANG,¹ BENLI YU,¹  YANLEI HU,²  CHENCHU ZHANG,² DENG PAN,^{1,3,*}  AND DONG WU³

¹State Key Laboratory of Opto-Electronic Information Acquisition and Protection Technology, Key Laboratory of Opto-Electronic Information Acquisition and Manipulation of Ministry of Education, Information Materials and Intelligent Sensing Laboratory of Anhui Province, School of Optoelectronic Science and Engineering, School of Mathematical Sciences, Anhui University, Hefei 230601, China

²CAS Key laboratory of Mechanical Behavior and Design of Materials, Key Laboratory of Precision Scientific Instrumentation of Anhui Higher Education Institutes, Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei 230027, China

³School of Mechanical Engineering, School of Instrument Science and Opto-Electronics Engineering, Anhui Province Key Lab of Aerospace Structural Parts Forming Technology and Equipment, Intelligent Interconnected Systems Laboratory of Anhui Province, Hefei University of Technology, Hefei 230009, China

⁴jjmath@ahu.edu.cn

*pandeng@ahu.edu.cn

Received 21 June 2026; revised 22 July 2026; accepted 23 July 2026; posted 27 July 2026; published 11 August 2026

We demonstrate efficient fabrication of ultra-large-area Dammann gratings using femtosecond laser line-field shaping. A cylindrical-lens phase loaded on a spatial light modulator reshapes a Gaussian beam into a high-aspect-ratio line focus, allowing rapid metal mask removal via continuous linear scanning. Compared with point-by-point writing, the efficiency is improved by around 10^4 times, producing a 2-inch grating. Various splitting configurations (1×6 , 2×2 , 3×3 , star-shaped, parallelogram) are realized with a uniformity of 98.58%. The fabricated gratings further generate structured light arrays (vortex, Airy, azimuthally modulated) as 6×6 highly uniform focal spots that preserve helical phase singularities and self-accelerating profiles without observable crosstalk. This approach provides a low-cost, high-throughput route for large-area Dammann gratings and advances parallel optical processing and structured light distribution. © 2026 Optica Publishing Group. All rights, including for text and data mining (TDM), Artificial Intelligence (AI) training, and similar technologies, are reserved.

<https://doi.org/10.1364/OL.608958>

Highly uniform massive parallel beam splitting is decisive in optical computing, large-scale interconnects, high-power laser processing, and high-throughput information processing [1–6], and acts as a key enabler to break the serial bottleneck of electronics [7,8]. Existing beam splitters suffer inherent limitations: cascaded splitters provide only a few channels with high loss, ordinary gratings yield nonuniform intensity, and spatial light modulators are costly and damage-prone [9–11].

Dammann gratings, binary diffractive elements [12], split a beam into equal-intensity sub-beams with uniformity

independent of the incident field and enable arbitrary array configurations, thus becoming the standard for laser direct writing, parallel particle manipulation, and structured-light metrology [13–18]. Maskless femtosecond laser writing [19–21] is ideal for large-size, non-standard, small-batch gratings, eliminating mask costs and shortening design-to-sample cycles. Its bottleneck is efficiency: on sapphire, single-pulse writing causes debris, periodic surface structures, and microcracks, demanding slow speeds or repeated passes; even with burst mode, a 12×12 grating still takes 72 min [22]. Spatial light modulation can produce beams with extended depth of focus, breaking the point-by-point speed limit. We previously generated line-shaped beams for photoresist processing [23], yet combining spatial light modulation with femtosecond direct writing for efficient Dammann grating fabrication remains unexplored.

In this study, we propose a femtosecond laser beam shaping method that uses a cylindrical lens phase on a spatial light modulator to generate a line focus combined with linear scanning, enabling efficient fabrication of ultra-large-area Dammann gratings with a 14,000-fold efficiency gain over conventional point-by-point processing and achieving 93.60% uniformity for a 6×6 splitting array under Gaussian illumination. Splitting tests on structured fields—including vortex, Airy, and a four-segment phase-modulated composite beam—show that each diffraction order retains the original wavefront without distortion or crosstalk, confirming the method's reliability in delivering high-quality devices for cutting-edge applications such as structured-light-array optical tweezers, mode-division-multiplexed communication, and multi-channel quantum information distribution.

In the fabrication setup (Fig. 1(a)), a femtosecond laser (Coherent Monaco, 517 nm, 290 fs, 250 kHz) with its energy

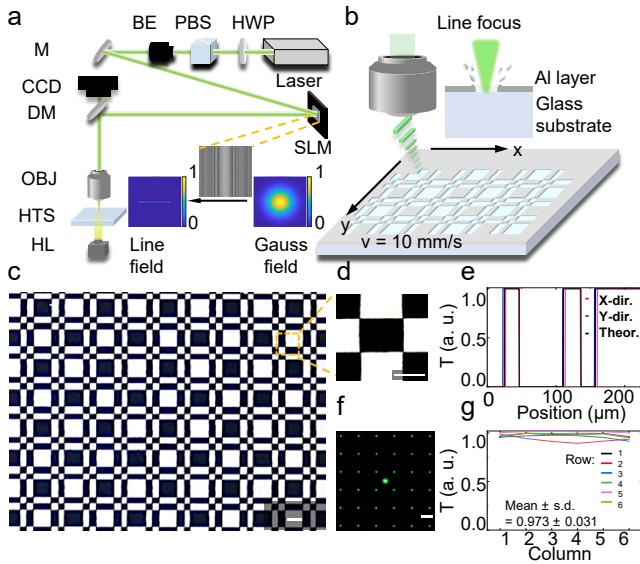


Fig. 1. Fabrication of the Dammann grating. (a) Schematic of the femtosecond laser beam shaping setup. BE, beam expander; DM, dichroic mirror; HL, halogen lamp; HWP, half-wave plate; OBJ, objective lens; PBS, polarizing beam splitter. (b) Customized linear scanning fabrication strategy. (c) Optical micrograph of the fabricated large-area 6×6 splitting grating. Scale bar: $50 \mu\text{m}$. (d) Magnified view of the region marked in (c). Scale bar: $20 \mu\text{m}$. (e) Comparison between theoretical and experimental transition point distributions. (f) Beam splitting result of the 6×6 Dammann grating. Scale bar: $200 \mu\text{m}$. (g) The normalized intensity of the grayscale of the 36 focal regions arranged in six rows in (f).

controlled by a zero-order half-wave plate and a polarizing beam splitter was directed onto a spatial light modulator (SLM) loaded with a cylindrical-lens phase mask, and the resulting line-shaped field (aspect ratio 20:1) was focused by a $50\times$ objective ($\text{NA} = 0.75$) onto a sample carried by a 3D nano-positioning stage (1 nm step, 100 nm repeatability). This pure-phase holographic shaping maximizes energy utilization and allows real-time adjustment of focal length, line length, and orientation without hardware changes.

Aluminized glass slides (Al 180 nm on 0.21 mm glass) were patterned by unidirectional linear scanning (Fig. 1(b)). Ultra-short pulses provide cold ablation; the line length ($20 \mu\text{m}$) sets the processing resolution. The scanning trajectory is optimized to the grating's transition points, and an optical shutter synchronously toggles the pulse train on only in removal zones while the stage moves continuously, eliminating start-stop motions and idle travel.

A fabricated 6×6 Dammann grating (Figs. 1(c) and 1(d)) exhibits sharp boundaries, no distortion, and complete metal removal. Measured transmittance profiles of a single period (Fig. 1(e)) match the theoretical design. Under collimated Gaussian illumination, a 6×6 focal-spot array forms at the back focal plane of a collection objective (Fig. 1(f)), with spot-to-spot intensity uniformity of 93.60% (Figs. 1(g) and S1 in Supplement 1). The uniformity is defined as: $\text{uni} = 1 - [I_n(\text{max}) - I_n(\text{min})] / [I_n(\text{max}) + I_n(\text{min})]$ (Where I_n is the focal spot intensity).

Fabrication quality is governed by the interplay of scanning speed and pulse energy. We systematically evaluated the ablation quality (which is recently emphasized in ultrafast processing of

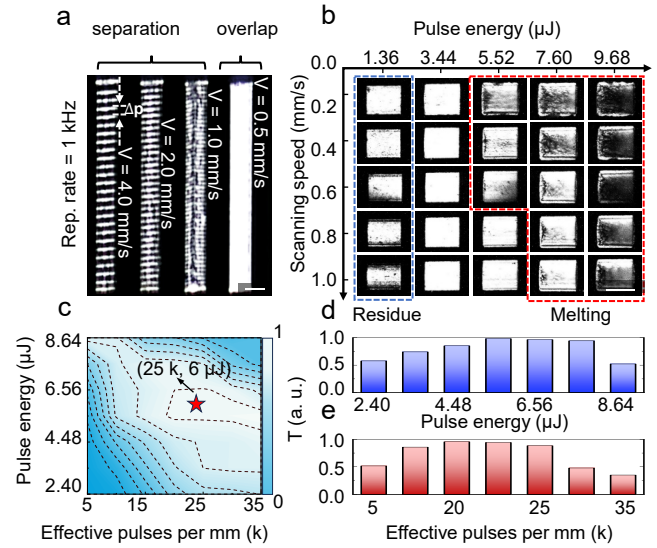


Fig. 2. Processing parameter window. (a) Separation and overlap of femtosecond laser pulses. Scale bar: $20 \mu\text{m}$. (b) Influence of pulse energy and scanning speed on the removal rate of the aluminum layer. Scale bar: $50 \mu\text{m}$. (c) Optimal processing parameter window based on transmittance. (d) Transmittance as a function of pulse energy. (e) Transmittance as a function of effective pulse number. Nanoscale characterization by SEM/EDS and profilometry is provided in Figs. S2 and S3 in Supplement 1.

transparent media [24]) under three representative pulse energies (1.2 μJ , 3.6 μJ , and 6.0 μJ) via SEM/EDS and profilometry (see Figs. S2 and S3 in Supplement 1), confirming that 3.6 μJ yields clean, damage-free removal. We temporarily fixed the repetition rate at 1 kHz and varied the scan speed. At this low repetition rate, adjacent pulses transition from full separation to high overlap as the speed decreases (Fig. 2(a)). Sufficient overlap creates a continuous energy deposition band that produces working areas with sharp boundaries and completely exposed substrate. With low pulse energy, reducing speed to increase overlap achieves complete metal removal and high transmittance. However, at high pulse energy, excessively low speed (high overlap) causes accumulated energy to penetrate the metal and melt the glass substrate, degrading surface flatness and transmittance (Fig. 2(b)). Consequently, higher scanning speeds require higher pulse energy to maintain removal efficacy, but excessive energy—even at moderate overlap—still induces irreversible thermal damage. A nonlinear speed–energy trade-off must be balanced. To quantitatively describe the degree of spatial pulse overlap determined jointly by the scanning speed and the pulse repetition rate, we define the effective pulse number as $\text{Eff} = \frac{f}{v}$, which represents the number of pulses acting per unit length along the scanning direction, where f is the laser repetition rate and v is the stage speed.

A larger effective pulse number Eff leads to stronger spatial overlap. Taking Eff and pulse energy as two variables, by characterizing the metal layer removal rate via optical transmittance measurements, we constructed the process window diagram shown (Fig. 3(c)). The dashed region enclosed by the contour lines corresponds to the high-quality processing window where the optical transmittance approaches 100%. Outside this region, either metal residues remain due to insufficient energy, or substrate damage occurs due to excessive energy. Considering

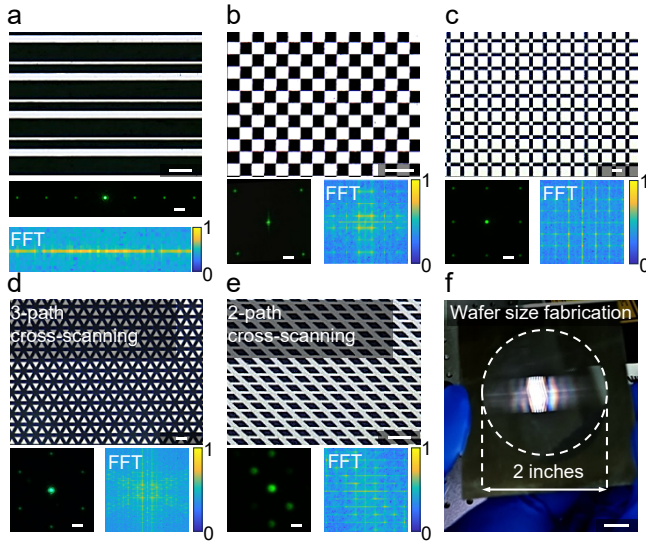


Fig. 3. Various gratings and their beam-splitting results. (a) 1×6 splitting. Scale bar: $200\ \mu\text{m}$. (b) 2×2 splitting. Scale bar: $200\ \mu\text{m}$. (c) 3×3 splitting. Scale bar: $200\ \mu\text{m}$. (d) Star-shaped splitting. Scale bar: $200\ \mu\text{m}$. (e) Parallelogram splitting. Scale bar: $200\ \mu\text{m}$. (f) A 2-inch large-area grating. Scale bar: $1\ \text{mm}$.

inevitable small fluctuations in laser energy and repeatability tolerance of the mechanical system, we did not select parameters at the window edge. Instead, we chose the working point marked by the red star, which lies inside the window and offers the widest process tolerance. As confirmed by Figs. 2(d) and 2(e), under the selected parameters, when pulse energy or Eff fluctuates over a relatively wide range, the optical transmittance remains consistently above 98%, ensuring quality consistency in long-duration continuous processing and batch production. A concise summary of the key processing parameters and their optimal windows is provided in Table S1 in Supplement 1. In addition, we verified that the polarization state of the incident laser has no significant influence on the ablation morphology (see Fig. S5 in Supplement 1), further relaxing the constraints on experimental implementation. To systematically verify the universality and structural uniformity of our fabrication method, we fabricated a series of Damman gratings with different designs, as shown in Figs. 3(a)–3(f). Figure 3(a) shows a one-dimensional 1×6 splitting grating, producing six equally spaced diffraction spots with highly uniform intensities. Figures 3(b) and 3(c) present two-dimensional 2×2 and 3×3 splitting gratings, respectively, yielding regular, distortion-free spot arrays. To demonstrate broad applicability, we designed and fabricated star-shaped (Fig. 3(d)) and parallelogram-shaped (Fig. 3(e)) splitting gratings; the resulting spot patterns precisely match theoretical expectations without introducing stray spots or morphological defects, confirming excellent design flexibility.

Benefiting from the high-aspect-ratio line-shaped light field and customized linear continuous scanning strategy, we successfully fabricated a large-area grating up to 2 inches in size, with a total processing time of approximately 2.8 hours (limited by hardware to a scanning speed of $10\ \text{mm/s}$; using a mainstream stage or galvo scanner, the time can be reduced to within 30 minutes), as shown in Fig. 3(f). The grating maintains uniformity over the entire area, and the efficiency is nearly 14,000 times higher than that of conventional point-by-point scanning, offer-

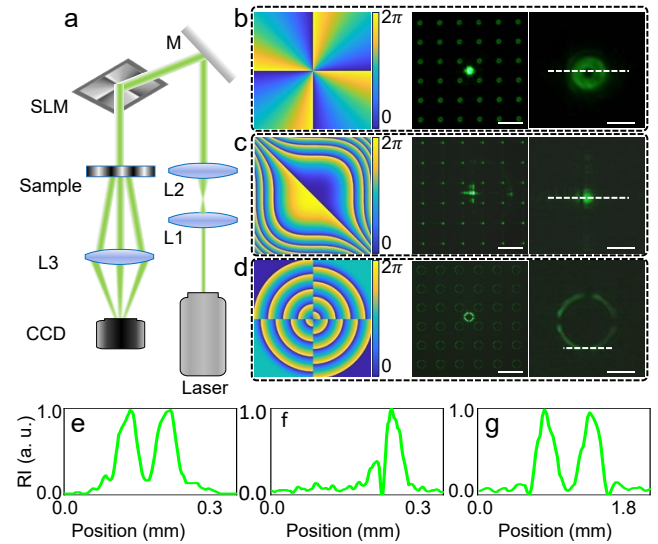


Fig. 4. Structured light beam splitting tests. (a) Experimental setup. (b)–(d) 6×6 arrays (left/middle) and magnified single spots (right) for vortex (topological charge 4), Airy, and four-segment annular beams, respectively. (e)–(g) Intensity profiles along the white dashed lines in (b)–(d). Scale bars: $200\ \mu\text{m}$ (arrays), $40\ \mu\text{m}$ (magnified spots).

ing a viable route for scalable rapid manufacturing of large-area gratings. We further measured the diffraction efficiency of the 6×6 grating. Using a $100\text{-}\mu\text{m}$ -radius mask to block the zero-order, three independent measurements yield non-zero-order efficiencies of $24.0\% \pm 1.8\%$ (mean $\pm$ s.d.).

Multi-channel replication of structured light fields is of great value for optical communication coding and quantum information processing [25]. We conducted structured light beam splitting experiments, as schematically shown in Fig. 4(a). A collimated Gaussian beam was modulated by an SLM loaded with three different phase masks to generate a vortex beam, an Airy beam, and a four-segment annular phase-modulated beam, respectively. Each beam then passed through the same 6×6 Damman grating and a Fourier lens to produce the corresponding focal spot array.

A spiral phase mask with topological charge 4 (Fig. 4(b), left) generated a vortex beam, yielding a uniform 6×6 vortex array (Fig. 4(b), middle); the magnified spot (Fig. 4(b), right) exhibits the characteristic annular profile with a dark core (Fig. 4(e)), confirming preservation of the phase singularity without distortion. Additional phase diagnostics via cylindrical-lens astigmatic transformation (Fig. S4 in Supplement 1) further confirm the preservation of helical phase singularities after passing through the grating. Switching to a cubic phase mask (Fig. 4(c), left) produced self-accelerating Airy beams, whose array (Fig. 4(c), middle) displays the expected curved tails, and the magnified spot with its intensity profile (Figs. 4(c), right and 4(f)) clearly resolves the main lobe and side lobes, demonstrating energy balance and wavefront fidelity even for asymmetric beams. An azimuthally modulated beam was generated by a four-segment annular phase mask (Fig. 4(d), left), which further produced a uniform 6×6 focal spot array (Fig. 4(d), middle); the magnified spot and profile (Figs. 4(d), right and 4(g)) confirm that the phase-induced intensity pattern is well preserved without crosstalk.

In summary, we have demonstrated a femtosecond laser line-field shaping strategy that enables rapid, mask-free fabrication of large-area Dammann gratings. Beyond the significant improvement in throughput, this method features high flexibility in phase-pattern customization and has been successfully applied to various splitting configurations (1×6 , 2×2 , 3×3 , star-shaped, and parallelogram). More importantly, this low-cost, high-efficiency approach is not limited to Dammann gratings; it can be readily extended to the rapid prototyping of other binary diffractive optical elements, offering a versatile route for scalable diffractive optics manufacturing.

Funding. National Key Research and Development Program of China (2024YFB4610700); National Natural Science Foundation of China (62325507, 52375582, 62205236, 62461160305, 62475066); Scientific Research Project of Anhui Provincial Department of Education (2025AHGXZK20171, 2024AH050067); Fundamental Research Funds for the Central Universities of China (PA2025IISL0103).

Acknowledgment. We acknowledge the Modern Experiment Technology Center of Anhui University and Experimental Center of Engineering for their help in sample characterization.

Disclosures. The authors declare no competing interests.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See Supplement 1 for supporting content.

REFERENCES

1. R. Athale and D. Psaltis, *Opt. Photon. News* **27**, 32 (2016).
2. J. Hu, D. Mengu, D. C. Tzarouchis, *et al.*, *Nat. Commun.* **15**, 1525 (2024).
3. Y. Huang, P. Zhou, K. Lau, *et al.*, *ACS Photonics* **11**, 5012 (2024).
4. Z. Kuang, W. Perrie, D. Liu, *et al.*, *Appl. Surf. Sci.* **273**, 101 (2013).
5. S. Wang, Y. Niu, W. Liu, *et al.*, *Laser Photon. Rev.* **20**, e03131 (2026).
6. X. Zang, Z. Liu, Y. Xu, *et al.*, *Sci. China Technol. Sci.* **67**, 60 (2024).
7. W. J. Zhiqing, P. Yeh, and X. Yang, *Opt. Eng.* **35**, 2136 (1996).
8. B. Sun, M. Zhang, Q. Sun, *et al.*, *Nat. Commun.* **16**, 2372 (2025).
9. S. M. Anne Margarete and F. A. Percival, *Proc. SPIE* **7155**, 71551J (2008).
10. Y. Xu, Y. Zheng, X. Xiao, *et al.*, *Front. Phys.* **10**, 2022 (2022).
11. Y. Yang, A. Forbes, and L. Cao, *Opto-Electron. Sci.* **2**, 230026 (2023).
12. C. Di and C. Zhou, *Appl. Opt.* **45**, 1993 (2006).
13. J. Lee, R. Ding, J. Christensen, *et al.*, *Nat. Commun.* **13**, 5131 (2022).
14. J. Li, *Light Sci. Appl.* **12**, 243 (2023).
15. M. Li, C. Zhou, C. Wei, *et al.*, *Proc. SPIE* **10818**, 108180V (2018).
16. B. Yu, W. Jia, C. Zhou, *et al.*, *Chin. Opt. Lett.* **11**, 080501 (2013).
17. J. Yuan, H. Zhang, C. Wu, *et al.*, *Opt. Lett.* **46**, 4184 (2021).
18. Y. Zhao and Q. Tan, *Appl. Opt.* **62**, 8279 (2023).
19. Q.-D. Chen, X.-F. Lin, L.-G. Niu, *et al.*, *Opt. Lett.* **33**, 2559 (2008).
20. Y. Li, J. T. Lu, and Y. Z. Zhu, *Chin. Opt. Lett.* **3**, S57 (2005).
21. Z. Zhao, X. Zuo, H. Yang, *et al.*, *Adv. Mater. Technol.* **8**, 2200861 (2023).
22. M. Long, R. Han, K. Cao, *et al.*, *Photon. Res.* **14**, 1299 (2026).
23. D. Pan, Y.-J. Yu, Y.-K. Wang, *et al.*, *Adv. Funct. Mater.* **34**, 2402323 (2024).
24. Z.-Z. Li, H. Fan, L. Wang, *et al.*, *Nat. Photon.* **18**, 799 (2024).
25. Z.-T. Liu, Y. H. Lei, X. H. Zhao, *et al.*, *Laser Photon. Rev.* **20**, e02265 (2026).