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Transforming scattering into a seed of a nanometric blade

Tong Ling[1,2,*] and Shih-Chi Chen[3,4,*]

Abstract

Chai et al. converted interferometric scattering from a persistent optical limitation into an effective tomoslicing technique, which delivers an unprecedented 7-nm kerf width and almost lossless wafering. Furthermore, this method is a robust and scalable approach for the low-waste manufacturing of transparent crystals and semiconductor substrates.

Keywords: Interferometric scattering, Optical tomoslicing, Ultrafast laser wafering, Kerf-free manufacturing, Transparent solids

Ultrafast lasers have steadily expanded the scope of optical manufacturing, from photonic structures in crystals to sub-20-nm surface nanowriting and the stealth dicing of hard wafers. In recent years, the lateral resolution of optical manufacturing has improved significantly through near-field, high-numerical aperture (NA) lenses and super-resolution schemes, thereby enabling advanced surface structuring, additive fabrication, and localised subsurface writing[1–13], as summarised in Table 1. However, such enhancement cannot directly translate to a small kerf when slicing crystals or transparent solids owing to the limited depth of field of a Gaussian beam. Although utilising Bessel beams may significantly extend the field depth, the resulting kerf widths measure hundreds of nanometres with rough surfaces[14]. This is not merely an engineering inconvenience. For high-value transparent materials such as laser crystals and semiconductor substrates, every additional micrometre of kerf translates into wasted feedstock, thicker polishing allowances, and higher costs. This bottleneck remains a longstanding problem in laser manufacturing.

Instead of pursuing conventional approaches such as optimising NAs or focusing techniques, Chai et al. transformed the physical role of scattering[4,5,8,9,13]. In most laser-processing scenarios, scattering is a detrimental mechanism, which perturbs focusing, redistributes energy, and degrades precision. Chai et al. inverted this logic. They intentionally created an initial nanopore via femtosecond-laser-induced micro-explosion and then used the nanopore as a seed scatterer. When the incident beam was laterally offset from the seed within a critical distance (approximately 200 nm in fused silica; Fig. 1b–d), the scattered field interfered with the undisturbed portion of the beam, thus yielding a sufficiently strong localised intensity maximum to generate a secondary nanopore. The secondary pore became the next scatterer, and the process was repeated in a controlled cascade. In other words, the structure being written participated in writing the next structure. This interferometric-scattering mechanism achieves energy localisation independent of the original focal ellipsoid. By adjusting the pulse offset, the authors steered the trajectory and orientation of sequential

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Table 1 Representative recent advances in optical manufacturing in terms of feature resolution and depth-to-width aspect ratio.

Processing technique	Material	Characteristic advance
Three-dimensional (3D) femtosecond laser writing[1]	Yttrium aluminium garnet (YAG) and sapphire	3D nanostructures with ~100 nm feature sizes
Femtosecond projection two-photon lithography[2]	Photoresist	Nanowires with lateral widths of 130–140 nm and axial heights down to 175 nm
Optical far-field-induced near-field breakdown[3]	TiO_2 films	Surface nanowriting with spatial resolution < 20 nm
Picosecond laser-induced micro-explosion[4]	4H-SiC	Picosecond slicing with cutting width < 2 μm and 250 μm thick wafers
Longitudinal laser-field material processing[5]	Sapphire, Si, and Cu surfaces	10–30-nm features with an aspect ratio > 16 in the far field
Kinetically regulated material assembly[6]	Metals, two-dimensional (2D) materials, oxides, and diamond	3D nanostructures with 20–200-nm resolution
Photoexcitation-induced chemical bonding[7]	Semiconductor quantum dots	3D nanoprinting with a minimum lateral linewidth of 81 ± 4 nm
Picosecond laser stealth dicing[8]	4H-SiC	Stealth dicing with a chipping width < 3 μm and section roughness < 500 nm
Super-stealth dicing[9]	Transparent solids including fused silica, $LiTaO_3$, $LiNbO_3$, YAG, Ce:YAG, and β-Ga_2O_3	Nanometric-precision dicing with cutting widths measuring tens of nanometres and aspect ratios of 1,000–10,000
3D nonlinear laser nanolithography[10]	Silicon	Embedded nanostructures with feature sizes down to 100 ± 20 nm deep inside silicon
Laser-induced periodic surface structures[11]	2D $NbOI_2$	Groove widths down to ~14.5 nm (~λ/73) fabricated in ambient air
Wet chemical etching-assisted aberration-enhanced single-pulsed femtosecond laser-supplemented nanolithography[12]	Crystals, glasses, and Si-based semiconductors	25-nm features, aspect ratios > 10^4:1, and 10 mm^2 holey nanostructures
Interferometric scattering-based optical tomoslicing[13]	Fused silica, YAG, and $MgAl_2O_4$	7-nm kerf, mass loss < 1%, 30 × 10 mm slicing, and theoretical industrial efficiency up to 400 mm^2/s

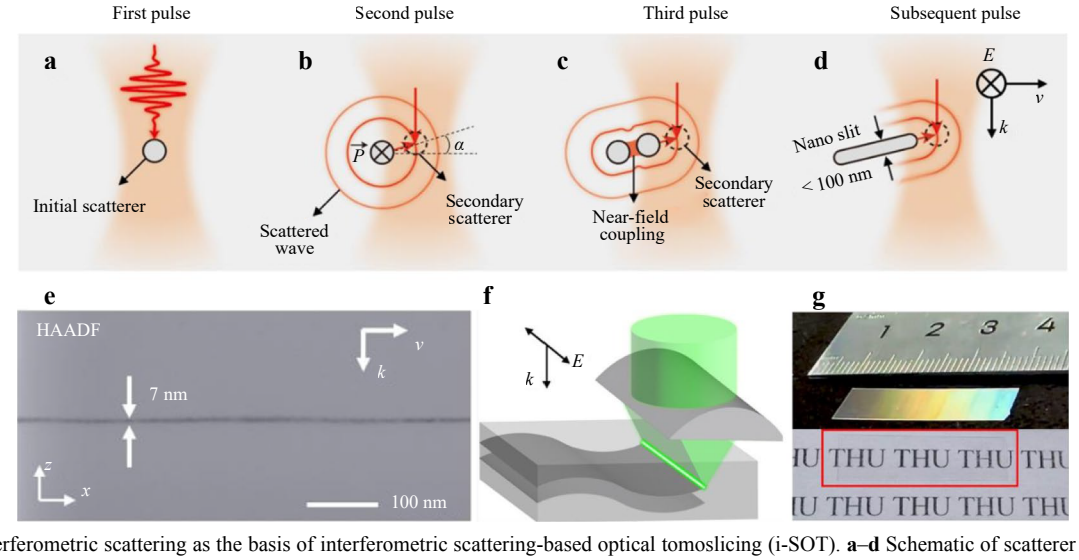

Fig. 1 Interferometric scattering as the basis of interferometric scattering-based optical tomoslicing (i-SOT). **a**–**d** Schematic of scatterer generation and propagation. **e** High-angle annular dark-field scanning transmission electron microscopy image of a horizontal nano-slit showing the 7-nm raw kerf. **f** Schematic of line-field generation using a cylindrical lens. **g** Planar wafering with high transmittance by cold splitting without etching. The wafer measures 30 × 10 mm (Images adapted from Ref. 13).

nanopores. Moreover, by shifting from a point focus to a line field generated using a cylindrical lens (Fig. 1f), they translated the same principle into interferometric scattering-based optical tomoslicing (i-SOT), which is a plane-slicing strategy instead of a conventional crack-guided separation process. This strategy offers high throughput (1 m/s) and scalability, and the resulting surface simultaneously offers superior quality (Ra = 9 nm)[13].

The performance metrics explain the importance of this concept. Additionally, the experiments were conducted with a modest NA of 0.6, thus avoiding the requirement for extremely high-NA optics. In fused silica, i-SOT yielded raw kerf widths down to 7 nm (Fig. 1e). Furthermore, the method accommodates geometries rarely attainable via conventional wafering, including multilayer slicing, 45° tilted planes, and wavy cross-sections. In addition to fused silica, Chai et al. applied i-SOT to crystalline yttrium aluminium garnet (YAG) and $MgAl_2O_4$, thus yielding ultrathin wafers that were approximately 8.6–9.5-μm thick and demonstrating that the sliced YAG plates retain notable mechanical integrity. i-SOT employs a line field instead of point-by-point raster scanning, thereby offering high throughput and precision. A 30 × 10 mm transparent slice can be created directly (Fig. 1g), and the authors predict that by adopting industrial-class femtosecond sources, the theoretical slicing efficiency may reach 400 mm^2/s. Most importantly, combining ultrathin wafering with nanometric kerfs reduces mass loss from approximately 30% to below 1%, thus bringing laser wafering close to an almost-ideal, "kerf-free" manufacturing process[13].

Perhaps the most profound impact of this study is conceptual. Over the past two decades, researchers have progressively leveraged principles from super-resolution optical imaging, nonlinear thresholding, and near-field confinement to enhance fabrication resolution. Chai et al. provided a different perspective: the medium can be actively engineered to serve as an interferometric contributor to the manufacturing process. Once scattering is seeded, directed, and cascaded, this process ceases to exert a parasitic effect and becomes a tool for energy localisation. This reversal is elegant yet practical and represents a family of laser-manufacturing strategies where sub-diffraction precision, high throughput, and low material loss are pursued simultaneously instead of through mutual compromise. For transparent solids, light scattering may have just changed from a nuisance into the blade itself [3,5,9,13].

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Conflict of interest

The authors declare no competing interests.

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