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Advancing Projection Two-Photon Polymerization for High-Repetition-Rate IFE Target Fabrication: Predictive Modeling and High-Sensitivity Materials

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The transition of Inertial Fusion Energy (IFE) from scientific ignition to a viable power source depends on the ability to mass-produce complex, high-precision targets —specifically low-density polymer foams and shells —at repetition rates exceeding 10 Hz.
While Two-Photon Polymerization (2PP) offers the necessary sub-micron resolution for controlling foam morphology, standard point-scanning approaches are prohibited by low throughput and excessive energy consumption.

Projection Two-Photon Polymerization (P2PP) offers a parallelized solution, yet faces challenges in optical confinement and material sensitivity required for industrial scale-up.
We present a dual-pronged approach to optimizing P2PP for IFE target fabrication, combining a comprehensive wave-optics simulation with novel resin chemistry. First, we developed a numerical model based on Fourier optics to characterize the spatio-temporal focusing dynamics of the printing process.
The simulation quantifies critical fabrication artifacts, identifying a $\approx 36\%$ axial elongation of voxels induced by the diffraction grating of the Digital Micromirror Device (DMD). Furthermore, we demonstrate that maximizing the spectral bandwidth of the laser source significantly improves axial confinement, a key parameter for defining the pore structure of low-density foams.

Second, to address the printing speed and energy efficiency bottleneck, we developed and characterized custom high-sensitivity photoresists. By utilizing the 4-methylcyclohexanone derivative (BBK) photoinitiator, we achieved a $>$ 40-fold increase in photosensitivity compared to commercial standards (IP-S). This sensitivity gain reduces the projected laser power consumption and increases the printing speed by a factor of 40. It enables the microsecond-scale exposure times required for advanced linescanning strategies. We further demonstrate that the process stability of these highly reactive resins can be precisely tuned using inhibitors (MEHQ) without compromising sensitivity. Finally, we present preliminary results on the synthesis of oxygen-free, vinyl-based liquid polystyrene resists, outlining a pathway to pure hydrocarbon (C-H) targets essential for minimizing Bremsstrahlung losses in fusion experiments.

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