Design and Development of Multilayer Dielectric Grating for Spectral Beam Combining Applications

Abstract

High-power laser systems have gained significant importance in modern defense technologies, particularly for directed-energy weapons, counter-drone systems, and other applications requiring precise delivery of high optical power over long distances. Beyond defense, these systems are also extensively employed in industrial material processing, advanced manufacturing, scientific instrumentation, and medical applications. However, scaling laser output power while maintaining beam quality remains a significant technological challenge. Spectral beam combining (SBC) offers an effective approach to overcome these limitations by combining multiple laser channels of different wavelengths into a common output beam. Multilayer dielectric gratings (MDGs) are promising components for high-power SBC systems due to their high diffraction efficiency, low optical absorption, and high laser-damage resistance. This thesis presents an integrated investigation of the design, fabrication, optimization, robustness assessment, and characterization of polarization-independent MDGs for high-power SBC applications.

An off-Littrow optimization methodology was developed to account for wavelength-dependent incidence angles required to achieve a common diffraction direction. Square, tapered, and trilayer-tapered MDG architectures were investigated using rigorous coupled-wave analysis (RCWA) combined with particle swarm optimization. The optimized trilayer-tapered architecture achieved an average diffraction efficiency of approximately 97.85% over the 1030–1080 nm wavelength range, with improved fabrication tolerance and reduced aspect ratio. Subsequently, an MDG was fabricated using dielectric thin-film deposition, direct laser writing, and inductively coupled plasma reactive ion etching. The fabricated grating demonstrated an average measured diffraction efficiency of approximately 94% over 1037.5–1067.5 nm.

A statistical RCWA–Monte Carlo framework was developed to investigate the influence of multilayer thickness variations, refractive-index fluctuations, and geometrical deviations on diffraction performance and fabrication yield. To further reduce fabrication complexity, a single-surface-relief MDG architecture was proposed, incorporating a trapezoidal Ta_2O_5 grating with independently optimized residual and matching layers. The proposed architecture achieved a sub-unity aspect ratio of 0.88 and a normalized cumulative −1st-order diffraction efficiency of 98.74% for 30 laser channels in a center-crossing SBC configuration. Furthermore, a non-destructive characterization methodology combining diffraction-efficiency measurements with ellipsometry-informed RCWA simulations was developed to estimate fabricated grating geometry, demonstrating close agreement with atomic force microscopy measurements.

Overall, this research establishes a fabrication-aware framework integrating optical design, experimental realization, statistical tolerance analysis, system-level performance, and non-destructive

characterization. The findings contribute toward developing efficient, robust, and scalable multilayer dielectric gratings for high-power laser systems, with particular relevance to emerging defense and directed-energy applications.