

Advancements and Applications of Diffractive Optical Elements in Contemporary Optics: A Comprehensive Overview

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Diffractive optical elements (DOEs) represent a revolutionary advancement in modern optics, offering unparalleled versatility and efficiency in various applications. Their significance lies in their ability to manipulate light waves with intricate patterns, enabling functionalities beyond what traditional refractive optics can achieve. DOEs find widespread use in fields such as laser beam shaping, holography, optical communications, and imaging systems. By precisely controlling the phase and amplitude of light, DOEs can generate complex optical structures, correct aberrations, and enhance the performance of optical systems. Moreover, their compact size, lightweight nature, and potential for mass production make them indispensable in designing compact and efficient optical devices for diverse industrial and scientific applications. From improving the performance of laser systems to enabling innovative display technologies, DOEs continue to drive advancements in modern optics, promising even more exciting possibilities in the future. In this review, the critical importance of DOEs is illuminated and explore their profound implications in the contemporary era.

1. Introduction

Diffractive Optical Elements (DOEs) stand at the forefront of modern optics, offering a versatile and powerful toolset for manipulating light with unprecedented precision and flexibility.^[1–3] Unlike conventional refractive optical components, which count on the bending of light through materials with varying refractive indices, DOEs exploit the wave nature of light to achieve complex optical functions through diffraction.^[4,5] These elements are engineered with precisely patterned structures, typically on a micro- or nanoscale, that modulate the phase, amplitude, or polarization of incident light waves.^[6] One of the key functionalities

of DOEs lies in their ability to shape light beams in ways that were previously unattainable with conventional optics.^[7–9] They can generate intricate intensity distributions, such as arbitrary patterns, arrays, or even non-diffracting beams like Bessel or Airy beams,^[10,11] by imparting controlled phase shifts across the wavefront.^[12] Such capabilities find applications across various fields, including laser material processing, focusing, beam shaping, optical trapping and manipulation, microscopy, and lithography.^[13–15]

Moreover, DOEs play a pivotal role in wavefront engineering and adaptive optics (AO) systems.^[16] By precisely tailoring the phase profile of incident light, these elements can correct aberrations in optical systems, enabling enhanced imaging resolution, beam quality, and focal spot control.^[17] In astronomy, for

instance, AO systems employ DOEs to compensate for atmospheric turbulence, resulting in sharper images of celestial objects. Similarly, in ophthalmology, DOEs are used to correct aberrations in the eye, leading to improved vision in corrective lenses.^[18] Another significant functionality of DOEs is their capacity for spectral and polarization control.^[19–21] Through careful design of their microstructure, DOEs can selectively diffract light of specific wavelengths or polarizations, enabling spectral filtering, wavelength multiplexing, and polarization manipulation. These capabilities are invaluable in telecommunications, where DOEs are utilized in wavelength-division multiplexing systems to route and manipulate optical signals with high efficiency and precision.^[22–24]

Furthermore, DOEs have revolutionized holography and display technologies, offering a compact and efficient means of generating complex 3D images. Liu et al. developed a dynamic bit-wise meta-holography system with extremely high computational and display frame rates.^[25] It was the first practical dynamic interactive metasurface (MS) holographic system which was divided into multiple channels, each projecting a different sub-pattern. By using bitwise operations instead of complex hologram calculations, a computational frame rate of 800 kHz and a display frame rate of 23 kHz on a low-power Raspberry Pi was achieved. This was demonstrated with an interactive holographic Tetris game

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