Optical Software-Assisted Design and Optimization of Bessel Beam Systems for applications to laser materials processing

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ABSTRACT

Bessel beams, known for maintaining focus over long distances, find many applications in imaging, nonlinear optics and laser material processing. For these applications, generating sub-micrometer Bessel beams is essential, but requires complex optical systems. Traditional optical software, designed for ray tracing, are challenged for this task. Here we show how we can use optical software to create and optimize optical design to generate these unconventional beams. The research involves high numerical aperture systems, investigates the influence of polarization, and the use of diffractive optical elements. Numerical findings are compared to experimental results, highlighting the potential of software-assisted beam design for various applications.

Keywords: Bessel beams, Laser ablation, optical system , ZEMAX OpticStudio@ANSYS

1. INTRODUCTION

Bessel beams are propagation-invariant solutions to the Helmholtz equation and have the unique property of maintaining a focus over distances significantly larger than Gaussian beams of the same diameter[1,2] . This characteristic makes Bessel beams highly advantageous for applications such as imaging[3] and laser nano-ablation[4] . Complex imaging systems with multiple lenses are required to generate such beams[5] . In this context, properly accounting for aberrations is crucial to designing high spatial resolution systems. This calculation quickly becomes complex, necessitating the use of software simulating optical systems. However, these programs were originally designed for conventional imaging problems and rely primarily on ray-tracing approximations. We demonstrate the potential benefits of utilizing software to aid in creating non-traditional beams. We will provide an overview of the design and optimization of various optical systems to generate Bessel beams, where we designed large numerical aperture systems or used diffractive optical elements. Our numerical results are compared to experimental results obtained in several projects.

2. OPTIMIZATION WITH THE STREHL RATIO

Generating Bessel beams with micrometer or sub-micrometer lateral dimensions typically requires complex optical systems with many components. Designing, optimizing, and aligning such systems can be challenging without specialized optical design software. ZEMAX OpticStudio@ANSYS (ZOS) is one of the most widely used software packages in academia. The software offers strong optimization capabilities, a range of components and material libraries, and various analysis tools, including the Strehl ratio[6] . This ratio assesses the imaging quality of an optical system by comparing the peak intensity of the actual point source image to the theoretical peak intensity when diffraction-limited. Although originally intended for classical imaging systems, this method can be adapted for use in ZOS to optimize and simulate Bessel beam profiles, which result from an interference, with a high degree of precision.

3. EXAMPLES OF SYSTEMS DEVELOPED USING ZOS.

This section presents examples where the use of ZOS was crucial in designing and optimizing Bessel beam generation setups. The section is divided into two main directions: optimizing setups to find suitable components and simulating specific behaviors.

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3.1 Design and Optimization of Setup

There are some applications of Bessel beams that require very high intensity in the central core of the beam, such as materials processing. Many interesting configurations have been proposed in the literature that produce central core dimensions that can be as low as 0.36λ. In general, all these techniques result in highly extended systems, high risk of damage to expensive components and are limited to relatively low focusing or cone angles. We have recently proposed a design that overcomes these limitations[5] . The core of our system is the coupling between a low angle axicon and a hemispherical lens. The correct design of the setup and subsequent component selection and simulation was only made possible by using ZOS.

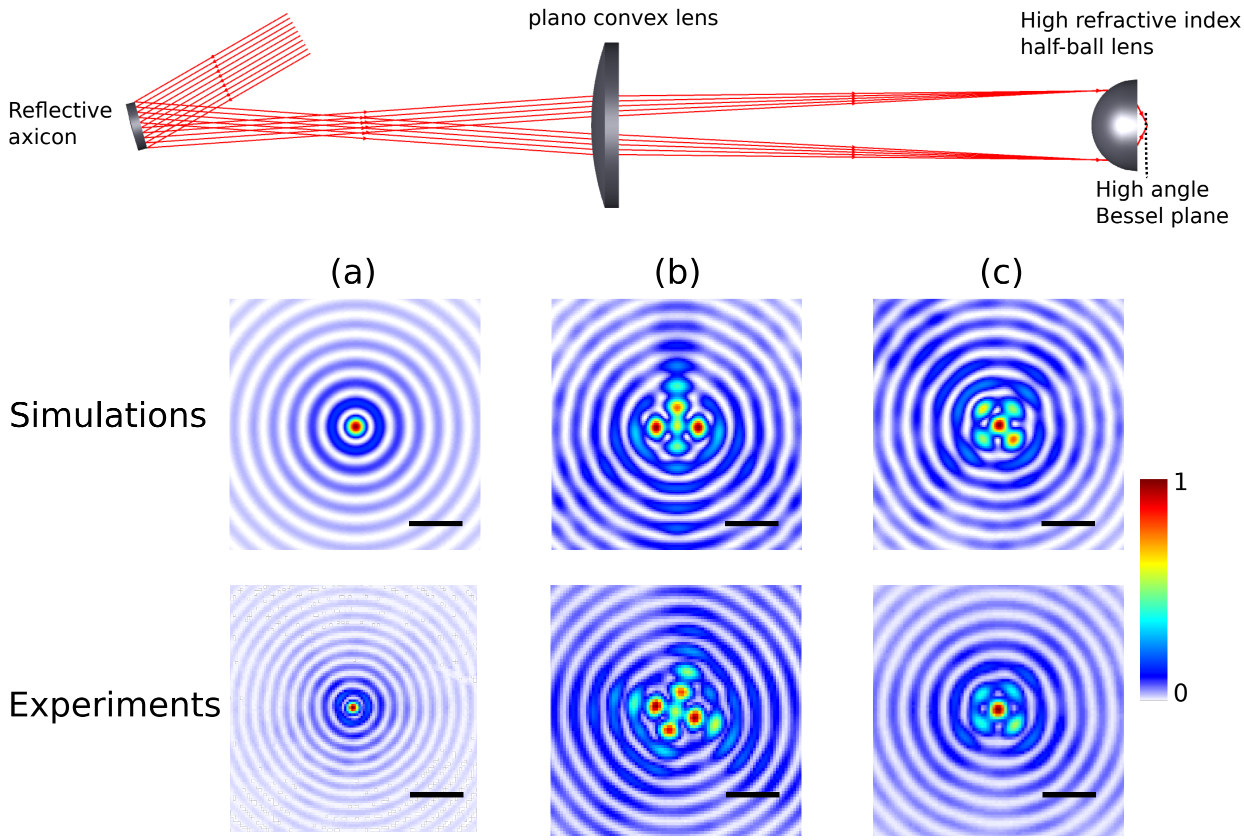

Figure 1. The generation of high NA Bessel beams. The setup is shown at the top, while the sections of the Bessel beams are shown at the bottom, including a comparison between the simulations obtained with ZOS (top line) and the experimental results (bottom line). Columns : (a) The Bessel beam is undisturbed, (b) the axicon is tilted by 0.14 °, (c) a $50\mu m$ shift of the half-ball lens is introduced. The scale bars represent $2\mu m$.

As can be seen in Fig.1, the first low angle axicon is a reflective off-axis axicon from Canunda (Canunda axicon AX-2-25-S). The axicon was simulated and optimised using a biconic surface type in the Sequential Lens Data Editor. The results shown in Fig. 1 show excellent agreement with the experimental validations, even under different misalignment conditions.

3.2 Simulation of Specific System Properties

In 2019, we conducted a comprehensive review of various achievements that showcase the use of Fourier transform and transfer functions in optics. These applications have led to remarkable advances in unconventional areas of optics, particularly in the spatial manipulation of complicated laser beams in terms of both their amplitude and phase characteristics. In particular, we have shown that it is possible to generate an achromatic Bessel beam with a central lobe diameter of $10\mu m$ FWHM, propagating over $7mm$, and with a spectral bandwidth of more than 200 nm. An achromatic Bessel beam was generated using a spatial light modulator due to its diffractive nature. It is worth noting that a classical refractive axicon is unable to produce this type of beam[7] . Wide band

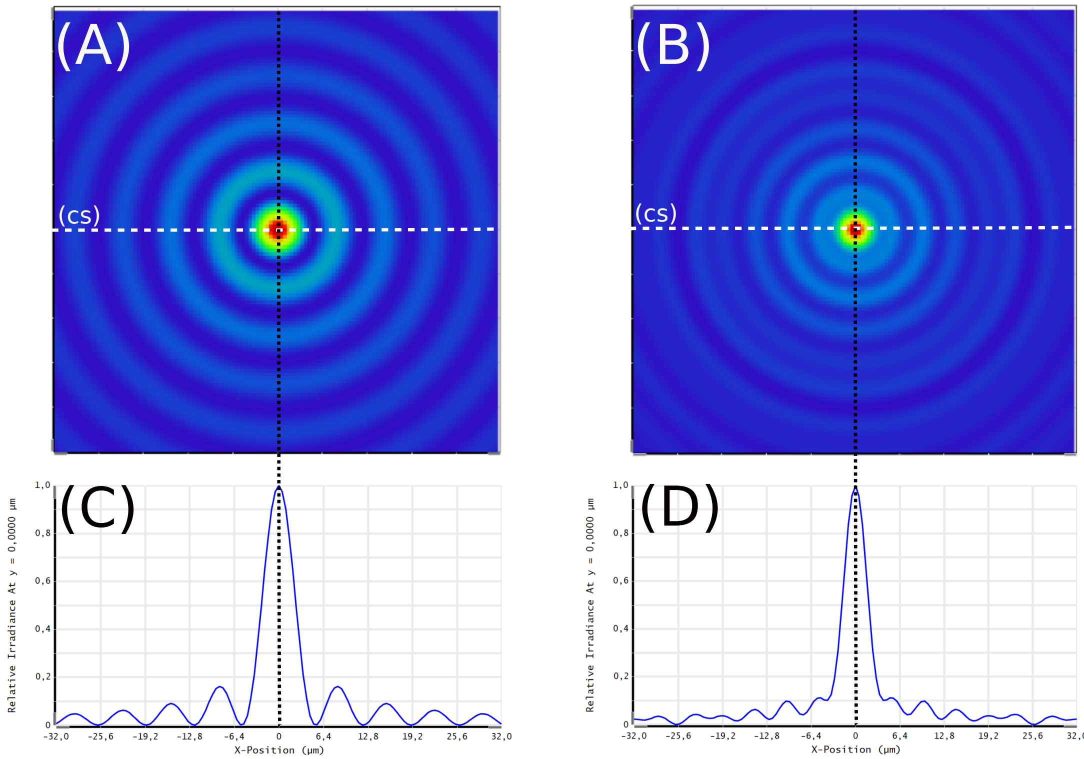

Figure 2. Simulations using ZOS to generate wide-band Bessel beam profiles with a bandwidth of $400nm$. The beam structure (A) and its cross-section (C) were obtained using a diffractive axicon. The cross-section was taken along the dotted line (cs). The beam structure (B) and its cross-section (D) were obtained using a refractive axicon. The cross-section was taken along the dotted line (cs).

Bessel beams were simulated using ZOS (Fig. 2). The results show that the achromaticity of diffractive axicons was retrieved as expected. However, in the case of the refractive axicon (Fig. 2(B)), the Bessel beam lobes are blurred as predicted too. To generate a diffractive axicon, we utilized the 'Optically Fabricated Hologram' surface type in the sequential lens data editor.

4. CONCLUSION

Designing and optimizing complex optical systems is necessary for generating high numerical aperture Bessel beams. Software such as ZOS can simplify this process. The results obtained through this method have been validated experimentally and are in excellent agreement. The Strehl ratio is a key optimization criterion for these models and can be used under certain conditions beyond conventional beams. The use of optical calculation software for Bessel beams enables the design and optimization of more complex systems in the future.

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