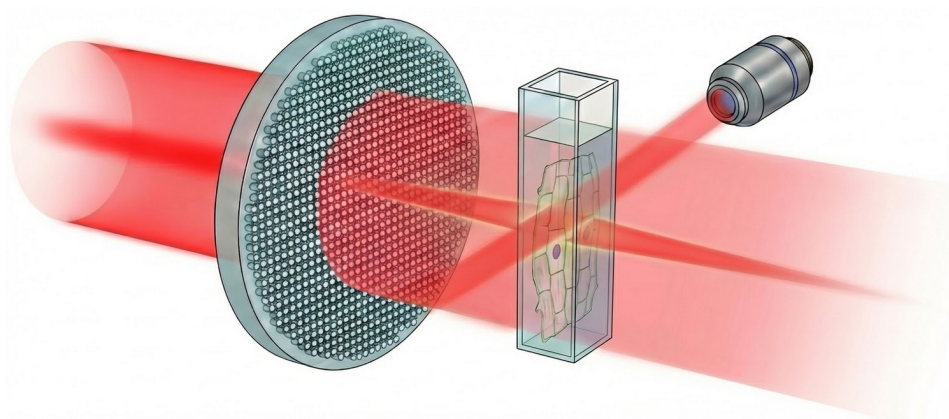


DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MADRAS
CHENNAI – 600036

Meta-optics Beam Shaping for Improved Bessel Light Sheets



A Thesis

Submitted by

JERIN GEOGY GEORGE

For the award of the degree

Of

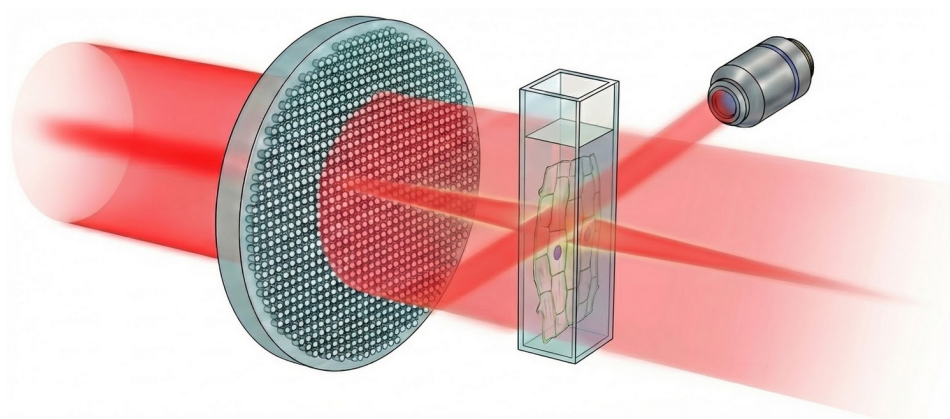
DOCTOR OF PHILOSOPHY

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When you're playing a point, it has to be the most important thing in the world. And it is. But when it's behind you, it's behind you. This mindset is crucial – because it frees you to fully commit to the next point with intensity, clarity, and focus.

– Roger Federer

*To my son, Jake, whose presence brought joy and reminded me
that there is more to life than a PhD.*

*To my wife, Nisha, for being by my side throughout this journey.
Your work ethic inspired me to stay focused.*

To my parents, for everything.

THESIS CERTIFICATE

This is to undertake that the Thesis titled **META-OPTICS BEAM SHAPING FOR IMPROVED BESSEL LIGHT SHEETS**, submitted by me to the Indian Institute of Technology Madras, for the award of **Doctor of Philosophy**, is a bona fide record of the research work done by me under the supervision of **Prof. Shanti Bhattacharya**. The contents of this Thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Chennai 600036

Jerin Geogy George

Date: February 2026

Dr. Shanti Bhattacharya

Research advisor

Professor

Department of Electrical Engineering

IIT Madras

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2. Jerin Geogy George, and Shanti Bhattacharya. "Overcoming challenges in fabrication of beam shaping meta-optics using sensitive mr-EBL resist." *Journal of Optical Microsystems* 4.4 (2024): 041402-041402.
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ABSTRACT

KEYWORDS Sidelobe-suppressed Bessel beam; Light-sheet microscopy; Beam shaping; Meta-optics; Metasurface fabrication

Beam shaping plays a crucial role in microscopy by improving spatial resolution and imaging performance. Conventional beam shaping relies on refractive and diffractive optical elements. Recent advances in ultrathin meta-optics have expanded beam-shaping capabilities and enable the generation of complex structured light fields. Light-sheet microscopy has recently emerged as a complementary alternative to conventional epi-illumination techniques. In this geometry, excitation and detection are arranged orthogonally, which reduces photodamage and improves optical sectioning. In light-sheet microscopy, Gaussian beams provide a limited field of view due to their low depth of focus. Bessel beams offer an extended depth of focus and are therefore attractive for light-sheet illumination. However, their strong sidelobes cause unwanted excitation and reduce image contrast. Meta-optics enable the realisation of arbitrary phase functions and allow the design of Bessel beams with reduced sidelobes. This capability provides a promising route for improving light-sheet imaging performance.

In this work, the generation of sidelobe-suppressed Bessel beams (SSBBs) for light-sheet microscopy is experimentally demonstrated using planar dielectric metasurfaces. Silicon and silicon nitride metasurfaces are designed to generate these beams at near-infrared and visible wavelengths. The design and fabrication of beam-shaping metasurfaces are systematically investigated, including key challenges in the fabrication process. The generated beams are implemented in a light-sheet microscopy setup, and imaging of onion epidermal cells is demonstrated. The performance of the SSBB-based light sheet is compared with that of a conventional Bessel-beam-based light sheet. To further enhance imaging performance, additional strategies are explored. Structured illumination using SSBBs is experimentally demonstrated using metasurface-generated beam arrays.

Furthermore, the applicability of SSBBs to the stimulated emission depletion (STED) principle in a light-sheet geometry is investigated. In this context, zeroth-order and first-order SSBBs for excitation and depletion are experimentally generated, while the resulting super-resolution light needle is demonstrated through simulations.

The metasurface-generated SSBBs exhibit 50–57% suppression of the first sidelobe compared to conventional Bessel beams in both silicon and silicon-nitride platforms. The SSBB depth of focus is about 1.7 times that of a Gaussian beam with a comparable beam size. An SSBB-based scanned light sheet also shows a substantial reduction in sidelobes compared with a Bessel-beam-based light sheet. Imaging of onion epidermal cells using the SSBB light sheet demonstrates a 55% improvement in image contrast compared to a Bessel beam. Structured illumination using SSBB is further demonstrated, where five nearly equal-intensity copies of the SSBB are generated using a metasurface. In addition, zeroth-order and first-order SSBB are generated for STED light-sheet microscopy, where the first-order SSBB exhibits a 45% reduction in the first sidelobe compared to a first-order Bessel beam.

These results demonstrate that SSBBs improve light-sheet imaging by reducing sidelobes and enhancing image contrast. Although the depth of focus of the SSBB is lower than that of a conventional Bessel beam, it exceeds that of an equivalent Gaussian beam, thereby extending the usable field of view. The realisation of SSBBs using meta-optics enables their implementation in light sheet microscopy using ultracompact optical elements. Furthermore, the additional strategies presented in this work, including structured illumination using SSBBs and the incorporation of the STED principle within a light-sheet geometry, provide further routes for improving light-sheet microscopy performance.

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ABBREVIATIONS

3D	Three-Dimensional.
BB	Bessel Beam.
CCD	Charge-Coupled Device.
CMOS	Complementary Metal Oxide Semiconductor.
CW	Continuous Wave.
DoF	Depth of Focus.
EBL	Electron Beam Lithography.
ED	Electric Dipole.
EQ	Electric Quadrupole.
FDTD	Finite-Difference Time-Domain.
FEM	Finite Element Method.
FFT	Fast Fourier Transform.
FWHM	Full Width at Half Maximum.
GDSII	Graphic Data System II.
HSQ	Hydrogen Silsesquioxane.
ICP	Inductively Coupled Plasma.
ICP-CVD	Inductively Coupled Plasma Chemical Vapor Deposition.
ICP-RIE	Inductively Coupled Plasma Reactive Ion Etching.
IPA	Isopropyl Alcohol.
LPCVD	Low-Pressure Chemical Vapor Deposition.
LSM	Light-Sheet Microscopy.

MD	Magnetic Dipole.
MIBK	Methyl Isobutyl Ketone.
MTF	Modulation Transfer Function.
ND	Neutral Density.
PB	Pancharatnam-Berry.
PECVD	Plasma-Enhanced Chemical Vapor Deposition.
PMMA	Polymethyl Methacrylate.
PSF	Point Spread Function.
RCWA	Rigorous Coupled-Wave Analysis.
RF	Radio Frequency.
SEM	Scanning Electron Microscopy.
SIM	Structured Illumination Microscopy.
SLM	Spatial Light Modulator.
SSBB	Sidelobe-Suppressed Bessel Beam.
STED	Stimulated Emission Depletion.
UV	Ultraviolet.

NOTATION

(f_x, f_y) spatial frequency coordinates

(u, v) spatial coordinates of the observation plane

(x, y) spatial coordinates of the source plane

Δu extent of the observation plane

Δx extent of the source plane

δ_m phase of the Fourier coefficient

η_{ps} probability of the spontaneous decay of the dye

γ effective saturation factor of the dye

λ wavelength

$\mathcal{I}$ image

ϕ optical phase / phase function

π ratio of the circumference of a circle to its diameter

ψ azimuthal phase term

τ_{STED} pulse width of the depletion beam

θ cone angle of the Bessel beam

$\tilde{t}_L$ complex transmission coefficient along the long axis of the nanofin

$\tilde{t}_S$ complex transmission coefficient along the short axis of the nanofin

ϑ rotation angle of the nanofin

ζ saturation factor of the dye

A amplitude of the Bessel beam field

c the speed of light in vacuum

c_m	amplitude of the Fourier coefficient
$E(x, y)$	electric field
f	focal length
f_p	spatial carrier frequency
$H(f_x, f_y)$	Fresnel transfer function
$h(x, y)$	impulse response
I	intensity
I_s	saturation intensity of the dye
I_{STED}	intensity of the depletion beam
J_0	Bessel function of zeroth-order
k	wave number
k_r	radial component of wave vector
k_z	longitudinal component of wave vector
k_{s1}	spontaneous decay rate of the dye
k_{vib}	vibrational relaxation rate of the dye
N	number of samples
n	refractive index
n_{eff}	effective index
p	period
r_0	core radius of the Bessel beam
T	binary transmission mask
z_R	Rayleigh distance of a Gaussian beam

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Microscopy is an imaging technique used to observe objects that are too small to be observed with the naked eye. In biological research, microscopy plays a crucial role in studying cells and detecting various diseases. Traditional microscopy employs the same objective for illuminating the sample and collecting the signal from it. However, this epi-illumination geometry has certain limitations. It illuminates not only the focal region of interest in the sample, but also the regions above and below it. When not properly filtered out, signals from out-of-focus planes contribute to image blur and decrease overall image contrast and resolution. To overcome this limitation, confocal microscopy was developed. By introducing a pinhole in a conjugate plane to the focal plane, confocal microscopy effectively blocks out-of-focus signal and enhances optical sectioning and image quality (Pawley (2006)). Although this approach significantly improves image clarity, it relies on point-by-point scanning of the sample, which increases the image acquisition time. It can also result in photobleaching due to multiple exposures, particularly during volumetric imaging.

Light-sheet microscopy (LSM) has emerged as a widely used technique for rapid 3D imaging, where the signal from the sample is collected along a direction orthogonal to the illumination. In this method, a thin sheet of light illuminates a fluorophore-stained sample, and the signal emitted from that illuminated plane is detected perpendicularly. This orthogonal detection geometry confines excitation to the region of interest, thereby minimising photobleaching (Reynaud *et al.* (2008); Santi (2011); Olarte *et al.* (2018)). Figure 1.1 illustrates a schematic of the light-sheet imaging approach. In its initial implementation, a Gaussian beam emitted from a laser is focused using a cylindrical

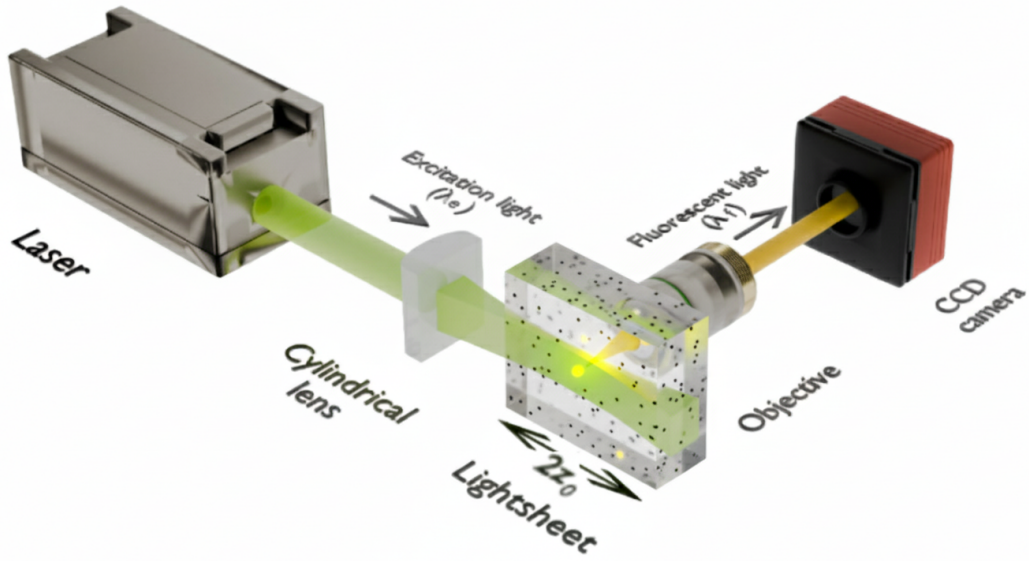


Figure 1.1: A schematic of a light-sheet microscopy setup

lens, which focuses light along one axis to form a thin sheet over the depth of focus. Later, to improve the uniformity of the sheet, a digitally scanned light-sheet configuration was introduced, in which a focused beam is rapidly scanned across the field of view to synthesise a uniform illumination sheet.

The optical sectioning capability and imaging contrast of the technique depend on the thickness and uniformity of the light-sheet, which are determined by the excitation point spread function (PSF) and its depth of focus (DoF). The image contrast, defined as $\frac{I_{max}-I_{min}}{I_{max}+I_{min}}$, quantifies the difference between the signal intensity and background intensity, thereby determining the visibility of image features. Conventional light sheets generated using Gaussian beams have a limited DoF, as the beam diverges rapidly beyond the focal region (Gao (2015); Nytk and Dholakia (2019)). This limitation restricts imaging depth or necessitates a compromise in axial resolution by employing a thicker light-sheet. To overcome these challenges, alternative beam profiles such as Bessel and Airy beams have been proposed for use in LSM (Durnin *et al.* (1987); McGloin and Dholakia (2005); Vettenburg *et al.* (2014)).

1.2 BESSEL BEAMS

Bessel beams are well known for their propagation-invariant and self-healing properties, which enable deeper penetration while preserving axial resolution. Essentially, they form “light needles” that maintain a nearly constant transverse profile well beyond the Rayleigh range of a Gaussian beam with a similar core radius. In fluorescence microscopy, Bessel beam-based excitation has demonstrated approximately a three-fold improvement in penetration depth compared to conventional Gaussian beam excitation (Purnapatra *et al.* (2012)). The simplest method to generate a Bessel beam is by placing a ring-shaped aperture at the front focal plane of a lens. This configuration produces plane waves that propagate along the surface of a cone. The interference of these conical rays along the optical axis results in a bright central core surrounded by concentric sidelobes (Fig. 1.2).

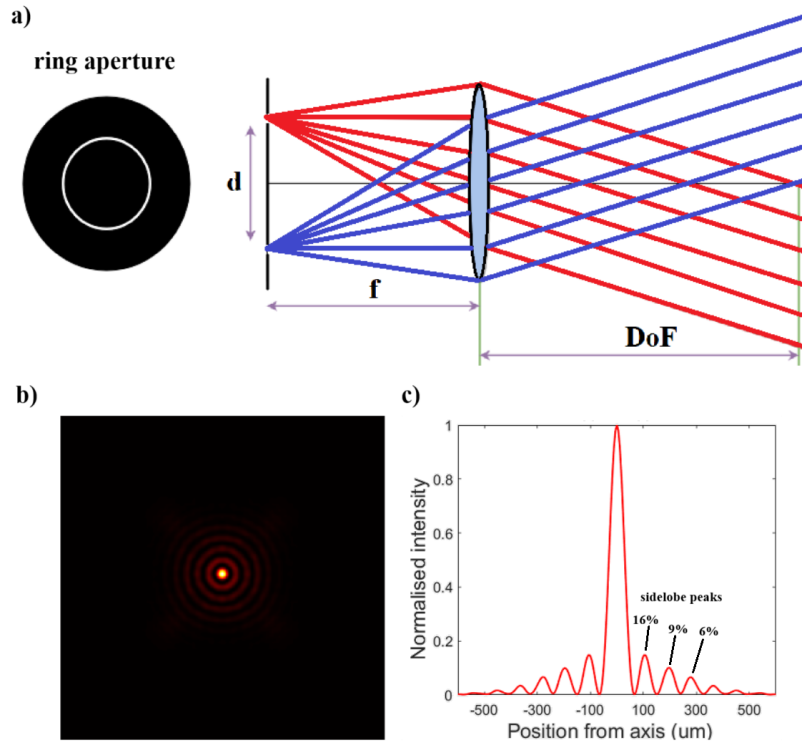


Figure 1.2: (a) Generation of a Bessel beam using a ring aperture. (b) Cross-sectional intensity profile and (c) line intensity profile of a Bessel beam.

Although Bessel beams possess multiple sidelobes, these sidelobes play a crucial role in maintaining the width of the central core nearly constant during propagation. As a

result, the DoF of a Bessel beam is much greater than that of a Gaussian beam with a comparable central core width, leading to their propagation-invariant nature. The DoF of a Bessel beam is defined by the cone angle (θ) and the radius (R) of the imaging lens.

$$DoF = \frac{R}{\tan(\theta)} \quad (1.1)$$

In addition to this property, Bessel beams exhibit a self-healing capability (Garcés-Chávez *et al.* (2002)). Since the central core is formed by the interference of rays originating from the annular regions, any obstruction along the beam axis only temporarily disturbs the intensity distribution, allowing the core to reconstruct itself beyond the obstacle. This unique feature makes Bessel beams particularly advantageous for imaging and illumination in turbid or scattering media (Fahrbach *et al.* (2013)).

These propagation-invariant and self-healing properties make Bessel beams highly suitable for light-sheet imaging. However, the presence of sidelobes remains a significant concern, as they lead to unwanted excitation within the sample. The cross-sectional intensity profile of a Bessel beam clearly reveals multiple sidelobes. The first sidelobe intensity of a Bessel beam is about 16% that of the main lobe peak intensity. This issue becomes more pronounced when the Bessel “light needle” is scanned to form a light sheet. During scanning, the sidelobes integrate with the main core, producing an elongated tail that compromises the excitation confinement, thereby diminishing the advantage of Bessel illumination over Gaussian beams (Planchon *et al.* (2011)).

1.2.1 Conventional Bessel beam generation

The initial generation of Bessel beams was demonstrated by placing a ring-shaped aperture in the front focal plane of a lens. While this approach is conceptually simple, it is highly inefficient, as a large fraction of the incident light is blocked by the aperture. A more efficient method for generating Bessel beams employs a refractive optical element known as a conical lens, or axicon. When illuminated by a collimated beam, an axicon produces a conical wavefront that interferes constructively along the propagation axis,

forming a Bessel-like intensity distribution. However, conventional refractive axicons become increasingly thick when designed for large cone angles, leading to increased bulk and fabrication challenges.

Diffractive optics offers a flatter and more compact alternative to conventional refractive elements, reducing optical thickness while enabling the realisation of complex phase profiles. Transforming a refractive element into a diffractive one involves “wrapping” the accumulated phase delays exceeding 2π during propagation through the lens thickness, analogous to the operating principle of a Fresnel lens. As the reproduction of continuous curved surfaces is impractical in this approach, the continuous phase profile is discretised into multiple phase levels, as illustrated in Fig. 1.3. These discrete phase structures can be fabricated using optical lithography techniques, rather than mechanical processes such as grinding, milling, or polishing that are typically required for conventional refractive lenses.

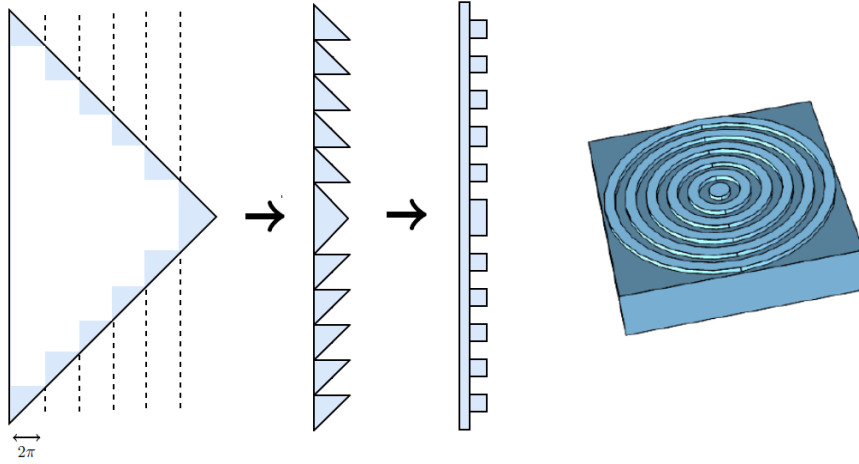


Figure 1.3: Conversion of a refractive axicon into a binary diffractive axicon through 2π phase wrapping and two-level phase discretisation.

Binary diffractive optical elements, which employ only two phase levels (0 and 2π), represent the simplest implementation and are relatively easy to fabricate. However, such elements suffer from low diffraction efficiency. Improving efficiency requires the use of multiple phase levels, which correspond to different physical heights in the diffractive

structure and consequently necessitate multiple lithography and etching steps. Although such multilevel fabrication techniques are achievable in advanced facilities, the associated complexity and fabrication overhead remain practical limitations in the realisation of highly efficient diffractive optical elements.

1.3 TECHNIQUES FOR IMPROVING BESSEL LIGHT SHEETS

As discussed earlier, Bessel beams offer great potential for light-sheet imaging due to their propagation-invariant and self-healing properties. However, the presence of sidelobes introduces certain challenges, which researchers have attempted to mitigate using various techniques. Some studies focus on rejecting signals from out-of-focus planes by modifying the detection path, while others aim to reshape the Bessel excitation beam itself to reduce unwanted exposure. The following sections discuss several of these approaches.

1.3.1 Confocal line detection

In confocal slit detection for LSM, the unwanted signal from out-of-focus planes is rejected by placing a physical or digital slit in a plane conjugate to the sample focal plane. This slit acts similarly to the pinhole in traditional confocal microscopy, but is extended into a line to match the line illumination strategy.

In the physical approach, a slit is positioned in the detection path at a plane conjugate to the sample focal plane. During imaging, the sample is illuminated by a thin light sheet or a scanned line (generated by a Bessel beam), and the emitted fluorescence is collected orthogonally. The slit allows passage of fluorescence originating only from the in-focus region of the illuminated line or sheet while blocking out-of-focus emission from regions above and below. Images are typically acquired sequentially, line by line, and subsequently reconstructed into a complete plane with reduced background and improved contrast compared to wide-field detection (Glaser *et al.* (2018); Ricci *et al.* (2020)).

The rolling shutter approach leverages the programmable exposure of modern scientific CMOS (sCMOS) cameras to create a "digital slit" detector. In this method, the rows of the camera sensor that are currently exposed are swept across the chip in synchronisation with the position of the scanned illumination beam (line or sheet). At any moment, only a narrow band of pixel rows is active and collects fluorescence, forming the digital equivalent of the physical slit. By carefully timing the illumination scan and rolling shutter movement, only the fluorescence from the in-focus region is admitted, while out-of-focus or scattered light is largely rejected. This approach eliminates the need for mechanical slits and allows high-speed imaging, fast frame rates, and flexible adjustment of the slit width (Baumgart and Kubitschek (2012); Yang *et al.* (2015); Kumar *et al.* (2016)).

In LSM, although confocal line detection significantly improves image contrast by rejecting out-of-focus fluorescence in the detection path, the illumination of the sample still occurs over the entire illuminated plane or line. This means that the sample regions within the illuminated volume remain exposed to the excitation light, resulting in photobleaching and potential phototoxicity despite background reduction at detection. Minimising photobleaching in LSM still requires careful control of both the illumination intensity and the exposure time.

1.3.2 Multiphoton excitation

Multiphoton LSM, including two-photon techniques using Bessel beams, combines the optical sectioning and reduced photodamage benefits of multiphoton excitation with the efficient planar illumination of LSM (Fahrbach *et al.* (2013)). As demonstrated in Escobet-Montalbán *et al.* (2018), three-photon LSM extends these benefits further by utilising longer wavelengths to reduce scattering and enabling deeper penetration in biological samples. Bessel beams are particularly advantageous in multiphoton LSM due to their propagation-invariant and self-healing properties, which generate thin, extended light sheets with a large depth of field while minimising blurring from side lobes through

nonlinear excitation confinement.

In multiphoton Bessel beam LSM, nonlinear excitation restricts fluorescence generation predominantly to the narrow central core of the beam, substantially reducing out-of-focus excitation and photobleaching compared to single-photon methods. Thus, the multiphoton process inherently suppresses background signals from sidelobes and scattering, improving optical sectioning without the need for extra detection-side confocal elements. This results in high-resolution volumetric imaging with lower phototoxicity and enhanced penetration depth (Olarde *et al.* (2012)).

However, multiphoton LSM requires pulsed lasers with high peak power, as continuous wave lasers cannot efficiently induce nonlinear excitation. While this approach significantly reduces out-of-focus photobleaching compared to one-photon methods, the high instantaneous power at the focal region may still cause localised photodamage and limit repeat imaging. Additionally, the optical setup is more complex and costly, involving the precise alignment of pulsed laser sources and additional beam-shaping optics, which can increase system complexity and maintenance demands. These factors pose practical challenges for routine use despite their advantages in deep, high-contrast imaging.

1.3.3 Sidelobe suppression of Bessel beams

Beam shaping approaches have also been explored to reduce sidelobe illumination in Bessel beams. One of the earliest methods, proposed by Mori (2015), involves creating a sidelobe-suppressed Bessel-like beam through the superposition of two coaxial Bessel beams. This is achieved by placing two ring apertures at the front focal plane of a lens, which generates two Bessel beams propagating along the same axis. By carefully optimising the radial positions and widths of these rings, the main lobes of the beams can be made to interfere constructively while the sidelobes interfere destructively, effectively reducing the sidelobe intensity (Fig. 1.4). However, similar to traditional methods of

generating Bessel beams, this technique is relatively inefficient as it blocks a significant portion of the light at the apertures, leading to low efficiency.

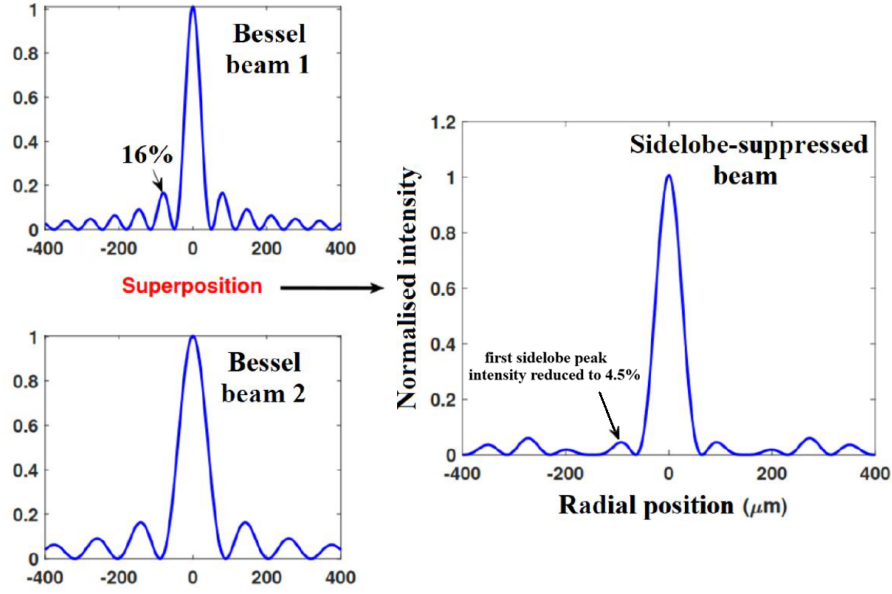


Figure 1.4: Simulation of Sidelobe-suppressed Bessel beam by the superposition of two Bessel beams.

In sidelobe-suppressed Bessel beams (SSBB), destructive interference of the sidelobes occurs primarily at the propagation plane where the longitudinal wave vectors of the two constituent Bessel beams coincide. This interference also reduces sidelobe intensity in regions just before and after this plane. However, it is important to note that SSBBs do not maintain the same DoF as a standard Bessel beam with the same core radius. A tradeoff exists between sidelobe suppression and DoF. The core radius of the SSBB lies between those of the individual Bessel beams involved and is determined by the weighting applied during their superposition. Additionally, the axial intensity of the SSBB exhibits periodic oscillations along the propagation direction, with a period governed by the difference in propagation constants of the component beams.

$$p = \frac{4\pi k}{|k_{r_1}^2 - k_{r_2}^2|} \quad (1.2)$$

From the above equation, it is evident that a smaller difference between the radial wave

vectors $\mathbf{k}_{r_1}$ and $\mathbf{k}_{r_2}$ results in a longer period p . At propagation distance which are multiples of this period, the SSBB exhibit the best axial intensity and sidelobe suppression. Moving away from this plane, the axial intensity starts to drop and sidelobes starts to increase. Typically, the propagation-invariant distance (effective DoF) of the SSBB falls within the range of $p/3$ to $p/2$, depending on the acceptable sidelobe threshold (Taneja *et al.* (2024)). In this work, we considered the effective DoF of the SSBB as the propagation distance over which the sidelobe peak intensity remains below a 10% threshold.

Di Domenico *et al.* (2018) implemented the concept of using two ring-shaped apertures differently by employing a spatial light modulator (SLM) in amplitude modulation mode to generate a sidelobe-suppressed Bessel beam, which they termed a “droplet beam”. They demonstrated that when the radial wave vectors $\mathbf{k}_{r_1}$ and $\mathbf{k}_{r_2}$ are close in value (i.e., the ratio $\mathbf{k}_{r_1}/\mathbf{k}_{r_2}$ approaches unity), the resulting beam achieves a long propagation-invariant range but shows reduced sidelobe suppression, similar to a conventional Bessel beam. In contrast, a greater difference between these radial wave vectors enhances sidelobe suppression but shortens the propagation-invariant distance. Thus, the ratio $\mathbf{k}_{r_1}/\mathbf{k}_{r_2}$ is a critical parameter that defines the beam’s characteristics, with effective sidelobe suppression typically observed when this ratio lies between 0.4 and 0.8.

This approach is similar to the ring aperture method; further, using an SLM introduces efficiency losses due to pixelation effects. Hence, an efficient way of generating the SSBB using a phase-only modulation is necessary. Such phase-only modulation techniques offer higher efficiency and improved beam quality, making them better suited for practical implementations.

1.3.4 Structured illumination

Structured illumination microscopy (SIM) was initially proposed to enhance contrast in conventional microscopy, where out-of-focus background often compromises image

clarity. By projecting a periodic pattern onto the sample and taking multiple images with the pattern at different lateral positions, SIM enables computational rejection of the out-of-focus signal. In this technique, the focal plane signal is strongly modulated by the pattern, while the out-of-focus planes experience only weak modulation. As a result, out-of-focus contributions can be effectively removed by image reconstruction (Planchon *et al.* (2011)).

For N total phase shifts, the final reconstructed image is given by:

$$\mathcal{I}_{\text{final}} = \left| \sum_{n=1}^N \mathcal{I}_n \exp \left(j \frac{2\pi n}{N} \right) \right|$$

where $\mathcal{I}_n$ is the fluorescence image acquired with the n -th phase of the pattern.

For example, when $N = 3$:

$$\mathcal{I}_{\text{final}} = \left| \mathcal{I}_1 + \mathcal{I}_2 \exp \left(j \frac{2\pi}{3} \right) + \mathcal{I}_3 \exp \left(j \frac{4\pi}{3} \right) \right|$$

While this method is well-established for widefield imaging with Gaussian beams, it can also be extended to volumetric imaging by using periodic Bessel beam illumination. In this adaptation, a Bessel beam lattice (array of Bessel needles) is projected into the sample, and the pattern is periodically shifted in the lateral direction. This procedure ensures that in-focus fluorescence remains strongly modulated by the pattern, while fluorescence from out-of-plane sidelobes is weakly modulated and thus computationally suppressed. Consequently, the combination of Bessel periodic illumination and structured image reconstruction enables robust removal of out-of-plane sidelobe contributions, yielding high-contrast volumetric images.

One limitation is that the inherent sidelobes of Bessel beams reduce the modulation contrast in the in-focus plane, somewhat diminishing the efficacy of structured illumination. Therefore, combining SSBBs with structured illumination could improve modulation contrast and image quality. Additionally, the use of phase-based methods for generating

structured illumination patterns with Bessel beams remains relatively underexplored, representing an opportunity for further development.

1.3.5 Stimulated emission depletion

Alternatively, Bessel beams have been proposed for use with the stimulated emission depletion (STED) principle to improve resolution beyond the diffraction limit and mitigate sidelobe effects. For instance, Yu *et al.* (2016) demonstrated the use of a higher-order Bessel beam as the depletion beam, combined with a Gaussian excitation beam in epi-illumination mode, achieving improved imaging depth. Theoretical work by Zhang *et al.* (2014) proposed employing zeroth-order Bessel beams for excitation and higher-order Bessel beams for depletion within a light-sheet geometry to enable faster super-resolution imaging via line scanning.

The concept of generating a super-resolution “light needle” offers excellent optical sectioning in two dimensions, while the resolution along the needle’s depth remains limited by optical diffraction. However, using a first-order Bessel beam as the depletion beam leads to significant photobleaching because its sidelobes are even more pronounced than those of the zeroth-order Bessel beam. This, when combined with the high power demands for depletion, will result in considerable photodamage.

Using SSBBs for both excitation and depletion in STED LSM presents an attractive solution. SSBBs can reduce photobleaching while maintaining super-resolution capabilities. Moreover, the generation of a first-order SSBB via a single, phase-only modulation function offers an interesting area for further exploration.

1.4 META-OPTICS FOR BEAM SHAPING

Meta-optics has recently emerged as a highly efficient flat optical solution for beam shaping. Unlike traditional optics, where phase control is achieved through accumulated propagation phase, metasurfaces manipulate phase using alternative mechanisms such as

effective index theory and resonant modes. Notably, metasurfaces eliminate the need for varying surface heights to generate different phase levels. Instead, sub-wavelength scatterers are employed, with their lateral dimensions varied to realise the desired phase modulation.

A diverse range of scatterer designs has been explored, including cylindrical disks, cross-shaped antennas, V-shaped antennas, and nanofins, to achieve full wavefront control. Early demonstrations often used V-shaped gold antennas, where phase manipulation relied on plasmonic resonances. However, metallic structures suffer from significant absorption losses, resulting in low transmission efficiency. Consequently, research has shifted towards dielectric materials for metasurface fabrication.

In the infrared regime, silicon is a widely used dielectric due to its high refractive index and ability to support both electric and magnetic resonant modes, enabling efficient phase control with low optical loss. While silicon can operate at the red end of the visible spectrum, its transmission efficiency decreases due to increased absorption. For visible wavelengths, materials such as titanium dioxide and silicon nitride are preferred. Their lower refractive indices require nanostructures with higher aspect ratios to achieve full $0-2\pi$ phase modulation. Unlike conventional diffractive optics, which use relatively large photolithography features, meta-optics requires sub-wavelength-scale patterning, typically fabricated using electron beam lithography and advanced pattern transfer techniques. The specific phase control mechanism depends on scatterer geometry, dielectric material, and scatterer dimensions.

The primary goal of a beam-shaping meta-optical element is to impart a spatially varying phase to incident light using unit cells (meta-atoms) of varying lateral dimensions distributed across the element. The main mechanisms for phase control in dielectric meta-optics include:

- Huygens metasurfaces

- Truncated waveguide
- Pancharatnam-Berry (PB) phase

Each approach differs in physical principles and experimental implications. For example, some types are polarisation-insensitive and less wavelength-dependent, while others require high aspect ratios, posing significant fabrication challenges.

1.5 RESEARCH GAPS AND RESEARCH OBJECTIVES

The use of Bessel beams in LSM is limited by the presence of sidelobes, which introduce unwanted excitation outside the focal region. Although several techniques have been explored to address this limitation, beam-shaping approaches aimed at sidelobe suppression remain relatively underexplored. The few existing studies have primarily relied on amplitude-based methods to reduce sidelobes; however, such approaches often suffer from low efficiency due to the inherent loss of optical power. In contrast, phase-based techniques for sidelobe suppression offer a more efficient and versatile alternative, yet they have not been thoroughly investigated. Furthermore, implementing these phase designs using metasurfaces presents an exciting opportunity to realise compact and efficient optical elements for light-sheet imaging.

To this end, the research objectives of this work are as follows:

- Design and fabricate meta-optics for generating SSBBs
- Optimise the meta-optics fabrication process to minimise process complexity
- Demonstrate SSBB-based light-sheet imaging using the designed meta-optics
- Implement additional strategies to enhance SSBB light-sheet performance

CHAPTER 2

SIMULATION METHODS

This chapter discusses the simulation methods employed in the work presented in this thesis. Mainly, two categories of simulation approaches are discussed. The first involves beam propagation simulations based on scalar diffraction theory, which are employed to predict the expected beam profiles for a given designed phase function and to refine the phase design according to the required performance. The second category comprises full-wave electromagnetic simulations based on Maxwell's equations, primarily implemented using the finite element method (FEM) in COMSOL Multiphysics. This simulation is primarily used for unit-cell analysis to generate phase and transmission look-up tables for metasurface design, and can also be applied to metasurfaces of relatively small overall dimensions. However, the simulation of large-area metasurfaces is computationally intensive due to the extremely high memory and time requirements.

2.1 BEAM PROPAGATION SIMULATION

During the design of the phase element, propagation simulations are required to predict the expected optical output before fabrication. While a full solution of Maxwell's equations would provide the most accurate description, it is computationally infeasible due to the extremely high memory and time requirements. Scalar diffraction formulations, therefore, offer a computationally efficient and sufficiently accurate alternative. The following section briefly outlines the beam propagation simulation techniques used in this work.

2.1.1 Scalar diffraction formulation

The scalar diffraction formula based on the Huygens-Fresnel theory can be used to evaluate the field distribution at an observation plane, given the field distribution at the

source plane. For normal incidence and spherical wavefronts, the formulation is given by

$$E(u, v) = \frac{z}{\lambda j} \iint E(x, y) \frac{\exp(jkr)}{r^2} dx dy \quad (2.1)$$

Here, (x, y) are the spatial coordinates in the source plane, and (u, v) are the spatial coordinates in the observation plane. The radius r is,

$$r = \sqrt{(z^2 + (u - x)^2 + (v - y)^2)} \quad (2.2)$$

For propagation regions that are not very close to the source plane and for small diffraction angles, Eq. 2.1 can be reduced to a simple and practical expression by approximating the spherical secondary wavelets in the Huygens–Fresnel principle with parabolic wavefronts. This approximation is based on the binomial expansion of the square-root term in Eq. 2.2, retaining only the first two terms. Accordingly, the radius can be approximated as:

$$r \approx z \left[1 + \frac{1}{2} \left(\frac{u - x}{z} \right)^2 + \frac{1}{2} \left(\frac{v - y}{z} \right)^2 \right] \quad (2.3)$$

In Eq. 2.1, r in the exponential term (numerator) is replaced using Eq. 2.3, whereas in the denominator, r is approximated by z (the first term in Eq. 2.3). This choice is justified by the relatively small error introduced in the evaluation. Under these approximations, Eq. 2.1 reduces to,

$$E(u, v) = \frac{e^{jkz}}{j\lambda z} \iint E(x, y) \exp \left[j \frac{k}{2z} \left((u - x)^2 + (v - y)^2 \right) \right] dx dy \quad (2.4)$$

Equation 2.4 can be written in convolution form as

$$E(u, v) = \iint E(x, y) h(u - x, v - y) dx dy \quad (2.5)$$

where the convolution kernel (impulse response) is given by

$$h(x, y) = \frac{e^{jkz}}{j\lambda z} \exp\left(j\frac{k}{2z}(x^2 + y^2)\right) \quad (2.6)$$

Another equivalent form of Eq. 2.4 is

$$E(u, v) = \frac{e^{jkz}}{j\lambda z} e^{j\frac{k}{2z}(u^2 + v^2)} \iint \left[E(x, y) \exp\left(j\frac{k}{2z}(x^2 + y^2)\right) \right] \exp\left(-j\frac{2\pi}{\lambda z}(ux + vy)\right) dx dy \quad (2.7)$$

The above expression represents the two-dimensional Fourier transform of the complex field multiplied by a quadratic phase factor. This form is known as the Fresnel diffraction integral. When this approximation is valid, the observation plane is said to lie in the near-field region. Equation 2.6 can be interpreted as the Fresnel diffraction impulse response, and its Fourier transform gives the corresponding transfer function,

$$H(f_x, f_y) = e^{jkz} \exp\left[-j\pi\lambda z \left(f_x^2 + f_y^2\right)\right] \quad (2.8)$$

In addition to the Fresnel approximation, if the propagation distance is large compared to the finite extent of the source plane, the quadratic phase term inside the integral becomes negligible. In this case, the diffraction pattern can be evaluated directly using a two-dimensional Fourier transform of the complex field. This approximation is known as the Fraunhofer approximation and is given by

$$E(u, v) = \frac{e^{jkz}}{j\lambda z} e^{j\frac{k}{2z}(u^2+v^2)} \iint E(x, y) \exp\left(-j\frac{2\pi}{\lambda z}(ux + vy)\right) dx dy \quad (2.9)$$

The above analytical expressions are generally implemented using numerical methods to evaluate Fresnel diffraction patterns. Accordingly, the source plane is discretised, and the resulting field at the observation plane is also obtained in discrete form. If the spatial frequency content of the source field is band-limited, the frequency content of the propagated field remains unchanged during free-space propagation (Mas *et al.* (1999)). The sampling rate must therefore satisfy the Nyquist criterion to ensure that the output field is accurately represented. However, as the propagation distance increases, the physical extent of the diffracted pattern also increases (Goodman (2005)). Consequently, simultaneously maintaining sufficient sampling and capturing the entire diffracted field becomes challenging.

If Δx denotes the finite extent of the input plane along the x -axis and Δu denotes the extent of the observation plane, they are related to the propagation distance z by (Goodman (2005))

$$\Delta u = \frac{\lambda z}{\Delta x}. \quad (2.10)$$

In numerical propagation, the input plane is discretised into N samples over the extent Δx , resulting in a sampling interval $\delta x = \Delta x/N$. The corresponding sampling interval in the observation plane is given by $\delta u = \lambda z/\Delta x$. Consequently, the total extent of the discretised observation plane becomes

$$\Delta u = N \delta u = \frac{\lambda z N}{\Delta x}. \quad (2.11)$$

Considering this relation, the evaluation zone can vary depending on the beam-propagation method employed, such as the direct method and the angular spectrum method, as discussed in the following section.

2.1.2 Direct method

From Eq. 2.7, it is clear that the Fresnel diffraction integral can be interpreted as the Fourier transform of the product of the input field and a quadratic phase factor. The overall result is also multiplied by another quadratic phase factor, which is analogous to the transfer function discussed in Eq. 2.8. Accordingly, Eq. 2.7 can be evaluated efficiently using a two-dimensional FFT after proper sampling.

$$E(u, v) = \exp \left[i\pi\lambda z \left(f_x^2 + f_y^2 \right) \right] \mathcal{F} \left\{ E(x, y) \exp \left(j \frac{k}{2z} (x^2 + y^2) \right) \right\} \quad (2.12)$$

Here, (f_x, f_y) represents the spatial frequency coordinates. The above expression is derived from Eq. 2.7 by applying the spatial frequency relations and substituting the spatial coordinates (u, v) with the corresponding frequency domain variables.

In FFT-based propagation algorithms, the number of sampling points N remains constant, while the sampling interval δu (and thus extent Δu) in the observation plane changes with propagation distance z . From Eq. 2.11, it is evident that as $z \rightarrow 0$, the numerically sampled output spatial extent (Δu) tends to zero. As a result, very near-field diffraction patterns cannot be accurately evaluated using this method. As the propagation distance increases, the spatial extent of the sampled output field increases linearly with z . The range of propagation distances over which the Fresnel diffraction pattern can be reliably evaluated using the direct method is given by (Mas *et al.* (1999))

$$z \geq \frac{\Delta x^2}{\lambda N}. \quad (2.13)$$

For large propagation distances, although the direct method can provide the full diffraction pattern, the sampling rate becomes insufficient to capture the rapidly varying phase information, leading to strong aliasing effects. In general, intensity distributions vary more slowly than the phase and can therefore be evaluated more reliably. Due to these

limitations, the direct method is primarily suitable for amplitude evaluation in the far-field regime.

2.1.3 Angular spectrum method

Equation 2.5 can be written using the convolution theorem as

$$E(u, v) = \mathcal{F}^{-1} [\mathcal{F}\{E(x, y)\} H(f_x, f_y)] \quad (2.14)$$

where $H(f_x, f_y)$ is the Fresnel transfer function given in Eq. 2.8. Equation 2.14 can also be used to evaluate the diffraction pattern and is referred to as the angular spectrum or transfer function method. In this method, the Fourier transform of the input field is first computed to obtain its angular spectrum. The angular spectrum is then multiplied by the free-space transfer function, and the propagated field is obtained by taking the inverse Fourier transform.

Unlike the direct method, the angular spectrum method does not introduce a coordinate scaling between the source and observation planes. Here, the Fourier transform is used to switch between the spatial and spatial-frequency domains, rather than to perform a scaled Fourier transform associated with free-space propagation. As a result, the inverse Fourier transform reconstructs the propagated field on the same spatial sampling grid as the input plane. Consequently, the spatial extent of the observation plane remains identical to that of the source plane, independent of the propagation distance.

This property provides improved numerical stability for near-field diffraction calculations, since the output sampling window does not shrink as the propagation distance approaches zero, in contrast to the direct method. In practice, it requires the output field to remain within the same sampling grid as the input, which holds approximately for (Mas *et al.* (1999))

$$z \leq \frac{\Delta x^2}{\lambda N}, \quad (2.15)$$

making it suitable for near-field Fresnel pattern evaluation.

The band-limited angular spectrum method further improves accuracy by truncating the angular spectrum with a frequency-domain filter that suppresses evanescent and aliased components, preventing high-frequency artefacts (Matsushima and Shimobaba (2009)).

In summary, the direct method enables far-field diffraction pattern calculation, while the angular spectrum method (including its band-limited variant for enhanced near-field stability) excels in the near field. Both methods overlap at intermediate distances, allowing Fresnel diffraction computation over any distance within the scalar approximation's validity, using the appropriate method for each regime. In this work, these approaches were employed to simulate beam propagation tailored to the specific evaluation distances.

2.1.4 Simulation of Bessel beams

An optical element that generates a Bessel beam produces a conical wavefront, where the cone angle determines the core radius of the beam. To introduce such a conical wavefront, the spatially varying target phase profile is given by

$$\phi_{BB}(x, y) = -\frac{2\pi}{\lambda} \sin \theta \sqrt{x^2 + y^2}, \quad (2.16)$$

where θ is the cone angle of the beam, λ is the design wavelength, and (x, y) are the in-plane coordinates of the phase profile.

The cone angle of the Bessel beam is defined by the relationship between the radial and longitudinal components of the wave vector, $\theta = \tan^{-1}(k_r/k_z)$, where $k_r = k \sin \theta$ and $k_z = k \cos \theta$. The core radius r_0 of a zeroth-order Bessel beam is given by

$$r_0 = \frac{2.405}{k_r}. \quad (2.17)$$

Thus, by selecting an appropriate cone angle, a Bessel beam with a desired core radius can be engineered to meet specific application requirements.

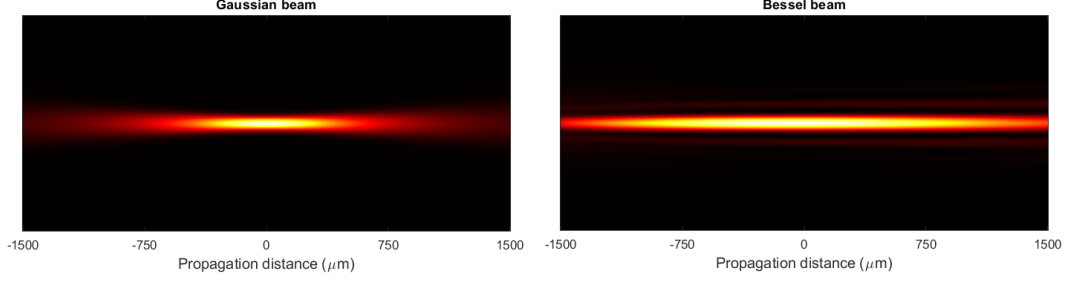


Figure 2.1: Depth of focus comparison of Gaussian and Bessel beams with similar beam size ($10\ \mu\text{m}$), simulated at a wavelength of $633\ \text{nm}$.

Figure 2.1 shows a comparison of the DoF of a Gaussian beam with a $1/e^2$ radius of $10\ \mu\text{m}$ and a Bessel beam with a similar beam size. The Bessel beam is simulated using the angular spectrum method with a cone angle of 1° . It can be clearly seen that the Bessel beam exhibits a significantly larger DoF compared to the Gaussian beam. The DoF of a Bessel beam depends on both the cone angle and the diameter of the generating element. For a fixed cone angle, increasing the aperture diameter extends the non-diffracting propagation length, whereas for a fixed aperture size, increasing the cone angle reduces the DoF.

As discussed earlier, the presence of sidelobes in a Bessel beam hinders its effective use in LSM. Figure 2.2 shows the transverse line intensity profile at the $z = 0$ plane of the Bessel beam simulated in Fig. 2.1. As expected, pronounced sidelobes are observed around the central core. In order to form a light sheet, the Bessel beam must be laterally scanned, and the resulting light-sheet intensity can be simulated by integrating the cross-sectional intensity distribution along the scanning axis. This integration causes the sidelobes to coherently add to the central beam, leading to an increased background intensity and further aggravating the sidelobe problem, as illustrated in Fig. 2.2.

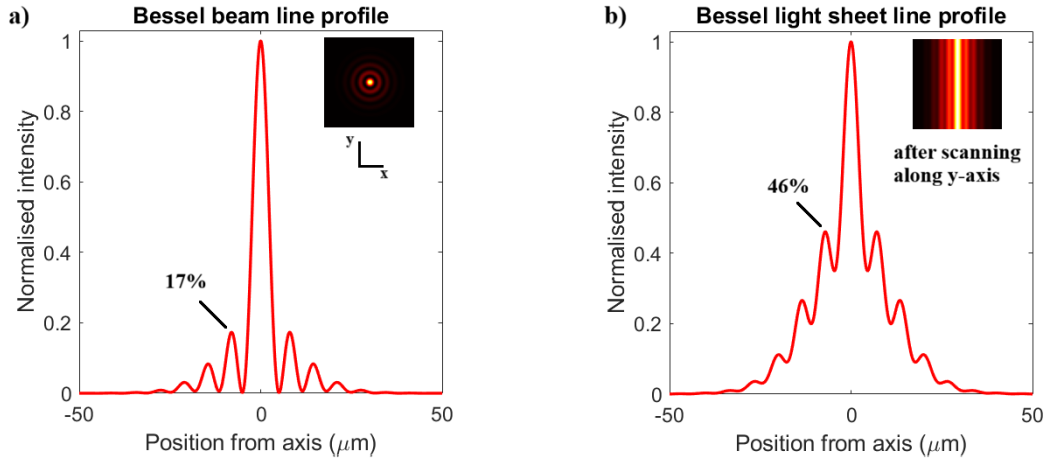


Figure 2.2: Line intensity profile of the simulated (a) Bessel beam and (b) Bessel light-sheet, where the light-sheet profile is obtained by integrating the cross-sectional intensity of the Bessel beam along the y-axis.

2.2 ELECTROMAGNETIC SIMULATION OF METASURFACES

The primary objective of electromagnetic simulations in metasurface design is to construct a lookup table that enables the conversion of a continuous target phase profile into a discretised metasurface layout. Any phase function spans phase values from 0 to 2π , and the corresponding scatterer geometries required to realise these phase shifts must be determined for a given operating wavelength and dielectric material, which is typically achieved through unit-cell simulations. In addition, small metasurfaces can be directly simulated using full-wave EM solvers to evaluate their near-field and short-distance propagation behaviour. The resulting complex field distribution at a chosen output plane can then be propagated using Fourier-based beam propagation techniques to accurately predict the far-field response. However, direct full-wave simulation of large-area metasurfaces is computationally demanding due to the substantial memory and time requirements.

2.2.1 Numerical simulation for meta-atom look-up table

To realise a desired phase function using metasurfaces, the continuous phase profile is discretised into multiple phase levels, each implemented using a corresponding meta-

atom. Since each scatterer occupies a finite spatial period, this assignment effectively samples the phase function in space with a period equal to that of the meta-atom. The period is typically chosen to be sub-wavelength, ensuring that only the zeroth diffraction order propagates while higher diffraction orders remain evanescent.

The meta-atoms required to impart the desired phase shifts are identified by constructing a lookup table, which relates the geometrical parameters of the scatterers to their phase and transmission responses. To generate this table, key geometrical parameters such as the lateral dimensions of the meta-atoms are systematically varied, while the period and height are usually kept fixed. The resulting dataset is then screened to select scatterers that provide full 0 to 2π phase coverage with high and uniform transmittance.

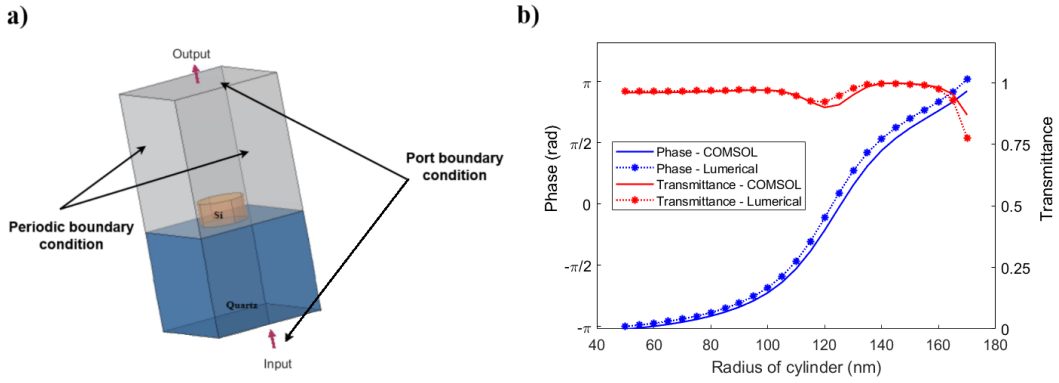


Figure 2.3: (a) COMSOL simulation model of a meta-atom (b) Phase and transmittance plot at $\lambda = 1064 \text{ nm}$, comparing COMSOL and Lumerical FDTD results. The period of the meta-atoms is 450 nm and height is 480 nm .

These simulations are commonly performed using periodic boundary conditions to model an infinite array of identical meta-atoms. While this assumption is well-suited for uniform metasurfaces, it becomes less accurate for phase-gradient metasurfaces, where neighbouring meta-atoms differ in geometry. In such cases, periodic boundary conditions can introduce spurious mutual coupling effects between adjacent scatterers. Despite this limitation, the periodic unit-cell approach remains the most widely adopted method for generating metasurface lookup tables.

Figure 2.3 shows the simulation of a cylindrical meta-atom using FEM implemented in COMSOL Multiphysics. The results are also compared with the FDTD simulation performed using Lumerical FDTD, which shows excellent agreement. In the graph, the range of radii that provide a phase spanning from 0 to 2π is shown. The corresponding transmittance is also plotted, which remains fairly uniform (the dip observed is due to resonance). These data points are then interpolated, and the appropriate meta-atom is selected based on the discrete phase level and its corresponding location in the overall phase function.

2.2.2 Metasurface beam deflector simulation

To demonstrate the simulation methodology, a small beam-deflector metasurface is considered, where beam deflection is achieved by implementing a single 0 to 2π phase variation across the element. As discussed earlier, the required phase modulation can be realised using different physical mechanisms, and each of these approaches is demonstrated through the following simulations.

Huygens metasurfaces

A Huygens metasurface is a class of dielectric metasurfaces that enables efficient wavefront control by employing meta-atoms that simultaneously support electric and magnetic dipole resonances. When the electric dipole (ED) and magnetic dipole (MD) responses of a scatterer spectrally overlap, the backwards-scattered fields are suppressed due to destructive interference, while the forward-scattered fields add constructively. This condition, commonly referred to as the Huygens condition, results in high transmission efficiency together with full phase control.

For a given operating wavelength, the spectral overlap of the ED and MD resonances leads to a rapid phase variation in transmission, with each resonance contributing approximately a $\pi/2$ phase shift. By varying the geometrical parameters of the meta-atom around this overlap condition, the transmitted phase can be continuously tuned over the full 0 to 2π

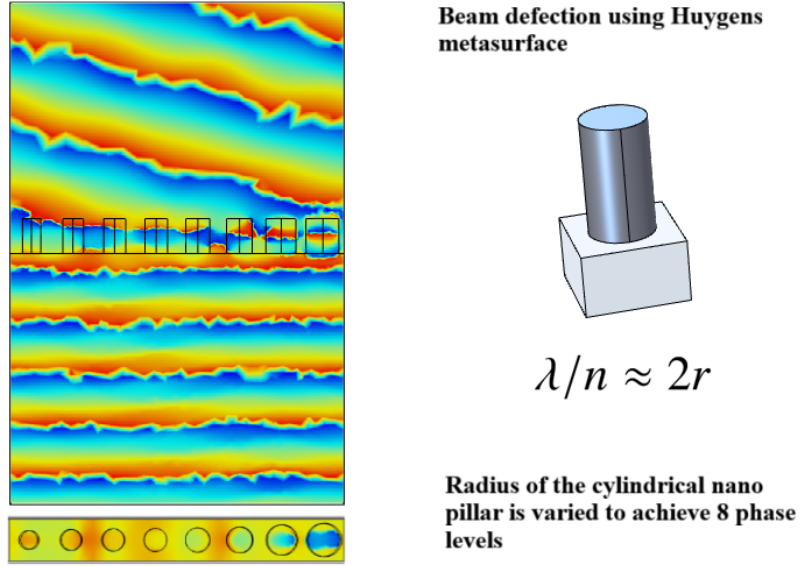


Figure 2.4: COMSOL simulation of a Huygens metasurface beam deflector. The phase control is achieved by varying the radius of the cylindrical nanopillars to span the full 0 to 2π range.

range while maintaining high transmittance. This property makes Huygens metasurfaces particularly suitable for implementing phase-gradient metasurfaces.

For simulating a beam deflector, a cylindrical dielectric nano-pillar is used as the meta-atom, and full-wave FEM simulations are employed to tune its geometrical parameters to achieve the ED–MD resonance overlap at the design wavelength. Figure 2.4 shows a COMSOL simulation of a small beam-deflector metasurface based on the Huygens principle, where the radius of the nano-pillars is varied to realise a linear phase gradient and the resulting beam deflection.

Truncated waveguides

Truncated waveguide metasurfaces operate in a non-resonant regime where the meta-atoms are sub-wavelength scatterers that modulate the effective refractive index rather than relying on optical resonances. The size of these meta-atoms is typically much smaller than the operating wavelength, which often necessitates taller structures to achieve

full 2π phase control (Fig. 2.5). Each meta-atom can be modelled as a short dielectric waveguide embedded in a host medium of lower refractive index. The combination of the high-index dielectric material and the low-index host medium creates an effective index, n_{eff} , which depends on the lateral dimensions and fill factor of the scatterer.

The optical phase ϕ accumulated by the wave passing through a scatterer of height h is given by

$$\phi = \frac{2\pi}{\lambda} n_{eff} h, \quad (2.18)$$

where λ is the wavelength of the host medium.

Since the scatterers act as truncated waveguides, they confine light efficiently, leading to high transmission. However, due to the sub-wavelength lateral dimensions, achieving the full phase range requires larger aspect ratios (height-to-width). In these structures, the phase response varies approximately linearly with the lateral dimension (for example, diameter in cylindrical pillars). Overall, truncated waveguide metasurfaces leverage

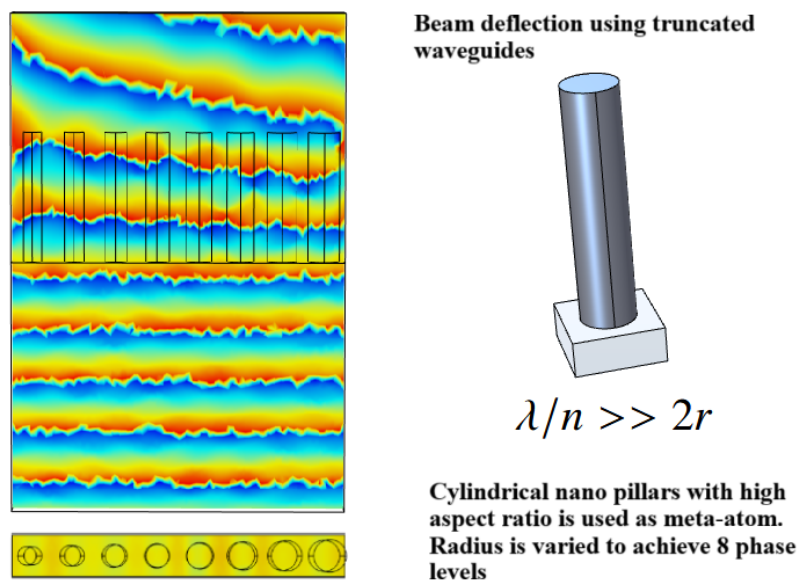


Figure 2.5: COMSOL simulation of a truncated waveguide metasurface beam deflector. The design utilises high-aspect-ratio nanopillars significantly taller than those in the Huygens metasurface to achieve phase control.

effective index modulation from geometric parameters rather than resonant scattering, offering low-loss phase control.

Pancharatnam-Berry phase

Pancharatnam–Berry (PB) phase metasurfaces employ sub-wavelength anisotropic scatterers, whose in-plane orientation is spatially varied to impart a phase shift to transmitted or reflected light. When illuminated with circularly polarised light, these meta-atoms convert part of the incident field into the opposite circular polarisation state, while introducing an additional phase shift known as the geometric or PB phase.

The PB phase depends solely on the in-plane rotation angle θ of the meta-atom and is given by 2θ for the cross-polarised output component. This phase is geometric in origin and is therefore independent of the physical thickness of the structure and the propagation-induced phase. The electromagnetic response of a PB metasurface can be described using Jones calculus as

$$\mathbf{E}_{\text{output}} = \frac{\tilde{t}_L + \tilde{t}_S}{2} \begin{pmatrix} 1 \\ i \end{pmatrix} + \frac{\tilde{t}_L - \tilde{t}_S}{2} e^{i2\theta} \begin{pmatrix} 1 \\ -i \end{pmatrix}, \quad (2.19)$$

where $\tilde{t}_L$ and $\tilde{t}_S$ are the complex transmission coefficients along the long and short axes of the scatterer, respectively.

By varying the rotation angle θ of the nanofins, an arbitrary phase profile covering the full $0 - 2\pi$ range can be imparted to the cross-polarised transmitted light, as shown in Fig. 2.6. While PB phase metasurfaces enable intrinsically broadband phase control, their operation is polarisation-dependent and requires circularly polarised illumination, with high efficiency achieved when the meta-atoms exhibit near half-wave plate behaviour.

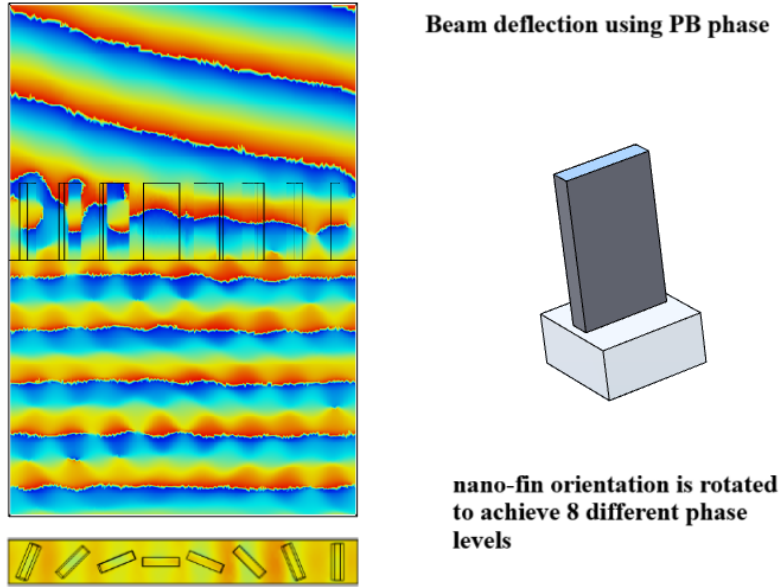


Figure 2.6: COMSOL simulation of a beam deflector using PB phase. A nano-fin is used as the meta-atom, which is rotated to achieve full phase control.

2.3 SUMMARY

In this chapter, Fourier-based beam propagation methods, including the direct method and the angular spectrum method, were discussed for modelling optical field propagation. The numerical simulation of a Bessel beam was presented to illustrate these propagation techniques. The chapter further described the electromagnetic simulation of meta-atoms and the generation of a meta-atom lookup table enabling full $0 - 2\pi$ phase control. Finally, the simulation of a metasurface beam deflector was demonstrated to validate the overall metasurface design methodology.

CHAPTER 3

SIDELobe-SUPPRESSED BESSEL BEAM PHASE DESIGNS

As discussed in Chapter 1, Bessel beams are of great interest in light-sheet microscopy due to their propagation-invariant and self-healing abilities (Durnin *et al.* (1987); McGloin and Dholakia (2005); Laycock and Webster (1992); Arlt *et al.* (2001)). To fully exploit the potential of Bessel beams in light-sheet imaging, it is essential to address the limitations imposed by their sidelobes. A zeroth-order Bessel beam has a main lobe surrounded by sidelobes (concentric rings) of equal energy. Typically, the peak intensities of the first, second and third sidelobes of a zeroth-order Bessel beam are about 16%, 9% and 6%, respectively (Mori (2015); He *et al.* (2017)). In LSM, Bessel beams have been shown to exhibit superior performance in multiphoton excitation modes due to nonlinear excitation effects (Escobet-Montalbán *et al.* (2018); Chen *et al.* (2018); Gasparoli *et al.* (2020)). However, under one-photon excitation, the use of Bessel beams in LSM requires additional techniques such as confocal line detection or structured illumination to exploit their potential fully (Fahrbach and Rohrbach (2012); Planchon *et al.* (2011); Gao *et al.* (2012); Power and Huisken (2017)). Although these approaches can effectively reduce the influence of sidelobes, they require additional optical components, thereby increasing the size and complexity of the system. Hence, it is of interest to generate Bessel-like beams with reduced sidelobes under one-photon excitation.

Surprisingly, limited research has been carried out so far to address this drawback. In a study conducted by Mori (2015), two coaxially travelling Bessel beams were combined using an amplitude element consisting of two annular slits. Although this method effectively achieved sidelobe suppression, it was inefficient since the slits blocked a significant portion of the incident beam. This technique was later used by other

researchers (Di Domenico *et al.* (2018)) for light-sheet microscopy, where an SLM operated in amplitude mode was used to generate a droplet beam with reduced sidelobes. Another study (Fan *et al.* (2022)) employed a genetic algorithm to design a phase profile to produce a sidelobe-suppressed two-dimensional light sheet. While this phase-based approach demonstrated a reduction in sidelobes near the central core, the resulting design featured a perturbed phase profile that is difficult to fabricate. Moreover, the generated beam still exhibited considerable sidelobe intensity outside a limited region.

In this chapter, the design of a phase function for generating a Bessel-like beam with reduced sidelobes (referred to as SSBB) is presented. The relationship between the DoF of the SSBB and the achievable degree of sidelobe suppression, along with the associated trade-offs, is also discussed. The experimental realisation of the SSBB using an SLM is demonstrated as a preliminary validation before extending the approach to a metasurface-based implementation. Furthermore, the design of a phase element capable of producing structured illumination using the SSBB is presented, highlighting its potential to further enhance light-sheet imaging performance. Finally, the application of the STED principle in a light-sheet geometry is explored by employing a zeroth-order SSBB as the excitation beam and a first-order SSBB as the depletion beam. For this purpose, the design of a phase function that generates a first-order SSBB is also discussed.

3.1 SIDELOBE-SUPPRESSED BESSEL BEAMS

An ideal zeroth-order Bessel beam can be described by,

$$E(r, z) = A J_0(k_r r) e^{ik_z z}, \quad (3.1)$$

where J_0 is the Bessel function of zeroth-order, and k_r and k_z are the radial and longitudinal components of wavevector. To reduce the sidelobe intensity, we use the technique mentioned in Mori (2015), the superposition of two Bessel beams with slightly different radial wavevectors. The interference of two Bessel beams has previously been

studied (Chávez-Cerda *et al.* (1998)), and it is shown that the resulting beam closely resembles each of the individual Bessel beams. The superposed beam can be represented by,

$$SSBB(r, z) = A_1 J_0(k_{r_1} r) e^{ik_{z_1} z} + A_2 J_0(k_{r_2} r) e^{ik_{z_2} z} \quad (3.2)$$

To reduce the sidelobes over a given propagation distance, the superposed beam's transverse intensity must be suppressed over the desired region and throughout the propagation distance. That means the Bessel beams' parameters (A_1, A_2, k_{r_1} and k_{r_2}) have to be optimised such that the following integral is minimised:

$$\int_{z_0}^{z_1} \int_{r_0}^{r_1} |SSBB(r, z)|^2 dr dz. \quad (3.3)$$

Here, r_0 to r_1 defines the transverse region, and z_0 to z_1 defines the propagation distance over which the sidelobes are suppressed. Minimising this integral means an overall reduction in the sidelobe energy, which in turn also reduces the peak intensity of the sidelobes. Another characteristic of the superposed Bessel beam is that its central core width oscillates between the core widths of the individual Bessel beams, with a period given by (Chavez-Cerda *et al.* (1998))

$$p = \frac{2\pi}{|k_{z_1} - k_{z_2}|}. \quad (3.4)$$

This occurs because the k_z vectors of the two Bessel beams interfere constructively and destructively along the propagation direction. This interference pattern persists up to the smaller DoF among the two beams. Constructive interference, accompanied by sidelobe suppression, occurs when the k_z vectors coincide and in the propagation planes surrounding this point.

The propagation-invariant distance of the SSBB is defined as the region over which sidelobes remain below a desired limit, and it depends on the period (p), which in

turn depends on the radial wavevector ratio, $m = k_{r1}/k_{r2}$. The propagation invariant distance increases with the period. However, as we can see from equation 3.4, the period increases for values of ' m ' closer to 1, which results in a lower reduction in the sidelobes as the two Bessel beams become more similar. Typically, the propagation invariant distance can exceed $p/3$. However, if a certain reduction in sidelobe suppression compared to the $z = 0$ plane is acceptable, lengths approaching $p/2$ can still be used for imaging applications (Taneja *et al.* (2024)). Previous studies (Di Domenico *et al.* (2018)) have reported that the reduction in sidelobes is better when ' m ' is in the range of 0.4 to 0.8, which we have also observed in our study. Thus, there is a trade-off between the sidelobe suppression and the propagation invariant distance. Accordingly, the propagation invariant distance can be regarded as the effective DoF of the SSBB when making comparisons with Gaussian beams.

3.1.1 Optimising Bessel beam parameters

The optimised Bessel beam parameters (A_1 , A_2 , k_{r1} , and k_{r2}) can be obtained by minimising the integral in equation 3.3. The lower limit of the transverse suppression region (r_0) can be fixed as the desired core radius of the SSBB. The upper limit (r_1) is considered to be ten times the core radius, as the sidelobes outside this region are negligible. The lower limit for the propagation region (z_0) is fixed to 0. The behaviour of the SSBB after a propagation distance ' p ' will be the same because of the oscillatory nature that arises due to the periodically coinciding k_z vectors. The upper limit (z_1) is taken as 1/3 times the period ' p '. It should be noted that the k_z vector is not an independent variable but is directly related k_r vector. If we want a desired core radius for the SSBB, the individual Bessel beam parameters should also satisfy an additional constraint while optimising, given by the following relation (George *et al.* (2022))

$$r_0 = \frac{2.405}{wk_{r1} + (1-w)k_{r2}}, \quad (3.5)$$

where $w = \frac{A_1}{A_1 + A_2}$ and r_0 is the desired core radius of the SSBB. Additionally, we

imposed the constraint $A_1 + A_2 = 1$ as a constraint. The Bessel beam parameters were then optimised using a brute-force technique. For comparison, we used a Bessel beam phase design whose core radius is defined as $r_0 = \frac{2.405}{k_r}$. The FWHM of both the SSBB and the corresponding Bessel beam can be related to this core radius through the relation $FWHM \approx 0.935 r_0$.

In our initial design, the core radius of the SSBB (as well as Bessel beam) is set to $60 \mu m$, which corresponds to a $1/e^2$ radius of about $44 \mu m$. The DoF of a Gaussian beam with the same $1/e^2$ radius is $19.22 mm$. We designed a phase function that generates an SSBB with a peak intensity of the sidelobes less than 10% the main lobe intensity while maximising the propagation-invariant distance.

3.1.2 Influence of radial wavevector ratios on sidelobe suppression

Initially, m is set to a fixed value while optimising Bessel beam parameters to observe its effect on sidelobe suppression and propagation invariant distance. Figure 3.1(a-d) shows the corresponding transverse intensity profile of the SSBB at the $z = 0$ plane. For $m = 0.5$, the first sidelobe peak intensity can be reduced to 2.52% at the $z = 0$ plane. In this case, other sidelobes appear in the outer regions and are more dominant than the first sidelobe. Even smaller values of m (less than 0.5) will further reduce the first sidelobe, but the propagation invariant distance will be reduced. When m is increased to 0.65, the first sidelobe peak intensity increases to 7.77% at the $z = 0$ plane. In this case, the first sidelobe is more dominant than other sidelobes. This happens because the two Bessel beams become more similar as m increases.

Figure 3.1e shows how the sidelobe peak changes with the propagation distance for different values of m . Although the first sidelobe can be reduced to low values at the $z = 0$ plane with a relatively small m (less than 0.55), the propagation invariant distance is less. This is understandable because a lower value of m means comparatively different Bessel beams are being superposed, giving a better destructive interference

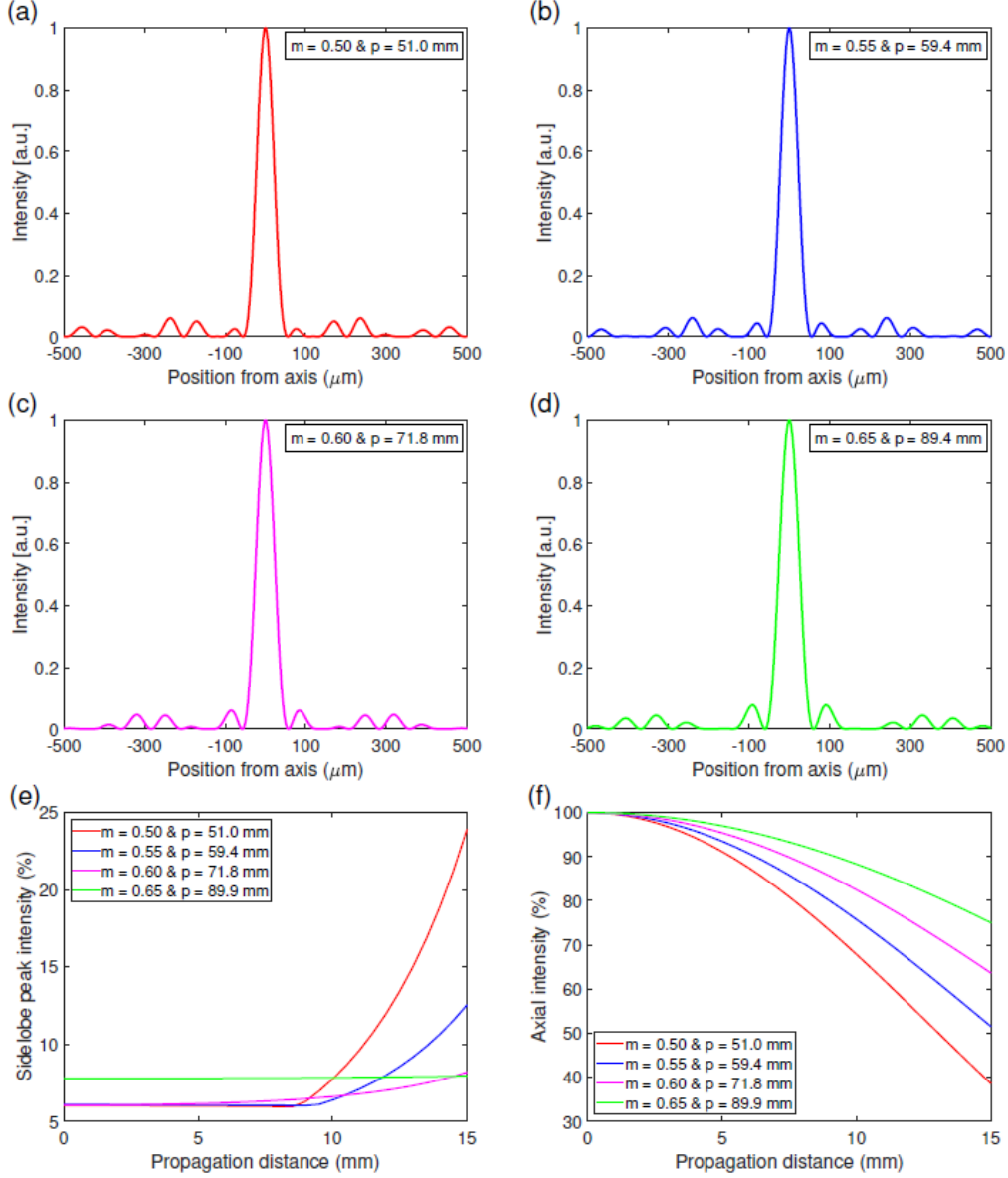


Figure 3.1: Influence of radial wavevector ratio (m) and period (p) on SSBB sidelobe suppression. (a-d) Transverse line intensity profiles at $z = 0$. (e) Sidelobe peak intensity and (f) normalised axial intensity as a function of propagation distance.

of the sidelobes. However, the rapid relatively varying k_z vectors of the Bessel beams reduce this suppression effect to a small region. As m increases, the first sidelobe peak at $z = 0$ increases, but its rate of increase is low with propagation distance. When m exceeds 0.72, the first sidelobe becomes greater than 10% (our desired limit) at $z = 0$ itself. This is because the Bessel beams are no longer much dissimilar, and the achievable

destructive interference of the sidelobes is minimal. Axial intensity variation is also an essential consideration when designing these beams. Figure 3.1f shows how the axial intensity changes with propagation distance for different m and p values. Axial intensity is maximum at the $z = 0$ plane and decreases as the propagation distance increases. The rate at which the axial intensity decreases is lower when m is increased. To experimentally demonstrate the generation of SSBB, we used $m = 0.61$ while optimising the Bessel parameters. This value is chosen, based on simulation, to limit sidelobe peak intensity to below 10% while maximising the propagation invariant distance. The optimised Bessel beam parameters obtained for designing the phase function are $A_1 = 0.495$, $A_2 = 0.505$, $k_{r1} = 3.044 \times 10^4$ and $k_{r2} = 4.99 \times 10^4$.

3.1.3 Effect of design parameters on imaging metrics

The optimisation of the parameters for generating the SSBB primarily aimed to maintain the sidelobe intensity threshold below 10% while achieving an effective DoF approximately twice that of an equivalent Gaussian beam. To achieve this, the radial wavevector ratio was maintained at 0.6 or higher. While a lower ratio can yield superior sidelobe suppression at the $z = 0$ plane, it leads to a rapid increase in sidelobe intensity as the beam propagates. By selecting a slightly higher ratio, we accept a marginally higher sidelobe level at the $z = 0$ plane in exchange for improved axial stability of the suppression. This ensures that the sidelobes do not increase as rapidly during propagation, which effectively extends the usable field of view of the light sheet for imaging.

The optical sectioning capability is connected to two factors. The thickness of the light sheet and the axial resolution of the detection objective ($\frac{2n\lambda}{NA^2}$). When the light-sheet thickness is smaller than the axial resolution of the detection objective, the optical sectioning is determined by the illumination profile. Otherwise, it is limited by the detection objective itself. However, an increased illumination of the out-of-focus region, especially near the depth of field of the detection objective, results in a degradation of

image contrast. In both the SSBB and the Bessel beam, the lateral scanning broadens the axial tails of the illumination profile. Therefore, the detection objective primarily determines the optical sectioning. Consequently, the depth of field of the detection objective can be matched to the width of the main lobe of the scanned beam. However, sidelobes still contribute to out-of-focus illumination, particularly near the depth of field of the detection objective, leading to reduced image contrast. The SSBB improves the overall image contrast by suppressing these sidelobes and thereby reducing out-of-focus illumination.

3.1.4 Designing SSBB phase function

Once the Bessel beam parameters for generating the SSBB are determined, the next step is to design the axicon phase function that generates the individual Bessel beams. The cone angle (θ) of a Bessel beam can be related to its wave vectors by the following relation,

$$\theta = \tan^{-1} \frac{k_r}{k_z}. \quad (3.6)$$

An SSBB is realised as a superposition of two Bessel beams. To implement this superposition, the phase profiles of the two beams are spatially multiplexed according to

$$\phi_{SSBB}(x, y) = T \cdot \phi_{BB_1}(x, y) + (1 - T) \cdot \phi_{BB_2}(x, y) \quad (3.7)$$

where T (function of x and y) is a binary mask that controls the relative weight of the two phase profiles. The ratio of the radial wave vectors, m , influences both the level of sidelobe suppression and the usable depth of focus for the SSBB. These phase functions are then spatially multiplexed by random multiplexing to synthesise the phase function for generating the SSBB. The multiplexing technique (Lathika *et al.* (2020)) combines the axicons after multiplying them with a random matrix consisting of 1s and 0s, which acts as a virtual mask. The transmittance of the mask is determined by the optimised Bessel parameters A_1 and A_2 . These transmittance values may be further tuned to get

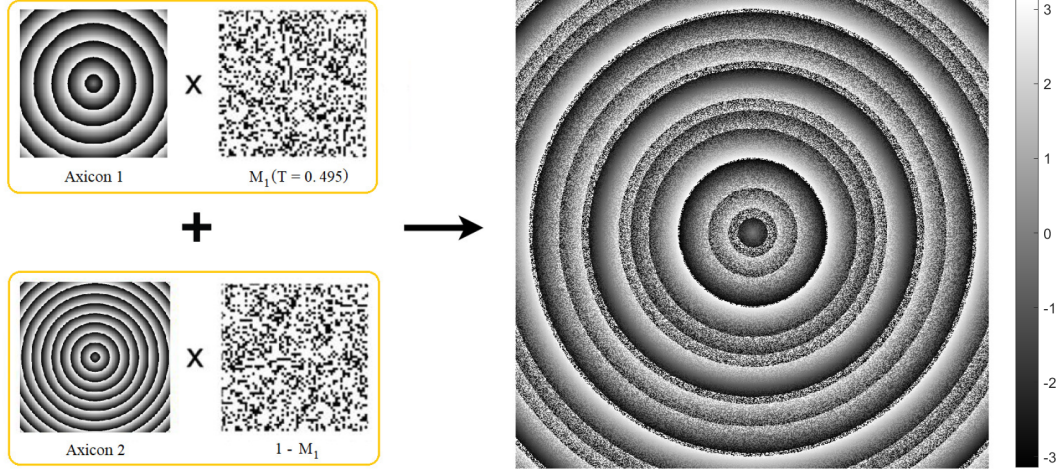


Figure 3.2: Phase function for generating SSBB. The cone angles (θ) of the beams from axicon 1 and axicon 2 are 0.175° and 0.29° , respectively. Transmittance of the virtual mask for axicon 1 is 0.495, and for axicon 2 is 0.505.

the exact amplitudes at the superposition plane. This process is shown in Fig. 3.2.

3.2 EXPERIMENTAL GENERATION OF SSBB USING SLM

The phase function (shown in Fig. 3.2) for generating SSBB is initially realised using an SLM. An SLM allows for the full wavefront control (0 to 2π) of the incident beam. The designed phase function can be directly uploaded onto the SLM, wherein the corresponding orientation of the liquid crystal molecules at each pixel induces the required local phase shift on the incident beam. This enables experimental validation of the designed phase function prior to meta-optics fabrication. However, the SLM is a costly, general-purpose device and cannot be integrated into a compact optical system. In addition, due to the inherent pixelation of the SLM, unwanted zeroth-order diffraction light is produced. To spatially separate the SSBB from this zeroth-order component, a carrier frequency is incorporated into the phase function to steer the desired beam away from the zeroth-order.

3.2.1 Experimental setup

The experimental setup used to generate the SSBB is shown in Fig. 3.3. A collimated beam from a He-Ne laser source operating at a wavelength of 633 nm is expanded using a lens combination to illuminate the (phase-only) SLM exhibiting the designed phase pattern. A polariser is used after the lenses to select the horizontal polarisation required by the SLM. The SSBB generated at the near field is captured on a charge-coupled device sensor using a beam splitter and an iris.

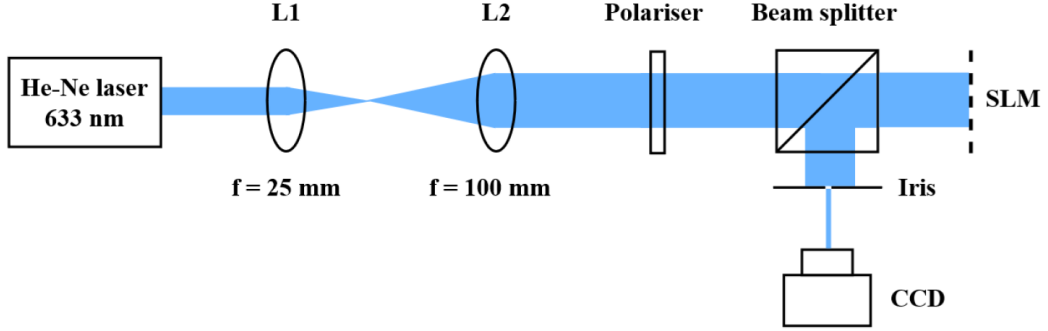


Figure 3.3: Experimental setup for generating SSBB using SLM. Holoeye PLUTO SLM with a spatial resolution of 1920×1080 pixels is used for pattern generation. A BC106-VIS CCD camera with $6.45\text{ }\mu\text{m} \times 6.45\text{ }\mu\text{m}$ pixel size is used to capture the SSBB.

As discussed in the previous section, the SSBB has a periodic nature along the direction of propagation, and the period of oscillation as per the design is $\approx 80\text{ mm}$. This means the SSBB will behave in a similar way at propagation distances that are multiples of the period as it does at the $z = 0$ plane. However, there is a limit to this behaviour determined by the depth of focus of the individual Bessel beams used for the superposition. The sidelobes of the SSBB are expected to be minimal at propagation distances which are multiples of this period. This is because the k_z vectors of the Bessel beams coincide at these planes, allowing for better destructive interference. The sidelobes of the SSBB will also stay low at regions closer to these propagation distances. In our experiment, we chose propagation regions closer to 160 mm (twice the period) as this made the setting up of the optics easier.

3.2.2 Characterisation of the generated SSBB

The experimental results of the SSBB and a Bessel beam with the same core radius are shown in Fig. 3.4. The maximum sidelobe suppression and axial intensity for the

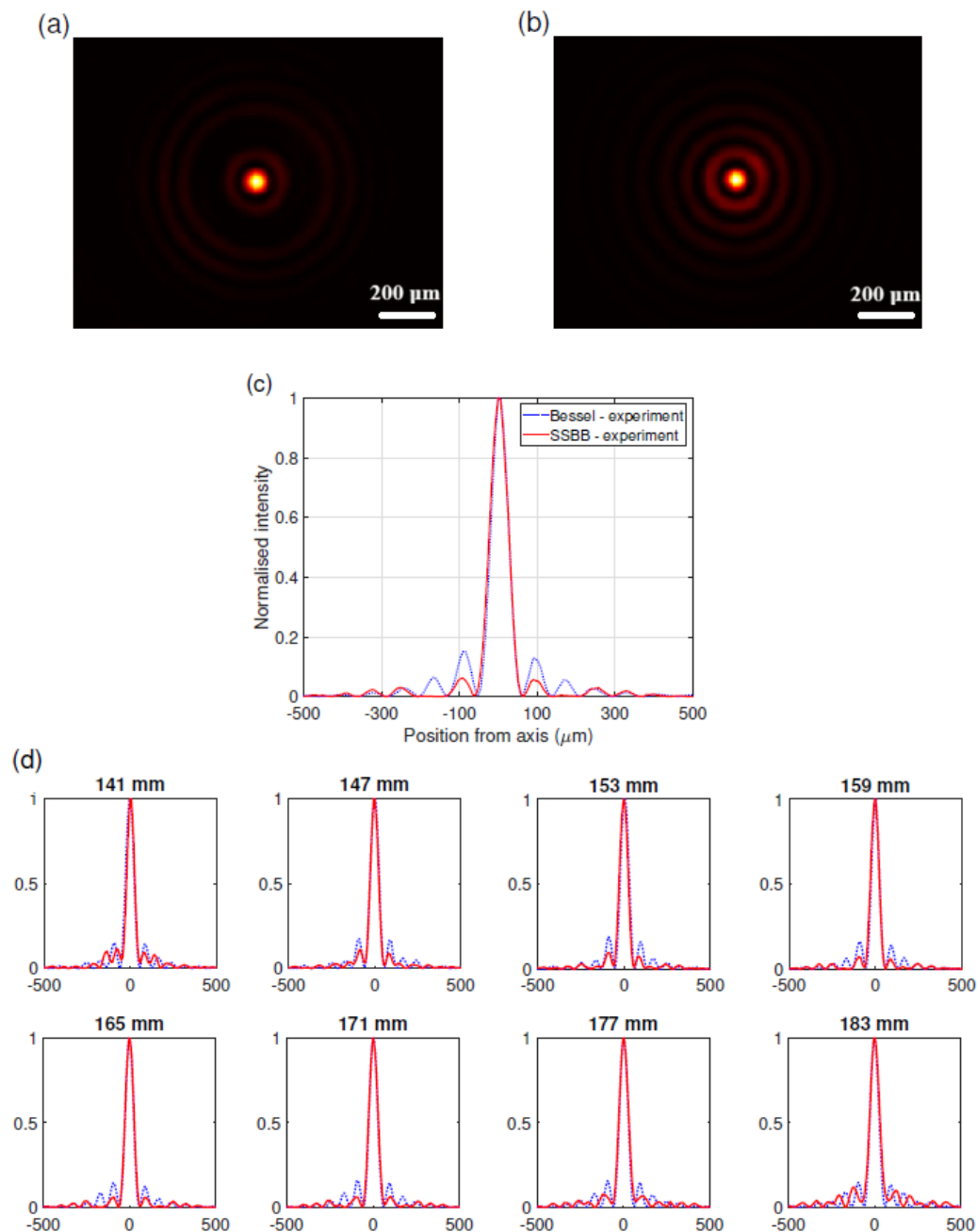


Figure 3.4: Experimental results of the SSBB and Bessel beams generation using SLM. (a-b) Cross-sectional intensity of the SSBB and Bessel beam, respectively, at $z = 163$ mm. (c) Corresponding 1D intensity profiles along the beam centres. (d) Intensity profiles at different propagation planes (141 mm to 183 mm).

experimentally generated SSBB are observed at a propagation distance of 163 *mm* from the SLM plane. The sidelobe peak intensity of the SSBB is only about 5.92% that of the main lobe peak intensity, unlike 13.36% in the case of the experimentally generated Bessel beam with a similar core radius. The $1/e^2$ radius of the SSBB at this propagation plane is measured to be 44 μm . This measured radius is used to define an equivalent Gaussian beam having the same $1/e^2$ beam waist, and all subsequent comparisons with a Gaussian beam are based on this equivalence criterion. The slight shift in the propagation distance at which the maximum sidelobe suppression and axial intensity are observed should be due to the variation in the experimentally achieved Bessel beam parameters compared to the optimised parameters. Moreover, the Bessel beam parameters (A_1 and A_2) will vary with propagation distance. But despite these issues, the generated SSBB is observed to have reduced sidelobes compared to a standard Bessel beam of the same core radius. To get a better comparison against the experimental results, the designed phase function is simulated using the Fourier beam propagation. In fig. 3.5, the sidelobe peak intensity, the axial intensity and the effective beam radius of the experimentally generated beams are compared against the simulation results for different propagation distances around 163 *mm*.

The sidelobe peak intensity of the SSBB is within 10% that of the main lobe peak intensity for a propagation distance of 39 *mm* in the region between 143 *mm* to 182 *mm* (fig. 3.5a). Fig. 3.5b shows that the central core width of the SSBB is almost invariant (varying only 20%) in this propagation region. Beyond this distance, the sidelobe peak intensity increases further, and as the propagation distance becomes closer to the next period, it will again decrease. The effective beam radius variation of a Gaussian beam with the same $1/e^2$ radius is also plotted against the SSBB, and the SSBB exhibits superior propagation invariant nature. The DoF of the Gaussian beam is only 19.22 *mm*. The axial intensity of the SSBB also decreases at a lower rate compared to an equivalent Gaussian beam (fig. 3.5c). The deviations between the experiment and simulation results can be attributed to the zeroth-order not being entirely removed from the near-field in the

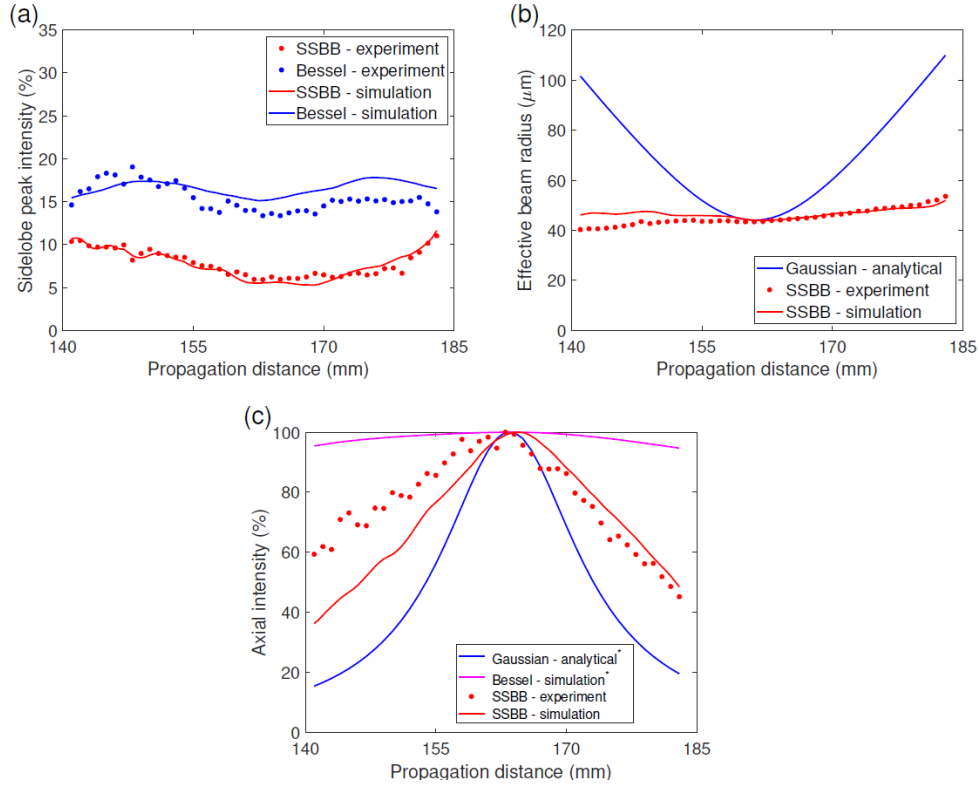


Figure 3.5: Characterisation of experimental and simulated SSBB and Bessel beams. (a) Sidelobe peak intensity (centred around 163 mm). (b) Measured $1/e^2$ radius and (c) normalised axial intensity compared against a Gaussian beam of equivalent radius. (* propagation distance in (c) is corrected to show the fall in axial intensity)

experiment.

3.3 SIMULATION STUDY FOR LIGHT-SHEET IMAGING APPLICATIONS

We have conducted a simulation study to investigate the potential benefits of using SSBB for light-sheet imaging by comparing it with a Bessel beam of equivalent core radius. A wavelength of 488 nm and a core radius of 2.1 μm are selected for the study due to their practicality in light-sheet imaging. light-sheet profiles for an SSBB and a Bessel beam are modelled using Fourier beam propagation (fig. 3.6a). The resolution and contrast information of the two beams for light-sheet imaging is then determined from the modulation transfer function (MTF). The MTF shown in Fig. 3.6b is obtained by computing the Fourier transform of the light-sheet intensity profile along the x-axis at

each propagation distance z .

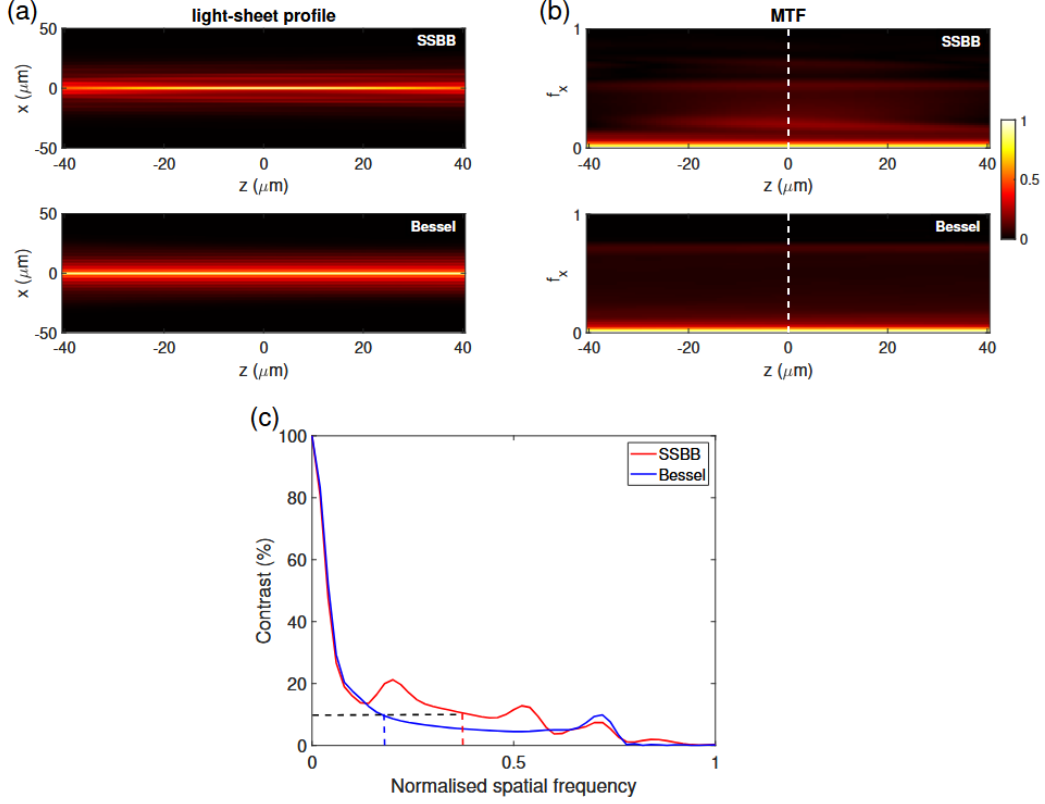


Figure 3.6: Simulation of an SSBB and a Bessel beam for light-sheet imaging. (a) x-z light-sheet cross sections. (b) Axial MTFs of the beams; spatial frequency (f_x) is normalised to $\frac{50}{L}$ ($L = 100 \mu\text{m}$). (c) MTF at $z = 0$ (white dashed line in b).

From the MTF plots (fig. 3.6b and 3.6c), it can be seen that the SSBB is capable of resolving higher frequencies than a standard Bessel beam while maintaining the same contrast. Our simulations of light-sheets predict a maximum axial resolution of $5.4 \mu\text{m}$ and $11.11 \mu\text{m}$ for the SSBB and Bessel beams, respectively, at 10% contrast. The improved imaging performance of the SSBB is further evident from Fig. 3.6c, where it provides a contrast enhancement ranging from 52% to 147% for feature sizes between $5 \mu\text{m}$ and $12.5 \mu\text{m}$.

The experimental generation of the SSBB confirms that the sidelobes can be effectively suppressed, although with a slight compromise in the DoF. Simulations comparing the

SSBB with the conventional Bessel beam further demonstrate an improvement in axial contrast, indicating reduced out-of-focus contributions. However, the SSBB still exhibits a broadened intensity tail, although significantly lower than that of the Bessel beam. Therefore, additional phase engineering strategies need to be explored to further enhance the confinement and overall performance of SSBB-based light sheets.

3.3.1 Trade-offs between sidelobe suppression and depth of focus

While the sidelobes in SSBB are suppressed compared to a Bessel beam, it does not exhibit the same DoF as the Bessel beam. As discussed earlier, SSBBs have a periodic nature, wherein the sidelobe suppression occurs at regular intervals along the propagation direction. This behavior arises from the constructive and destructive interference of the longitudinal wave vector components. In contrast, a Bessel beam maintains its transverse intensity profile over a much longer propagation distance. This behavior is illustrated in Fig. 3.7a.

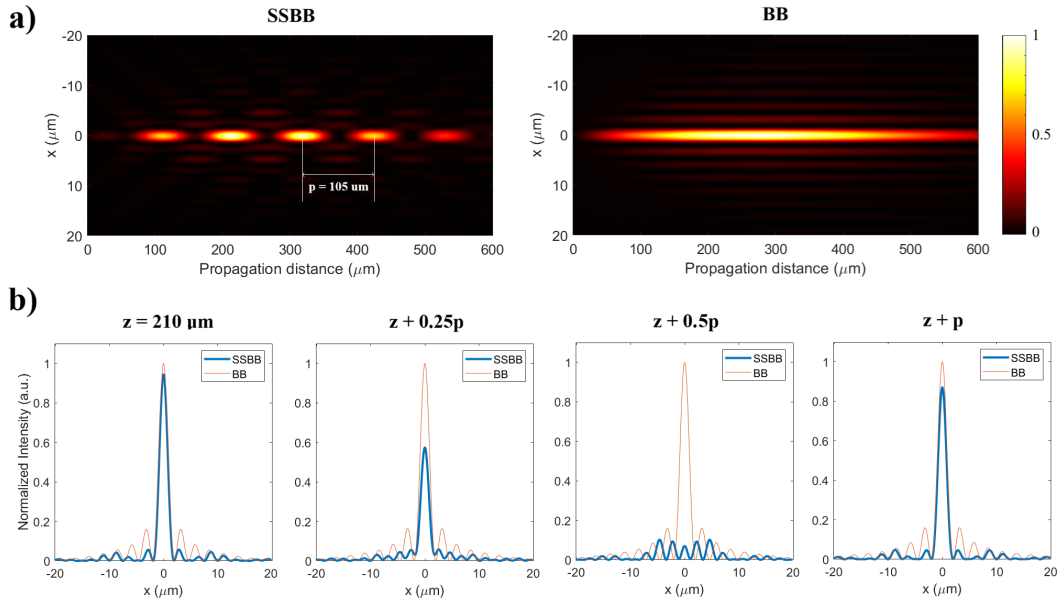


Figure 3.7: (a) Comparison of SSBB and Bessel beams intensity profiles (same core radius) along the propagation direction. (b) Line intensity profiles at different axial (z) positions.

The core radius of the beams in Fig. 3.7a is $2.1 \mu\text{m}$, and the period of the SSBB is

105 μm . SSBBs exhibit optimal sidelobe suppression and maximum axial intensity at integer multiples of this period. In this case, the peak axial intensity is observed at 210 μm , which is about 94% of that of a Bessel beam at the same plane. When the propagation distance is shifted by approximately $p/4$, the axial intensity decreases to about 57%, while the sidelobe peak is around 10%.

Considering these values as acceptable thresholds for axial intensity and sidelobe level, the effective depth of focus (DoF) of the SSBB can be approximated as $p/2$ (two times $p/4$). A similar effective DoF has been reported in Wang *et al.* (2024), where the sample was imaged in two steps. The sample was first imaged over half the period. A π phase shift was then applied to shift the field by $p/2$, allowing the remaining region to be imaged. In this way, the full DoF, comparable to that of a Bessel beam, was effectively utilised.

3.4 ENHANCING SSBB LIGHT SHEETS

In this section, we discuss some approaches aimed at further enhancing the performance of the SSBB for use in light-sheet microscopy. The objective is to achieve improved axial confinement and reduced background signal while maintaining a sufficient DoF. Various illumination strategies are explored to overcome the residual intensity tails observed in the existing SSBB implementation and to realise light sheets with superior imaging contrast and resolution.

3.4.1 Structured illumination of SSBB

Structured illumination involves projecting a periodic light pattern onto the imaging plane to modulate the spatial frequency content of the sample. Multiple images are then acquired with phase-shifted illumination patterns, and computational reconstruction is performed to reject out-of-focus contributions. Bessel beams, when viewed in an orthogonal geometry, form elongated focal regions like light needles. By arranging a one-dimensional array of such Bessel beam light needles, the principles of structured

illumination can be applied. Structured illumination using Bessel beam arrays mitigates sidelobe artefacts by illuminating the sample with a periodic Bessel beam pattern that is phase-shifted in discrete steps; the resulting raw images are then jointly reconstructed into a single high-contrast optical section (Planchon *et al.* (2011)). While this approach can reduce out-of-focus signals, the sidelobes of the Bessel beams may interfere with the focal-plane modulation and thereby degrade the image quality.

Structured illumination with the SSBB can further improve the focal plane modulation due to its reduced sidelobes. To implement this concept, the SSBB generation is combined with a beam-splitting approach, wherein a single phase element simultaneously generates the SSBB and acts as a diffraction grating. This enables a compact and efficient optical configuration. In structured illumination using SSBBs, the beam produced from the designed phase function is divided into multiple copies of equal intensity. This can be accomplished using a diffraction grating whose Fourier coefficients are engineered to yield equal amplitudes across the desired diffraction orders. The phase function of such a grating, which distributes the incident energy into N finite modes can be expressed as follows (Romero and Dickey (2007)):

$$\phi_{\text{split}}(x) = \tan^{-1} \left(\frac{\sum_{m=-\frac{N-1}{2}}^{\frac{N-1}{2}} c_m \sin(f_p x + \delta_m)}{\sum_{m=-\frac{N-1}{2}}^{\frac{N-1}{2}} c_m \cos(f_p x + \delta_m)} \right), \quad (3.8)$$

Here, c_m and δ_m are the relative amplitude and the phase of the Fourier coefficient of mode m . These parameters can be optimised to obtain equal energy in the different copies of the beam. The parameter f_p is a spatial carrier frequency which determines the angle between the diffraction orders. The optimisation process is discussed in detail in Romero and Dickey (2007). The optimised values of c_m and δ_m for generating three, five, seven or nine equal-intensity copies are also provided in that work. The final phase

profile implemented using meta-optics is simply

$$\phi_{\text{final}}(x, y) = \phi_{\text{SSBB}}(x, y) + \phi_{\text{split}}(x). \quad (3.9)$$

Initially, we simulated the beam splitting phase design (Fig. 3.8a). For the simulation, we used $\lambda = 1064 \text{ nm}$ and design ϕ_{final} to produce five SSBB copies with a $200 \mu\text{m}$ pitch. The optimised values for $c_m = [0.905, 0.459, 1.08, 0.459, 0.905]$, and $\delta_m = [\pi, \pi/2, 0, -\pi/2, \pi]$. The opening angle of the axicons are 0.53° and 0.94° and the SSBB core radius considered is $60 \mu\text{m}$.

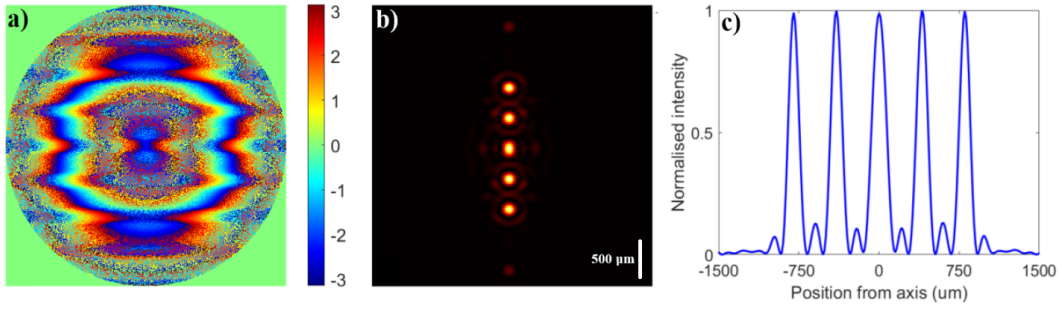


Figure 3.8: Simulation of structured illumination with five SSBB copies generated by $\Phi_{\text{final}}(x, y)$. (a) Phase design, (b) transverse intensity, (c) axial line profile at the vertical axis.

Based on the simulation results (Fig. 3.8b,c), compared to the structured illumination using conventional Bessel beams discussed in Planchon *et al.* (2011), the SSBB-based structured illumination exhibits significantly reduced in-plane artefacts. This improvement can enhance the modulation contrast at the focal plane, thereby improving optical sectioning.

3.4.2 STED-based SSBB light sheets

STED is a super-resolution microscopy technique in which the sample is first excited using a diffraction-limited excitation spot. Subsequently, a second beam, typically of a longer (red-shifted) wavelength and having a ring-shaped intensity profile, is used to deplete fluorescence in the outer region of the excitation spot via stimulated emission. The molecules in this depletion region are forced to return to the ground state without

emitting fluorescence photons, while only the molecules at the centre (where the depletion beam intensity is zero) emit light through spontaneous emission. As a result, the effective fluorescence spot becomes smaller than the diffraction limit, achieving super-resolution imaging.

Typically, a Gaussian beam is used for excitation, while a Laguerre–Gaussian beam is employed for depletion. The sample is scanned in a manner similar to confocal microscopy, where the super-resolved spot is raster-scanned laterally across the focal plane to form an image. Hence, the resolution improvement in conventional STED microscopy is primarily in the lateral direction. Alternatively, in orthogonal beam geometry, a zeroth-order Bessel beam can be used as the excitation beam, and a first-order Bessel beam can be used as the depletion beam. This configuration can produce a super-resolved light needle, achieving axial super-resolution, although the lateral dimension remains diffraction-limited. However, a major limitation of this scheme is the presence of pronounced sidelobes in the first-order Bessel beam and the associated high depletion power requirement. In this context, the use of a zeroth-order SSBB for excitation (at a wavelength of 520 nm) and a first-order SSBB for depletion (at a wavelength of 642 nm)

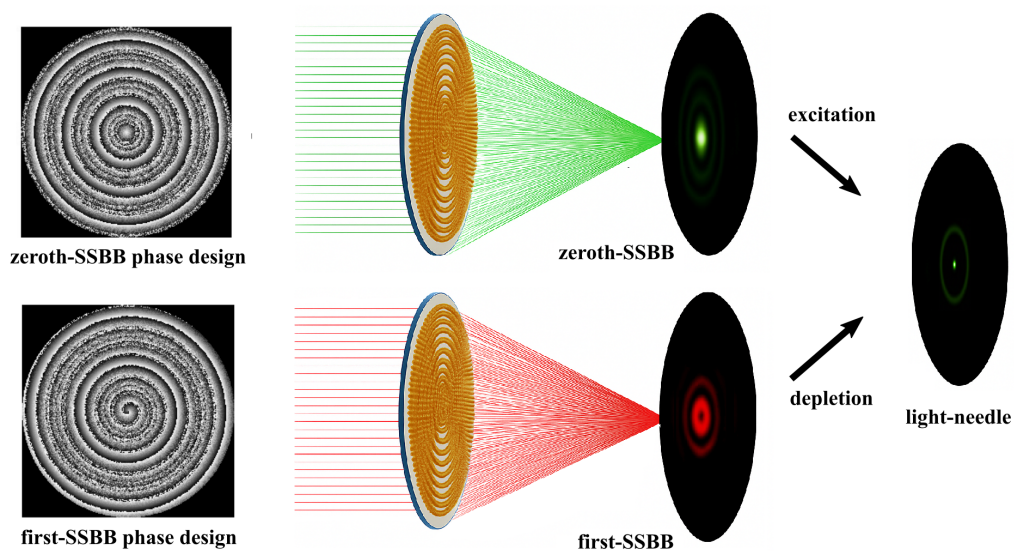


Figure 3.9: Schematic diagram showing the generation of zeroth- and first-order SSBBs using metasurfaces.

is worth exploring. A schematic diagram of this configuration is shown in Fig. 3.9.

To design the phase function for generating the first-order SSBB, a spiral phase term, $l\psi$ can be incorporated into the zeroth-order SSBB phase function. Where $\psi = \tan^{-1}y/x$. When $l = 1$, the resulting beam corresponds to the first-order SSBB. The phase function for generating first-order SSBB can be expressed as,

$$\phi_{first} = \phi_{zero} + l\psi \quad (3.10)$$

The above phase functions, along with the Bessel beam phase function, were used along with Fourier beam propagation techniques to study the propagation characteristics of the beams.

The propagation invariant nature and sidelobe suppression of the excitation beam (zeroth-

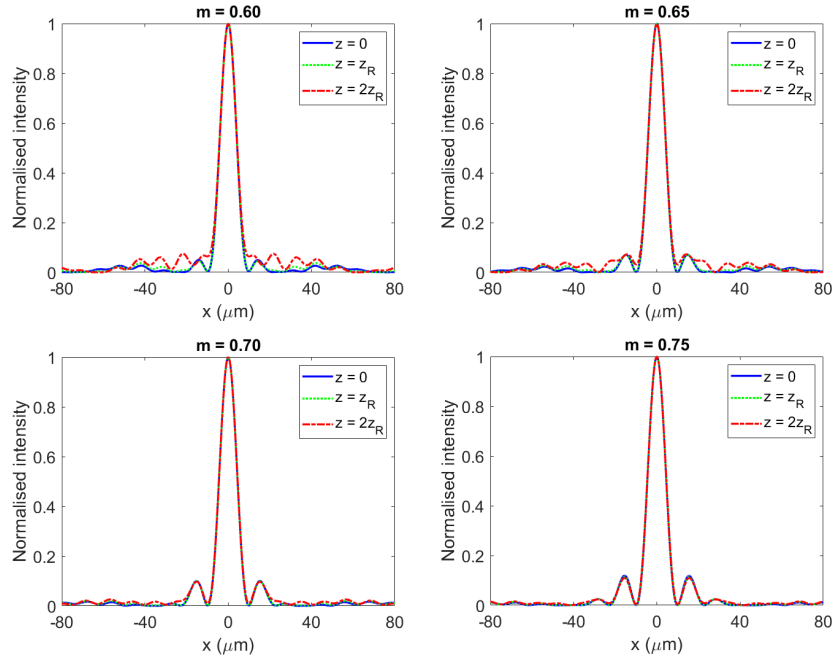


Figure 3.10: Zeroth-order SSBB (excitation beam) profile at $z = 0$, z_R and $2z_R$ for different radial wavevector ratios. The Rayleigh distance ($z_R = 304 \mu m$) is calculated based on the $1/e^2$ radius measured from the simulated plots, corresponding to an equivalent Gaussian beam. Simulations are performed at a wavelength of $520 nm$.

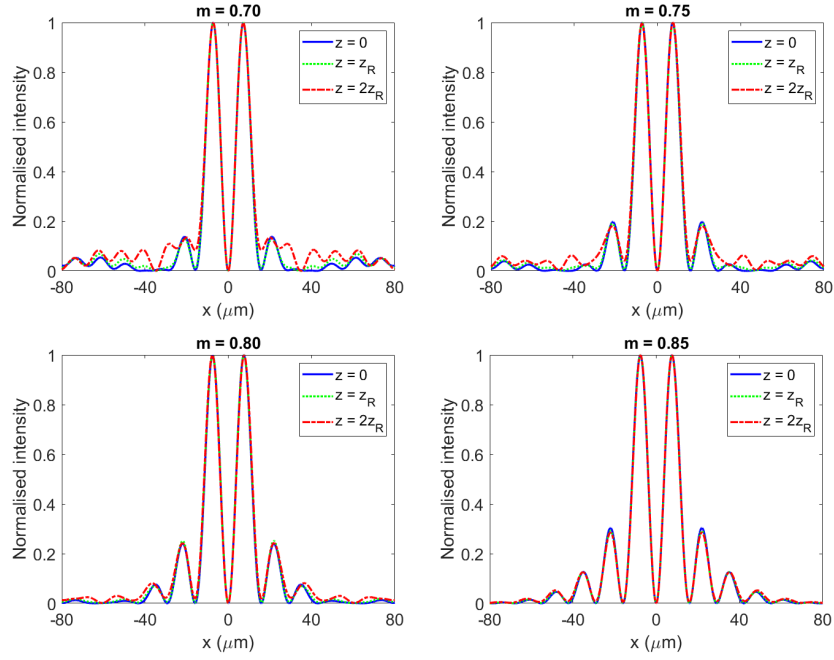


Figure 3.11: First-order SSBB (depletion beam in SSBB-STED) profile at $z = 0$, z_R and $2z_R$ for different radial wavevector ratios. Simulation is done at 642 nm .

order SSBB) are studied for different radial wavevector ratios (m). The line intensity profile for the different cases is shown in Fig. 3.10. It can be seen that $m = 0.70$ (for the excitation beam) gives the best sidelobe suppression (below 10%) while maintaining the propagation invariant nature (same FWHM) over twice the Rayleigh range. Hence, $m = 0.70$ is considered for the phase design of the excitation beam.

As was done for the excitation beam, different radial wavevector ratios of the first-order SSBB are also simulated (Fig. 3.11). The propagation invariant nature of the first-order SSBB is found to be less than that of the zeroth-order SSBB. Hence, larger m values are required to maintain propagation invariance over twice the Rayleigh range. The first-order SSBB also exhibits higher sidelobes than the zeroth-order SSBB for equivalent suppression settings, but its sidelobe levels are still substantially lower than those of a first-order Bessel beam. This will be beneficial when used as a depletion beam when applying STED principle. Hence, $m = 0.80$ is considered for the phase design of the depletion beam.

3.4.3 Selective sidelobe suppression

Bessel beams are formed by the interference of plane wavefronts travelling along the surface of a cone. Typically, this can be achieved using a ring aperture at the front focal plane of a lens or via a refractive axicon, which engineers the wavefronts to create a propagation-invariant central core through constructive interference. When scanned along one axis in light-sheet microscopy, the sidelobes inherent to Bessel beams cause broadening of the light-sheet tails along that axis. Selective suppression of the sidelobes along the scanning axis can reduce this broadening. This can be achieved by modifying the conventional ring aperture, using only two opposite sections while blocking the regions along the y-axis (scanning axis). This selective aperture blocks sidelobes along the scanning axis, improving the light-sheet contrast without significantly compromising the depth of field, since the remaining radial sections still contribute to the central core's constructive interference.

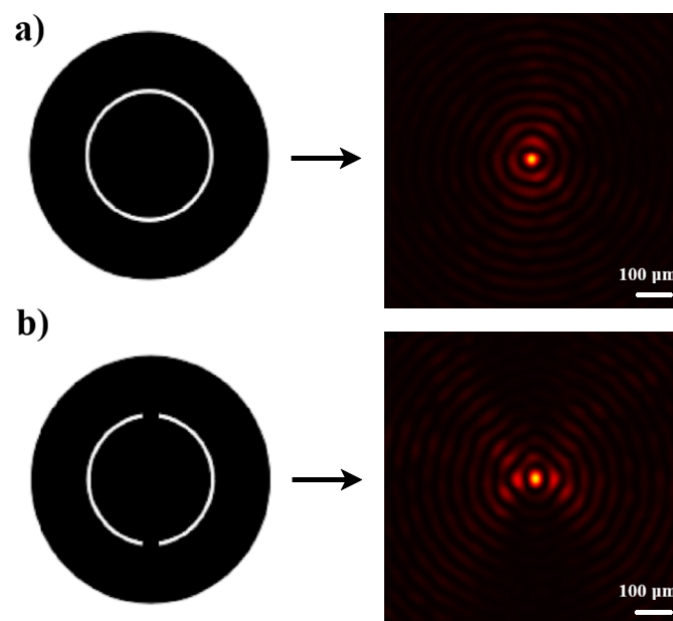


Figure 3.12: Concept of selective sidelobe suppression. (a) Ring aperture and the resulting Bessel beam. (b) Aperture with two sections and the selective suppression (along the vertical axis)

Figure 3.12 illustrates the concept of selective suppression of sidelobes in a Bessel beam.

In one case, a ring aperture generates a Bessel beam, while in the other, two opposite sections of the ring generate a Bessel beam with reduced sidelobes along the vertical axis. The beams shown were experimentally generated using apertures printed on transparent sheets with an inkjet printer. This approach does not necessarily require a sectioned aperture; instead, a commercially available refractive axicon or a meta-axicon can be used. By employing a lens to project the beam to the far field, selectively blocking the ring region along the scanning axis, and then using another lens to form the selectively suppressed beam, higher efficiency can be achieved. However, this method may reduce the total beam energy and alter the beam symmetry.

3.5 SUMMARY

In summary, this chapter discusses the design of a phase function for generating SSBB. The designed phase function is experimentally implemented using an SLM, successfully validating the concept. The generated SSBB exhibits significantly reduced sidelobes compared to a conventional Bessel beam. Furthermore, several strategies for enhancing SSBB-based light-sheet illumination are explored. These include the phase design for structured illumination using SSBBs, the incorporation of the STED principle by employing a zeroth-order SSBB as the excitation beam and a first-order SSBB as the depletion beam, and a concept for selective sidelobe suppression in Bessel beams. The next chapter discusses the fabrication details for realising these phase designs using meta-optical elements.

CHAPTER 4

FABRICATION OF OPTICAL METASURFACES

The previous chapter mainly discussed the design of a phase element to generate an SSBB, a sidelobe-suppressed Bessel beam. Although the phase for generating a conventional BB can be realised using either refractive or diffractive optics, implementing the phase required for an SSBB with such conventional optics becomes practically challenging. In principle, one could employ a refractive axicon-based setup where the generated BB is split into multiple copies with different magnifications and then recombined to form an SSBB. However, such a configuration results in a bulky and complex optical setup with stringent alignment requirements. Alternatively, diffractive optics can be used, where multi-level phase patterns could be fabricated through multiple lithography steps to approximate the required phase at a coarse sampling. But this approach inevitably increases fabrication complexity and alignment sensitivity, while not fully addressing issues such as reduced beam efficiency. These challenges make such conventional approaches less suitable for compact and scalable implementations. Therefore, metasurfaces emerge as an ideal alternative, offering a compact, ultra-thin, single-layer solution with sub-wavelength phase control required to realise arbitrary phase functions like in the case of SSBB.

Over the past decade, metasurfaces have emerged as an efficient and relatively straightforward approach for realising arbitrary phase elements (Yu and Capasso (2014)). Several studies have demonstrated the fabrication of meta-lenses exhibiting high efficiency (Wang *et al.* (2021)), achromatic performance (Wang *et al.* (2018)), and polarisation insensitivity (Khorasaninejad *et al.* (2016)), among other functionalities. Owing to the nanometer-scale features of metasurfaces, electron-beam (e-beam) lithography has become the most commonly used technique for their fabrication.

Although well established, e-beam lithography inherently suffers from low throughput. For large-scale or high-volume fabrication of meta-optical components, deep UV and nanoimprint lithography have been explored as more practical alternatives (Yu and Capasso (2014); Oh *et al.* (2021)). Table 4.1 summarises the commonly used lithography techniques for fabricating metasurfaces and their key characteristics.

Table 4.1: Comparison of common lithography techniques used in optical metasurface fabrication

Method	Advantages	Disadvantages	Ref.
Photolithography	• High throughput for mass production • Deep UV can give high-resolution	• Not flexible for rapid prototyping • Requires mask typically written by e-beam lithography	Zhang <i>et al.</i> (2022); Li <i>et al.</i> (2020); Park <i>et al.</i> (2019)
E-beam lithography	• Very high resolution (sub-10 nm) and precise control • Suitable for rapid prototyping and research development	• Low throughput (limits the size of the element) • Costly equipment and requires high maintenance	Su <i>et al.</i> (2018); Tan <i>et al.</i> (2023)
Nanoimprint lithography	• Very high feature resolution (sub-10 nm) • High throughput and large-area patterning	• Master mould required (relies on e-beam lithography) • Demolding issues and pattern defects	Baracu <i>et al.</i> (2021); Dirdal <i>et al.</i> (2020); Einck <i>et al.</i> (2021); Austin <i>et al.</i> (2004)
Two-Photon polymerisation	• High resolution (down to 100 nm) and flexibility • Clean room facility not required	• Low throughput (layer-by-layer construction) • Expensive equipment and limitations in material compatibility	Faraji Rad <i>et al.</i> (2021); Vanmol <i>et al.</i> (2024)

For the fabrication of the phase elements in this research work, e-beam lithography is utilised since it is a reliable technique to demonstrate the proof of concept for the designs. While the patterning time in e-beam lithography remains a consideration, this work discusses possible process flow optimisations associated with e-beam lithography-based pattern transfer.

4.1 CONVERSION OF PHASE FUNCTION INTO METASURFACE LAYOUT

The designed phase function requires a phase variation from 0 to 2π . In refractive or diffractive optics, the phase delay introduced depends on both the thickness and the refractive index of the material. In meta-optics, the phase delay is imparted using sub-wavelength scatterers arranged in a lattice. Typically, the height of these scatterers is kept constant, while their lateral dimensions are varied to achieve different phase levels. In this work, cylindrical nanopillars arranged in a square lattice are considered as scatterers due to their polarisation-insensitive nature. The choice of materials for structuring the scatterers depends on factors such as the wavelength of interest, complex refractive index and the ease of the fabrication process. As discussed in Chapter 1, a parametric sweep over the radius, height, and period, using the refractive index of the chosen material, was performed to create a lookup table that maps the scatterers to the full 0 to 2π phase coverage. The material parameters used for generating this lookup table are important, as they significantly affect the efficiency of the meta-optical element. Although FEM or FDTD simulation software includes built-in materials with standard refractive index data, these parameters need to be calibrated based on the material properties obtained from the deposited film for better accuracy.

4.1.1 Choice of dielectric material

While metallic scatterers were initially employed to demonstrate beam shaping, subsequent research shifted toward dielectric materials owing to their significantly lower absorption losses. However, the choice of dielectric material must be carefully selected for the operating wavelength. In general, materials with a sufficiently high refractive index are preferred to achieve the required phase modulation within subwavelength thicknesses, while maintaining a low absorption coefficient to ensure high transmission efficiency.

For metasurfaces operating in the near-infrared (NIR) region, polysilicon is often chosen because it provides a high refractive index ($n \approx 3.5$ at $1.55 \mu\text{m}$) along with low absorption losses compared to metals. In addition, polysilicon can be deposited using

well-established CMOS-compatible processes such as low-pressure chemical vapour deposition (LPCVD) or plasma-enhanced chemical vapour deposition (PECVD), making it suitable for fabrication. In contrast, at visible wavelengths, titanium dioxide and silicon nitride are more suitable choices due to their low absorption loss compared to silicon across the visible spectrum. Titanium dioxide offers a moderately high refractive index and can be deposited using atomic layer deposition. Silicon nitride, although lower refractive index than titanium dioxide, is more CMOS compatible and can be deposited using CVD-based techniques.

Polysilicon for NIR wavelengths

The initial attempt to generate an SSBB using meta-optics was carried out in the NIR range, specifically at a wavelength of 1064 *nm*. Polysilicon is chosen as the dielectric material for fabrication. The polysilicon layer is deposited on a quartz substrate by using LPCVD. Silane (SiH₄) is used as the precursor gas at a process temperature of 640 °C. The dissociation of silane (SiH₄) into silicon (Si) and hydrogen (H₂) can be represented by the following chemical reaction:



The optical properties of the deposited film are measured using a spectroscopic ellipsometer (J.A. Woollam). The model used for the measurements is described in Petrik *et al.* (2000). The refractive index of the LPCVD-deposited film is then compared with standard literature data for validation, as shown in Fig. 4.1. At 1064 *nm*, the refractive index of polysilicon is approximately 3.53, and the absorption coefficient of the film is negligible at this wavelength. These optical parameters are subsequently used in the numerical simulations (FEM) for generating the meta-atom lookup table.

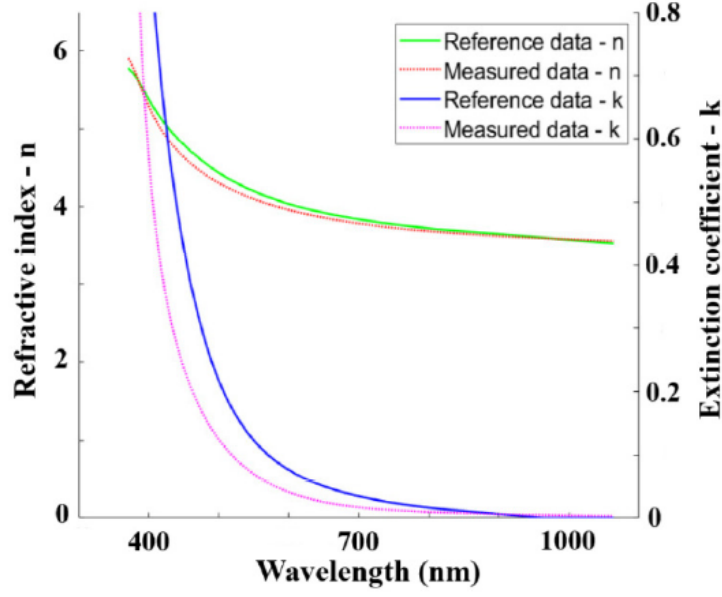
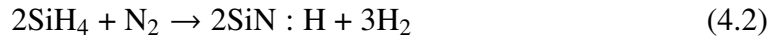


Figure 4.1: Optical constants (n and k) of the deposited polysilicon film compared against reference data (McGahan *et al.* (1996)).

Silicon nitride for visible wavelengths

While several studies have utilised polysilicon at the red end of the visible spectrum, the absorption coefficient of our LPCVD-deposited film was not sufficiently low at these wavelengths. Therefore, silicon nitride was considered for the fabrication of the metasurface operating in the visible range. Silicon nitride was deposited using inductively coupled plasma chemical vapour deposition (ICP-CVD) with silane (SiH_4) and nitrogen (N_2) as the process gases at a temperature of 70°C . The chamber pressure and plasma power were maintained at 10 mT and 500 W , respectively. The chemical reaction involved can be represented as follows:



The deposited film is hydrogenated silicon nitride (SiN : H), and its optical properties are characterised using a spectroscopic ellipsometer. The measured data are analysed using a Cauchy model, assuming the film is deposited on a quartz substrate. At a wavelength of

642 nm, the refractive index of the film is approximately 2, and the absorption coefficient is negligible, indicating a highly transparent film in the visible region. The variation of the refractive index across the visible spectrum is shown in Fig. 4.2.

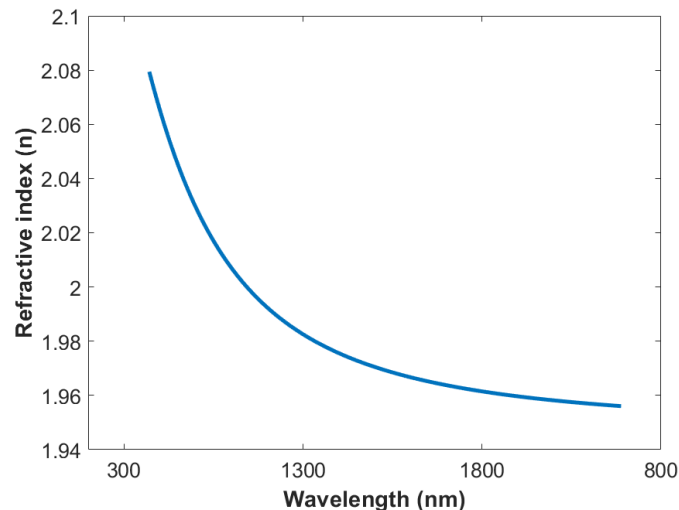


Figure 4.2: Refractive index (n) of the ICP-CVD deposited silicon nitride film

4.1.2 GDSII layout generation

To create a layout suitable for patterning using e-beam lithography software, the meta-atoms have to be arranged accordingly. This is typically done using programming, as a large number of meta-atoms need to be positioned precisely. For example, Fig. 4.3 illustrates the conversion of a blazed grating phase into a corresponding 4-level meta-atom layout. The continuous sawtooth phase profile ranging from 0 to 2π is first discretised into four phase levels, and each level is then implemented using a meta-atom of a specific radius. Although the figure shows only one meta-atom per phase level for clarity, in the actual device, many meta-atoms of the same radius are repeated in a region of the same phase level.

To arrange the meta-atoms in the desired pattern, an in-house Python-based software (Fig. 4.4) is used to assign the appropriate meta-atom to each pixel based on interpolated data from the lookup table (Dharmavarapu *et al.* (2020)). The software scans through the phase map (formatted as pixels) and replaces each phase value with its corresponding

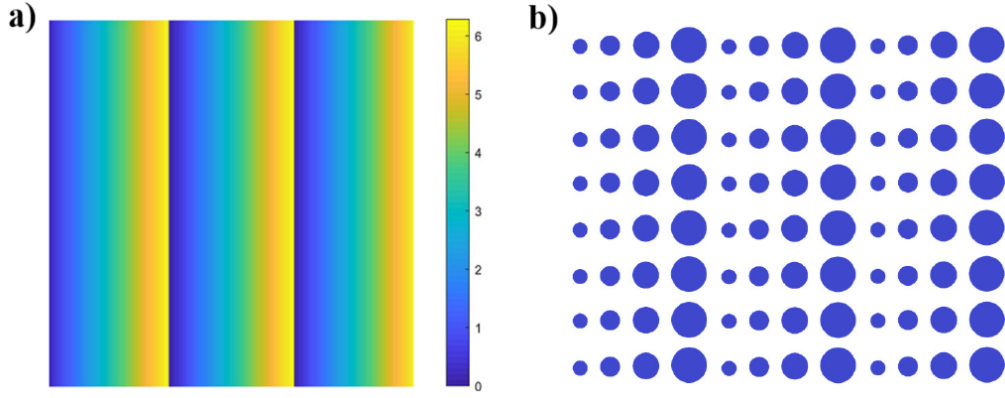


Figure 4.3: Conversion of a blazed grating phase to a meta-atom layout. (a) Phase variation from 0 to 2π in a sawtooth profile. (b) Corresponding 4-level phase realisation using discrete meta-atoms.

meta-atom geometry. It allows the user to upload both the lookup table and the phase profile to be converted, and it supports discretisation into different phase levels, such as 4-level or 8-level realisations. The tool also includes built-in libraries for several commonly used meta-atom designs, along with functions to generate phase profiles for elements such as Fresnel zone plates, spiral phase plates, and axicons. The final output is a GDSII file, which can be directly imported into the e-beam lithography system.

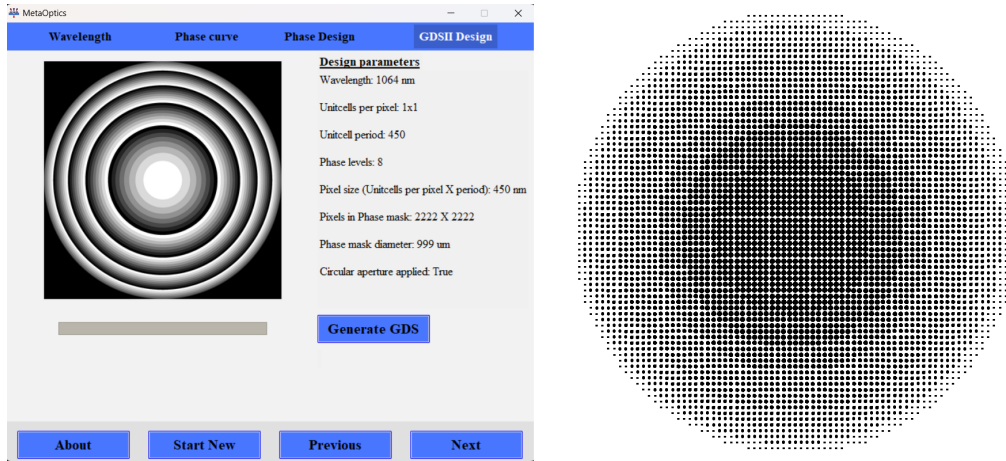


Figure 4.4: Python-based software for generating the GDSII file for patterning. The figure on the right side shows the GDSII file opened in KLayout.

4.2 PATTERNING AND PATTERN TRANSFER

Typically, meta-optical elements fabricated using e-beam lithography face scalability challenges, primarily due to long patterning times and the high computational load associated with generating complex patterns (Greve and Holst (2013); Park *et al.* (2019); She *et al.* (2018)). These limitations often restrict the use of such elements in real applications or even in preliminary experimental testing (Zheng *et al.* (2021)). In e-beam lithography, the pattern is first written onto a resist layer, which undergoes a chemical modification upon exposure to the electron beam. After development, the exposed (or unexposed, depending on the resist tone) regions form the desired pattern. The total patterning time is influenced by several factors, most notably the sensitivity of the e-beam resist and the beam current used during exposure (Greve and Holst (2013)).

4.2.1 E-beam resists

Patterning in e-beam lithography can be carried out using either positive or negative tone resists, each offering advantages depending on the desired feature geometry. Positive resists are typically preferred for creating hole-type structures, as the exposed regions become more soluble and are removed during development, while negative resists are

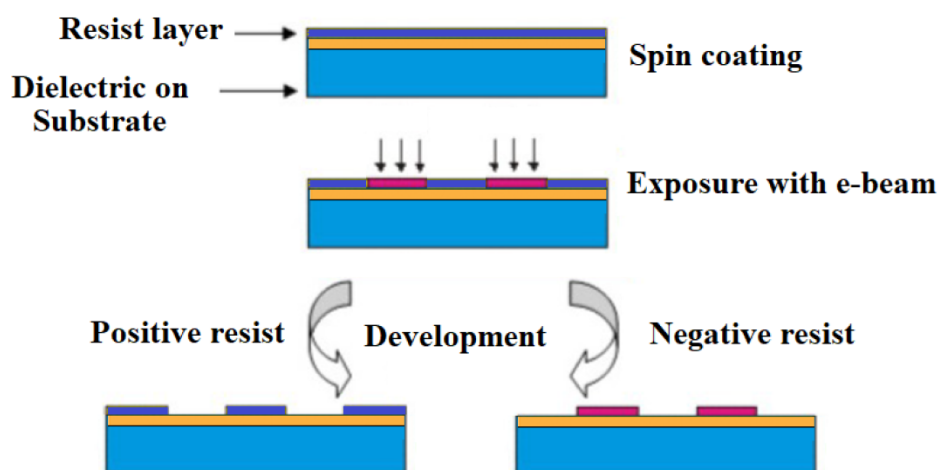


Figure 4.5: Comparison of positive and negative resist development following e-beam exposure. Positive resists result in the removal of exposed areas; negative resists retain them.

better suited for generating pillar-like features because the exposed areas cross-link and remain after development (Fig. 4.5). Among positive resists, poly(methyl methacrylate) (PMMA) and ZEP-520 are widely used owing to their good resolution and reliable processing behaviour. For negative-tone applications, hydrogen silsesquioxane (HSQ) is the most commonly employed resist due to its exceptionally high resolution and its ability to transform into a silicon-oxide-like material upon exposure. Other negative resists, such as the ma-N 2400 series and the mr-EBL 6000 series are also gaining popularity for their improved sensitivity and compatibility with high-throughput fabrication. Table 4.2 summarises the key strengths and limitations of these resists, highlighting their suitability for patterning meta-optical elements.

Table 4.2: Different popular e-beam resists and comparison of their performance parameters

Resist (tone)	Benefits	Drawbacks	Ref.
PMMA (positive)	• High resolution (sub-10 nm) • Good balance of sensitivity and contrast	• Low etch resistance • Risk of pattern collapse	Grigorescu and Hagen (2009); Gangnaik <i>et al.</i> (2017)
HSQ (negative)	• High resolution (sub-5 nm) • High dry etch resistance (can be used as hard mask)	• Limited shelf life • Sensitivity is relatively low • Not suitable for glass substrates	Rommel <i>et al.</i> (2013); Gangnaik <i>et al.</i> (2017)
ZEP-520 (positive)	• High resolution (sub-20 nm) • High sensitivity • Good etch resistance	• Relatively expensive • Complex development and removal process	Gangnaik <i>et al.</i> (2017); Koshelev <i>et al.</i> (2011)
maN-2400 (negative)	• High resolution (about 20 nm) • Sensitivity better than PMMA	• Sensitive to precise conditions of pre- and post-exposure bakes • Adhesion issues	Andren <i>et al.</i> (2020); Kato <i>et al.</i> (2021)
mr-EBL 6000 (negative)	• High sensitivity • High etch resistance • Good resolution (about 75 nm)	• Limited process data available • Sensitivity to process conditions	Martin <i>et al.</i> (2007); Taal <i>et al.</i> (2021)

4.2.2 Patterning resolution

Scatterers used in meta-optics are typically extremely small, often reaching sub-100 *nm* dimensions, especially at shorter operating wavelengths. Achieving such feature sizes requires high-resolution patterning, which is strongly influenced by the acceleration voltage of the e-beam. Higher acceleration voltages reduce forward scattering of electrons, enabling finer features when combined with appropriate proximity-effect corrections. State-of-the-art e-beam systems, though expensive, can operate at acceleration voltages up to 100 *keV*, whereas more accessible, mid-range systems are typically limited to around 30 *keV*. In 100 *keV* systems, the achievable feature size can approach roughly one-tenth of the resist thickness, while in 30 *keV* systems it is typically limited to about one-half to one-third of the resist thickness (Rooks *et al.* (2002); Zhou and Yang (2006)). Although patterning resolution can be improved by reducing the resist thickness, excessively thin resists make the subsequent pattern transfer, especially etching, more difficult and less reliable.

For instance, meta-optics fabricated using PMMA often rely on a metallisation and lift-off process to define a hard mask for subsequent etching. Ideally, the lift-off can be performed with a PMMA layer roughly twice the thickness of the deposited metal film (Shao *et al.* (2021)); however, in practice, resist thicknesses exceeding three times the metal thickness are commonly required to ensure clean and reliable lift-off. This requirement imposes a lower bound on the resist thickness, which in turn constrains the minimum achievable feature size for a given acceleration voltage. Employing higher acceleration voltages helps relax this constraint, as thicker resists can still support high-resolution patterning, thereby simplifying lift-off.

For negative-tone resists, the pattern can typically be transferred directly into the underlying material through etching, provided the resist offers sufficient etch selectivity. In such cases, the resist thickness dictates the maximum etch depth achievable without compromising the pattern fidelity. Although 100 *keV* e-beam systems offer advantages

in this context by enabling high resolution at larger resist thicknesses, they are expensive and generally require higher exposure doses, resulting in longer patterning times. Consequently, fabricating meta-optical elements with lower acceleration voltage systems (below 30 *keV*) remains challenging and demands careful balancing of resist thickness, patterning resolution and etch requirements to obtain satisfactory performance.

4.2.3 Patterning time

Conventional refractive and diffractive elements typically have a size in the order of centimetres. Due to time constraints associated with e-beam lithography patterning, researchers fabricate down-sized meta-optical elements to demonstrate the proof of concept. However, to use these meta-optical elements in a specific application (e.g., beam shaping), they need to be at least in the mm range. Even patterning millimetre-sized elements takes hours, especially when employing a low beam current in the pA range. The patterning time in an e-beam lithography patterning can be calculated as (Greve and Holst (2013)),

$$\text{Exposure time} = \frac{\text{Exposure dose} \times \text{Exposure area}}{\text{Electron beam current}}.$$

For example, PMMA typically requires an exposure dose of about 200 - 400 $\mu\text{C}/\text{cm}^2$ at 30 keV, which contributes to longer write times when patterning large areas. In contrast, certain chemically amplified resists, such as mr-EBL series can achieve patterning with doses in the range of 10 - 15 $\mu\text{C}/\text{cm}^2$ at the same acceleration voltage. This lower dose requirement enables a proportionally shorter patterning time, making such resists attractive when throughput is a priority. It is important to note, however, that PMMA offers advantages in resolution, process reliability, and lift-off compatibility, so the choice of resist depends strongly on the specific fabrication route and performance requirements.

Patterning time can also be reduced by selecting a larger beam current through the use of a larger aperture. While this improves throughput, it may introduce issues such as

charging and beam drift, particularly when working with low-conductivity substrates. Hence, when patterning on such substrates, it is often preferable to use the smallest beam current that still ensures stable operation. Additionally, lower aperture sizes improve pattern fidelity by providing a larger depth of focus for the electron beam (Zhang *et al.* (2011)).

4.2.4 Mask preparation for etching

After patterning the resist layer, the pattern must be transferred onto the underlying dielectric material using an etching process. The exact approach depends on whether a positive or negative resist is used.

Metallisation and lift-off for PMMA

When patterning using PMMA, metallisation followed by a lift-off process is commonly employed to create a metal mask for etching. Metallisation can be performed using several deposition techniques, with e-beam evaporation and thermal evaporation being the most widely used. After deposition, the metal coats both the exposed regions (holes) and the top surface of the resist. During lift-off, the resist is dissolved, removing the metal sitting on top of it and leaving behind only the metal that was deposited inside the patterned openings (Fig. 4.6a). Lift-off is typically carried out by soaking the sample in warm acetone, and gentle ultrasonication may be used to accelerate the process when necessary.

Lift-off can be particularly challenging when dealing with nanostructures that have high aspect ratios, which is often the case in metasurface fabrication. One of the major drawbacks of lift-off processes involving e-beam evaporation is the possibility of PMMA shrinkage or bubbling, both of which can lead to incomplete or defective lift-off (Sun *et al.* (2021)). In some cases, PMMA shrinkage severely hinders lift-off, and the use of gentle ultrasonication may help remove the metal more effectively. However, ultrasonication carries the risk of damaging or collapsing small, high aspect-ratio structures. Thermal

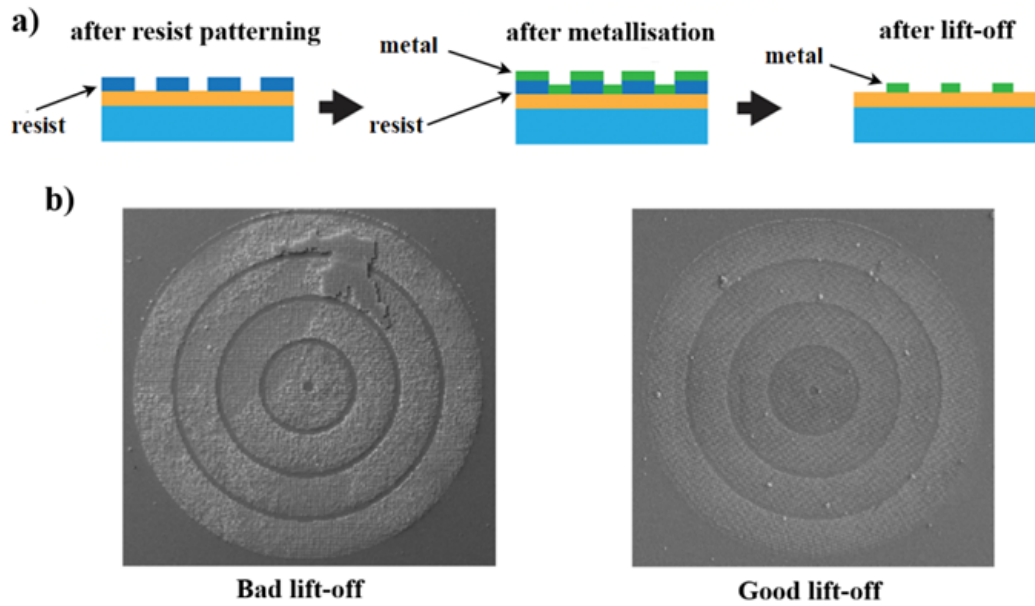


Figure 4.6: (a) Schematic diagram showing the metallisation and lift-off process using PMMA resist. (b) SEM images of the pattern after lift-off, showing good and bad cases.

evaporation, in contrast, does not induce significant heating of the resist and therefore avoids PMMA shrinkage or bubbling. Although its directionality is lower compared to e-beam evaporation, it remains a viable and often advantageous option for lift-off processes, especially when resist stability is a concern. Figure 4.6b shows representative good and bad PMMA lift-off cases.

Resist as mask

Negative resists are often well-suited for forming pillar-like structures, and the resulting resist pattern can therefore be used directly as an etch mask without requiring additional metallisation or lift-off steps. However, this approach depends strongly on the etch selectivity and process compatibility of the resist. HSQ, for example, offers excellent selectivity when etching materials such as silicon and silicon nitride, but it requires very high exposure doses (typically above $1000 \mu\text{C}/\text{cm}^2$) and must be removed using hydrofluoric acid, making it incompatible with quartz substrates (Rommel *et al.* (2013)). The mr-EBL 6000 series and ma-N 2400 series are negative resists with moderate etch

selectivities. The ma-N 2400 series requires exposure doses comparable to PMMA, while mr-EBL resists are highly sensitive and can be patterned using significantly lower doses.

Figure 4.7 illustrates the patterns on mr-EBL 6000.3 resist after development. In Fig. 4.7 b, the cylinders that are designed to have circular shapes with the same diameter, exhibit varying shapes. This is mainly attributed to the charging-induced pattern distortion. Furthermore, edge roughness is also observed in the patterns after development. The altered shape, as well as the edge roughness, will result in distorted structures while etching. This will affect the diffraction efficiency of the meta-optical element (Zhang *et al.* (2011)). By optimising the dose factor and the development time, a good resist profile can be obtained.

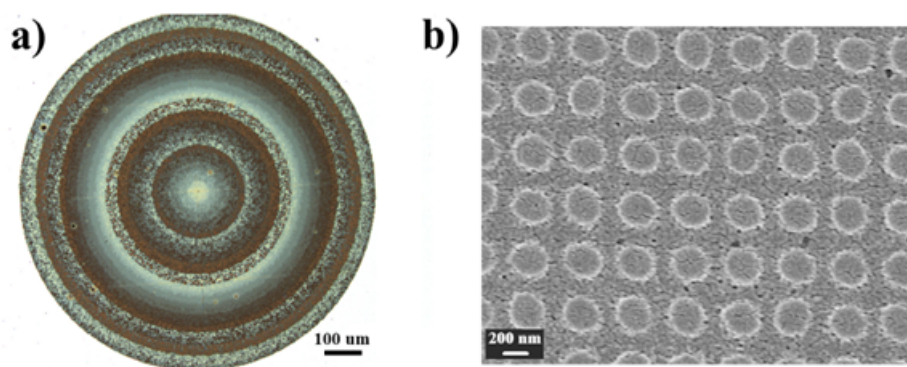


Figure 4.7: Patterned resist after development. (a) Confocal microscope image of the pattern. (b) SEM image of the resist pillars (imaged after gold coating)

4.2.5 Dry etching

Meta-optical structures typically require pillars with high aspect ratios, vertical sidewalls, and minimal sidewall roughness to achieve the desired optical performance. Inductively coupled plasma–reactive ion etching (ICP-RIE) is commonly used for this purpose, as it can provide highly anisotropic etching with good control over feature profiles. However, it is important to note that dry etching does not inherently guarantee anisotropy. The final etch profile is strongly influenced by process parameters such as chamber pressure,

RF bias power, and ICP source power.

The ICP power primarily controls the density of reactive species and ions in the plasma, whereas the RF bias power mainly sets the ion energy at the substrate and thus the degree of directional physical bombardment that enables anisotropic etching. When these parameters are not optimally balanced, the etch becomes less anisotropic and lateral etching increases. This reduced anisotropy produces a rounded etch profile (dotted purple curve in Fig. 4.8a), indicating simultaneous vertical and lateral etching. Under more extreme conditions, enhanced lateral etching leads to a significant undercut at the base of the polysilicon pillars, which can cause mechanical instability and eventual pillar collapse, as observed in Fig. 4.8b. Therefore, careful optimisation of ICP power, RF bias power, chamber pressure, and gas composition is essential to achieve vertical profiles with smooth, stable sidewalls suitable for meta-optics fabrication.

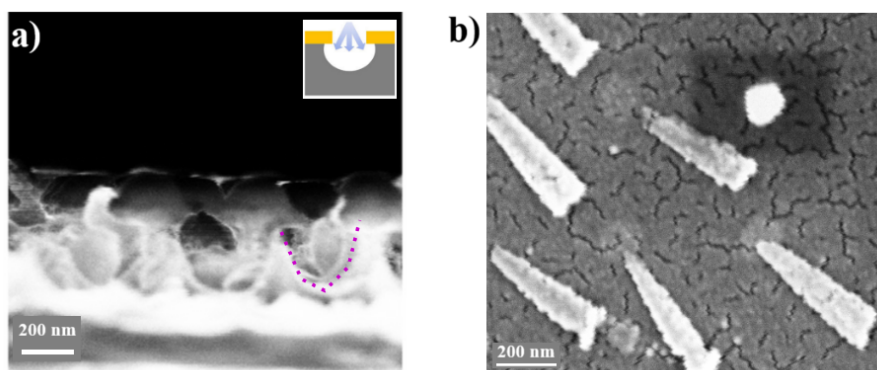


Figure 4.8: (a) Isotropic etch profile of polysilicon pillars, showing simultaneous vertical and lateral etching that produces rounded sidewalls. (b) Top-view image of etched structures illustrating severe lateral undercut and collapse.

4.3 PROCESS FLOW WITH POSITIVE-TONE PMMA RESIST

The positive-tone PMMA-based process was initially used for patterning due to its widespread use in electron-beam lithography and the availability of well-established process recipes. In positive resists, exposure followed by development removes the exposed regions, which is suitable for defining hole-type features. However, when the

electron beam penetrates the resist, forward scattering can widen the exposed area with depth, and backscattered electrons from the substrate can further enlarge the bottom of the feature. As a result, the holes tend to become broader at the bottom. Therefore, inverting the tone to create pillars using PMMA is not ideal (Fig. 4.9), because the resulting pillars would have a narrower base, making them mechanically unstable and prone to collapse.

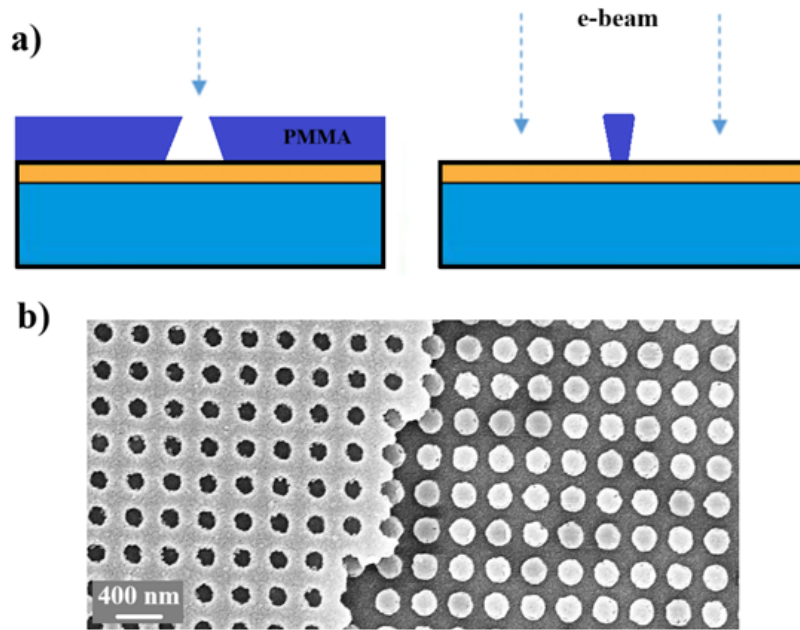


Figure 4.9: (a) Schematic illustration of PMMA patterning for hole formation (left) and the corresponding inverted tone (right) used to define pillars. (b) SEM image of the hole-type pattern in PMMA resist. The partial lift-off observed in this case indicates that the holes at the bottom are broadened.

There are different variants of PMMA resist, which can be categorised based on their thickness as well as their molecular weight. PMMA A2, A4, and A8 are common series, corresponding to the percentage of anisole in the PMMA solution. The anisole content determines the resist thickness when spin-coated at a standard spin speed. Similarly, PMMA resists are available in different molecular weights, such as 950k and 450k, which influence their sensitivity to e-beam exposure. For the present patterning process, PMMA A4 and A8 (950k) were used, yielding thicknesses of approximately 250 nm at 3000 rpm and 500 nm at 7000 rpm, respectively. These thicknesses were selected

based on the required patterning resolution and the mask thickness needed for subsequent processing steps.

After coating, the resist is prebaked at $180\text{ }^{\circ}\text{C}$ for 90 s before patterning. The patterning is carried out using a Raith 150 Two e-beam lithography system. For an optical metasurface composed of pillar structures, a metal mask must be formed from the patterned holes. This is achieved through a metallization process followed by lift-off, which creates pillar-like metal features in the regions where the holes were initially defined. Metallisation is performed using thermal evaporation of aluminium, where a 2 cm aluminium wire yields a film thickness of approximately 50 nm . The metal-coated sample is then immersed in warm acetone ($55\text{ }^{\circ}\text{C}$) for the lift-off step, during which the resist and the metal deposited on top of it are removed. Gentle ultrasonication is applied to ensure a clean lift-off.

Then, the dielectric material is etched using this metal mask by ICP-RIE, and the etch gases depend on the dielectric material being etched. Finally, the metal mask is removed using an aluminium etchant, and the optical element is ready.

4.3.1 Silicon metasurfaces

In the near-infrared (NIR) wavelength range, silicon metasurfaces are widely used due to their low absorption and high refractive index. To fabricate an element operating at 1064 nm , polysilicon was deposited by low-pressure chemical vapour deposition (LPCVD) using silane (SiH_4) as the precursor gas with a flow rate of 30 sccm . The film was grown at a process temperature of $640\text{ }^{\circ}\text{C}$ and a process pressure of 200 mT . The deposited silicon layer was then patterned by electron-beam lithography using PMMA A8/A4 as the resist, chosen according to the required lateral resolution. PMMA A8 was spin-coated at 7000 rpm to obtain a thickness of approximately 500 nm , whereas PMMA A4 was spin-coated at 3000 rpm to obtain a thickness of approximately 250 nm . Patterning was performed with an exposure dose of $300 - 350\text{ }\mu\text{C}/\text{cm}^2$. The patterned pillar diameters ranged from 160 nm to 330 nm , with a pillar height of 480 nm and a

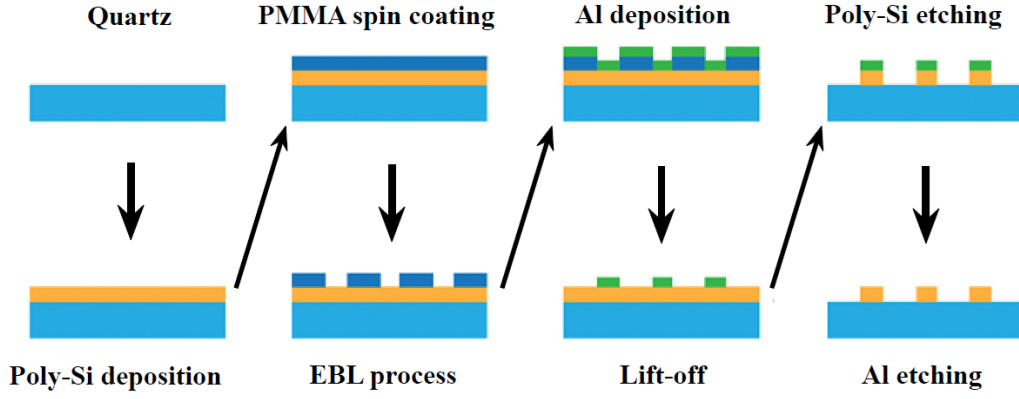


Figure 4.10: The process flow for the fabrication of silicon metasurfaces

period of 450 *nm*.

The resist was developed in an MIBK : IPA (1:3) solution for 50 *s*, followed by an IPA rinse for 30 *s*, then metallisation of aluminium (40 *nm*) and lift-off in acetone. Etching was carried out at a chamber pressure of 15 *mT* using SF₆ (5 *sccm*) and CHF₃ (18 *sccm*) as the etch gases. The RF power was 30 *W* and the ICP power was 1000 *W*. The overall fabrication process flow is shown in Fig. 4.10.

4.3.2 Silicon nitride metasurface

In visible regime, silicon metasurfaces are not suitable due to their high absorption coefficient. Silicon nitride is used as the dielectric material for the elements that were designed for 642 *nm* and 520 *nm*. A silicon nitride film is deposited using the ICP-CVD technique using SiH₄ and N₂ as process gases with flow rates 15 *sccm* and 12 *sccm*, respectively (Yang and Pham (2018)). The process pressure is 10 *mT*, and the ICP power is 500 *W*. The refractive index of the film is measured using a spectroscopic ellipsometer to be ≈ 2 at a wavelength of 642 *nm*. Following silicon nitride deposition on quartz, electron beam lithography was employed for patterning. A positive resist, PMMA A4, was spin-coated at 3000 *rpm*, resulting in a thickness of ≈ 250 *nm*. As silicon nitride is insulating, significant charging effects occur during exposure, which hinder efficient patterning. To mitigate this, approximately 15 *nm* of gold was deposited on the resist

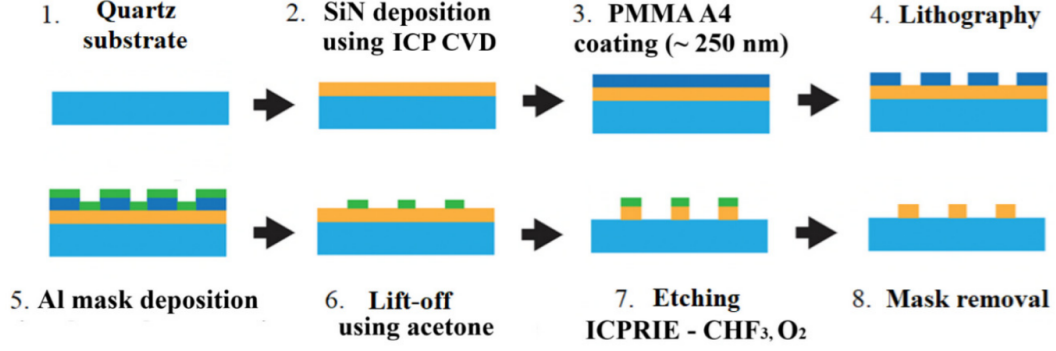


Figure 4.11: The process flow for the fabrication of silicon nitride metasurfaces.

before exposure to prevent charge build-up. After exposure of the sample with a dose of $\approx 300 \mu\text{C}/\text{cm}^2$, the gold layer was removed from the resist using an iodine–potassium iodide–water solution before development. The patterned pillar diameters ranged from 140 nm to 300 nm , with a pillar height of 1040 nm and a period of 380 nm .

The resist was developed in an MIBK : IPA (1:3) solution for 50 s , followed by an IPA rinse for 30 s , after which pattern transfer was carried out. Pattern transfer was carried out using a metallisation and lift-off process. Aluminium was deposited by thermal evaporation to act as a hard mask. Following lift-off, the structures were etched using ICP-RIE with CHF_3 and O_2 as the etch gases, with flow rates of 40 sccm and 10 sccm , respectively (Sun *et al.* (2023)). The process pressure was 15 mT , the RF power was 40 W , and the ICP power was 200 W . Finally, the aluminium mask was removed, completing the fabrication of the metasurface. Fabrication process flow is shown in Fig. 4.11.

4.3.3 Images of the fabricated elements

Figure 4.12 shows the SEM images of the fabricated elements produced using the PMMA-based process flow, along with zoomed-in planar and tilted views of the meta-atoms. Figure 4.12a corresponds to the element designed for generating a Bessel beam, while Fig. 4.12b corresponds to the element for generating an SSBB. Both elements are designed to operate at a wavelength of 1064 nm . Figure 4.12c presents a zoomed-in planar view

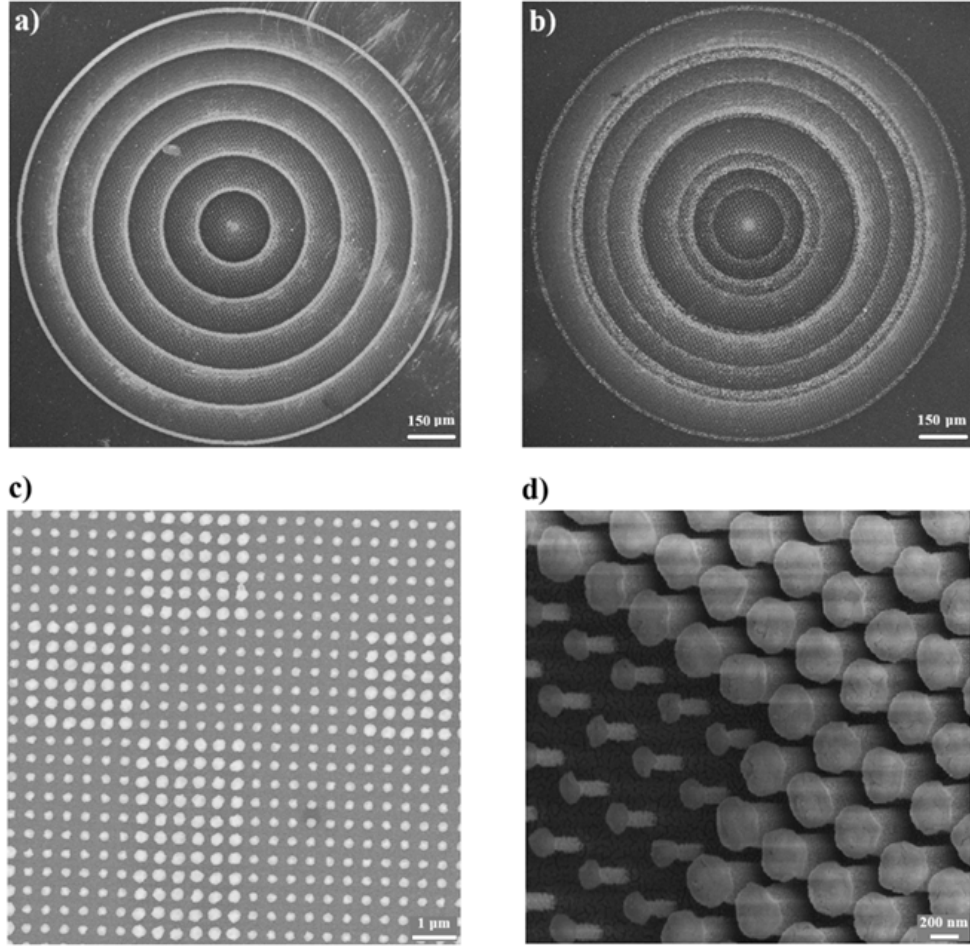


Figure 4.12: SEM images of the polysilicon metasurface elements using the PMMA-based process flow. Elements designed for generating (a) a Bessel beam and (b) an SSBB. (c) Zoomed-in planar view and (d) tilted view of the meta-atoms.

of the meta-atoms, where the phase at each location is implemented using a 6×6 unit cell. This approach helps reduce the GDSII file size and introduces local periodicity to better match the periodic boundary conditions. Figure 4.12d shows the tilted view of the meta-atoms; the top layer visible is the metal mask, as the imaging was performed before its removal.

The Bessel beam and SSBB elements are also fabricated using silicon nitride metasurfaces designed to operate at 642 nm . Figure 4.13a and Fig. 4.13b show the optical microscope images of the fabricated Bessel and SSBB elements. The eight distinct regions visible

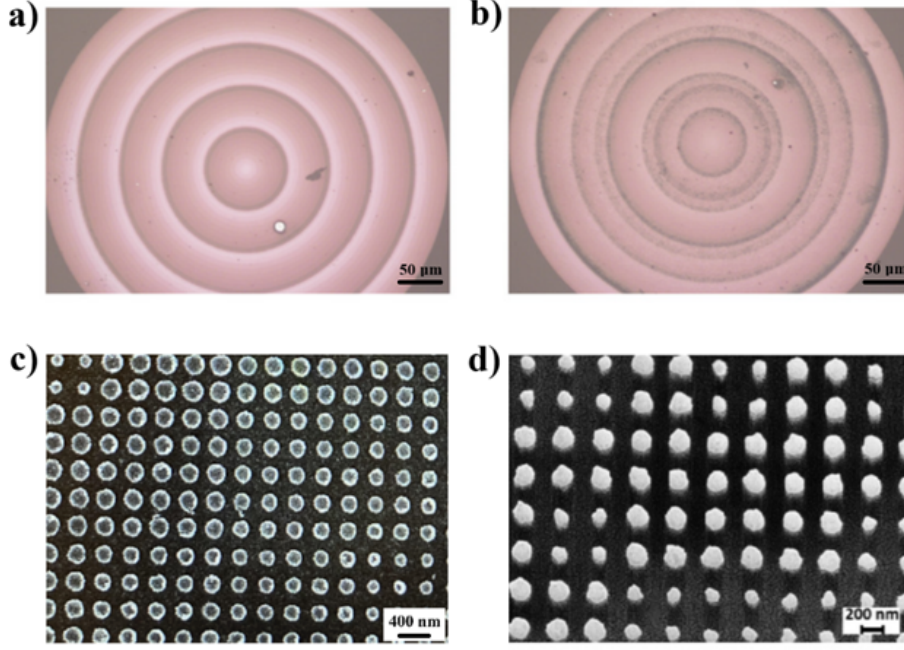


Figure 4.13: (a) Optical microscope image of the Bessel beam and (b) SSBB element with silicon nitride metasurface. SEM image of the (c) metal mask after lift-off and (d) meta-atoms of the final element.

in the images correspond to the eight phase levels used in the design. Figure 4.13c shows the SEM image of the mask after lift-off, and Fig. 4.13d presents the SEM image of the meta-atoms of the final element. For the meta-atoms used in both the silicon and silicon nitride elements (with diameters ranging from 140 nm to 330 nm), dimensional variations of approximately 15 nm to 30 nm were observed, with smaller-diameter pillars generally exhibiting lower variations. The silicon nitride meta-atoms also exhibited greater deformation compared to the silicon meta-atoms, possibly due to the higher-aspect-ratio structures in the former.

Bessel and SSBB elements with five copies are also fabricated to demonstrate structured illumination using metasurfaces. These elements are designed to operate at a wavelength of 642 nm , as shown in Fig. 4.14a and Fig. 4.14b.

The proposed STED experiment using SSBBs requires the generation of a zeroth-order

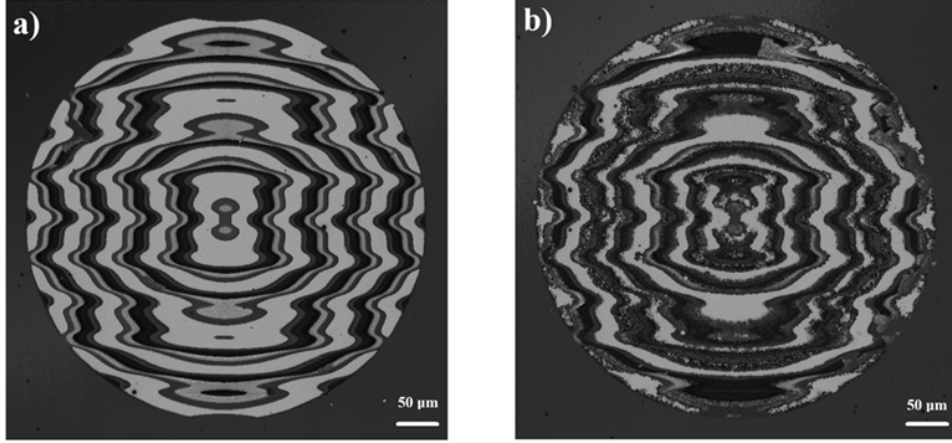


Figure 4.14: Confocal microscope image of the fabricated silicon nitride metasurface elements designed to generate five copies of (a) a Bessel beam and (b) an SSBB.

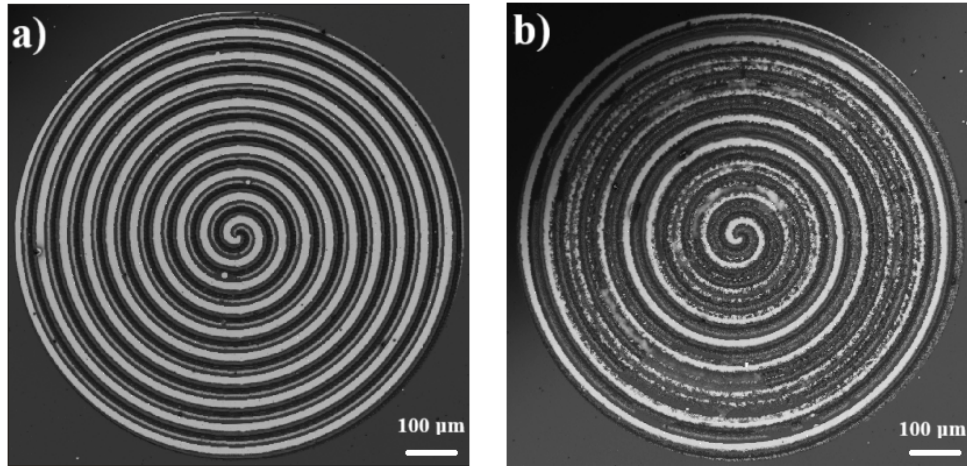


Figure 4.15: Confocal microscope image of the fabricated silicon nitride metasurface elements designed to generate a first-order (a) Bessel beam and (b) SSBB.

SSBB at 520 nm and a first-order SSBB at 642 nm . The zeroth-order SSBB element is similar to the one fabricated for other wavelengths, except that the lateral dimensions of the meta-atoms are adjusted accordingly. The fabricated element for the first-order SSBB, along with the corresponding first-order Bessel beam element, is shown in Fig. 4.15.

4.4 PROCESS FLOW WITH NEGATIVE-TONE MR-EBL RESIST

In the fabrication of meta-optical elements typically composed of quartz/glass substrates, a charging effect during e-beam patterning is encountered (Arat *et al.* (2019)). Employing a high e-beam current can reduce patterning time, but it may lead to heating and charging effects in substrates where conductivity is not good (Zhang *et al.* (2011); Greve and Holst (2013)). The use of highly sensitive mr-EBL resist can effectively reduce the patterning time even when employing a low beam current (Taal *et al.* (2021)). Another critical consideration is the ease of pattern transfer from the resist to the material responsible for phase variation. The mr-EBL resist can also be employed as an etch mask for pattern transfer, ensuring a lower number of process steps compared to PMMA-based pattern transfer (Martin *et al.* (2007); Taal *et al.* (2022)).

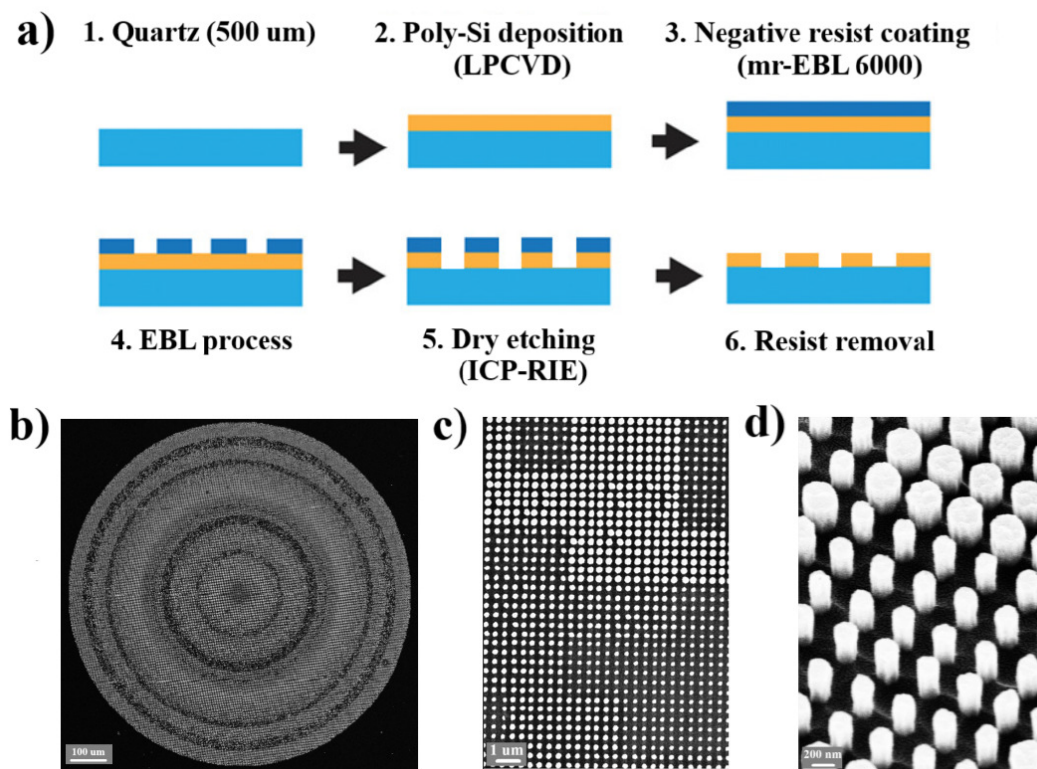


Figure 4.16: Meta-optics fabrication using mr-EBL resist. (a) Process flow of the fabrication with mr-EBL 6000.3 resist. SEM image of the (b) fabricated element, (c) planar view of the meta-atoms, and (d) tilted view of the meta-atoms

To demonstrate the advantages of mr-EBL over PMMA, the fabrication of SSBB design is considered. The final meta-optical element, consisting of polysilicon nanostructures, operates at 1064 nm and is fabricated using a 30 keV e-beam system (Raith 150 TWO) on the highly sensitive mr-EBL 6000.3 resist (Micro Resist Technology). In our fabrication process, the polysilicon-deposited sample is coated with mr-EBL 6000.3 resist, which is spun at 3000 rpm to achieve a thickness of approximately 300 nm , and then prebaked at $90\text{ }^{\circ}\text{C}$ for 5 minutes. Patterning is performed at an acceleration voltage of 30 keV and a beam current of 18 pA using a $7.5\text{ }\mu\text{m}$ aperture. Owing to the high sensitivity of the resist, an exposure dose of only $15\text{ }\mu\text{C}/\text{cm}^2$ is used (significantly lower than that required for conventional e-beam resists) thereby reducing the overall patterning time. After exposure, the resist is post-baked at 110°C for 5 minutes and developed in mr-Dev 600 for 50 seconds. Figure 4.16a shows the fabrication process flow. The fabricated element for generating SSBB is shown in Fig. 4.16b, along with the planar view (Fig. 4.16c) and tilted view (Fig. 4.16d) of the meta-atoms.

Compared to the PMMA-based process flow, the mr-EBL process can eliminate metallisation and lift-off steps, allowing the sample to proceed directly to etching after resist development. This is advantageous, as lift-off often introduces several fabrication challenges. Moreover, the sensitivity of the mr-EBL resist is approximately 20 times higher than that of PMMA. Although the full improvement in patterning time cannot be realised due to the beam-speed limitations imposed by the pattern generator of the lithography system, the high sensitivity enables the use of very low beam currents while still maintaining reasonably short patterning times.

Fabrication on silicon nitride was also attempted using mr-EBL; however, because silicon nitride is non-conducting, a thin gold layer had to be deposited on top of the resist. Since negative resists are typically porous, the presence of the gold coating interfered with the development process, preventing proper pattern formation. Consequently, the silicon nitride devices in this work were fabricated using the PMMA-based process flow instead.

4.5 SUMMARY

This chapter discussed the fabrication process steps used to realise the metasurfaces employed in this work on silicon and silicon nitride platforms. The fabrication workflows employing the positive electron-beam resist PMMA and the negative resist mr-EBL were described in detail. Key challenges encountered during the fabrication process were also discussed. In addition, SEM images of the fabricated meta-atoms designed for generating Bessel beams and SSBBs were presented.

CHAPTER 5

GENERATION OF BEAMS USING META-OPTICS AND APPLICATIONS

In the previous chapter, the fabrication process of meta-optical elements was discussed, and the successful realisation of both polysilicon and silicon nitride metasurfaces was demonstrated. In this chapter, the experimental characterisation of these fabricated elements and the generation of BBs and SSBBs are presented. Initially, beam generation at a wavelength of 1064 nm using polysilicon metasurfaces is discussed, along with the corresponding experimental testing at this wavelength. The latter part of the chapter focuses on the experimental generation of the beams at visible wavelengths using silicon nitride metasurfaces. The implementation of BBs and SSBBs in a light-sheet microscopy configuration using these elements is also discussed.

5.1 SSBB USING POLYSILICON META-OPTICS

To generate the SSBB, a collimated laser beam of 1 mm diameter at a wavelength of 1064 nm is incident on the metasurface, which also has a diameter of 1 mm . In the far field, the SSBB is expected to exhibit two concentric rings corresponding to the two co-propagating Bessel beams. However, fabrication imperfections can lead to the presence of an unconverted zeroth-order beam as well as unwanted higher-order diffraction beams. These effects become apparent in the far-field observation (Fig. 5.1). Since the desired diffracted beams are spatially separated from the zeroth-order beam in the far field, the unwanted diffraction orders can be removed using spatial filtering. A $4f$ optical system is employed both for spatial filtering and for relaying the near field of the metasurface. This configuration also enables controlled magnification or demagnification of the beam, depending on the application requirements. The experimental setup used to

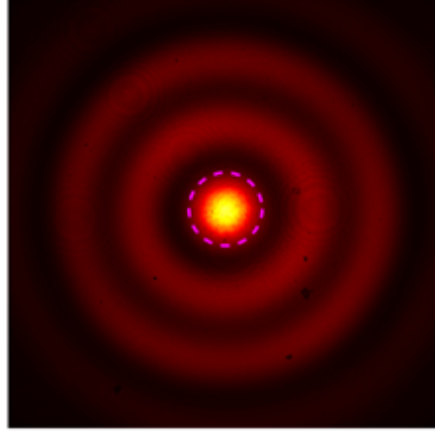


Figure 5.1: Far-field intensity pattern of the SSBB element showing the zeroth-order beam (dotted circle) along with two concentric rings. Minor higher-order diffraction components are also visible.

generate the zeroth-order SSBB is shown in Fig. 5.2. The beam is finally captured using a camera-based beam profiler (Thorlabs BC106-VIS). The transmission efficiency of the element was measured to be 66%, while the diffraction efficiency is about 40%.

Figure 5.3 shows the generated zeroth-order SSBB at the $z = 0$ plane. In the generated zeroth-order SSBB (after relaying), the FWHM observed is $96 \mu m$, which closely matches the expected FWHM of $90 \mu m$. The sidelobe peak intensity of the zeroth-order SSBB is 6.8% that of the main lobe peak intensity at the $z = 0$ plane. The expected sidelobe peak intensity based on the Fourier beam propagation simulation was 4.8%. With careful

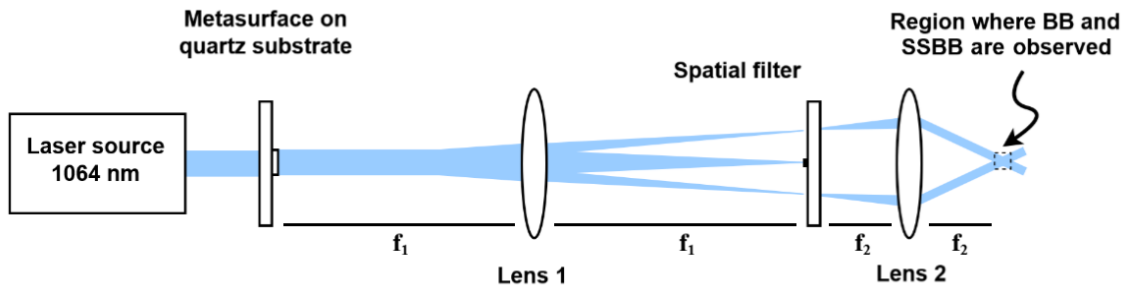


Figure 5.2: Experimental setup of the 4f optical system used for spatial filtering and near-field relaying of the SSBB. Focal length of lens 1 is 250 mm and lens 2 is 400 mm.

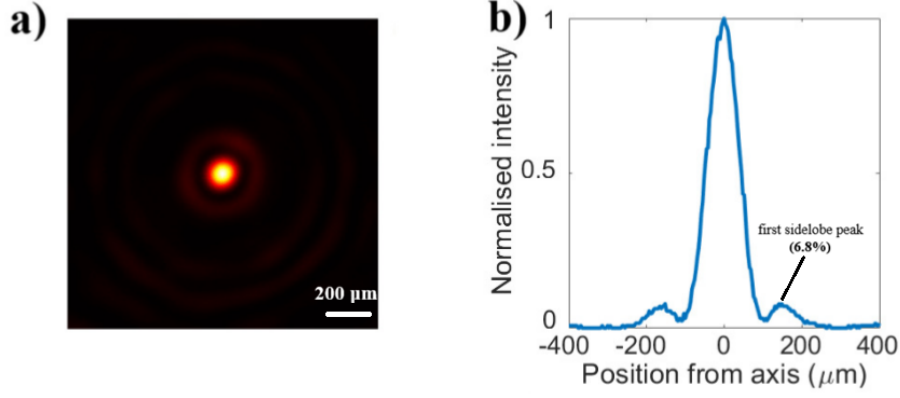


Figure 5.3: Generation of SSBB using polysilicon metasurface at 1064 nm . (a) Cross-sectional intensity of the SSBB at the $z = 0$ plane and (b) its x-axis line profile.

fabrication optimisation, the sidelobe intensity of the experimentally generated SSBB can be further reduced. The cross-sectional intensities and the line profiles of the SSBB at different propagation planes are shown in Fig. 5.4.

The sidelobe peak intensity of the zeroth-order SSBB remains below 10% of the main lobe intensity over a propagation distance of approximately 57 mm (Fig. 5.5a). The propagation-invariant nature of the SSBB is essential for obtaining single-shot depth information from the sample, as confirmed in Fig. 5.5b. At the $z = 0$ plane, the zeroth-order SSBB exhibits an FWHM of $96 \mu\text{m}$. Over a propagation distance of 57 mm centred at $z = 0$, the FWHM increases by only about 5%. Therefore, this propagation length can be regarded as the effective DoF of the SSBB based on a sidelobe peak intensity threshold of 10%. This corresponds to an approximately 1.7 times increase in DoF compared to a Gaussian beam with a similar beam size.

Another unique property of the BBs is their self-healing ability. When imaging deep inside the sample, BBs exhibit excellent resistance to scattering. Since the SSBB is generated by the superposition of two BBs, it also exhibits this self-healing ability. To demonstrate the self-healing property of the zeroth-order SSBB, an obstacle of $\approx 500 \mu\text{m}$ is placed in the path of the beams. In a standard BB, self-healing occurs immediately after

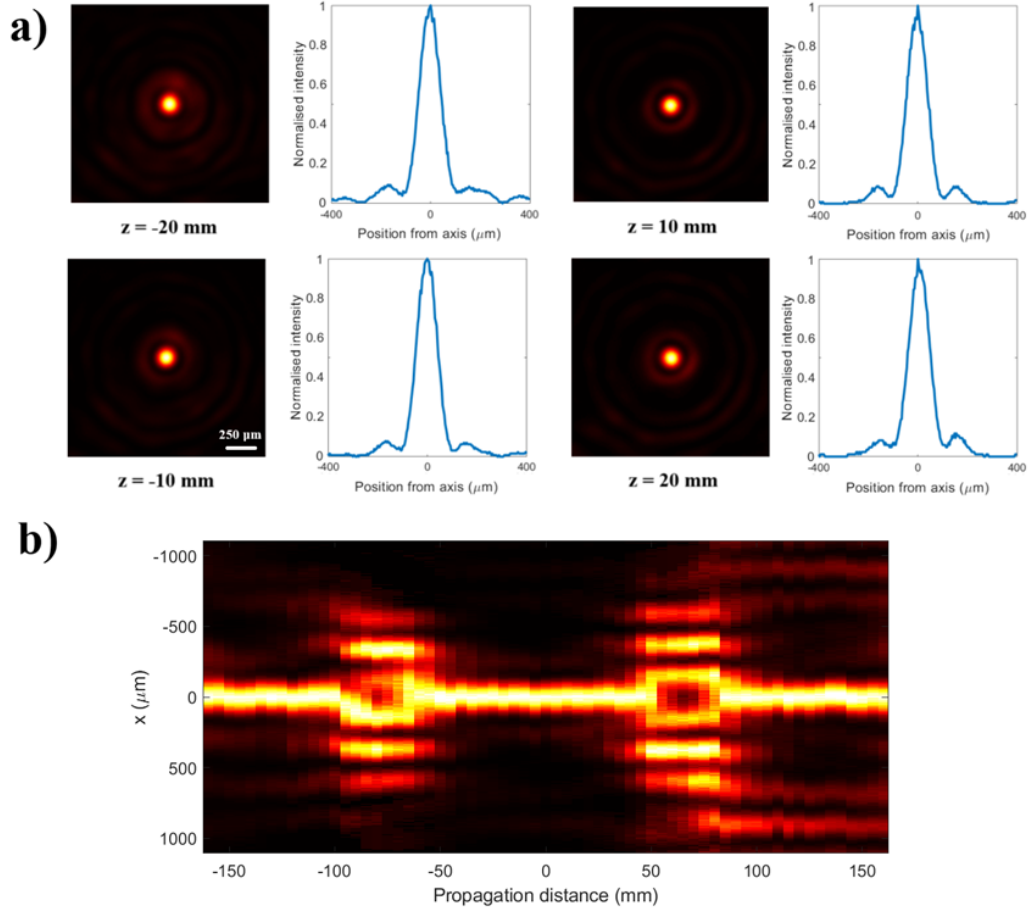


Figure 5.4: (a) Cross-sectional intensity profiles and corresponding line profiles of the SSBB at different propagation planes. (b) Experimental x - z intensity plot showing the propagation behaviour of the SSBB.

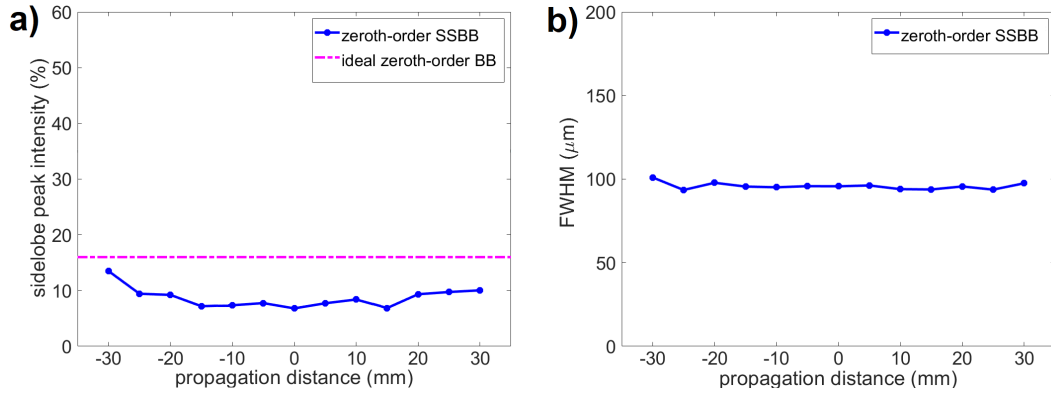


Figure 5.5: (a) Sidelobe peak intensity vs propagation distance of the zeroth-order SSBB compared to respective BB (b) FWHM vs propagation distance of the zeroth-order SSBB.

the shadow region of the obstacle. However, in an SSBB, the axial oscillatory behaviour results in regions within a period where the sidelobes become dominant, making the immediate reconstruction of the central core ambiguous. Consequently, self-healing is most clearly observed in the subsequent axial period, which is approximately 120 mm in the experiments. The reconstruction has been experimentally demonstrated in Fig. 5.6. From the experimental data provided in Fig. 5.5 and 5.6, it is clear that the SSBBs have lower sidelobes compared to BBs while retaining the propagation-invariant and self-healing nature. However, reducing the sidelobes also reduces the DoF of the SSBB compared to the BB. This technique is useful because the DoF of the zeroth-order SSBB is still about twice that of a Gaussian beam with the same core radius.

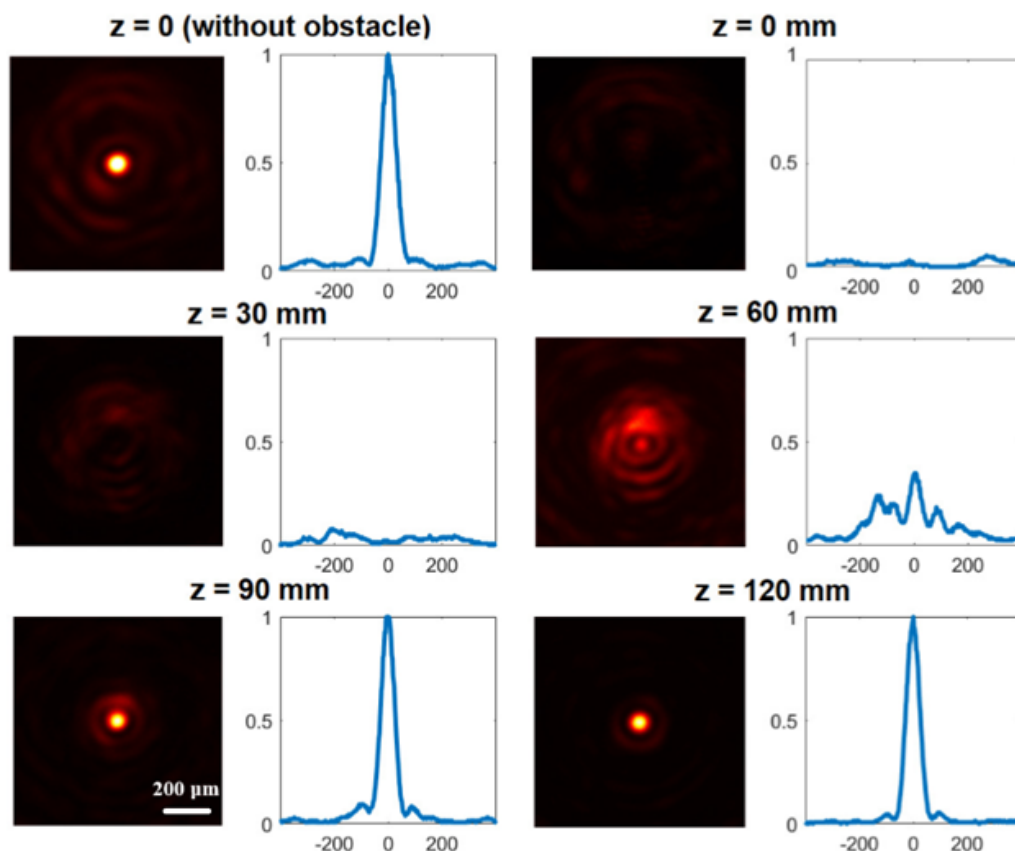


Figure 5.6: Experimental demonstration of self-reconstruction of the zeroth-order SSBB after obstruction by a $500\text{ }\mu\text{m}$ obstacle placed near the coinciding plane. Beam reconstruction is observed at the next coinciding plane. The x-axis represents the transverse position (μm), and the y-axis shows the normalised intensity.

Several studies have demonstrated the generation of a first-order BB using a spiral phase plate or a fork grating in combination with an axicon. Before implementing a single phase metasurface design for the direct generation of a first-order SSBB, this conventional approach was initially explored. The aim was to investigate whether a first-order SSBB could be obtained by introducing a spiral phase plate immediately after the metasurface used to generate the zeroth-order SSBB. A spiral phase plate (Vortex Photonics) with a topological charge of 1 was placed in front of the metasurface to convert the generated zeroth-order SSBB into a first-order SSBB.

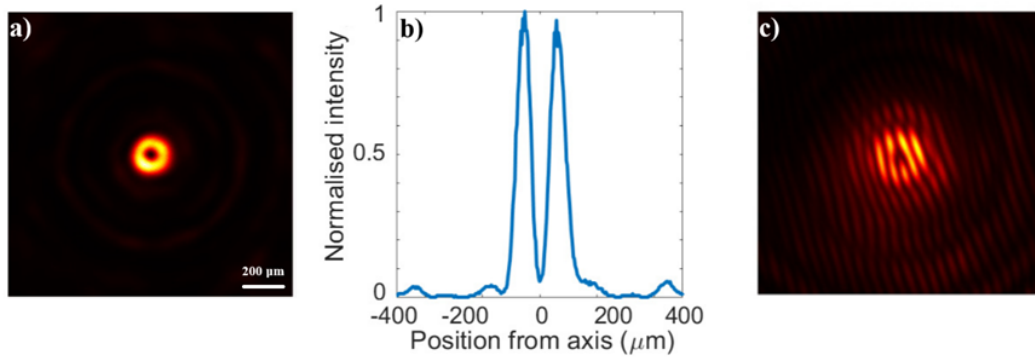


Figure 5.7: Generation of first-order SSBB using a polysilicon metasurface and a spiral phase plate of charge 1 at 1064 nm. (a) Cross-sectional intensity of the SSBB at $z = 0$ plane and (b) its x-axis line profile. (c) Interference pattern of the first-order SSBB with reference beam showing phase singularity.

Figure 5.7a shows the cross-sectional intensity profile of the generated first-order SSBB, and a substantial suppression of sidelobe intensity is observed, as quantified in Fig. 5.7b. In an ideal first-order Bessel beam, the first sidelobe intensity is approximately 35% of the main lobe intensity. The presence of a phase singularity is confirmed by interference of the SSBB with a reference beam, revealing a single fork dislocation corresponding to a topological charge of 1 (Fig. 5.7c).

At the $z = 0$ plane, the sidelobe peak intensity of the first-order SSBB is only 3.71% relative to the main lobe peak. The sidelobe peak intensity of the first-order SSBB is suppressed by at least 40% compared to that of a standard Bessel beam over a propagation

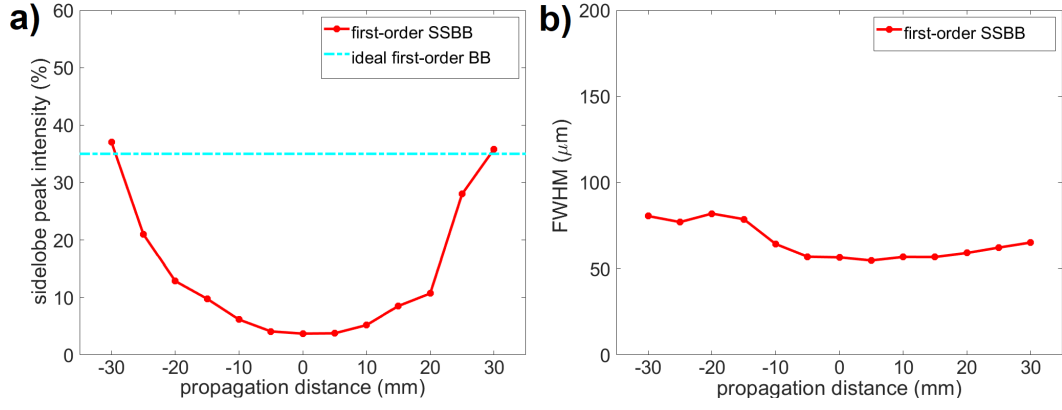


Figure 5.8: (a) Sidelobe peak intensity vs propagation distance of the first-order SSBB (b) FWHM vs propagation distance of the first-order SSBB. FWHM of the ring is considered for the first-order SSBB.

distance of approximately 48 mm. The first order SSBB has an FWHM of the ring of $57 \mu\text{m}$ at the $z = 0$ plane. Over a propagation distance of 48 mm centred at $z = 0$, the FWHM increases by approximately 50%. It should be noted that this approach requires two separate elements, one to generate the zeroth-order SSBB and another to impart the phase singularity. In later sections, the generation of a first-order SSBB using a single metasurface is demonstrated.

5.2 SSBB LIGHT-SHEET IMAGING WITH SILICON NITRIDE META-OPTICS

Although the generation of SSBBs using polysilicon metasurfaces was successfully demonstrated, their application in imaging was limited by the wavelength of operation. While attempts were made to fabricate polysilicon metasurfaces at 642 nm , the efficiency of these elements was found to be quite poor. Consequently, a more suitable dielectric material, silicon nitride, which is well-suited for operation in the visible wavelength range, was selected for the fabrication of the metasurface elements.

5.2.1 Experimental generation of the beams

To generate the SSBB and the Bessel beam, a collimated 642 nm laser beam with a diameter of $500 \mu\text{m}$ was used to illuminate the corresponding metasurfaces of similar

size. The unwanted orders due to the design and fabrication imperfections were removed using a 4f optical system. In the Fourier plane, the Bessel beam element produces a single ring (Fig. 5.9a). To suppress undesired diffraction orders at this plane, an iris is used, and a central block (realised by coating a coverslip) removes the uncoupled zeroth-order light. Given that we already employ an amplitude filter in the Fourier plane, we explored whether this filter could also be designed to suppress sidelobes, at least in the scanning direction. In the Fourier plane, we used a line-shaped filter that selectively blocks the zeroth-order and the top and bottom portions of the spatial-frequency ring, as

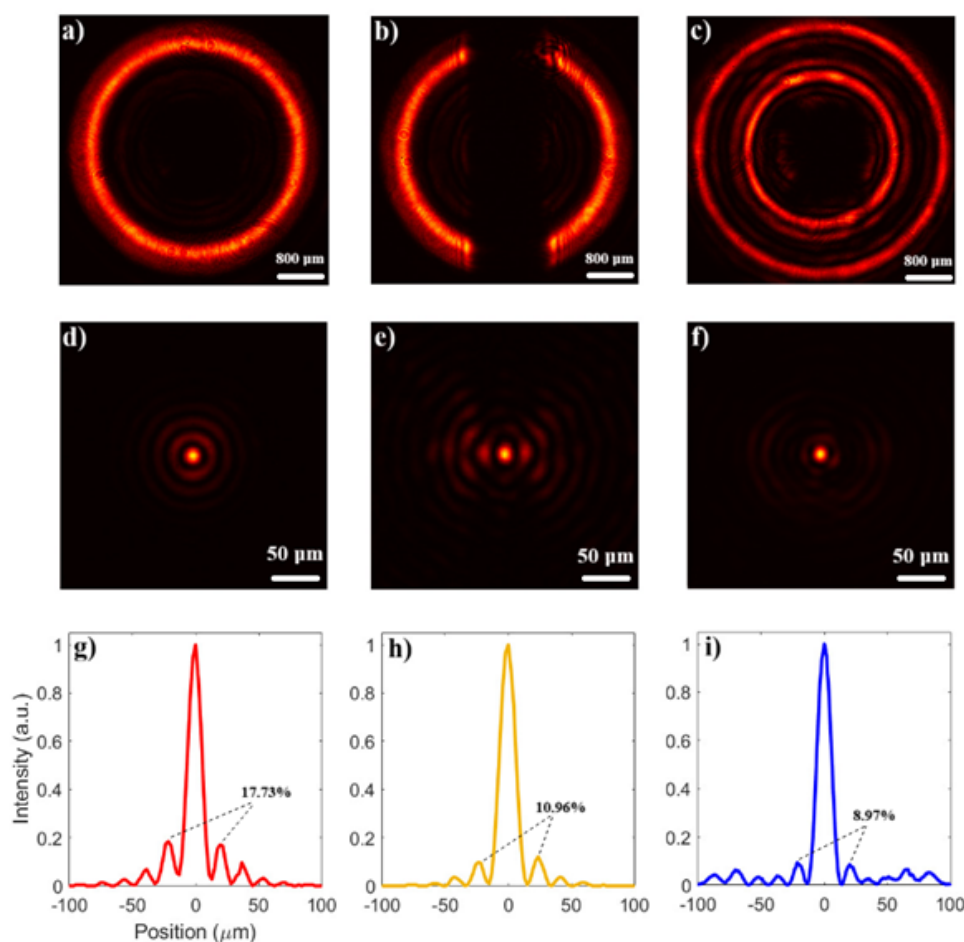


Figure 5.9: Experimental generation of the Bessel beam, sectional Bessel beam, and SSBB using silicon nitride metasurfaces. (a–c) Far-field beam profiles after Fourier-plane filtering. (d–f) Cross-sectional intensity profiles. (g–i) Corresponding y-axis line profiles. The sidelobe percentage is calculated as the average of the two sidelobe peaks.

shown in (Fig. 5.9b). Although this filter does reduce the sidelobes along the scanning axis, the improvement is modest. For the SSBB, the Fourier plane shows two rings (Fig. 5.9c), corresponding to two coaxially co-propagating Bessel beams with different radial wave vectors. To compare the effect of the sidelobe suppression, with respect to a conventional Bessel beam, phase metasurfaces were used to generate all three beams, i.e. a BB, a BB with a spatial filter in the setup to suppress sidelobes in the direction of scanning and a fully suppressed BB (the SSBB).

The Fourier plane is again transformed using another lens, and the beams are captured at the focal plane of the lens. Figure 5.9d shows the Bessel beam generated from the single ring. The first sidelobe intensity (average of two peaks) is about 17.73% that of the main lobe peak intensity (Fig. 5.9g). Figure 5.9e shows the "sectional Bessel beam" generated after selectively blocking the ring along the scanning axis. From the intensity profile, it is evident that blocking spatial-frequency components along the scanning axis reduces the corresponding sidelobes, with the first sidelobe peak falling to 10.96% (Fig. 5.9h). However, the sidelobes along the orthogonal axis increase. This approach is beneficial because, during scanning, the integration occurs along the scanning direction, and reducing sidelobes along that axis leads to a cleaner main lobe. In the case of the SSBB (Fig. 5.9f), the overall sidelobe intensity is significantly reduced, with the first sidelobe intensity measuring only 8.97% regardless of the axis. This substantial reduction in sidelobe intensity can greatly enhance the quality of the scanned light-sheet. The FWHM values are comparable for the three beams, with $\approx 13 \mu m$ for the Bessel beam and the SSBB, and a slightly larger value of $\approx 14 \mu m$ for the sectional Bessel beam. The silicon nitride elements exhibited a transmission efficiency of nearly 80%, with diffraction efficiencies of about 31% for the Bessel beam and 25% for SSBB.

5.2.2 Generation of SSBB and Bessel light sheets for imaging

In order to use these beams in light-sheet imaging, we need to create a sheet of light. In the case of Gaussian beams, a light-sheet can be created without scanning, but with the

use of cylindrical lenses (Huisken and Stainier (2009)). For Bessel beams, the beam is rapidly scanned to form the sheet, in a process called digital scanning (Keller *et al.* (2008)). We used a galvanometer mirror (Thorlabs GVS101), driven by an Arduino, to move the mirror at high speed. The mirror was placed after the second Fourier-transforming lens. The sheets created for the three cases by scanning along the vertical axis are shown in Fig. 5.10. The cross-sectional intensity of the light-sheet helps us to understand the improvement in the axial PSF of the different beams that we explored.

From Fig. 5.10a and 5.10d, it can be seen that the Bessel beam produces broadened tails when scanned. The first minimum of the main lobe is at 44% of the peak. The first sidelobe peak intensity of the scanned beam is about 54% of the main lobe peak intensity. The second (30%) and third (15%) sidelobes are also strong. In the sectional Bessel beam, the minimum of the main lobe is much lower (25%) compared to the Bessel beam. After scanning, however, the sidelobe tail increases slightly. This increase originates

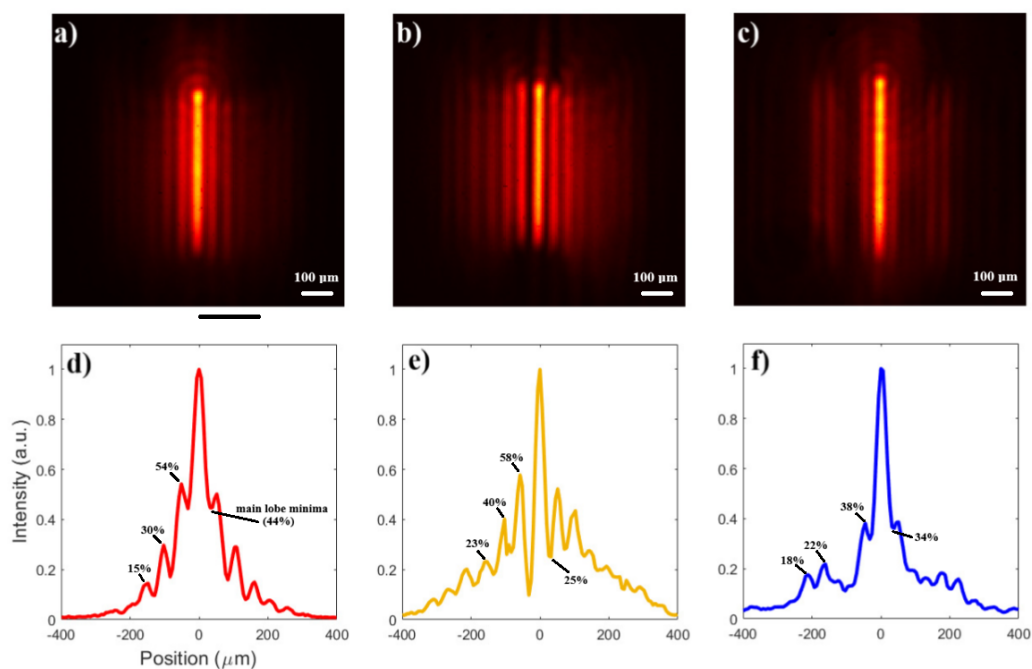


Figure 5.10: Bessel and SSBB light sheets. (a-c) Cross-sectional intensity and (d-f) line profile along the x-axis of the scanned Bessel beam, the sectional Bessel beam, and the SSBB, respectively.

from the sidelobe enhancement present along the orthogonal axis of the unscanned beam, resulting in first, second, and third sidelobes of 58%, 40%, and 23%, respectively (Fig. 5.10b and 5.10e). The lower minimum of the main core will nevertheless help achieve better optical sectioning when used for light-sheet imaging. In the case of the SSBB, both the main lobe minimum and the sidelobe intensities are noticeably reduced. The main lobe minimum is at 34%, while the first, second, and third sidelobes are at 38%, 22%, and 18%, respectively (Fig. 5.10c and 5.10f). This reduction not only improves optical sectioning but also minimises unwanted exposure.

5.2.3 Light-sheet imaging of onion epidermal cells

After generating the scanned beams, we used them to perform imaging experiments on onion epidermal cells. A single peel of the epidermal layer was stained with methylene blue dye for about 5 minutes to enhance contrast and was then mounted in a transparent cuvette filled with glycerol (refractive index ≈ 1.47) for index matching. The sample was fixed such that the light sheet intersected a portion of the epidermal cell. The sample was excited at 642 *nm* wavelength, and an ND filter slider was used to adjust and match the optical power at the sample across the three light-sheet cases. The galvanometer mirror (Thorlabs GVS101) completed one forward – backward scan in 60 *ms*, synchronised

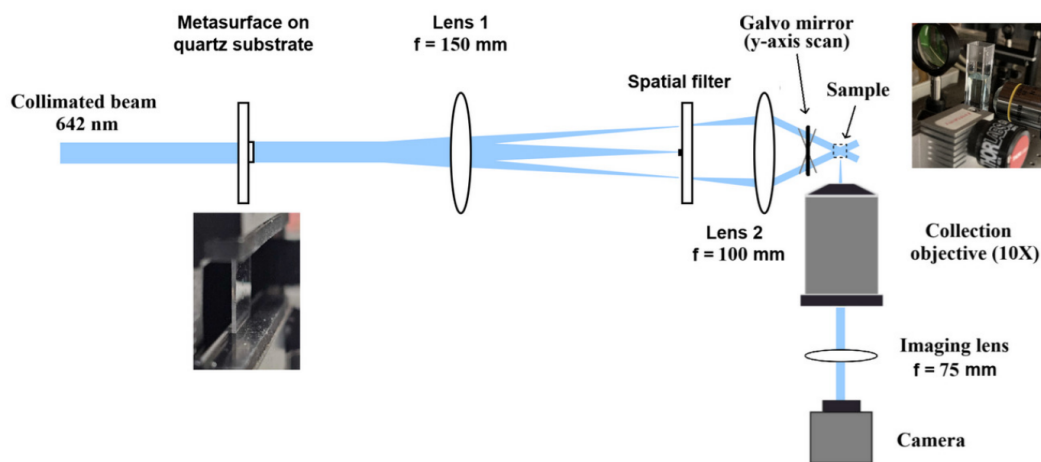


Figure 5.11: Experimental setup for imaging the onion epidermal layer using the Bessel beam, sectional Bessel beam, and SSBB.

with the camera exposure to ensure uniform sheet formation. The signal from the sample was collected orthogonal to the illumination axis using a 10X objective lens coupled with a 75 mm imaging lens, and recorded on a CCD camera (Thorlabs BC106-VIS, pixel size 6.45 μm). This orthogonal configuration ensures that only the plane defined by the light-sheet is imaged, thereby improving sectioning and reducing out-of-focus background. The experimental setup for light-sheet imaging is shown in Fig. 5.11.

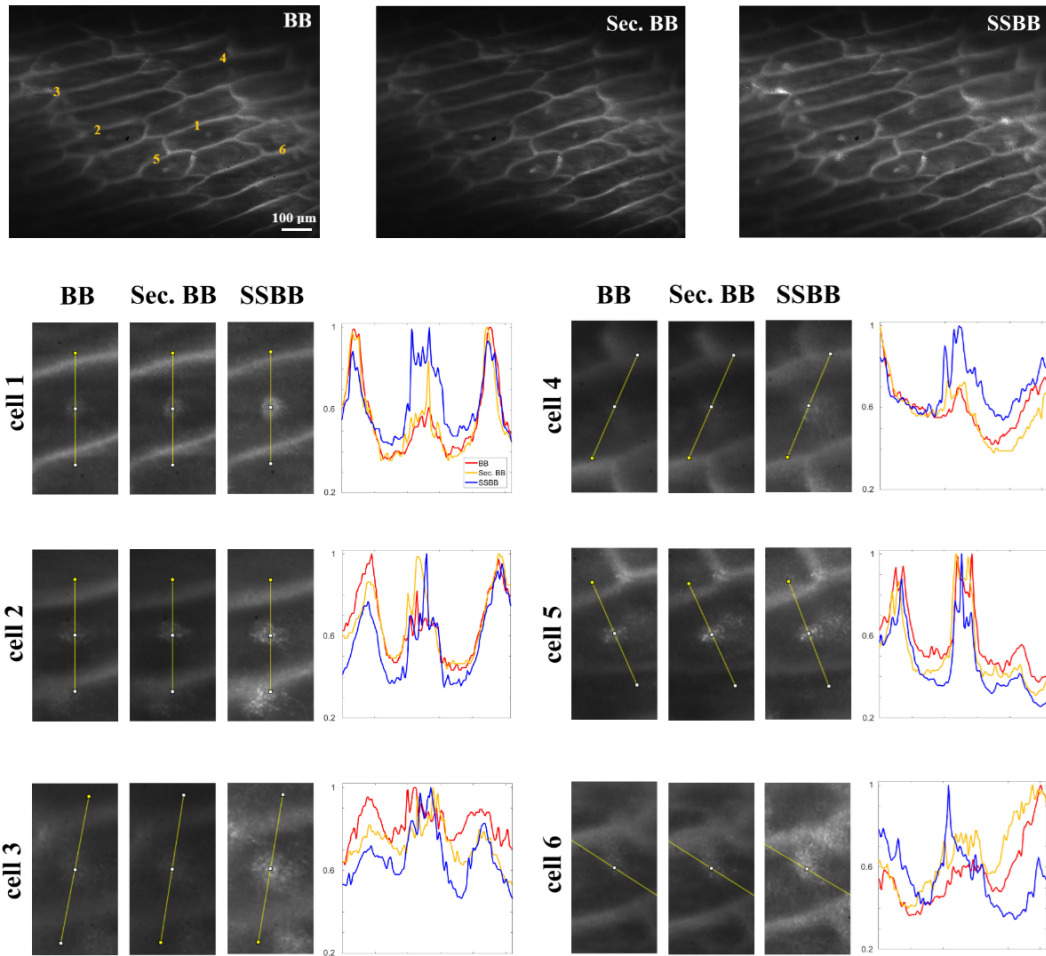


Figure 5.12: Experimental light-sheet imaging of the onion epidermal cells using the Bessel beam, the sectional Bessel beam, and the SSBB. The top row shows the full field-of-view images acquired under each illumination scheme, with the six analysed cell regions marked in the BB image. For each selected cell (cells 1–6), the corresponding zoomed-in regions obtained with BB, Sec. BB and SSBB illumination are shown. Yellow lines indicate the positions along which the intensity line profiles are extracted.

The cell walls and nuclei of the onion epidermal layer were clearly visible under all three cases. SSBB provided the highest imaging contrast, particularly considering the nuclear region (Fig. 5.12). This improvement is attributed to its significantly reduced sidelobe intensity as well as an improved main lobe. The sectional Bessel beam also improved imaging contrast, primarily by enhancing the main lobe of the light-sheet. However, unwanted sidelobe illumination outside the optically sectioned plane is still present. To quantify the improvement in imaging contrast, six cells were analysed in each case, and line profiles were drawn across the cell wall–nucleus–cell wall region to capture both peaks and valleys. Profiles were normalised to the peak intensity to account for power variations, and image contrast was defined as

$$\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}.$$

Using this metric, SSBB-based imaging achieved a 55% contrast improvement over the Bessel beam, while the sectional Bessel beam showed a 27% improvement; these values correspond to the average measured across six cells.

5.3 STRUCTURED ILLUMINATION USING SSBB

While SSBB-based light sheets showed a significant improvement in imaging contrast, further enhancement in both resolution and contrast can be achieved using structured illumination. Structured illumination of the SSBB, as well as the Bessel beam, was implemented using a custom phase function designed to create five copies of each beam. The elements were fabricated using the silicon nitride metasurface process flow described in the previous chapter. Under 642 nm laser illumination and with appropriate Fourier filtering, the metasurfaces generated five copies of the Bessel beam (Fig. 5.13a) as well as the SSBB (Fig. 5.13b), both with nearly equal intensity.

Each SSBB copy acts as a light needle that penetrates the sample, creating a periodic illumination pattern. Although the beam possesses reduced sidelobes, these still expose

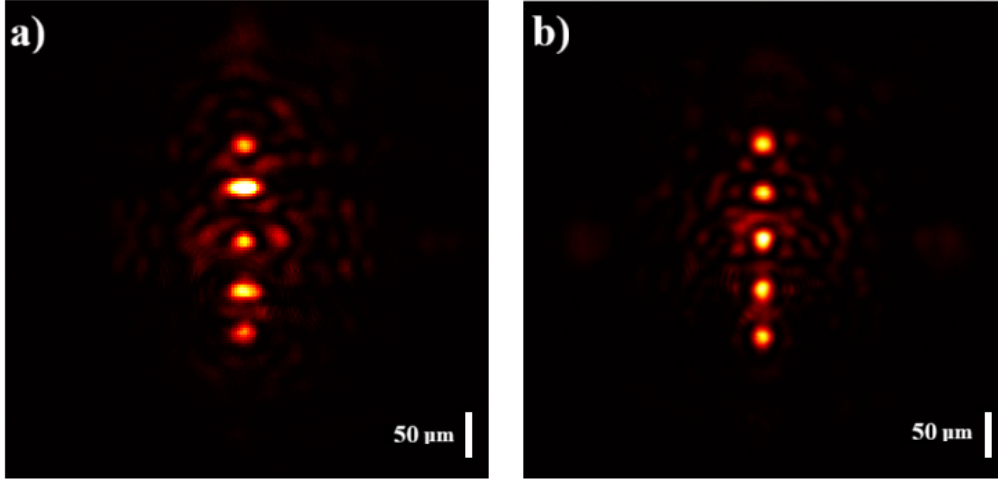


Figure 5.13: Structured illumination of Bessel beam and SSBB. Cross-sectional intensity profile showing five copies of (a) the Bessel beam and (b) the SSBB generated by the meta-element.

regions outside the focal plane of interest. In structured illumination, the beams are not used in a scanning mode. Instead, the illumination patterns are laterally shifted, and multiple images are acquired. Computational reconstruction is then performed by applying the appropriate phase modulation to each shifted image. From the cross-sectional intensity distribution, it is evident that the in-focus regions are strongly modulated by the illumination patterns, while the out-of-focus regions are weakly modulated. This enables the effective computational removal of out-of-focus signals. While structured illumination using a conventional Bessel beam can also provide resolution enhancement, the strong sidelobes lead to reduced modulation in the focal plane and increased unwanted exposure in the out-of-focus regions. In contrast, the SSBB exhibits significantly reduced sidelobes, resulting in stronger focal-plane modulation and lower background exposure.

This approach has the potential to enhance optical sectioning, thereby improving both image contrast and resolution in LSM. In this study, although the generation of multiple copies of the Bessel beam and SSBB using a metasurface was experimentally demonstrated, the implementation of light-sheet imaging with laterally translated illumination patterns could not be realised due to the lack of access to a suitable

high-precision translation stage. Nevertheless, the proposed approach represents a highly feasible pathway toward structured illumination-based LSM using metasurface-generated beams.

5.4 SSBB FOR POTENTIAL STED APPLICATIONS

To evaluate the potential of SSBBs for super-resolution microscopy, we investigated the incorporation of the STED principle within a light-sheet geometry. While the excitation and depletion beams based on SSBBs were generated experimentally, the super-resolution ‘light-needle’ generation was demonstrated through numerical simulations. A zeroth-order SSBB was generated at 520 *nm* to serve as the excitation beam, while a first-order SSBB was generated at 642 *nm* to act as the depletion beam. The fabrication details of the elements for the beam generation have been presented in the previous chapter. The corresponding beam profiles are shown in Fig. 5.14. For comparison, zeroth-order and first-order Bessel beams, with similar beam sizes, were also generated. As evident from the figure, the zeroth-order and first-order SSBB exhibit a significant reduction in sidelobe intensity, consistent with the results demonstrated in earlier sections.

The zeroth-order SSBB exhibits a first sidelobe peak intensity approximately 57% lower than that of the zeroth-order BB, with the outer sidelobes being negligible. For the first-order BB, the first sidelobe peak intensity is relatively high at about 37.53% of the main lobe peak intensity, which can cause substantial photobleaching when used as a depletion beam. In comparison, the first-order SSBB reduces this sidelobe intensity to about 20.47% of the main lobe peak, representing a 45% reduction relative to the first-order BB. This reduction is slightly lower compared to the zeroth-order beam due to the higher wavevector ratio used in the first-order SSBB to improve its DoF. As noted in the design section, sidelobe suppression for the first-order SSBB can be enhanced further, but this would reduce the DoF.

The main advantage of using SSBB in the STED principle lies in the significant

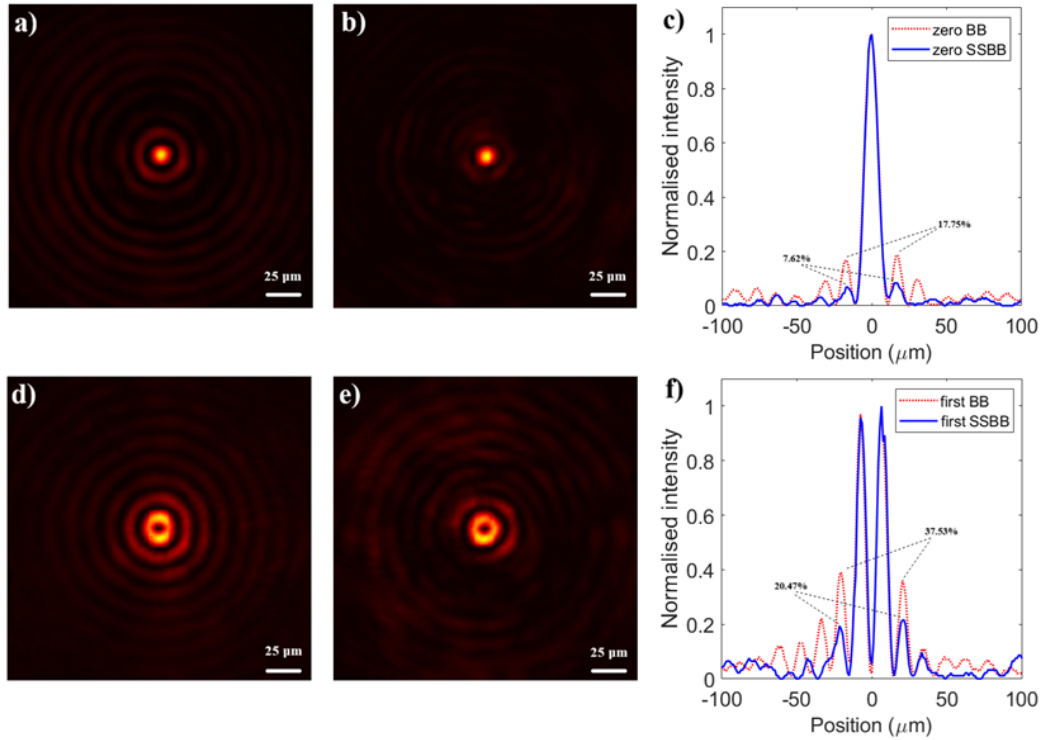


Figure 5.14: The STED principle with SSBB. (a, b) Cross-sectional intensity profiles of the zeroth-order BB and the zeroth-order SSBB, respectively. (d, e) Cross-sectional intensity profiles of the first-order BB and the first-order SSBB, respectively. (c, f) Corresponding line intensity profiles along the x-axis for the zeroth-order and first-order beams, respectively.

suppression of sidelobes in the first-order depletion beam. Depletion beams require very high power levels, beyond the fluorophore's saturation intensity, to effectively initiate stimulated emission. While this high power enables super-resolution imaging, it also causes severe photobleaching. The first-order BB has strong sidelobes that contribute to unwanted photobleaching without improving resolution. In contrast, the first-order SSBB can greatly reduce these sidelobes, and could potentially minimise unnecessary photobleaching while maintaining imaging performance.

Studies have shown that photobleaching in fluorescent dyes scales superlinearly with intensity, with Atto 647N exhibiting a response exponent of approximately 1.4 and Atto 565 approximately 1.9. This superlinear dependence amplifies the advantage of using an SSBB as the depletion beam. By suppressing sidelobe peaks (thereby reducing the local

power density near the centre) and redistributing energy to outer regions, SSBBs enable greater than linear reductions in photobleaching. This could lead to improved STED imaging performance and enhanced fluorophore longevity.

5.4.1 Beam propagation through dye

The cross-sectional intensity profiles of Fig. 5.14 show a substantial reduction in the sidelobes for both the zeroth-order and first-order SSBBs. However, for the SSBBs to operate efficiently in improving resolution, this sidelobe suppression must be maintained over a sufficient propagation distance. To study the propagation characteristics of the individual beams, the beams were recorded in an orthogonal imaging geometry after propagating through a fluorescent dye solution. For 520 nm excitation, a rhodamine dye solution was used since it can be efficiently excited at this wavelength. Similarly, for visualising the depletion beam at 642 nm , methylene blue dye was used. The experimental setup used to capture the beam propagation through the fluorescent dye is shown in Fig. 5.15. The input beam for generating both excitation and depletion beams is matched to

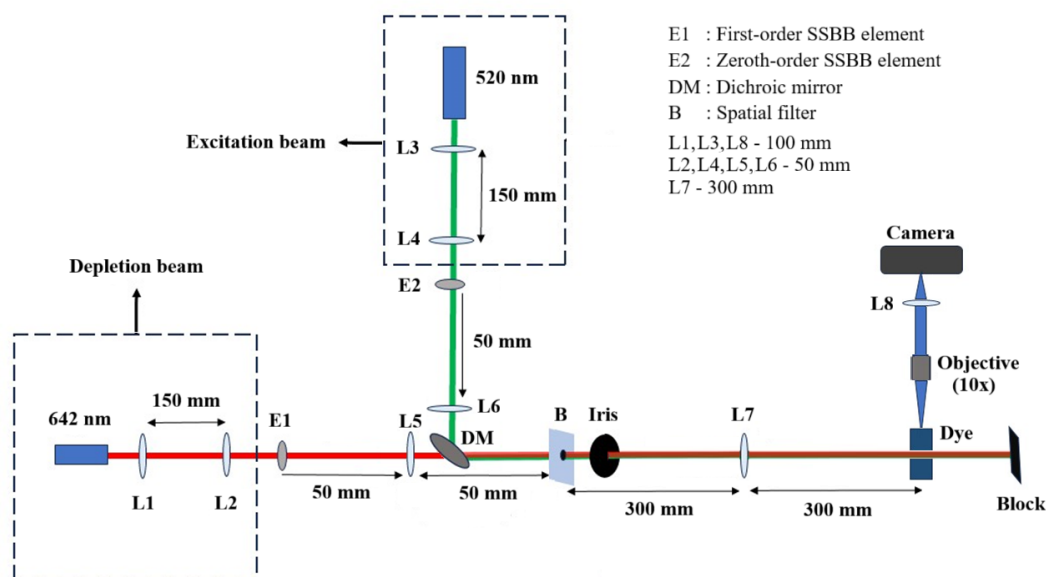


Figure 5.15: Experimental setup for observing propagation characteristics of zeroth-order and first-order beams. Rhodamine dye is used to observe the 520 nm excitation beam (depletion beam blocked), while methylene blue dye is used to observe the 642 nm depletion beam (excitation beam blocked).

the element size ($500\ \mu\text{m}$) using lenses. The two wavelengths are then combined using a dichroic mirror, which transmits the $642\ \text{nm}$ wavelength and reflects the $520\ \text{nm}$ beam. After this, a 4f system is used wherein the far field, the unconverted zeroth-order beam and higher orders are blocked along with 6X magnification. The magnification is used to properly capture the beam which is otherwise small. The propagation of the beams through the dyes is presented in Fig. 5.16.

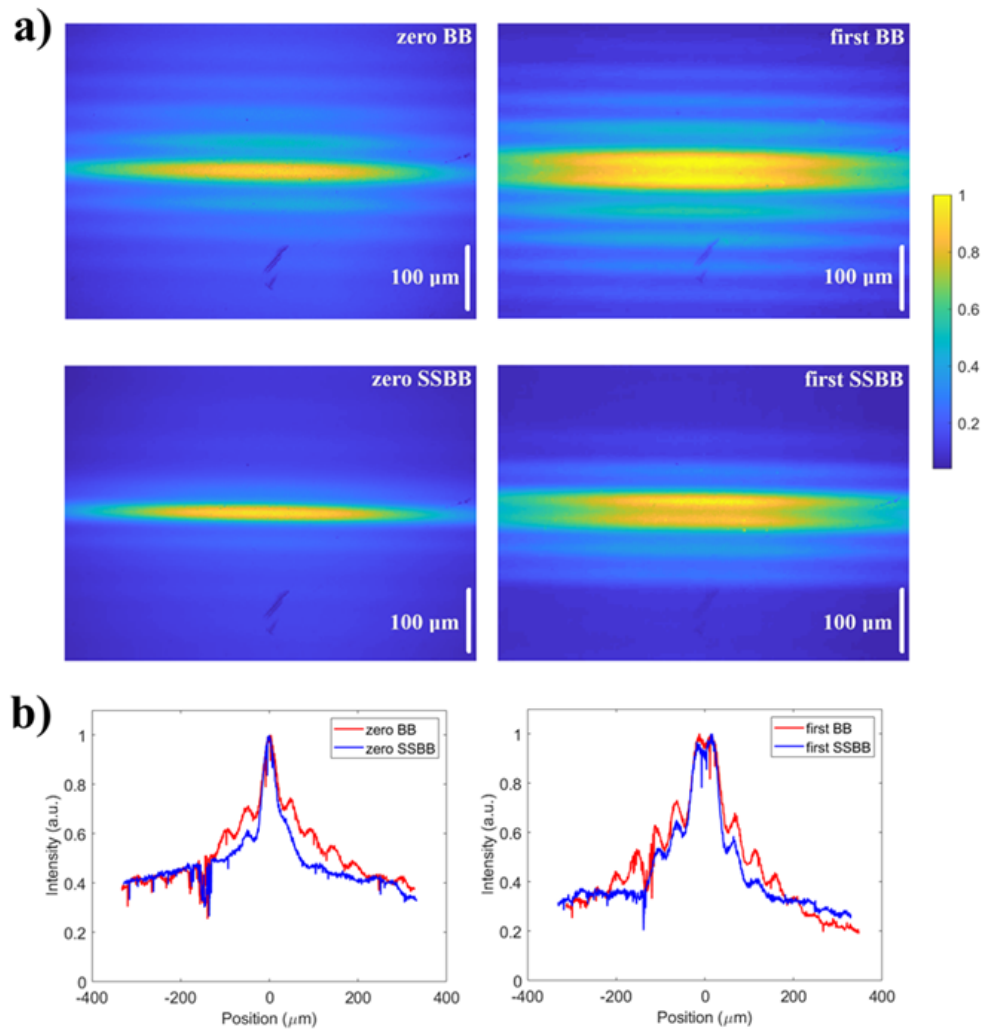


Figure 5.16: Visualisation of beam propagation in fluorescent dye under light-sheet geometry. (a) Orthogonal fluorescence images of the zeroth-order and first-order BBs (top row) and the corresponding SSBBs (bottom row), displayed on a quadrature scale for improved visibility in the presence of background fluorescence. (b) Corresponding line intensity profiles (linear scale) taken along the y-axis through the beam centres.

Figure 5.16a shows that both the zeroth-order and first-order SSBBs exhibit reduced sidelobes over a sufficient propagation distance when compared to the corresponding zeroth-order and first-order BBs. The images are displayed on a quadrature scale to enhance visibility, as a certain amount of background fluorescence is present. The corresponding line profiles (linear scale) taken along the y axis through the centre of the beams are shown in Fig. 5.16b. It should be noted that these beam profiles are recorded without scanning, and the fluorescence from out-of-plane regions integrates along the detection path, resulting in a broadened tail in the measured profiles. In reality, at each orthogonal cross-section the sidelobe suppression is much clearer, as shown earlier in Fig. 5.14. This integration effect is also the reason why the central nulls are not clearly visible when observing the first-order beams through the fluorescent dye. Nevertheless, a clear reduction in sidelobe intensity for the SSBBs compared to BBs is evident.

An experimental demonstration of depletion was attempted using Atto 565 dye, for which the excitation and depletion wavelengths were compatible. However, the maximum available power of the depletion laser was limited to approximately 24 *mW* and was operated in continuous wave mode. In addition, the presence of the unconverted zeroth-order input beam further reduced the effective power available for depletion. Although the objective was to observe at least partial depletion, these limitations, together with the axial spreading of power inherent to the SSBB (which distributes the optical energy over an extended propagation length and lowers the peak depletion intensity), prevented any measurable depletion from being detected. Consequently, a simulation study was carried out to evaluate the effectiveness of the SSBB in a STED light-sheet configuration at the same wavelengths.

5.4.2 Simulation of light needle

To evaluate the effectiveness of the proposed beams in STED-based light-sheet microscopy, a simulation study was performed using a zeroth-order SSBB at 520 *nm* and a first-order SSBB at 642 *nm*, which are suitable wavelengths for the fluorescent dye Atto 565.

The band-limited angular spectrum propagation technique and the analytical model of fluorophore emission in STED were used for the simulations (Zhang *et al.* (2014)). The probability of spontaneous decay (η_{ps}) of the fluorophores in STED can be analytically described by (Leutenegger *et al.* (2010)),

$$\eta_{ps} \approx \frac{1 + \gamma \exp[-k_{s1}\tau_{STED}(1 + \gamma)]}{1 + \gamma}. \quad (5.1)$$

Here, γ is the effective saturation factor, k_{s1} is the spontaneous decay rate, and τ_{STED} is the pulse width of the depletion beam. The parameter γ is related to the saturation factor ζ , the vibrational relaxation rate k_{vib} , and k_{s1} as $\gamma = \zeta k_{vib} / (\zeta k_{s1} + k_{vib})$. The saturation factor ζ is given by I_{STED}/I_s , where I_s is the saturation intensity.

In the continuous wave (CW) STED case, the depletion pulse width becomes equal to the excitation period. When $k_{s1}\tau_{STED}(1 + \gamma) \gg 1$, which corresponds to long interaction times or sufficiently high STED intensity, the exponential term vanishes and the above expression simplifies to

$$\eta_{ps} \approx \frac{1}{1 + \gamma}. \quad (5.2)$$

This represents the maximum achievable fluorescence suppression in the CW STED regime.

When the STED intensity I_{STED} equals I_s , the stimulated emission rate equals the spontaneous emission rate. $I_{STED} \gg I_s$ implies stimulated emission is the dominating emission process. For Atto 565, k_{s1} is approximately $1/(3.9 \text{ ns})$ and k_{vib} is considered to be $1/(5 \text{ ps})$. For a continuous wave depletion beam with a power of 500 mW , the probability of spontaneous decay rate (η_{ps}) is determined in the volume of interest. Then the effective PSF is determined by taking the product of the excitation signal and η_{ps} .

The radial wavevector ratio ($m = k_{r1}/k_{r2}$) used for the excitation beam is 0.7, and the depletion beam is 0.8 as similar to the fabricated elements. However, in the simulations, the radial wavevectors were adjusted to achieve a 20X demagnification, thereby reducing the beam size by a factor of 20. The simulation of the SSBBs and the light needle is shown in Fig. 5.17.

The results of the SSBB-STED configuration are compared against a BB-STED and a conventional STED configuration. For BB-STED, a zeroth-order BB is used as the excitation beam and a first-order BB is used as the depletion beam. For a conventional STED configuration, a Gaussian beam is used as the excitation beam and a Laguerre-Gaussian beam is used as the depletion beam. The excitation and depletion beam sizes

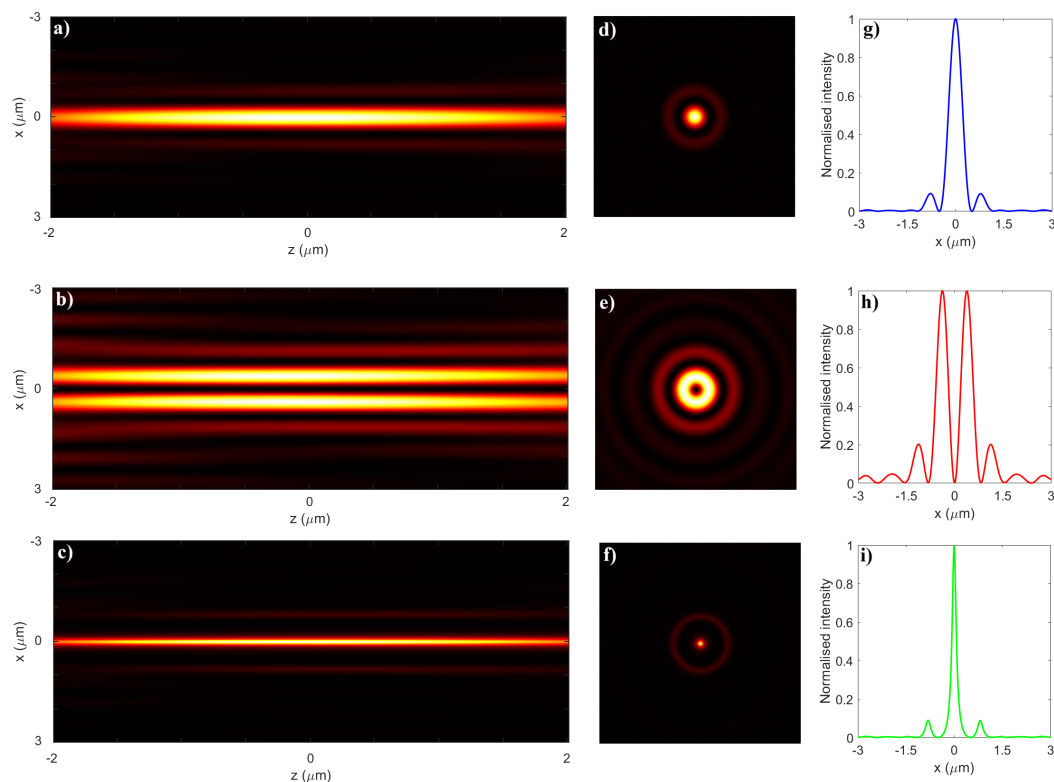


Figure 5.17: Simulation of a light needle with SSBBs applying the STED principle. (a–c) Intensity distributions (x-z plane) at different propagation distances for the zeroth-order SSBB, first-order SSBB, and the resultant beam after depletion, respectively. (d–f) Cross-sectional intensity of the same at the $z = 0$ plane. (g–i) Line intensity profiles at the $z = 0$ plane.

used in all the configurations are ensured to be similar. Figures 5.18a-c show the effective PSFs for the SSBB-STED, BB-STED and conventional STED, respectively. SSBB-STED and BB-STED maintain their FWHM beyond twice the Rayleigh distance (z_R), while conventional STED's FWHM increases substantially (Fig. 5.18d). Here, $z_R \approx 0.93 \mu\text{m}$ is the Rayleigh distance of a Gaussian beam matching the excitation FWHM. At the $z = 0$ plane, conventional STED requires significantly lower power (120 mW) compared to the SSBB and BB configurations (500 mW) to achieve a comparable FWHM for the effective PSF. This difference in power efficiency arises because the Laguerre-Gaussian (LG) depletion beam in conventional STED concentrates its total energy into a small

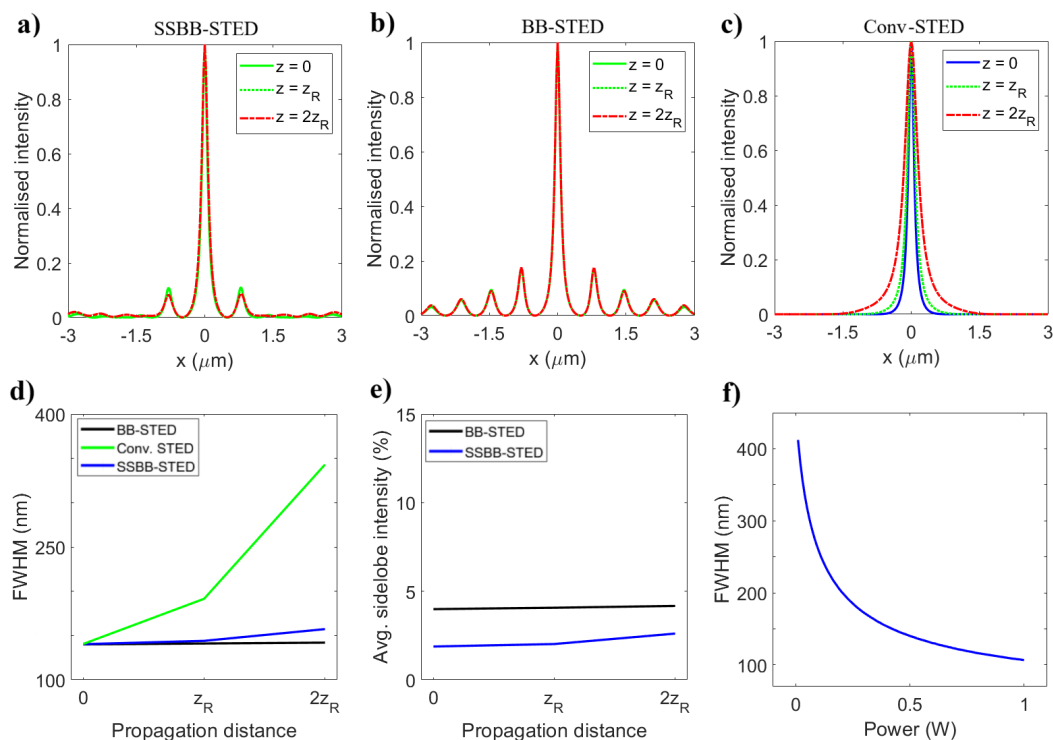


Figure 5.18: Simulation of different STED configurations. (a-c) Effective PSF of SSBB-STED, BB-STED, and conventional STED at $z = 0$, z_R , and $2z_R$. The excitation beam has an FWHM of $\approx 462 \text{ nm}$ and a Rayleigh range (z_R) of about $0.93 \mu\text{m}$. (d) FWHM of the effective PSF as a function of propagation distance, evaluated at $z = 0$, z_R , and $2z_R$. (e) Average sidelobe intensity of the depletion beams in SSBB-STED and BB-STED, calculated by averaging the intensity from the outer ring radius up to ten times that radial distance. (f) FWHM of the effective PSF in SSBB-STED for different depletion beam powers.

focal volume, whereas the BB and SSBB distribute their energy along the propagation axis. Consequently, a higher total input power is required for the non-diffracting beams to match the peak intensity and depletion efficiency of the LG beam. While conventional STED is more power-efficient within a localised region, it lacks the DoF required for single-shot volumetric light-sheet imaging, as it suffers from rapid defocusing. By maintaining 500 *mW* for both the BB and SSBB-STED simulations, a direct and fair comparison is established between the two non-diffracting depletion beams.

From the simulation results, the FWHM of the effective PSF in SSBB-STED is 140 *nm* at the $z = 0$ plane. At $z = 2z_R$, the FWHM increases by only about 12% (Fig. 5.18a and 5.18d). For BB-STED, the FWHM remains almost invariant over the same propagation distance. The FWHM increase in SSBB-STED is small compared to conventional STED, and it arises from the faster reduction of the depletion beam intensity with propagation in SSBB-STED relative to BB-STED.

The primary advantage of SSBB-STED over BB-STED lies in the significantly lower sidelobe intensity of the depletion beam, which can lead to a substantial reduction in photobleaching outside the region of interest. As shown in Fig. 5.18e, the average sidelobe intensity in SSBB-STED is considerably lower than that in BB-STED, particularly in regions close to the optical axis. Previous experimental studies have shown that, for Atto565, the photobleaching rate scales approximately as $I_{STED}^{1.9}$, where I_{STED} is the depletion beam intensity (Oracz *et al.* (2017)). As a result, even a small reduction in sidelobe intensity leads to a much larger reduction in photobleaching. Furthermore, SSBB depletion beams offer tunability of the sidelobe intensity through adjustment of the radial wavevector ratio. This parameter is directly related to the depth of field of the beam and enables an effective trade-off between sidelobe suppression, propagation invariance, and photobleaching reduction.

Figure 5.18f shows the dependence of the FWHM of the effective PSF on depletion

beam power in SSBB-STED. Higher depletion powers reduce FWHM but increase photobleaching risk. SSBB depletion beams minimise unwanted photobleaching outside the central region of interest compared to conventional BB depletion beams. However, the central region receives the same depletion power and bleaching risk for equivalent resolution in both BB and SSBB.

5.5 EFFECT OF FABRICATION IMPERFECTIONS ON DIFFRACTION EFFICIENCY

Additional FDTD simulations were performed to analyse the efficiency loss in the fabricated elements. The silicon nitride Bessel beam element was simulated using both a continuous phase profile and an 8-level discretised phase profile to evaluate the effect of phase discretisation on the diffraction efficiency. The efficiency loss due to phase discretisation was found to be minimal. While the continuous-phase element directed approximately 95% of the transmitted energy into the ring, the 8-level discretised element showed only a slight reduction to about 90%. The corresponding results are shown in Fig. 5.19.

To introduce fabrication imperfections related to patterning and etching processes, a lateral undercut of 15%, inward sidewall tapering of 1%, and pillar deformation of ± 15 nm were incorporated into the simulations. The results are shown in the Fig. 5.20. These imperfections redistribute a larger fraction of the transmitted energy into the zeroth and higher diffraction orders. Approximately 12.5% of the transmitted energy is observed in the zeroth order, while about 17% is distributed into the higher orders. About 70.5% of the energy is observed within the desired ring.

For the silicon metasurfaces, the experimental diffraction efficiencies were measured to be approximately 48% for the Bessel beam and 40% for the SSBB. For the silicon nitride metasurfaces, the corresponding values were 31% and 25%, respectively. The comparatively lower efficiency of the silicon nitride metasurface could be due to its higher-

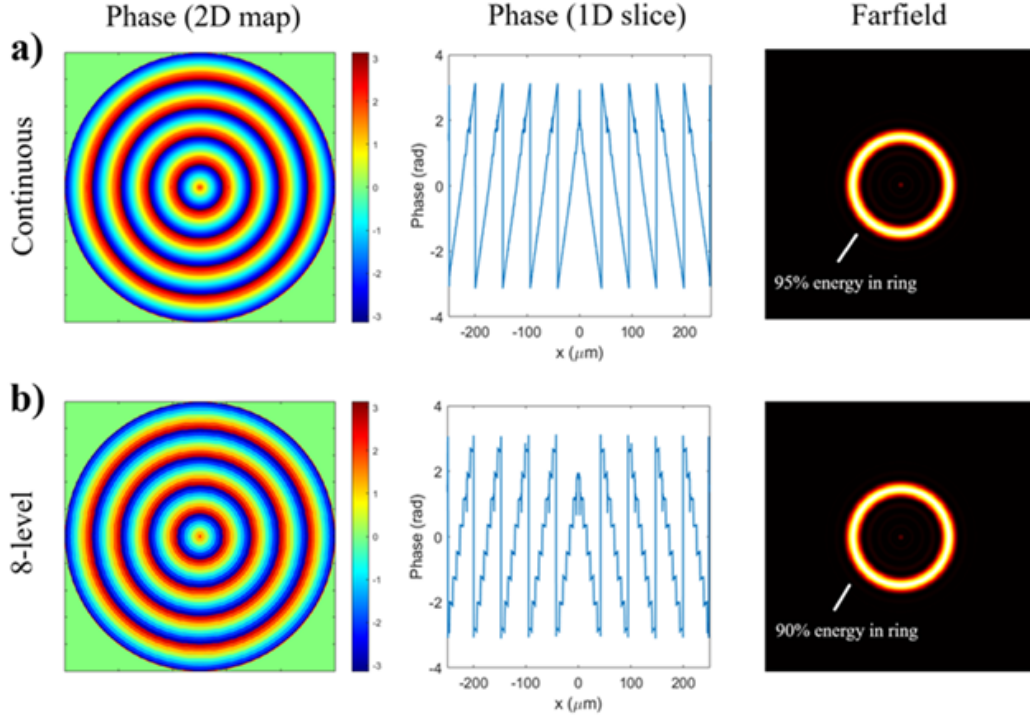


Figure 5.19: Comparison of the simulated (FDTD) silicon nitride Bessel beam metasurface using (a) a continuous phase profile and (b) an 8-level discretised phase profile.

aspect-ratio nanopillars, which are more susceptible to fabrication-induced imperfections. The further reduction in efficiency observed experimentally, compared to the simulations, may be due to a greater degree of structural imperfections, along with additional factors such as non-homogeneity in the dielectric film and etching-induced roughness.

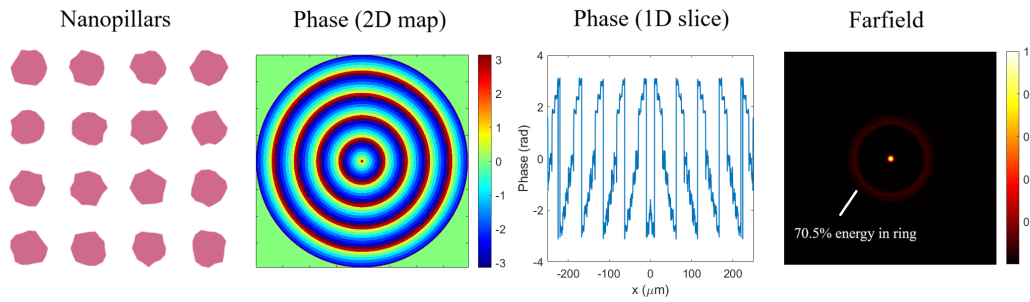


Figure 5.20: FDTD simulation of the silicon nitride Bessel beam metasurface incorporating fabrication imperfections.

5.6 SUMMARY

This chapter presented the experimental generation of SSBBs at 1064 *nm* using a polysilicon metasurface. The SSBB demonstrated more than a 50% reduction in the first sidelobe peak intensity compared to the BB. The generated SSBB also exhibited propagation-invariant and self-healing properties, which are crucial for depth imaging in biological samples. However, this sidelobe suppression comes with a trade-off. As the sidelobe suppression increases, the DoF decreases compared to the BB. Nevertheless, SSBBs offer significant flexibility, as the sidelobe suppression and DoF can be tuned by adjusting the radial wavevector ratio.

Using the same metasurface combined with a spiral phase plate, a first-order SSBB was also generated, which showed substantial sidelobe reduction compared to the first-order BB. Its propagation-invariant and self-healing properties were likewise confirmed. However, despite successful beam generation, practical implementation was limited by the operating wavelength of the polysilicon metasurface. To overcome this limitation, silicon nitride metasurfaces were explored in the latter part of the study.

Using silicon nitride metasurfaces, the generation of SSBBs and BBs at 642 *nm* was demonstrated. Additionally, a selective spatial filtering technique in the far field was employed to achieve sidelobe reduction in the BB along a particular axis. All these beams were scanned using a galvanometer mirror to form light sheets. The scanned SSBB light-sheet exhibited a reduced tail compared to the BB, while the sectional BB showed moderate improvement, mainly through a reduction in the main-lobe minima after scanning. These different light sheets were then used to image an onion epidermal peel stained with methylene blue dye. The imaging results showed a 55% improvement in image contrast for the SSBB light-sheet compared to the BB, whereas the sectional BB light-sheet showed a 27% improvement.

In the later sections of the chapter, additional strategies to enhance the SSBB light-sheet

were explored. The generation of five copies of SSBB using a single metasurface at 642 *nm* was demonstrated. This structured illumination approach enables computational enhancement of imaging performance. Furthermore, a STED-based light-sheet configuration was proposed using a zeroth-order SSBB as the excitation beam and a first-order SSBB as the depletion beam. For this purpose, the zeroth-order beam was generated at 520 *nm*, and the first-order SSBB was generated at 642 *nm* using a single metasurface. Although experimental STED depletion was attempted, the low depletion beam power prevented the observation of measurable depletion. Therefore, a simulation study based on the analytical expression of STED was carried out, which successfully validated the performance of the proposed STED-based SSBB light-sheet microscopy.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

This thesis explored the generation of SSBBs using metasurfaces and assessed their performance in light-sheet imaging. Fabrication process flow optimisation was investigated, leading to the development of multiple fabrication routes for visible and near-infrared metasurfaces. Furthermore, structured illumination and STED-based approaches employing SSBBs were examined to improve light-sheet imaging performance.

The main contribution of this work is the generation of SSBBs using silicon and silicon nitride metasurfaces operating at both near-infrared and visible wavelengths. Sidelobe suppression is achieved using a single metasurface while largely preserving the propagation-invariant and self-healing characteristics of conventional Bessel beams. When applied to light-sheet imaging, the SSBBs exhibited reduced tail artefacts in the scanned light-sheet and improved image contrast. Furthermore, the generation of multiple copies of SSBBs enables their application in structured illumination microscopy using a single ultrathin metasurface. In addition, the simulation-based implementation of the STED principle, employing a zeroth-order SSBB as the excitation beam and a first-order SSBB as the depletion beam, demonstrates a viable pathway toward achieving super-resolution light-sheet imaging using SSBBs.

The findings of this thesis demonstrate that ultrathin meta-optical elements can be effectively integrated into light-sheet microscopy systems using complex light to improve imaging performance without the need for bulky conventional optical components. The design tunability of the SSBBs enables control over the propagation-invariant length, which directly determines the achievable field of view while simultaneously reducing

unwanted sample exposure caused by sidelobes. In this regard, SSBBs are not presented simply as "better Bessel beams" but rather as an engineered compromise between the conventional Gaussian and Bessel beams. Specifically, the design can be optimised to increase the field of view at the expense of increased sidelobes, or conversely to suppress sidelobes further by accepting a decreased field of view. This flexibility provides an intermediate solution that balances the trade-off between the limited field of view of a Gaussian sheet and the excessive sidelobe-induced background of a standard Bessel sheet. Furthermore, the incorporation of structured illumination and the application of the STED principle offer additional strategies to enhance resolution in light-sheet microscopy using SSBBs.

The light-sheet imaging demonstrations using SSBBs in this thesis were carried out only at a fundamental level, primarily due to constraints related to sample preparation and the available optical experimental setup. Fabrication reliability also remains a limitation, as variations in the dimensions of the meta-atoms resulted in reduced optical efficiency and the presence of unwanted zeroth-order diffraction that required filtering during the experiments. Although metasurfaces capable of generating beams suitable for structured illumination microscopy and STED-based light-sheet microscopy were designed and demonstrated, their full experimental implementation in light-sheet imaging was not realised because of limitations in light-source availability and precision positioning stages.

Future research will aim to enhance the efficiency of SSBB generation by reducing zeroth-order uncoupled light through improved metasurface design and fabrication control. Experimental realisation of structured illumination microscopy using SSBBs is another important direction, enabling further improvements in contrast and resolution. Additionally, the implementation of STED-based light-sheet microscopy using SSBBs as excitation and depletion beams presents a promising route toward super-resolution imaging.

Overall, the results presented in this thesis highlight the potential of metasurface-based SSBBs and their associated beam-engineering strategies for the future development of compact and high-resolution light-sheet microscopy systems.

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