

SLM-Based Generation and Simulated Quadrant Response of a Structured Laser Beam

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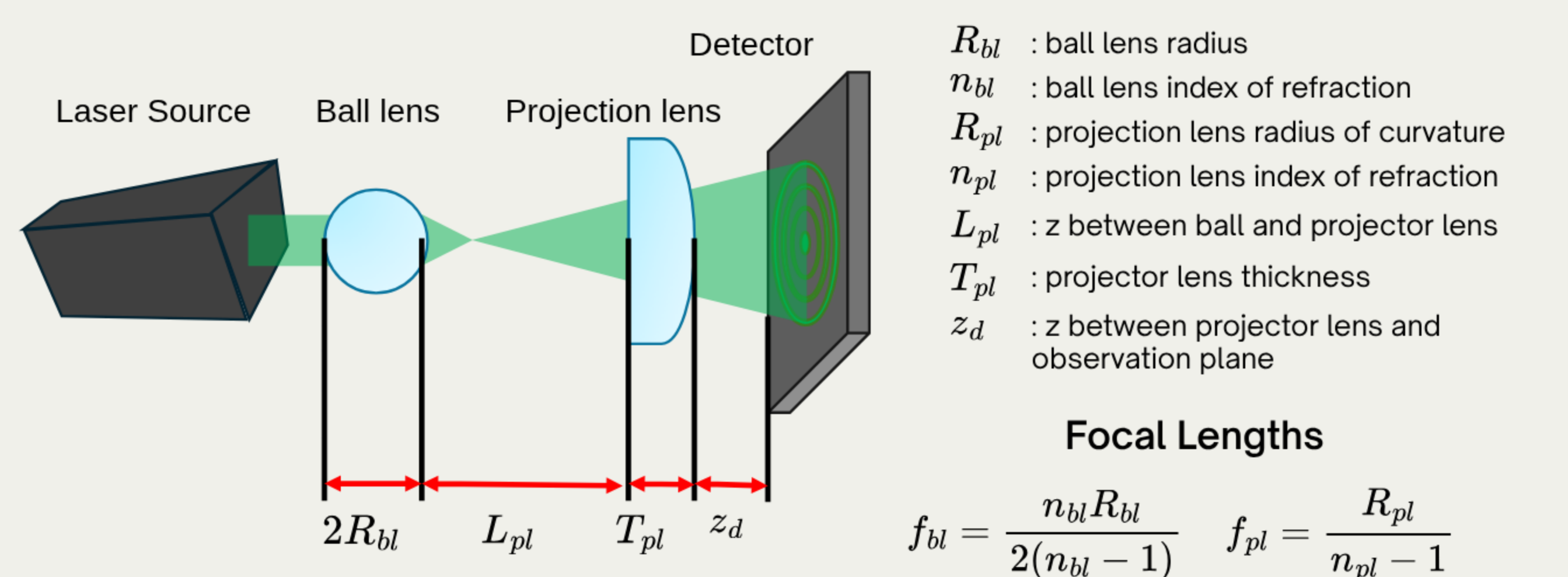
Motivation

The Structured Laser Beam (SLB) is produced by a beam generator that resembles a Keplerian telescope. This generator has the capability to generate non-diffractive light at distances that are essential for straight-line reference systems used in particle accelerators. In fact, experiments have confirmed that the SLB only diverges by 0.1 mrad at a propagation distance of 900 m [1].

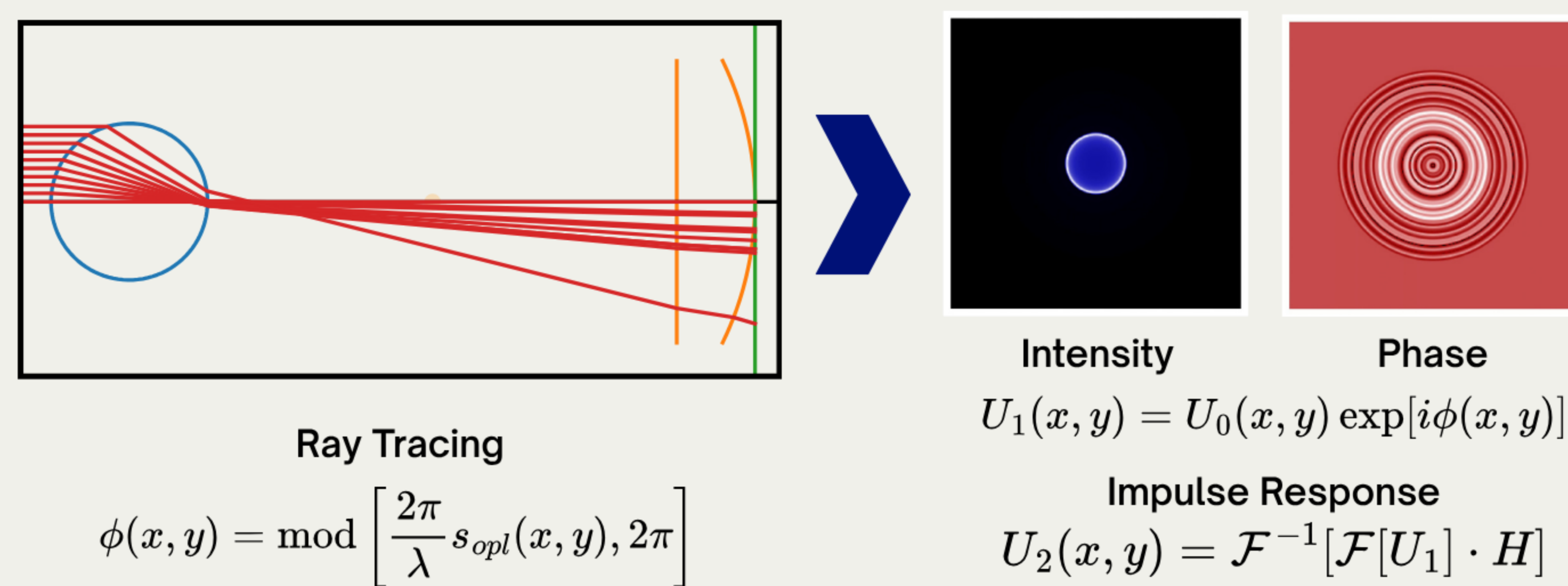
A typical misalignment detection method involves using a CMOS camera, and the response from the camera is analyzed using center-of-mass algorithms. We propose an alternative detection method using a quadrant detector (QD). QDs offer a simpler circuit construction, fewer junction pins, and reduced systemic noise propagation compared to multi-arrayed cameras.

To expedite the optimization of the beam generator in terms of QD size, we employ a Spatial Light Modulator (SLM). With the SLM, we can freely manipulate the SLB by computationally generating a hologram with multiple degrees of freedom such as the propagation distance and the lenses' index of refraction.

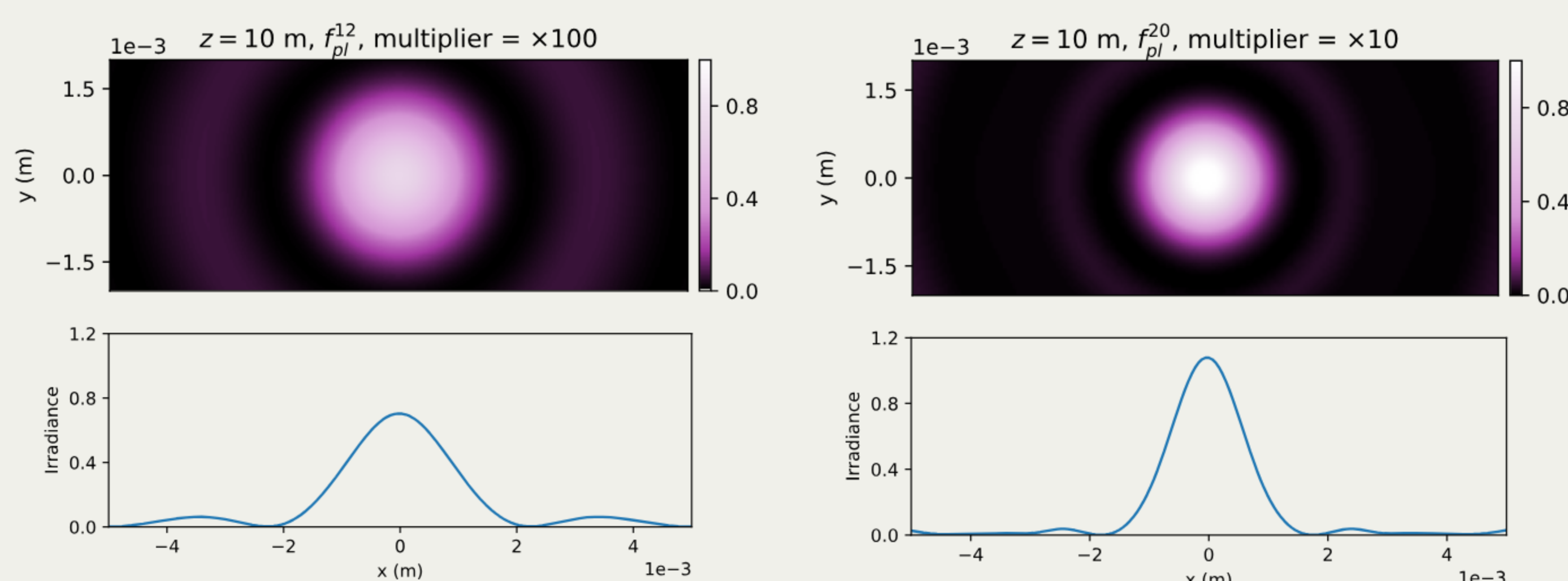
Generation of SLB [1,2]



The optical generator of the SLB resembles a Keplerian beam telescope, but the plano-convex lens at the telescope entry is replaced by a ball lens. Computationally propagating an SLB involves treating the light as rays within the optical generator and as a wave after the projection lens. Tracing the rays within the ball lens generates spherical aberrations while the projection lens expands the beam profile. At the plane tangent to the projection lens, the beam produced a wavefront (U_1), with an intensity profile ($U_0(x,y)$) resembling a soft ring aperture illuminated by a plane wave and a concentric phase profile ($\phi(x,y)$). Lastly, a Fresnel impulse response function was used to propagate the beam until $z=10m$. This results into a beam with field $U_2(x,y)$.



We generate two SLB setups with $f_{pl}^{12} = f_{pl} = 1.2$ cm and $f_{pl}^{20} = f_{pl} = 2.0$ cm. The focal lengths were similar to the ones used from the experimental setups in [2].

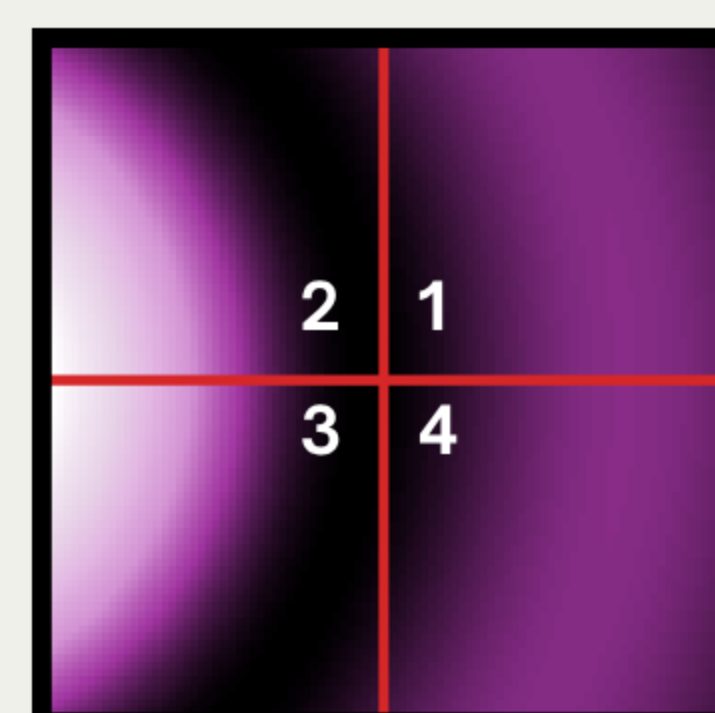


Shown here are the 2D (top) and 1D (bottom) intensity profile of the SLB setups after $z = 10m$ propagation distance, with the corresponding multiplier. The beam generated with f_{pl}^{20} projection lens has a smaller core and higher intensity compared to the f_{pl}^{12} beam.

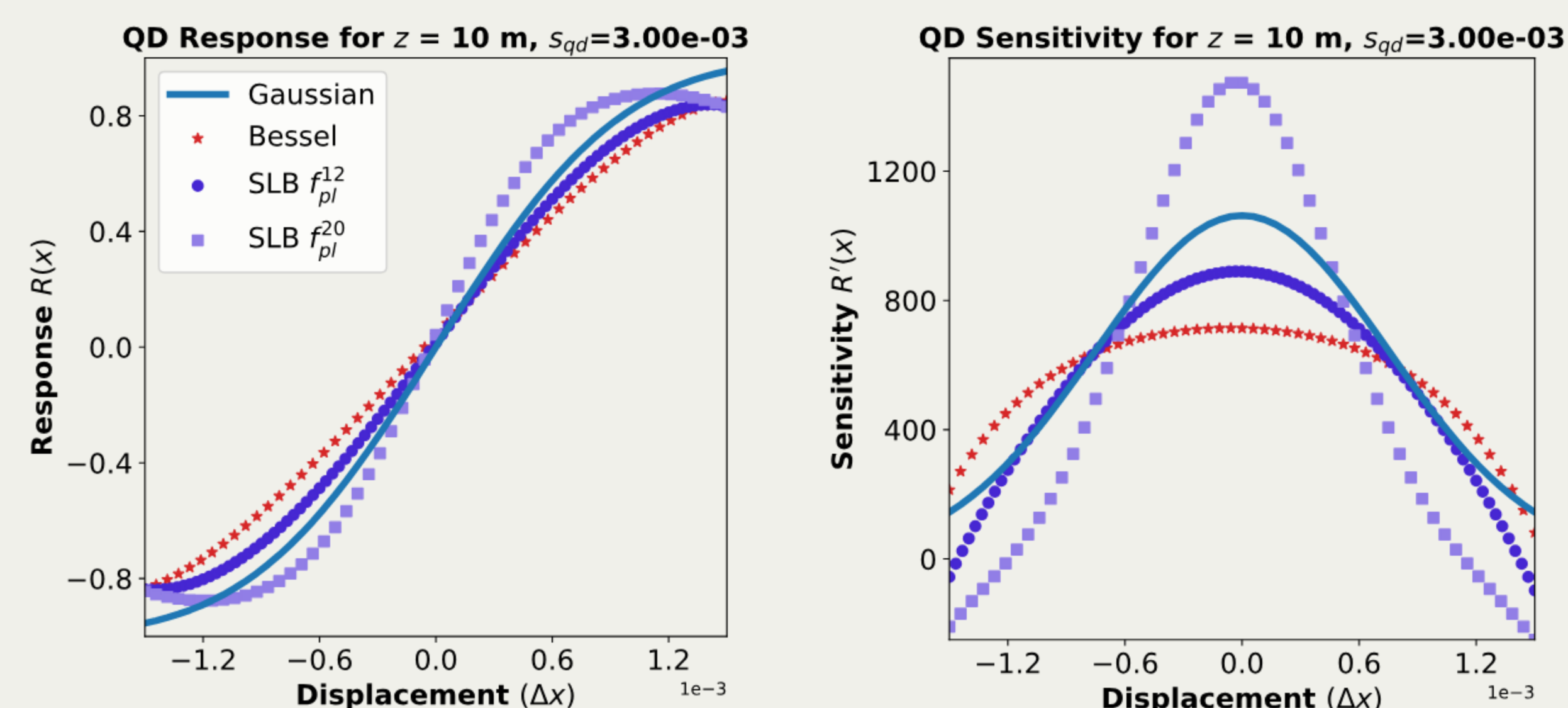
QD Response [3]

The schematic of an SLB beam traversing the QD is shown at the right. The area numbers correspond to the quadrant positions, and the response in terms of displacement along x is calculated by solving the area of the SLB intensity $I(x,y) = |U_2(x,y)|^2$ using

$$R_x(x, y) = \frac{(\int_1 I \cdot ds + \int_4 I \cdot ds) - (\int_2 I \cdot ds + \int_3 I \cdot ds)}{\sum_i \int_i I \cdot ds}$$



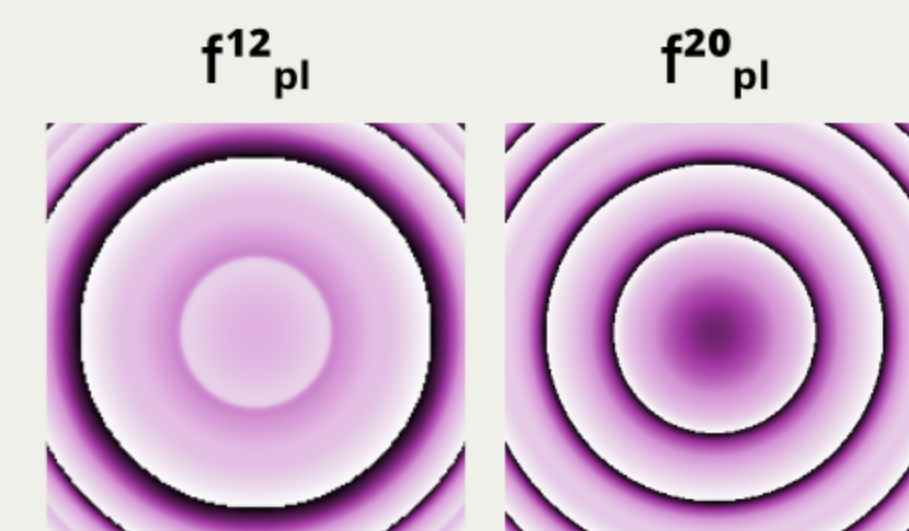
We translated the SLB setups within a square detector of size 3 mm, and compared it with the Bessel beam with an inner core radius of 1.5 mm and a Gaussian beam with a waist size of 1.5 mm propagated at $z = 10$ m.



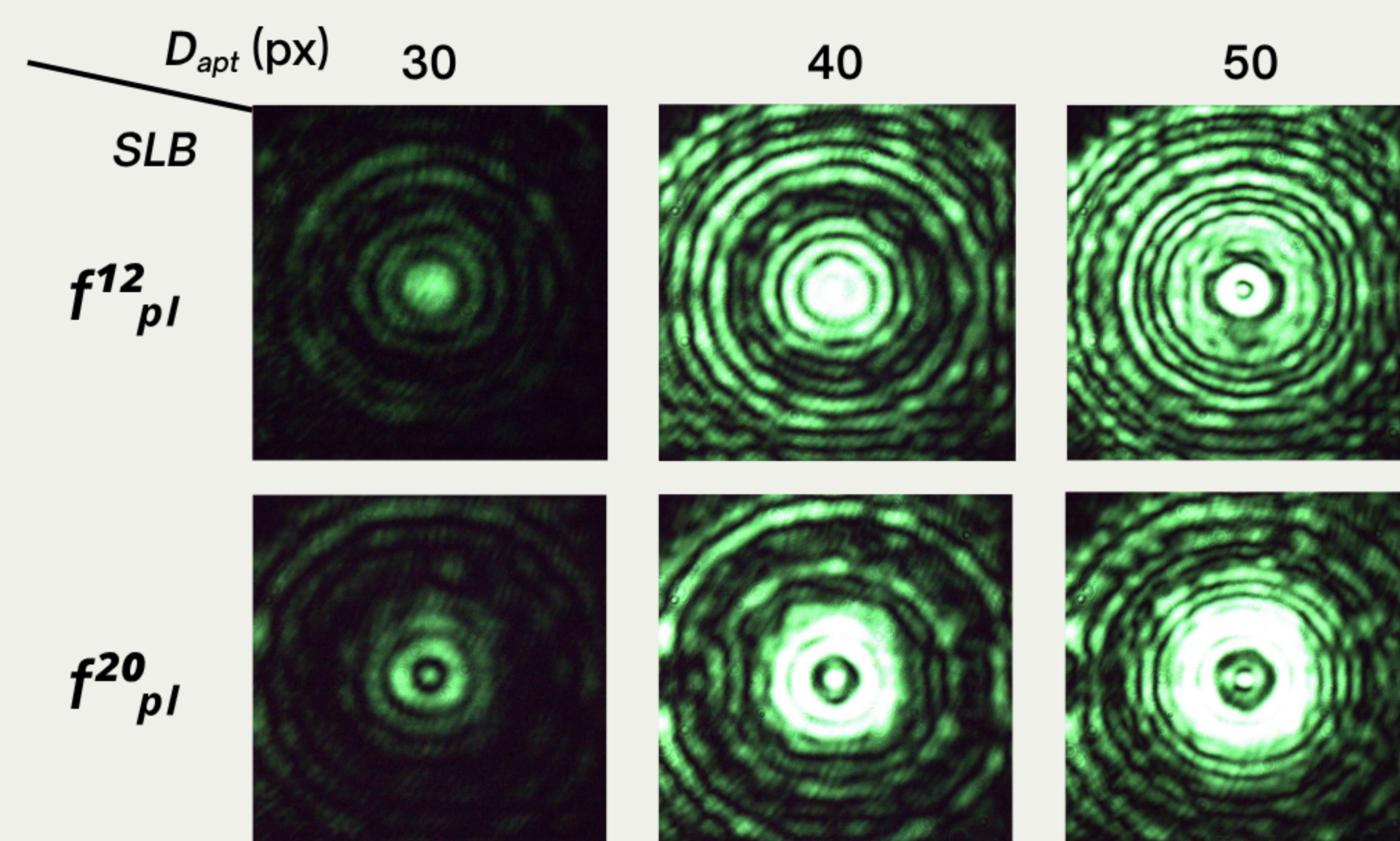
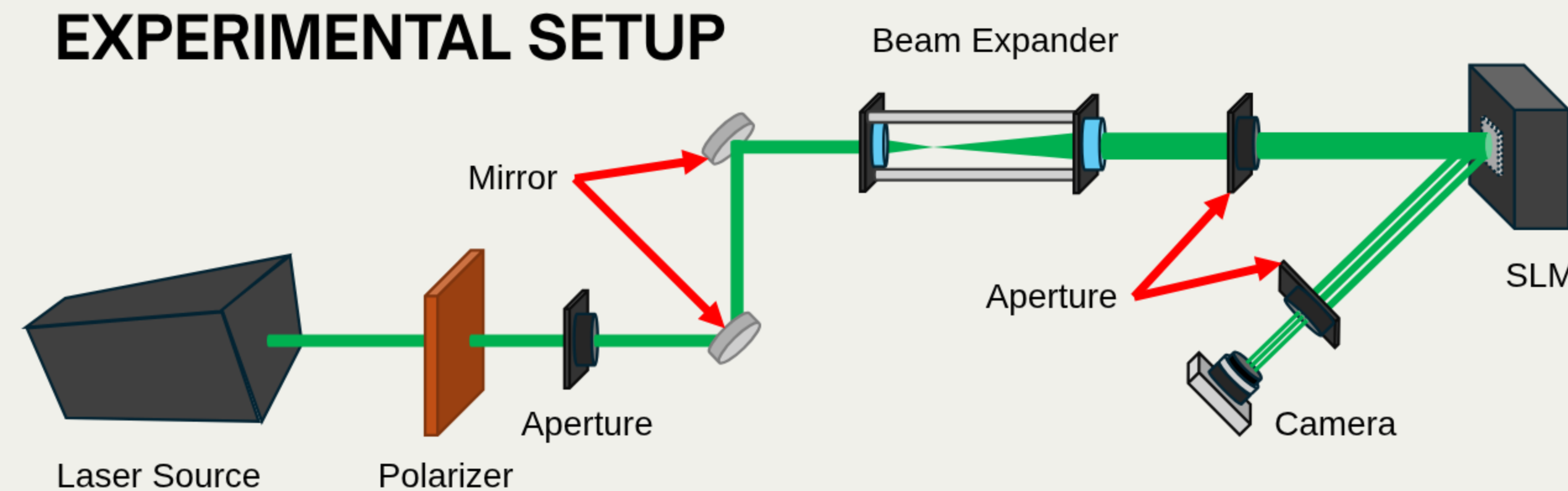
Shown here are the plots for response $R(x)$ (left) and sensitivity $R'(x)$ (right). $R(x) = -1$ indicate that most of the beam wavefront is translated at the left, while $R(x) = 1$ indicate the opposite. A steeper response corresponds to greater sensitivity ($R'(x)$). In addition, $R'(x) < 0$ values indicate beam truncation. This means that in terms of response sensitivity, $SLB f_{pl}^{20} > \text{Gaussian} > SLB f_{pl}^{12} > \text{Bessel}$, and for truncation tolerance, $\text{Bessel} > \text{Gaussian} > SLB f_{pl}^{12} > SLB f_{pl}^{20}$. We will experimentally verify these results in the future.

SLM Reproduction

Shown in the right are the phase distributions of $SLB f_{pl}^{12}$ and $SLB f_{pl}^{20}$ from their $U_2(x,y)$ field. These were uploaded to the SLM truncated, with a circular aperture D_{apt} with a diameter measured in pixels (px). For the $SLB f_{pl}^{12}$, 1 px $\sim 33 \mu m$ while for the $SLB f_{pl}^{20}$, 1 px $\sim 58 \mu m$.



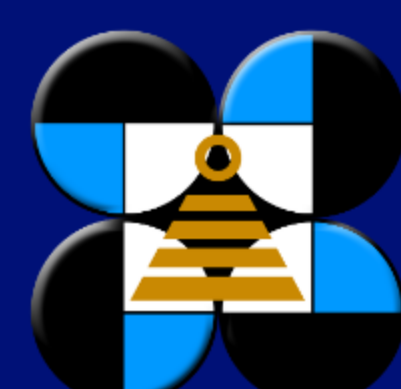
EXPERIMENTAL SETUP



Shown above are the first-order SLM holograms of the uploaded phase distributions for SLB. We show that a 40 px circular aperture provides sufficient first-order contrast for clear SLB reproduction, while smaller and larger apertures show reduced reconstruction quality.

References:

- [1] Polak, K., Dusek, M., Sulc, M., and Gayde, J.C. (2024). Approximate analytical description of the structured laser beam in the far zone. Opt. Express, 32(27)
- [2] Niewiem, W., Polak, K., Dusek, M., Mergelkuhl, D., Gayde, J.C., Wieser, A., and Sulc, M. (2023). Variation of structured laser beam pattern and optimization for an alignment reference line creation. Opt. Express, 31(26).
- [3] Narag, J., and Hermosa, N. (2017). Response of quadrant detectors to structured beams via convolution integrals. J. Opt. Soc. Am. A. 34(7).



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