Reconfigurable Polarization Shaping with a Single Metasurface

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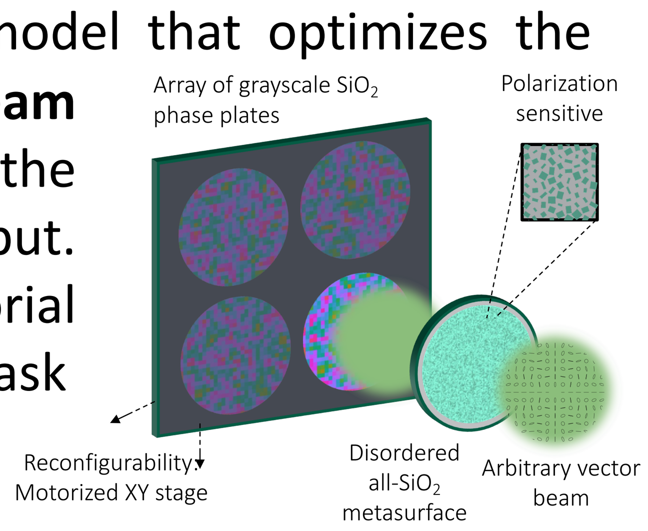
Motivation and Objectives

Metasurfaces are commonly used for beam structuring since they are made up of **sub-wavelength resonators** that offer control at the nano-scale of the form birefringence. This makes them the best option for **polarization shaping**. However, beam shaping techniques that rely on metasurfaces face a great challenge when structuring **vectorial light** at high power. To operate below the damage threshold of these materials, the beam is expanded, so large metasurfaces are required. As a result, fabrication costs become extremely high, imposing restraints on applications that rely on these beams, such as material processing and laser-induced nuclear fusion. For this reason, we aim to design a system that requires only **one static birefringent metasurface** capable of **multifunctional vectorial shaping,** drastically reducing production costs. To design this system, we use **Machine Learning (ML) techniques** described below.

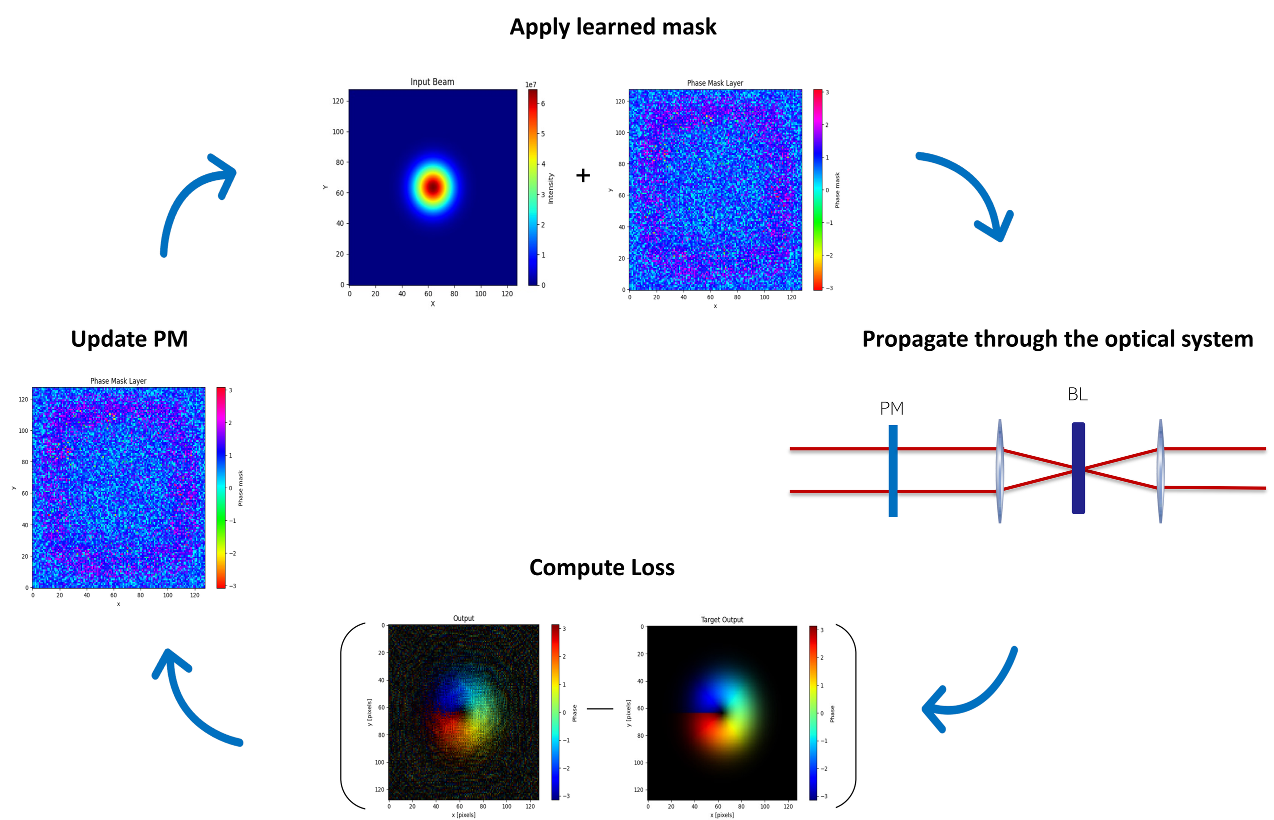
Fundamentals

Light beams can be engineered to have arbitrary spatial distributions of their degrees of freedom. In the case of **vectorial light**, its **polarization** states are manipulated to have an **anisotropic distribution**. In this work, we tailor the beam's polarization using a single birefringent layer with a random profile. This is possible using a ML model that optimizes the phase profile of the **scalar input beam** that needs to be propagated through the optical system to get the target output. This way, we can get several vectorial beams by simply adjusting the phase mask in the system.

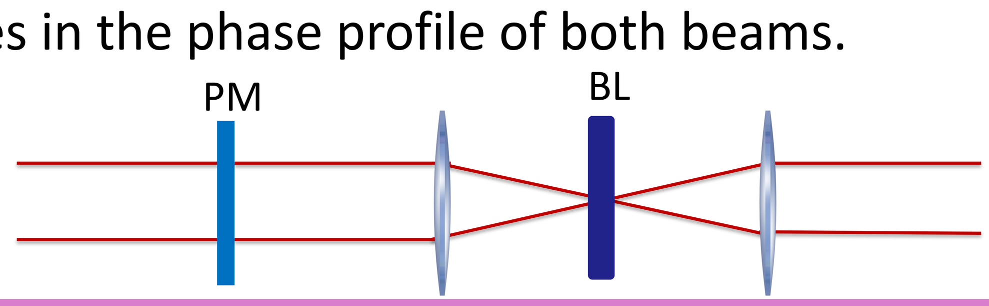


Methods

To obtain arbitrary vectorial outputs from a single disorder-engineered birefringent metasurface layer (BL) in combination with custom scalar phase plates, we designed a ML algorithm that optimizes the phase mask (PM) that needs to be placed in the system, so the output is the target vector beam.

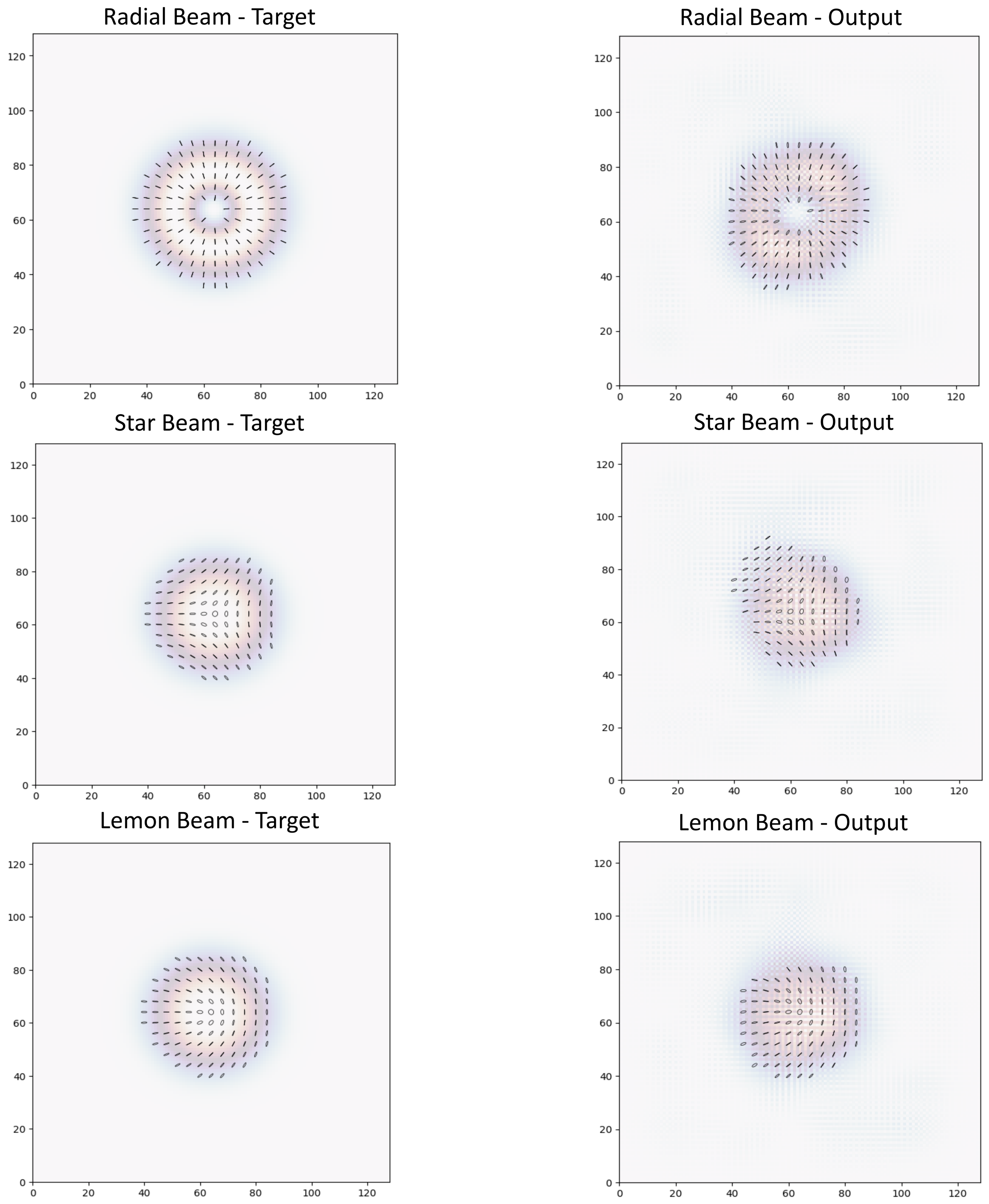


The BL generates a fast-axis orientation angle map - $\theta(x,y)$ - from a specified probability distribution function, acting like an array of **random half-wave plates (HWP)**. For each distribution, we train the PM using ***AdamW*** and ***CosineAnnealingLR*** with gradient clipping. After testing, the final model is the one with the best overlap between the output and the target. The optical system is constituted by linear differentiable layers, so the non-linearity comes from the loss function chosen. This function computes the mean squared error between the output and the target but also considers losses in the overlap error and differences in the phase profile of both beams.



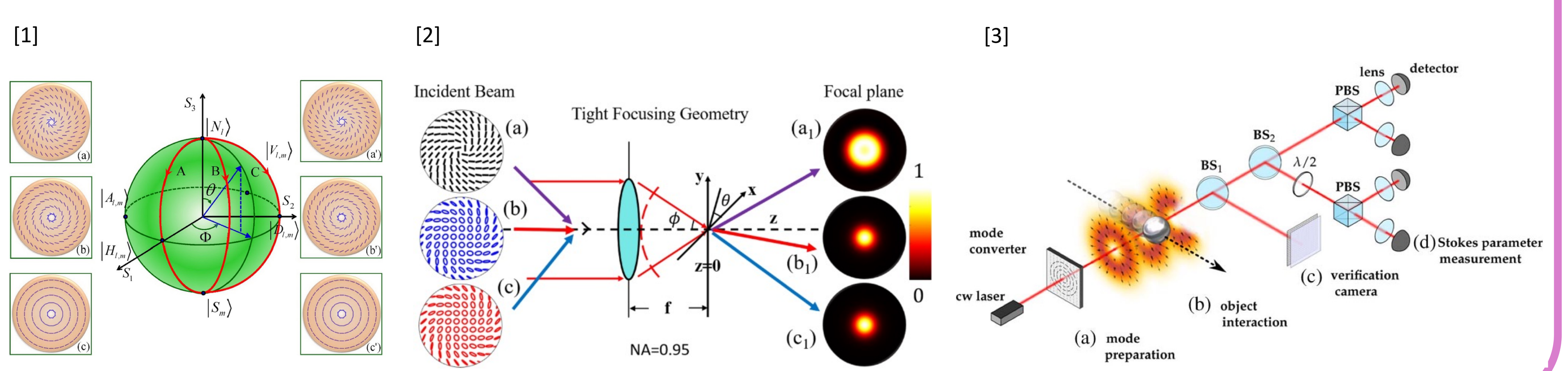
Simulation Results

Starting from a **simple horizontally polarized Gaussian (scalar)**, we were able to obtain progressively more complex vector beams **using a single birefringent metasurface**: from radially polarized vector vortex beams, to beams with polarization singularities such as lemons and stars.



Conclusions

Vector beams are crucial for many applications like material processing, optical trapping, imaging, optical communications, among others. As such, it is vital that the generation of these beams is straightforward and budget-friendly. With our system, we can perform **multifunctional vectorial modulation** using a simple scalar input and one single metasurface with engineered disorder. Fabricating this metasurface in resistant materials like fused silica, allows the generation of this beams at high power, unlocking the door for wide use of these beams in the applications mentioned above.



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References

[1] Xunong Yi et al., Phys. Rev. A 91, 023801 (2015)
[2] Pal, S.K. et al., Sci Rep 14, 13565 (2024)
[3] Stefan Berg-Johansen et al., Optica 2, 864-868 (2015)

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