Analog logic gates of structured light based on Optical Neural Networks

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Motivation and Objectives

Optical Neural Networks (ONNs) have multiple applications, like information processing or image recognition. One of them can be Optical Logic Gates. This work aims to experimentally perform an **AND analog logic gate**, using an optical system based on nonlinear ONN. An AND gate is the most basic nonlinear testbed, and so, once its realization is demonstrated, new potentialities with ONNs can be unlocked. Hence, it will serve as a proof of concept of the potential of nonlinear ONN. Even more, this work can lead to a new way of obtaining structured light.

The project will be carried out in two phases. The first phase is focused on studying **optical nonlinearity**, particularly in Kerr media, to introduce nonlinearity into the system. The second phase is the experimental realization of an **Optical Decoder based on ONNs,** which involves the training of a Machine Learning Model to obtain the holograms for the Physical Neural Network.

In the image on the right, the optical decoder 2x3 aimed is shown.

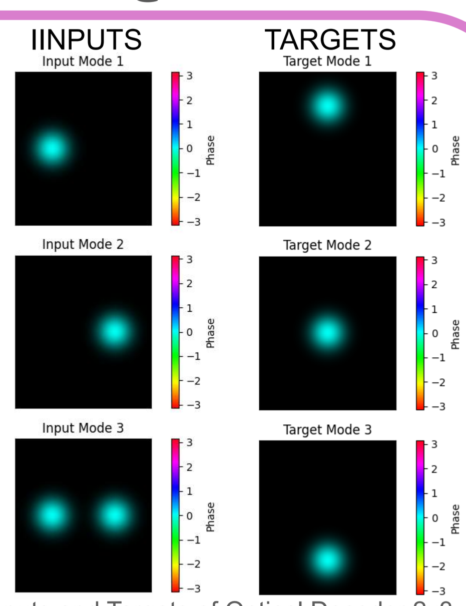


Fig 1: Inputs and Targets of Optical Decoder 2x3

Fundamentals

- **Optical Kerr Effect**

Third Order Term

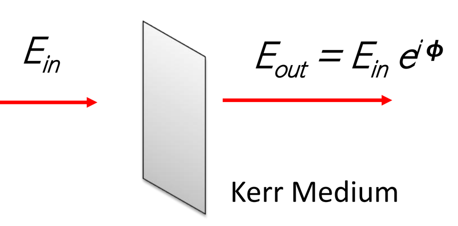
$$\mathbf{P} = \epsilon_0[\chi^{(1)}E + \chi^{(2)}EE + \chi^{(3)}EEE + ...]$$

Change in the refractive index:

$$n = n_0 + n_2 I$$

Nonlinear Index

Gaussian Beam propagating in a Kerr Medium will result in a change in the phase front, and a phase shift that can be quantified. This phase shift will result in a self-focusing effect.



Phase Shift: $\delta\Phi = \frac{2\pi}{\lambda} n_2 L I$

Fig 2: Phase Shift of a beam passing through a Kerr Medium

- **Spatial Light Modulator and Holograms**

To have a tunable ONN, a Spatial Light Modulator (SLM) is introduced. This device has the ability to modulate the phase of the incident light. By using Liquid Crystals and an applied voltage, it is possible to display any hologram. To know the holograms to display, a **machine learning model** needs to be trained, to obtain the best phase masks.

Materials and Methods

- **Z-Scan**

The Z-Scan technique relies on the spatial distortion of a Gaussian beam and the self-focusing effect to study the nonlinear Kerr effect. The method uses the changes in the far field intensity distributions to calculate the nonlinear index.

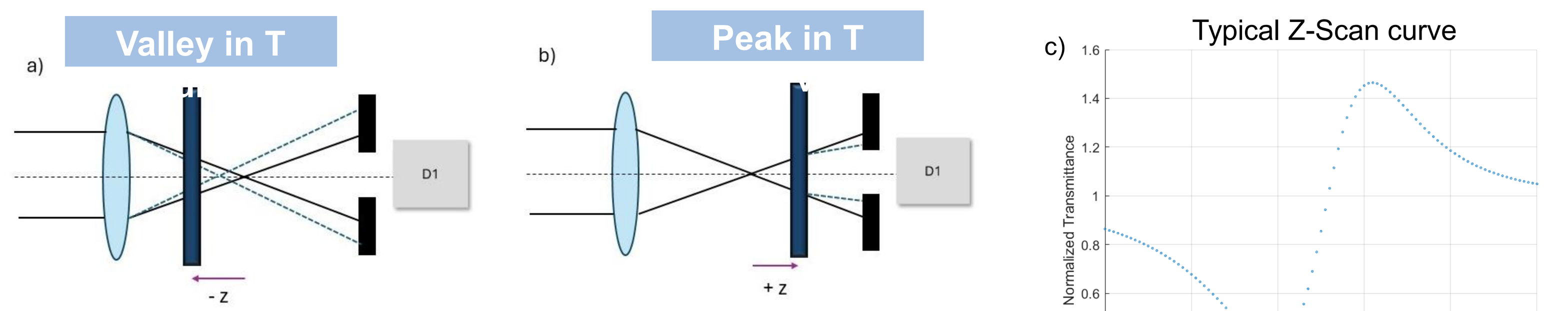


Fig 3: (a) Sample before focus; (b) Sample after focus. The solid lines are the linear optics propagation, and the blue dashed lines are the propagation considering the nonlinearity of the sample. (c) Z-Scan Curve for sample with positive nonlinear index

- Experimental Set-up for the Z-Scan:

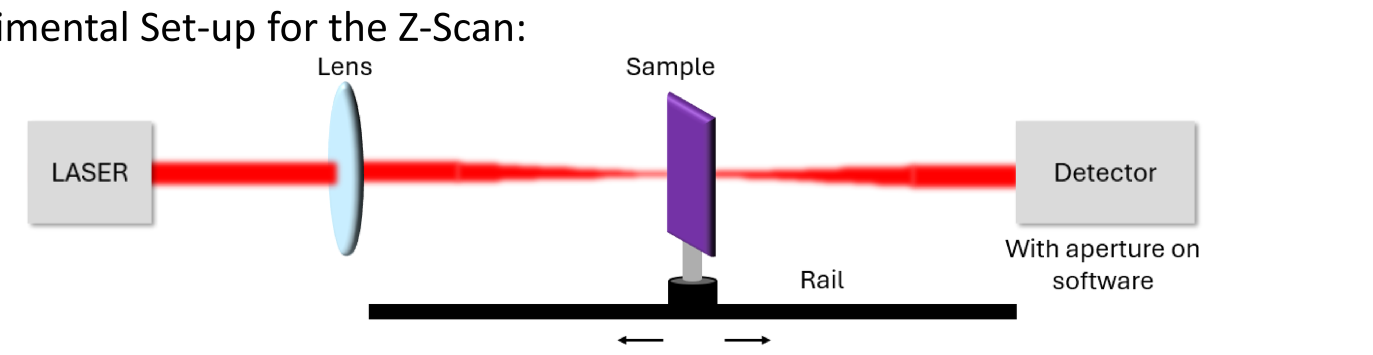
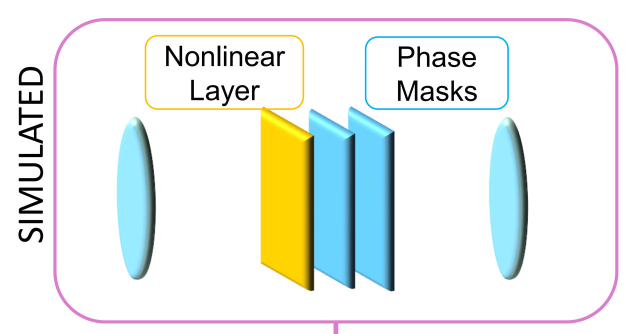


Fig 4: Experimental Set-up used for the Z-Scan measurements. Detector used was a CCD Camera, and no physical aperture was used, only digital.

- **Optical Decoder**



- Machine Learning (ML) Model to simulate the system, using **PyTorch**
- Each component of the physical system is defined as a layer on the simulation
- The trainable parameters of the Neural Network are the Phase Masks (PM)
- The goal of this ML model is to obtain the PM to input in the SLM

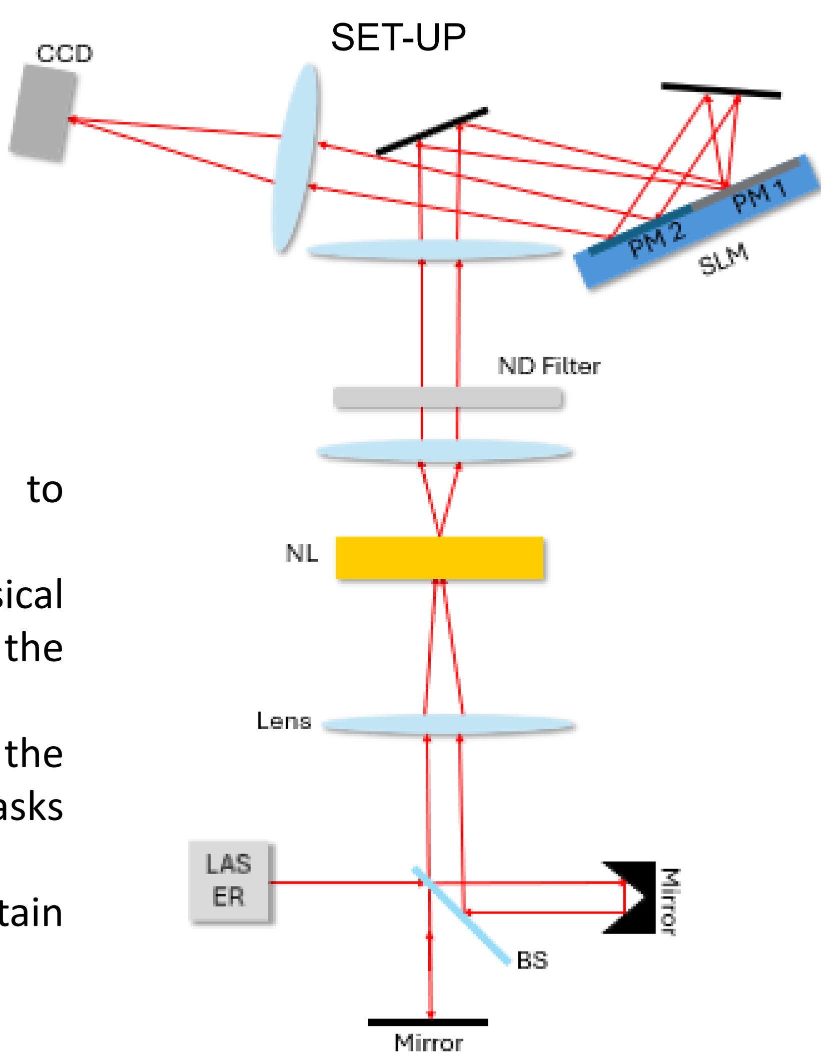
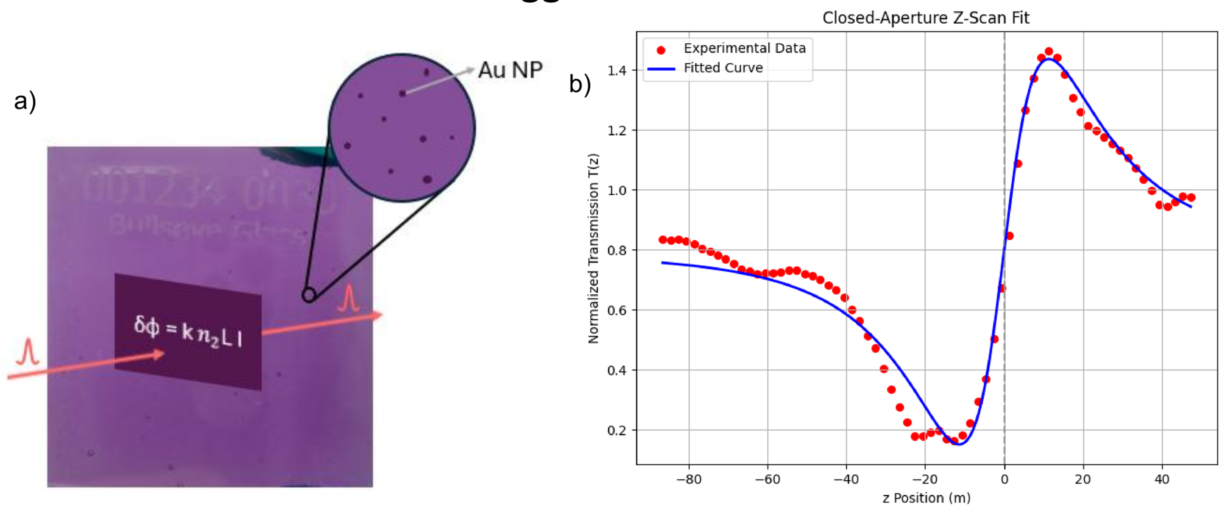


Fig 5: Experimental Set-up for the Optical Decoder.

Simulation Results

- **Z-Scan and Kerr Medium**

To choose the best material for the nonlinear layer, a z-scan was performed on some samples. The samples were of fused silica (SiO_2) and fused silica with gold (Au) nanoparticles (NP). The purple glass with Au NP was the one with bigger phase shift, hence it is the one chosen for the physical system.



At 15 µJ, 2 kHz, 450 fs:

- $\delta\Phi = 2.2$ rad
- $n_2 = 6.2 \times 10^{-16} cm^2/W$

Fig 6: (a) purple glass sample; (b) z-scan measure with fitted curve to obtain phase shift and nonlinear index.

- **Simulation of Kerr Effect**

To add the nonlinear layer to the ML model, a good simulation of the Kerr Effect is needed. The simulation showed the intended self-focusing effect and nonlinearity.

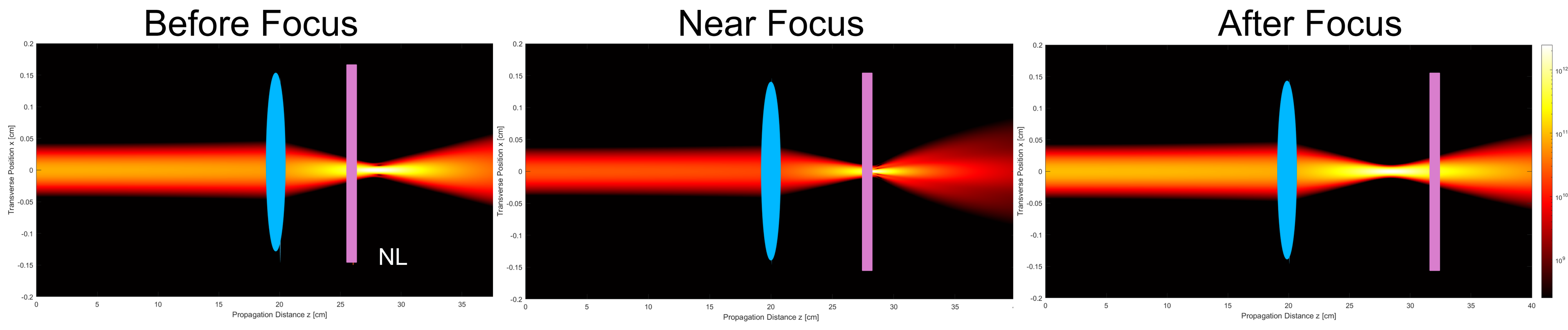


Fig 7: Simulation of a gaussian beam converging and passing through a nonlinear layer (NL), at three different positions of NL.

- **Simulation of Optical Decoder**

The ML model was changed to match the experimental set-up. It was then tested with and without the nonlinear layer, proving that **nonlinearity in the system improves the results**. The model was trained considering the real input beams, distances and optical components. At last, learned phase masks are obtained from this model.

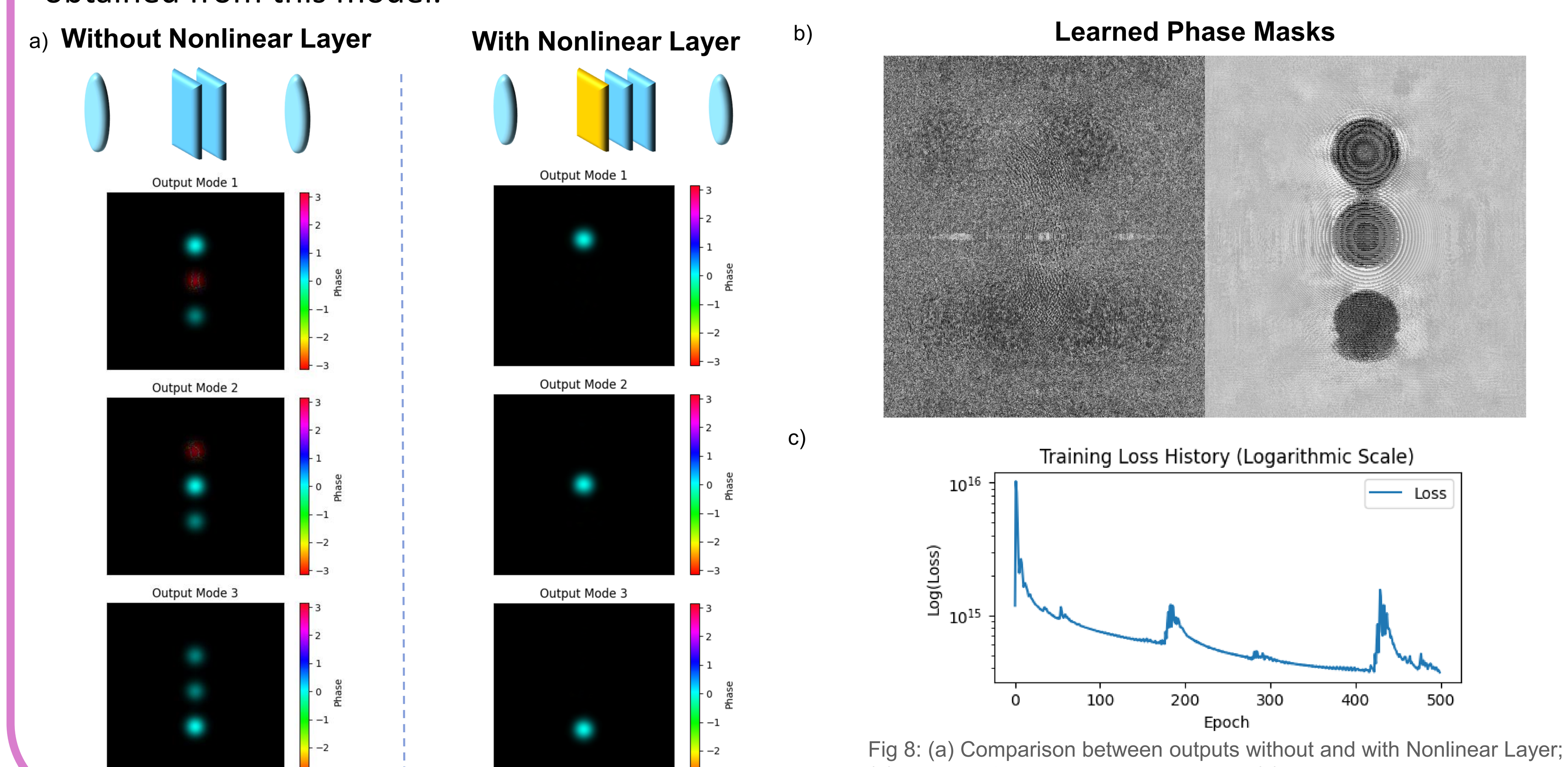


Fig 8: (a) Comparison between outputs without and with Nonlinear Layer; (b) Learned Phase Masks by ML model; (c) Training Loss History

Conclusions

- In conclusion, with this work the aim is to experimentally perform a 2x3 Optical Decoder based on Optical Neural Networks architecture. First, a study on third order nonlinearity was performed on some samples, in order to choose the best one for the system. The choice was a purple glass with gold nanoparticles. The second part of the project consists of training a Machine Learning model, that simulates the physical system, to obtain the holograms for the Spatial Light Modulator.
- The **future step** of this project is to experimentally test the phase masks in the optical decoder set-up.
- This project demonstrates how **Machine Learning** is applied to physics, not only in simulation and computational grounds, but in this case also the theoretical ideas in Neural Networks are applied to the physical system.

Funding

We acknowledged funding from the **European Research Council** (ERC StG) under the European Union's Horizon Europe research and innovation program (Grant agreement No. 101161858). INESC MN is supported by the **Fundação para a Ciência e a Tecnologia** (FCT) through the BASE (UIDB/05367/2020) and PROGRAMATICO (UIDP/05367/2020) programs, CTI (Centro de Tecnologia e Inovação)---Missão Interface/PRR (RE-C05-i02).

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