ALIGNMENT OF HIGHER-ORDER MODE SOLID-STATE LASER SYSTEMS WITH MACHINE LEARNING DIAGNOSTIC ASSISTANCE

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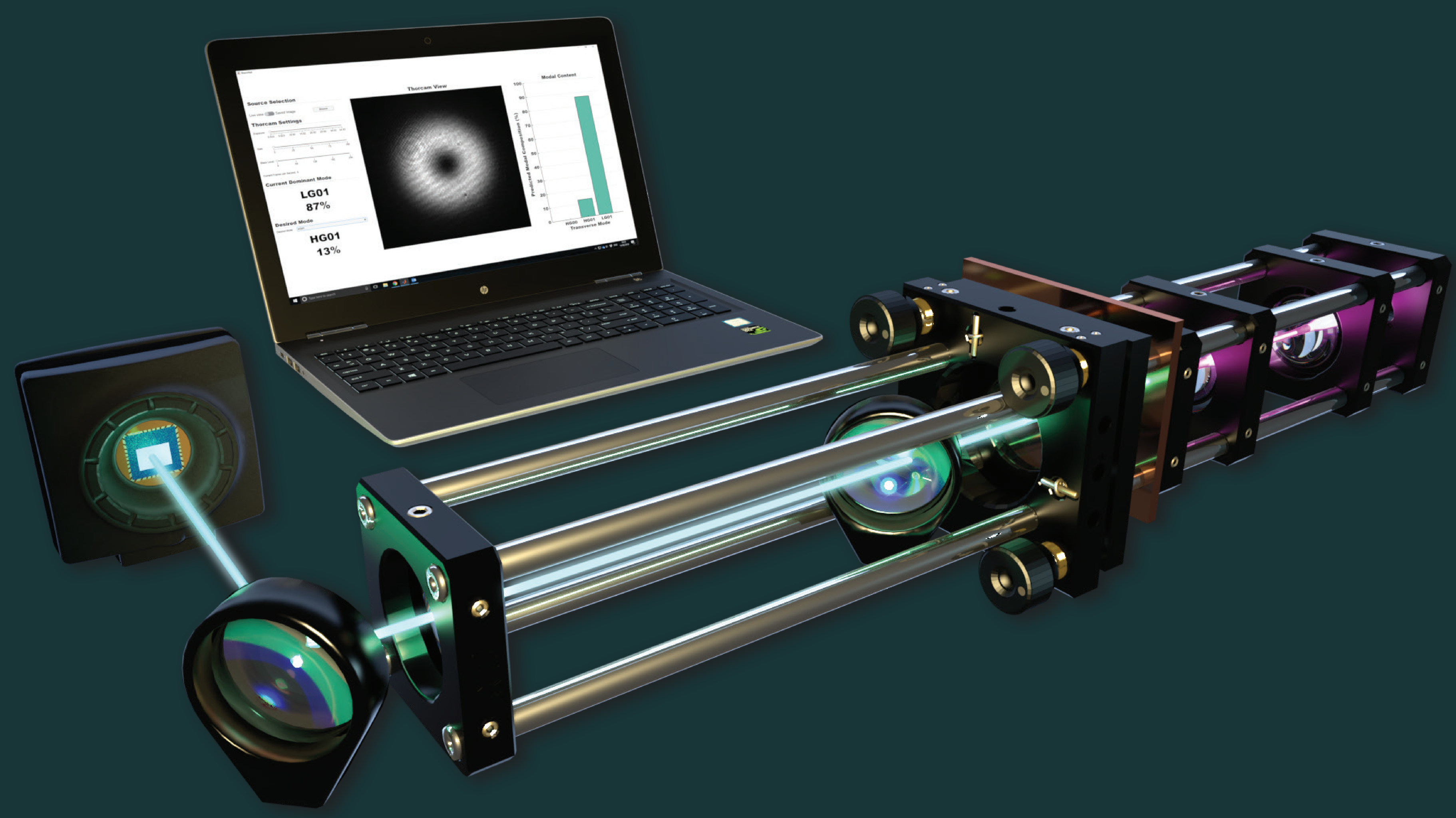
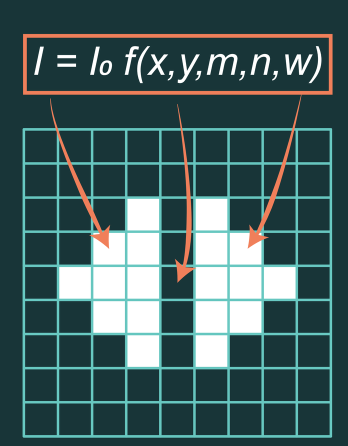
I. Introduction

- Higher-order mode lasers are seeing increased use and benefit in applications such as laser processing [1].
- We have characterization tools for power, wavelength, and temporal characteristics - but we don't have a fast metric for modal content [2].
- We developed a machine learning algorithm to predict transverse modal composition in **real-time**.
- It only requires a CCD/CMOS camera and an average computer.
- It works with any mathematically defined modes.

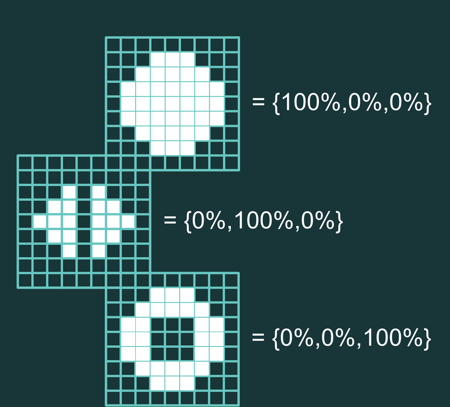


II. Method



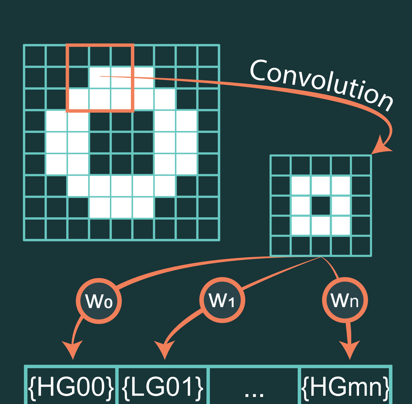
1. Training data

Training data is generated by calculating pixel values using equations for Hermite-Gaussian (HG) and Laguerre-Gaussian (LG) laser modes. Peak intensity, rotation, beam radius, and position are randomized. Incoherent additions of modes are generated in systematically spaced ratios.



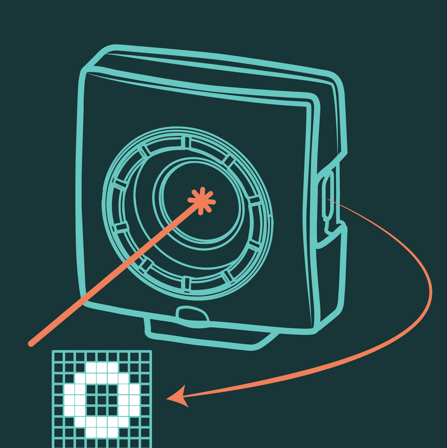
2. Labelling

18,000 128x128 8-bit greyscale images of pure and incoherently combined laser modes are generated for a training dataset. Each image is assigned a vector label of the format {mode1%, mode2% ... modeN%} denoting the fractional modal composition of the image.



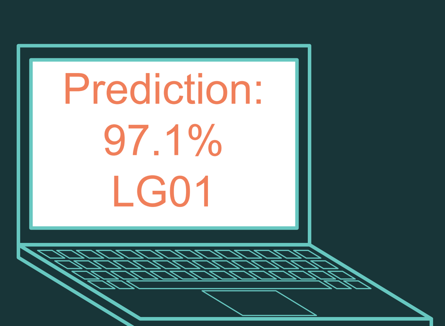
3. Training the network

The training images are convolved with a series of filter matrices to pick out the defining features of a mode. Using many layers connected with weighted nodes [3], the network can "learn" modal composition within 10 minutes by adjusting modal weights to reduce the error in the prediction.



4. Beam image capture

A Thorlabs DCC1545M CMOS camera captures a live-feed of a laser mode. The camera is subsampled to provide 128x128 pixel frames at 30 fps. Each frame is then passed to the trained convolutional neural network for modal content analysis.



5. Modal content prediction

Our trained neural network can predict the modal composition of an incident laser beam in **under 3 ms**, using only single-plane intensity images. We have information about the modal composition within timescales of upper-state laser lifetimes.

III. Results

Theoretical benchmarking

To test our trained convolutional neural network (CNN), 1,000 previously unseen theoretical images of mixtures of HG00, HG01 and LG01 modes were analysed. Our CNN was able to analyse modal composition with greater than **92% accuracy**. Examples of the predictions performed by the CNN are shown in the table on the right. Despite only single-plane intensity images, the CNN was able to accurately predict the modal content.

Theoretical Modes						
	Actual	CNN	Actual	CNN	Actual	CNN
HG00	100%	100%	0%	0%	0%	0%
HG01	0%	1%	0%	1%	75%	70%
LG01	0%	0%	100%	98%	25%	26%

Experimental testing

To experimentally verify the use of the CNN as a real-time modal content metric, a 1030 nm Yb:YAG laser was constructed which could be tuned to a variety of higher-order modes. The output mode was imaged using the CMOS camera as shown in the render above. The CNN provided a fast numerical metric which allowed the laser to be tuned to the desired modal composition. Examples of obtained modes are shown in the table on the right.

Experimental Modes			
	CNN	CNN	CNN
HG00	100%	0%	0%
HG01	0%	13%	75%
LG01	1%	87%	26%

IV. Conclusions

A convolutional neural network was created and trained using 18,000 theoretically generated, randomized images of incoherent combinations of HG00, HG01 and LG01 laser modes. The CNN was able to predict modal composition of 1,000 previously unseen modes with **>92% accuracy**, at under **3 ms** per image. An Yb:YAG laser was constructed and was aligned using the modal composition analysis of the CNN. This provided a real-time diagnostic to align pure and mixed modes.

Our CNN provides a vital new metric of modal composition which enables rapid alignment and characterization of lasers and amplifiers. This development of such a fast modal composition metric paves the way for complex control mechanisms to dynamically optimize the modal output of a laser to suit the desired application.

[1] V. G. Niziev et. al. J. Phys. D 32, 1455 (1999)
[2] O. A. Schmidt et. al. Opt. Express 19, 6741 (2011)
[3] A. Krizhevsky et. al. NeurIPS 25, 1097 (2012)

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