HiPPo: SMART LASERS FOR HIGH-POWER PHOTONICS

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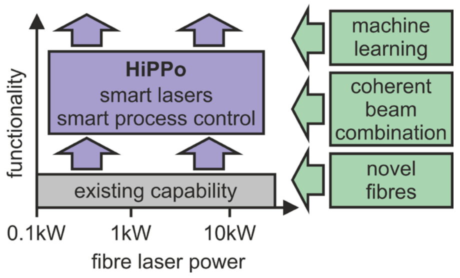

Figure 1: Creating the next generation of "smart" fibre lasers.

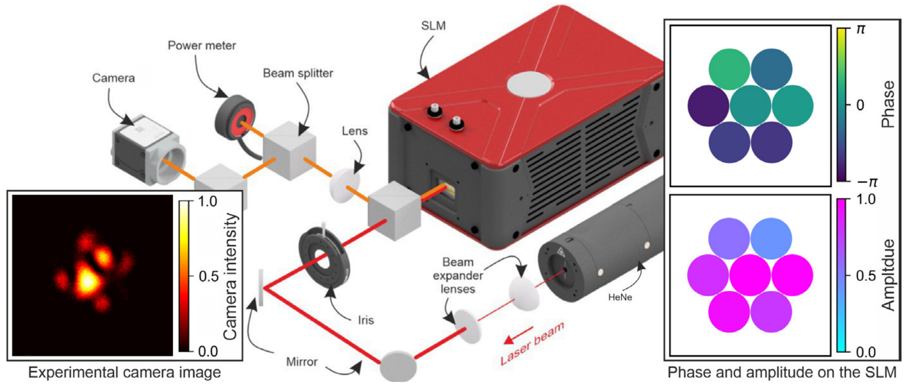

Figure 2: Using a spatial light modulator to experimentally simulate coherent beam combination of multiple fibre lasers.

A NEW ERA OF SMART FIBRE LASERS

Imagine fibre lasers that think on their feet, adjusting beam shape and power on the fly to suit any task. That's the mission of the Smart Fibre-Optic High-Power Photonics (HiPPo) programme, a five-year effort led by the University of Southampton's Optoelectronics Research Centre. The HiPPo project aims to turn today's "fixed" industrial fibre lasers into intelligent, reconfigurable tools that optimise themselves in real time (see Figure 1). Instead of a one-size-fits-all beam, these smart lasers will adapt their settings, compensate for disturbances, and deliver precisely the right laser light for each job. As the project reaches the halfway mark, we provide a progress update to the community.

THE CHALLENGE FOR HIGH POWER FIBRE LASERS

Conventional fibre lasers hit physical limits as power climbs, as single fibres suffer nonlinear effects and instabilities. A powerful solution is coherent beam combination, through merging multiple moderate-power fibres into a single high-power beam. Most importantly, coherent beam combination also unlocks dynamic beam shaping, as exotic intensity patterns can be generated simply by tweaking relative phases. However, even tiny phase drifts or noise can spoil the combined output, and so real-time phase correction is mandatory. This is where the HiPPo project comes in. We are developing high-speed, real-time, machine learning control systems that can correct phase errors in a single step, keeping tens (or even hundreds) of fibre lasers synchronised.

DEVELOPING THE MACHINE LEARNING APPROACHES

We have created a dedicated "photonics and AI" laboratory, where we experimentally simulate the effect of coherent beam combination through using spatial light modulators and eye-safe lasers (see Figure 2), to allow rapid iterations on the designs of our machine learning algorithms. We can choose the number of beams (in this case, seven beams), along with their phase and amplitude, and then we can observe the combined beam on the camera, which would in practice be the beam shape at the workpiece.

In the case of seven beams (i.e., seven fibres), if the phase values are random, then the combined beam will likely be not useable for manufacturing applications (see Figure 3). For many cases, you might want the phases of all beams to be the same, to make all the intensity combine into a single spot. However, a major advantage of coherent beam combination is the ability to produce exotic beams on demand, such as petal shapes.

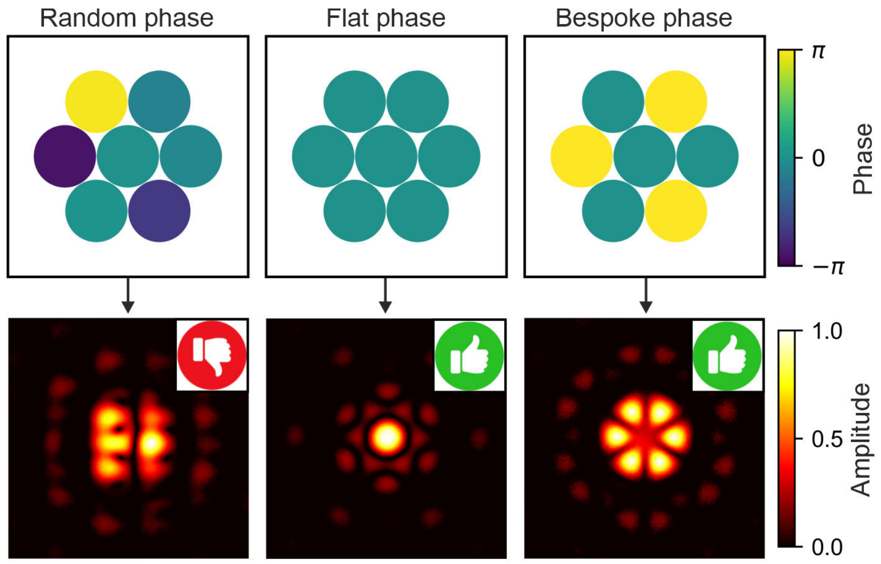

Figure 3: Examples of combined intensity patterns for different phase values.

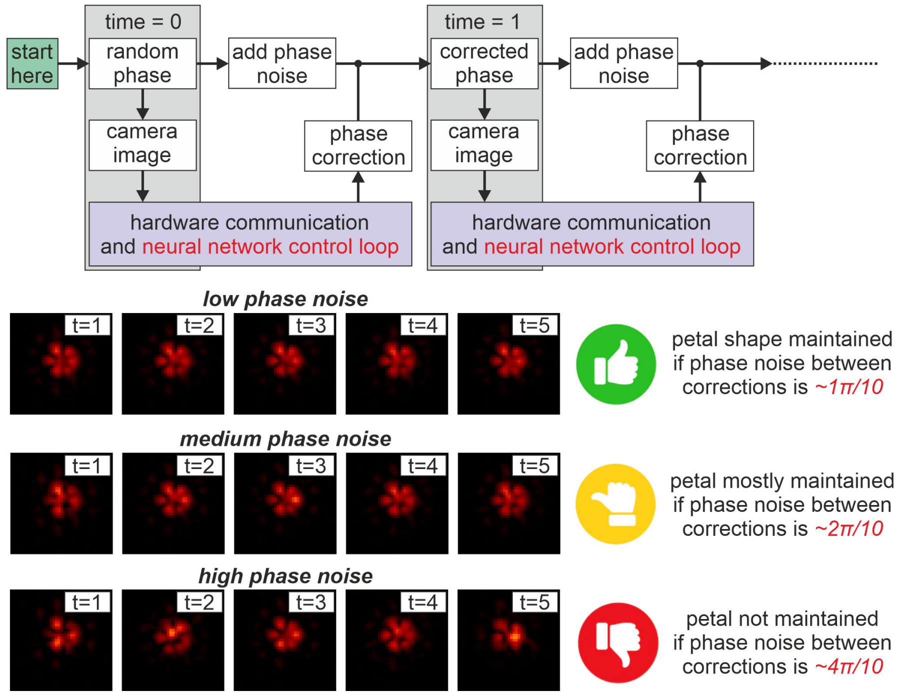

Figure 4: Real-time machine learning control loop schematic, and experimental demonstration of maintaining a petal beam, from seven beams, for different noise levels.

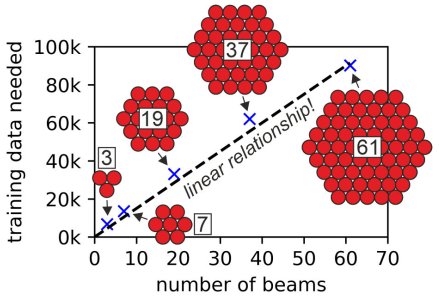

Figure 5: The amount of training data needed increases linearly as the number of beams increases.

Our machine learning approach for controlling the phases of the beams is to send a camera image of the combined beam to a neural network, which then identifies and applies the phase corrections needed for each fibre, to create the desired beam shape (see Figure 4). In this experimental demonstration, we requested that the neural network produce a petal beam shape at each time step by correcting the phase values of the seven beams. Of course, the beam shape at each time step could be different, and hence optimised for a specific manufacturing task. Whilst the neural network phase correction is extremely accurate, the latency of the network and computer hardware means that additional random phase noise occurs during the correction time step, and therefore we are always correcting for the "previous" time step. This fundamental constraint means the speed of the neural network correction loop is paramount, and solving this engineering challenge has become a major focus.

AMPLITUDE MONITORING

It turns out that this same neural network can also detect the power of each beam. In real factories, fibres do not stay at 100% output forever, as they degrade, flicker, and sometimes fail. Our neural network can read subtle changes in fringe brightness and fringe shifts, simultaneously identifying both amplitude and phases changes. For industrial users, this means future smart-laser arrays could self-monitor beam alignment and power balance, compensating for ageing fibres and fluctuating pump power on the fly, just by observing the combined beam shape on the workpiece.

SCALING TO HIGHER NUMBERS OF FIBRES

The question we always get asked is "how much training data do you need for higher numbers of fibres". Whilst it is true that ChatGPT needs a huge amount of training data, it turns out that the training data requirements for coherent beam combination is much more convenient. It appears that in our control scheme the increase in required training data as the number of fibres increases is linear (i.e. proportional to N and not N^2 as generally anticipated, see Figure 5), meaning our approach could be extended to control hundreds of fibres.

APPLICATION TO REAL FIBRE LASERS

Of course, all these results are using a spatial light modulator, and so the question is whether this actually works on real fibre lasers... indeed it does! In a separate laser lab, we have very recently shown a three-channel Yb-doped fibre amplifier MOPA tiled-aperture system with sub-millisecond phase control. Through a novel "self-learning" neural network technique, and a range of other tricks to make the neural network run at very high speed, we simply collect a few minutes of random combined intensity patterns on a camera, followed by ten minutes of neural network training, and then we have full control over our three-fibre system for sub-millisecond beam steering and beam shaping. We are in the process of scaling this up to higher number of fibres.

THE ROAD AHEAD FOR HIPPO

Building on our success so far, our next phase will scale the system, adding more fibres, boosting power, and continuing to add functionality. We look forward to contributing to the development of the AI-powered fibre lasers of the future!

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