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U.S. DEPARTMENT OF ENERGY
Office of Science

Digital Low Level Optical Control for Multidimensional Coherent Laser Combining

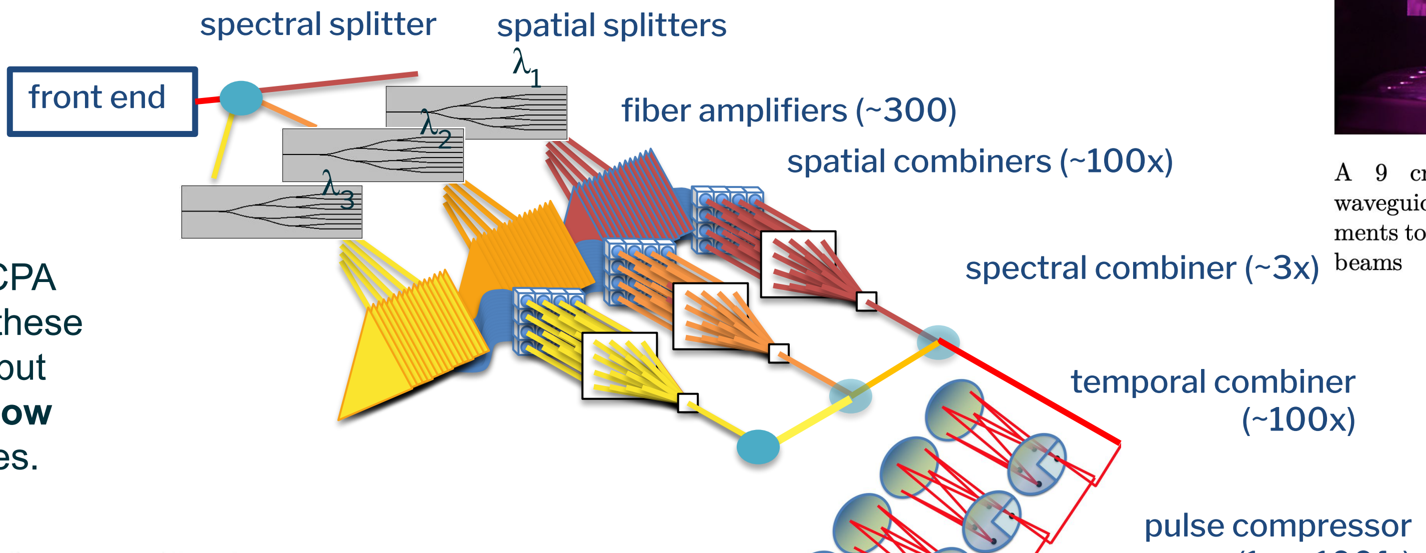
Qiang Du

2023/10/24
LLRF Workshop 2023

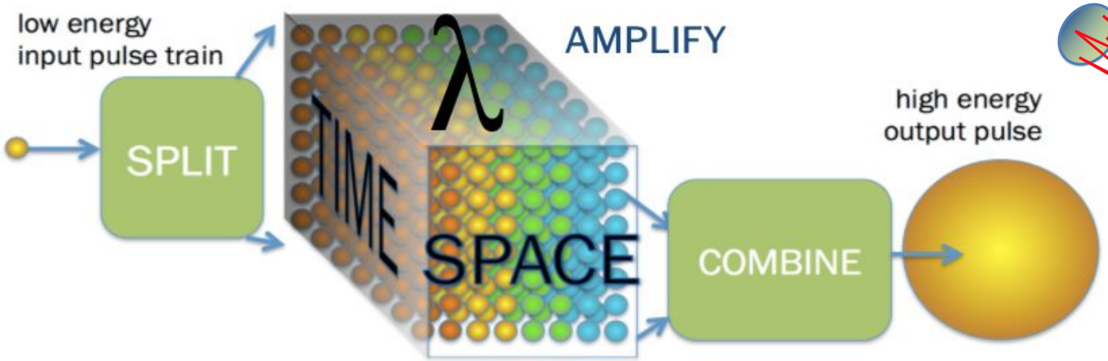
LLRF2023
LOW LEVEL RADIO FREQUENCY WORKSHOP 2023
OCTOBER 22-27, 2023
IN GYEONGJU, REPUBLIC OF KOREA

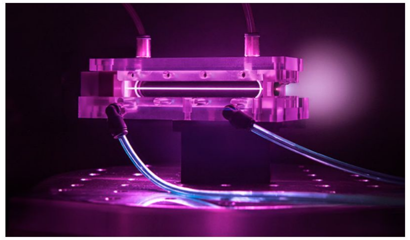
Multi-dimensional coherent laser combining control

Enabling future laser plasma wakefield accelerator, and more scientific applications

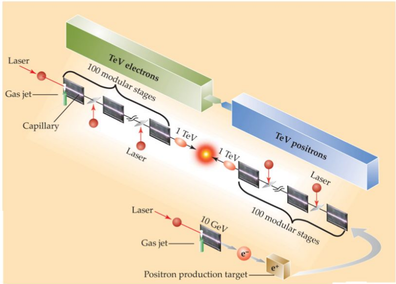


Ti:Sapphire CPA can achieve these peak power, but only at **very low** repetition rates.



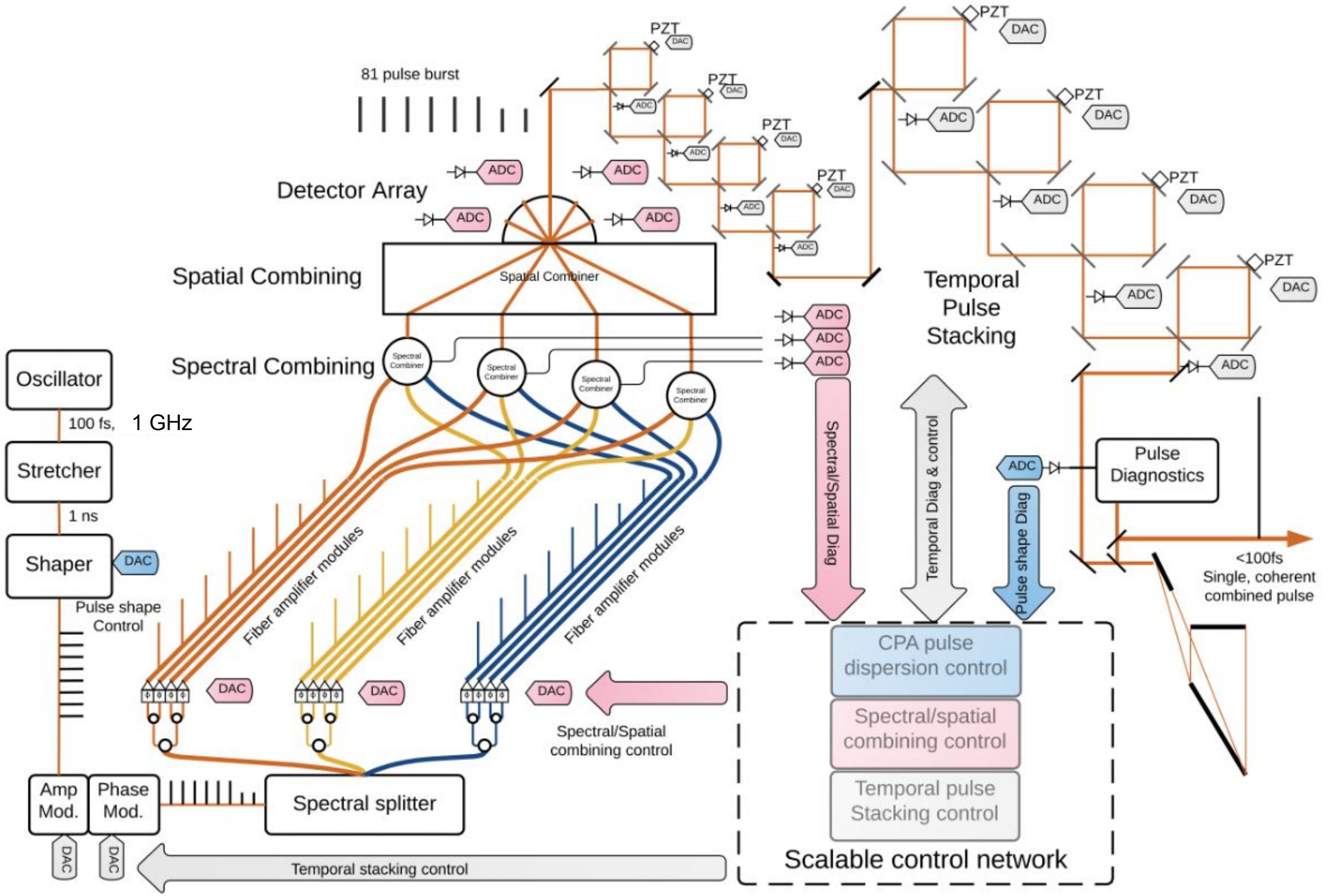


A 9 cm-long capillary discharge waveguide used in BELLA experiments to generate multi-GeV electron beams



A 2-TeV electronâĂŞpositron collider based on LPA might be < 1 km long

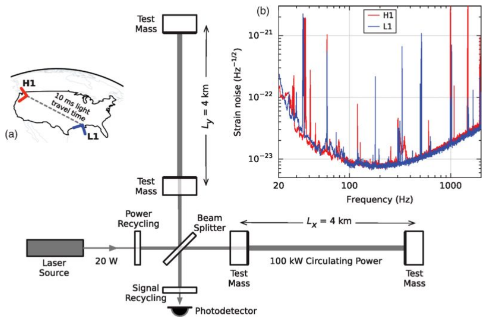
Parameter	Spec
Beam Energy per channel	10mJ
Combined Beam Energy	3J
Pulse duration	30 - 130fs
Reprate	1 - 10kHz
Average power	3 - 30kW
Peak power	30 - 100TW
Carrier Frequency	300 THz



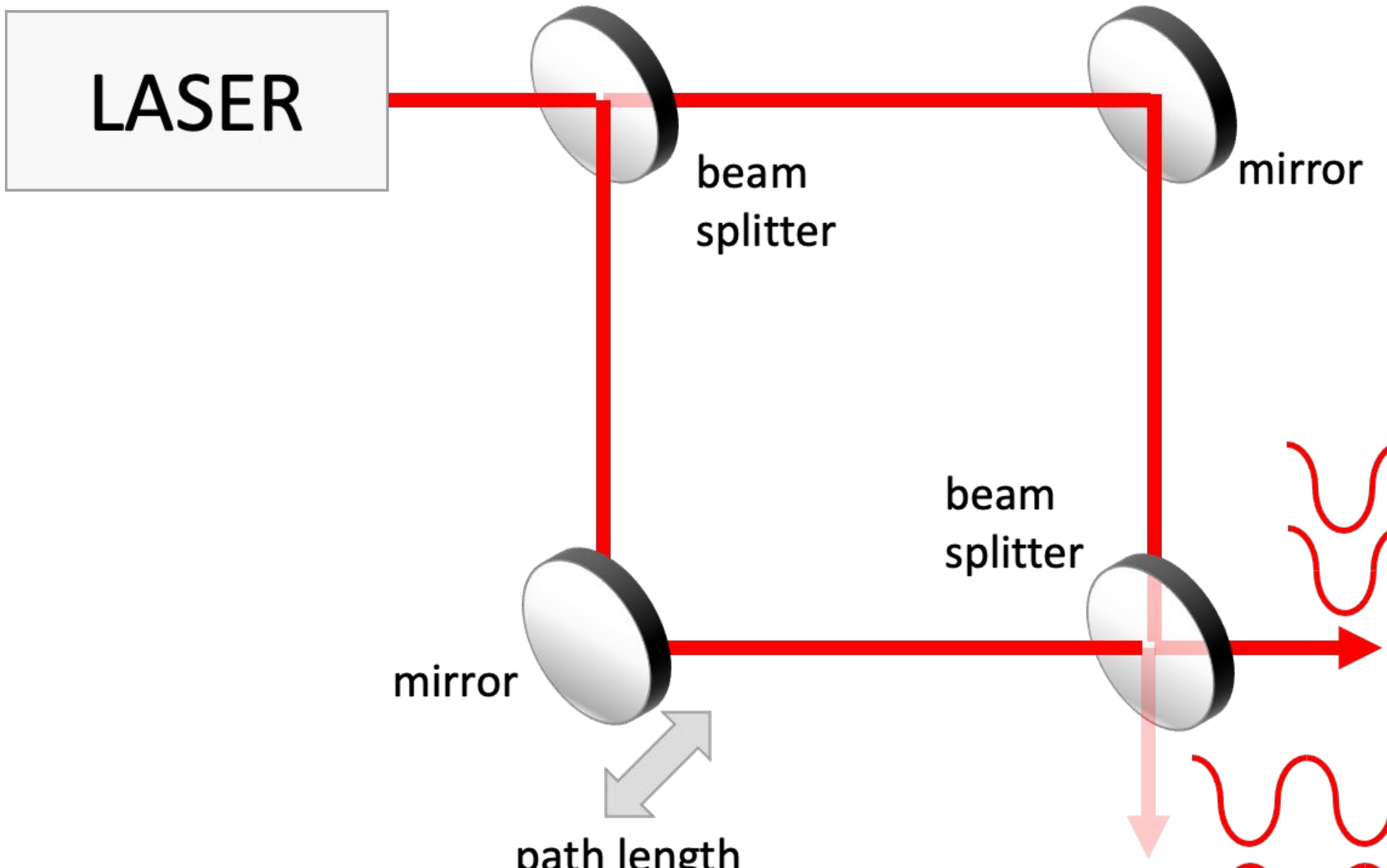
Multi-dimensional Coherent Laser Combining control

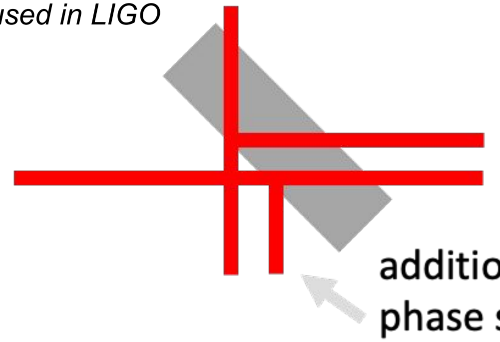
- Temporal Stacking
  - 4 Cascaded optical cavities
  - 81 amplified pulse train
  - In-pulse gain saturation control
- Spatial Combining
  - 3x9 diffractional addition
  - deterministic pattern recognition
- Spectral Combining
  - Spectral amplitude control
  - Spectral phase control
- Fast interlock for machine protection

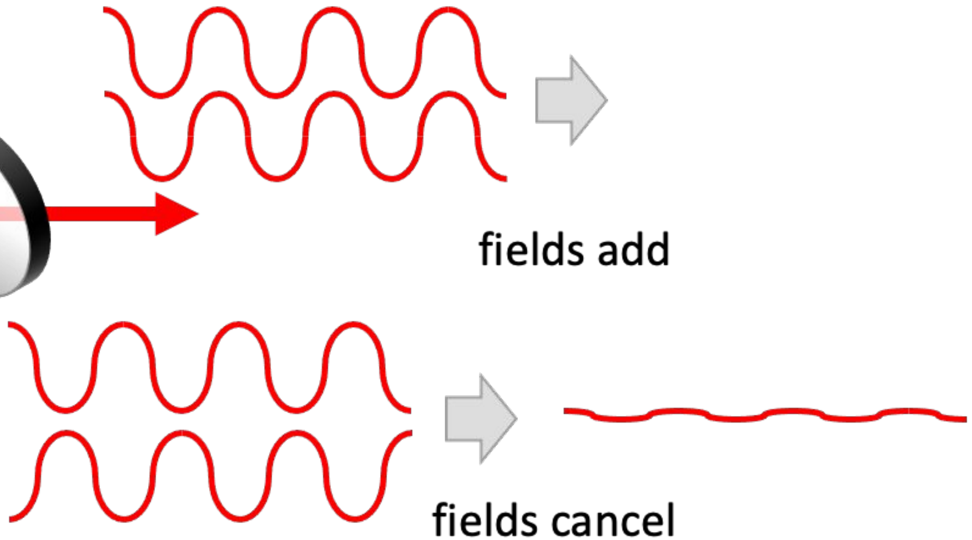
Mach Zehnder Interferometer



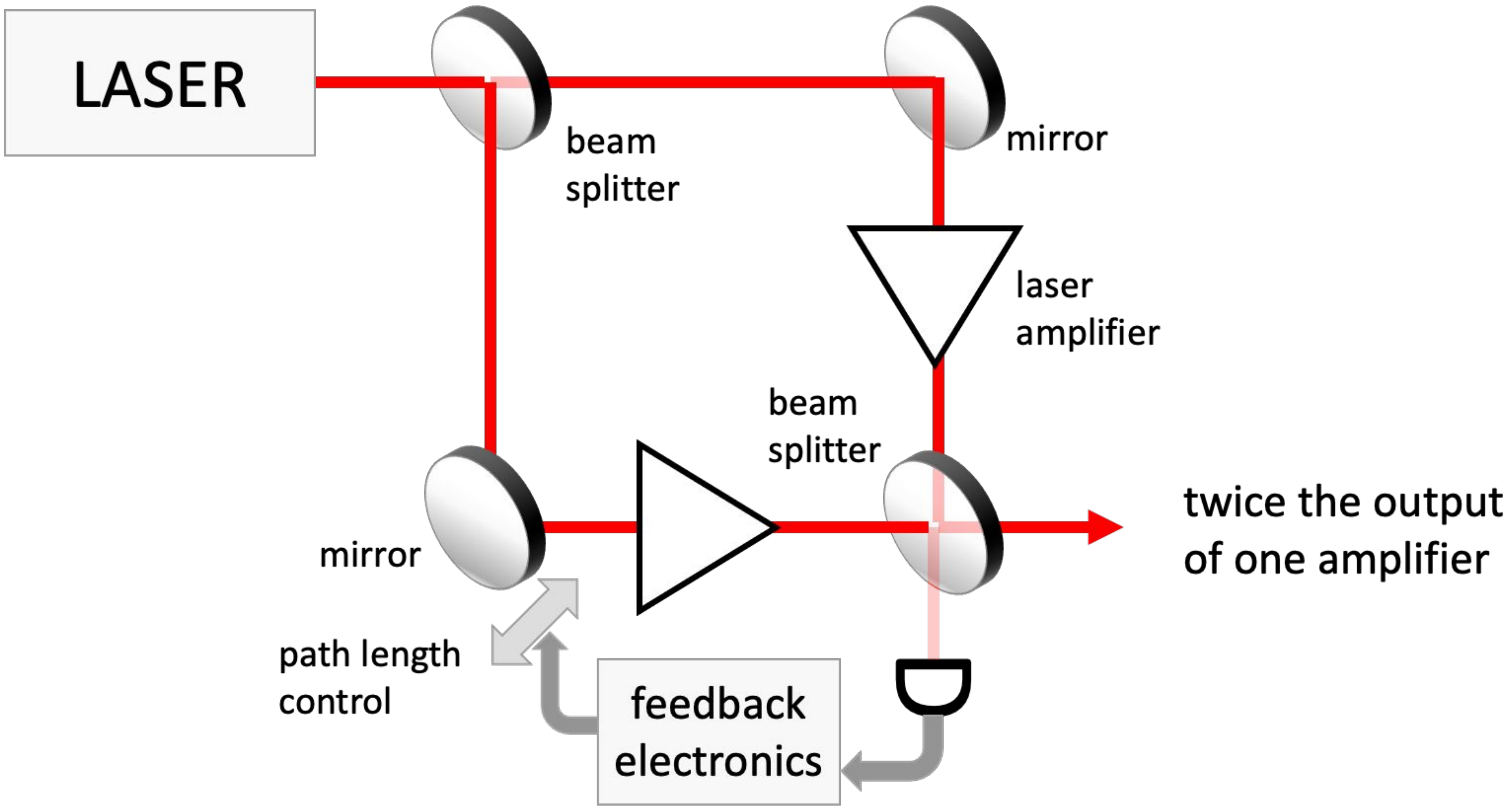
As used in LIGO



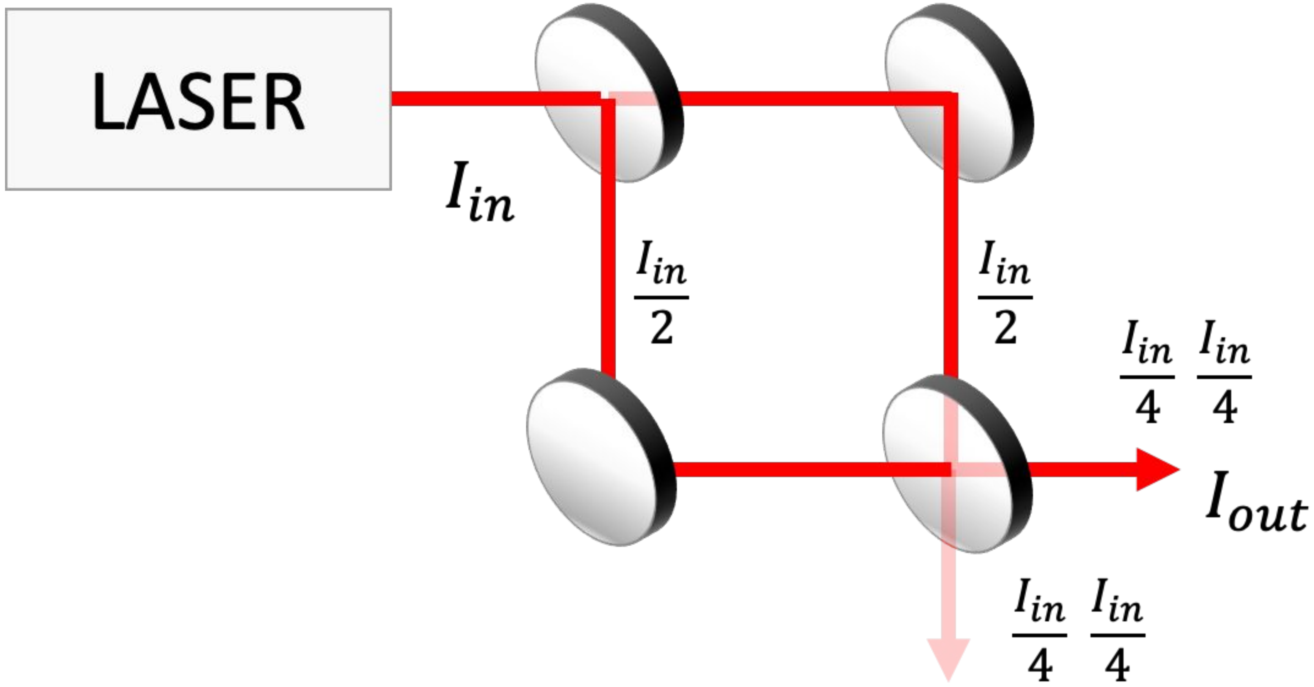




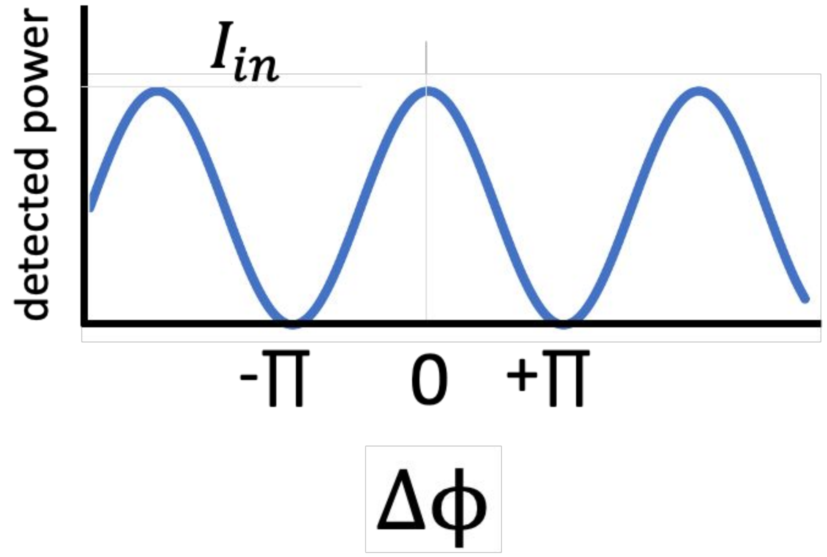
Mach Zehnder Interferometer, with feedback



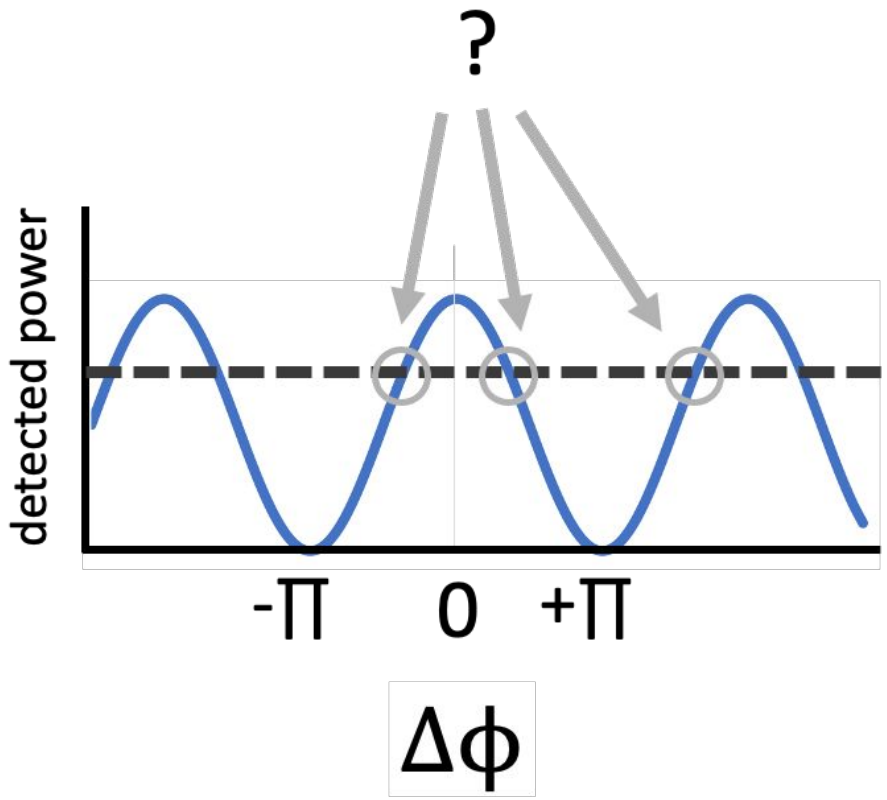
Mach Zehnder Interferometer, as a beam combiner

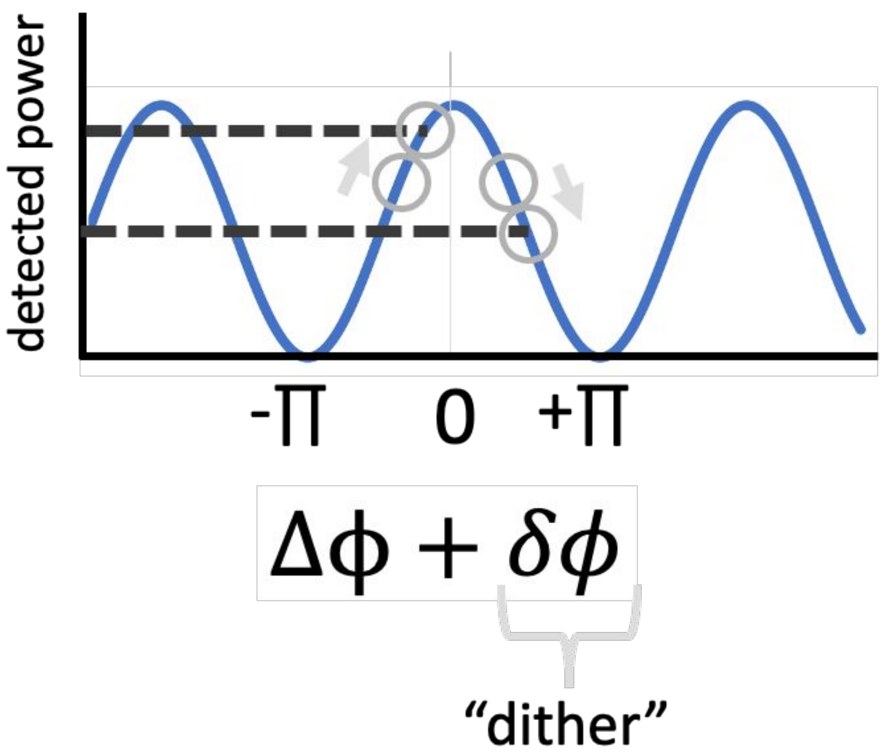


$$I_{out} = 2\frac{I_{in}}{4}\underbrace{(1 + \overbrace{\cos(\Delta\phi)}^{\text{interference term}})}_{\text{0 to 2}}$$



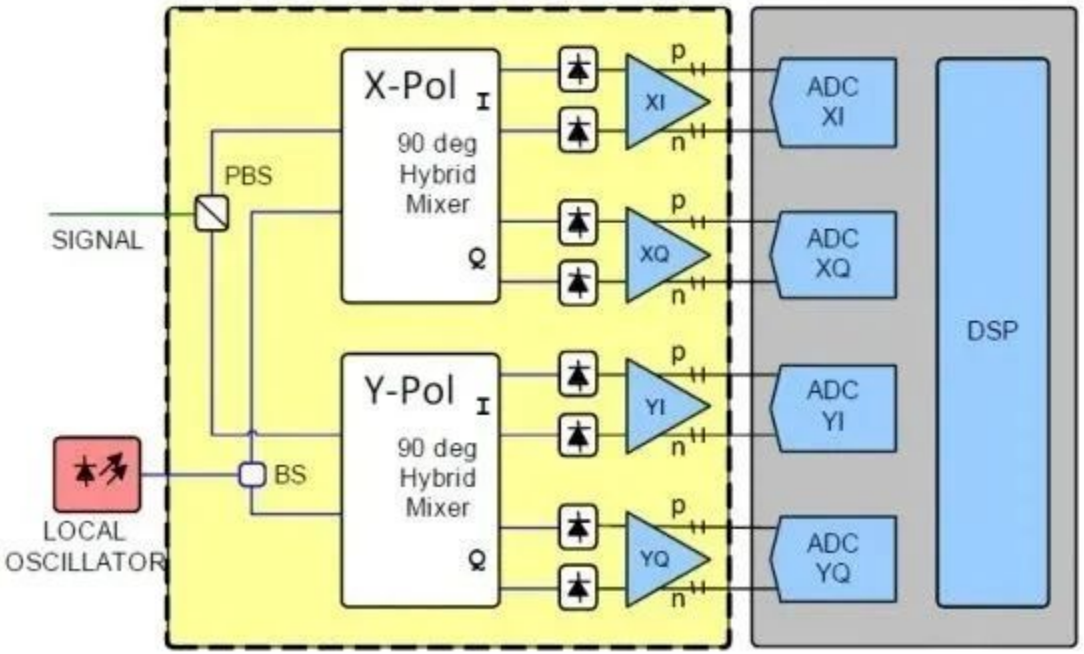
Problem for feedback: phase ambiguity

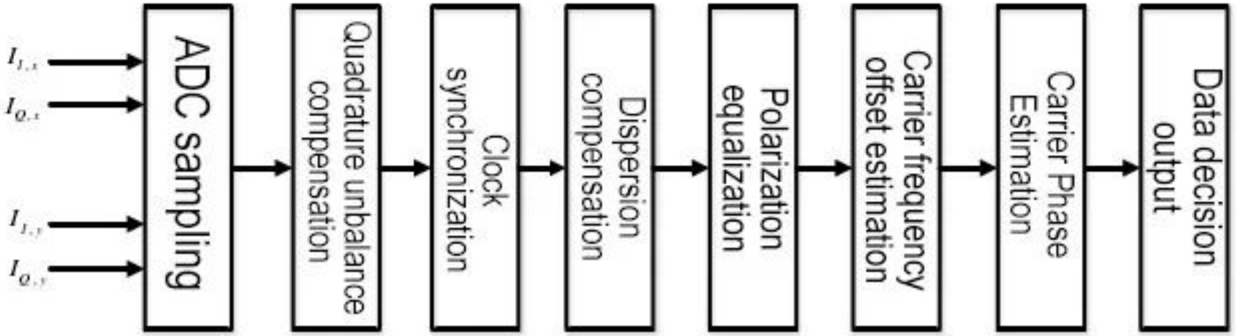




Coherent optical receiver (heterodyne detection at 300THz)

Telecom approach, but maybe not suitable for us





- Too expensive for large number of channels
- Optical LO distribution and synchronization?
  - frequency comb?
- For multi-channel, free space combiner:
  - pointing stability?
  - beam profile variation?

A N×N beam combiner is almost too hard to control

01	Large dimensionality	• N**2 beams • N**2 - 1 dimensional action space (phase)
02	Non-observable, Needs high precision	• Only beam powers are measurable • Phase information are lost @ 300THz • ~3 nm per degree of optical length control
03	Time variant, High noise bandwidth	• Beam power variation • Pointing stability • Polarization stability • Phase noise bandwidth: ~10 kHz
04	Nonlinear, Non-uniqueness	• Detector dynamic range / saturation • Many-to-one phase-pattern mapping

Popular solution: Stochastic Parallel Gradient Descent (SPGD, dither & search)

Our journey towards a scalable coherence control

Physics	Scalability	Robustness	Speed

Physics

- **Identify** control problems
- **Discover** optical physics
- **Develop** simulation
- **Characterize** experimental system
- **Demonstrate** 3x3 combining

Scalability

- **Demonstrate** 9x9 combining
- **Demonstrate** Neural Network based pattern recognition
- **Solve**: non-uniqueness, non-observable, non-linear

Robustness

- **Develop** model-free training against drift;
- **Develop** Deep Reinforcement Learning
- **Demonstrate** experimental stabilization
- **Study** Online-learning

Speed

- **Develop** FPGA accelerated deep learning controller:
  - Xilinx DPU: 1μs
  - High-level synthesize ML: 72ns
  - Portable NN Engine: 1μs

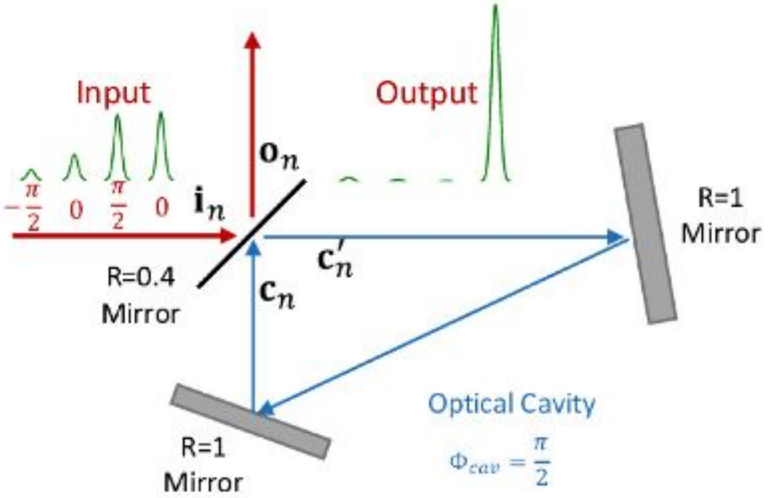
Temporal Pulse Stacking Control

Coherently stack up-to-81 ultrafast laser pulses into one, using resonance optical cavities

Gires Tournois Interferometer (GTI) as resonance cavity

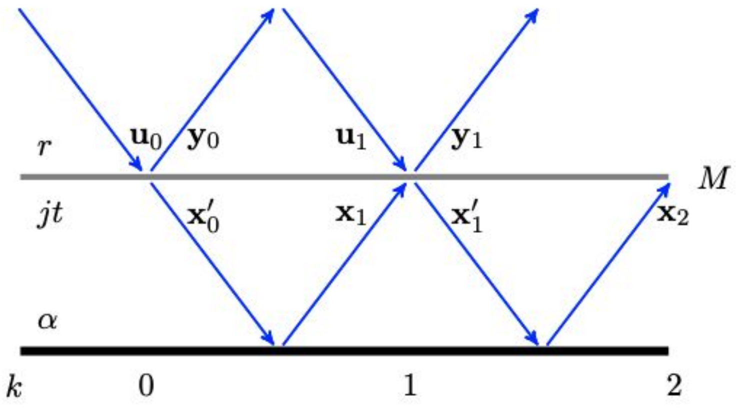
Coherence control by amplitude / phase modulation on each pulse at 1Gsps

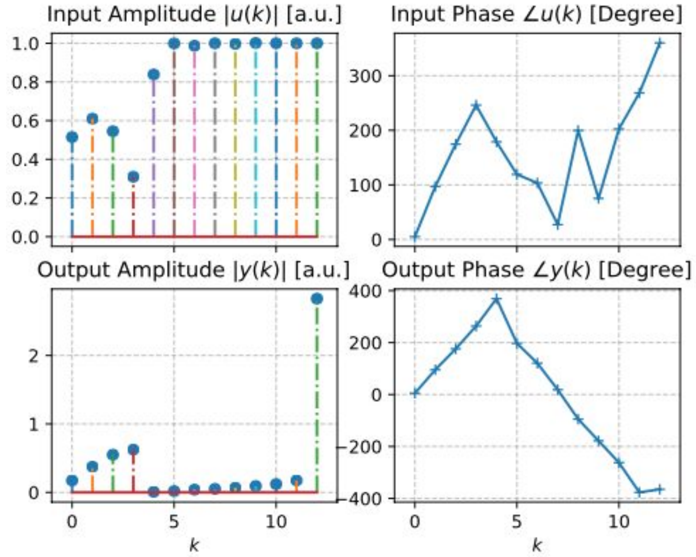
GTI Optical Cavity physis



$$\begin{pmatrix} \mathbf{o}_n \\ \mathbf{c}_n' \end{pmatrix} = \begin{pmatrix} r & it \\ it & r \end{pmatrix} \begin{pmatrix} \mathbf{i}_n \\ \mathbf{c}_n \end{pmatrix}$$

Control system model





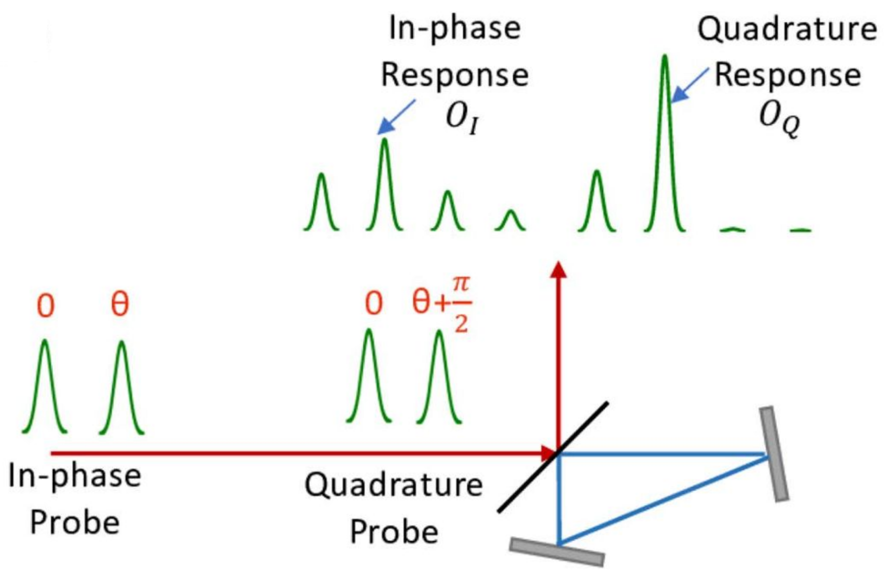
$$\begin{cases} \mathbf{x}_k' & = r \cdot \mathbf{x}_k + jt \cdot \mathbf{u}_k \\ \mathbf{y}_k & = jt \cdot \mathbf{x}_k + r \cdot \mathbf{u}_k \\ \mathbf{x}_{k+1} & = \alpha e^{j\delta} \cdot \mathbf{x}_k' \\ x_0 & = 0 \end{cases}$$

$$\begin{pmatrix} z\mathbf{X}(z) \\ \mathbf{Y}(z) \end{pmatrix} = \begin{pmatrix} \alpha e^{j\delta} r & \alpha e^{j\delta} jt \\ jt & r \end{pmatrix} \begin{pmatrix} \mathbf{X}(z) \\ \mathbf{U}(z) \end{pmatrix}$$

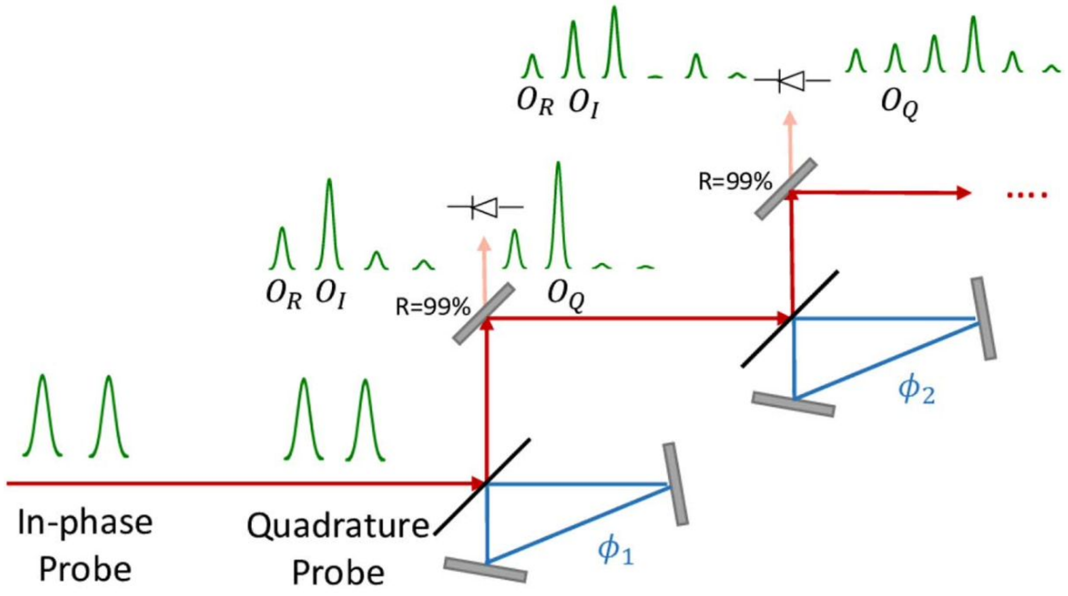
Cascaded optical cavity phases are directly measured

using the first order digital filter characteristics

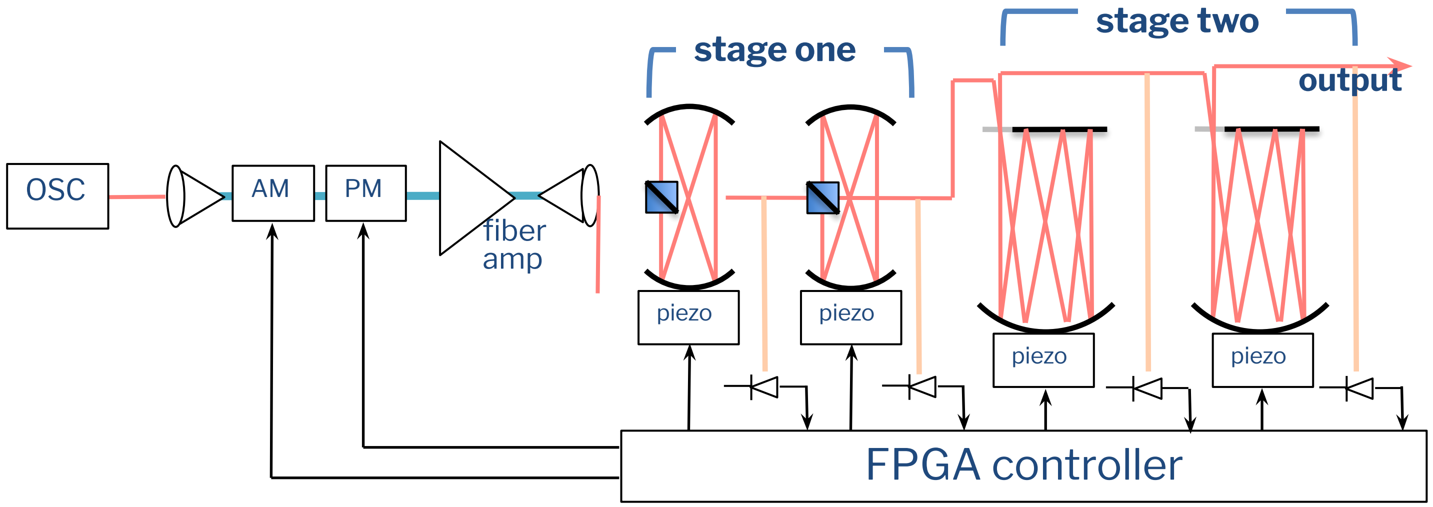
Single cavity impulse response



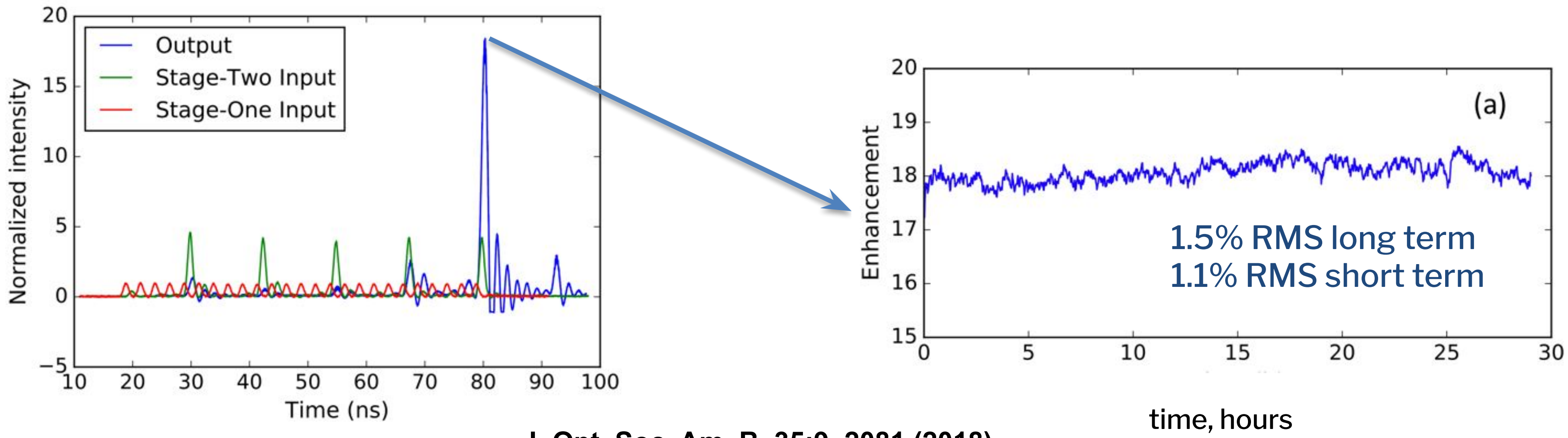
Cascaded cavity impulse response



FPGA based coherence control for 25 pulses stacking



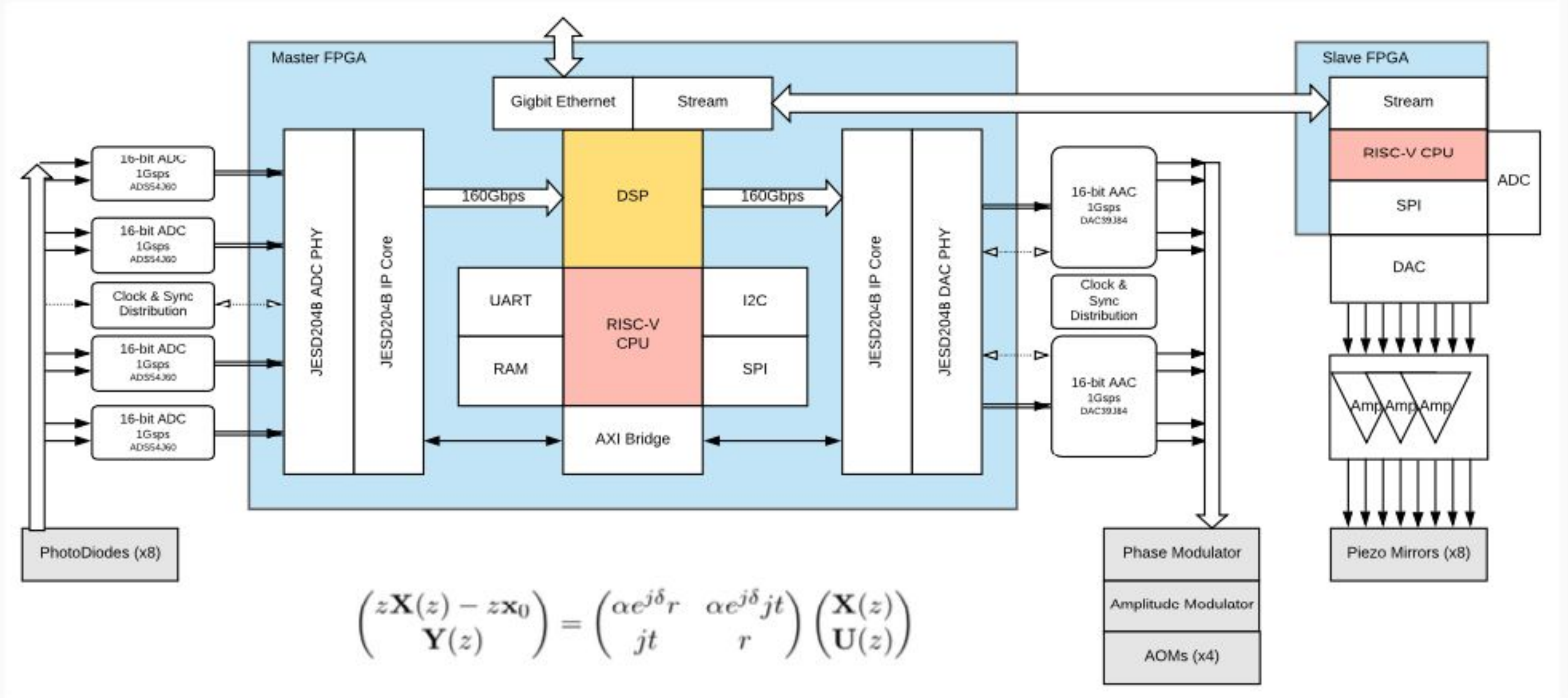
25 pulses added,
~18x power increase



J. Opt. Soc. Am. B, 35:9, 2081 (2018)

IEEE J. Quantum Electron. 54:1, 2081 (2018)

81 pulse stacking using VC707+FMC120x2

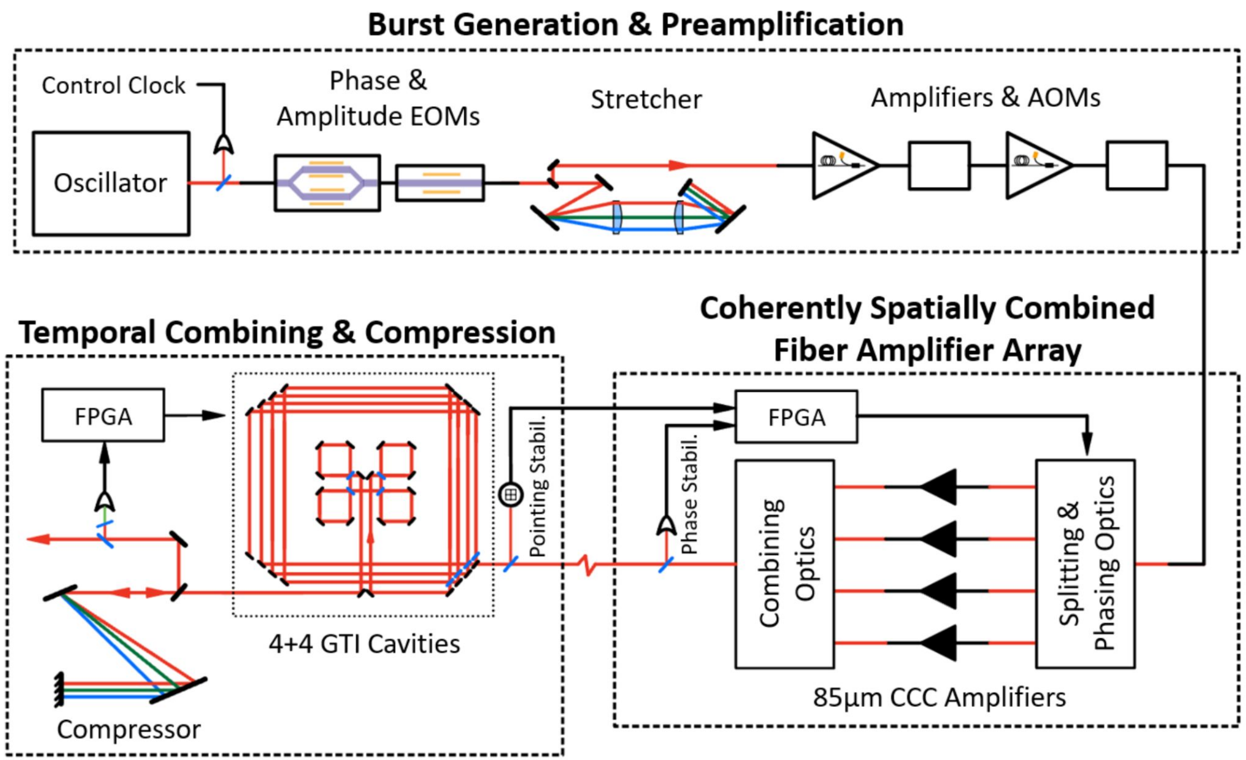


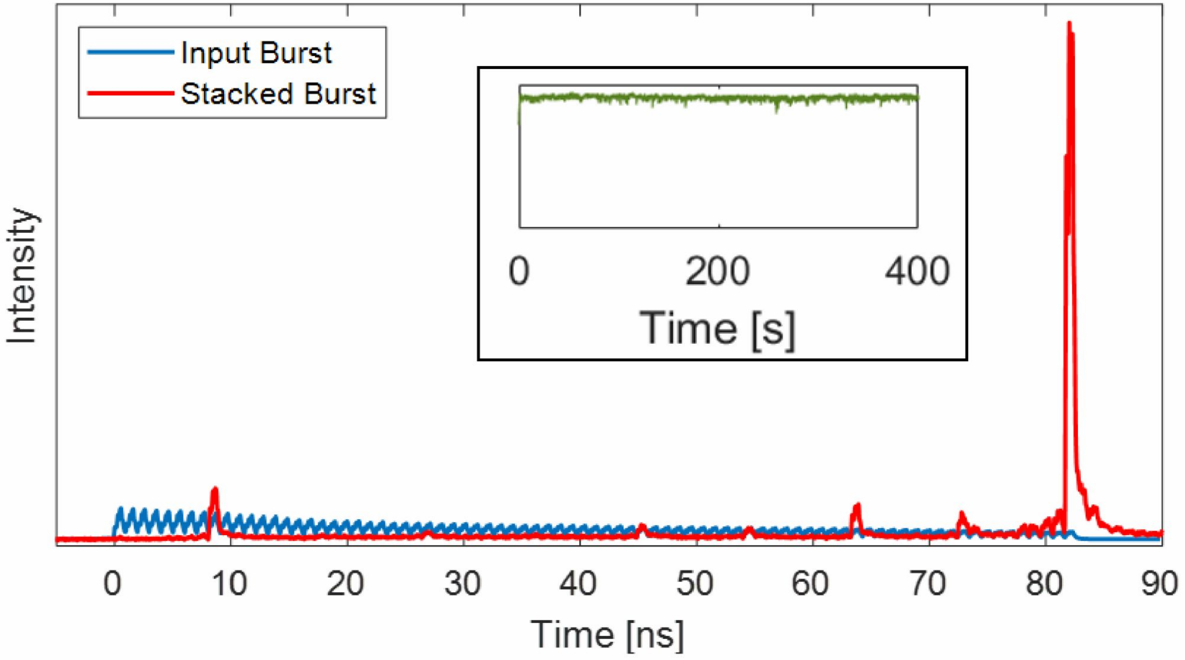
Stabilization of cascaded optical cavity phase

1Gsps 8-in 8-out FPGA chassis

200ksps 8-in 8-out

81 pulses stacked Coherent Pulse Stacking Control





81 pulses stacked with intensity RMS stability < 1%

A. Rainville, M. Whittlesey, C. Pasquale, Y. Jing, Q. Du, and A. Galvanauskas, "Stable and Efficient Coherent Pulse Stacking Amplification of 81 Pulses with Four Channel Coherent Spatial Combining at 7mJ/Fiber," in CLEO 2023 SF3H.6.

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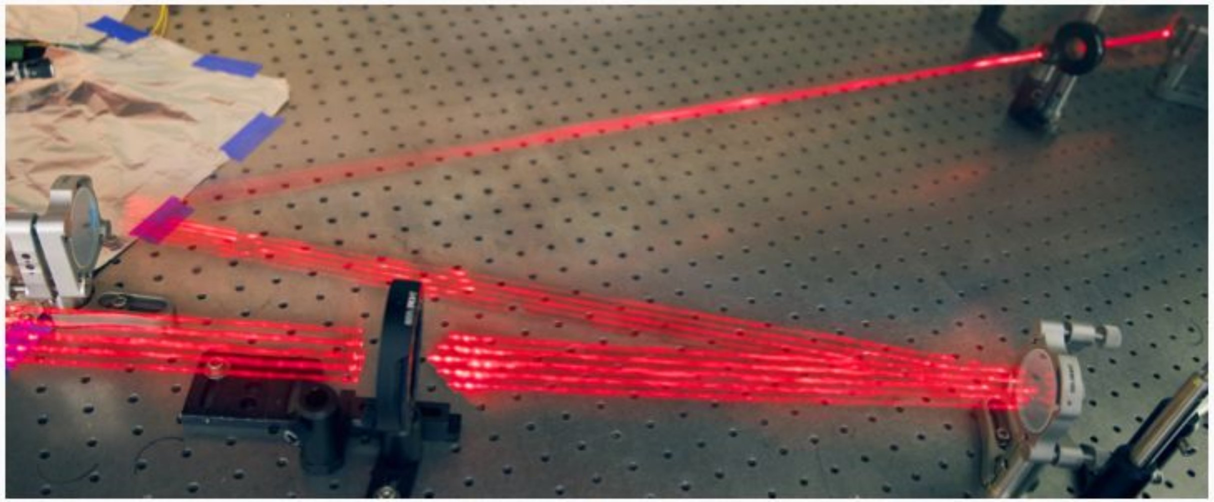
Spatial Beam Combining Control

Coherently combining up to 81 parallelly amplified laser beams into one, by a single element



Filled Aperture Diffractive Optical Combining

Need for many-in-many-out coherence control

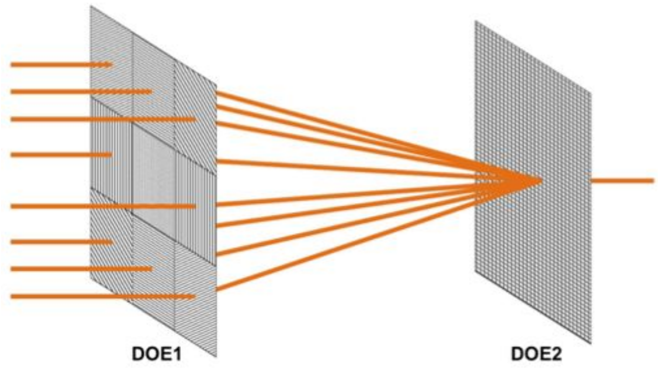
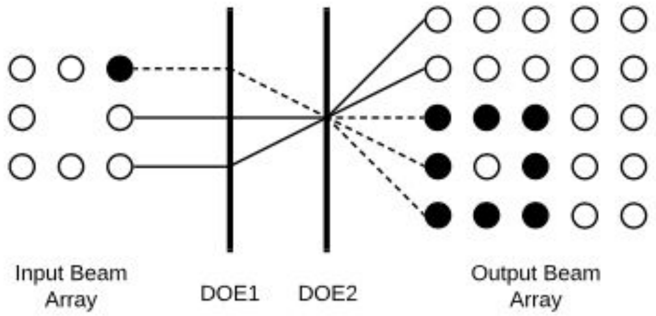
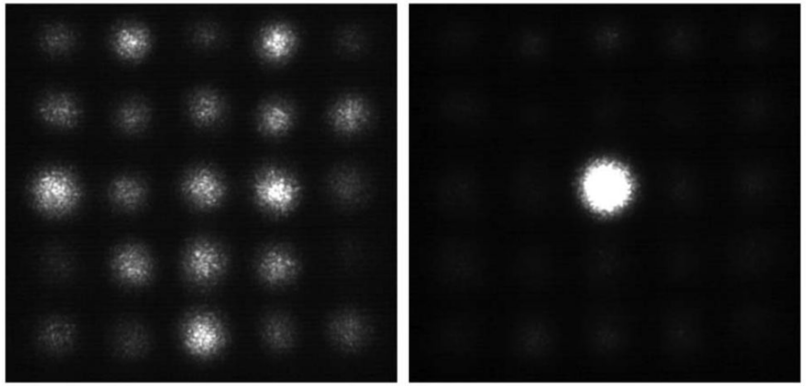
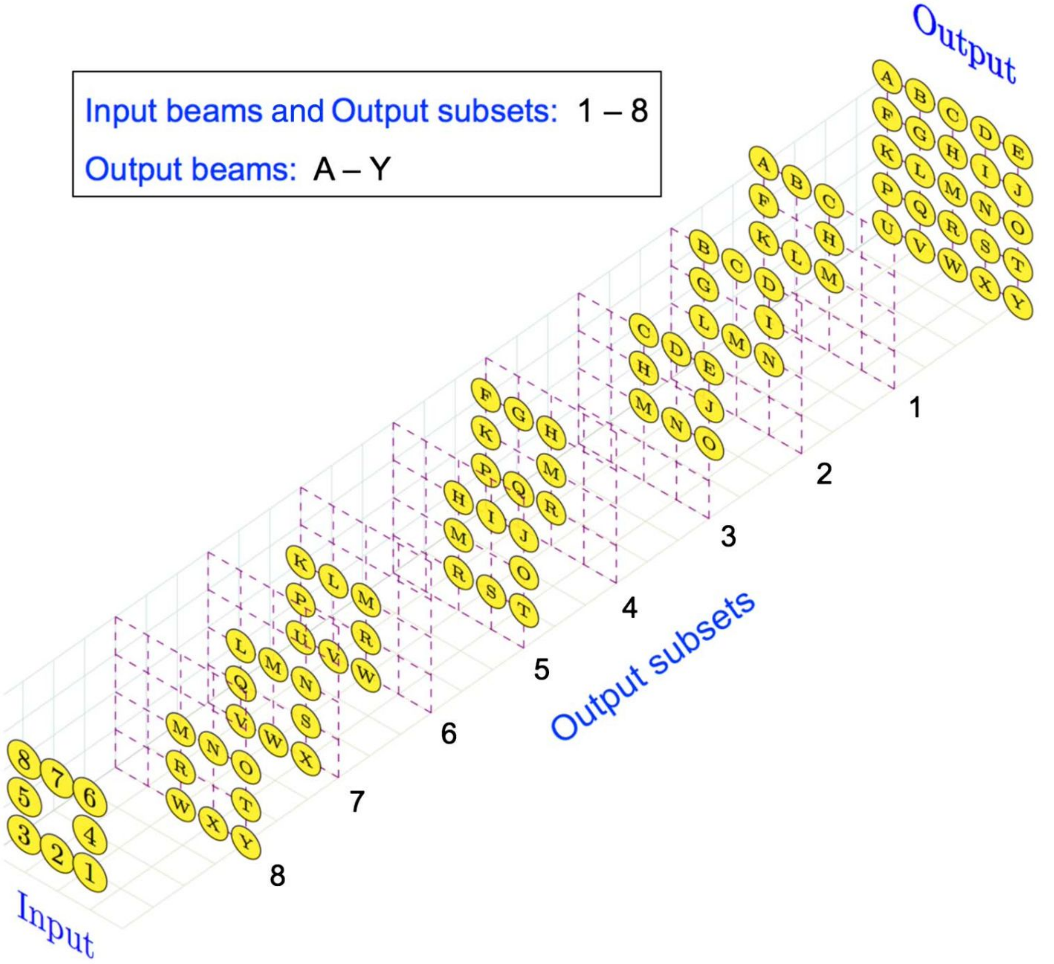


Fig. 1. Concept of the two-dimensional diffractive combiner.





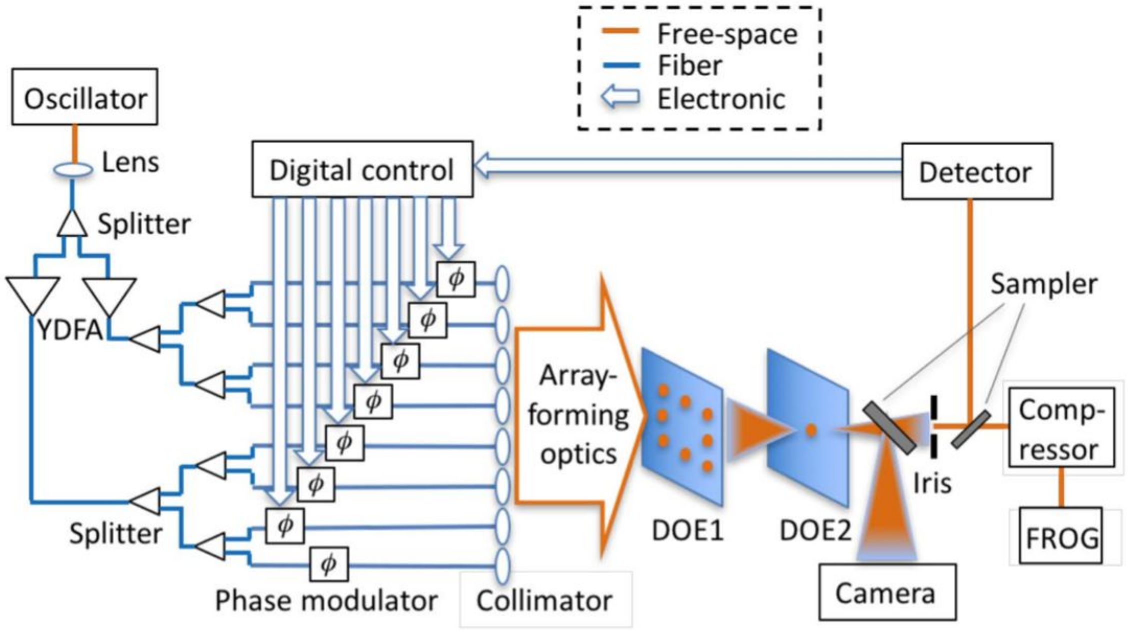
(a) Free running (b) Phase controlled



Opt. Lett. 42, 4422 (2017)
Opt. Lett. 43, 3269 (2018)

Superposition of waves

2-D, 8-way, ultrafast combiner



Opt. Lett. 42, 4422 (2017)
Opt. Lett. 43, 3269 (2018)

2-D, 8-way, pattern recognition MIMO feedback

DOE transmission function

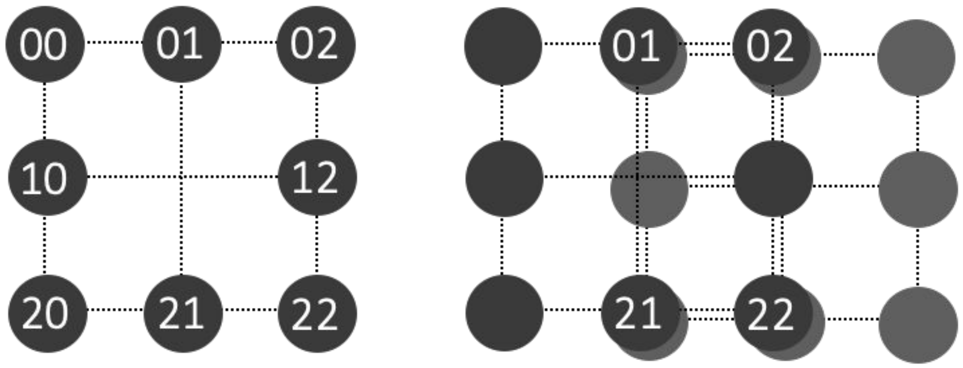
$$d_{3\times3} = \begin{pmatrix} 1 & i & 1 \\ 1 & 0 & -i \\ -1 & 1 & 1 \end{pmatrix}.$$

Input beam complex amplitude

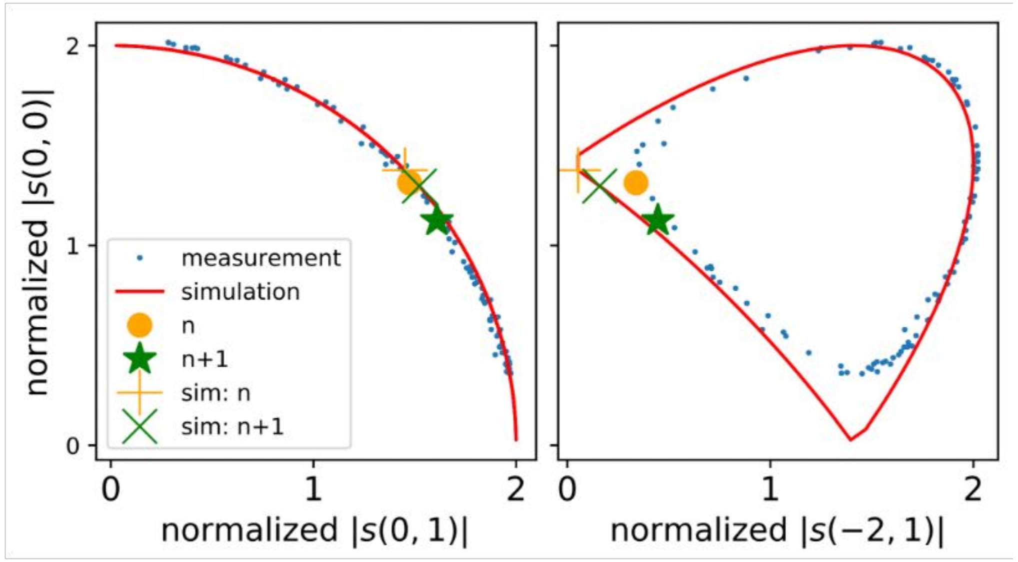
$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix} ** \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix} = \begin{pmatrix} 1 & \boxed{2} & 3 & \boxed{2} & 1 \\ \boxed{2} & 2 & 4 & 2 & \boxed{2} \\ 3 & 4 & 8 & 4 & 3 \\ \boxed{2} & 2 & 4 & 2 & \boxed{2} \\ 1 & \boxed{2} & 3 & \boxed{2} & 1 \end{pmatrix}.$$

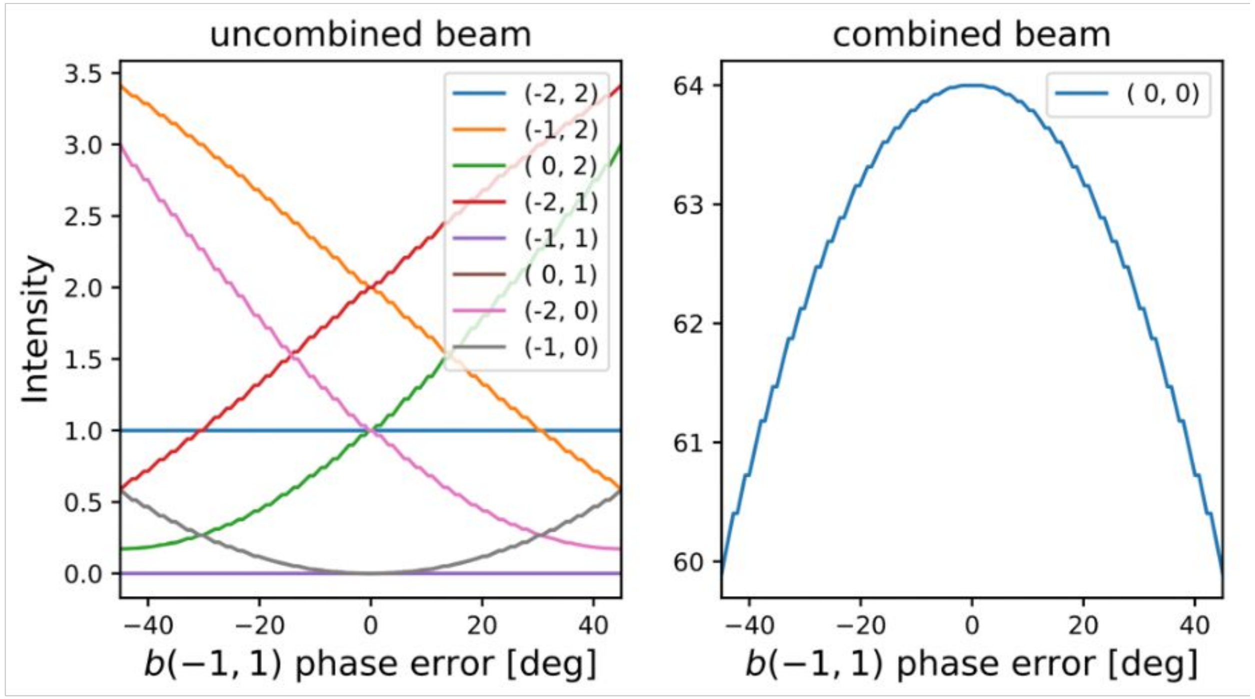
Opt. Lett. 44, 4554 (2019)

Identify optical combiner phase transfer function



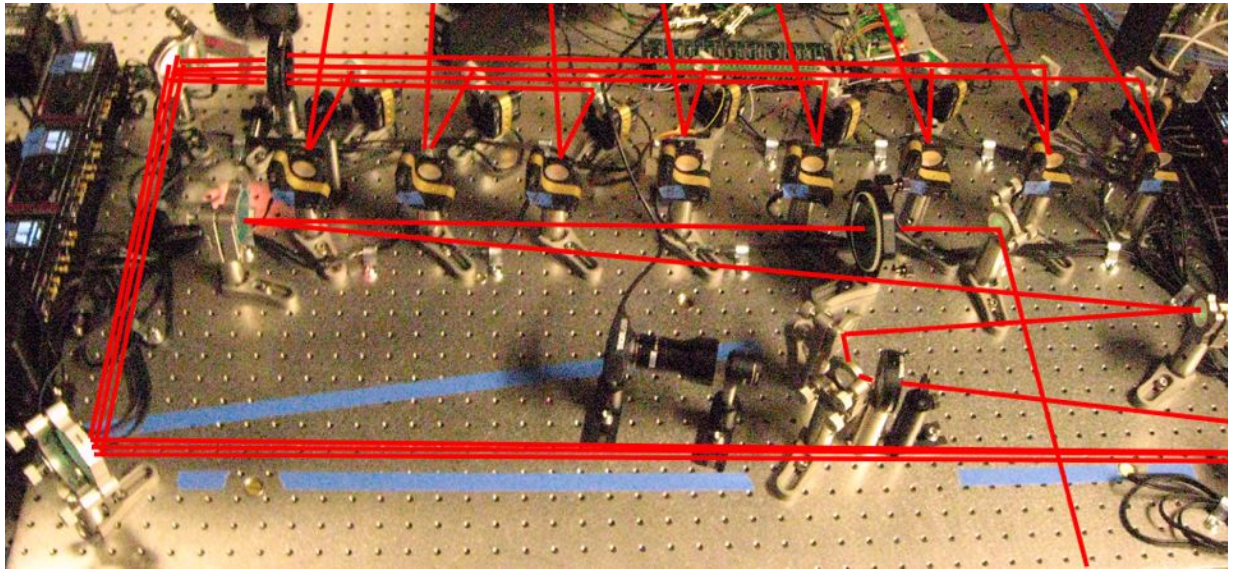
correlations reveal quadrature phase!

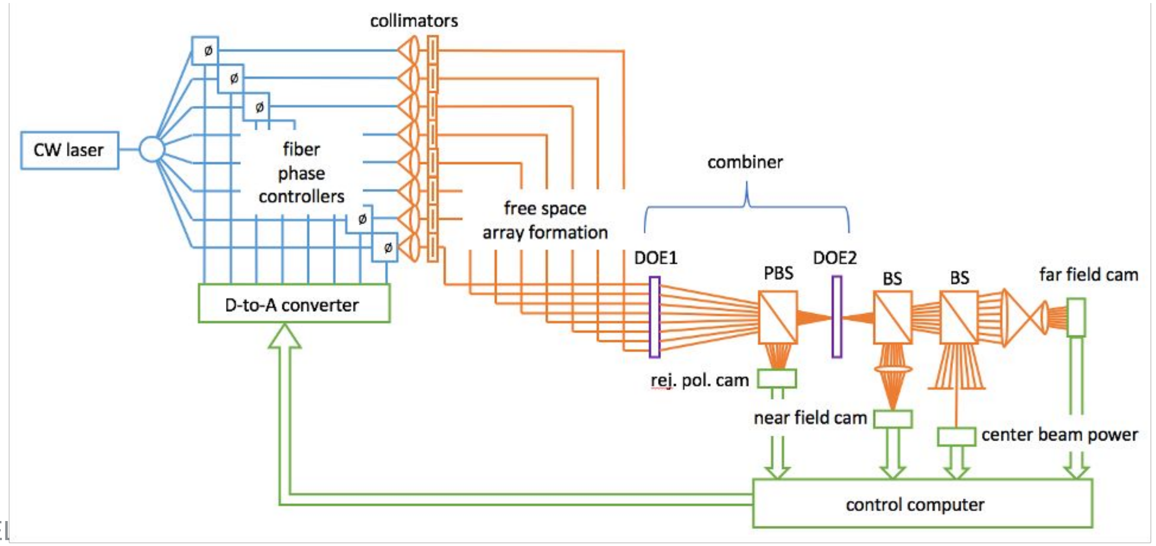


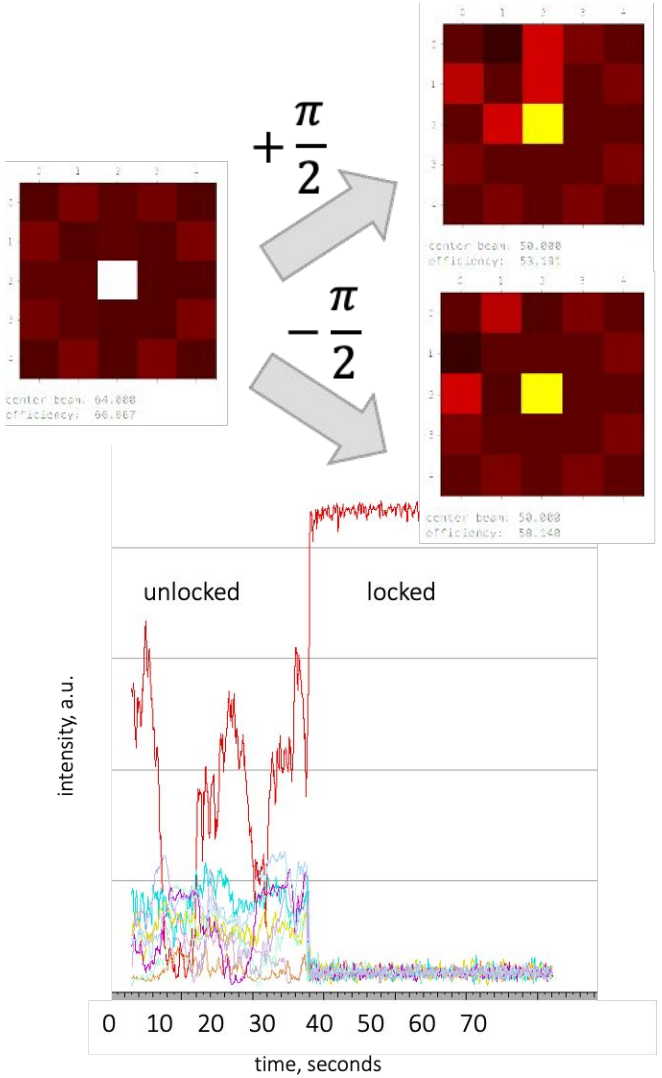


$$\text{measured } \angle d(x, y) = \begin{pmatrix} 0 & +\frac{\pi}{2} & 0 \\ 0 & & -\frac{\pi}{2} \\ \pi & 0 & 0 \end{pmatrix}$$

Machine Vision based pattern recognition feedback







Opt. Lett. 44, 4554 (2019)

Discovered physics of diffractional beam combining

Complex valued matrix convolution:

$$\hat{s}(i,j) = \hat{b}(i,j) ** \hat{d}(i,j)$$

Main plus side beams result from input beams convolved with DOE function

Phases drift, amplitudes not so much.
Efficient combination when:

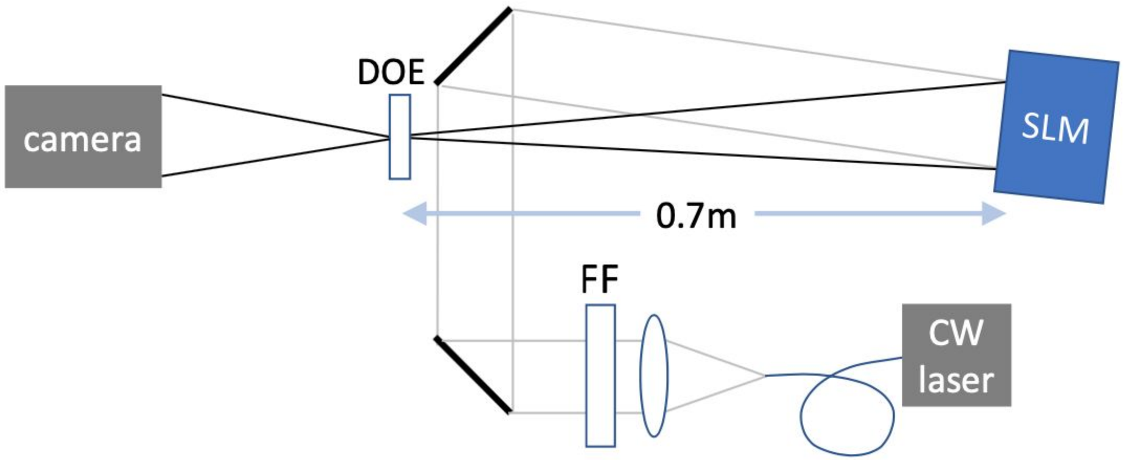
$$\angle\hat{b}(i,j) = -\angle\hat{d}(-i,-j)$$

input beam phases equal DOE phase function,

but in reverse, because it's combining, not splitting

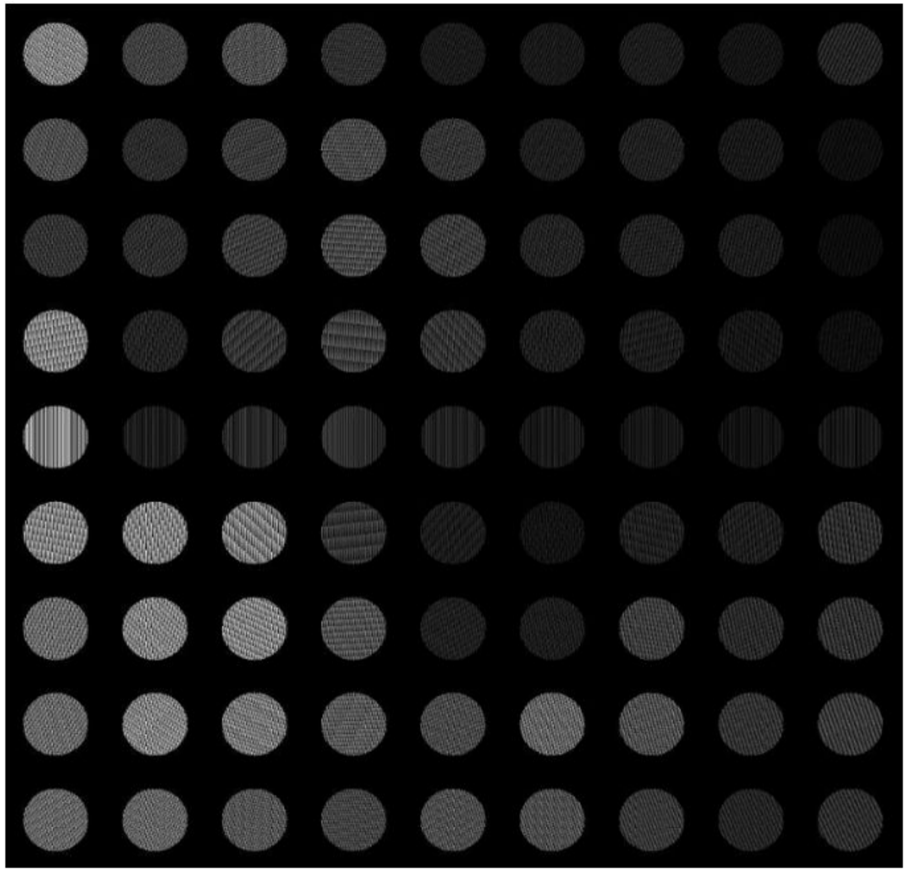
81 beams: a simple test bed for a complex problem

Computer generated hologram enables 9x9x6 degrees of freedom using Spatial Light Modulator



- Amplitude: Modulation depth
- Phase: Modulation start offset
- Angle X/Y: Modulation spatial freq. in x/y
- Shift X/Y: Modulation pixel position
- Beam spacing / shape / profile...

Hologram on SLM for generating 9x9 beams.

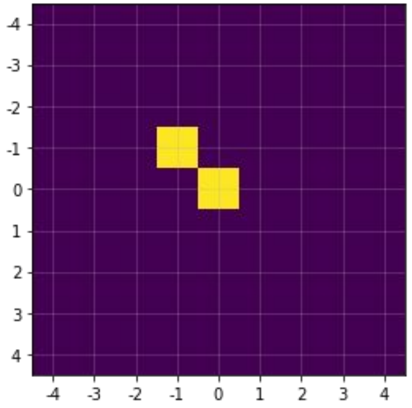


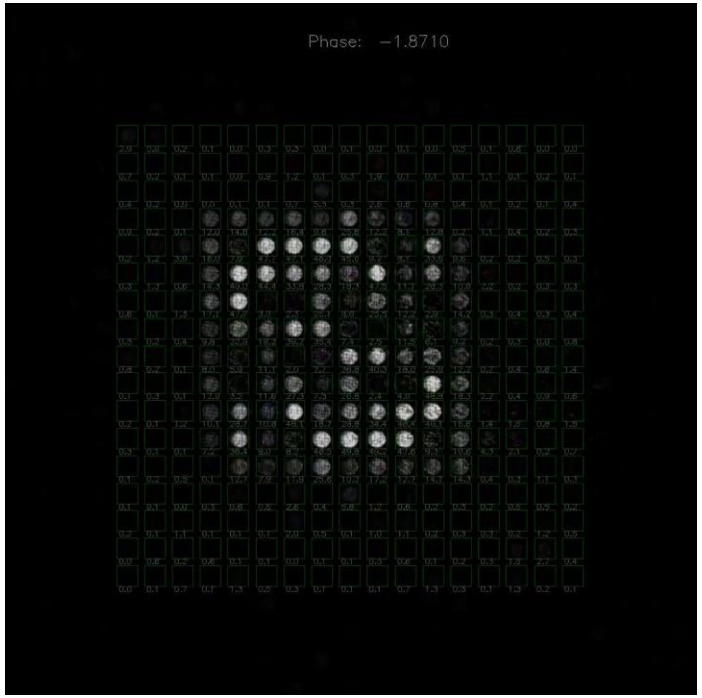
Physics

System identification: beam phase induced pattern

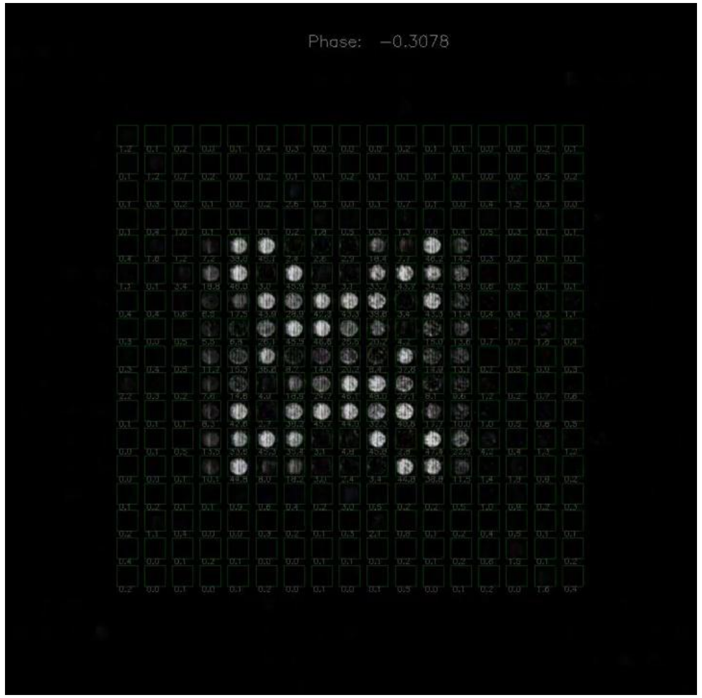
Phase scanning two-beam interference data reveals complex transmission function

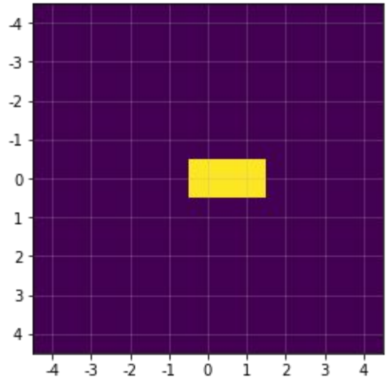
Center + upper left beam





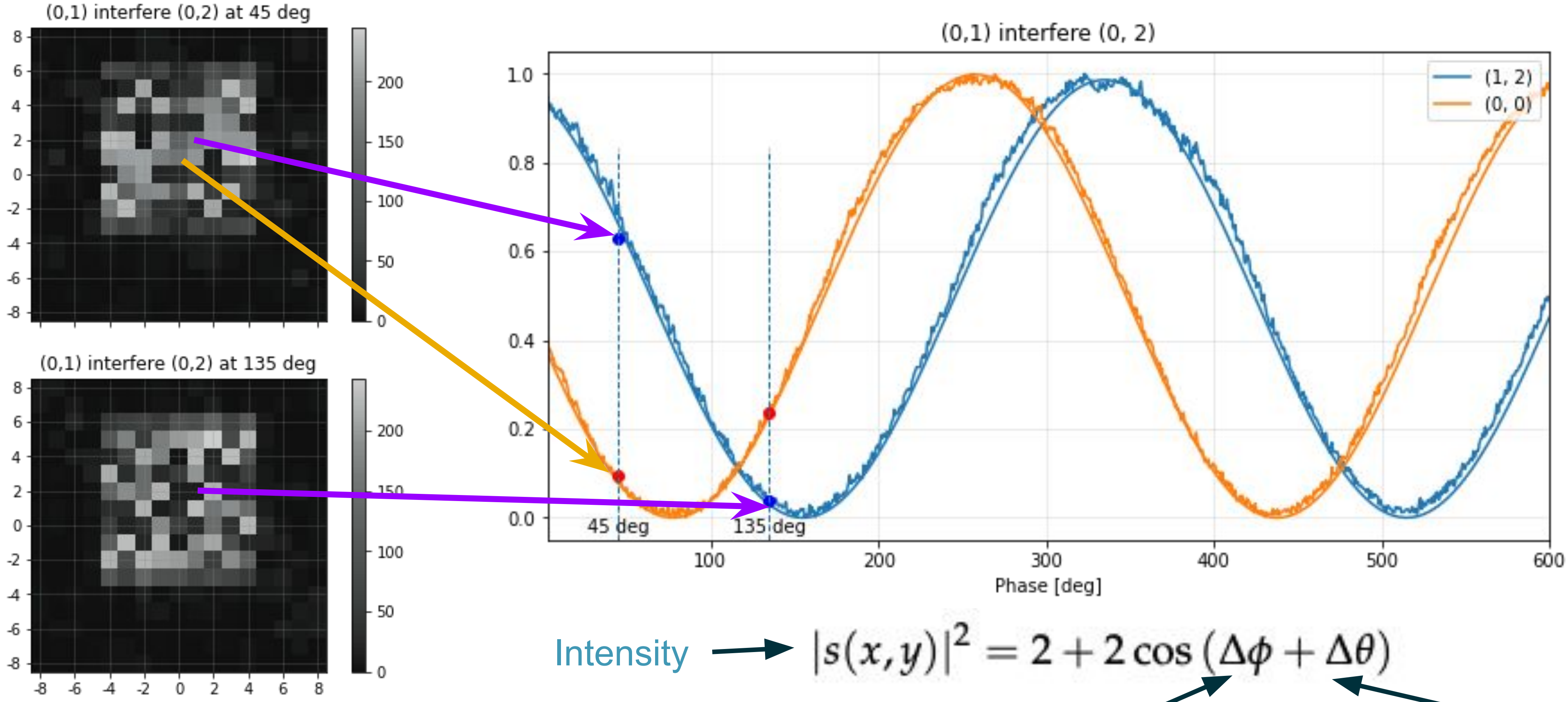
Center + Right beam





Intensity is function of DOE *modulated* beam phase

2 pairs of horizontal / vertical adjacent beam scannings completes the puzzle



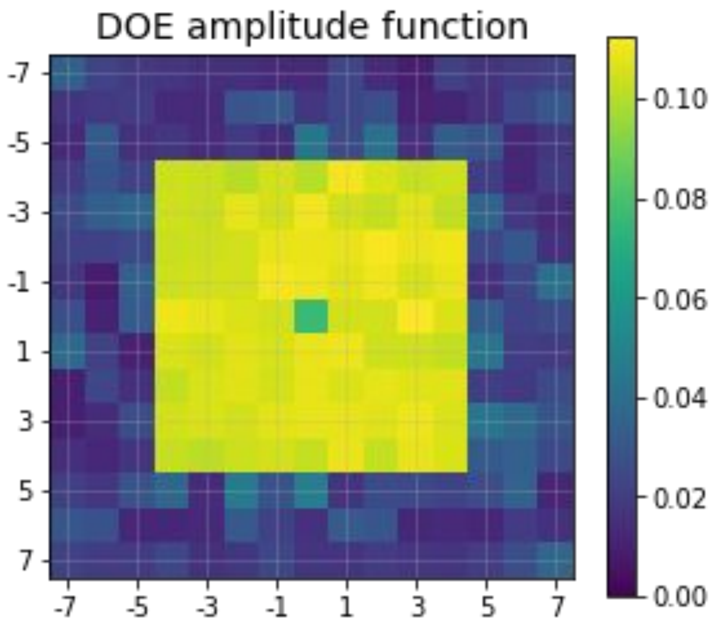
Intensity → $|s(x,y)|^2 = 2 + 2\cos(\Delta\phi + \Delta\theta)$

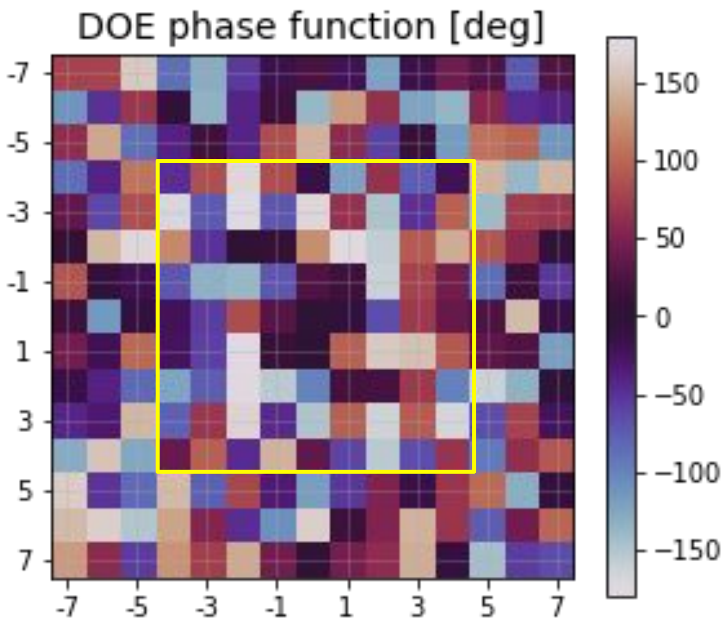
Beam phase diff

DOE phase function

9x9 diffraction transmission function characterized

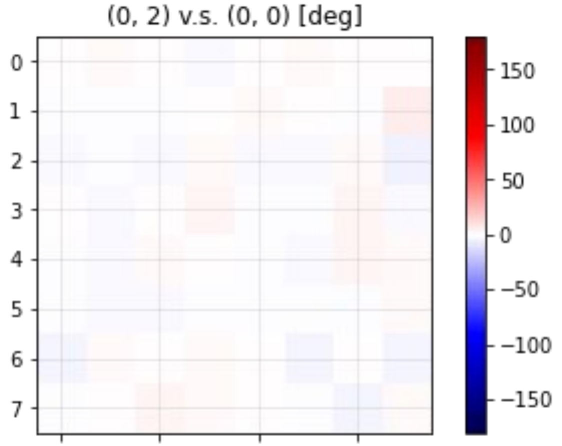
15x15 transmission function (1st order 9x9)

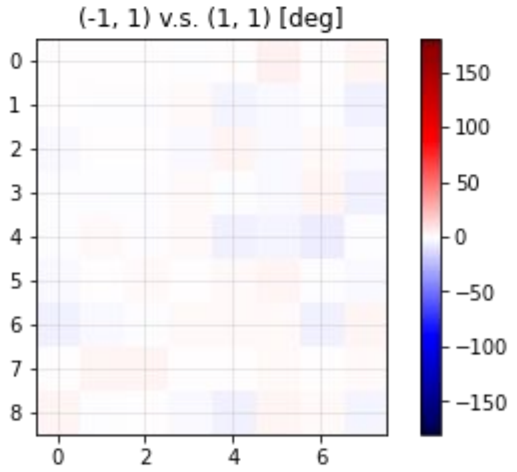




Phase function accuracy: < 1.6 deg

measured by other test beams





- **Power unit:**
  - **1/81 of each input beam**
- **Amplitude unit:**
  - **1/9 of each input beam**

Scalability

81 beams combined experimentally

Diffractional Combining Physics:

2-D convolution

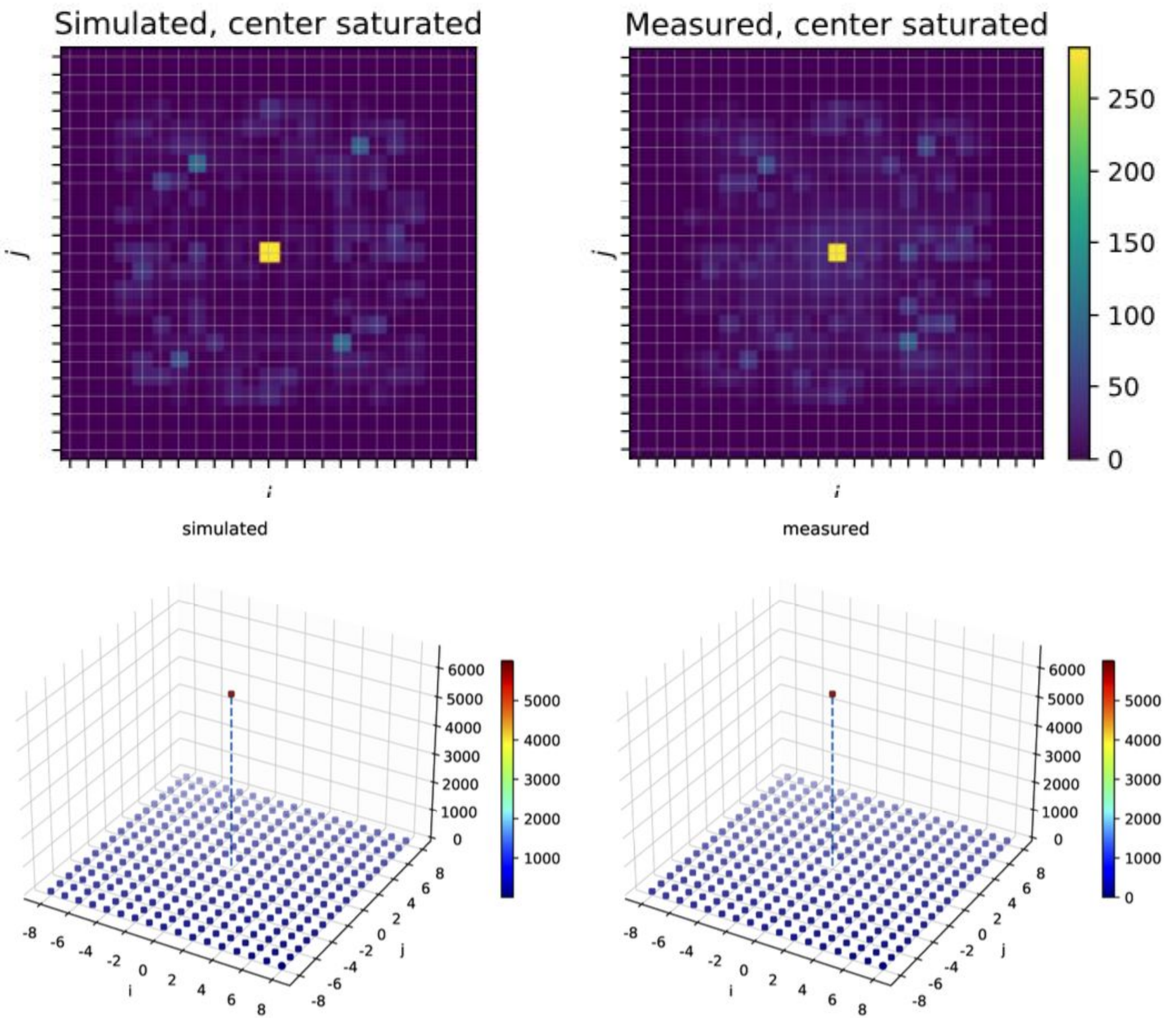
$$s(x,y) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} b(x,y) d(x-m, y-n)$$
$$= b(x,y) ** d(x,y)$$

input beam **DOE transmission function**

Ideal input beam phase:

$$\angle b(x,y) = -\angle d(-x,-y)$$

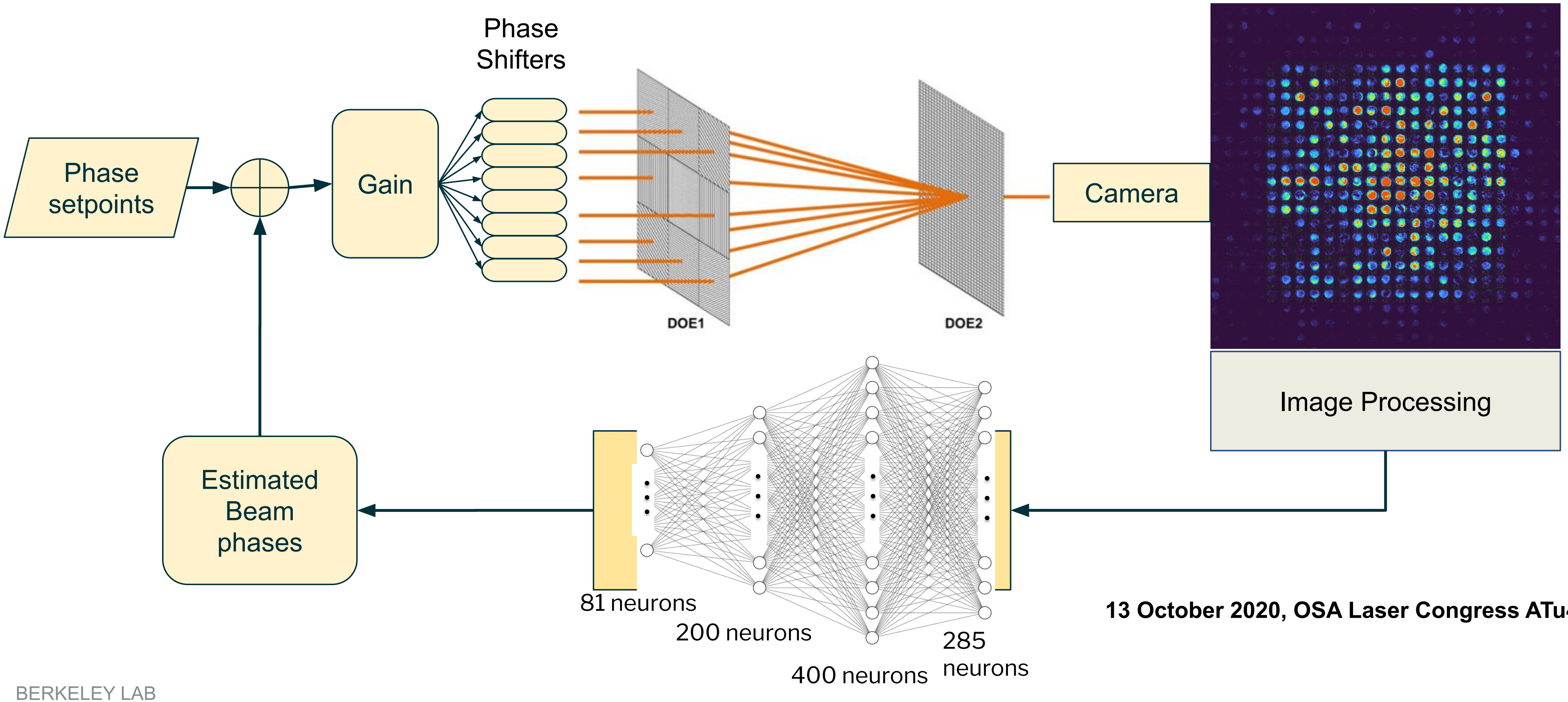
Optics Express 29(4), 5407, 2021



Scalability

Deep learning based active stabilization

Neural network translates a 17x17 diffraction pattern into a 9x9 phase error array



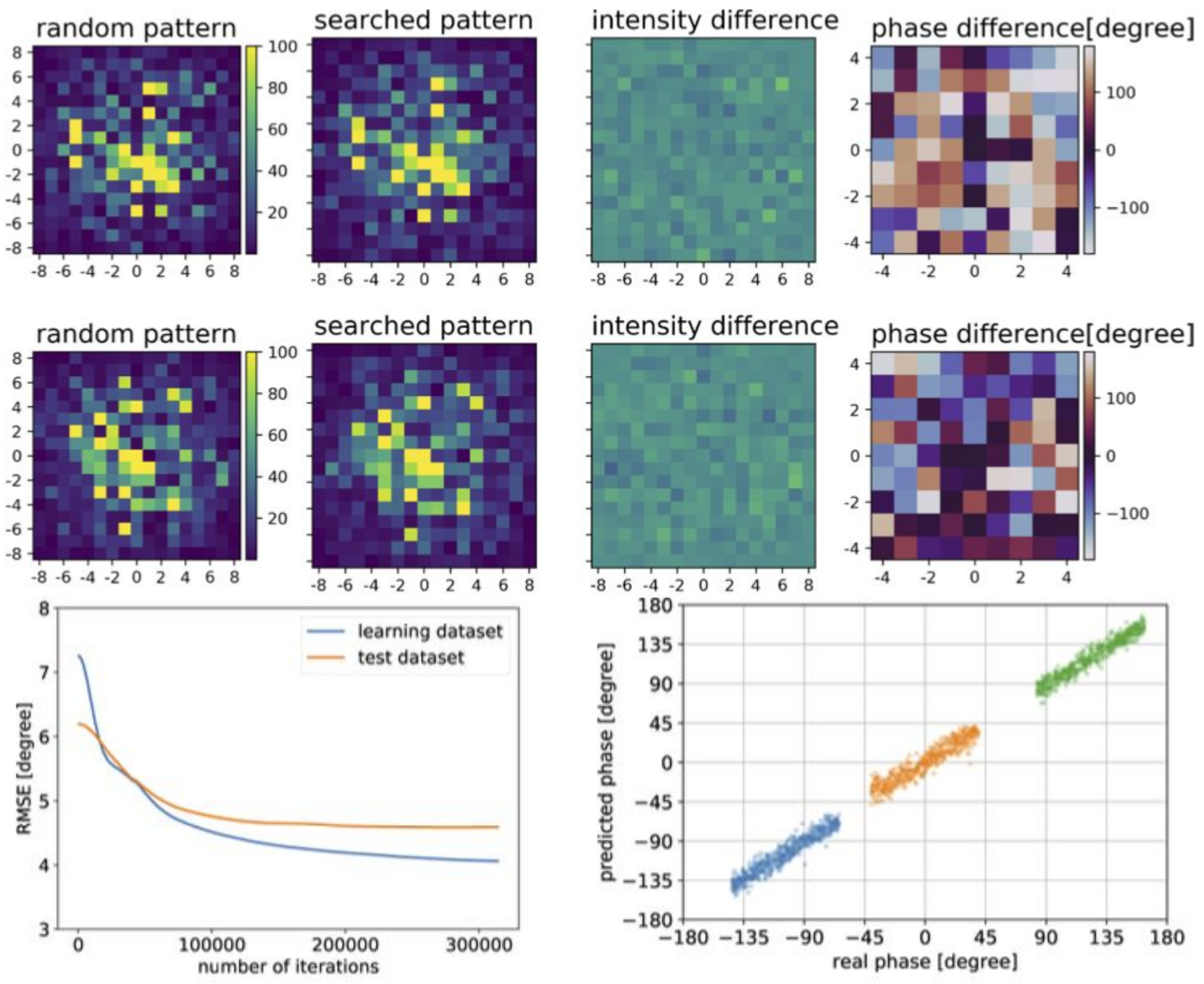
13 October 2020, OSA Laser Congress ATu4A.6

Training range can be a small fraction of phase space

Non-uniqueness problem addressed

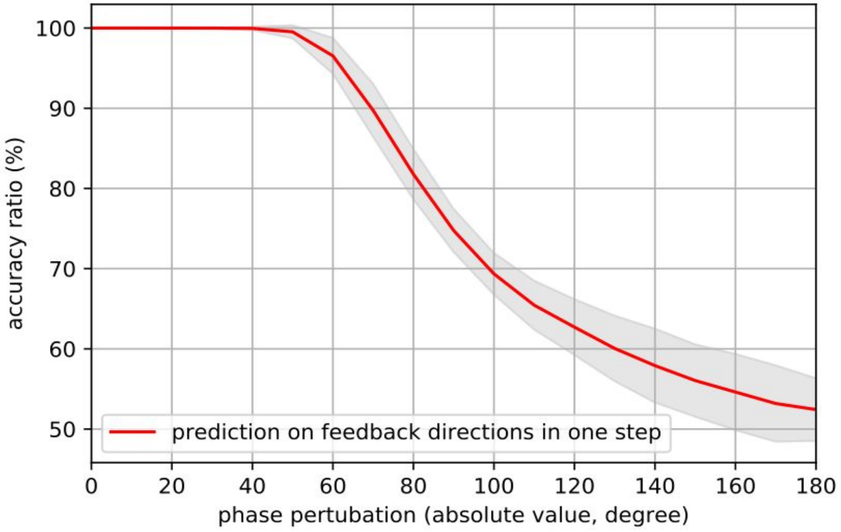
Examples of same pattern generated by different phases

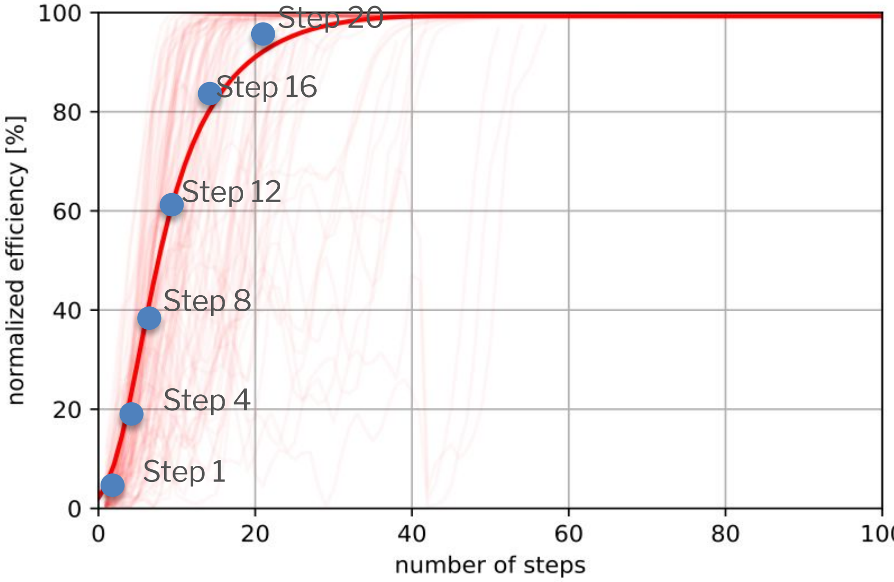
Training dataset phase range: ±40° around optimal



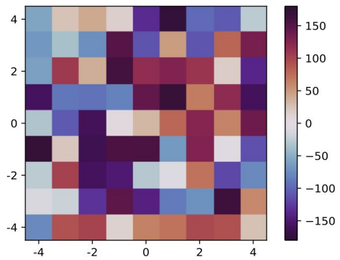
NN recognition even works outside training range

Prediction accuracy drops, but always > 50%

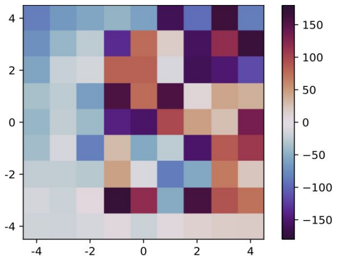




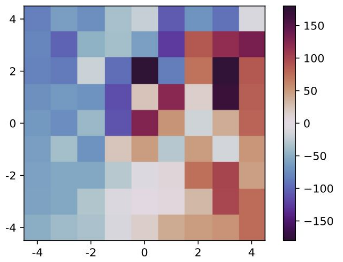
Error (Step 1)



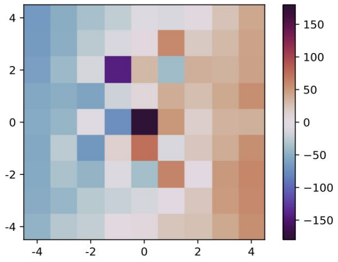
Error (Step 4)



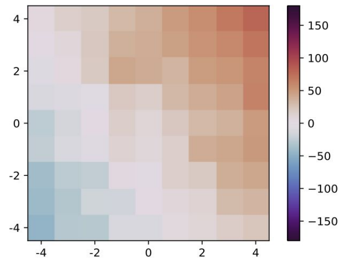
Error (Step 8)



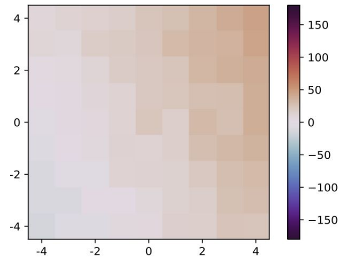
Error (Step 12)



Error (Step 16)



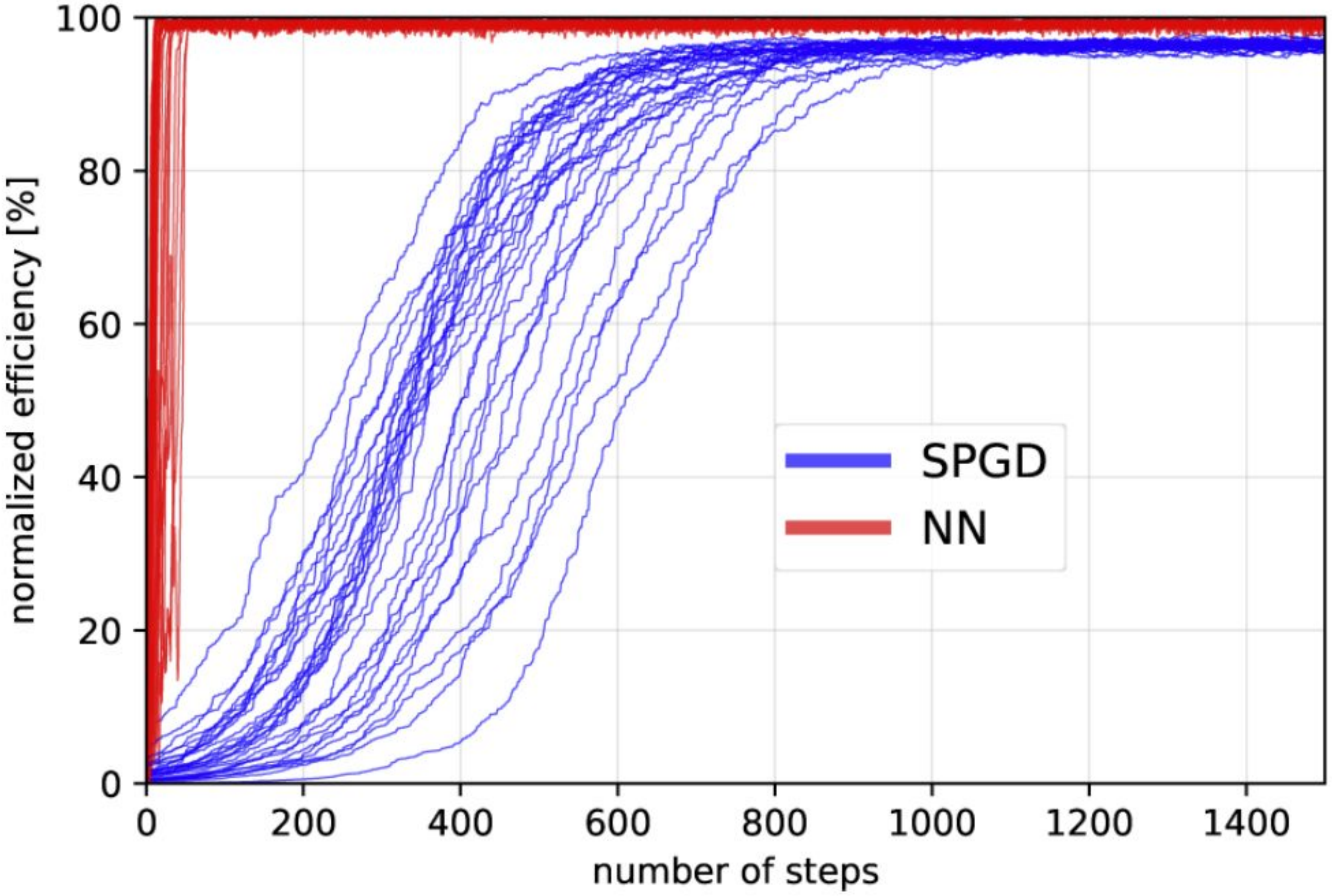
Error (Step 20)



Scalability

NN feedback is scalable, faster, no dither, more accurate

Demonstrated in simulation



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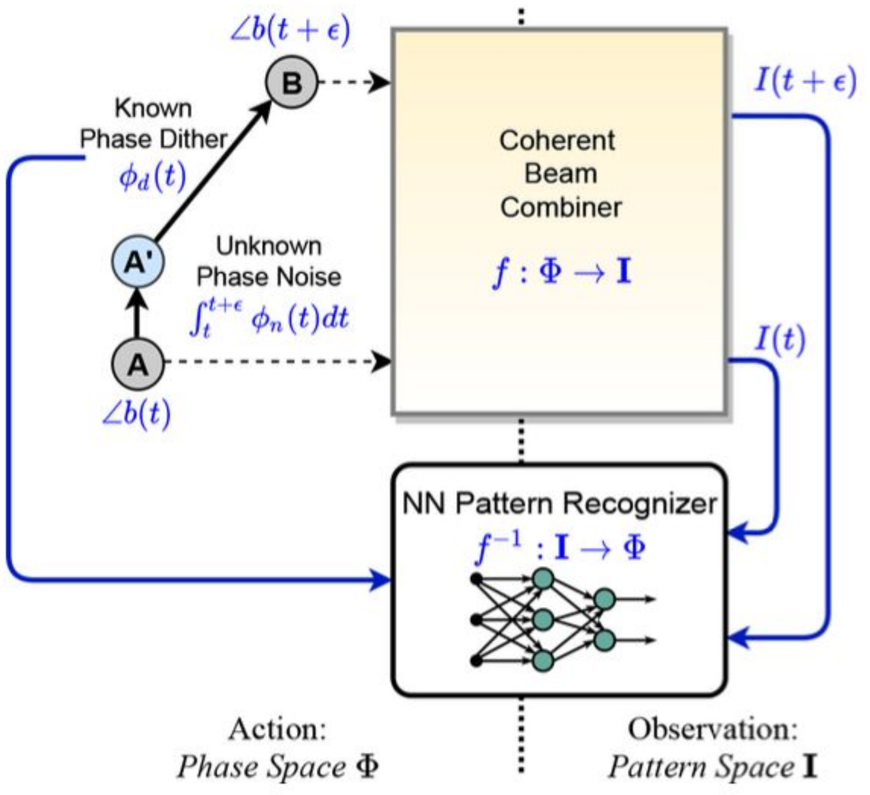
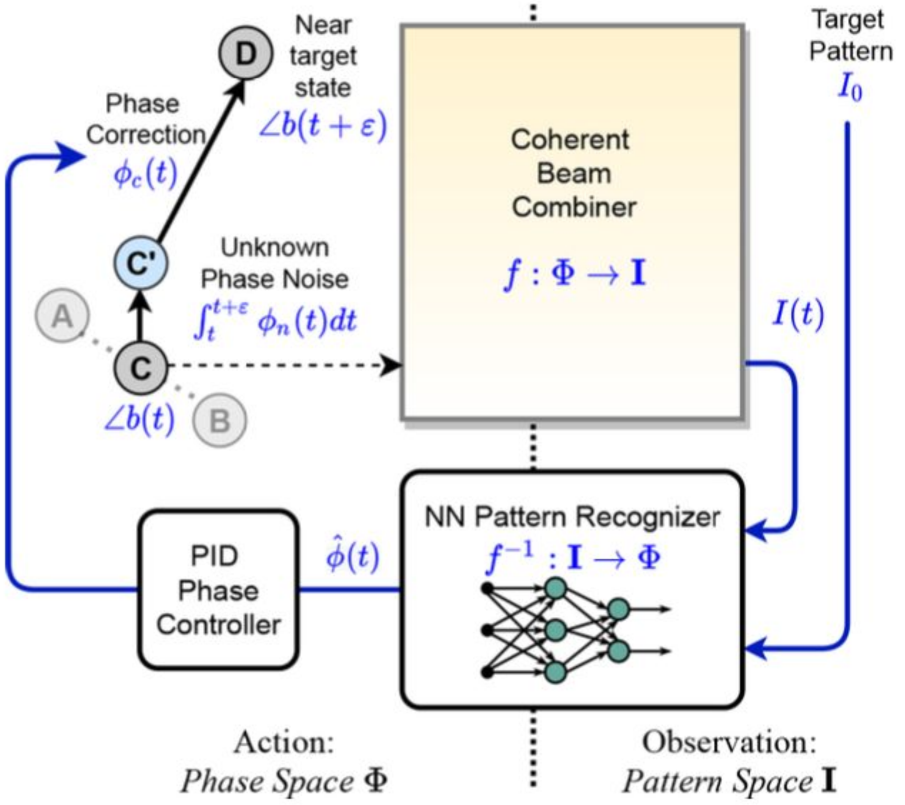
Shooting at a moving target: training in experiment

Training using orthogonally random dithering, faster than spontaneous phase drifting.



Training on pairing 2 patterns with a known dither



Feedback by predicted error using differential mapping

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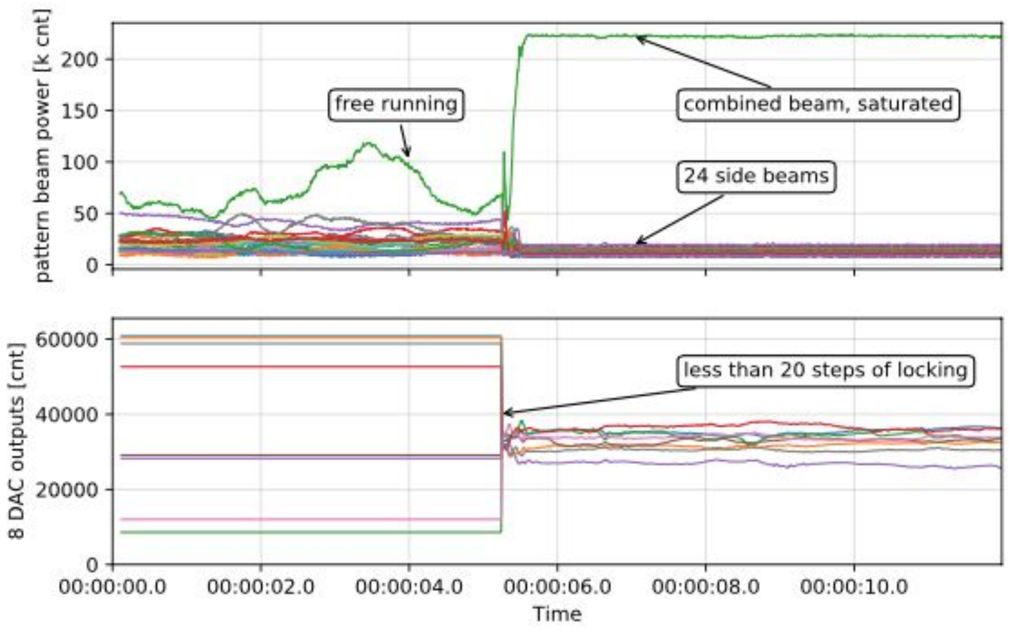
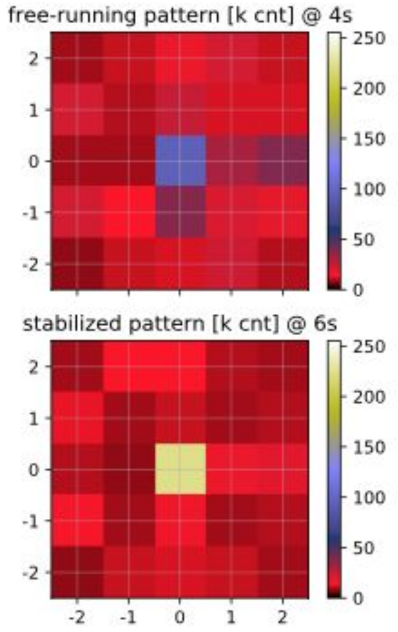
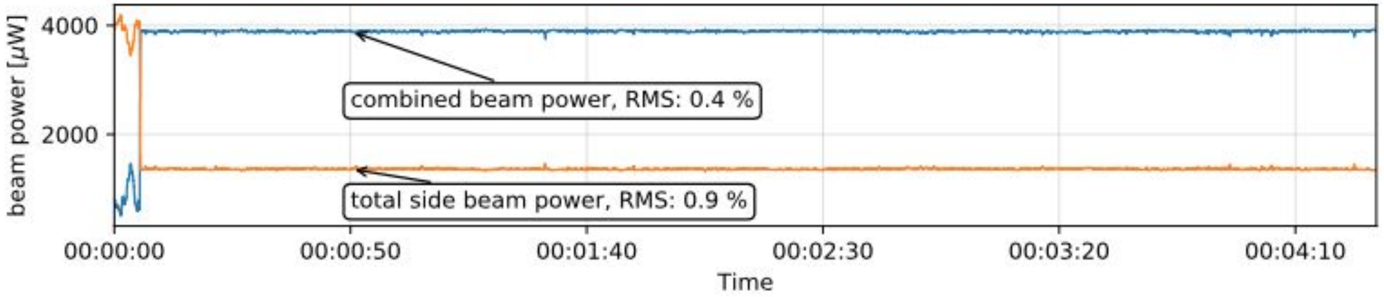
Experimentally combined 8 beams with < 0.4% RMS stability



(a) time history of output beam powers before and after activating stabilizer



(b) output diffraction patterns



(c) out-of-loop measurements of combined and side beam power

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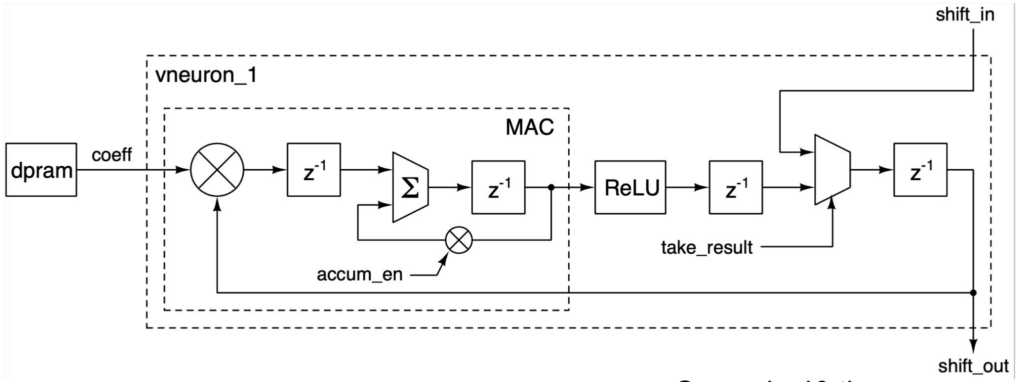
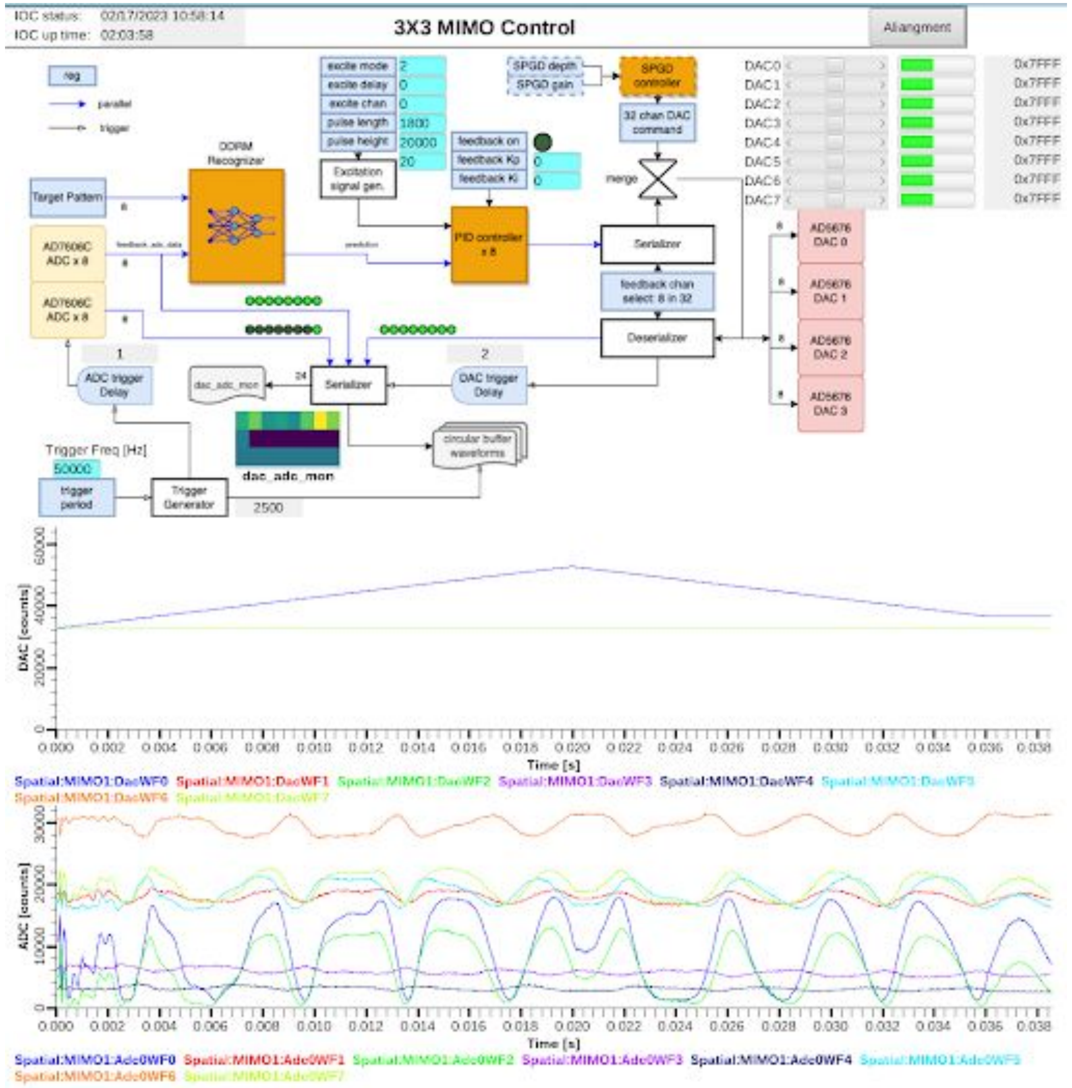
ML@FPGA + Physics informed control platform



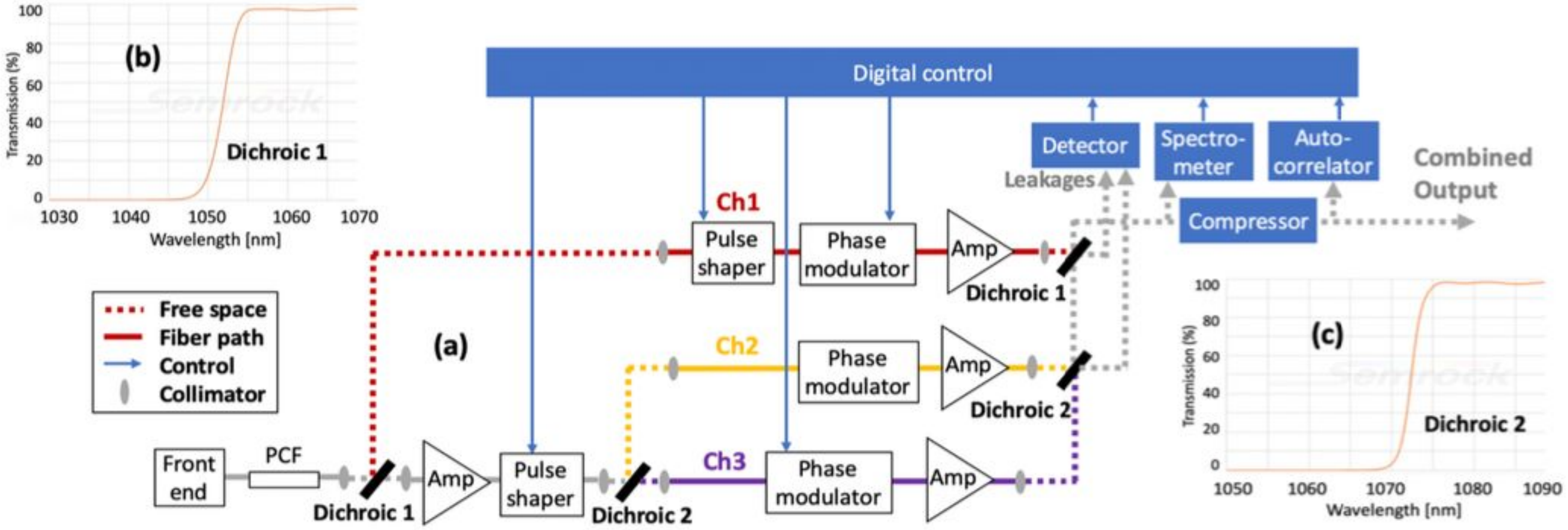
Cascade 40 times

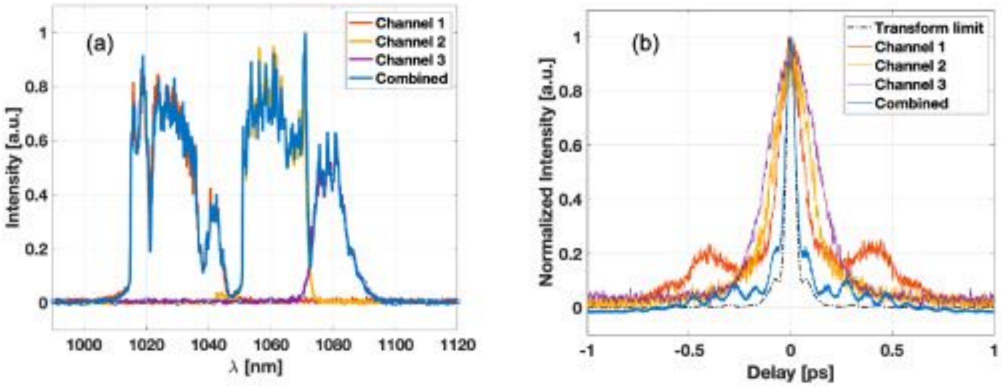


- Physics informed ML model, training against phase drift
- AI accelerator engine design and development (Larry Doolittle):
  - Support scalable NN structure with fully connected layers and ReLU activation (Multi-Layer Perceptron);
  - Works on any FPGA device;
  - Run-time configurable weights
  - Suitable for multi-input, multi-output, real-time feedback control
- Demonstrated quantized training, feedback control and FPGA inference in simulation:
  - Inference time: 131 cycles (1048 ns at 125MHz) for a 16-input, 8-output, 3 layer, 1600 parameters NN
  - Accuracy: 18-bits
  - Resource: 40 DSP48E and 40 BRAM18
- Closed loop in simulation
- Experiment development in progress

Spectral Beam Combining Control

Broadband spectral combining of three pulse-shaped fiber amplifiers with 42fs compressed pulse duration





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Conclusion

✓ Physics	✓ Scalability	✓ Robustness	✓ Speed

✓ Physics

- **Identify** control problems
- **Discover** optical physics
- **Develop** simulation
- **Characterize** experimental system
- **Demonstrate** 3x3 combining

✓ Scalability

- **Demonstrate** 9x9 combining
- **Demonstrate** Neural Network based pattern recognition
- **Solve**: non-uniqueness, non-observable, non-linear

✓ Robustness

- **Develop** model-free training against drift;
- **Develop** Deep (Reinforcement) Learning
- **Demonstrate** experimental stabilization

✓ Speed

- **Develop** FPGA accelerated deep learning controller:
  - Xilinx DPU: 1μs
  - High-level synthesize ML: 72ns
  - Portable NN Engine: 1μs

Thank you!

Collaborators: Tong Zhou, Russell Wilcox, Larry Doolittle, Dan Wang, Siyun Chen, U.Michigan team, et al.