BERKELEY LAB
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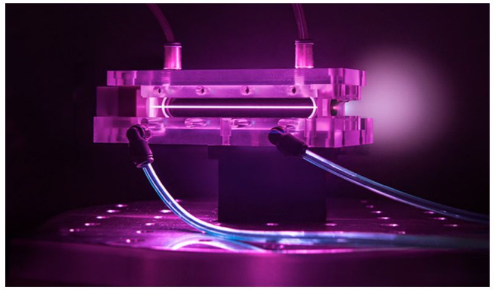
U.S. DEPARTMENT OF ENERGY
Office of Science

Innovations on Digital Low Level Laser Coherence Control

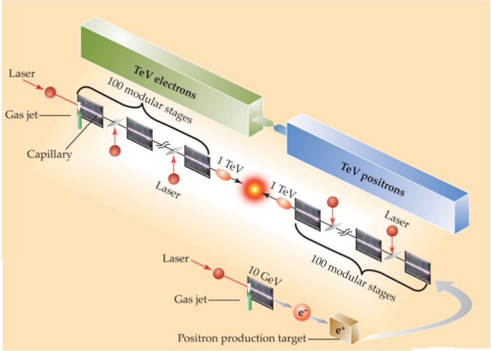
Qiang Du

2023/01/26
USPAS Houston

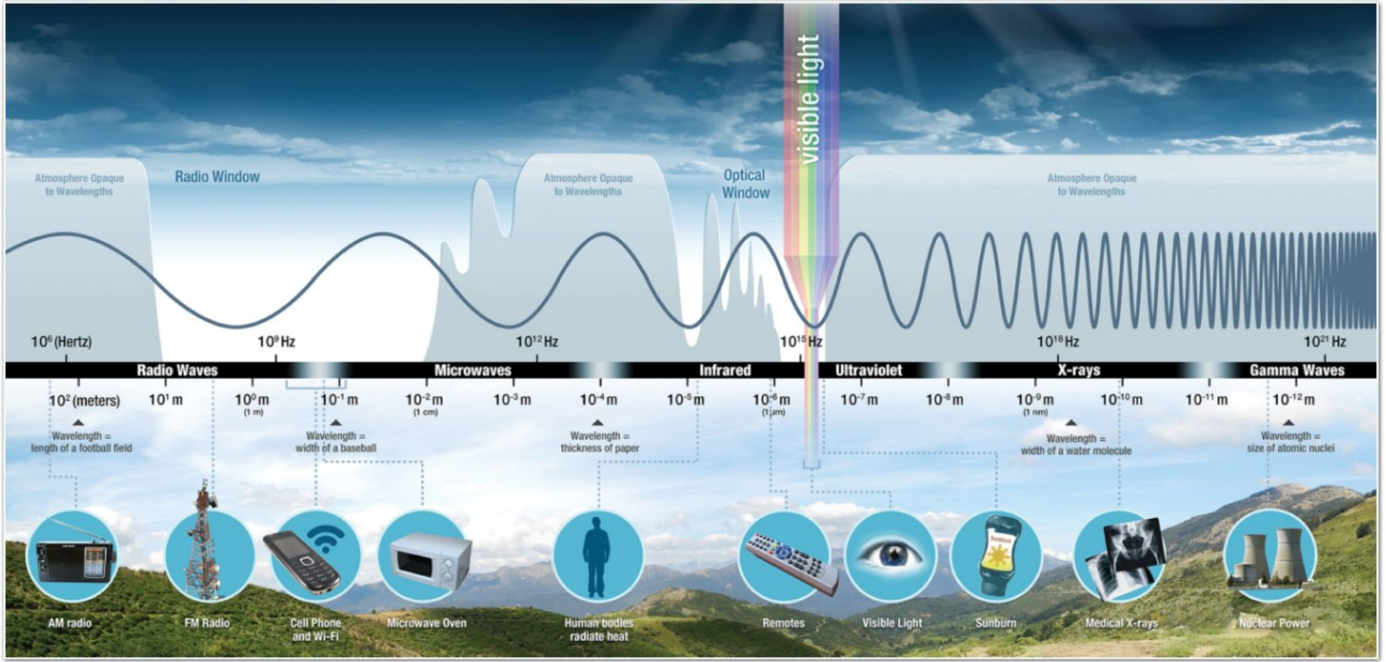
Broad spectrum of digital Low Level ~~RF~~ Coherence control



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

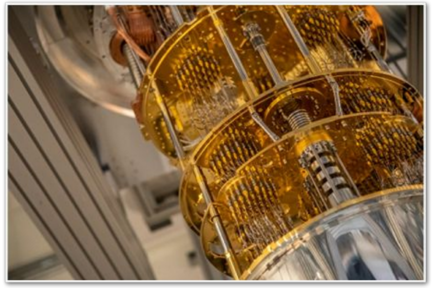


A 2-TeV electronâĂŞpositron collider based on LPA might be < 1 km long



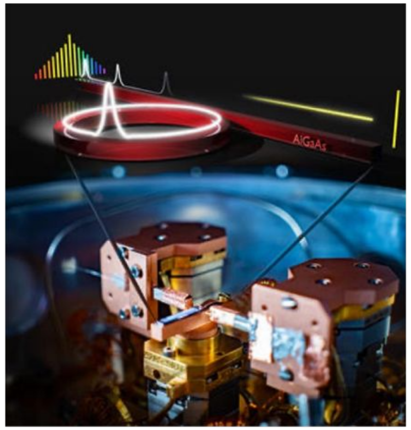
Electromagnetic spectrum

Source: NASA



Quantum Computers

Source: DOE

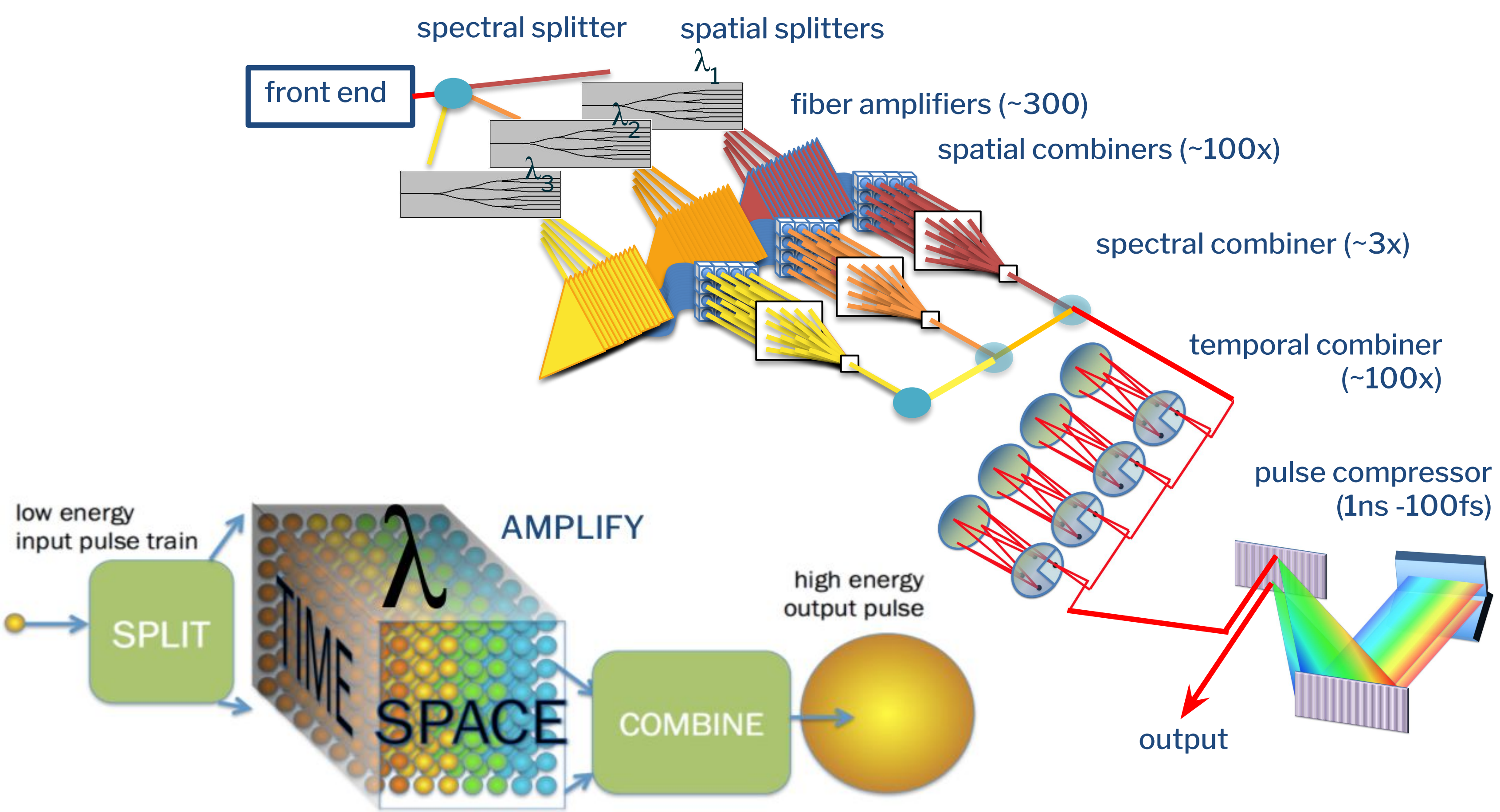


microresonator frequency comb

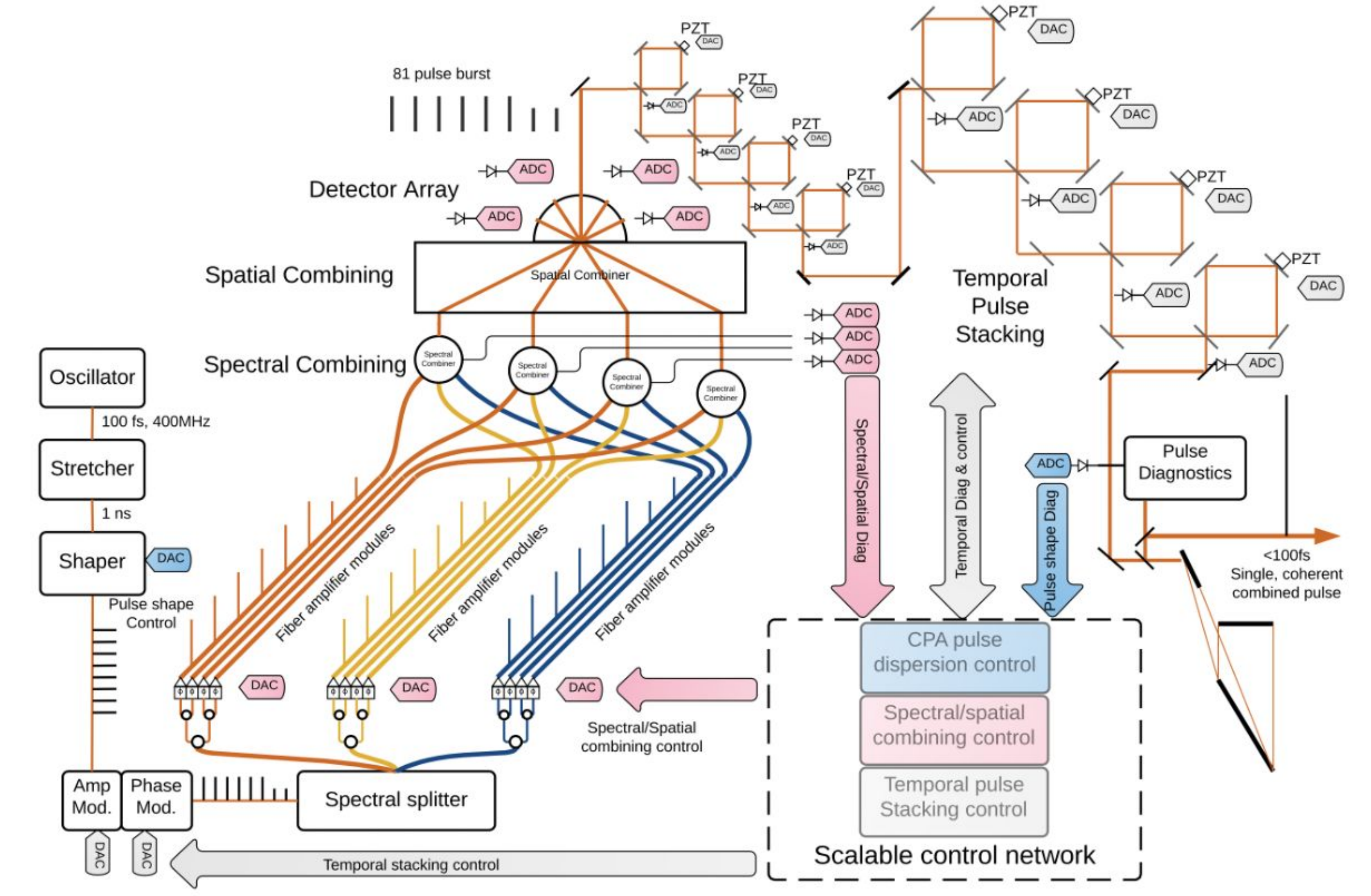
Source: NIST

Multi-dimensional coherent laser combining control

Enabling future laser plasma wakefield accelerator, and more scientific applications



Parameter	Spec
Beam Energy per channel	10mJ
Combined Beam Energy	3J
Pulse duration	30 - 130fs
Reprate	1 - 10kHz
Average power	3 - 30kW



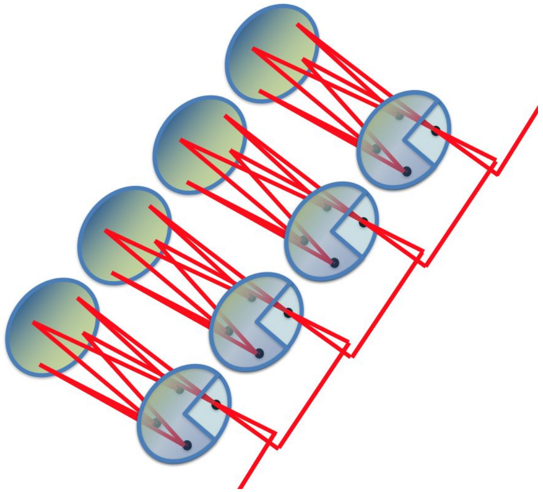
Multi-dimensional Coherent Laser Combining control

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

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

01	Large dimensionality	• N**2 beams • N**2 - 1 dimensional action space (phase) • (2N-1)**2 dimensional observation space
02	Non-observable, Needs high precision	• Only beam powers are measurable • Phase information are lost @ 200THz • ~10 nm optical length control
03	Time variant, High noise bandwidth	• Beam power variation • Pointing stability • Polarization stability • Phase noise bandwidth: kHz
04	Nonlinear, Non-uniqueness	• Camera dynamic range / saturation • Many-to-one phase-pattern mapping

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



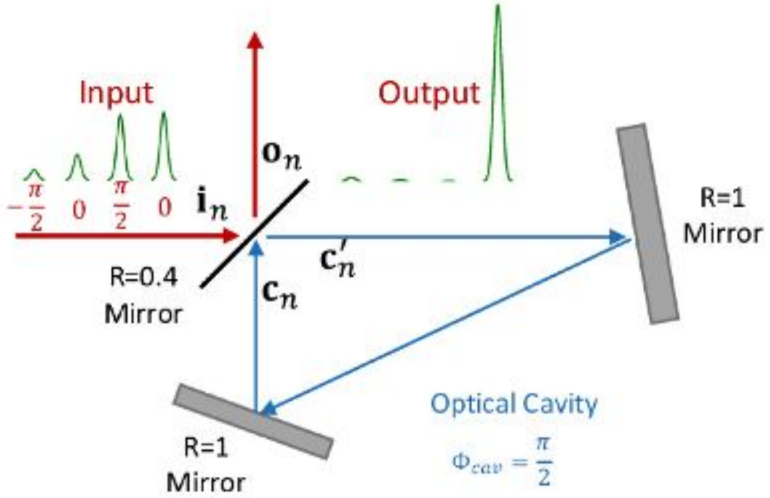
Temporal Pulse Stacking Control

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

Gires Tournois interferometer (GTI) as resonance cavity

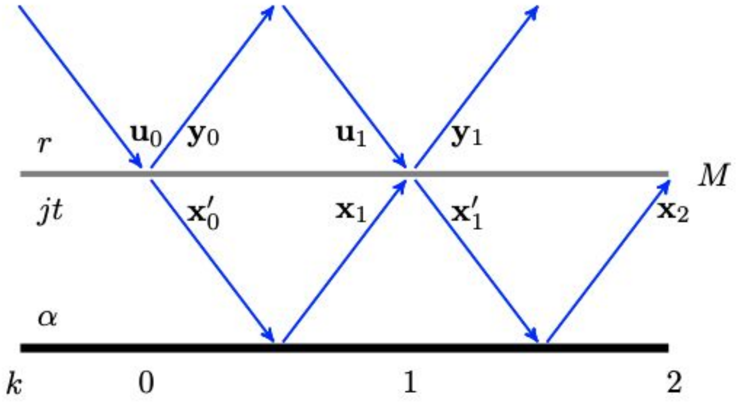
Coherence control by amplitude / phase modulation on each pulse at 1Gsps

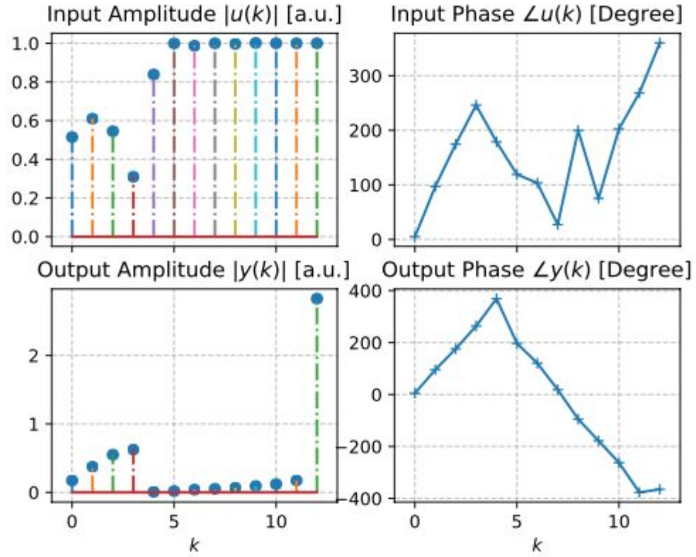
GTI Optical Cavity physis



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

Control system model

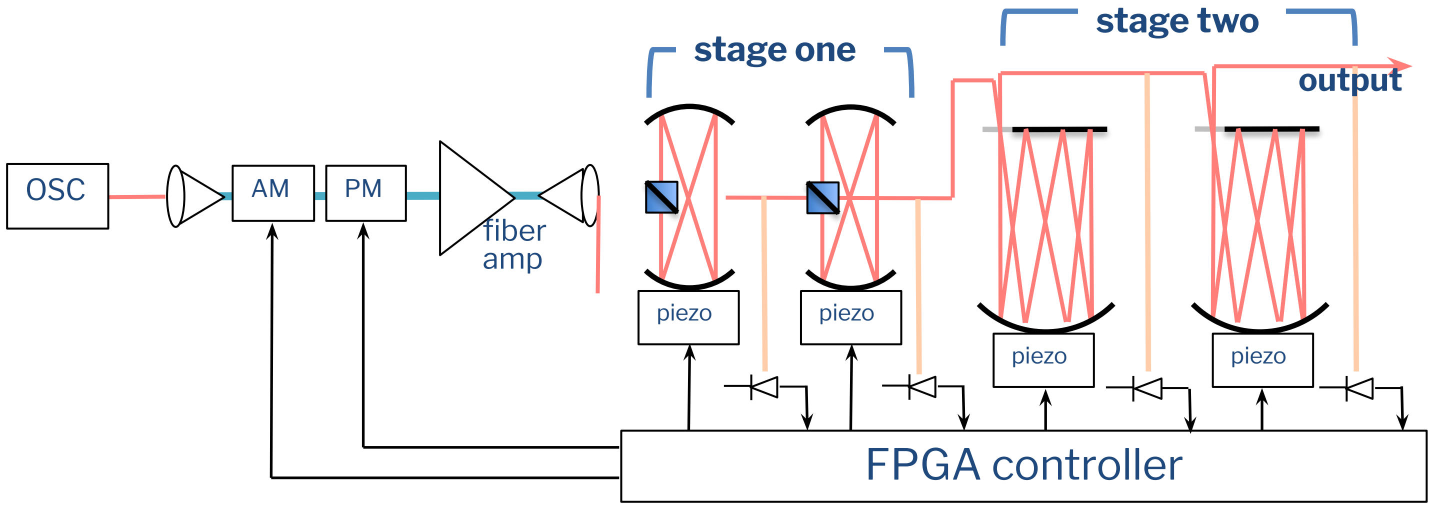




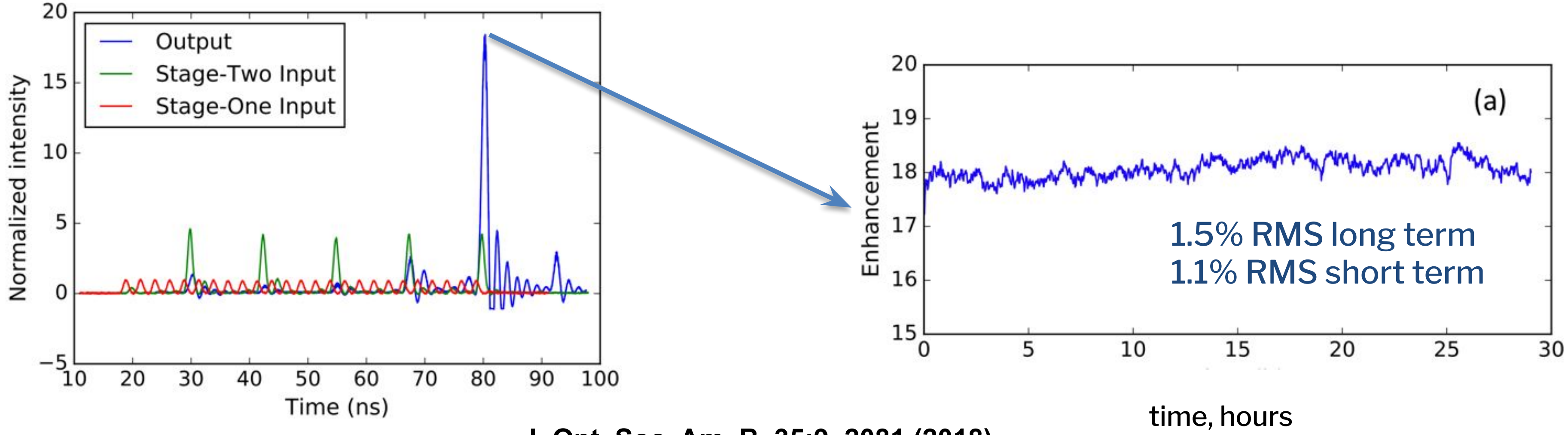
$$\begin{cases} \mathbf{x}_k' & = r \cdot \mathbf{x}_k + jt \cdot \mathbf{u}_k \\ \mathbf{y}_k & = jt \cdot \mathbf{x}_k + r \cdot \mathbf{u}_k \\ \mathbf{x}_{k+1} & = \alpha e^{j\delta} \cdot \mathbf{x}_k' \\ x_0 & = 0 \end{cases}$$

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

FPGA based coherence control for 25 pulses stacking



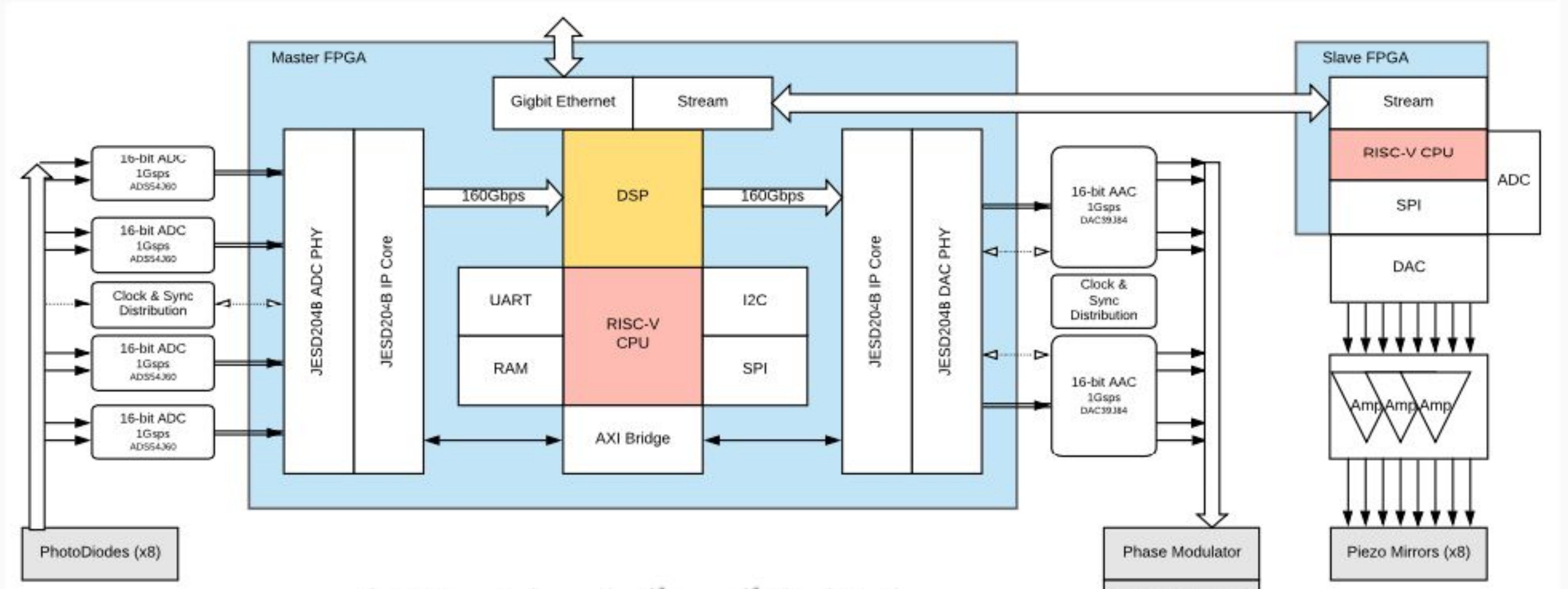
25 pulses added,
~18x power increase



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

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

81 pulse stacking using VC707+FMC120x2



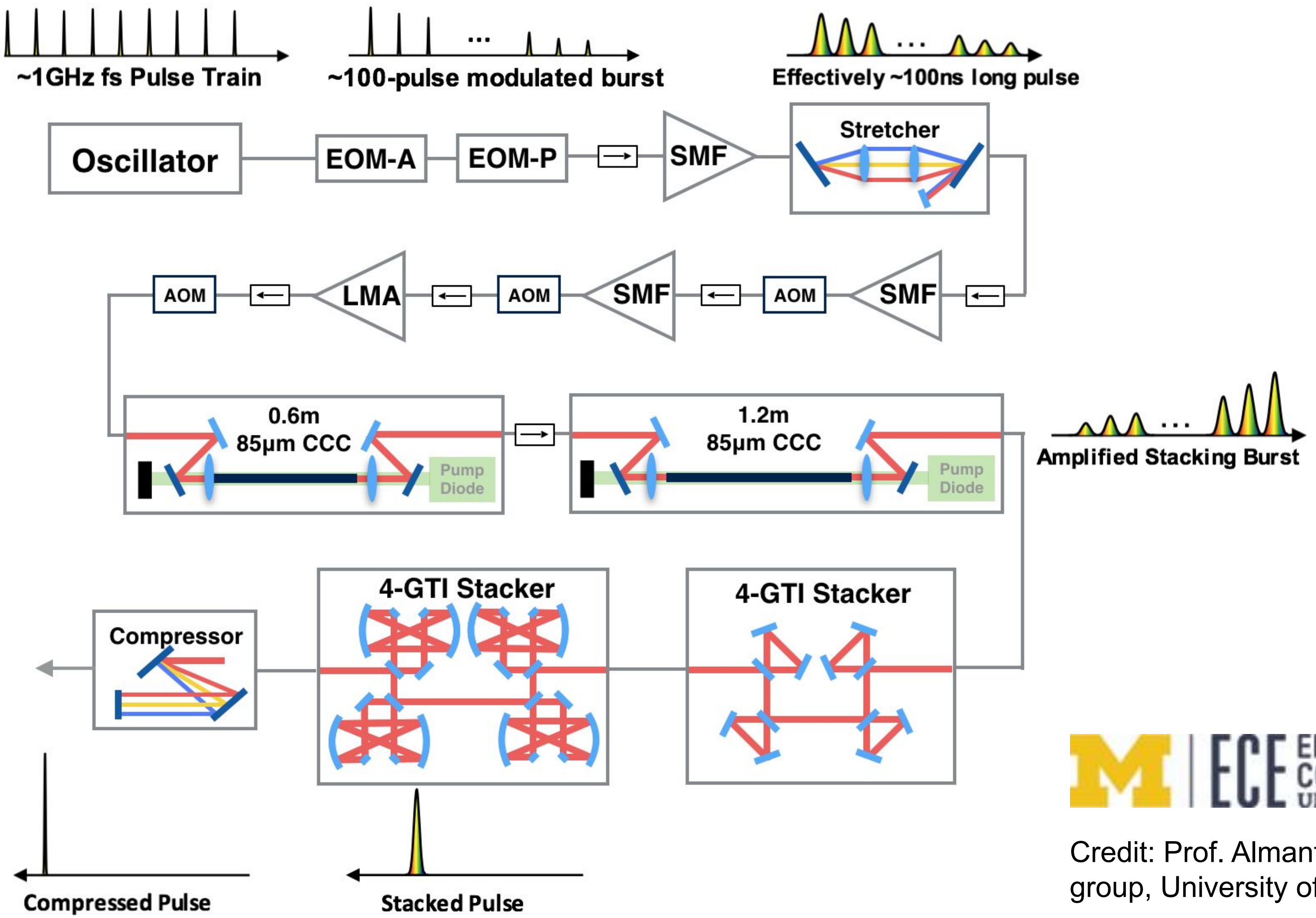
$$\begin{pmatrix} z\mathbf{X}(z) - z\mathbf{x}_0 \\ \mathbf{Y}(z) \end{pmatrix} = \begin{pmatrix} \alpha e^{j\delta} r & \alpha e^{j\delta} jt \\ jt & r \end{pmatrix} \begin{pmatrix} \mathbf{X}(z) \\ \mathbf{U}(z) \end{pmatrix}$$

Stabilization of cascaded optical cavity phase

1Gsps 8-in 8-out FPGA chassis

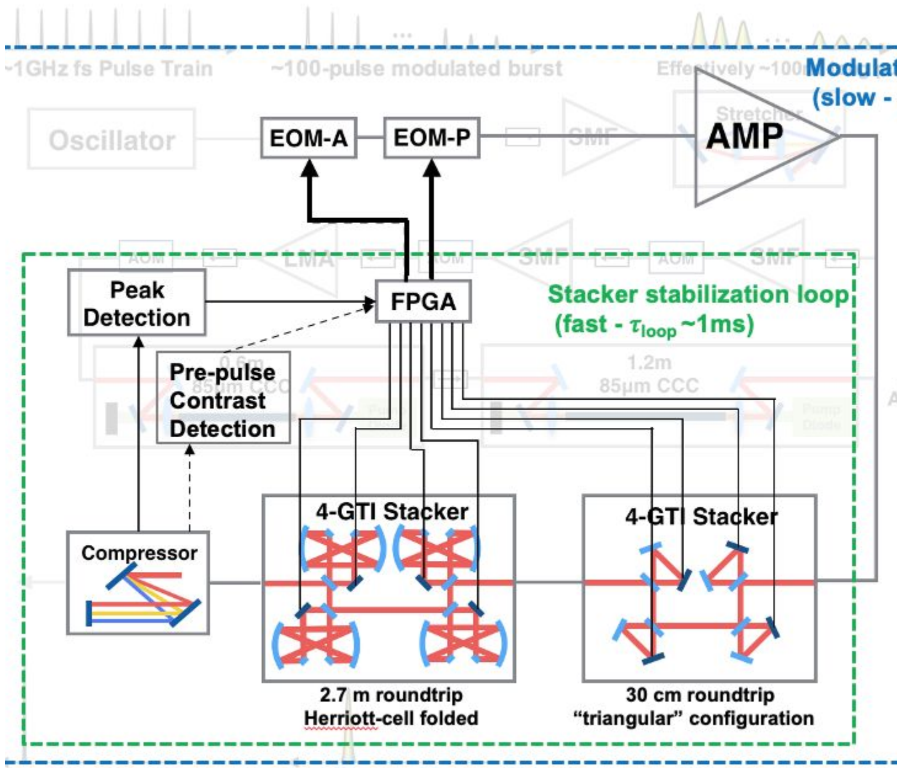
200ksps 8-in 8-out

University of Michigan: Coherent Pulse Stacking Control



Credit: Prof. Almantas Galvanauskas group, University of Michigan

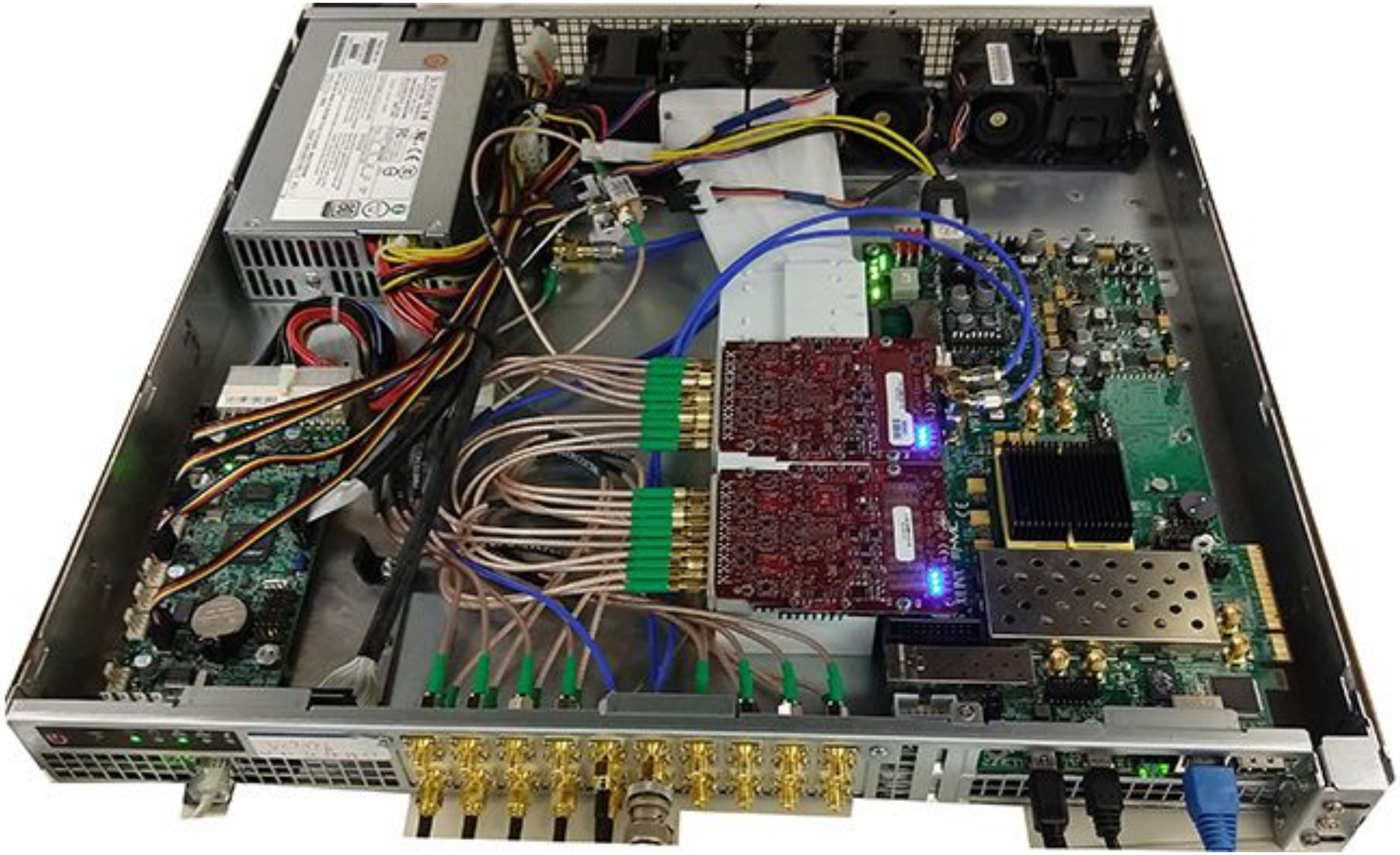
Record breaking 81 ultrafast pulses stacked at U.of.M.

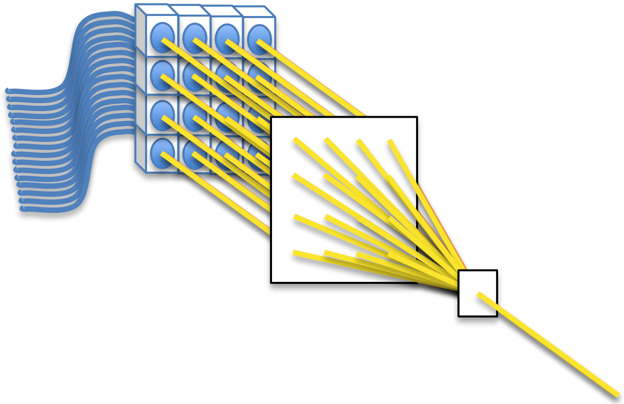


Credit:
University of Michigan

The same FPGA platform is used by Qubit Control

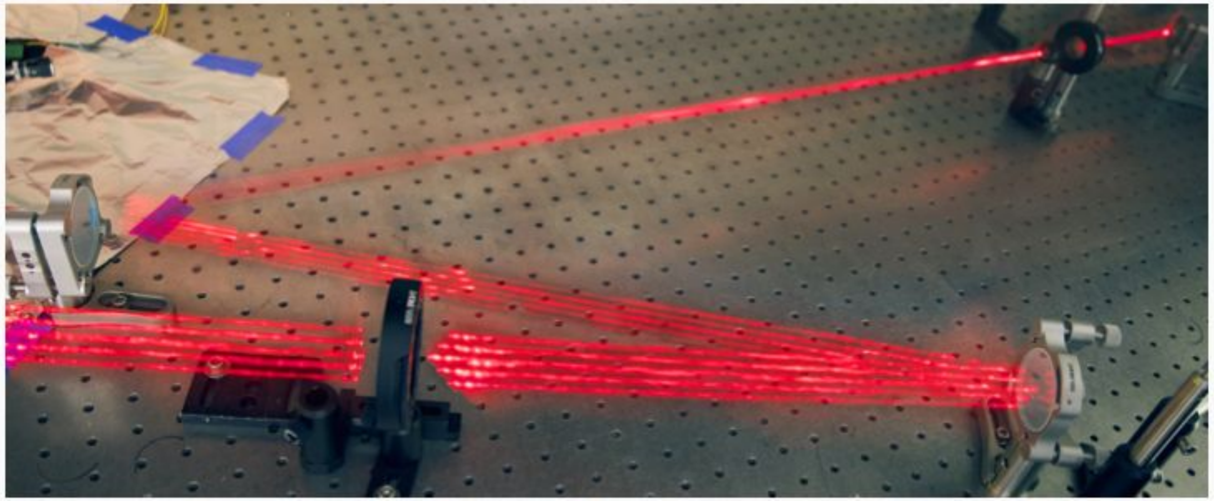
Advanced Quantum Testbed (AQT) at Berkeley Lab





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

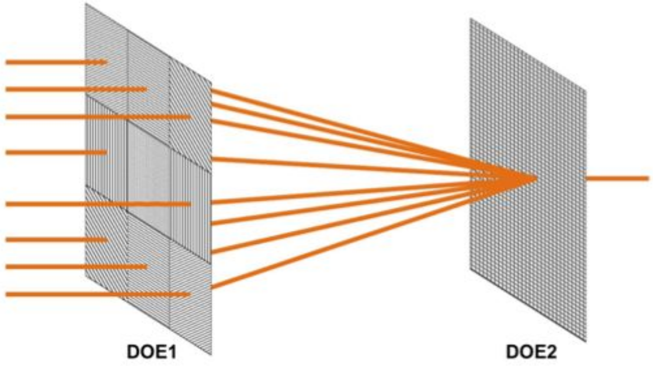
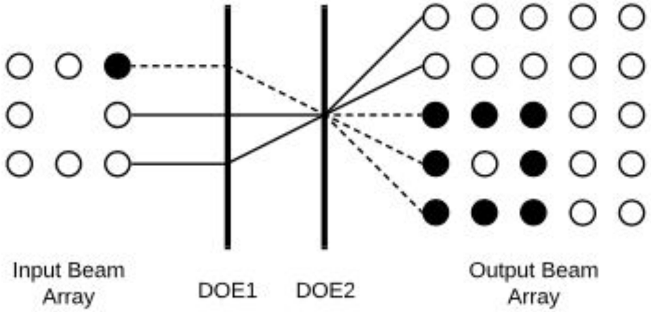
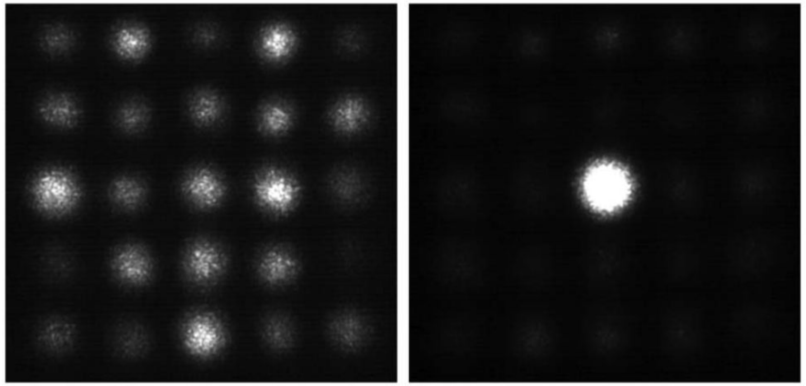


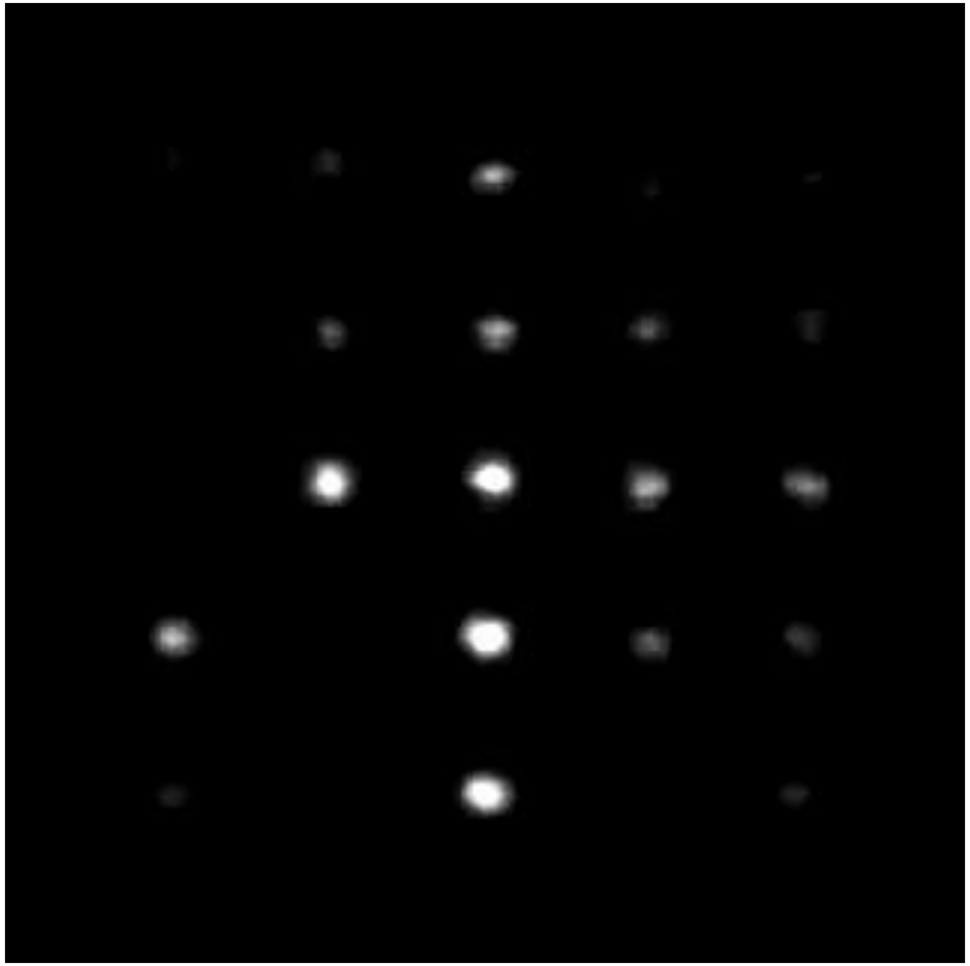
Fig. 1. Concept of the two-dimensional diffractive combiner.





(a) Free running (b) Phase controlled

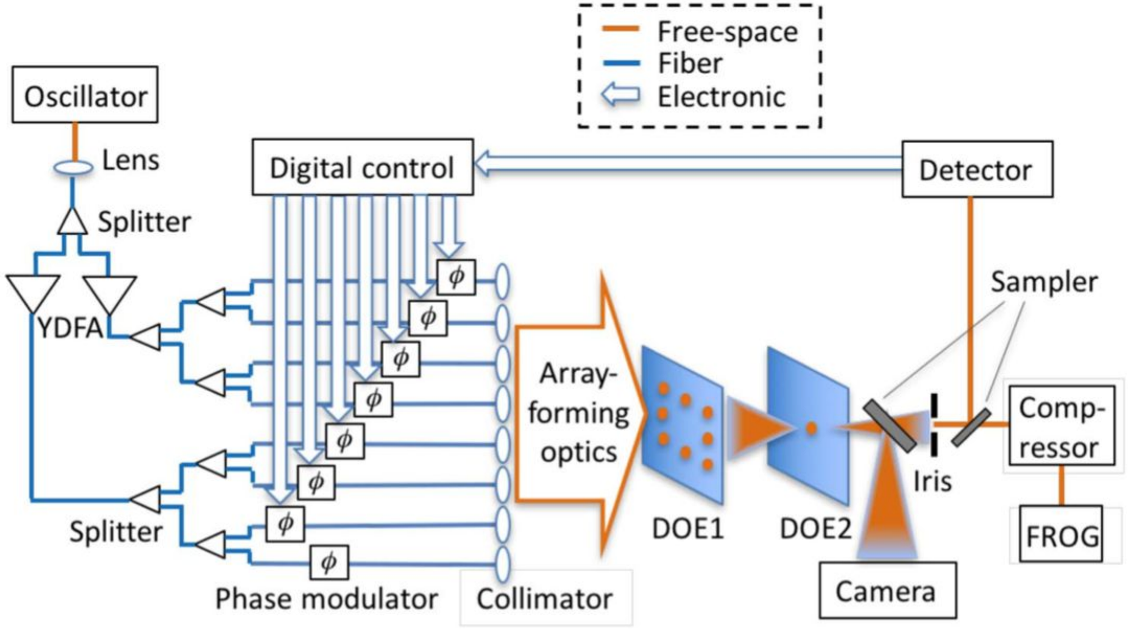
Opt. Lett. 42, 4422 (2017)



Free running 3x3 combiner output pattern

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

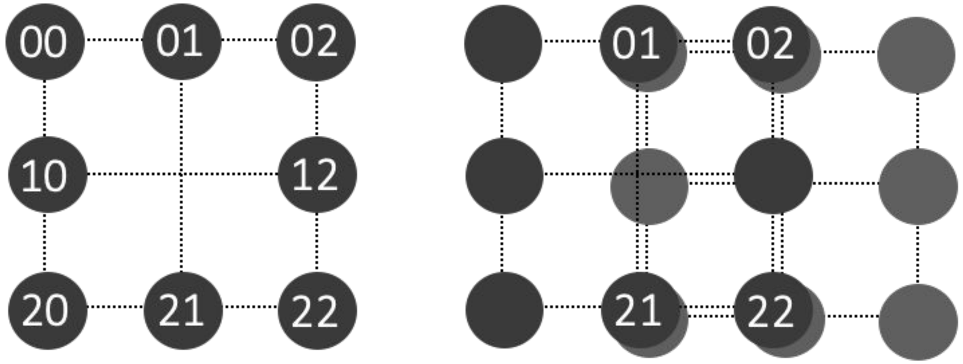
$$d_{3\times 3} = \begin{pmatrix} 1 & i & 1 \\ 1 & 0 & -i \\ -1 & 1 & 1 \end{pmatrix}.$$

Input beam complex amplitude

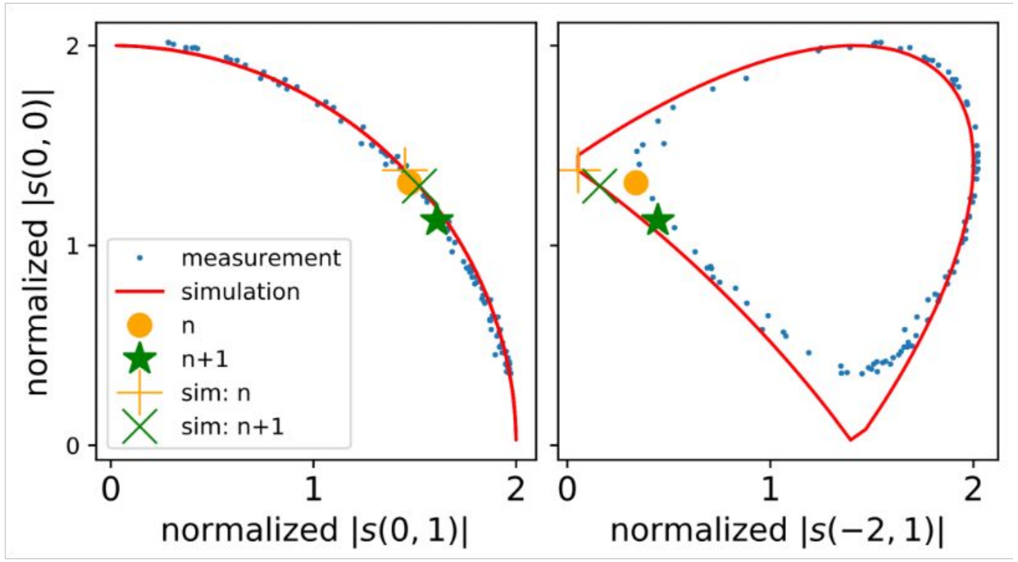
$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix} ** \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix} = \begin{pmatrix} 1 & \boxed{2} & 3 & \boxed{2} & 1 \\ \boxed{2} & 2 & 4 & 2 & \boxed{2} \\ 3 & 4 & 8 & 4 & 3 \\ \boxed{2} & 2 & 4 & 2 & \boxed{2} \\ 1 & \boxed{2}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

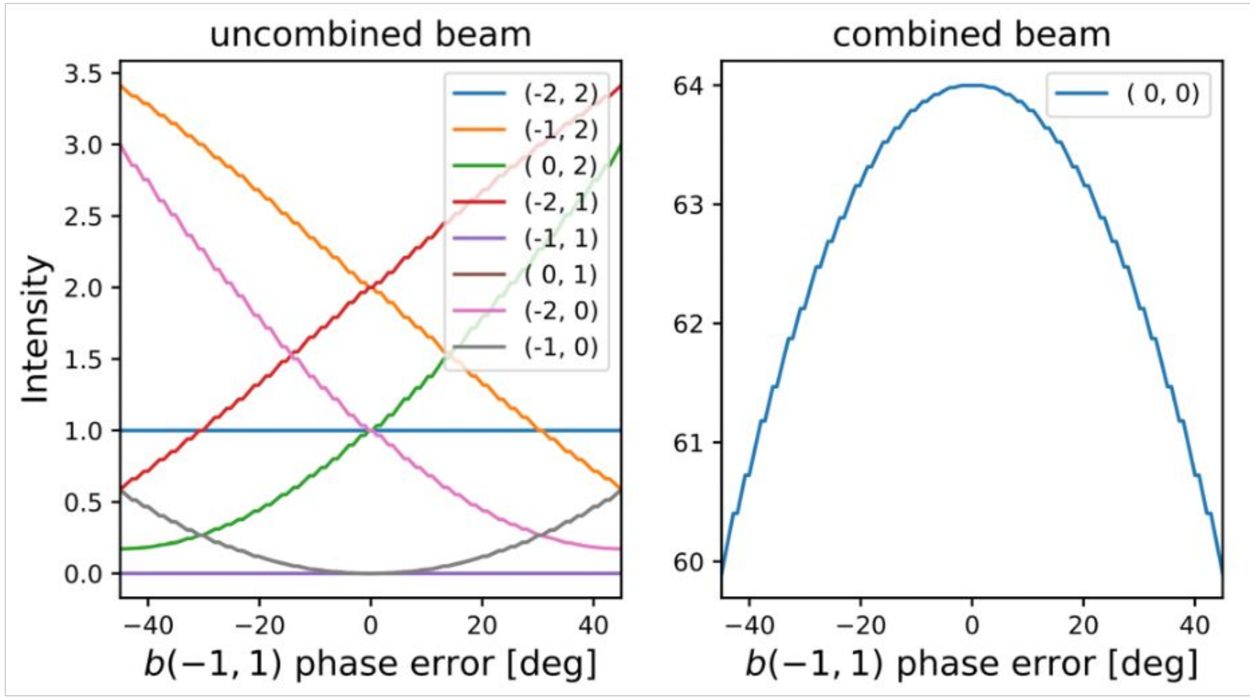
Opt. Lett. 44, 4554 (2019)

Identify optical combiner phase transfer function



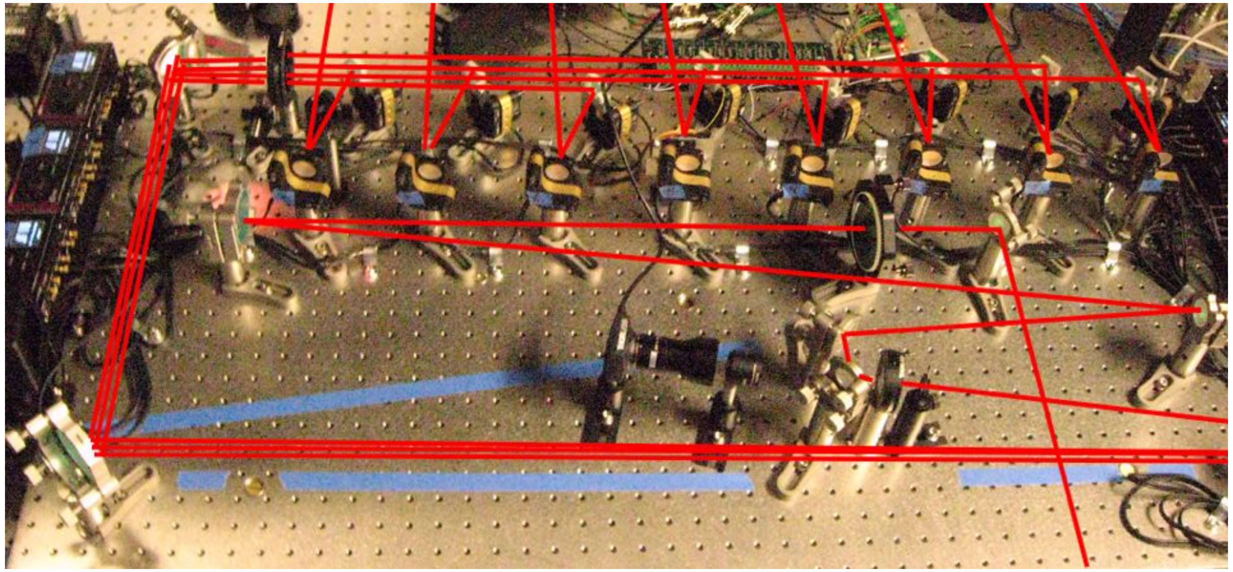
correlations reveal quadrature phase!

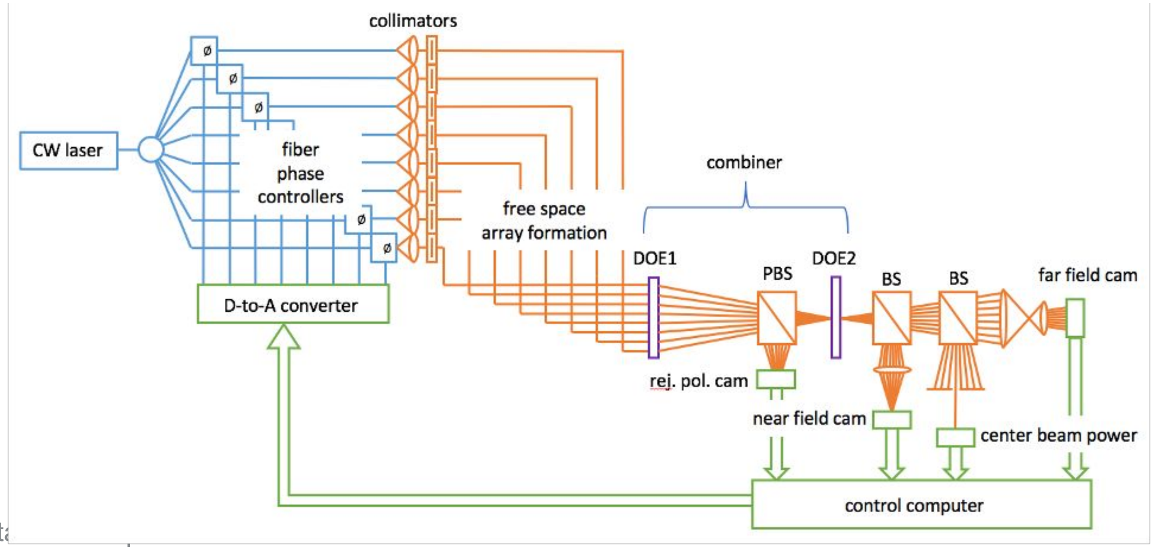


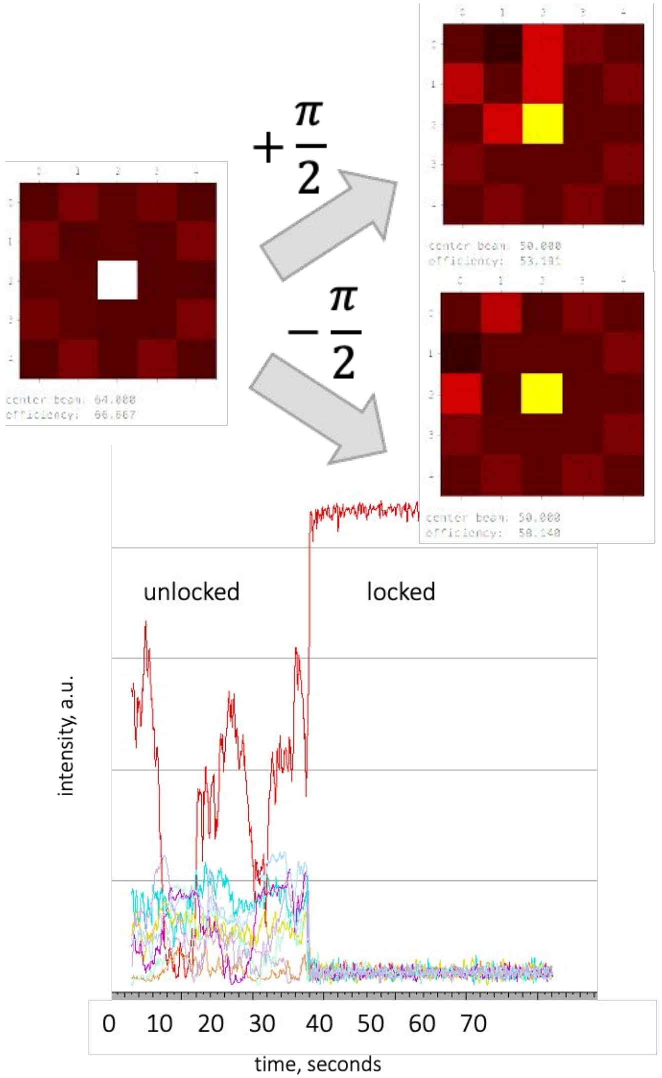


$$\text{measured } \angle d(x,y) = \begin{pmatrix} 0 & +\frac{\pi}{2} & 0 \\ 0 & & -\frac{\pi}{2} \\ \pi & 0 & 0 \end{pmatrix}$$

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:

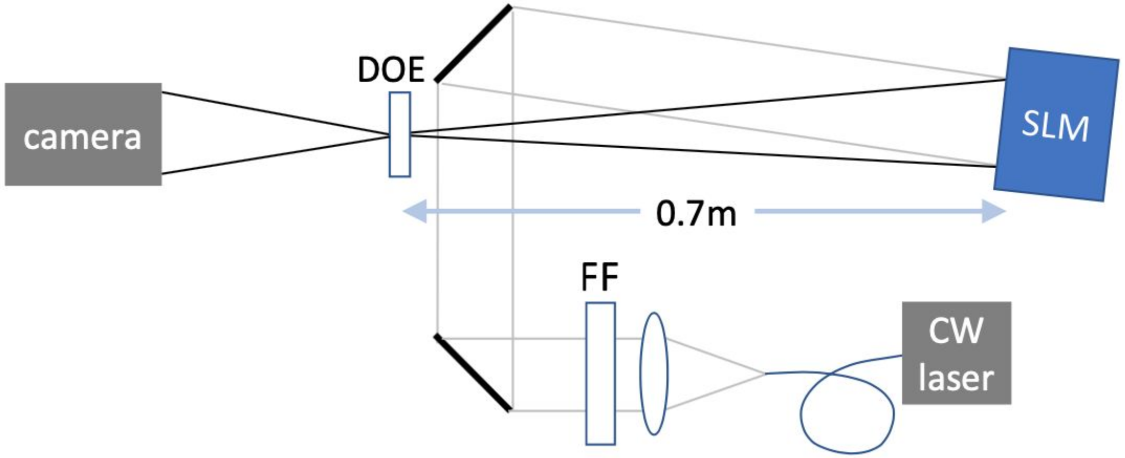
$$\angle\hat{b}(i,j) = -\angle\hat{d}(-i,-j)$$

input beam phases equal DOE phase function,

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

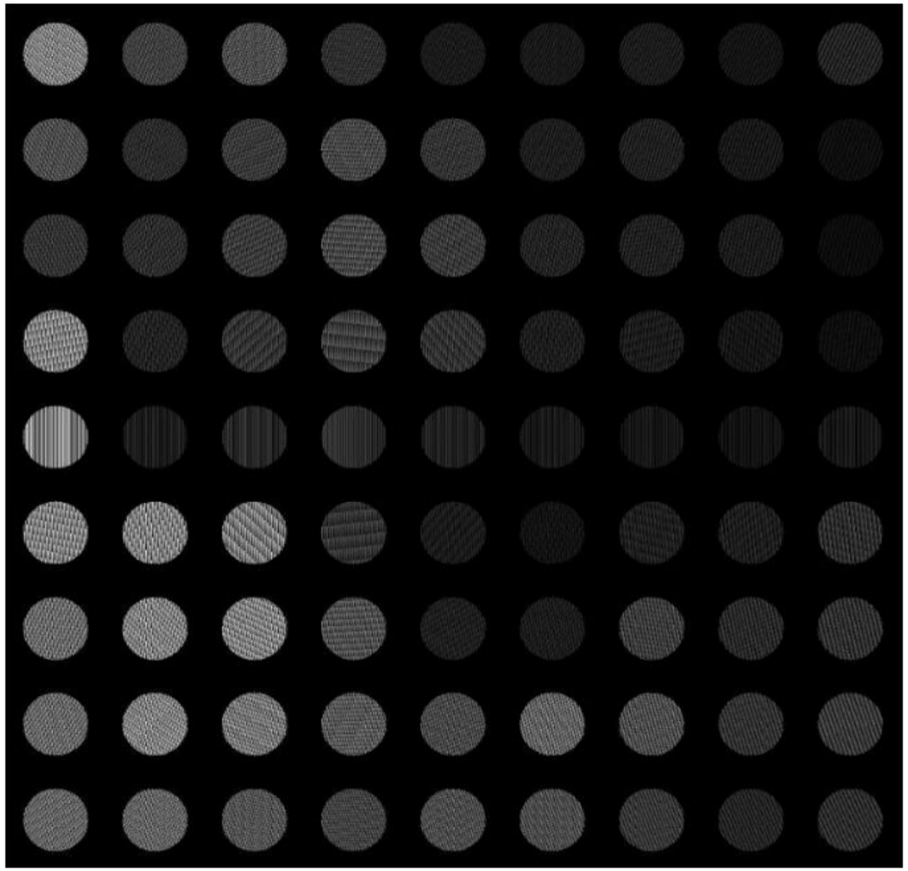
81 beams: a simple test bed for a complex problem

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...

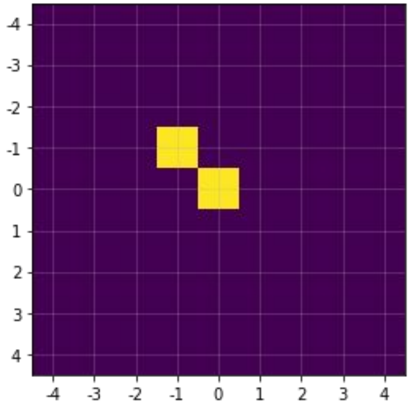
Hologram on SLM for generating 9x9 beams.

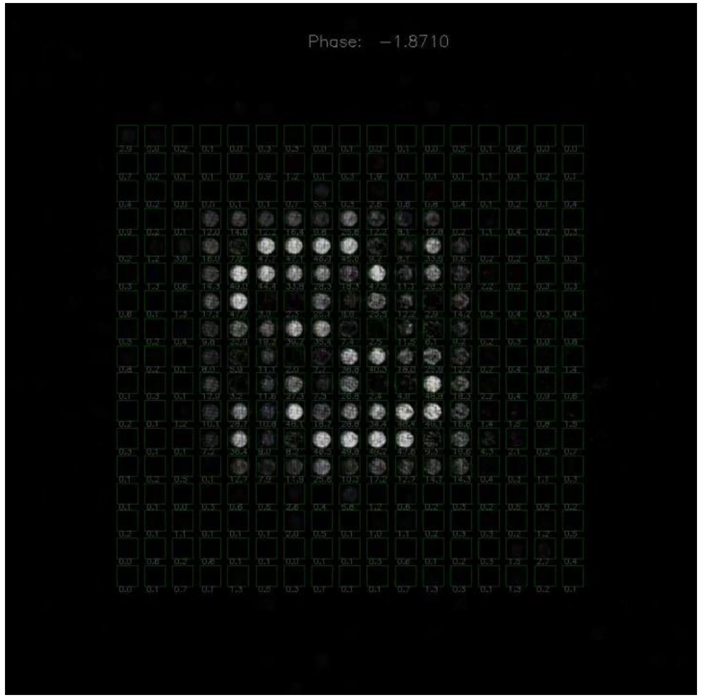


System identification: beam phase induced pattern

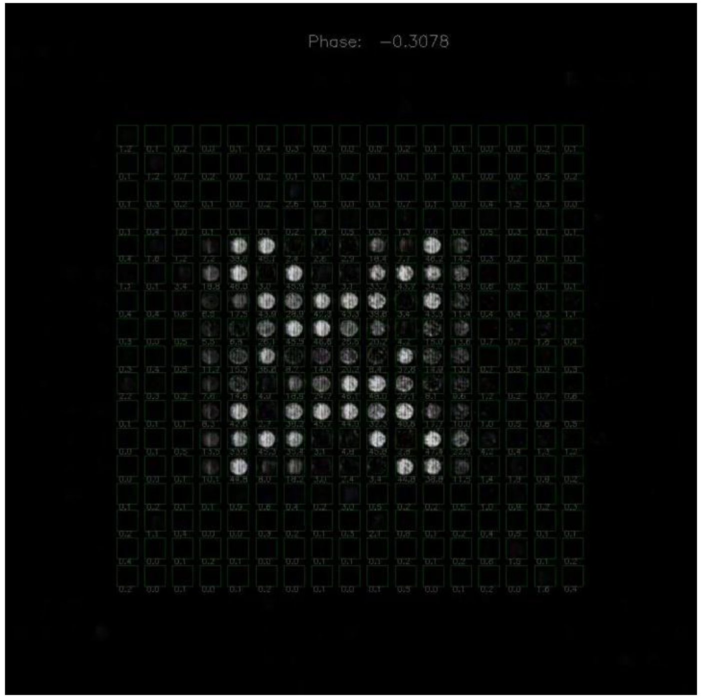
Phase scanning two-beam interference data reveals complex transmission function

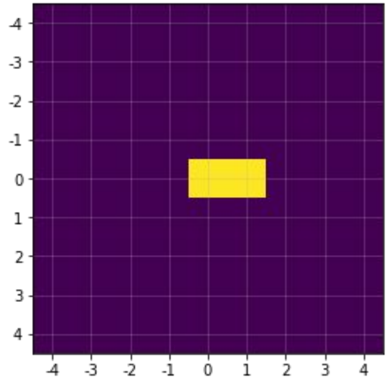
Center + upper left beam





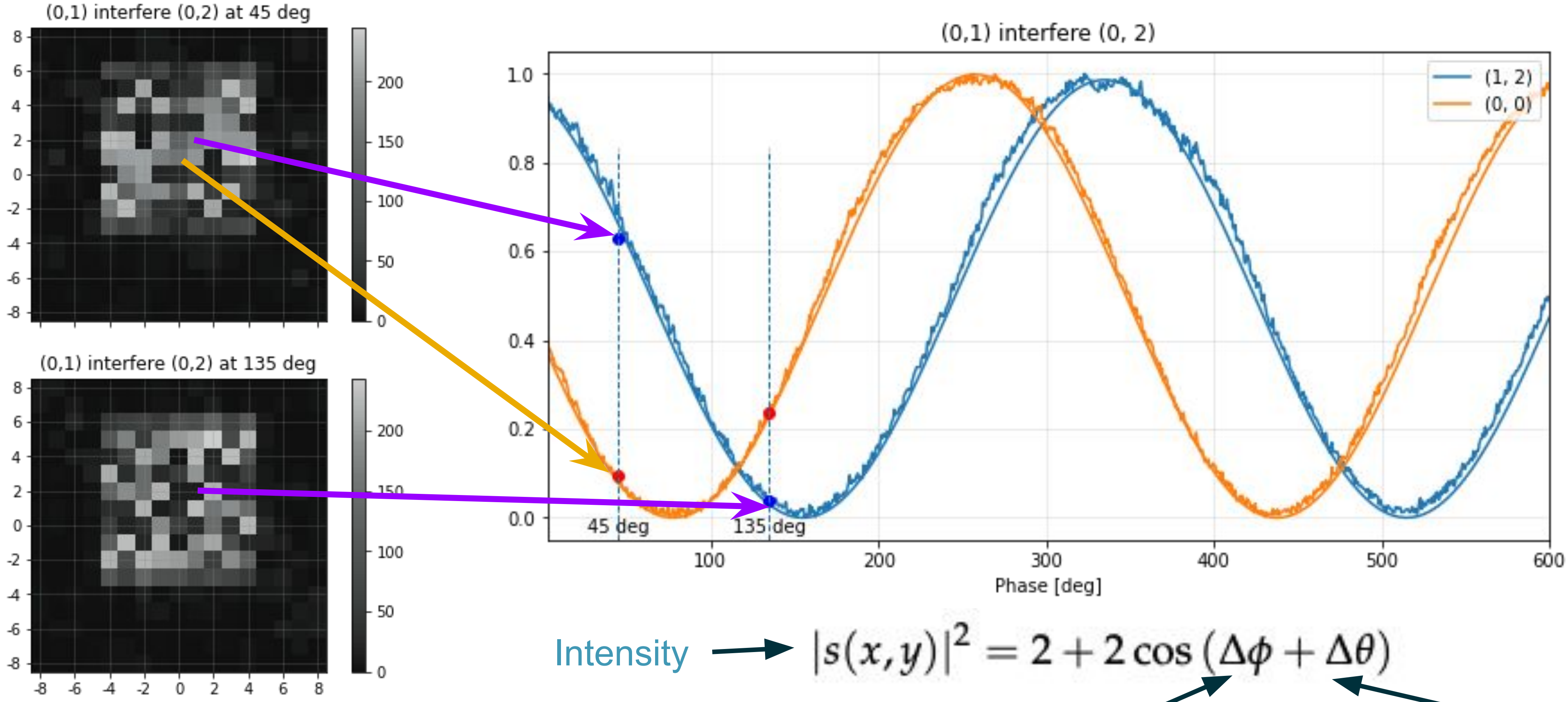
Center + Right beam





Intensity is function of DOE *modulated* beam phase

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



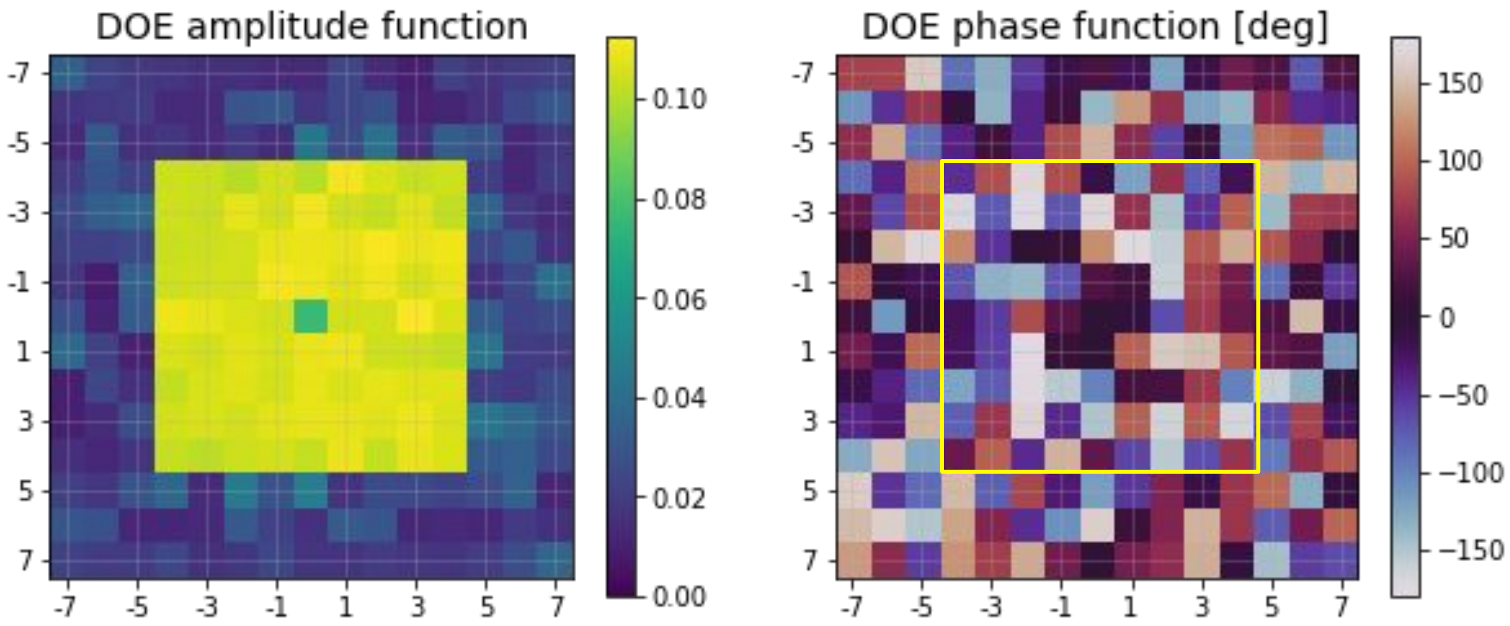
Intensity → $|s(x,y)|^2 = 2 + 2\cos\left(\Delta\phi + \Delta\theta\right)$

Beam phase diff

DOE phase function

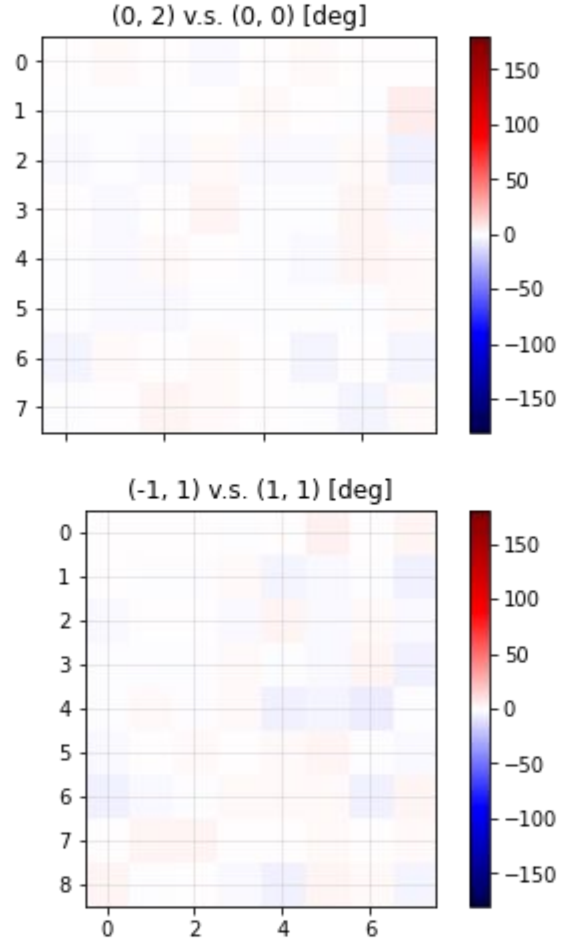
9x9 diffraction transmission function characterized

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**

81 beams combined experimentally

Diffractional Combining Physics:

2-D convolution

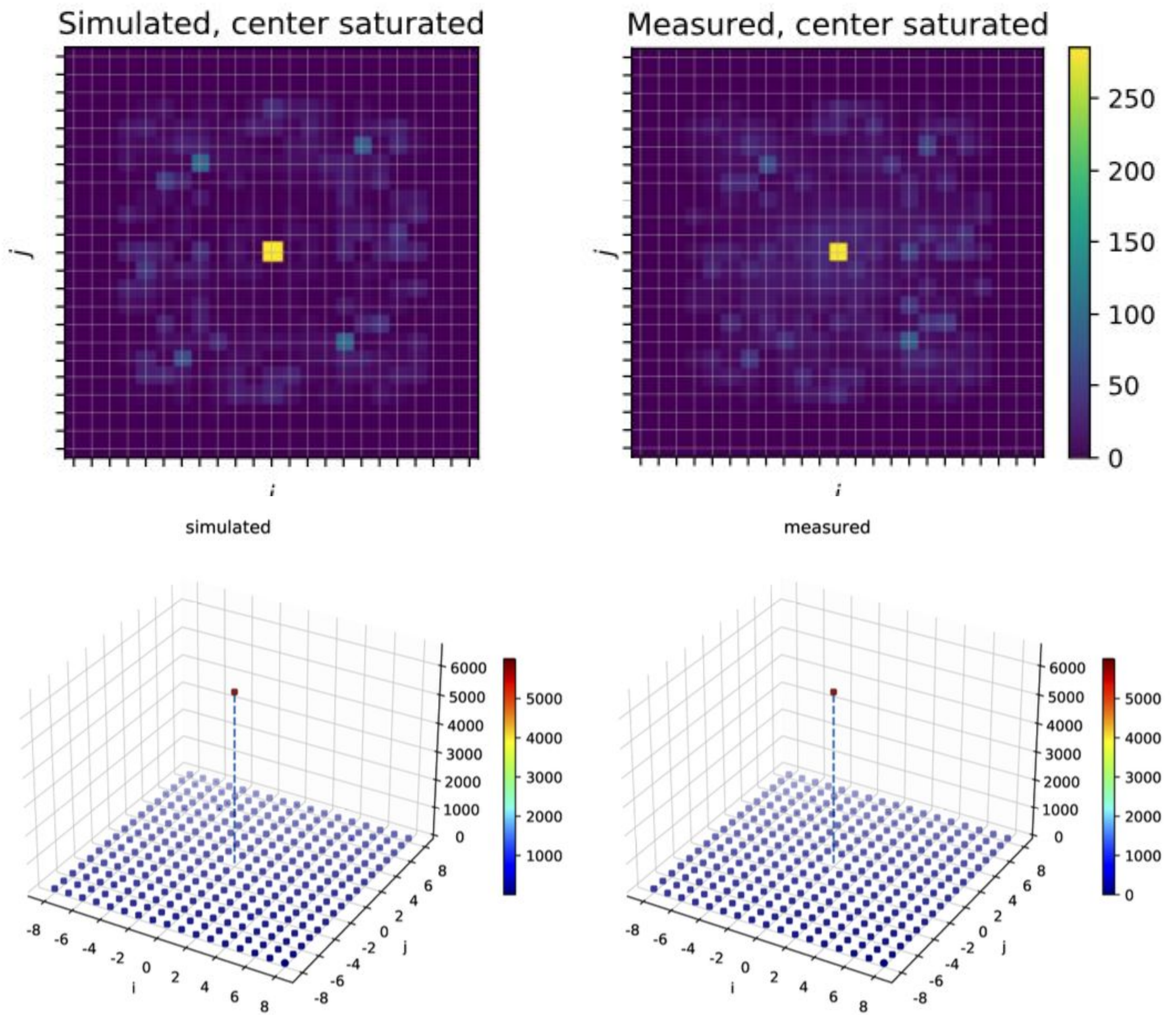
$$s(x,y) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} b(x,y)d(x-m,y-n)$$
$$= b(x,y) ** d(x,y)$$

input beam **DOE transmission function**

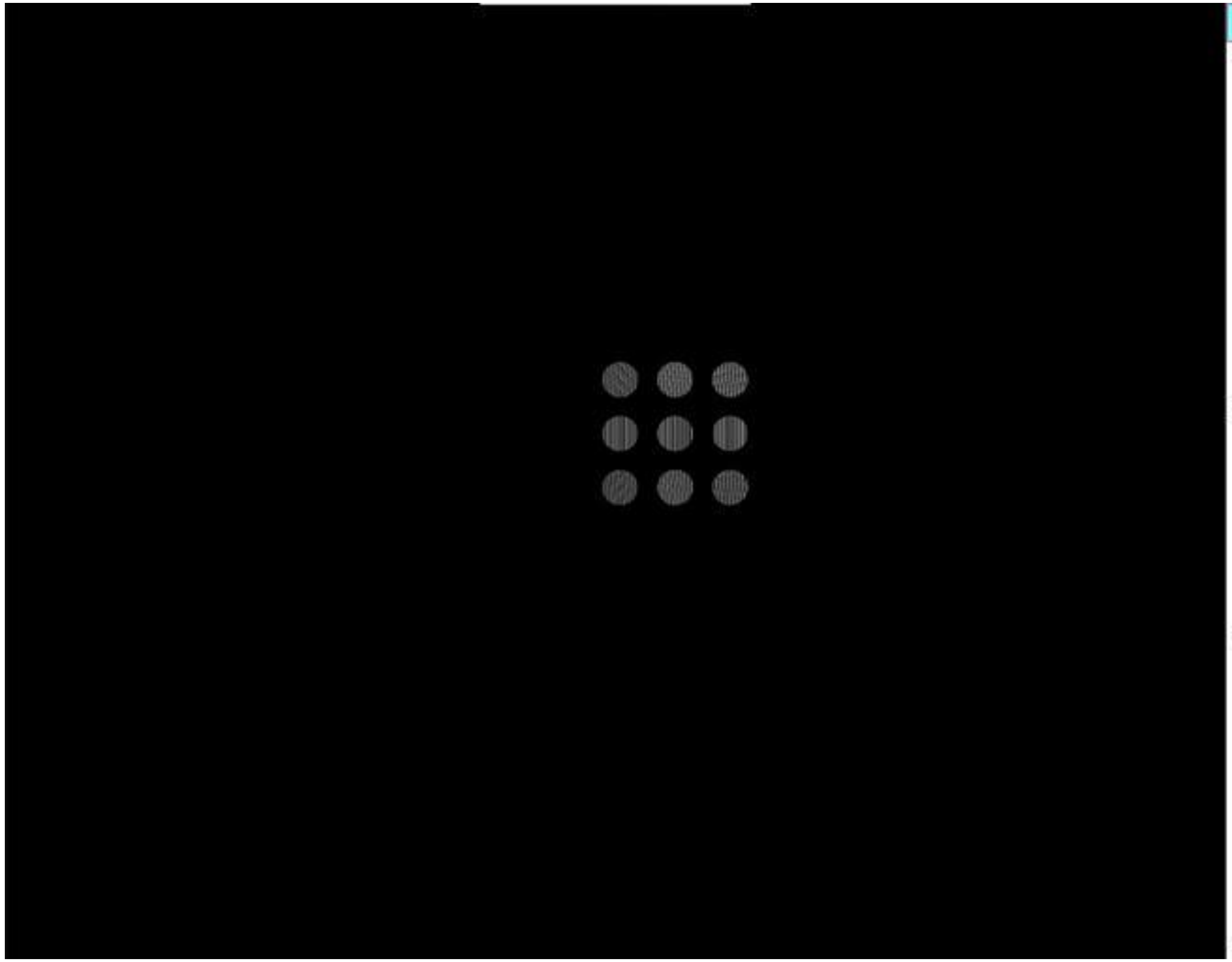
Ideal input beam phase:

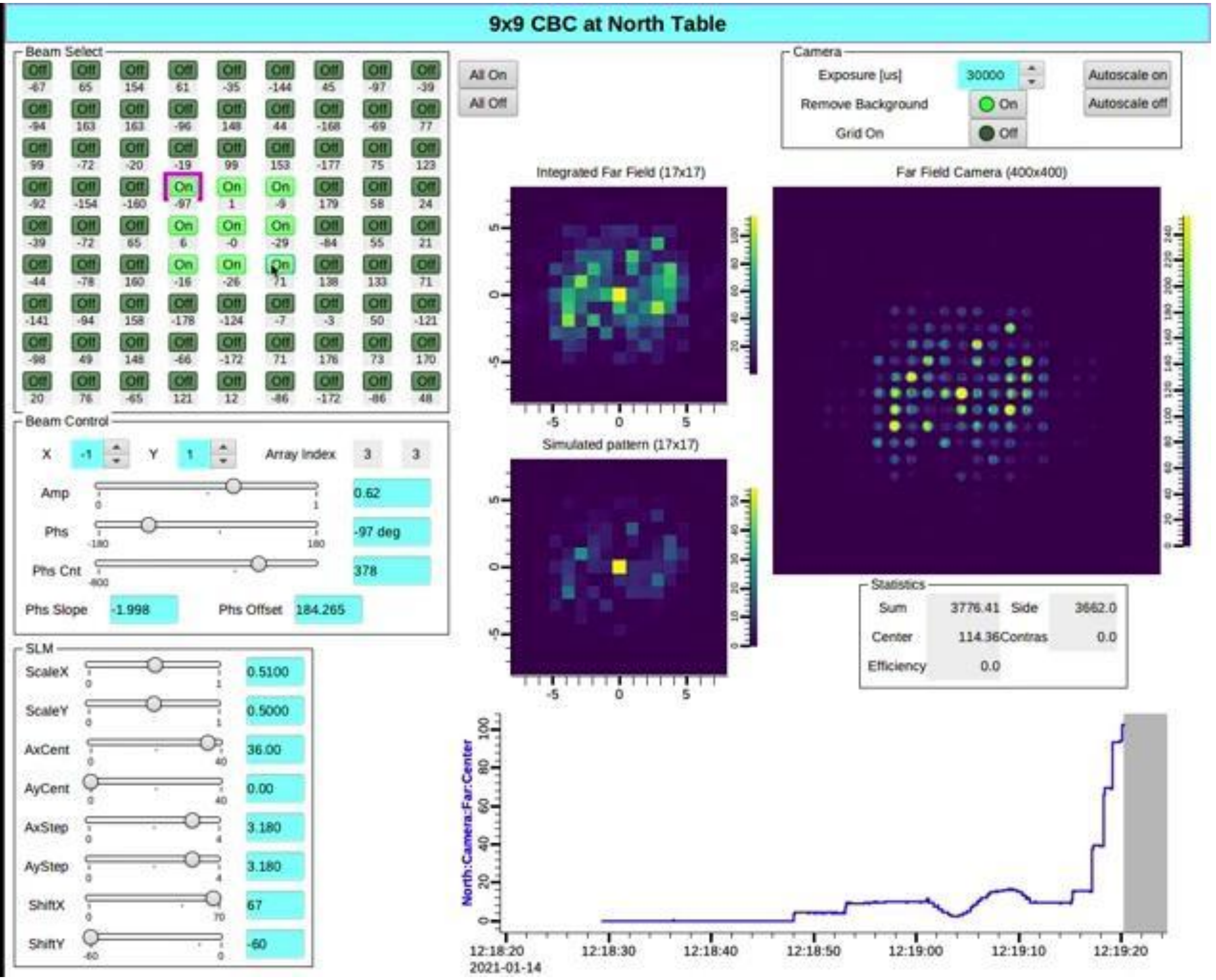
$$\angle b(x,y) = -\angle d(-x,-y)$$

Optics Express 29(4), 5407, 2021



81 beams combined experimentally

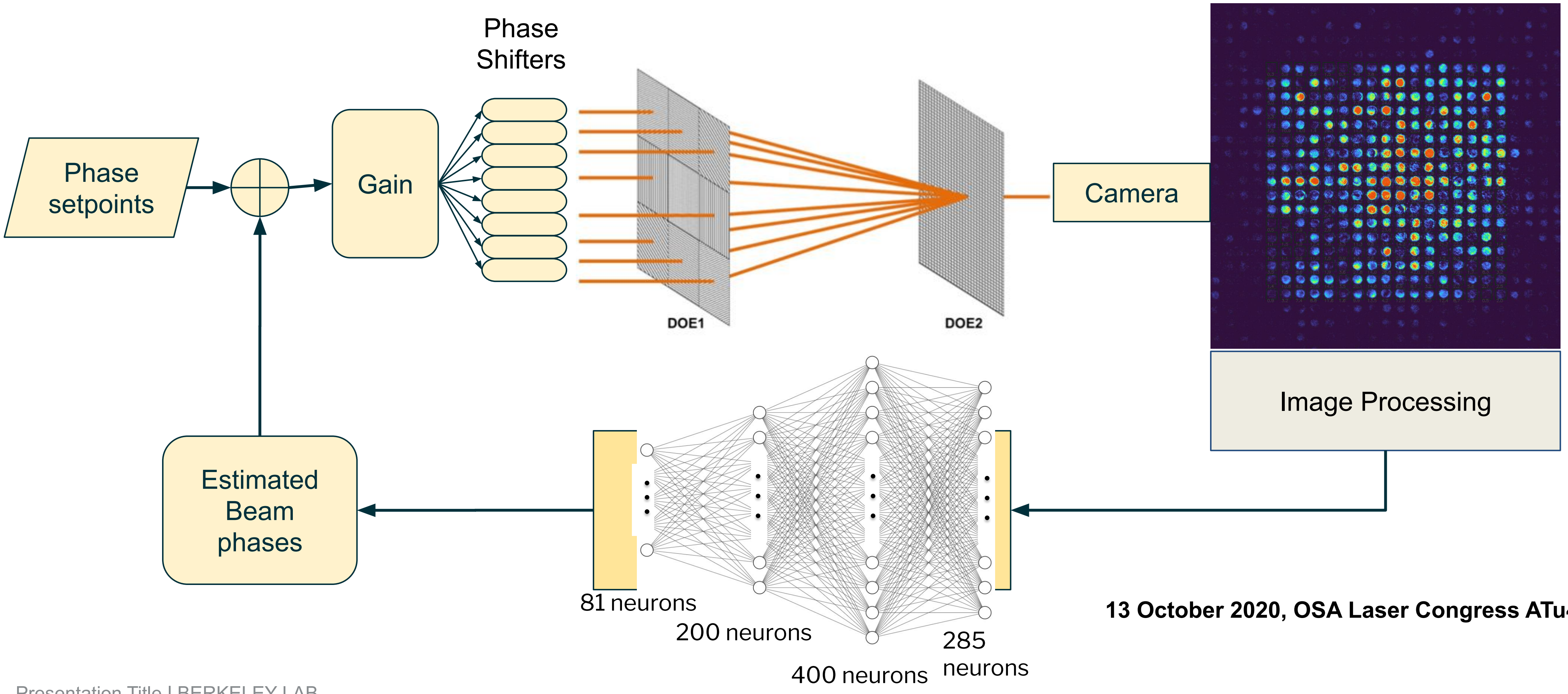




Scalability

Deep learning based active stabilization

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



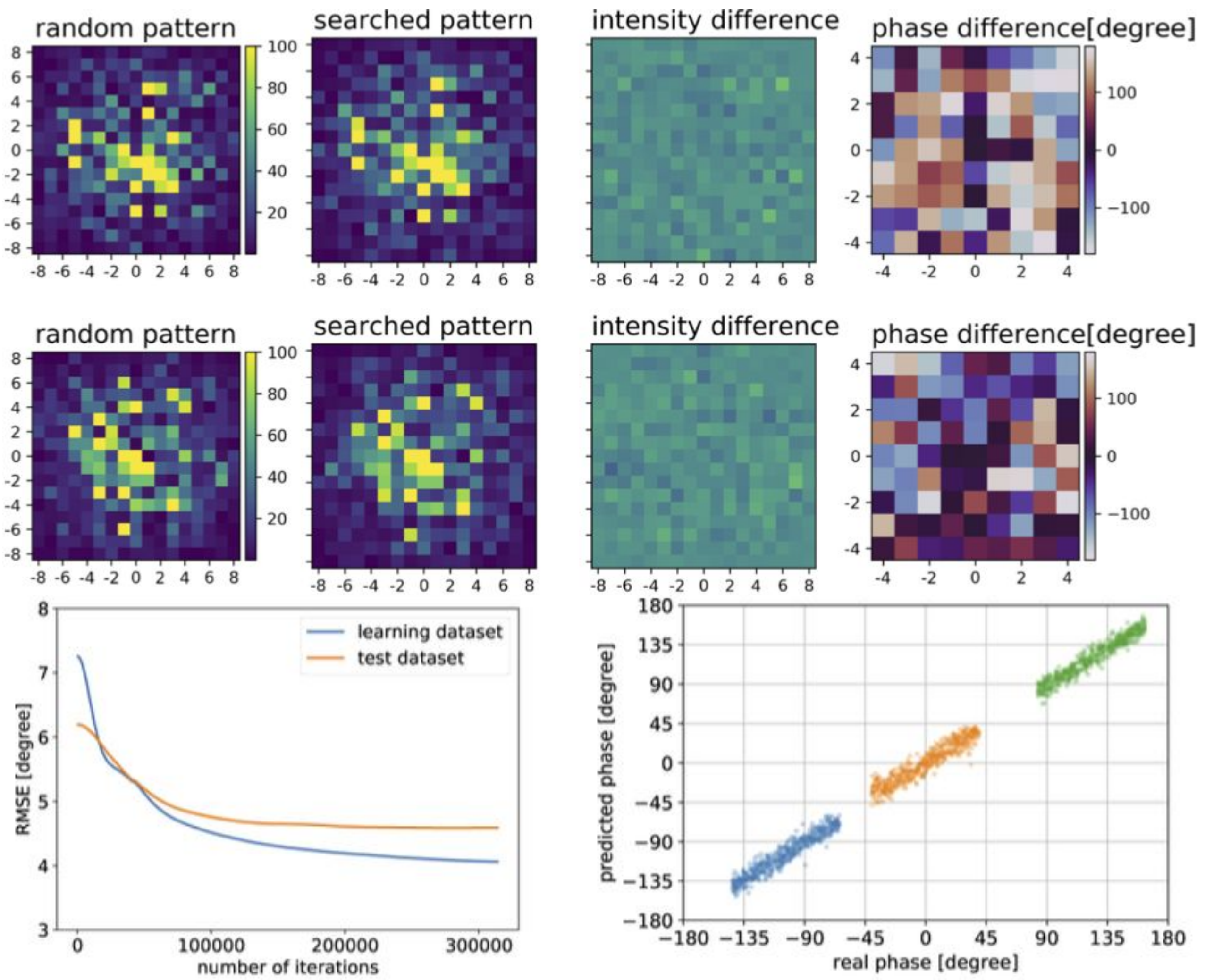
13 October 2020, OSA Laser Congress ATu4A.6

Training range can be a small fraction of phase space

Non-uniqueness problem addressed

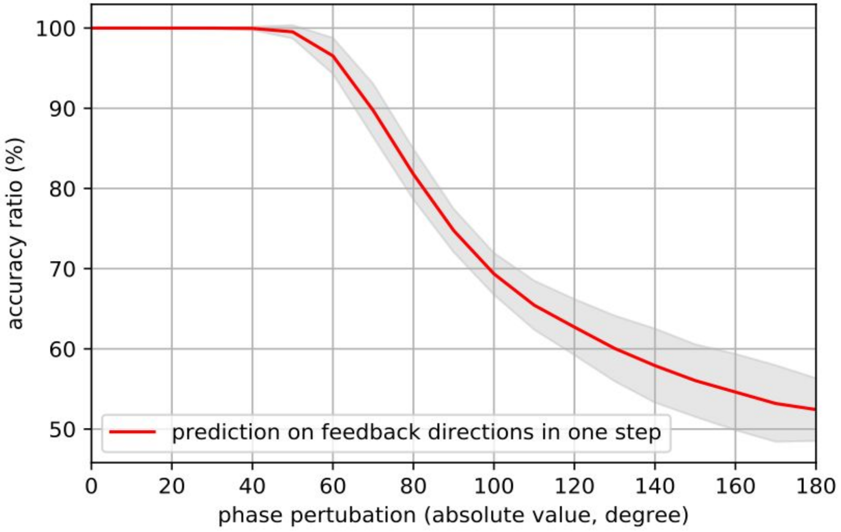
Examples of same pattern generated by different phases

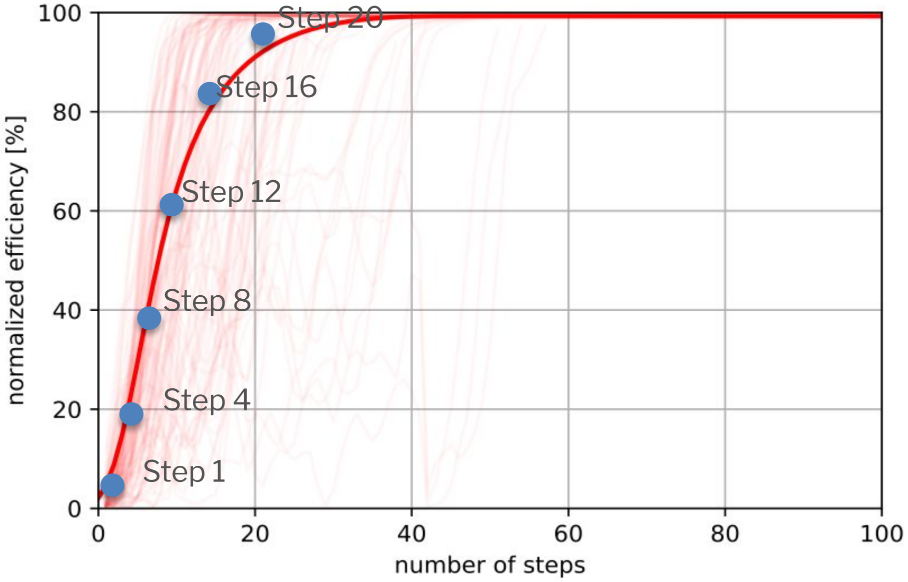
Training dataset phase range: ±40° around optimal



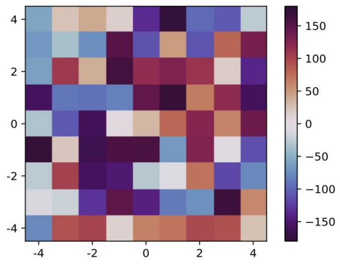
NN recognition even works outside training range

Prediction accuracy drops, but always > 50%

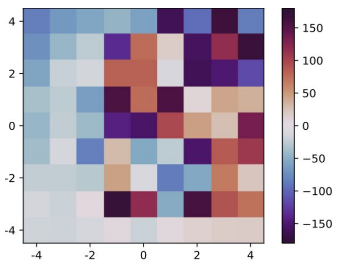




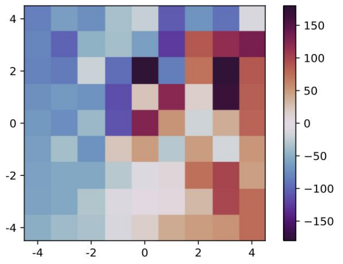
Error (Step 1)



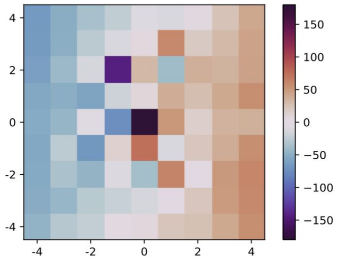
Error (Step 4)



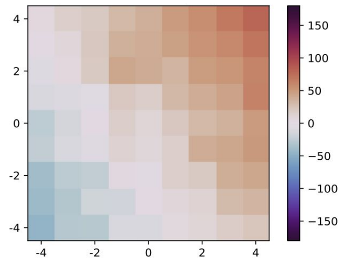
Error (Step 8)



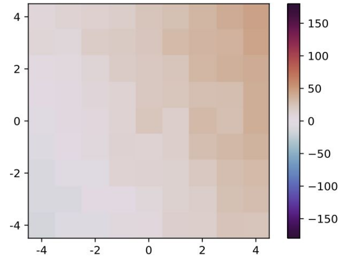
Error (Step 12)



Error (Step 16)

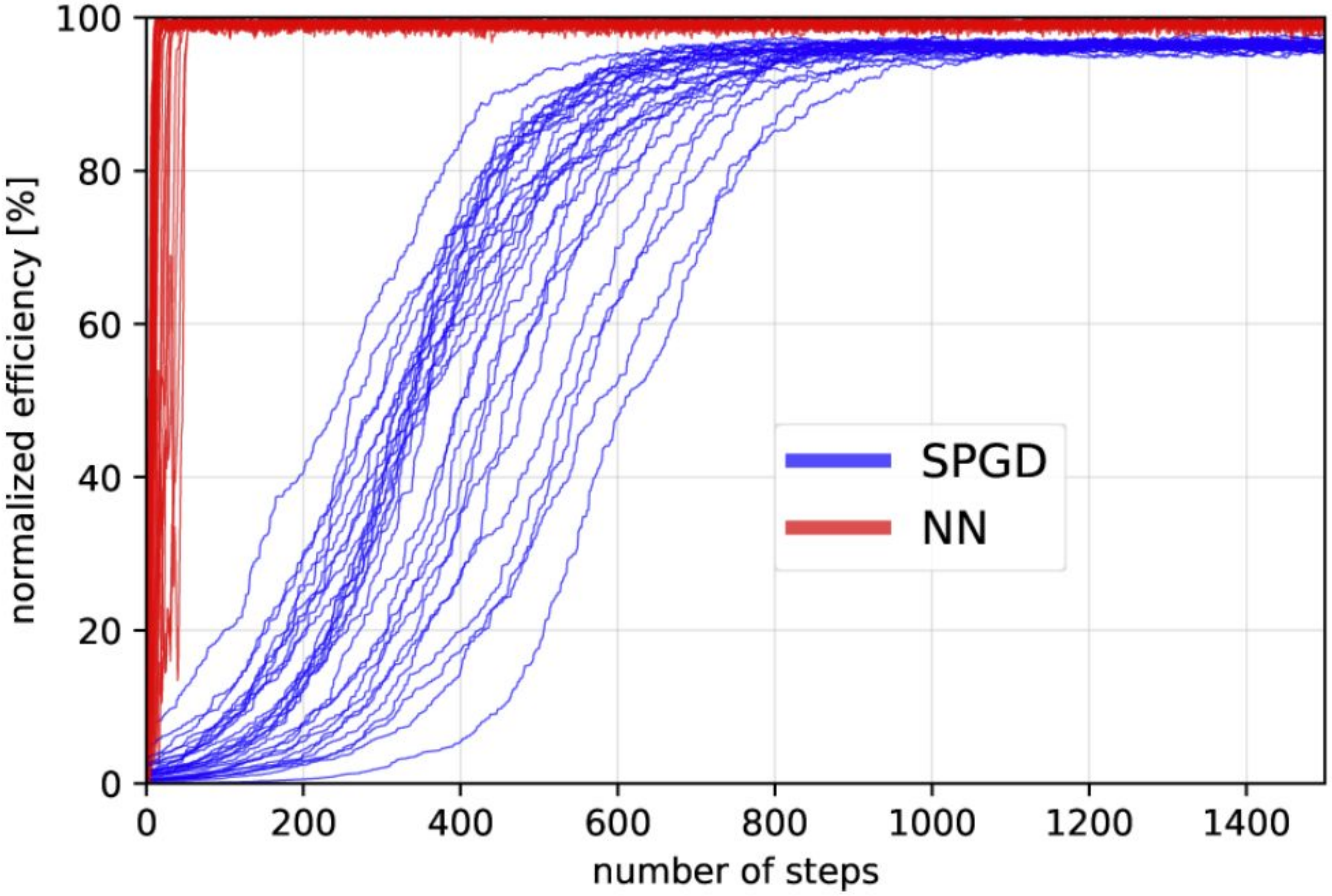


Error (Step 20)



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

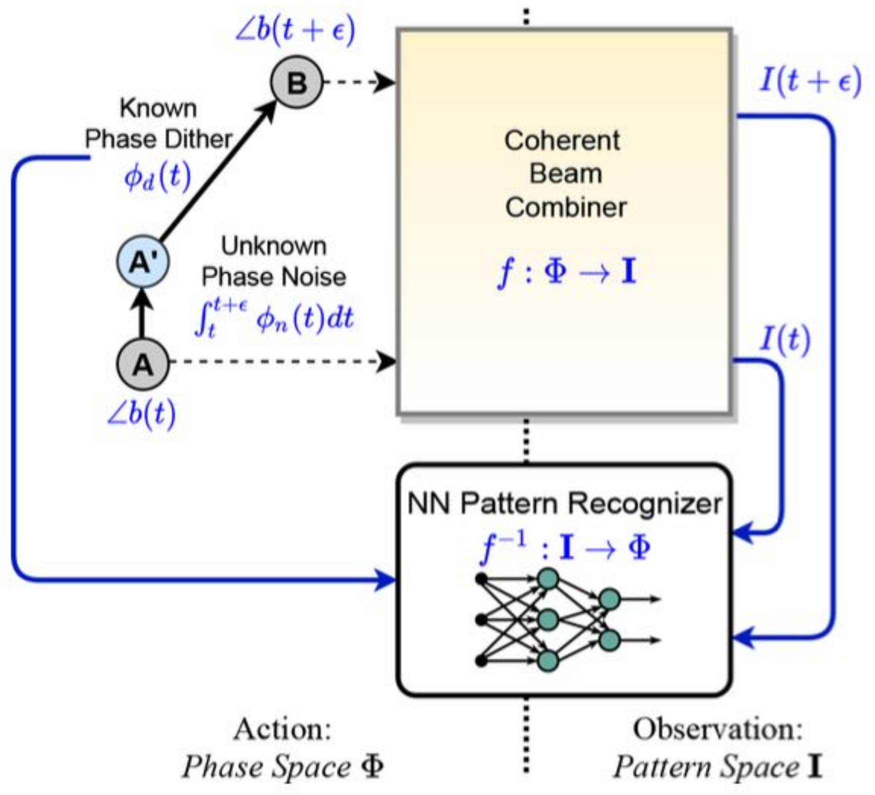
Demonstrated in simulation



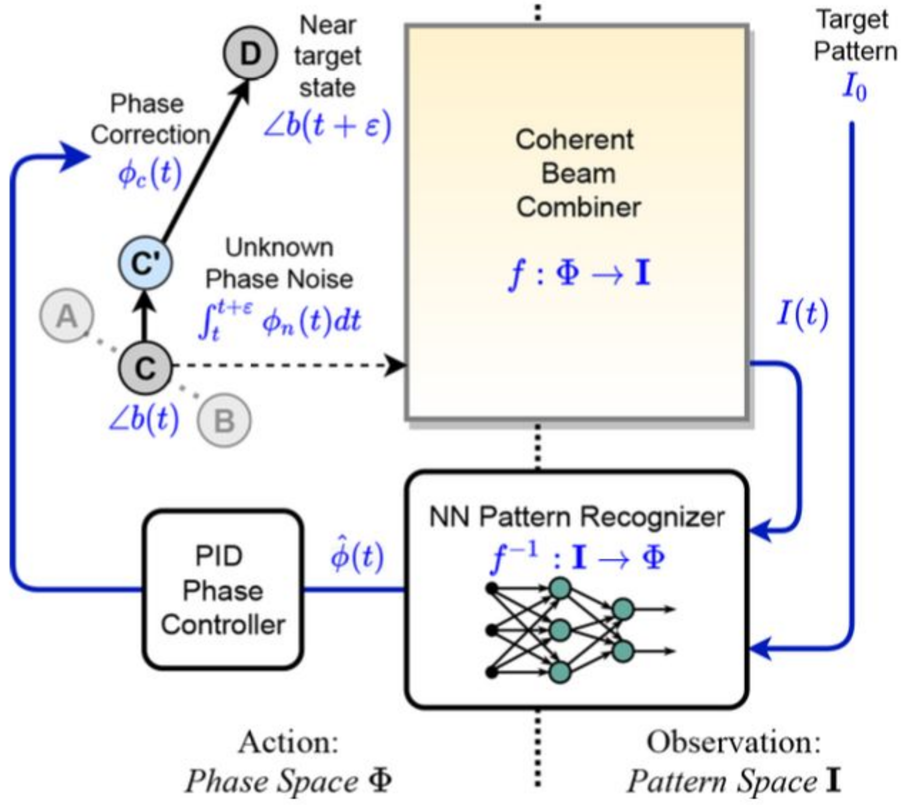
Optics Express, 29(4) 5694, 2021

Shooting at a moving target: training in experiment

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

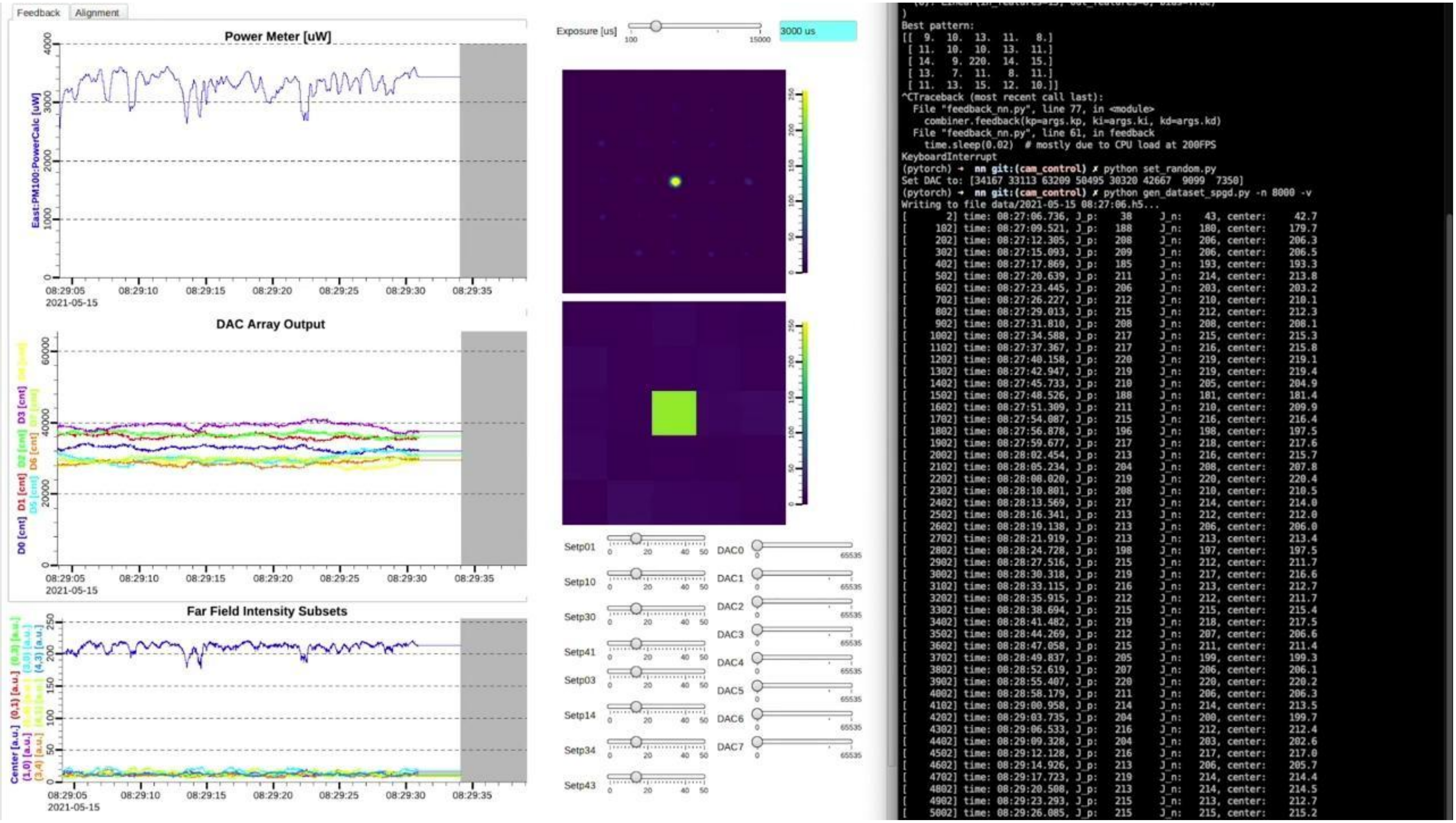


Training on pairing 2 patterns with a known dither

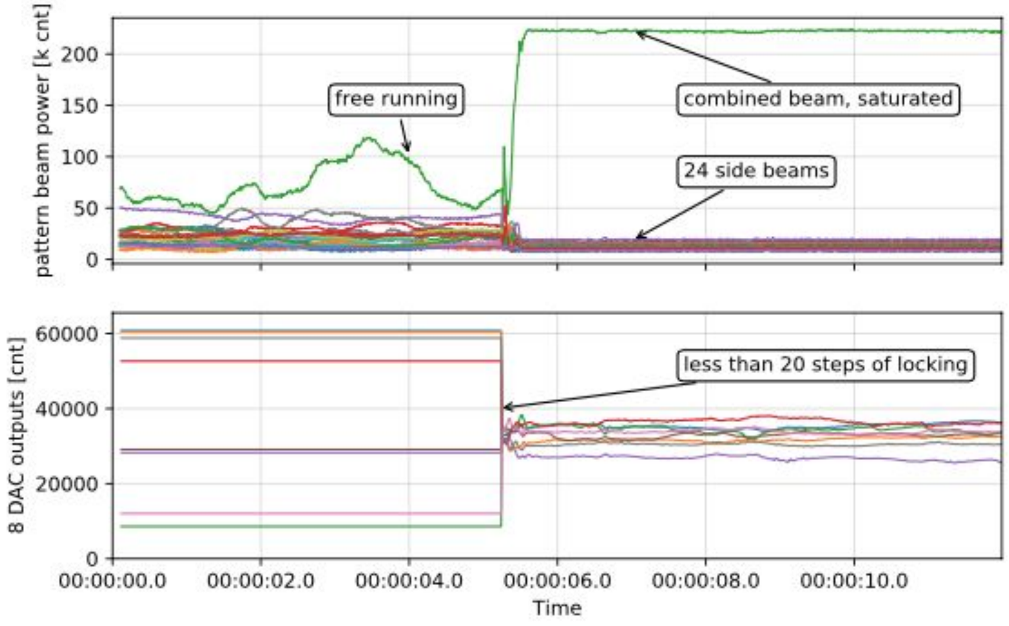


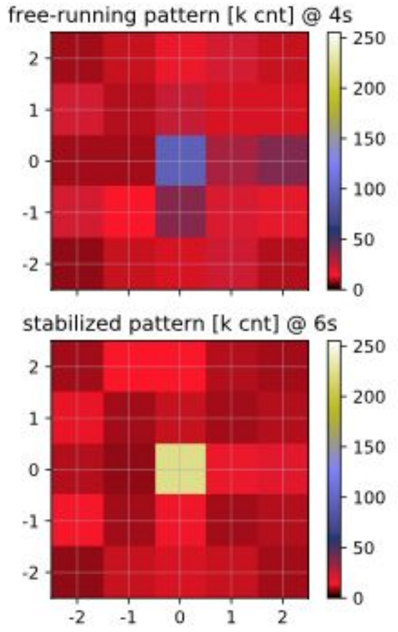
Feedback by predicted error using differential mapping

Optics Express, 30(8) 12639, 2022


Feedback
Alignment
Power Meter [uW]
East:PM100:PowerCalc [uW]
08:29:05
2021-05-15
08:29:10
08:29:15
08:29:20
08:29:25
08:29:30
08:29:35
DAC Array Output
D0 [cnt]
D1 [cnt]
D2 [cnt]
D3 [cnt]
D5 [cnt]
D6 [cnt]
Far Field Intensity Subsets
Center [a.u.]
(0,1) [a.u.]
(0,3) [a.u.]
(1,0) [a.u.]
(3,0) [a.u.]
(3,4) [a.u.]
(4,3) [a.u.]
Exposure [us]
3000 us
Setp01
Setp10
Setp30
Setp41
Setp03
Setp14
Setp34
Setp43
DAC0
DAC1
DAC2
DAC3
DAC4
DAC5
DAC6
DAC7
65535
)
Best pattern:
[[9. 10. 13. 11.   8.]
 [11. 10. 10. 13. 11.]
 [14.   9. 220. 14. 15.]
 [13.   7. 11.   8. 11.]
 [11. 13. 15. 12. 10.]]
^CTraceback (most recent call last):
  File "feedback_nn.py", line 77, in <module>
    combiner.feedback(kp=args.kp, ki=args.ki, kd=args.kd)
  File "feedback_nn.py", line 61, in feedback
    time.sleep(0.02) # mostly due to CPU load at 200FPS
KeyboardInterrupt
(pytorch) → nn git:(cam_control) ✗ python set_random.py
Set DAC to: [34167 33113 63209 50495 30320 42667 9099 7350]
(pytorch) → nn git:(cam_control) ✗ python gen_dataset_spgd.py -n 8000 -v
Writing to file data/2021-05-15 08:27:06.h5...
[2] time: 08:27:06.736, J_p: 38   J_n: 43, center: 42.7
[102] time: 08:27:09.521, J_p: 188   J_n: 180, center: 179.7
[202] time: 08:27:12.305, J_p: 208   J_n: 206, center: 206.3
[302] time: 08:27:15.093, J_p: 209   J_n: 206, center: 206.5
[402] time: 08:27:17.869, J_p: 185   J_n: 193, center: 193.3
[502] time: 08:27:20.639, J_p: 211   J_n: 214, center: 213.8
[602] time: 08:27:23.445, J_p: 206   J_n: 203, center: 203.2
[702] time: 08:27:26.227, J_p: 212   J_n: 210, center: 210.1
[802] time: 08:27:29.013, J_p: 215   J_n: 212, center: 212.3
[902] time: 08:27:31.810, J_p: 208   J_n: 208, center: 208.1
[1002] time: 08:27:34.588, J_p: 217   J_n: 215, center: 215.3
[1102] time: 08:27:37.367, J_p: 217   J_n: 216, center: 215.8
[1202] time: 08:27:40.158, J_p: 220   J_n: 219, center: 219.1
[1302] time: 08:27:42.947, J_p: 219   J_n: 219, center: 219.4
[1402] time: 08:27:45.733, J_p: 210   J_n: 205, center: 204.9
[1502] time: 08:27:48.526, J_p: 188   J_n: 181, center: 181.4
[1602] time: 08:27:51.309, J_p: 211   J_n: 210, center: 209.9
[1702] time: 08:27:54.087, J_p: 215   J_n: 216, center: 216.4
[1802] time: 08:27:56.878, J_p: 196   J_n: 198, center: 197.5
[1902] time: 08:27:59.677, J_p: 217   J_n: 218, center: 217.6
[2002] time: 08:28:02.454, J_p: 213   J_n: 216, center: 215.7
[2102] time: 08:28:05.234, J_p: 204   J_n: 208, center: 207.8
[2202] time: 08:28:08.020, J_p: 219   J_n: 220, center: 220.4
[2302] time: 08:28:10.801, J_p: 208   J_n: 210, center: 210.5
[2402] time: 08:28:13.569, J_p: 217   J_n: 214, center: 214.0
[2502] time: 08:28:16.341, J_p: 213   J_n: 212, center: 212.0
[2602] time: 08:28:19.138, J_p: 213   J_n: 206, center: 206.0
[2702] time: 08:28:21.919, J_p: 213   J_n: 213, center: 213.4
[2802] time: 08:28:24.728, J_p: 198   J_n: 197, center: 197.5
[2902] time: 08:28:27.516, J_p: 215   J_n: 212, center: 211.7
[3002] time: 08:28:30.318, J_p: 219   J_n: 217, center: 216.6
[3102] time: 08:28:33.115, J_p: 216   J_n: 213, center: 212.7
[3202] time: 08:28:35.915, J_p: 212   J_n: 212, center: 211.7
[3302] time: 08:28:38.694, J_p: 215   J_n: 215, center: 215.4
[3402] time: 08:28:41.482, J_p: 219   J_n: 218, center: 217.5
[3502] time: 08:28:44.269, J_p: 212   J_n: 207, center: 206.6
[3602] time: 08:28:47.058, J_p: 215   J_n: 211, center: 211.4
[3702] time: 08:28:49.837, J_p: 205   J_n: 199, center: 199.3
[3802] time: 08:28:52.619, J_p: 207   J_n: 206, center: 206.1
[3902] time: 08:28:55.407, J_p: 220   J_n: 220, center: 220.2
[4002] time: 08:28:58.179, J_p: 211   J_n: 206, center: 206.3
[4102] time: 08:29:00.958, J_p: 214   J_n: 214, center: 213.5
[4202] time: 08:29:03.735, J_p: 204   J_n: 200, center: 199.7
[4302] time: 08:29:06.533, J_p: 216   J_n: 212, center: 212.4
[4402] time: 08:29:09.328, J_p: 204   J_n: 203, center: 202.6
[4502] time: 08:29:12.128, J_p: 216   J_n: 217, center: 217.0
[4602] time: 08:29:14.926, J_p: 213   J_n: 206, center: 205.7
[4702] time: 08:29:17.723, J_p: 219   J_n: 214, center: 214.4
[4802] time: 08:29:20.508, J_p: 213   J_n: 214, center: 214.5
[4902] time: 08:29:23.293, J_p: 215   J_n: 213, center: 212.7
[5002] time: 08:29:26.085, J_p: 215   J_n: 215, center: 215.2

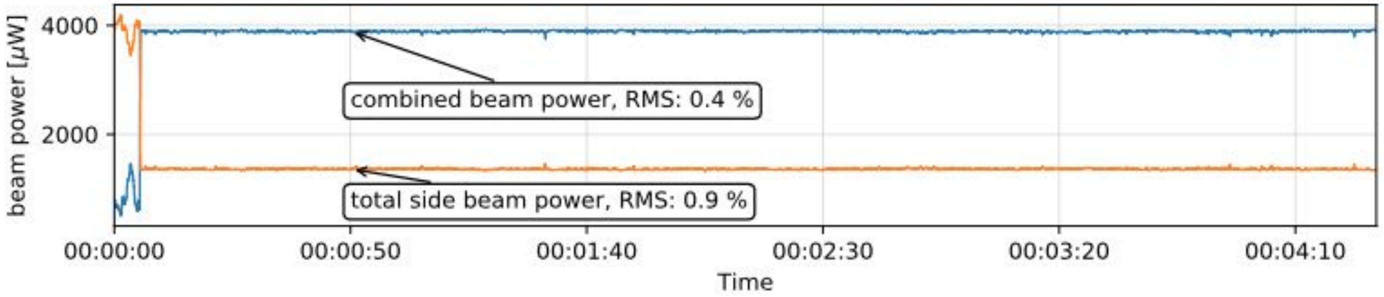
Experimentally combined 8 beams with < 0.4% RMS stability





(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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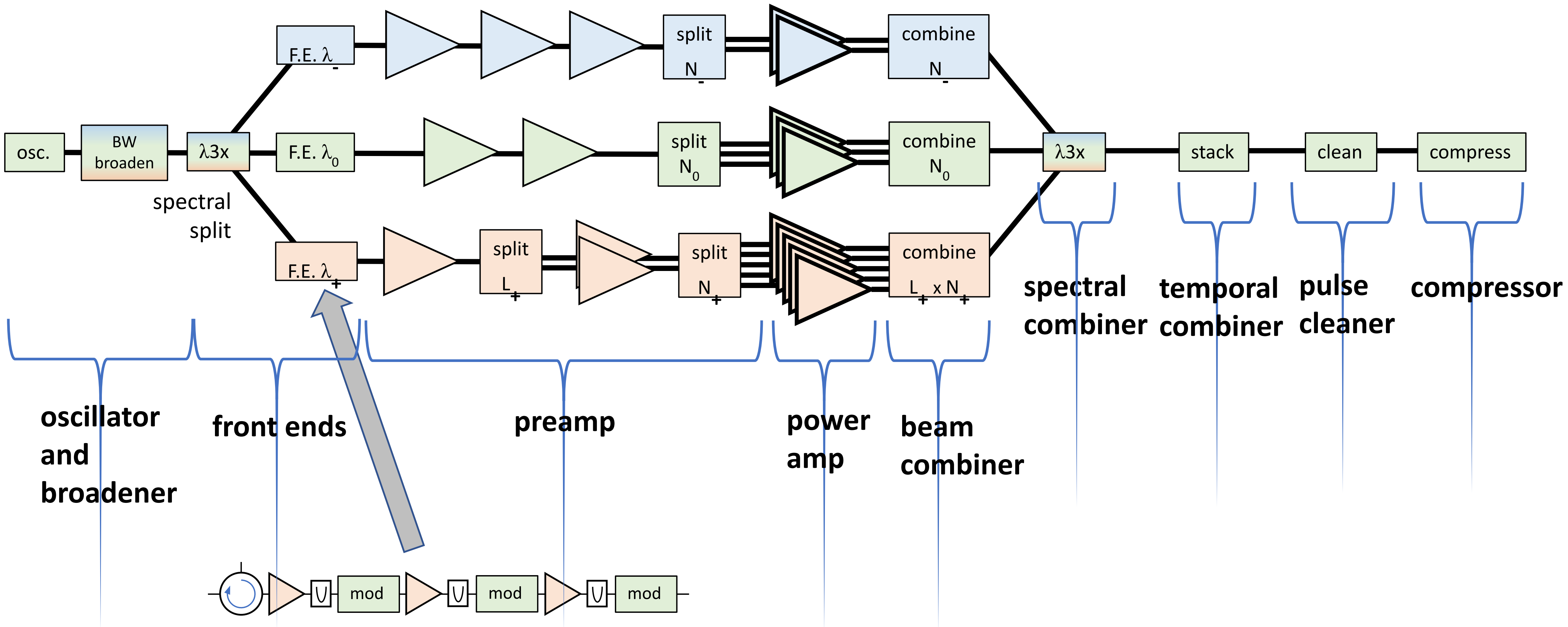
Spectral Beam Combining Control

Architecture of spectrally combined system



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
- **Study** Online-learning

Speed

- **Develop** FPGA accelerated deep learning controller:
  - 10GbE camera interface
  - Xilinx DPU quantization & inference
  - High-level synthesize quantization & inference