



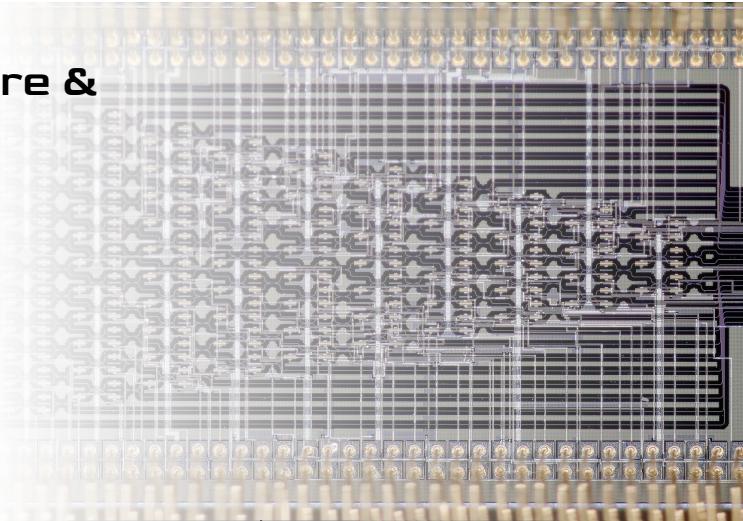
Co-design of machine intelligence and hardware & the need for verifiable AI

MIT AI Hardware Program Symposium | 2025.11.12

Dirk Englund ∈ {RLE, MTL, EECS}@MIT

Quantum Computing & Networking

ML signal processing

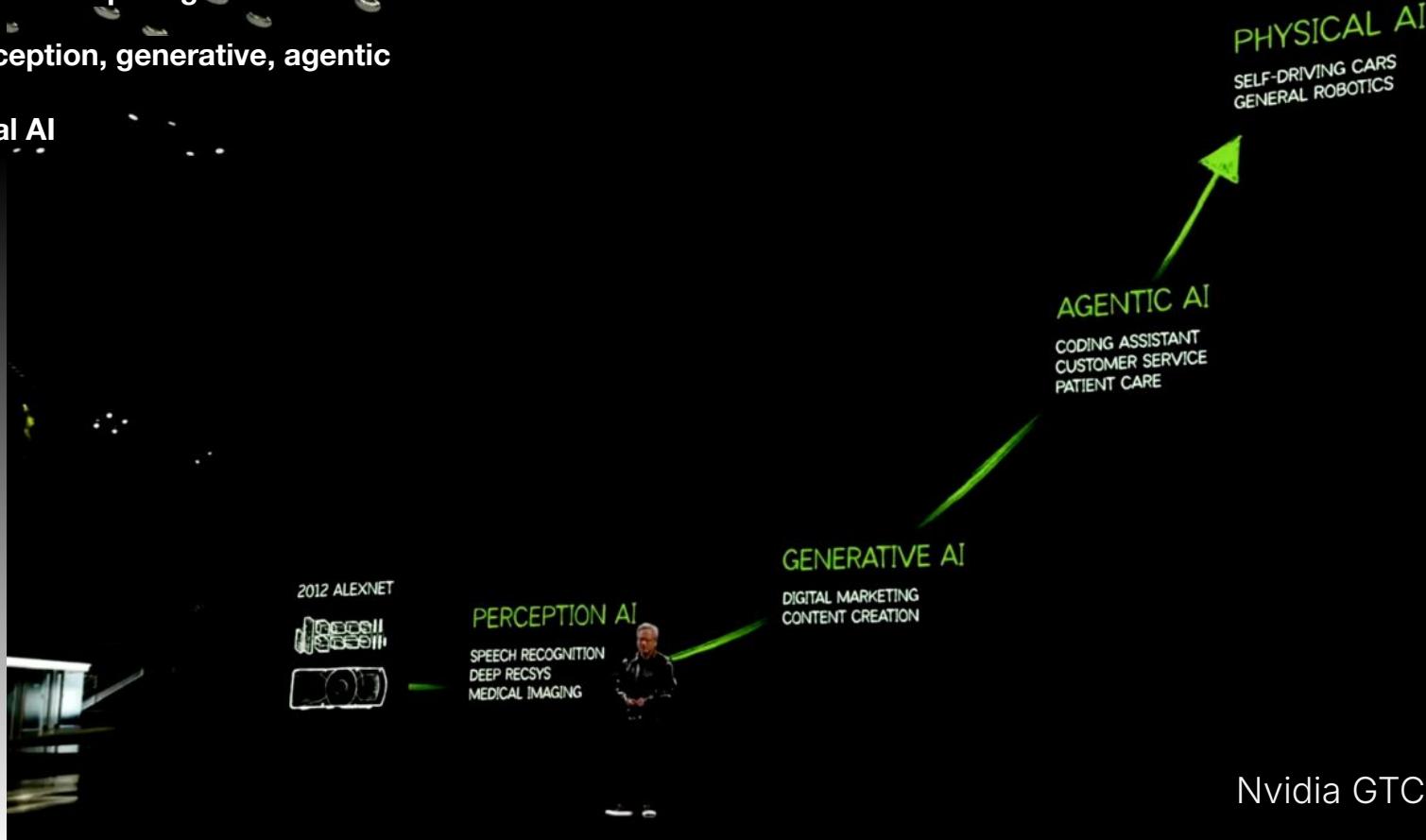


A Renaissance in Specialized Computing

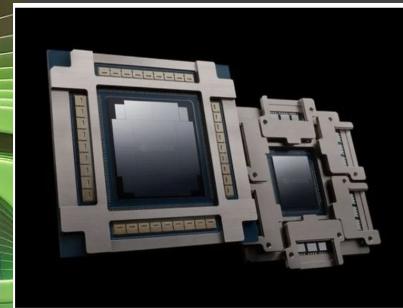
1. Quantum Computing

2. AI: perception, generative, agentic

3. Physical AI



Photonics at the forefront



Nvidia looks to silicon photonics to cut datacentre AI power

Technology News | March 21, 2025

By Nick Flaherty

OPTOELECTRONICS

AI

POWER MANAGEMENT

Nvidia GTC, 2025

MIT research themes

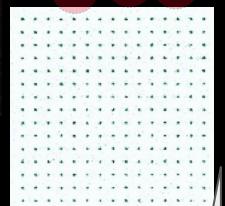
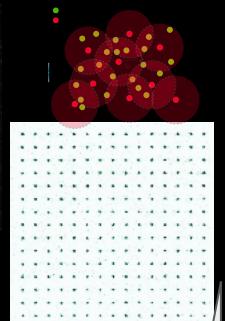
Scalable qubit systems (10^3 - 10^6)

.. in solids

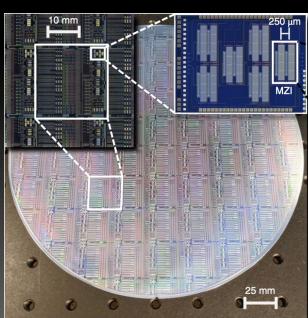


M Bhaskar et al, Nature 2020
N. Wan et al, Nature 2021; PRL 2022, PRX 2022

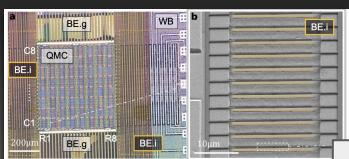
.. or vacuum (with CUA: Vuletic, Greiner, Lukin)



Semiconductor devices

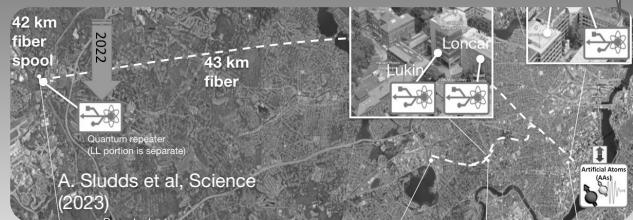


M Dong et al, Nature Photonics 2021



L Li et al (with Prof Ruonan Han)

Full systems: quantum networks, AI, quantum sensors



A. Sludds et al, Science (2023)

Theory & algorithms: physics, control theory, CS

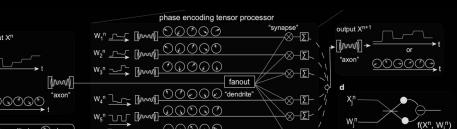
QP-MIT

qp-slm

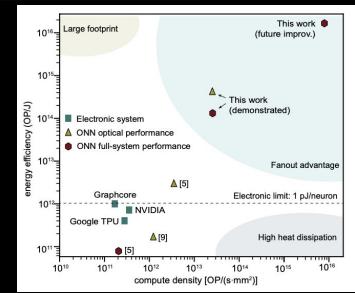
$$H = \frac{\hbar\Omega_{\mu\nu}}{2} \sum_i \sigma_x^i - \frac{\hbar\delta_{\mu\nu}}{2} \sum_i \sigma_z^i + \sum_{i \neq j} \frac{C_3}{R_{ij}^3} (\sigma_+^i \sigma_-^j + \sigma_-^i \sigma_+^j)$$



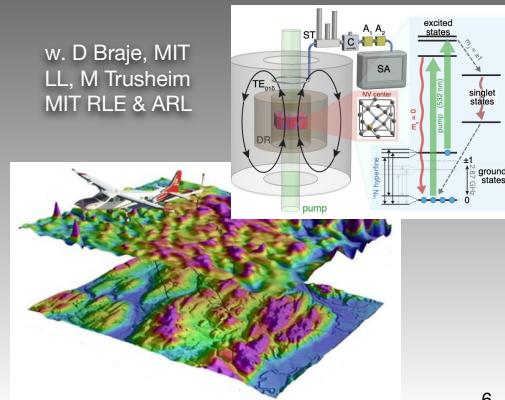
AI / machine learning



Z. Chen, Nature Photonics (2023)



w. D Braje, MIT
LL, M Trusheim
MIT RLE & ARL



PIC technology



M Saha, Y. Henry Wen, et al, arXiv <https://arxiv.org/abs/2406.17662> (2025)

See also

M Dong et. al, Nature Photonics (2021)

A Menssen et. al, Optica (2023)

- MIT-Sandia National Laboratory - MITRE - Harvard
Separately: QuEra - SNL

- Process pioneered by Matt Eichenfield et al at Sandia NL

Spin-off company in the works on PIC displays & sensors - Interested ?

16-CH APIC lithium niobate on insulator³

MIT QP \diamond CSEM

\rightarrow Lightium, Inc

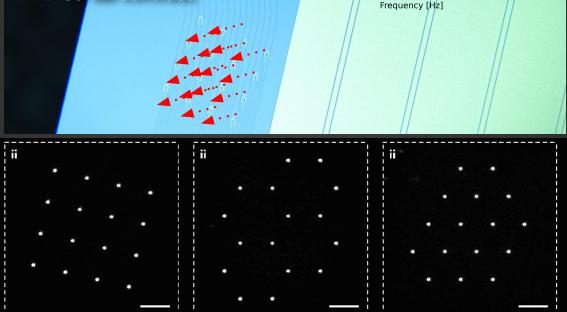
Mod rate > 5 GHz,

Pulse area error $\alpha < 1\%$

Low voltage (<3V)

Scalable >>16 channels

> 30 dB contrast

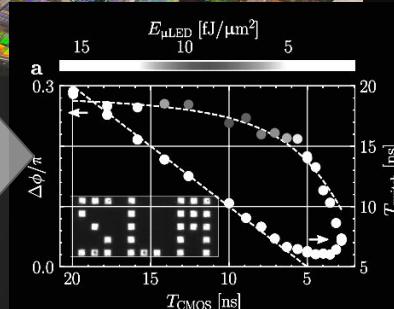
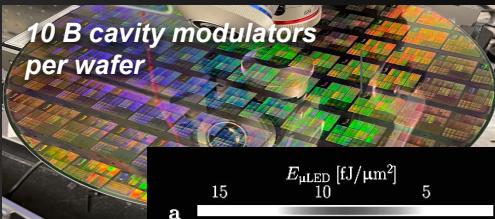


16 programmable beams, 10 GHz bandwidth

³I. Christen et al, Nature Comm (2025)

H. Larocque, D. Vitullo, et al,

2D Spatial Light Modulator in Si demonstrator ($v_{\text{mod}} \sim 1 \text{ GHz}$)⁴



⁴C. Panuski et al, Nature Photonics (2022)
[CP awarded the 2022 Carl E. Anderson Division of Laser Science Dissertation Award]

48-ch EOMs ($v_{\text{mod}} > 30 \text{ GHz}$):
A. Sludds et al, Science **378** (2022).

Nanophotonic waveguide chip-to-world beam scanning at 68M Spots/s·mm²

Matt Saha^{*,1}, Y. Henry Wen,^{*,1,2,✉} Andrew S. Greenspon^{*,1,2}, Matthew Zimmermann^{*,1}, Kevin J. Palm^{1,2}, Alex Witte¹, Yin Min Goh², Chao Li², Jonathan Bumstead³, Kevin Schädler⁴, Mark Dong^{1,2}, Andrew J. Leenheer⁶, Genevieve Clark^{1,2}, Gerald Gilbert^{5,*}, Matt Eichenfield^{6,7,✉}, and Dirk Englund^{2,4†}

M Saha, Y. H. Wen, A. Greenspon, M. Zimmerman, et al,
<https://arxiv.org/pdf/2406.17662>

The Scanning Waveguide Micro-Display
for Augmented Reality

MITRE team,

PoC: Dr Henry Wen, MITRE

Henry Wen <hwen@mitre.org>



The challenge:

3000
nits

12hr
batt

~1 cc
~1 gram

4K ~8 MP

A bright, efficient, dime-sized, high-res display for
each eye, in the frame of light-weight glasses



Case study: Meta Orion

Most advanced research prototype

Result of >\$10B R&D

Not mass producible

>\$10,000 per unit cost

Large Field-of-View (70°) 

Low resolution (13 PPD → 0.39 MPix) 

Low Brightness (400 nits → indoor only) 

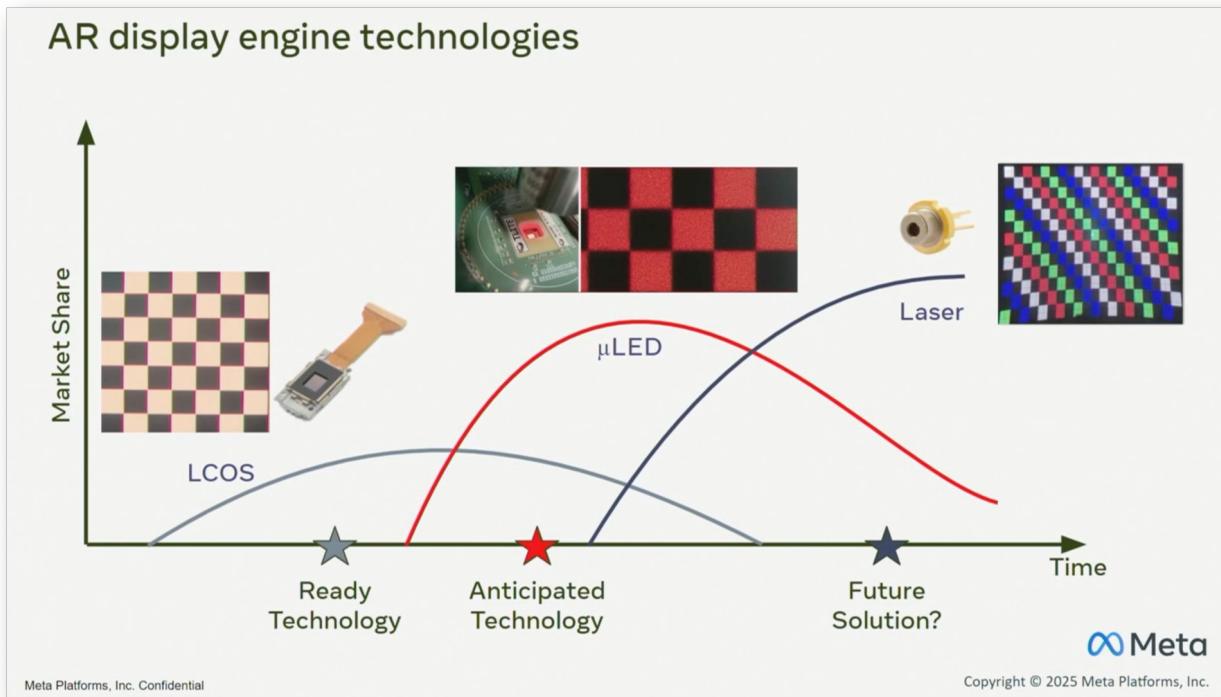
Short battery (2-3hrs) 

Requires: → 8 MP for immersive

→ 3000 nits for outdoor

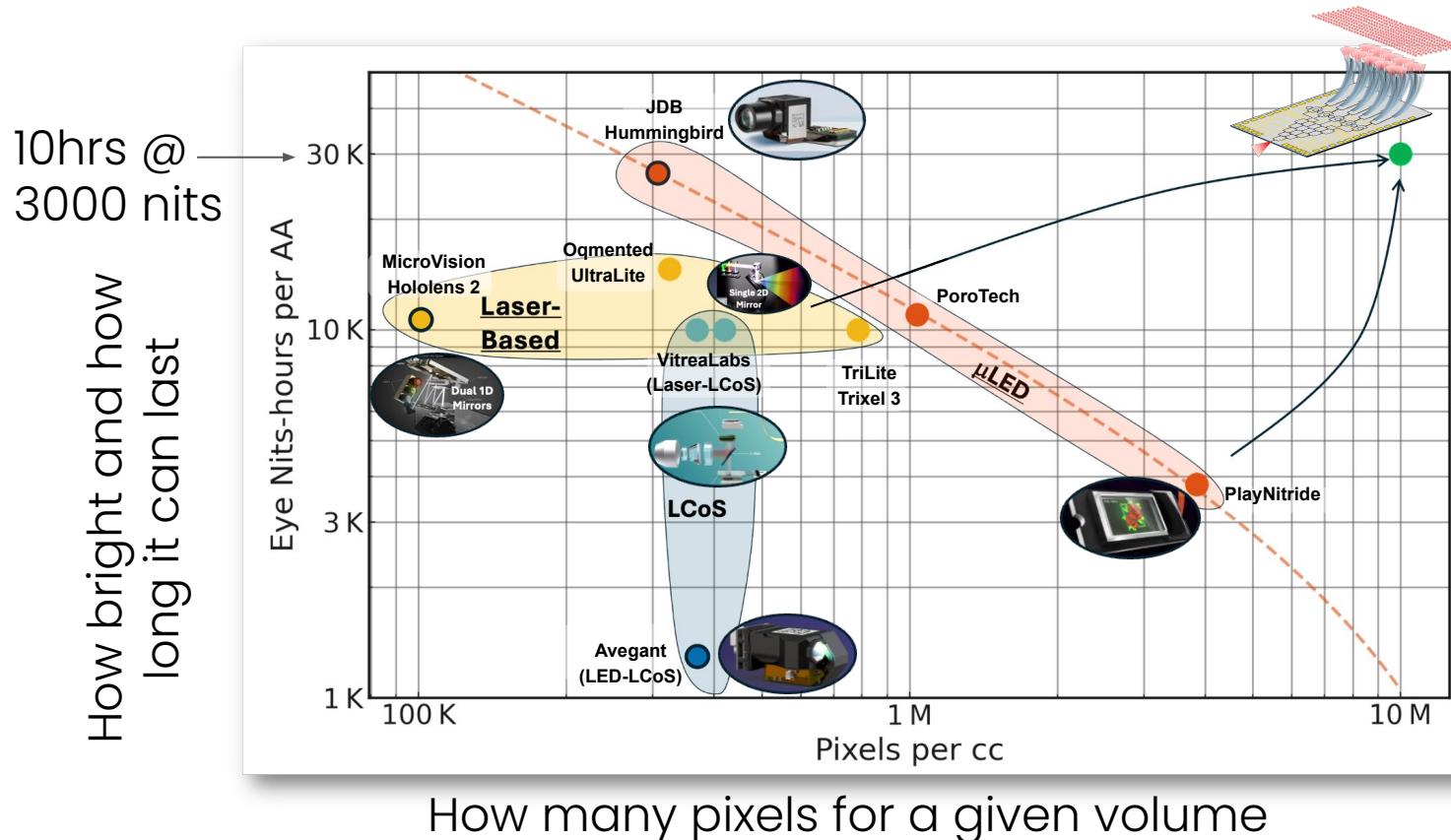


Bright + efficient requires lasers



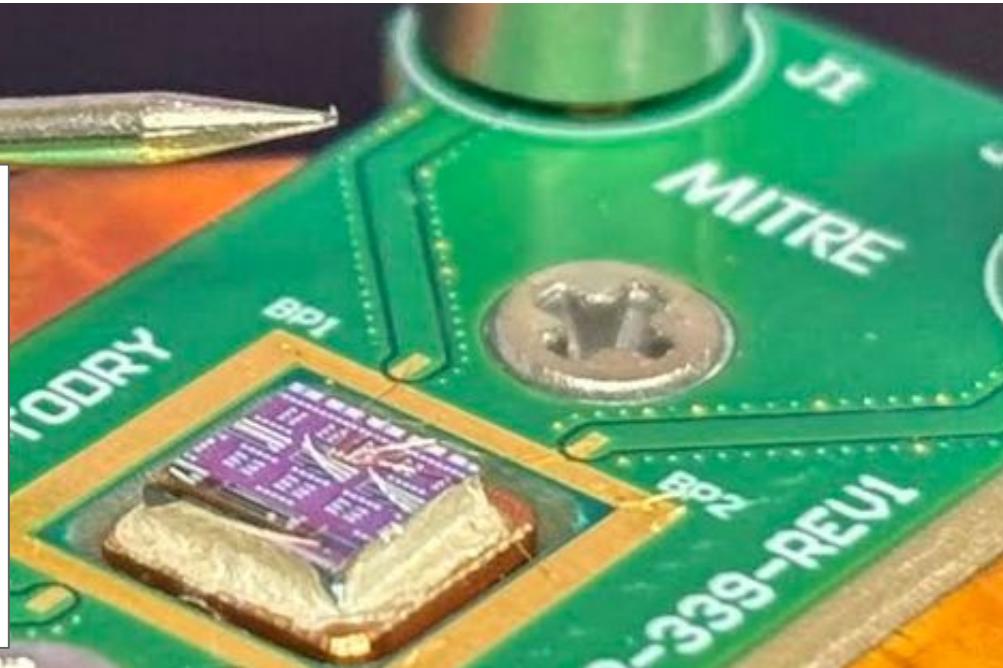
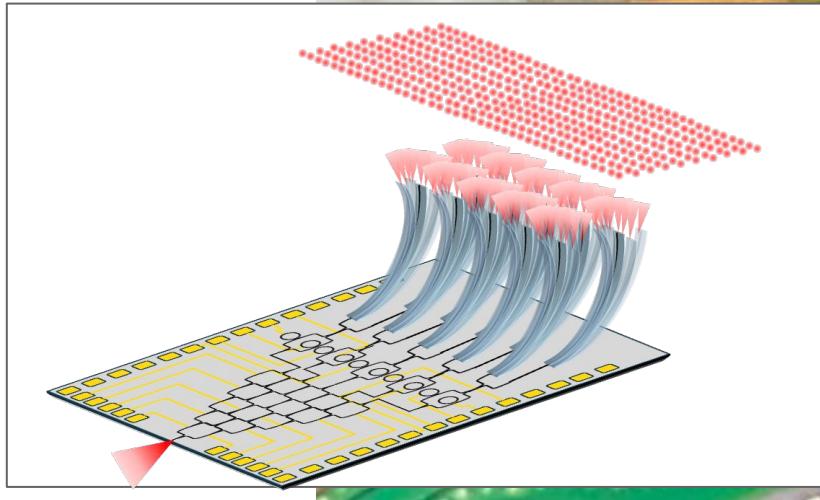
State of art

17



Nanoelectromechanical PIC display

18



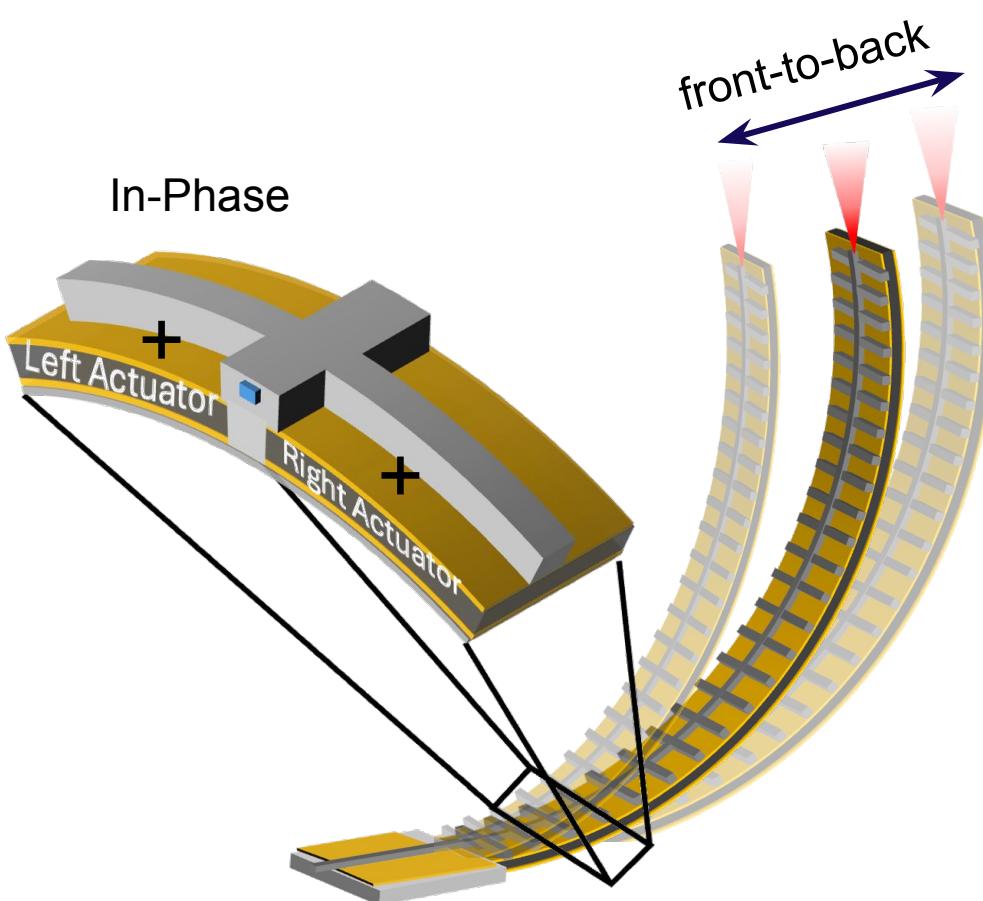
Scan

Low voltage (<5V) requirement enables CMOS compatibility

Scan frequency > 4 KHz

<1 um pixel pitch

6.8M pixels per second per scanner



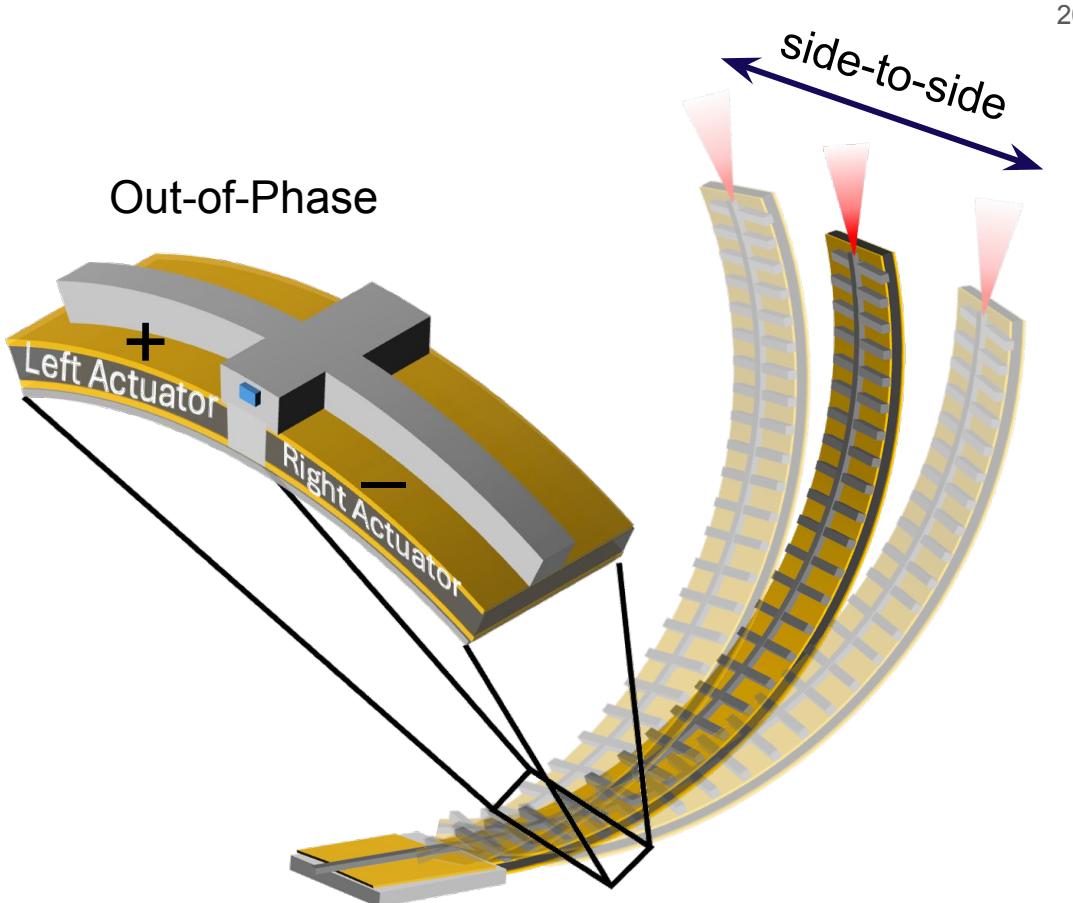
Scan

Low voltage (<5V) requirement enables CMOS compatibility

Scan frequency > 8 KHz

<1 um pixel pitch

6.8M pixels per second per scanner

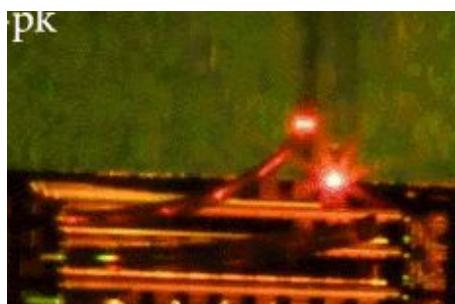


TECH DEMONSTRATION

21

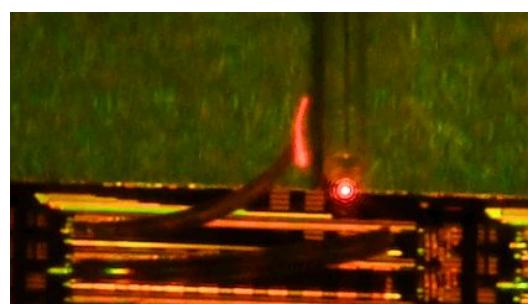
1 FRONT-BACK

Front-to-back movement



2 SIDE-TO-SIDE

Side-to-side movement

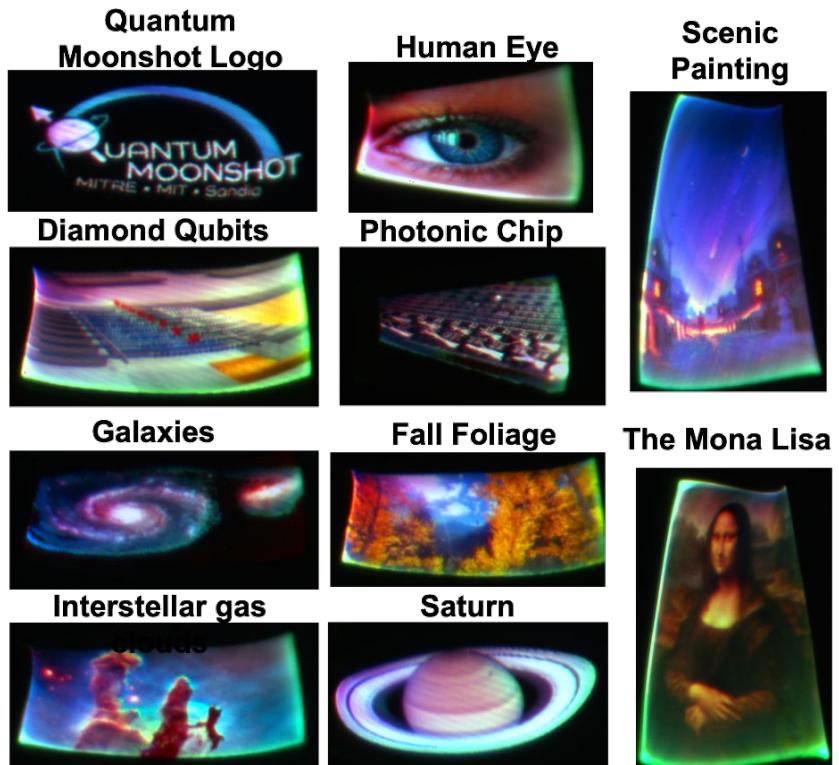
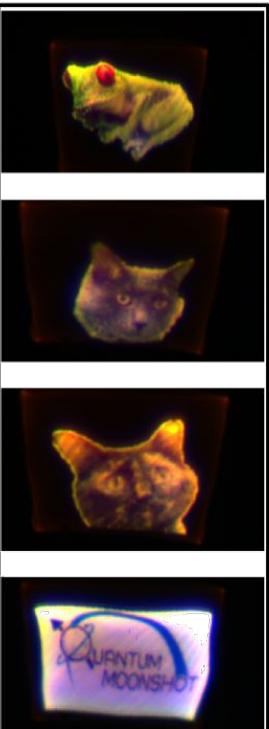
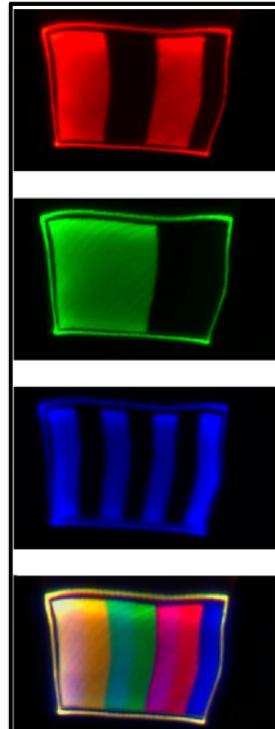


3 COMBINED

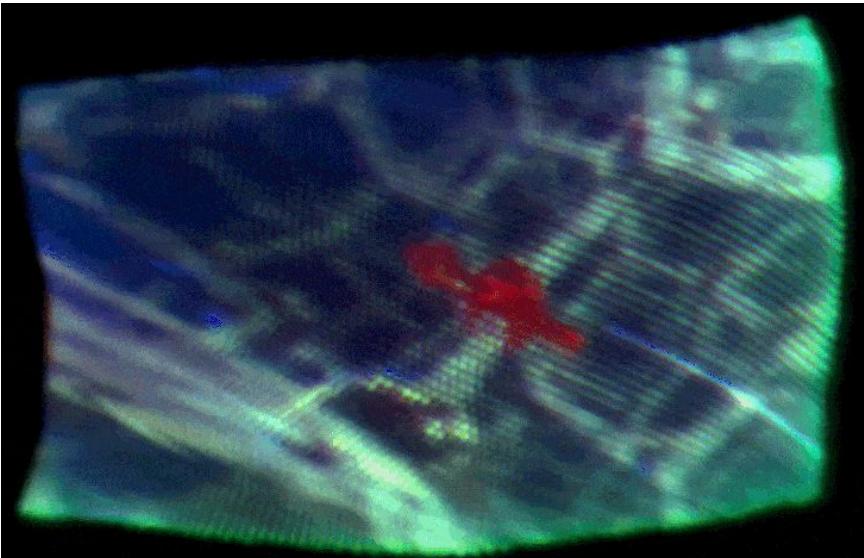
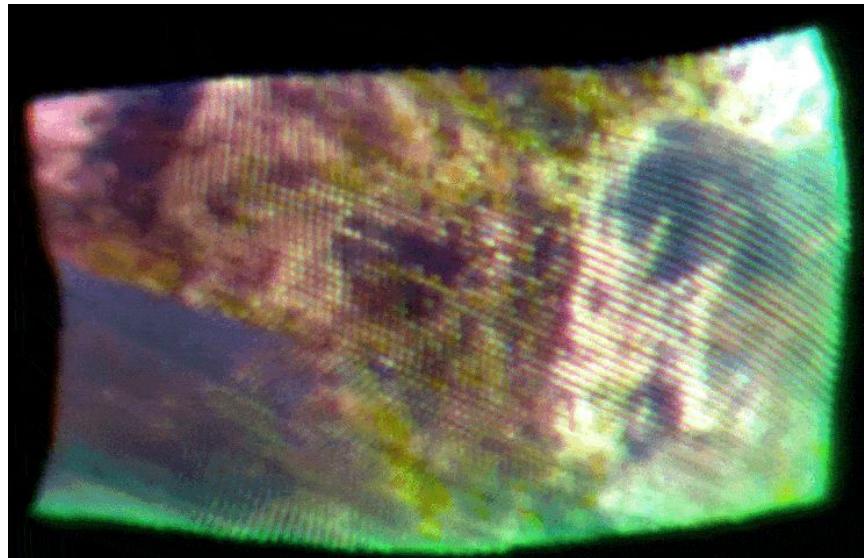
Arbitrary control

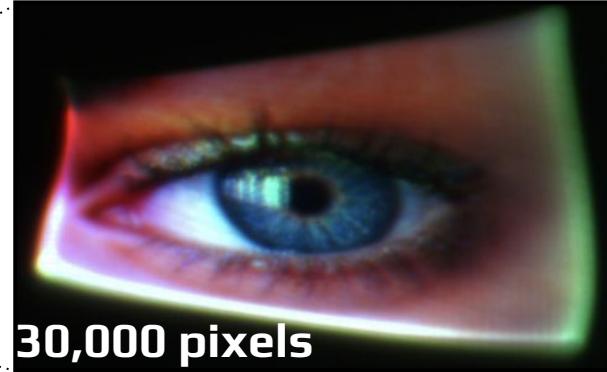
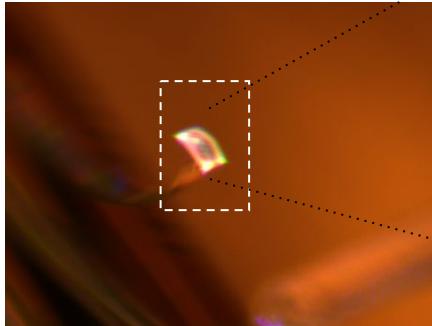


FULL COLOR IMAGES

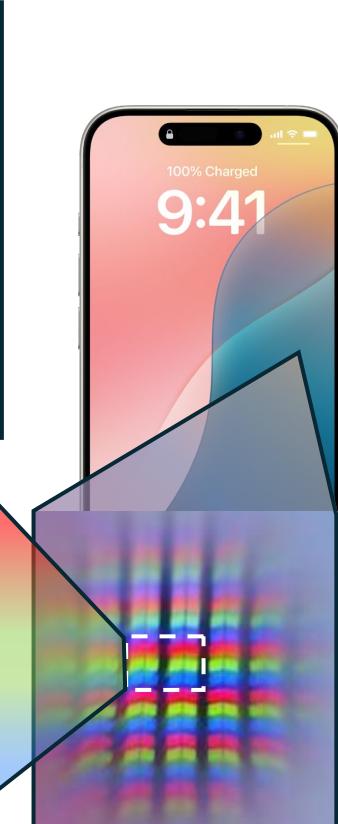
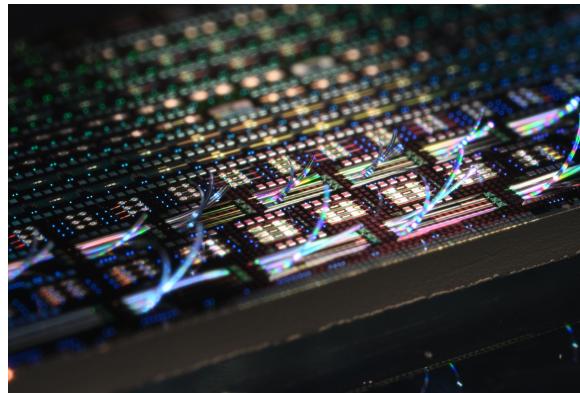


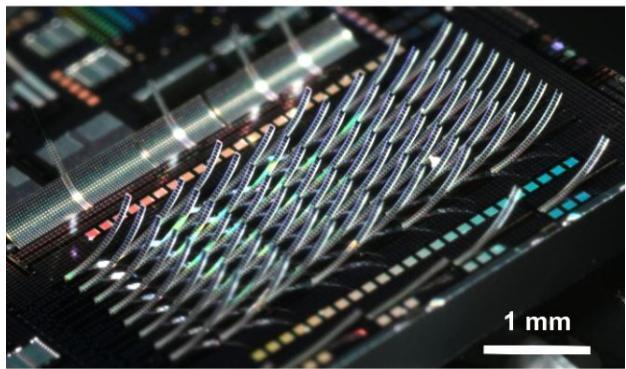
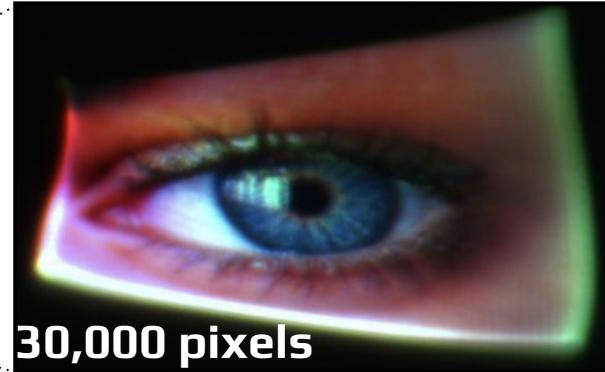
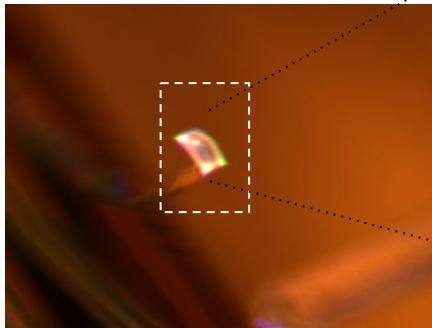
FULL COLOR VIDEO





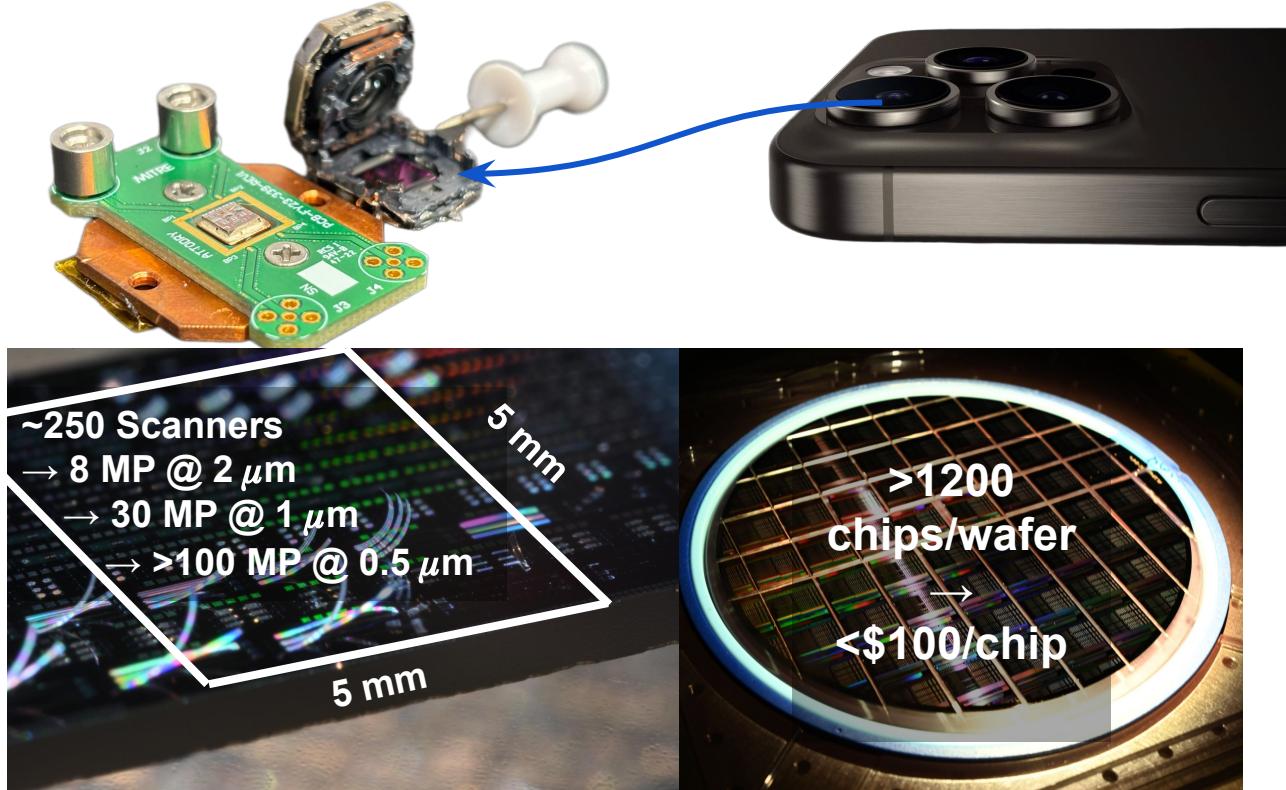
in the area of





SWARM: Scanning waveguide AR microdisplay

27



WHAT'S NEXT: LAB TO DEVICE

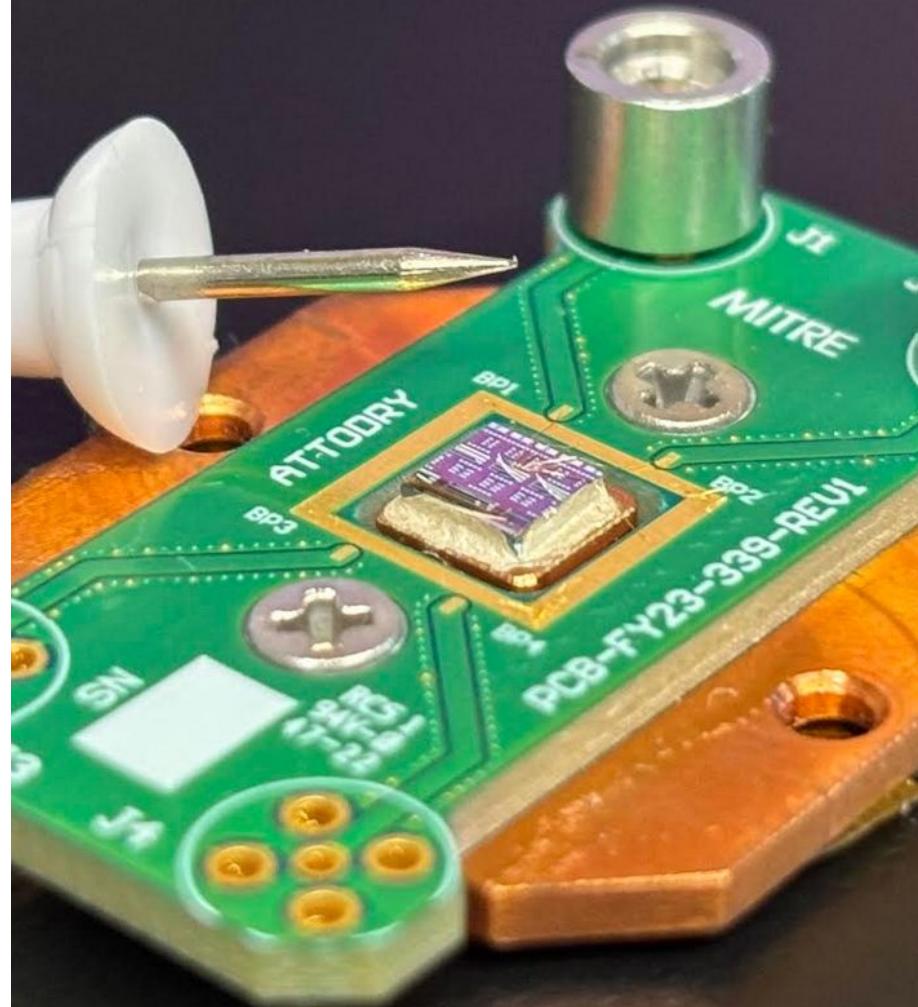
FABRICATION UNIFORMITY

MICROLENS ARRAY DESIGN FOR
ABERRATION COMPENSATION

COUPLING OPTICS INTEGRATION

ELECTROMECHANICAL INTEGRATION
INTO SMALL FORM FACTOR

CONTROL & SOFTWARE INTERFACE



Deep-Dive #2:

Verifiable Measurements

Bidirectional Nonlinear Optical Tomography: Unbiased Characterization of Off- and On-Chip Coupling Efficiencies

Bo-Han Wu,^{1,2,*} Mahmoud Jalali Mehrabad,¹ and Dirk Englund¹

¹*Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

²*Electrical and Computer Engineering, University of Hawai'i at Mānoa, Honolulu, Hawai'i 96822, USA*

(Dated: October 16, 2025)

Squeezed light generation and detection

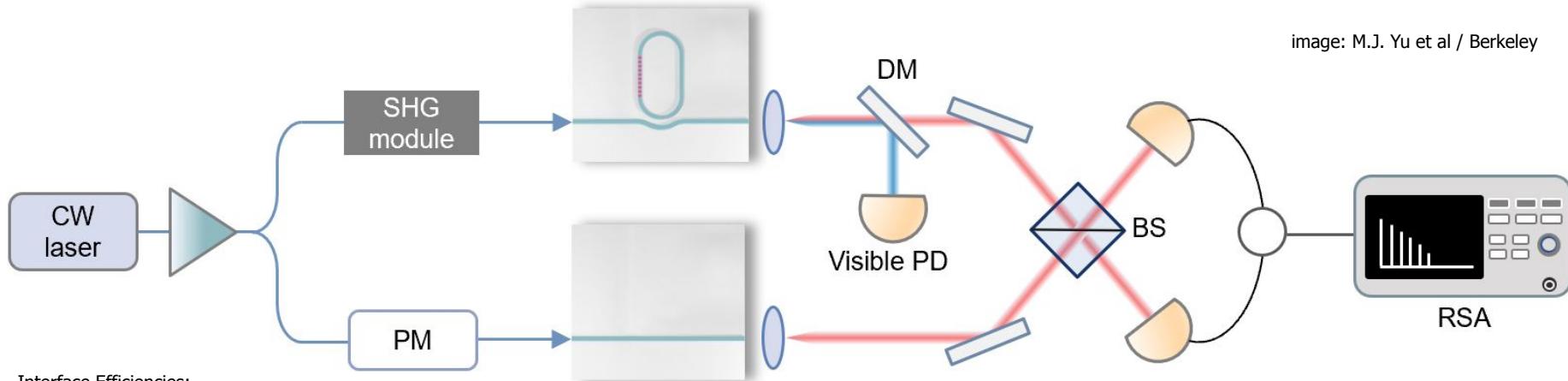


image: M.J. Yu et al / Berkeley

A1: Single-Mode Operation

- All fields propagate in the fundamental TE mode.
- Scattering to higher-order modes is negligible.
- Justification: Mode overlap calculations indicate greater than 99% fundamental mode content.

A2: Lorentzian Resonance

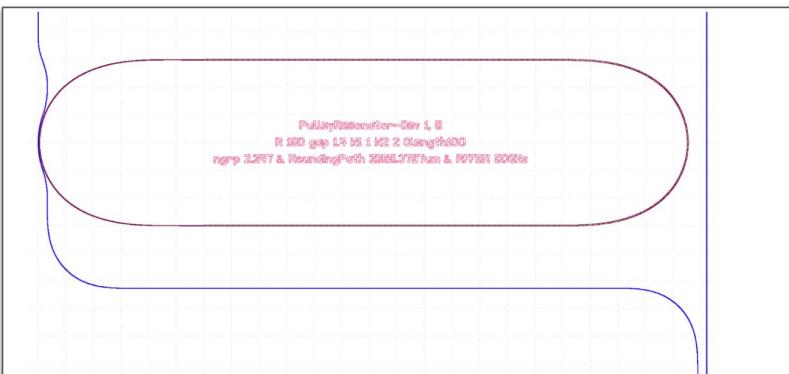
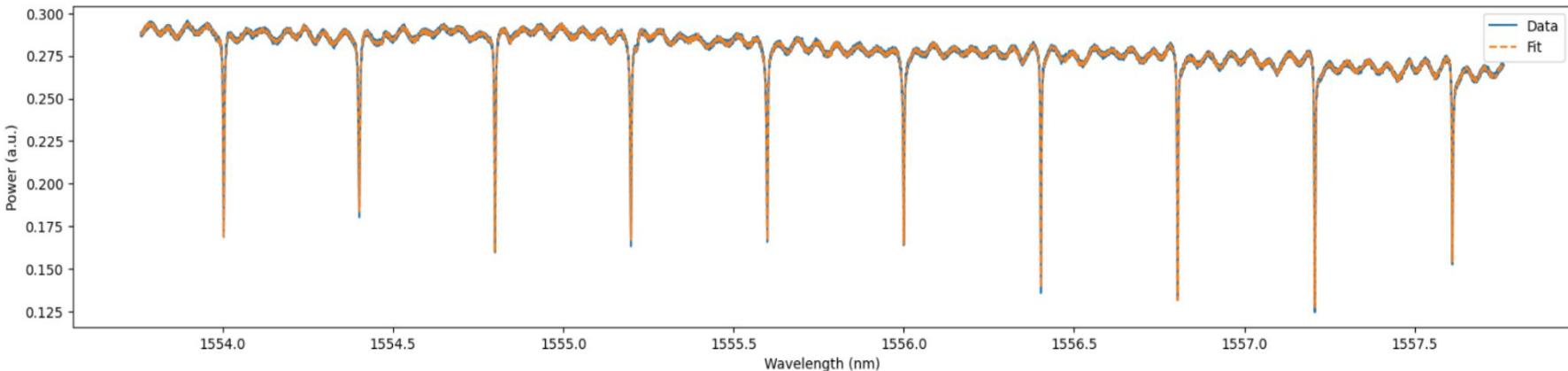
- The cavity transmission exhibits a Lorentzian lineshape, valid for $Q > 10^4$ (typical for TFLN rings).
- Mathematical Representation: $T(\omega) = \kappa^2 / ((\omega - \omega_0)^2 + (\kappa_{tot}/2)^2)$

A3: Time-Invariant Device (not currently the case → experiment upgrades + model upgrades). We want, but can't have: Device parameters (κ, μ, ω_0) remain constant during measurements;

- $n\omega = 2.18$: Refractive index at 1550 nm
- $n2\omega = 2.14$: Refractive index at 775 nm
- $d\text{eff} = 19.5 \text{ pm/V}$: Effective nonlinear coefficient

Digital twin: fitting the data with ambiguity

- Refined fitting routine give is expressive enough -- but it's not unique.
-



Ring

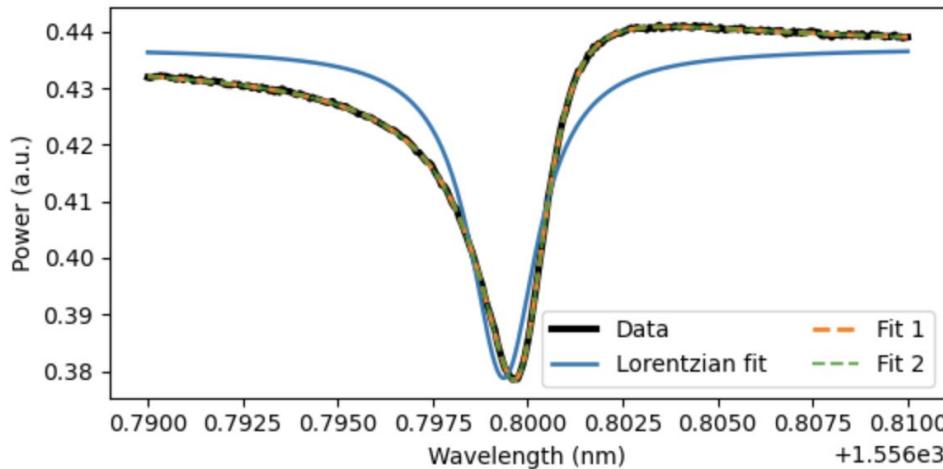
Bending radius = 150um
Gap = 1.4, 1.2, 1.0, 0.9, 0.8, 0.7um
Bus wg width = 1 um
Ring wg width = 2 um
Coupling length = 100 um
Ring path length = 2668 um
FSR = 50 GHz
Simulated neff = 1.939147
Simulated ng = 2.242544

Estimated bus waveguide length (facet to facet) = 9.1 mm

S. Y. Ma / MIT
Berkeley team
(measurements)

Digital twin: fitting the data with ambiguity

- Different parameters can lead to the same fitting curve: ambiguity



fitting includes laser model +
detector model + linear optics

$$E_{\text{det}}(\omega) = E_{\text{chip}}(\omega) + E_{\text{bg}}(\omega),$$
$$P(\omega) = |E_{\text{det}}(\omega)|^2.$$

Dispersive coupler

$$\kappa(\omega) = \kappa_0 + \kappa_1(\omega - \omega_{\text{ref}})$$

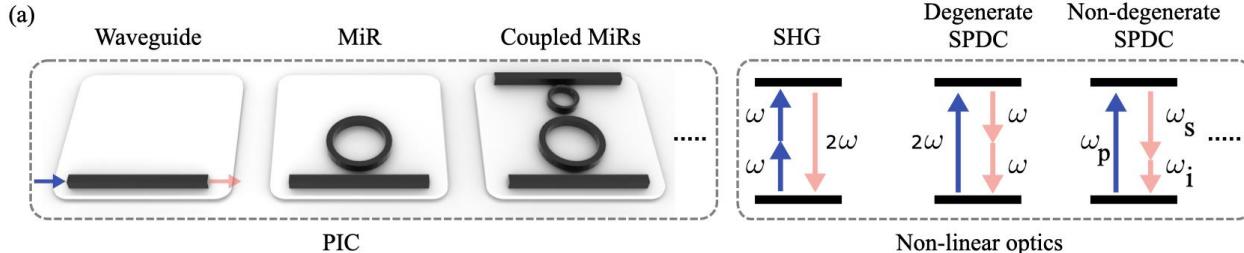
Lorentzian fit: default symmetric fitting.

Fit 1: backscattering $c = 0.0173$, minor model $|E_{\text{bg}}| < 0.001$.

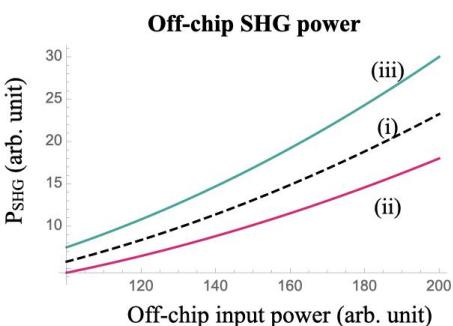
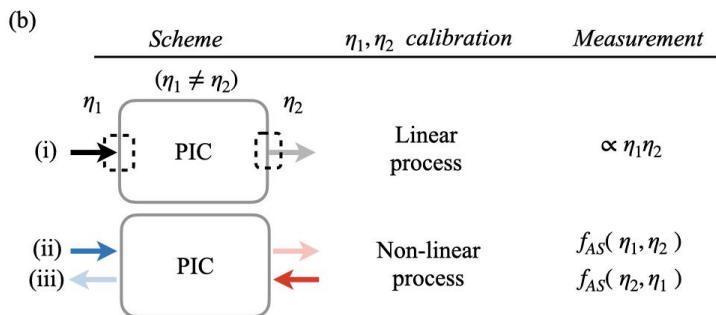
Fit 2: backscattering $c = 0.001$, minor model $|E_{\text{bg}}| \sim 0.008$, altered $\kappa \sim 2\%$.

Cannot uncover ground truth in **one measurement** → Need to lift collinearity with

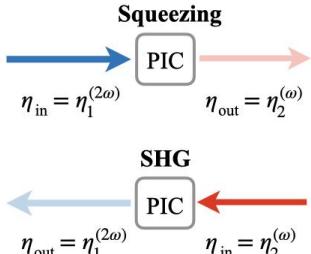
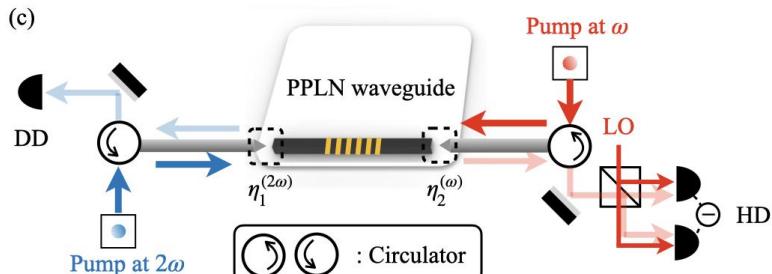
Bidirectional nonlinear optical tomography (BNOT)



→ A general calibration framework for nonlinear integrated optics.



→ Conv. approach, (i), uses linear process to “**degenerately**” estimate interface efficiencies.



→ Particularly important for strongly squeezed light experiments (i.e., >16 dB).

Closed-Loop Architecture

Workflow: (1) Ingest lab data → (2) Run BNOT → (3) Update twin → (4) Predict performance



M.J. Yu group,
Berkeley

Toolchain: Python-based simulator with pytest validation suite and continuous integration.

Deep Learning on Wireless Networks:

Matching the Accuracy of Von Neumann Machines below Their Thermodynamic Limits

Sri Krishna Vadlamani, Kfir Sulimany, Zihui Gao, Tingjun Chen, and Dirk Englund - [arXiv:2504.1775](https://arxiv.org/abs/2504.1775)

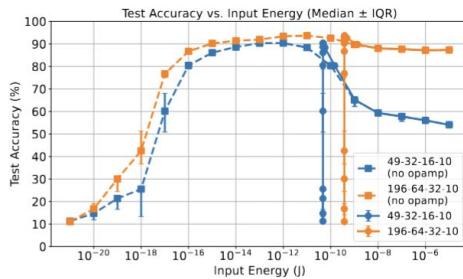
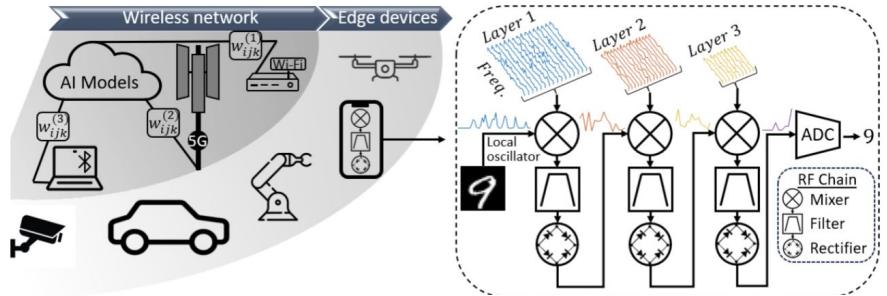
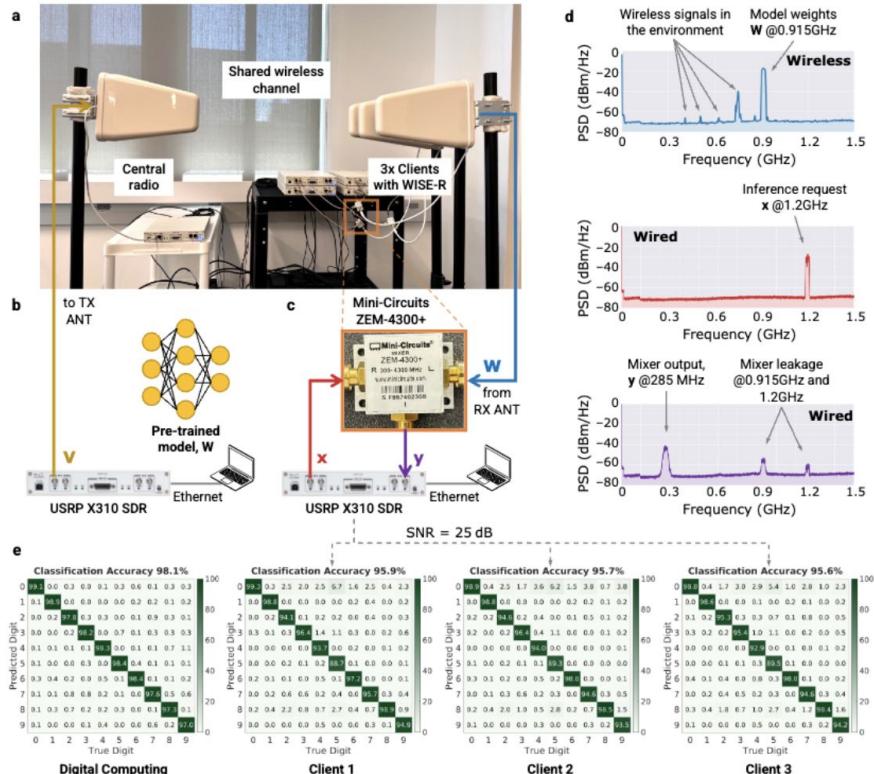


FIG. 4. MNIST classification accuracy of RF analog and digital deep learning. MNIST classification accuracy is presented as a function of the total energy per MAC for digital and analog systems.

FIG. 3. Energy per MAC versus inputsize of the inner product vectors

Disaggregated Deep Learning via Physics Computing at Radio Frequency

Zihui Gao, Sri Krishna Vadlamani, Kfir Sulimany, Dirk Englund, and Tingjun Chen - [arXiv:2505.09267](https://arxiv.org/abs/2505.09267)



Basic research

Technology transition

Industry, gov't partnerships

Startups

LIGHTMATTER



<https://lightmatter.r.co/>

matrix PARTNER Hewlett Packard Enterprise



Viking SPARK CAPITAL SIP Global Partners

Google ventures



Quantum Network Technologies, Inc

Quantum communications,
interconnects, memories

qunett.com

QuEra

Compute the Impossible™

AWS re:Invent

NOV. 29 - DEC. 5, 2021 | LAS VEGAS, NV

CELEBRATING 10 YEARS OF RE:INVENT

THE 22 STARTUPS TO WATCH
IN BOSTON IN 2022

MIT Technology Review

Mathematicians are deploying algorithms to
stop gerrymandering

This new startup has built a record-breaking
256-qubit quantum computer



DUST IDENTITY



SAP PARTNER KLEINER PERKINS LOCKHEED MARTIN AIRBUS VENTURES



CASTLE ISLAND VENTURES ANGULAR VENTURES

LIGHTIUM

GRAFTING LIGHT, SHAPING THE FUTURE

PRODUCTION-GRADE
PHOTONIC FOUNDRY FOR
THIN-FILM LITHIUM NIOBATE

OptiCore

Home Team News



Zaijun Chen



Menglie Yu
Co-founder



Ryan Hamery
Co-founder

Startup hiring (<https://netpreme.com/>)

Netpreme

Dr. Zhizhen Zhong

Axiomatic AI

First-Principles Engineering

Boston (HQ) · Toronto · Barcelona
<https://axiomatic-ai.com>

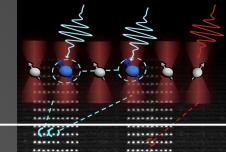
From question to solution-question to...



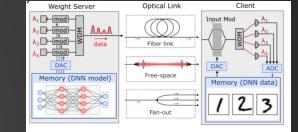
requirement / question q



q = "I need photonic control system"



q = "Develop reconfigurable photonic link for AI acceleration"



$$\min_{\Theta} C$$

Benchmarking



Design system $s_{\Theta} \rightarrow$
target $s(x)$:

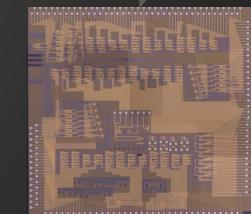
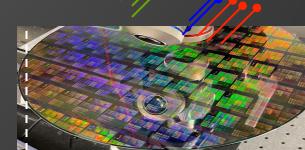
$$\min_{\Theta} C = \|s_{\Theta}(x) - s(x)\|$$

 \rightarrow optimum a

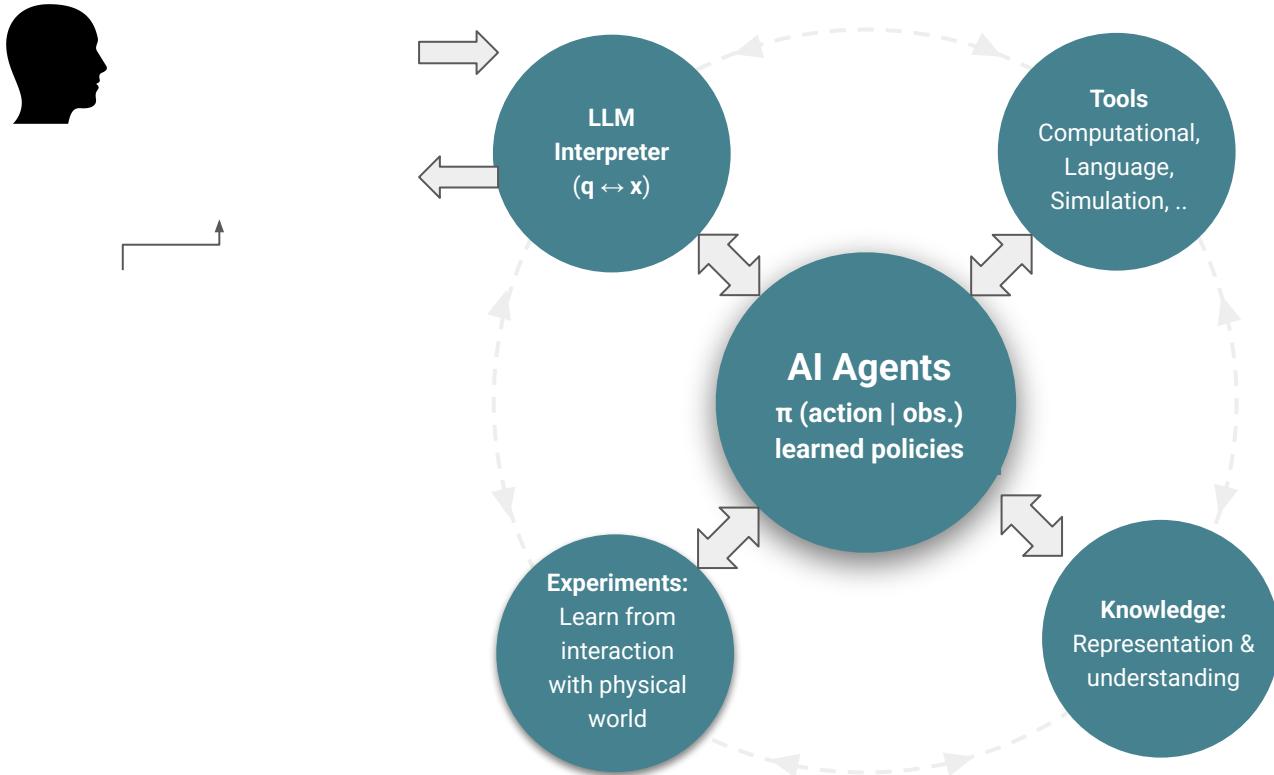
answer a

$$f_{KG}(\cdot)$$

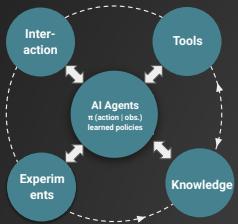
s_{Θ} = high-speed
beam array projector



What “generative design” may look like



Example 1: math-grounded reasoning



OpenAI's GPT5

ChatGPT 5 >

We are solving the equation:

$$5.9 = x + 5.11$$

Step 1: Isolate x

Subtract 5.11 from both sides:

$$x = 5.9 - 5.11$$

Step 2: Perform the subtraction carefully

$$5.90 - 5.11 = 0.79 - 0.00 - 0.21 = -0.21$$

(We can think of $5.90 - 5.11$ as subtracting 5.11 from 5.90 directly, which equals -0.21.)

Final Answer:

$$x = -0.21$$

So the solution is:

$$x = -0.21$$

Ask anything

Ask anything

The Verification Gap

Leading LLM error rates of 10^{-2} are much too high for science, math, engineering

P.R. Mishra¹ , Yogesh Kumar²

¹ Scientific Analysis Group,  Prasanna Technologies

² R. C. Bose Centre for Cryptology and Security, Sustech

³ Department of Mathematics, IIT Bombay

Abstract. The notion of branch number is crucial for both linear and zero elements in a state diagram of active S-Boxes. The branch number of a SPN cipher, specifically, is the minimum number of non-singular matrix over a finite field. This paper presents an algorithm for computing branch number on the existing classical computational complexity class. A comparative study of the proposed algorithmic estimation of the computational complexity of that of the classical approach.

Keywords: Branch number, Finite field

1 Introduction

Claude Shannon, in his seminal work "A Mathematical Theory of Communication" [19] introduced the core properties for any cryptograph. The diffusion property is a linear layer, often represented as a significant alteration in the strength of the diffusion layer. The optimal branch number is achieved when the diffusion layer is a linear layer.

In [8], Daemen introduced the formation as a measure of its performance into two types: differential branching (or linear) branch number.

4 Mishra et al.

Remark 1. [9, Page 144] It is impossible to number $B_d(M)$ of a matrix A equal to C generated by the matrix $[I \mid A]$, minimum distance of the dual code C^\perp .

Remark 2. [9, Page 132] It is noted that $B_d(M)$ and $B_h(M)$ is $n + 1$. Although equal, a matrix with the highest possible will have the same value for both.

In this paper, our focus lies on the which we will simply refer to as the

3 The New Algorithm for Branch Number

In this section, we propose a new algorithm for a non-singular matrix over a finite field, but it does not improve the computational complexity of the proposed algorithm. The analysis of the proposed algorithm is based on the existing classical computational complexity class. A comparative study of the proposed algorithmic estimation of the computational complexity of that of the classical approach.

Theorem 1. The branch number of $B(M)$ is

$$B(M) = \min \left\{ \min \left\{ h(M, x), h(M, x) + w_h(Mx) \right\} \right\},$$

where $h(M, x) = w_h(x) + w_h(Mx)$.

Proof. To begin with, recall that for $n > 1$, the branch number $B(M)$ of M is

$$B(M) = \min \{ h(M, x) \mid x \in \mathbb{F}_q^n \},$$

As $x \neq 0 \Rightarrow w_h(x) \neq 0$. Consequently,

$$B(M) = \min \{ h(M, x) \mid x \in \mathbb{F}_q^n \},$$

We partition the set $\{1, \dots, n\}$ into two parts: $\{1, \dots, n\} \setminus \{n\}$ to compute $B(M)$ as

$$B(M) = \min \left\{ \min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\}, \min \{ h(M, x) \mid x \in \mathbb{F}_q^n, w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \} \right\}.$$

Therefore,

$$B(M) = \min \left\{ \min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\}, \min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor, w_h(Mx) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\} \right\}.$$

Note that the right-hand side of (4) is always greater than or equal to the left-hand side of (4). Therefore, if we include this extra term in (3), it will not affect

Therefore,

$$\min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\} \leq$$

$$\min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor, w_h(Mx) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\}.$$

Note that the right-hand side of (4) is always greater than or equal to the left-hand side of (4). Therefore, if we include this extra term in (3), it will not affect

A New Algorithm for Computing Branch Number

5

Next, we divide the second term on the right-hand side of (1) into the cases where $w_h(Mx) \leq \left\lfloor \frac{n+1}{2} \right\rfloor$ and $w_h(Mx) > \left\lfloor \frac{n+1}{2} \right\rfloor$. Therefore, we have

$$\begin{aligned} & \min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, \left\lfloor \frac{n+1}{2} \right\rfloor < w_h(x) \leq n \right\} \\ &= \min \left\{ \min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, \left\lfloor \frac{n+1}{2} \right\rfloor < w_h(x) \leq n, w_h(Mx) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\} \right\}, \\ & \min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, \left\lfloor \frac{n+1}{2} \right\rfloor < w_h(x) \leq n, w_h(Mx) > \left\lfloor \frac{n+1}{2} \right\rfloor \right\}. \end{aligned} \quad (2)$$

Note that for the second term of the right-hand side of Equation (2), $h(M, x) = w_h(x) + w_h(Mx) > 2 \left\lfloor \frac{n+1}{2} \right\rfloor + 1 \geq n + 1$. However, we know that the upper bound for $B(M)$ is $n + 1$. Therefore, we conclude that the second term of the right-hand side of (2) will not contribute to the computation of the branch number.

Therefore, from (1) and (2), we have

$$\begin{aligned} B(M) &= \min \left\{ \min \left\{ h(M, x), h(M, x) + w_h(Mx) \right\} \right\}, \\ \text{where } h(M, x) &= w_h(x) + w_h(Mx). \end{aligned} \quad (3)$$

Again, we note that

$$\begin{aligned} & \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor, w_h(Mx) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\} \\ & \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\}. \end{aligned}$$

Therefore,

$$\begin{aligned} & \min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\} \leq \\ & \min \left\{ h(M, x) \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor, w_h(Mx) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\}. \end{aligned} \quad (4)$$

Note that the right-hand side of (4) is always greater than or equal to the left-hand side of (4). Therefore, if we include this extra term in (3), it will not affect

GPT5: "Nothing wrong in the derivation"

Thought for 2m 5s >

Short answer: the argument is essentially correct; I only see small nits/tuos and a couple of places where you can tighten the logic. Here's a quick pass:

What's correct

- The reduction to the two regimes $w_h(x) \leq \lfloor (n+1)/2 \rfloor$ and $w_h(x) > \lfloor (n+1)/2 \rfloor$, then discarding the subcase $w_h(x), w_h(Mx) > \lfloor (n+1)/2 \rfloor$, is valid: in that subcase

$$h(M, x) = w_h(x) + w_h(Mx) \geq 2 \left(\left\lfloor \frac{n+1}{2} \right\rfloor + 1 \right)$$

which is $> n + 1$ for all n . Hence those x can't achieve the minimum (since there always exists some x with $h(M, x) \leq n + 1$; see the note below).

- The change of variables $y = Mx$ and the equality $h(M, x) = h(M^{-1}, y)$ are correct, and the final identity

follows since $\min \{ \min_S a, \min_S b \} = \min_S \min \{ a, b \}$ over the same finite set S .

Ax Prover: Verification failed

```
1767 -- KEY SORRIES: THE ORIGINAL PROOF USES MINIMUMS OF EMPTY FINSETS, WHICH ARE NOT DEFINED
1768 have h_constrained_low_nonempty : {x ∈ (@low_weight_vectors p q n _ _ _ ) | wh (M.mulVec x) ≤ (n + 1) / 2}.Nonempty := by sorry
1769 have h_first_set_nonempty : {y ∈ (@high_weight_vectors p q n _ _ _ ) | wh (M.mulVec y) ≤ (n + 1) / 2}.Nonempty := by sorry
1770 have h_second_set_nonempty : {y ∈ (@high_weight_vectors p q n _ _ _ ) | wh (M.mulVec y) > (n + 1) / 2}.Nonempty := by sorry
```

Ax-Prover: A Deep Reasoning Agentic Framework for Theorem Proving in Mathematics and Quantum Physics

Marco Del Tredici¹, Jacob McCarran¹, Benjamin Breen¹, Javier Aspuru Mijares¹, Weichen Winston Yin¹, Jacob M. Taylor¹, Frank Koppens², and Dirk Englund^{1,3}

¹Axomatic AI

²Institut de Ciències Fotòniques (ICFO)

³Massachusetts Institute of Technology (MIT)

Concrete scenario:

VVUQ of patent (100+ equations)

U.S. Patent Jul. 21, 2009 Sheet 9 of 12 US 7,564,534 B2

(12) United States Patent
Den Boef et al.

(10) Patent No.: US 7,564,534 B2
(45) Date of Patent: *Jul. 21, 2009

(54) At 11 US 7,564,534 B2

(75) Inv 12

(73) As Inv

(*) Ne Inv

(21) At Inv

(22) F1 Inv

(65) US Inv

(63) Au Inv

(62) Au Inv

(30) Jun. 11 Inv

(31) Inv

(46) Inv

(47) Inv

(48) Inv

(52) U.S. Inv

angle of 49 radians for $\lambda=533$ nm. To measure such a low spatial frequency, the angular size of the illumination beam must be limited to a diameter of about 40 mrad.

In the alignment system 10, the illumination spot is circularly polarized to reduce the amount of beam light to be rejected with the aid of polarizing beam splitter 17 and a quarter wave plate 18 as shown in FIG. 3.

For coarse gratings with a pitch much greater than the wavelength of the illumination beam, the choice of polarization is not critical. However, where the marker pitch is of the same order as the wavelength, the diffraction efficiency depends on the polarization alignment marker can acts as a polarizer.

Light that is not deflected, light that is deflected, light that is always a chance very low for one particular light contains two orthogonal states of polarization so there is no efficient differentiation of light.

In order to suppress spurious light, it is necessary to tilt the quarter wave plate 18. The to minimize the amount of light that is reflected, it is also possible to change the design of the objective lens.

The interometer produces (virtual) images of the pupil plane. The total optical field in the pupil plane is:

$$I_1(k) = \frac{1}{2} |E(k)|^2 + \frac{1}{2} |E(-k)|^2 + |E(k)| |E(-k)| \cos(\varphi(k) - \varphi(-k)); \quad (5)$$

and

$$I_2(k) = \frac{1}{2} |E(k)|^2 + \frac{1}{2} |E(-k)|^2 + |E(k)| |E(-k)| \cos(\varphi(k) + \varphi(-k)). \quad (6)$$

If two detectors 15 with a width 2M are placed at positions $k = k_1$ and $k = -k_1$ in the pupil plane 14, the optical powers P_1 and P_2 captured by these detectors are given by:

$$P_1(k_1) = \int_{-k_1-2M}^{k_1-2M} |E_1(k_1, z_1)|^2 dk + \int_{-k_1-2M}^{k_1-2M} |E_2(k_1, -k_1)|^2 dk + \int_{-k_1-2M}^{k_1-2M} E_1(k_1, z_1) E_2^*(k_1, -k_1) dk; \quad (7)$$

$$P_2(k_1) = \int_{-k_1-2M}^{k_1-2M} |E_1(k_1, z_1)|^2 dk + \int_{-k_1-2M}^{k_1-2M} |E_2(k_1, -k_1)|^2 dk + \int_{-k_1-2M}^{k_1-2M} E_1(k_1, z_1) E_2^*(k_1, -k_1) dk; \quad (8)$$

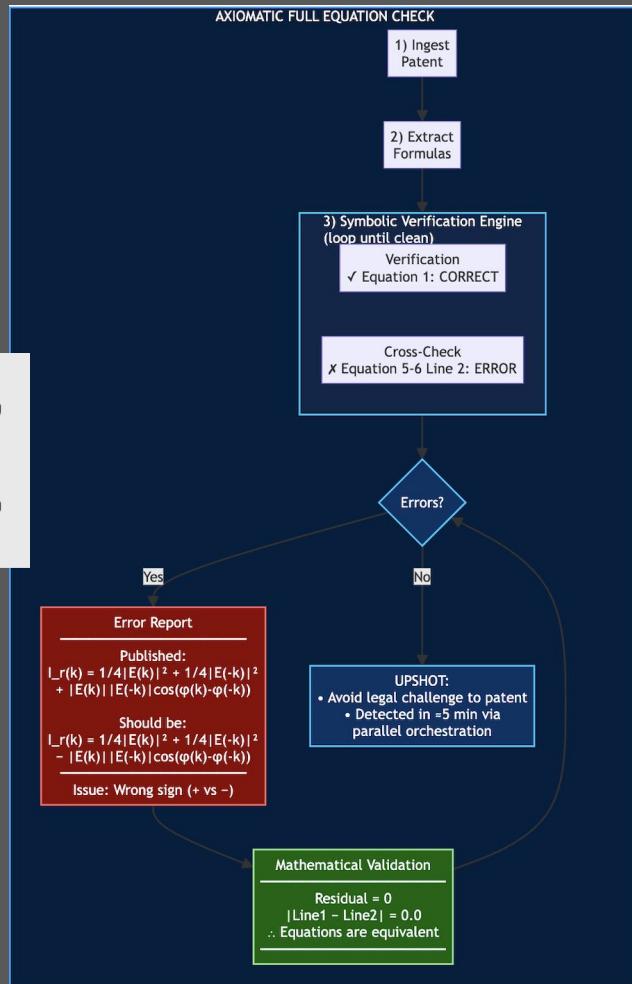
FIG. 5 shows the signal formation graphically. Because of the mirror operation, the horizontally hatched areas overlap and interfere and the diagonally hatched areas overlap and interfere. The phase difference between the two fields controls the pattern formation.

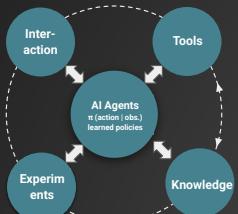
The images of the pupil are orthogonally and linearly polarized and interfere between them is therefore not visible in the form of intensity variations (fringes). In order to translate phase variations in intensity variations, the images must be rotated 90° in the same direction. This is realized with a polarizing optical element, which may be a dichroic sheet polarizer, a regular polarizing beam splitter based on a multi-layer coating, or a birefringent beam splitter such as a Savart plate, a Willaston Prism, a Glan-Taylor beam splitter or a "wire grid" polariser.

the total intensity equals the intensity that is incident on the beam splitter 18. Thus, both branches contain position information and can be used for alignment. This means that it is possible to use one branch for x-position detection and the other for y-position detection, allowing use of a smaller aperture stop to be used for alignment. Conversely, one branch can be used with a small aperture stop for x-position detection and the other branch with a large aperture stop for capturing. A further alternative is to use one branch for one set of wavelength and the other branch for another set of wavelengths.

Alignment markers are often placed in the scribe line very close to product structures which may lead to product cross-talk. Light scattered by the product influences the alignment signal. Product cross-talk can be significantly attenuated by using a sufficiently large illumination beam. However, a small illumination beam is not preferred for various reasons. With a small illumination beam, the position of the illumination spot becomes more critical. For example, in the extreme case of a single pixel, a small illumination spot results directly in alignment position drift. Also, capture becomes more critical since there is a greater chance that the marker is very poorly illuminated after the substrate W is loaded on the substrate table WT. Finally, a greater illumination beam is needed which makes the detection of coarse gratings more difficult.

The images of the pupil are orthogonally and linearly polarized and interfere between them is therefore not visible in the form of intensity variations (fringes). In order to translate phase variations in intensity variations, the images must be rotated 90° in the same direction. This is realized with a polarizing optical element, which may be a dichroic sheet polarizer, a regular polarizing beam splitter based on a multi-layer coating, or a birefringent beam splitter such as a Savart plate, a Willaston Prism, a Glan-Taylor beam splitter or a "wire grid" polariser.





AX-Prover: A DEEP REASONING AGENTIC FRAMEWORK

Example of “basic” math (abstract algebra)

For example, a competition problem may ask to determine all positive integers a, b such that

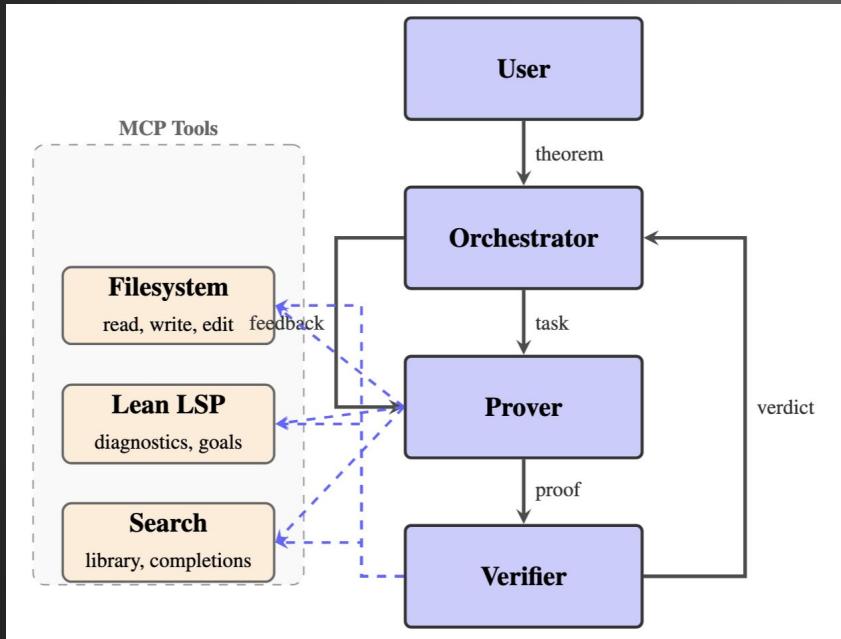
$$\frac{a^2 + b^2}{ab + 1} \in \mathbb{Z},$$

Example cryptography proof

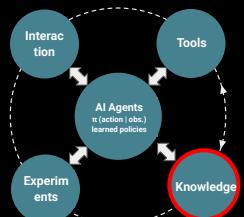
Theorem 1. The branch number of an invertible matrix $M \in M_n(\mathbb{F}_q)$ is given as

$$\mathcal{B}(M) = \min \left\{ \min \{h(M, x), h(M^{-1}, x)\} \mid x \in \mathbb{F}_q^n, 1 \leq w_h(x) \leq \left\lfloor \frac{n+1}{2} \right\rfloor \right\},$$

where $h(M, x) = w_h(x) + w_h(Mx)$.

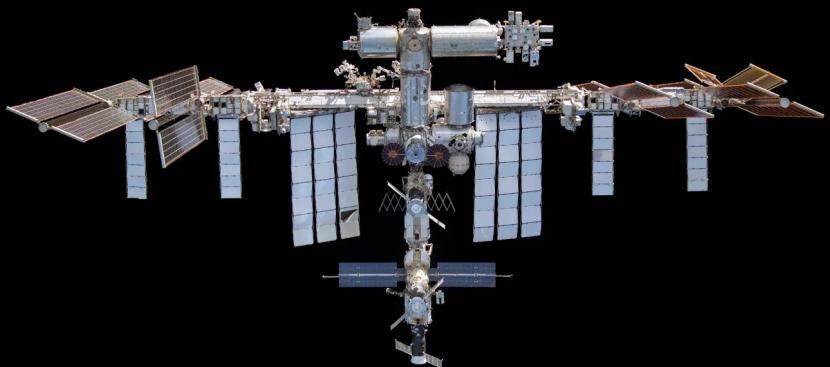


Dataset	Subset	Ax-Prover (pass@1)	Sonnet (pass@1)	DS-Prover (pass@1)	Kimina [†]
NuminaMath	solved-K	81%	7%	48%	100%
	solved-H	47%	8%	14%	0%
	unsolved	26%	1%	18%	0%
	total	51%	5%	28%	31%
AbstractAlgebra	easy	72%	10%	26%	12%
	intermediate	56%	6%	22%	14%
	total	64%	8%	24%	13%
QuantumTheorems	easy	100%	54%	88%	72%
	intermediate	92%	18%	48%	34%
	total	96%	40%	61%	57%



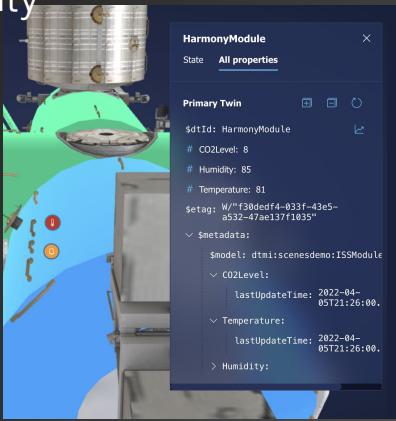
The Knowledge (Ingress) Gap

understand, model



control, refine

Reality

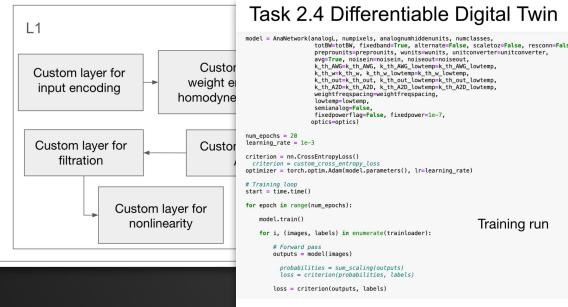


Quantum - extension to EDA

MIT postdoc: "Ansys is state of art but building models containing quantum physics was impossible.. [...] I ended up instead using python, then pytorch, ... and maybe eventually connect with to Ansys, Synopsis tools

Task 2.1 Differentiable Digital Twin

PyTorch digital twin for machine learning applications

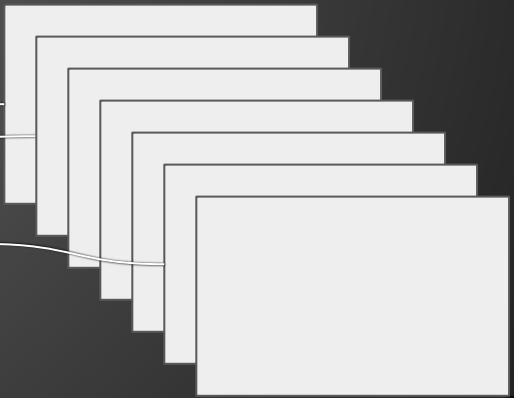
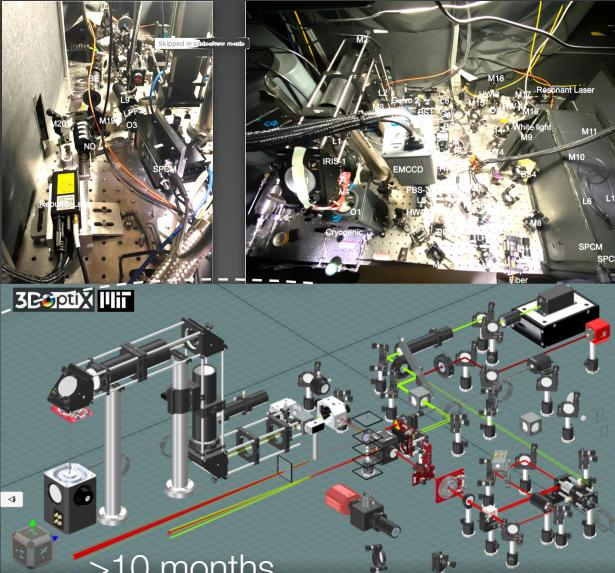
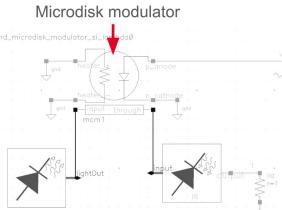


Cadence Virtuoso ADE Suite

MIT postdoc : “ I didn’t know about digital twin modeling before joining this project, i wish they’d teach that in grad school”

- Demonstrate chirp-free operation
- Demonstration of eye diagram with PAM4 carrying 40 Gbps

The cr



Example 1: Reading comprehension

AXIOMATIC PRESENTS

lemma

Your co-explorer for science, math, and engineering

Talk to lemma...

What can you do? Design me an MZI and visualize it

What is the frequency response of a ring resonator? Tell me a joke

npj quantum materials

Published in partnership with Nanjing University

Article

<https://doi.org/10.1038/s41535-025-00771-6>

Optical properties, plasmons, and orbital Skyrme textures in twisted TMDs

Lorenzo Cavicchi^{1,2}*, Koen J. A. Reijnders², Mikhail I. Katsnelson² & Marco Polini²

Check for updates

In the long-wavelength limit, Bloch-band Berry curvature has no effect on the bulk plasmons of a two-dimensional electron system. In this Letter, we show instead that bulk plasmons are a probe of real-space topology. In particular, we focus on orbital Skyrme textures in twisted transition metal dichalcogenides, presenting detailed semiclassical and quantum mechanical calculations of the optical conductivity and plasmon spectrum of twisted MoTe₂.

Forty years ago¹ Michael Berry introduced what are now routinely called “Berry phase” and “Berry curvature”^{2–4}. Soon after, Joshua Zaks realized that these geometric concepts could be generalized to Bloch-periodic systems, where the parameters (quasi-momenta) are varied in closed loops (bands or Fermi surfaces) by applying electric fields.

Berry phase and Berry curvature have been powerful tools for understanding a system’s intrinsic (i.e., geometric) contributions to crystal⁵ properties. These properties of the bulk Bloch bands have been identified to play a pivotal role in a wide range of physical phenomena, including electric polarization⁶, magnetic oscillations in metals⁷, anomalous Hall effects^{8–11}, orbital magnetism¹², quantum Hall effects of various kinds^{12–14}, and quantized charge pumping¹⁵. Additionally, they are crucial also in systems where no Berry curvature is present, such as in systems with spin textures (e.g., when spin skyrmion lattices are present)¹⁶. Originally proposed in nuclear physics by Skyrme in 1962¹⁷, skyrmions have become fundamental in understanding spin structures in condensed matter systems. Initially conceptualized as vertices in the spatial distribution of spin magnetization in crystals¹⁸, skyrmions have been experimentally observed in magnetic materials^{19–21} and other physical systems, including focused photonic vector beams²² and specially designed space-coupling metasurfaces for localized spoof plasmons²³.

In this Letter, we focus on a different solid-state platform where skyrmion lattices play a crucial role, i.e., twisted transition metal dichalcogenide (TMD) bilayers, such as twisted MoTe₂ monolayers. These materials have recently attracted a great deal of attention because of the experimental discovery of fractional Chern insulating states²⁴ and magnetic fields that are readily switchable²⁵. Available continuum model Hamiltonians²⁶ describing these single-particle topological moiré bands— which have been recently dubbed *skyrmion Chern-band models*^{27,28}— harbor orbital (rather than spin) skyrmion lattices.

Intriguingly, because of the presence of this orbital skyrmion lattice, it is possible to approximately map these models into the problem of Landau levels subject to a periodic potential^{29,30}. More precisely, by means of an adiabatic approximation on the layer-pseudospin degree of freedom, the twisted TMD Hamiltonian transforms into one for holes under the effect of a periodic potential and a periodic magnetic field^{31,32}. This effective periodic magnetic field has a non-zero average, and its strength is related to the topological charge of the effective skyrmion lattice^{33,34}.

In this Letter, we first perform a thorough theoretical study of the optical and plasmonic properties of these skyrmion Chern-band models. Although numerical results are presented for the case of twisted MoTe₂, the theoretical presentation is carried out in general. We then argue that plasmons in twisted TMD bilayers are a probe of orbital skyrmion textures (see Fig. 1) in the sense that the gap at zero wave number is approximately related to the uniform component of the skyrmion effective magnetic field. Our findings are in quantitative agreement with the available experimental data³⁵, thus qualitatively understanding the main properties of this class of systems, while an accurate quantum treatment is instead needed for obtaining quantitative results. In addition, we perform a derivation of the mapping onto a single layer-pseudospin sector, which is an alternative to the refs. 33,34 and based on semiclassical techniques. This gives rise to a formal series expansion, providing us with a systematic way of constructing all higher-order terms in the adiabatic parameter.

Results

Plasmons are collective excitations of the electron density in a crystal³⁶, and their behavior can indeed be influenced by various factors, including the underlying band structure and, in principle, its topological properties. To unravel the impact of Berry curvature on plasmons, it is convenient to turn up coupledless hydrodynamic equations, which describe the long-wavelength collective motion of the electron fluid. These can then be coupled to Hamilton equations of motion describing an electron wave packet in a crystal³⁷.

$$\hat{r} = \frac{1}{\hbar} \nabla_{\mathbf{k}} \epsilon_{\mathbf{k}}(\mathbf{k}) + \Omega_{\mathbf{k}}(\mathbf{k}) \times \hat{\mathbf{k}}, \quad (1)$$

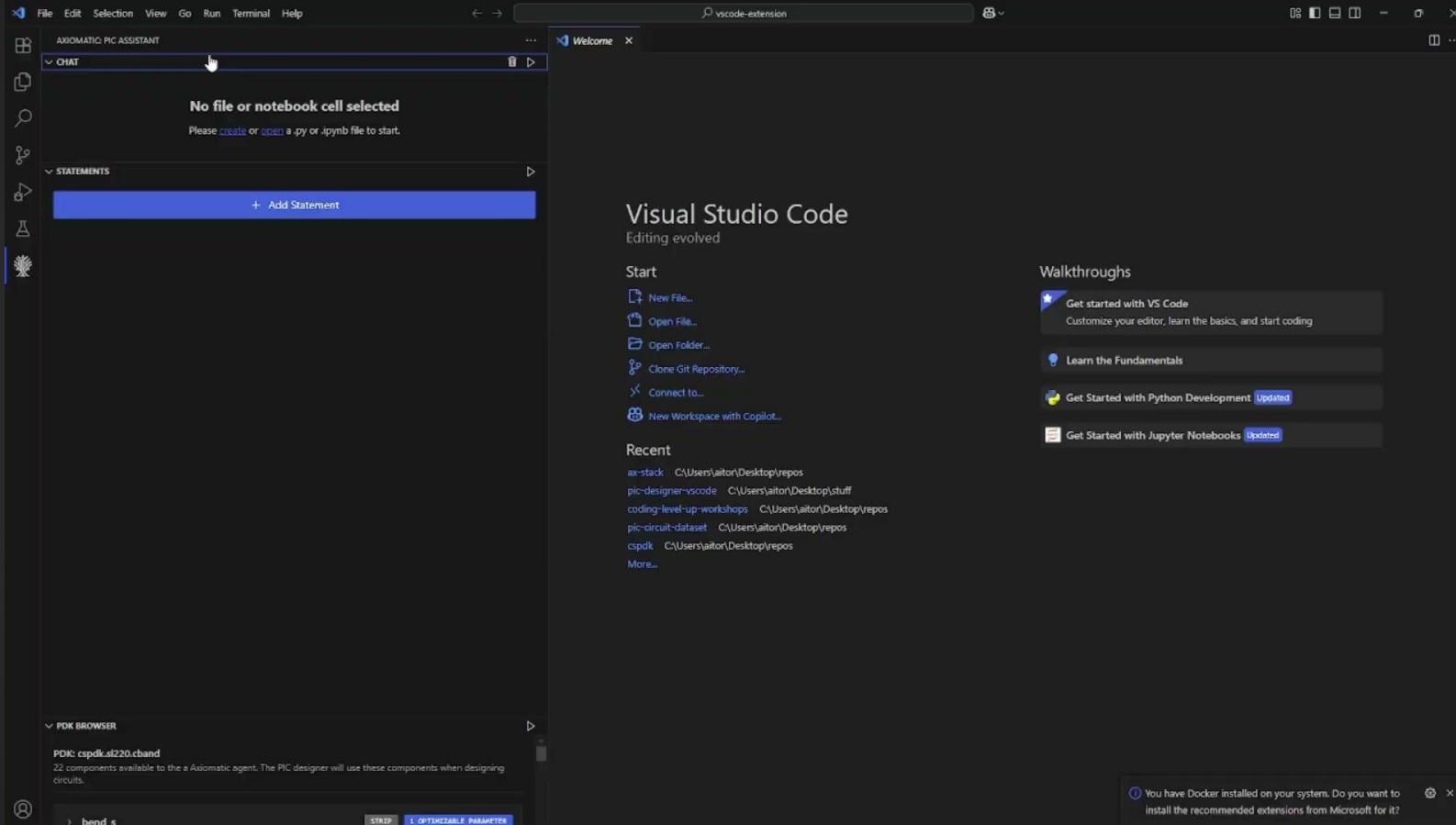
¹Soucia Normale Superiore, Pisa, Italy. ²Dipartimento di Fisica dell’Università di Pisa, Pisa, Italy. ³Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands. ⁴ICFO-Institut de Ciències Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels, Barcelona, Spain.
✉ e-mail: lorenzo.cavicchi@nsa.sns.it

npj Quantum Materials | (2025)10:83

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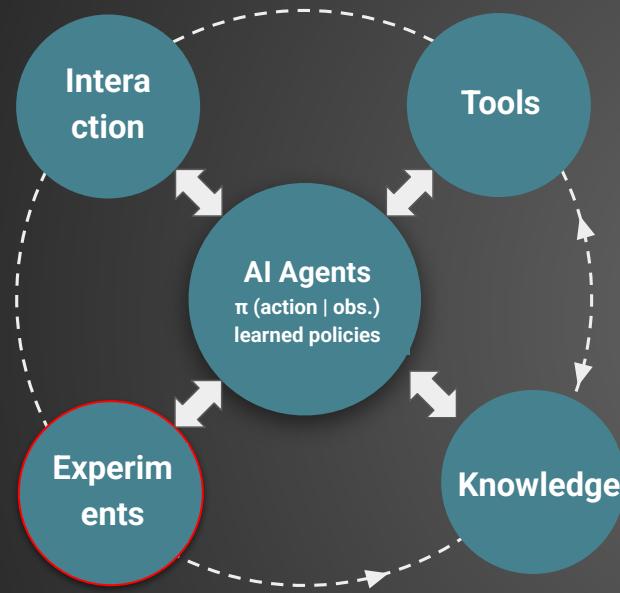
Photonic integrated circuit design, automated

U. Toronto - Axiomatic_AI -
GDSFactory - MIT

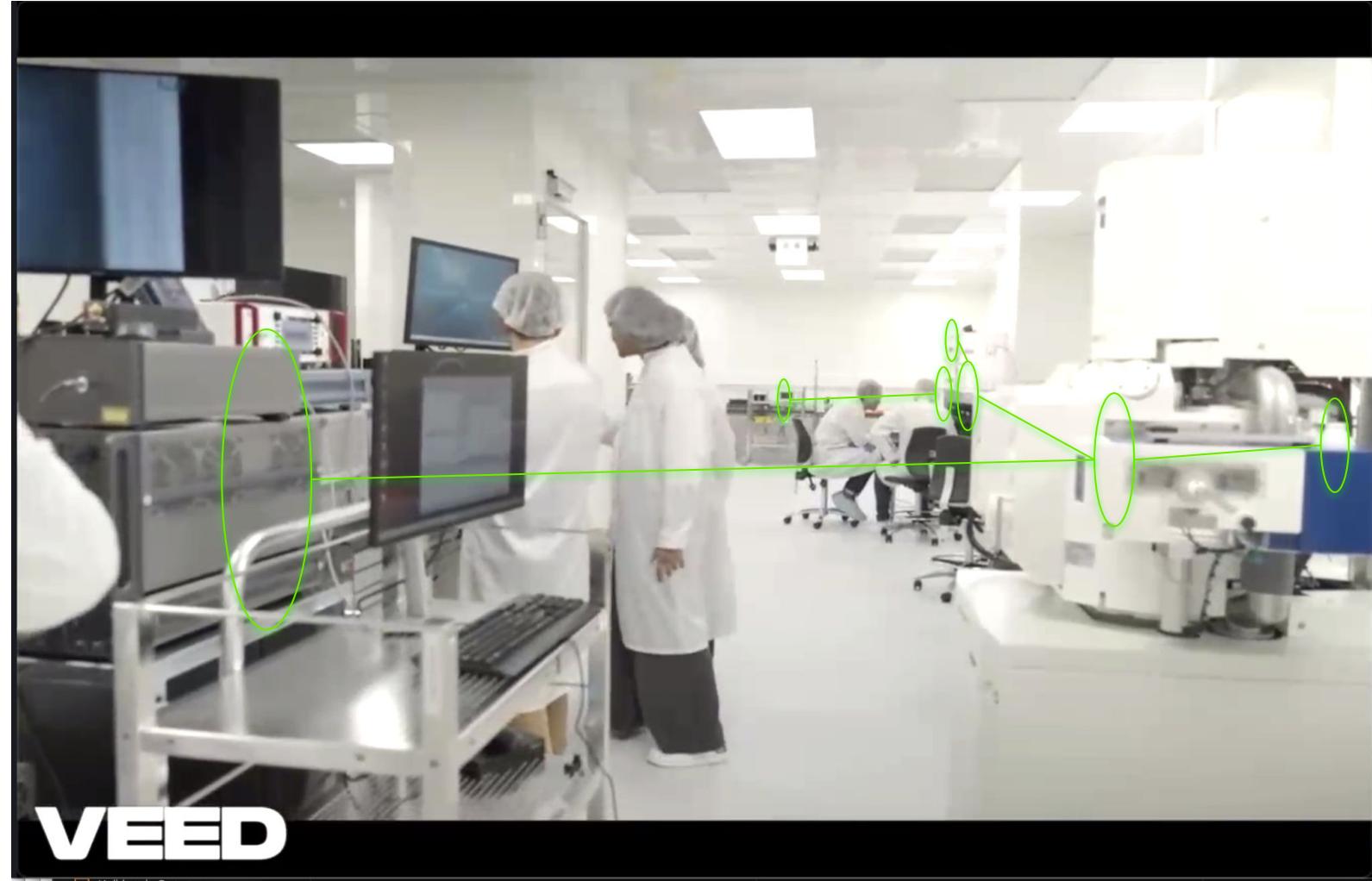


Opensource: <https://github.com/JPPhotonics/PhIDo-Release>

A Sharma, V Ansari, Y Fu, R Iyer, J Matres, T Tamas, O Akdeniz, D E , J Poon, OFC 2024; to be published;



4. Experiments



VEED

Unleashed. Connected.

Digital twins to make the physical world intelligible

- Infinite space for compiling computing into physics and control.
- Math-grounded AI can help us explore this space of deep computational design

“To reach true AI, we need to build machines that learn models of the world in a self-supervised manner.”

Y. LeCun, “A Path Towards Autonomous Machine Intelligence” (2022)

The Verification Principle:

An AI system can create and maintain knowledge only to the extent that it can verify that knowledge itself.

Rich Sutton, “Verification: The Key to AI” (2002)