U.S. ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND

CHIP-SCALE OPTICAL PHASED ARRAYS TO ENABLE RELIABLE COMMUNICATIONS

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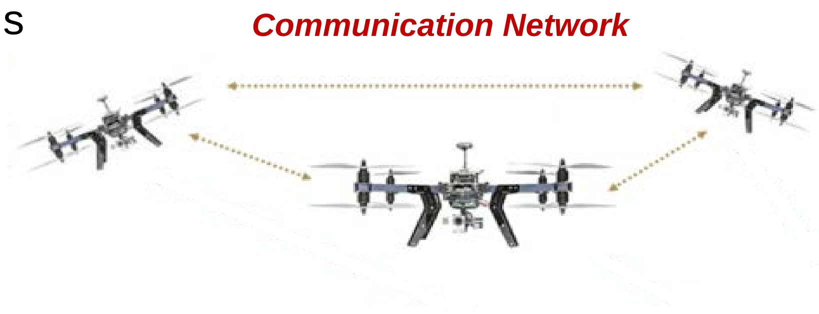
ARMY COMMUNICATIONS

"Fighting is likely to take place in urban areas and in a degraded electronic as well as a cyber environment. Communication will likely be problematic, and adversaries will be both competent and elusive." – GEN Milley (CSA)

Army Network Modernization requires reliable and secure communications anywhere, anytime, in all domains, in all environments, against any foe.

ELECTROMAGNETIC SPECTRUM DOMINANCE

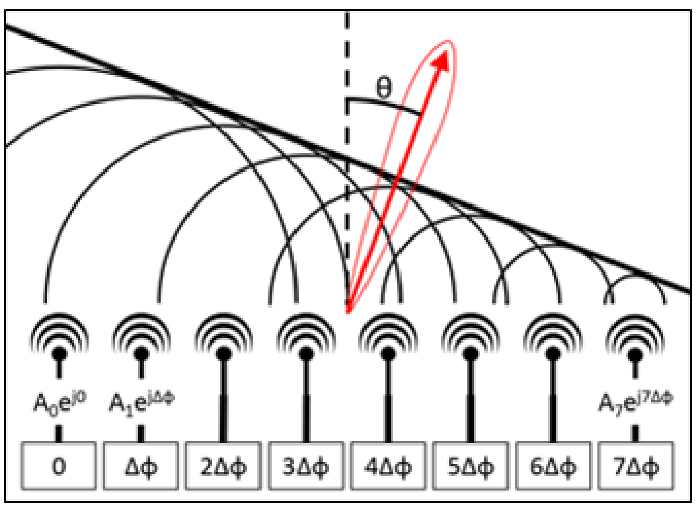
- Need assured and adaptive connectivity for highly dispersed forces that allows for reliable jam-resistant multipoint communications
- Despite the maturity of conventional-RF systems, it is imperative in the future fight that the Warfighter be equipped with technologies that exploit all available resources, employing unconventional spectrum, channels, devices, and networking modalities
- For communications, RF has low directivity and is highly susceptible to jamming



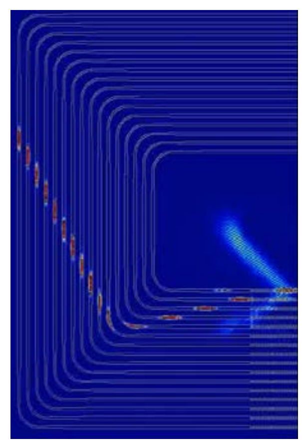
- Build resiliency in communications architecture by employing a variety of techniques, including **optical solutions**
  - Optical spectrum allows for expansion of bandwidth and brings diversity of spectrum to communication systems
  - Low Probability of Detect (LPD) / Low Probability of Intercept (LPI)
  - No frequency approval requirements

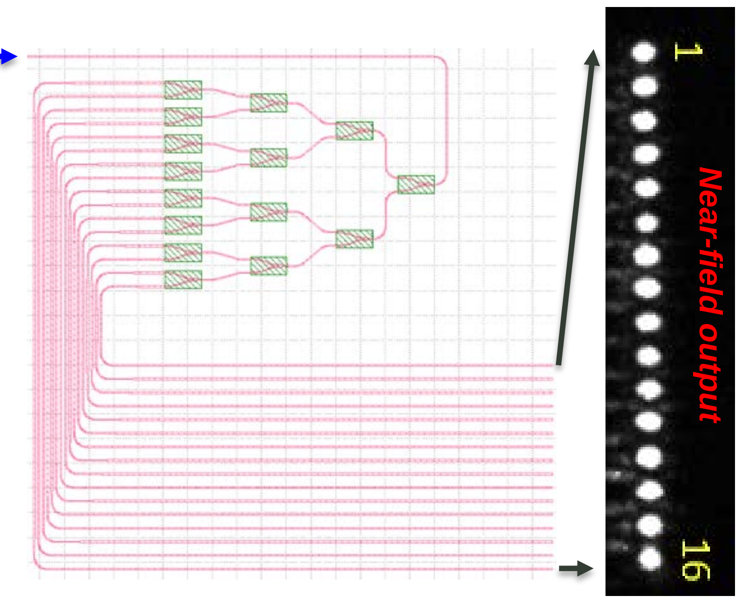
OPTICAL PHASED ARRAY (OPA)

- Optical analog of **Phased Array Radar** - an array of antennas which creates a beam of waves which can be electronically steered to point in different directions, without moving the antennas
- An OPA has multiple optical antenna elements that are fed equal-intensity coherent signals
- Variable phase control is used at each element to generate a far-field radiation pattern and point it in a desired location



www.analogphotonics.com/technology/

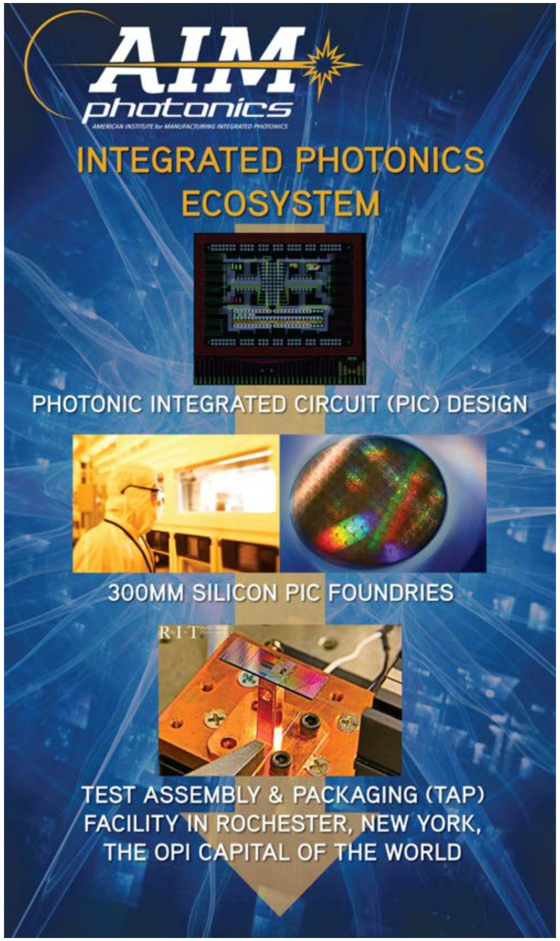




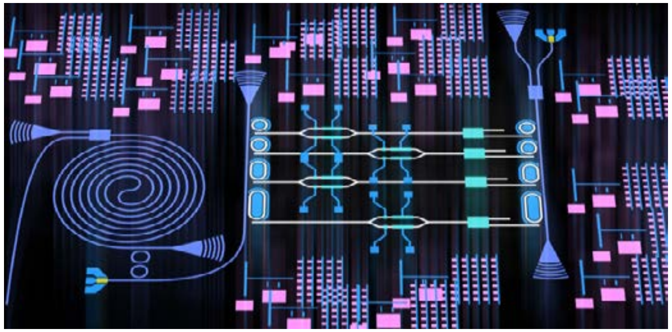
Optical arrays can provide a directional networking capability that enables stealth and anti-jam characteristics, but current devices do not meet demanding SWaP-C requirements.

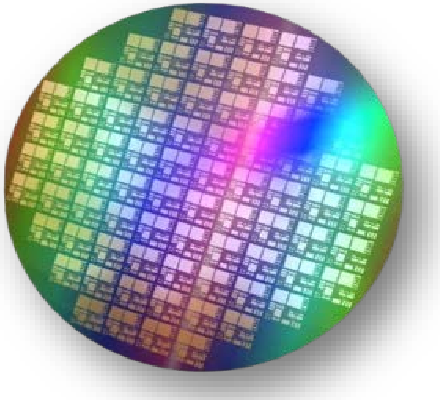
INTEGRATED PHOTONICS

Using an optical phased array is the solution;
Silicon integrated photonics is the enabling technology



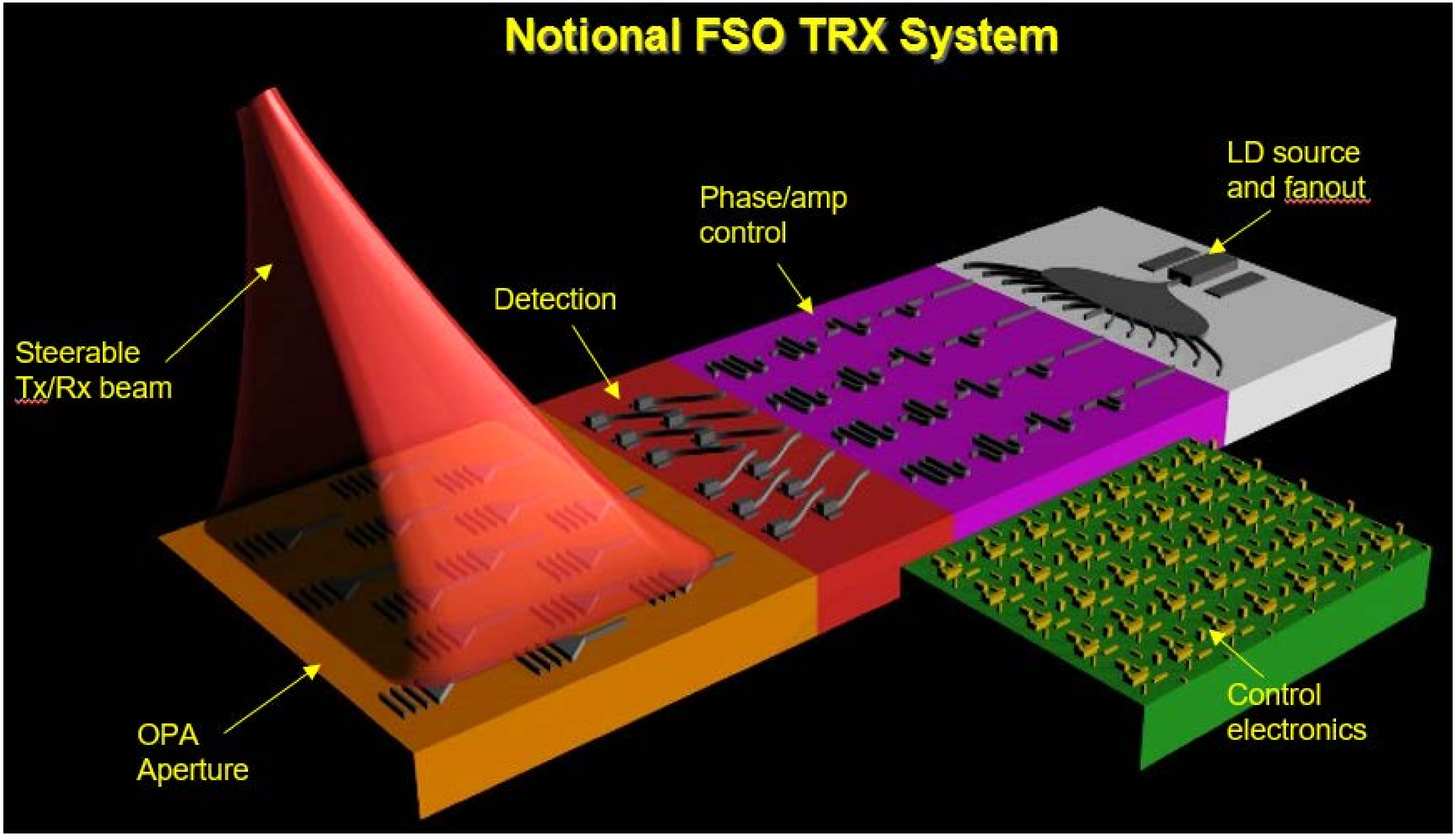
Photonic Integrated Circuits (PICs) are entire photonic *systems* on a chip





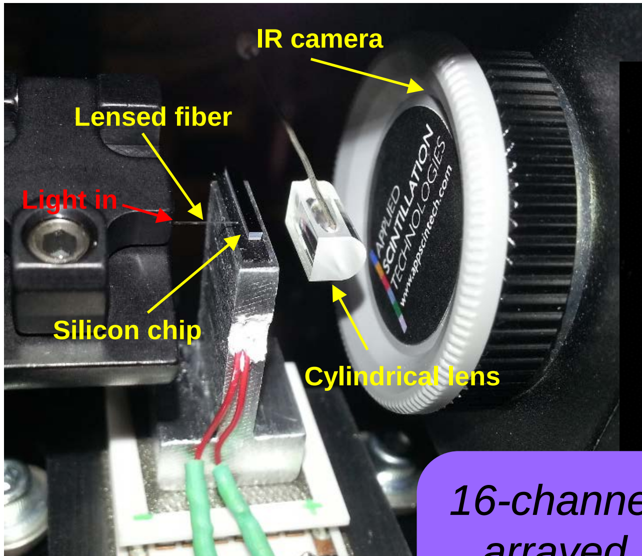
- Chip-scale integrated photonics is significantly lighter and smaller than bulk optics or RF systems with similar capability
- PICs may be batch fabricated, allowing very large quantities of flexible optical systems to be produced
- Integrated photonics tightly coupled with integrated silicon electronics offers very powerful backend processing and control
- AIM Photonics (U.S) integrated photonics manufacturing ecosystem expands upon a highly successful public-private partnership model (government, academia, industry) with open-access to world-class shared-use resources and capabilities

CHIP-SCALE OPA

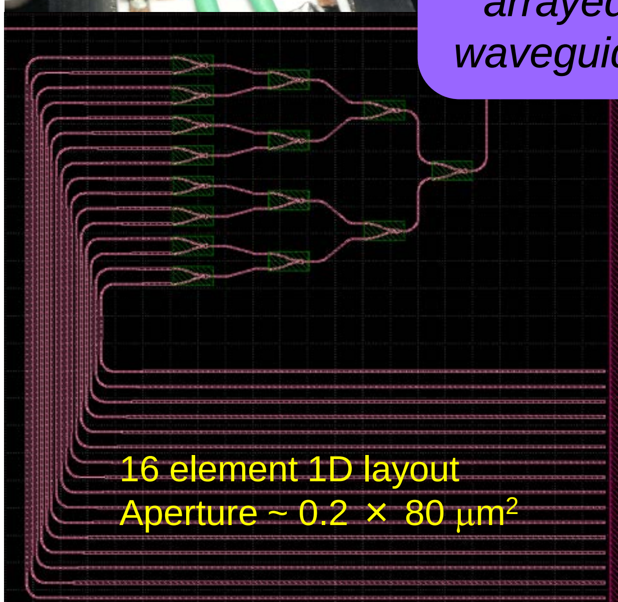


- Exploiting the advantages of PICs to develop OPAs that enable ad hoc free-space optical communication with a direct path to mass manufacturing

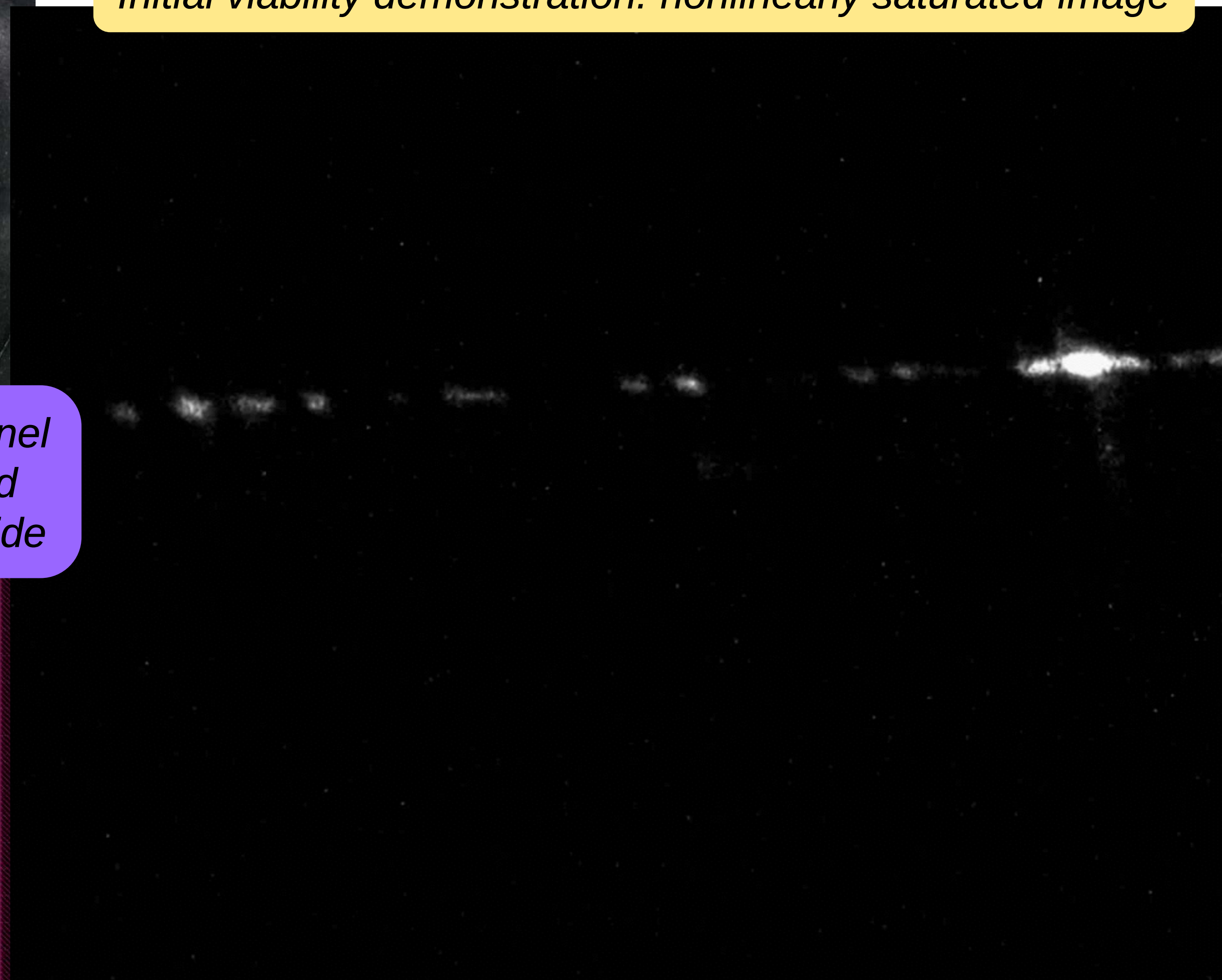
DEMONSTRATION MEASURED 1D SCAN



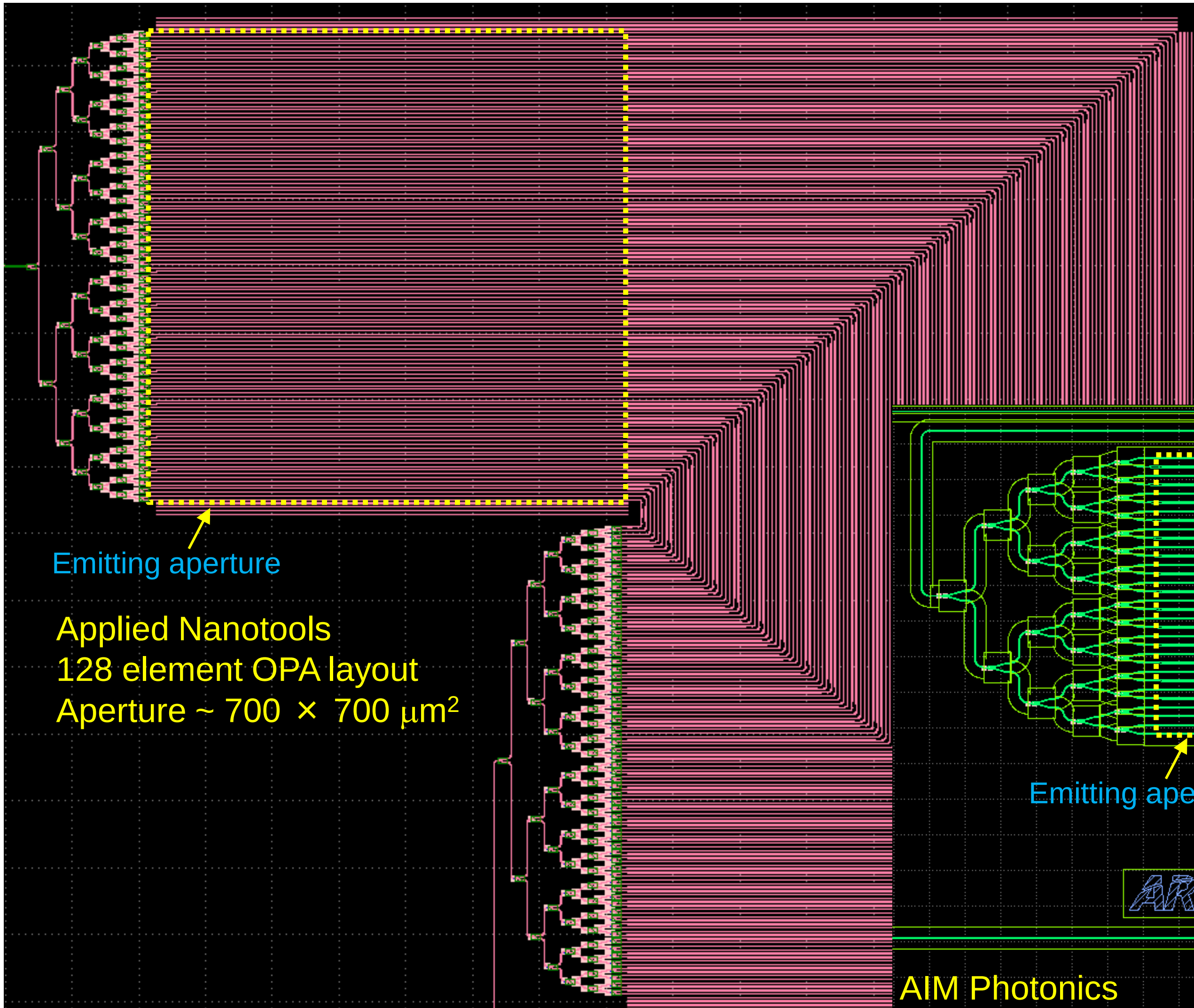
16-channel arrayed waveguide

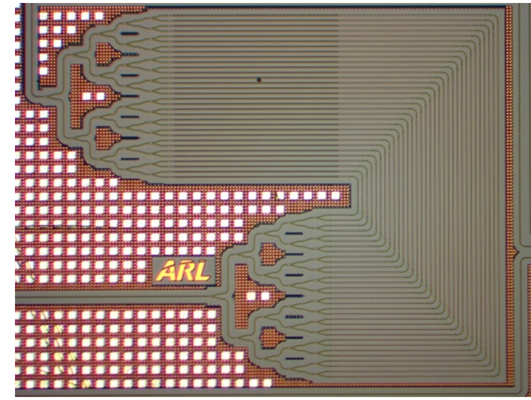


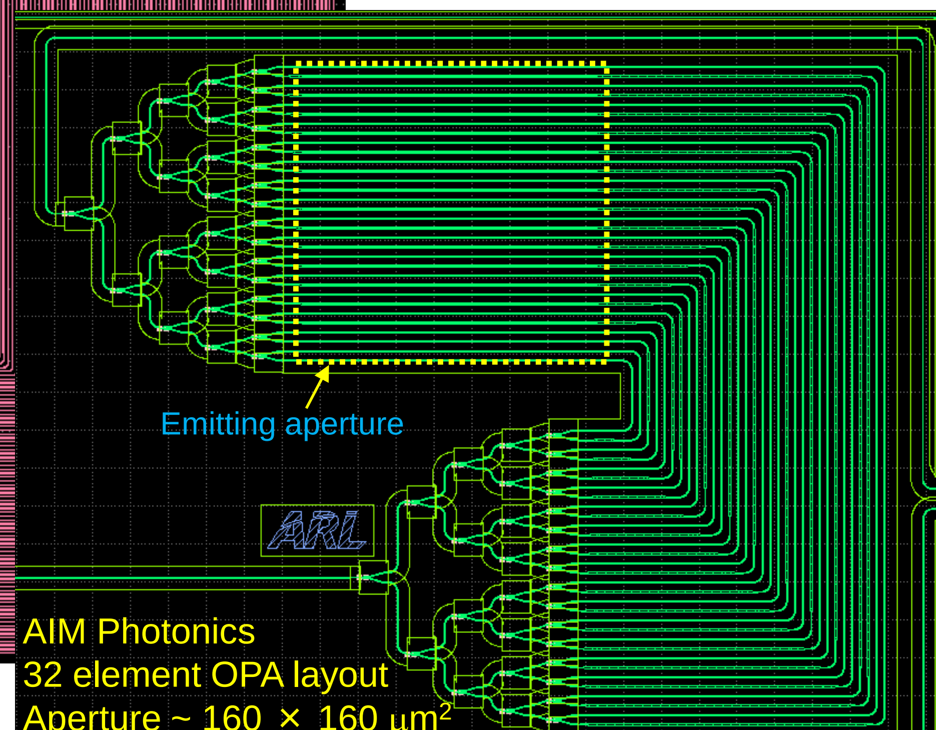
Initial viability demonstration: nonlinearly saturated image



2D DESIGNS

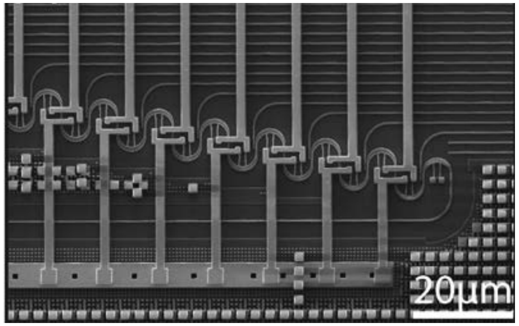

Emitting aperture
Applied Nanotools
128 element OPA layout
Aperture ~ 700 × 700 µm2


ARL


Emitting aperture
ARL
AIM Photonics
32 element OPA layout
Aperture ~ 160 × 160 µm2

RESEARCH

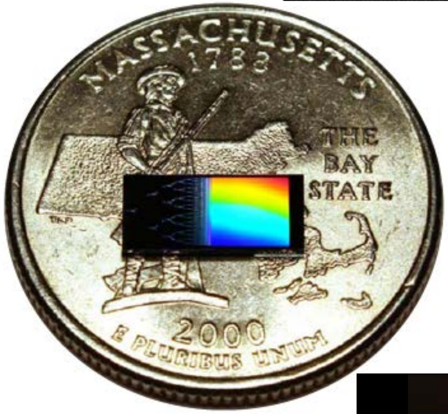
- Explore system design concepts to reach our beam forming goals (focusing on novel OPA emitter designs):
  - Prior PIC OPA research programs have proven viability of coherent beam steering by advancing PIC components
  - Address how best to shape beams to suite our FSO communication system goals by borrowing ideas from sparse radar phased array antennas
- Simulate, design, and test OPA chips fabricated using AIM Photonics' and Applied Nanotools' MPW fabrication services; supplementing these with in-house ARL fabrication as needed
- Packaging concepts being explored to investigate the limits of SWaP-C reduction
  - Establish packaging scheme in AIM Photonics' TAP
  - Develop electronics embedded in fab process
- Investigating SWAP impact on communication link distance



<u>OPA Engagement</u>

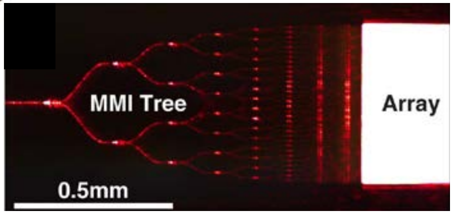
Prof. Mike Watts

- MIT professor + CTO of AIM + CEO of Analog Photonics (provided all of AIM's PDK components)
- Running an AIM OPA project
- Actively seeking automotive OEM commercialization
- Collaborating on AIM-compatible high-speed phase modulator designs



ARL-NE Melissa Flagg

- Introduced to OPA program and is willing to provide endorsement support
- Open to give ARL NE support of SBIR, STTR if coordinated with ARO
- Looking to engage Prof. Watts locally in Boston and is attracted to Academia-Industry-Government collaboration through ARL Open Campus



BACK UP

CHALLENGES

- Biggest challenge is controlling the phase of every element. Control can be effected by:
  - Fabrication variation / process non-uniformity.
  - Thermal crosstalk / waveguide width.
- Engineering effort for longer distance – more elements to control.
  - UAV-UAV distances easier than longer range.
  - Long-range requires OPA beams to have a small diffraction angle and high power.

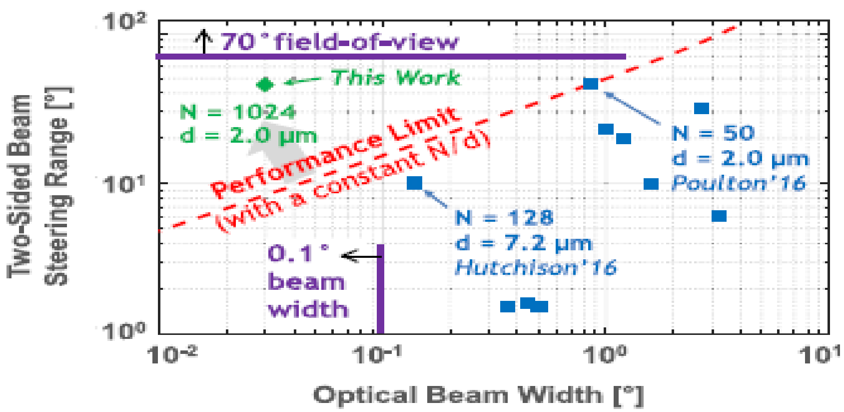


Fig. 2. Design tradeoff between beam-steering range and beamwidth for a constant N/d, where N is the number of antennas and d is the antenna pitch in a uniform optical phased array.

CHUNG *et al.*, IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 53, NO. 1, JANUARY 2018.

PIC WAVELENGTHS

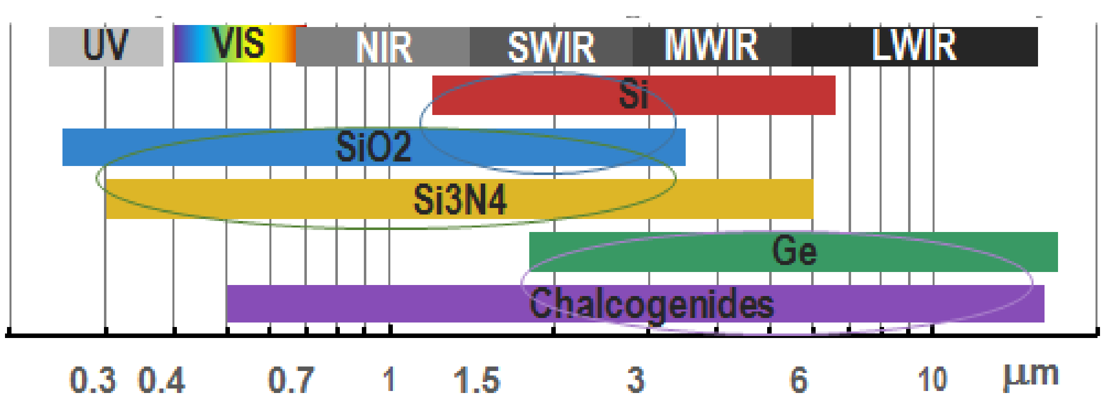
Many PIC applications may be <u>wavelength agnostic</u>

- With electrical IO

But for those that are not…

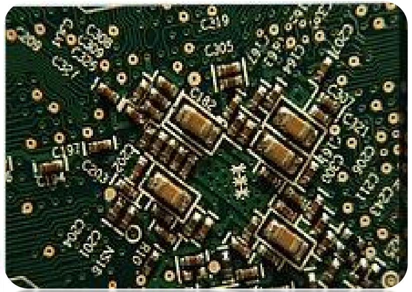
- **Si core / SiO_2 clad (1200 - ~3000 nm)**
  - Passives, modulators, and detectors – <u>now</u>
  - Sources – in package: <u>now</u>, on-chip: <u>1 yr</u>
- **Si_3N_4 core / SiO_2 clad (~400 - ~3000 nm)**
  - Passives, modulators, and detectors – <u>now</u>
  - Sources – in package: <u>now</u>, on-chip: <u>1-2 yr</u>
- **Ge core / Si clad (~2 - ~14 um)**
  - Passives, modulators, and detectors – <u>5-8 yrs</u>
  - Sources – in package: <u>3 yrs</u>, on-chip: <u>5 yrs</u>

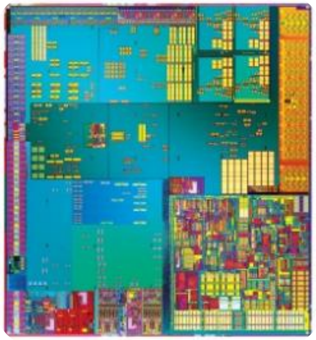
No industry to push InP substrate PIC technology mass production



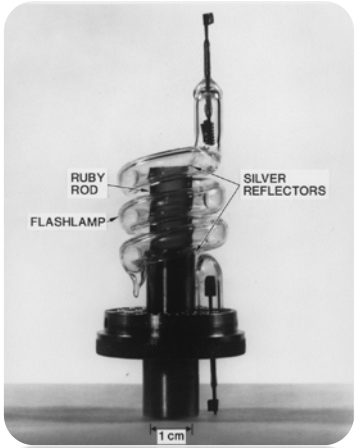
PROGRESSION OF ICS AND PICS

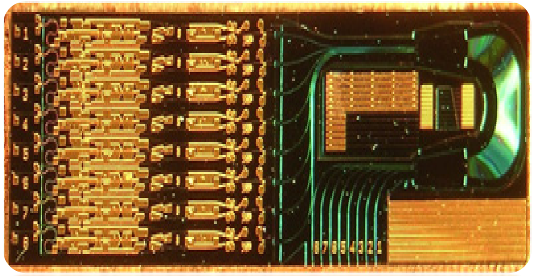
The *revolutions* provided by electronic ICs …

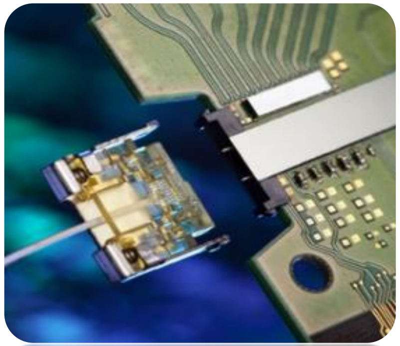




Is being mirrored by PICs …



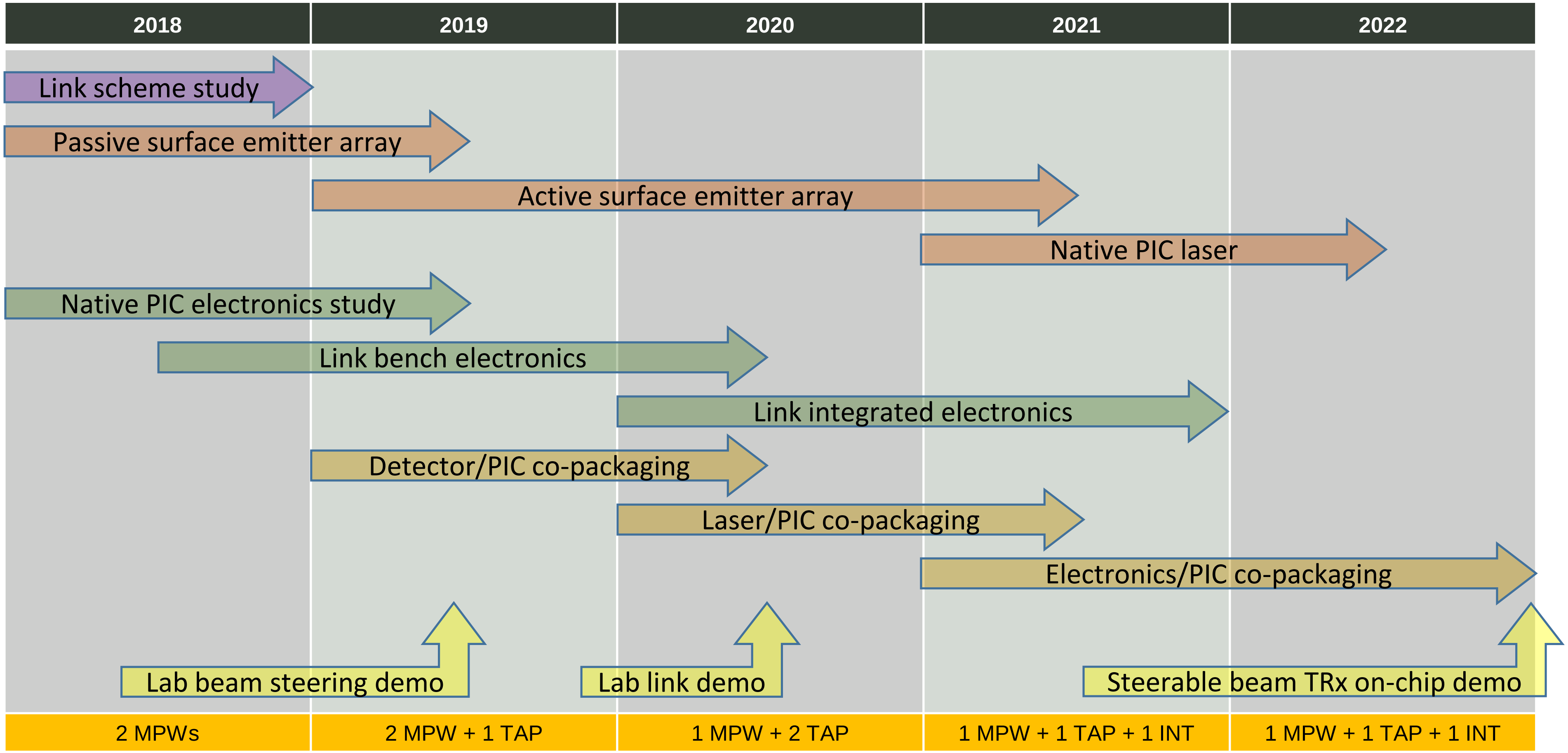




MAIN INTEGRATED OPA MECHANISMS & SHORTCOMINGS

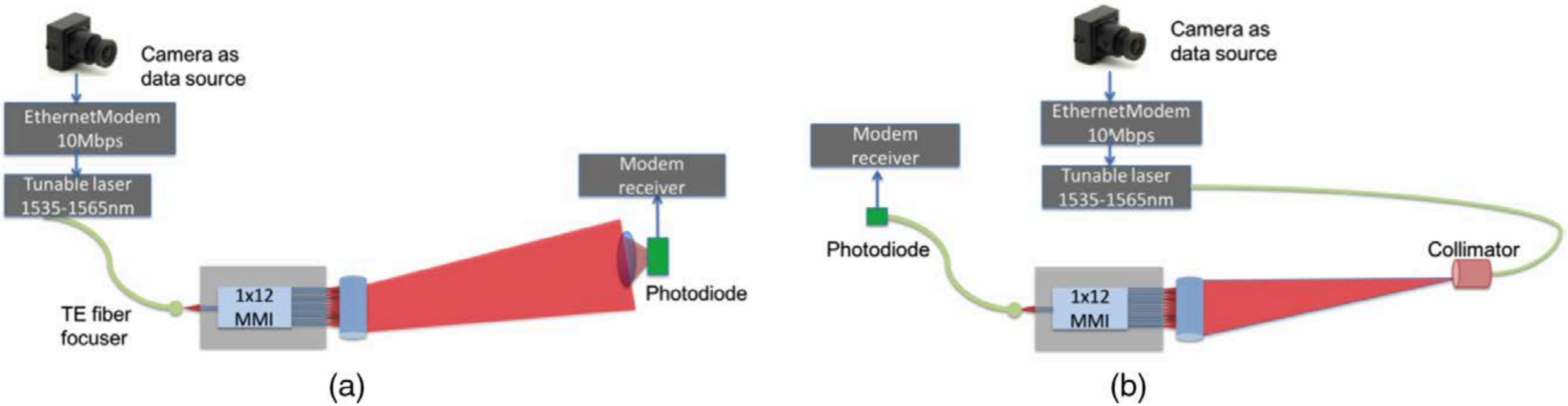
- Phase shifts generated using waveguides with heaters to provide index change through Thermo-Optic effect.
  - This provides 1-D scanning with relationships of beam scanning range & beam divergence related to N – number of Elements and d pitch of Elements
- 2-D scanning is nominally achieved using wavelength tuning combined with grating couplers – this eliminates Tx/Rx OPA.
- Others have attempted 2-D steering through thermo-optic heating of grating output coupler – this steering gives less than 10 deg.
- Other methods such as charge injection have been used to explore alternate means to alter index and thus phase.
- Recently attempts have been made to densify the arrays and have been reasonably successful (N=1024, d=2 microns).
- Steering angle ranges of 45-50 degrees full width have been demonstrated.
- Beam divergence of 0.5 mrad has been demonstrated.

NOTIONAL OPA SCHEDULE



Timeline is dependent on investment and can be shortened significantly, as we are labor and MPW run-cost limited, not platform limited.

NRL OPA FSO data link in (a) transmit and (b) receive mode.



PIC Applications Fulfill Modernization Priorities

Examples of existing programs directed at supporting CSA priorities using Integrated Photonics

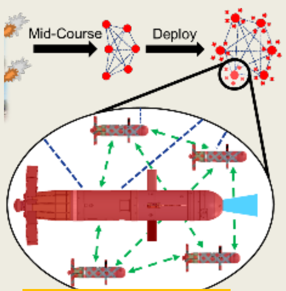
Optical Phased- Array for communication & Ranging

- *Long-Range Precision Fires (LRPF)*
- *Army Network*
- *Next Generation Combat Vehicles (NGCV)*

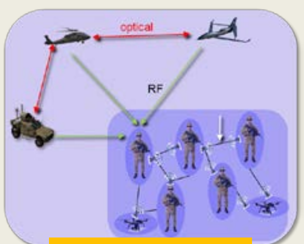
Wearable Performance Monitoring System

- **Solider Lethality**

ERAs



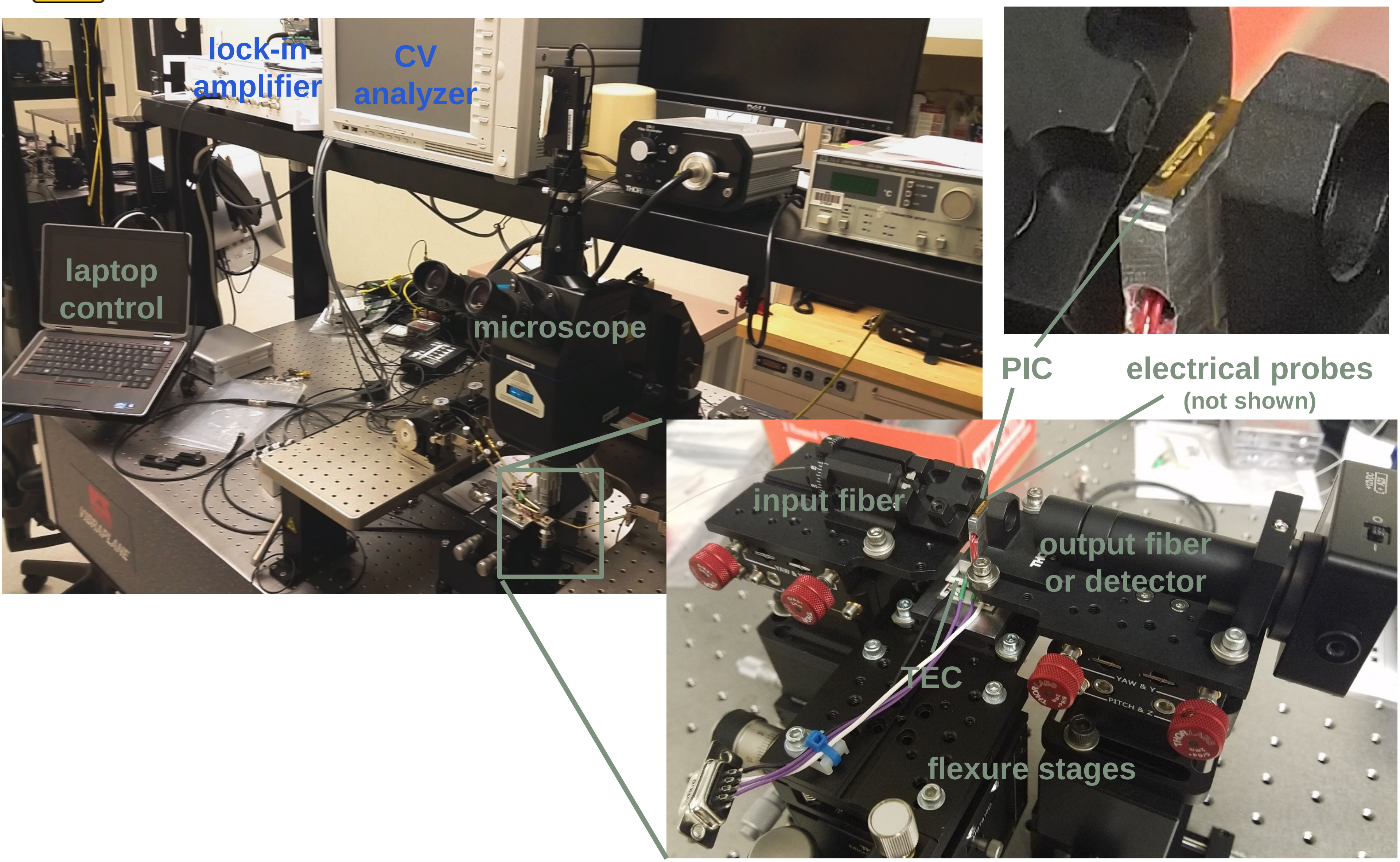
DCECE



CETCE

HAT

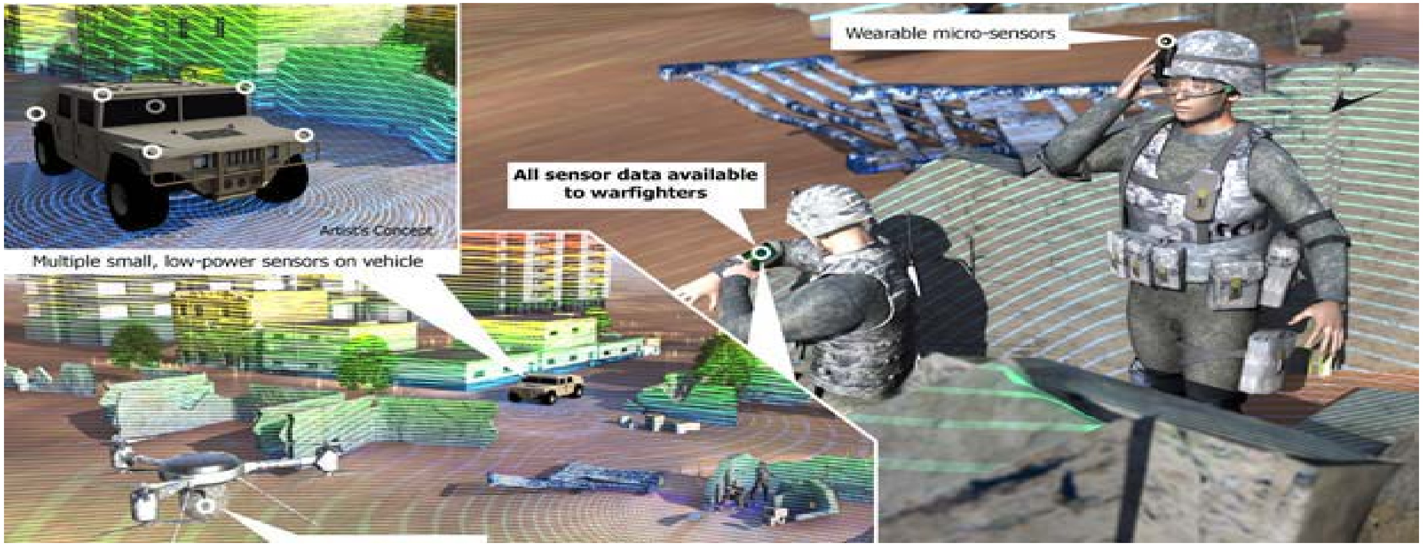
GENERAL PIC TEST SETUP



DARPA PROGRAMS

Short-range Wide-field-of-view Extremely agile Electronically steered Photonic EmitteR (**SWEEPER**)

Electronic-Photonic Heterogeneous Integration (**E-PHI**)



Pushed SOA in integrated photonic beam steering from ~ 2011-present main performers were Massachusetts Institute of Technology; the University of California, Santa Barbara; the University of California, Berkeley; and HRL Laboratories.