USC University of Southern California

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Monolithic Optical Phased Array Transceiver in Commercial Foundry CMOS SOI Process

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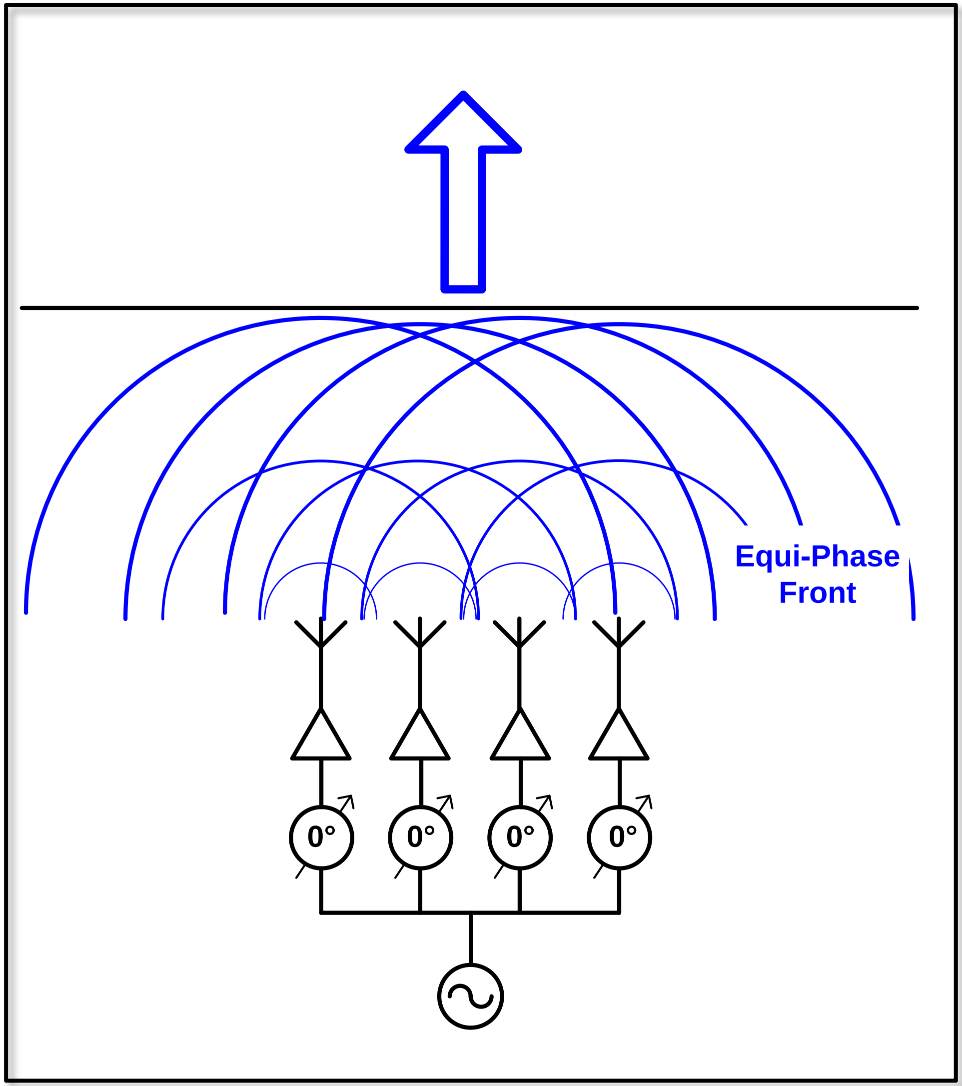
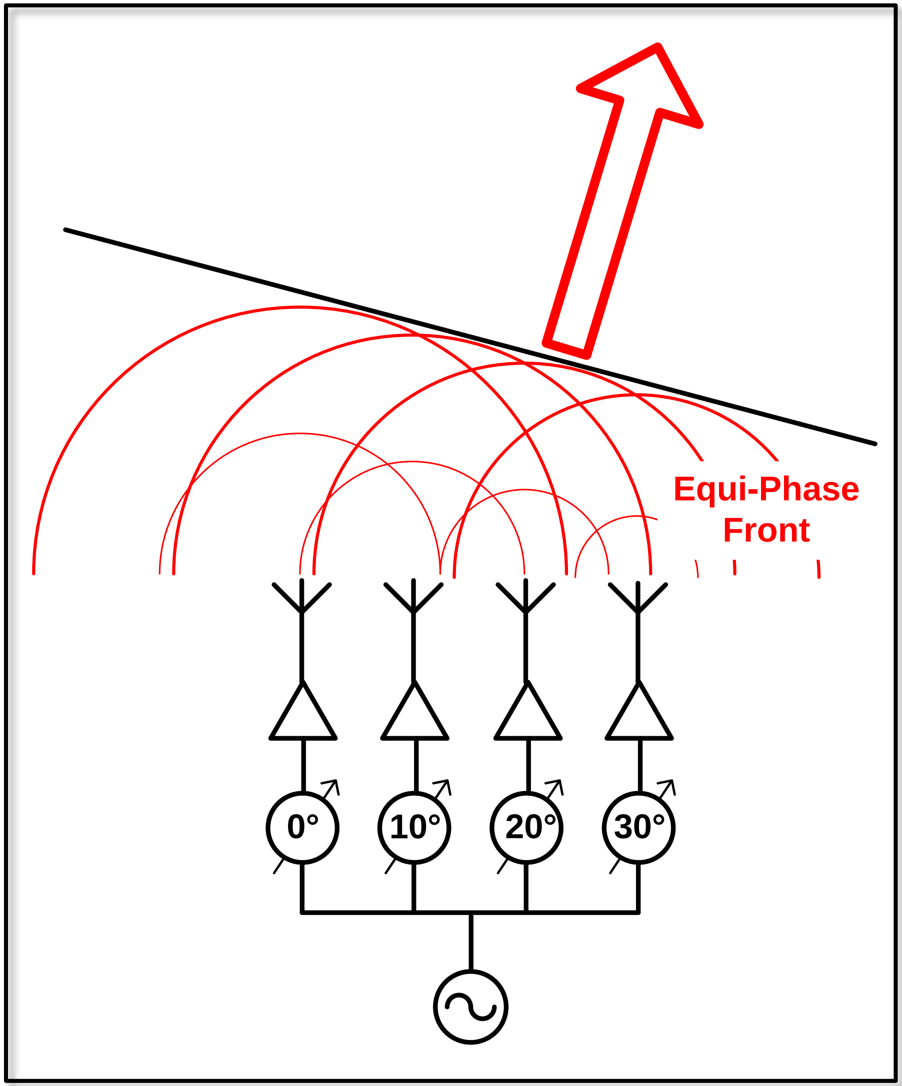
USC Viterbi
School of Engineering

Outline

- Radio Frequency Phased Arrays
- Optical Beam Steering
- Monolithic Optical Phased Array Transceiver in SOI CMOS
- Conclusions

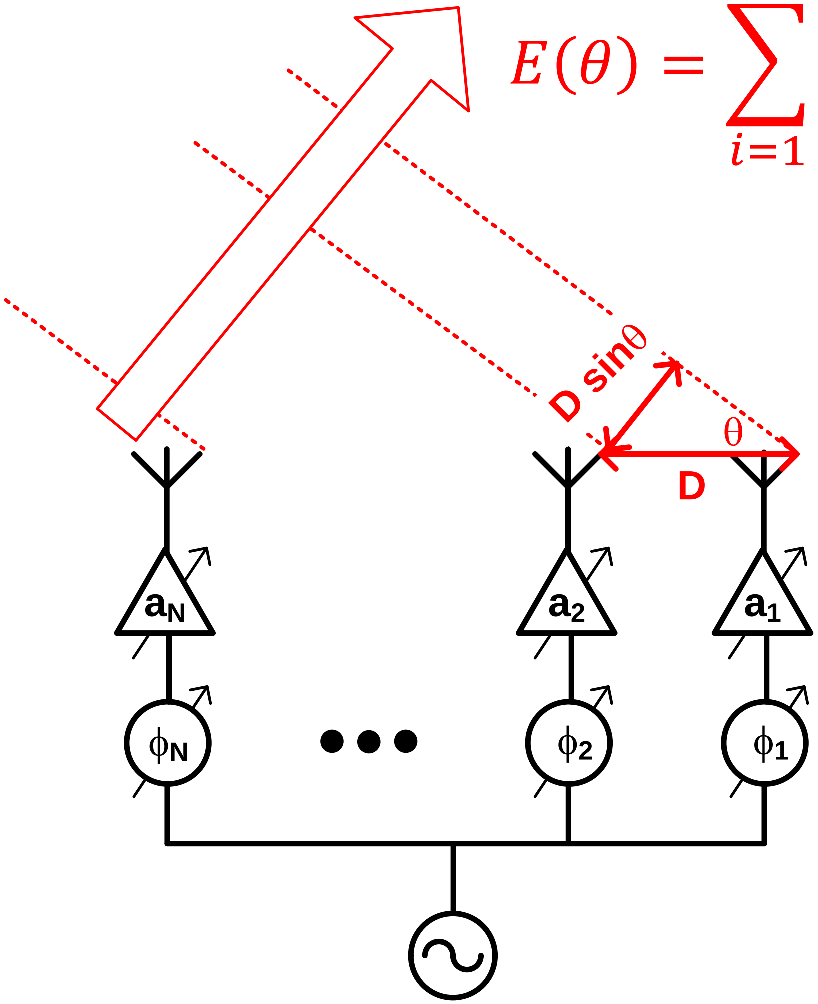
Phased Array Principle





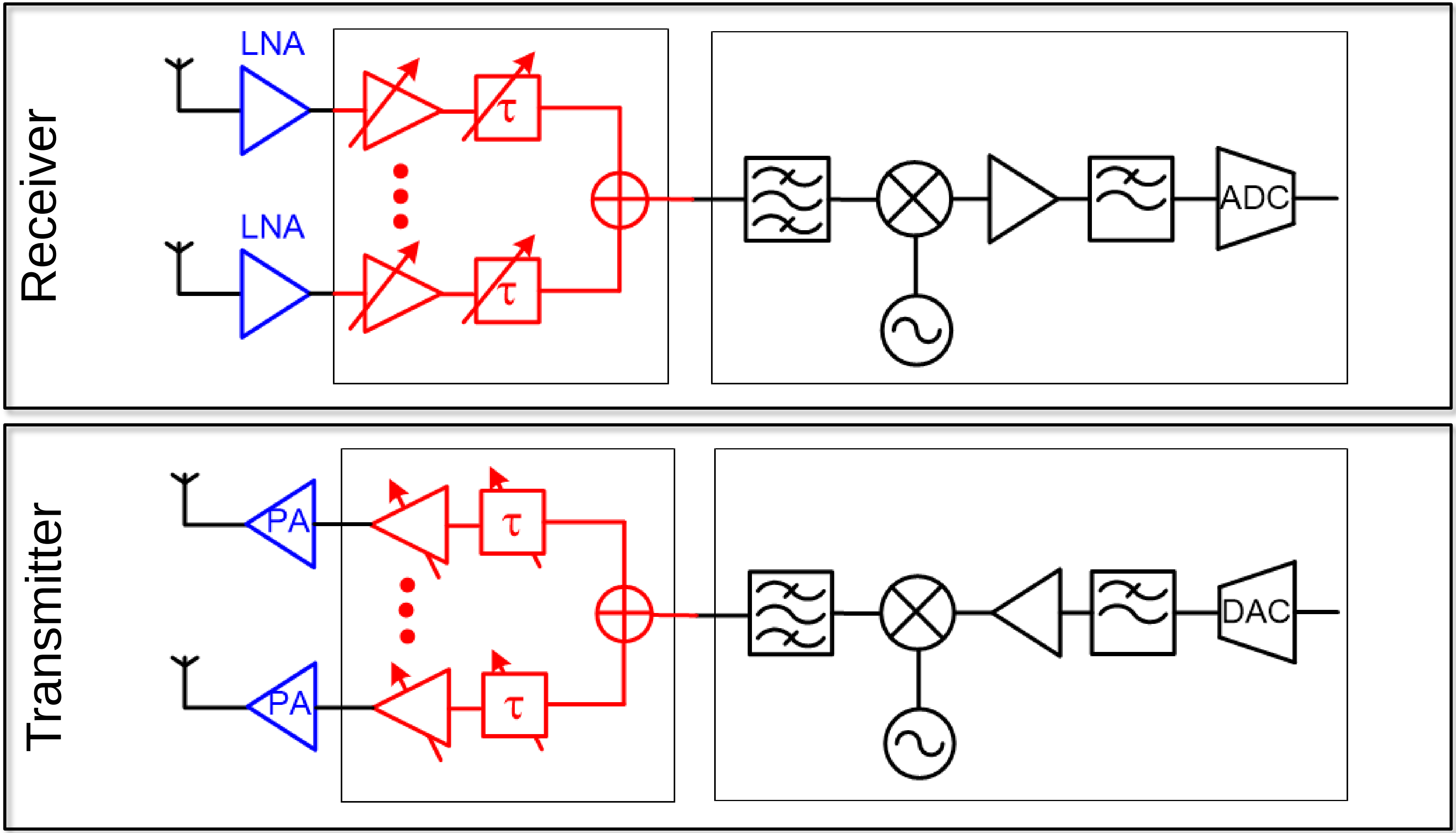
Far Field Calculation in Phased Arrays

$$E(\theta) = \sum_{i=1}^{N} a_i e^{-\left(2\pi i \frac{D}{\lambda} \sin\theta + \phi_i\right)}$$

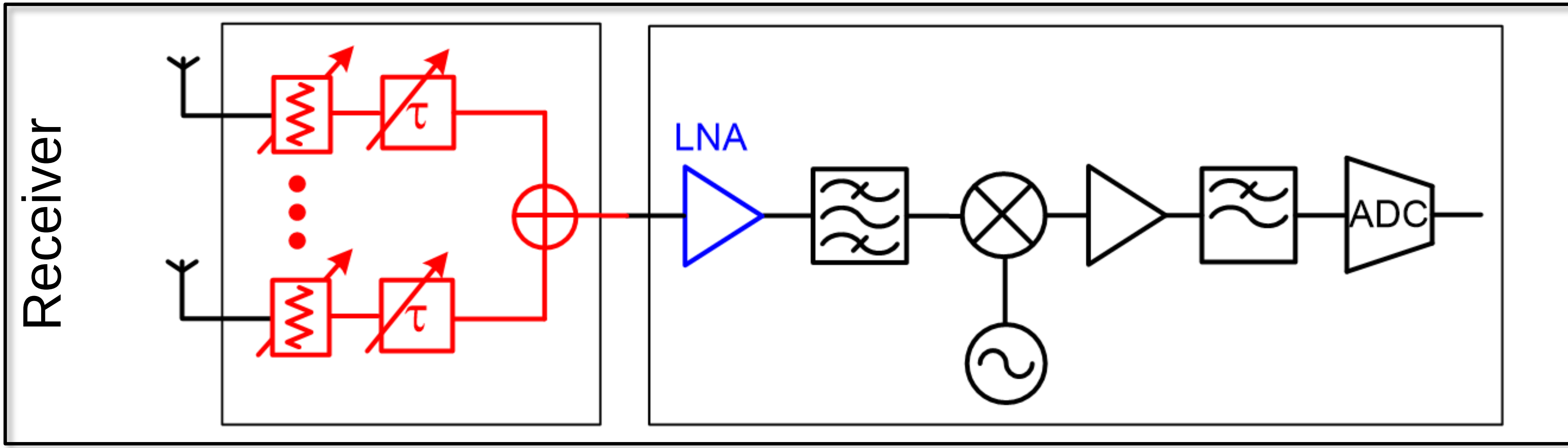


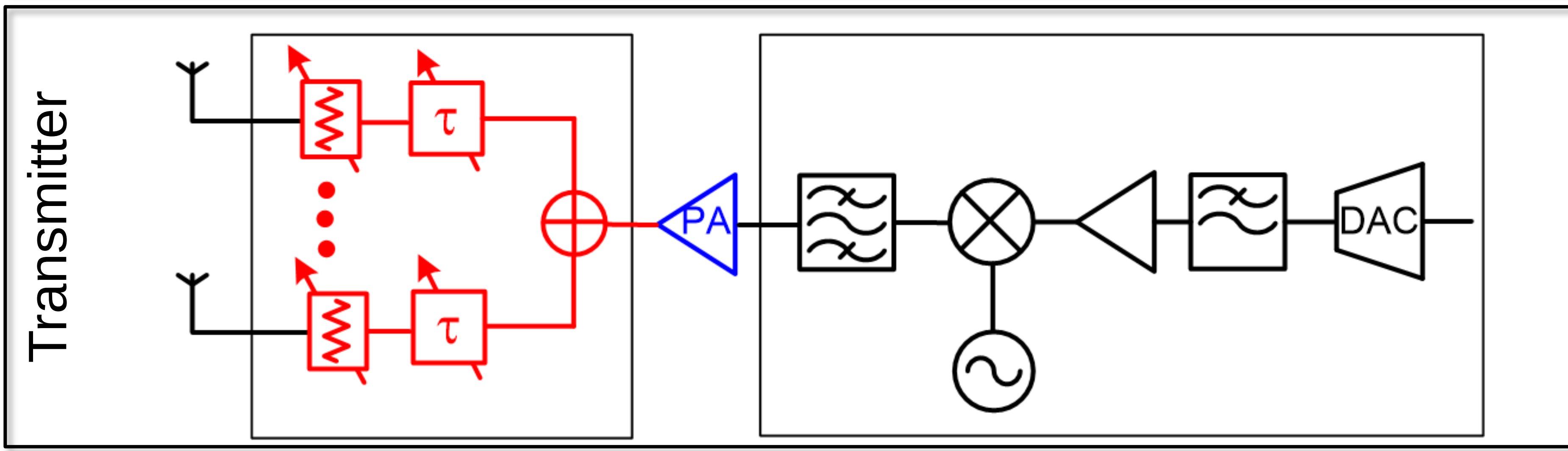
- ✓ Typically, $D = \lambda / 2$
- ✓ a_i & ϕ_i define a *spatial filter* response at ω_o. The spatial filter can have one or more peaks, nulls, etc. at various directions.
- ✓ Generally, beam-width (for the peaks of these spatial filters) is proportional to $(N \times D / \lambda)$
- ✓ From reciprocity, radiation patterns (spatial filters) are similar in TX and RX.

Delay-and-Sum RF Beam-Forming
aka “Timed Array”



Passive Delay-and-Sum RF Beam-Forming





Approximating Time Delay with Phase Shift

$$\boxed{a(t)\cos\big(\omega t + \varphi(t)\big)}$$

True time delay different between different antenna elements of the phased array $\longrightarrow$ $\boxed{\tau}$

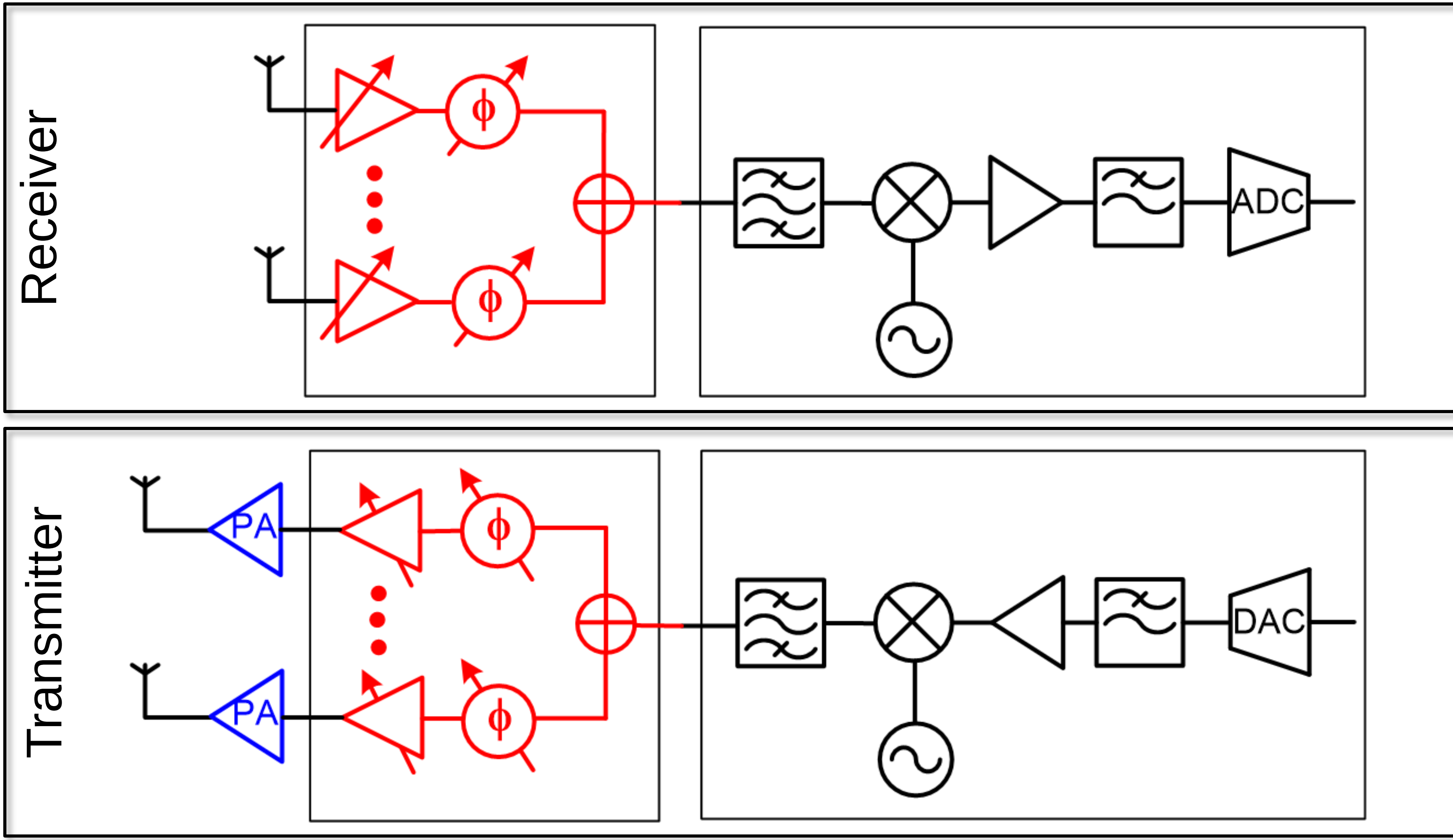
$$\boxed{a(t-\tau)\cos[\omega(t-\tau) + \varphi(t-\tau)]}$$

Narrowband assumption: amplitude & phase modulations are much slower compared with 1 / τ. $\longrightarrow$ $\boxed{\sim}$

$$\boxed{a(t)\cos[\omega t + \varphi(t) - \omega\tau]}$$

Delayed version of a generic narrowband modulated waveform can be approximated with a phase shifted version of the waveform.

Narrowband RF Beam-Forming
aka "Phased Array"



First Antenna Array: 1909

"It had always seemed most desirable to me to transmit the waves, in the main, in one direction only." *Karl Braun Nobel Lecture, December 11, 1909.*

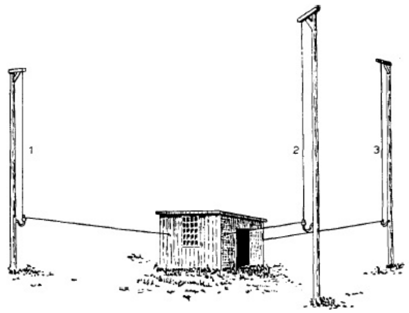


Fig. 13.

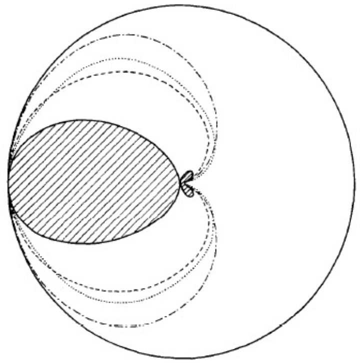


Fig. 14.

Karl Ferdinand Braun

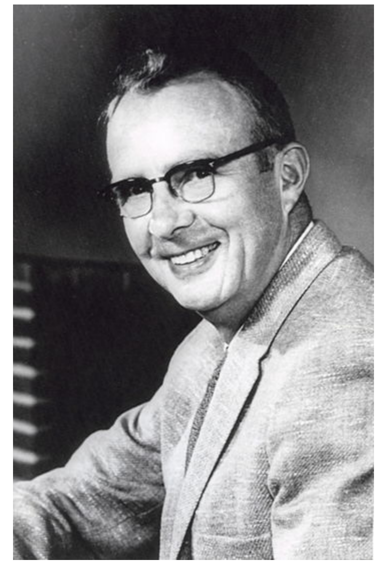
1909 Nobel Prize for Physics
with Guglielmo Marconi

"*contributions to the development of wireless telegraphy*"

First Phased Array Radar: 1943

B-29 Superfortress with AN/APQ-7 EAGLE

6 meter long array of 250 transmitting dipoles at X band placed in the aircraft's leading edge wing capable of electronically steering the beam over an 60° angle in front of the aircraft.



Luis Walter Alvarez

1968 Nobel Prize for Physics

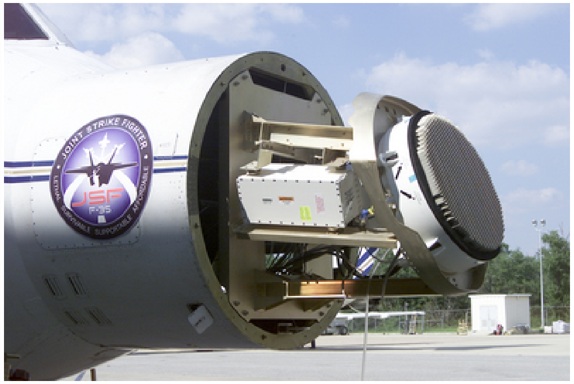
Developed the first Phased Array Radar, AN/APQ-7 EAGLE, at MIT's newly established Radiation Laboratory in 1943.

Modern RF Phased Array Radars

Electronically Scanned Arrays (ESA)

F35 Lightning

AN/APG-81



0.7m Diameter

1,200 Elements

X Band (8 – 12.5 GHz)

Tracking 23 aerial targets

GaAs T/R Modules

PATRIOT

Phased Array Tracking Radar to Intercept On Target

2.44m Diameter

5,161 Elements

C Band (4 – 8 GHz)

Tracking of 100 targets

Iron Dome

Scalable Dimensions

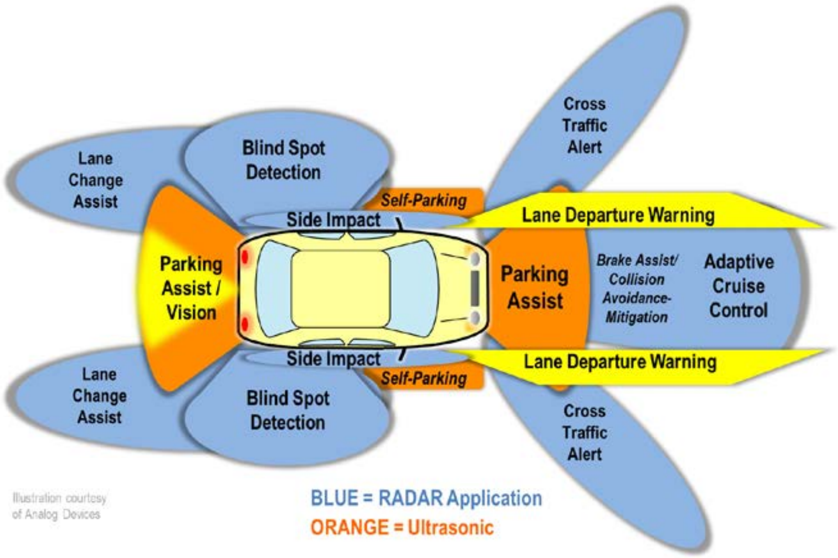
Varying number of elements

S Band (2 – 4 GHz)

Tracking of 1200 targets

Modern Commercial RF Phased Arrays

Automotive Radar



Frequency Band:	76 – 77 GHz
Frontend Tech.:	GaAs or SiGe
Manufacturers:	Delphi, Bosch, …

Wireless Connectivity

Frequency Band:	59 – 64 GHz
Technology:	CMOS
Manufacturers:	SiBeam, Wilocity, …

The “Moore’s Law” Paper

Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

The author

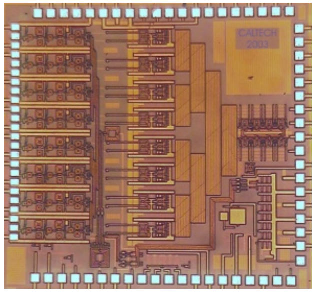
Dr. Gordon E. Moore is one of the new breed of electronic engineers, schooled in the physical sciences rather than in electronics. He earned a B.S. degree in chemistry from the University of California and a Ph.D. degree in physical chemistry from the California Institute of Technology. He was one of the founders of Fairchild Semiconductor and has been director of the research and development laboratories since 1959.

Electronics, Volume 38, Number 8, April 19, 1965

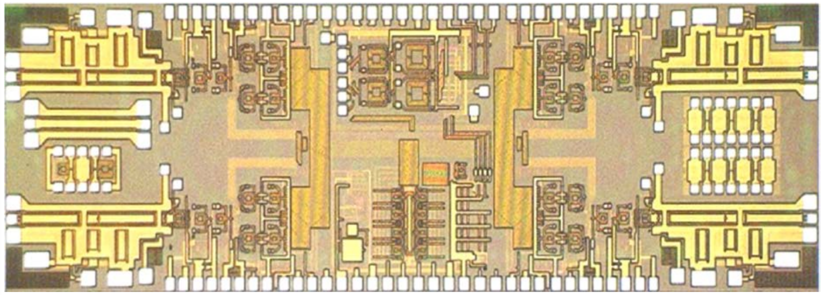
The Same Paper Predicts: Chip Scaled Phased Array Radars

Even in the microwave area, structures included in the definition of integrated electronics will become increasingly important. The ability to make and assemble components small compared with the wavelengths involved will allow the use of lumped parameter design, at least at the lower frequencies. It is difficult to predict at the present time just how extensive the invasion of the microwave area by integrated electronics will be. The successful realization of such items as phased-array antennas, for example, using a multiplicity of integrated microwave power sources, could completely revolutionize radar.

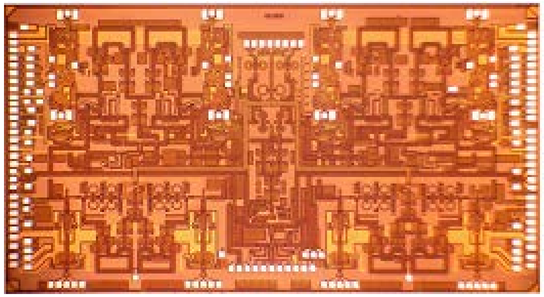
Early University Demonstrations (2003 – 2008)



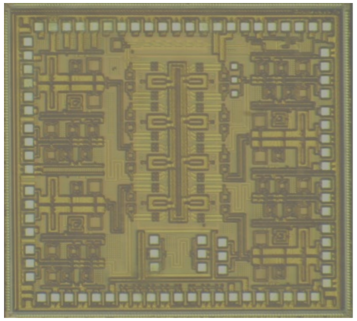
8-Ch 24-GHz RX
180nm SiGe HBT
[Caltech 2004]



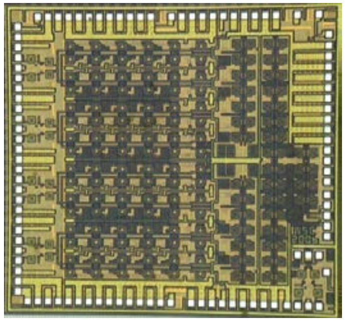
4-Ch 24-GHz RX
180nm SiGe HBT
[Caltech 2005]



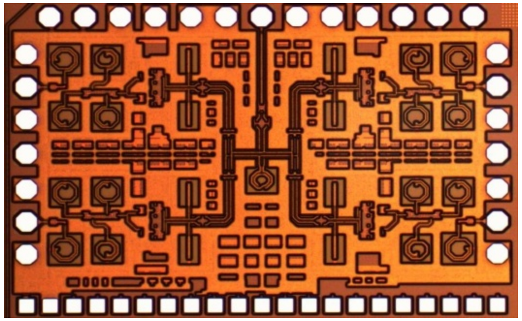
4-Ch 77-GHz RX
130nm SiGe HBT
[Caltech 2006]



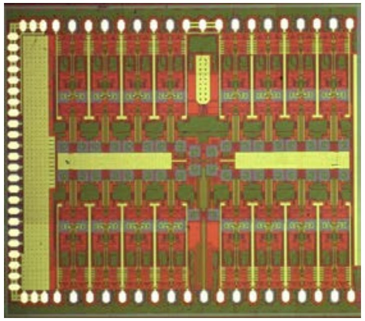
4-Ch 24-GHz TX+RX
130nm CMOS
[USC 2006]



4-Ch 1-15 GHz RX FE
130nm CMOS
[USC 2007]

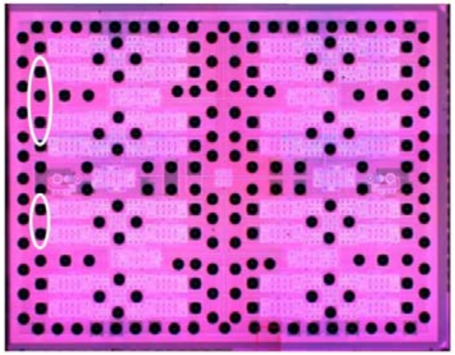


4-Ch 24-GHz RX FE
130nm CMOS
[UCSD 2008]

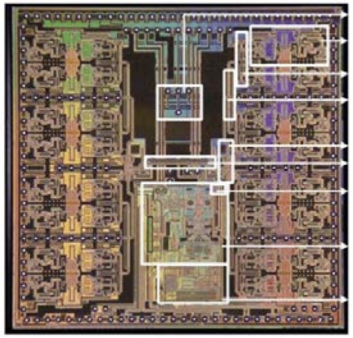


16-Ch 45-GHz TX FE
130nm SiGe HBT
[UCSD 2008]

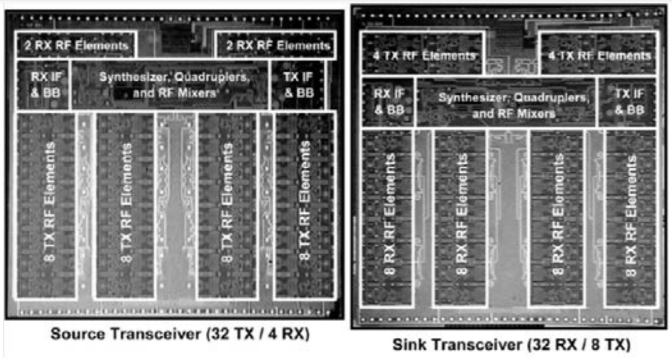
Representative Industry Demonstrations (2010 – 2014)



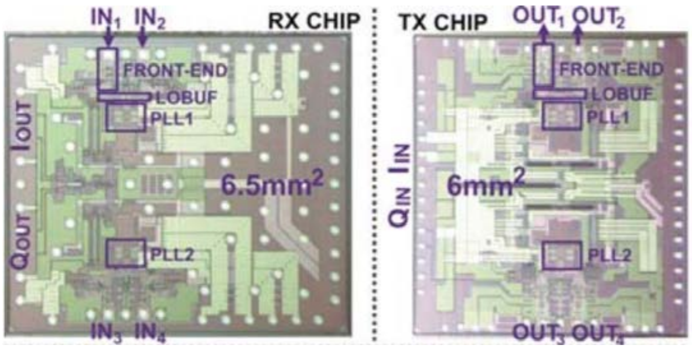
32-Ch 60-GHz Transceiver
90nm CMOS
[Intel 2010]



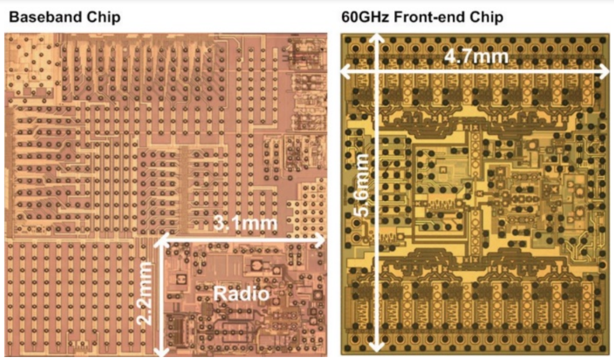
16-Ch 60-GHz RX
130nm SiGe HBT
[IBM 2010]



32-Ch 60-GHz Transceiver
65nm CMOS
[SiBeam 2011]



4-Ch 60-GHz Transceiver
40nm LP CMOS
[IMEC 2013]



16-Ch 60-GHz Transceiver
40nm LP CMOS
[Broadcom 2014]

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- Optical Beam Steering
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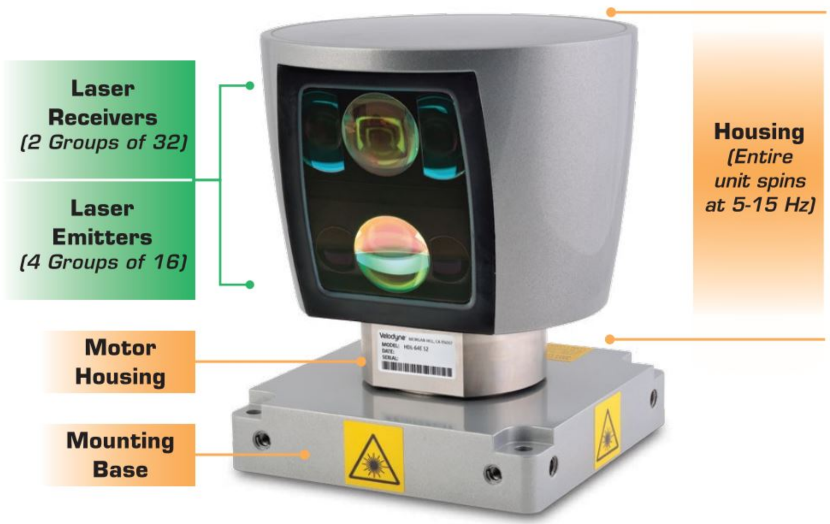
Optical Beam Steering Applications

LIDAR



64 Lasers / Detectors

Spin Rate: 300 – 900 RPM

Unit Cost: ~$85,000 (Velodyne HDL-64E)

Used in Google Self-Driving Cars

Laser Barcode Scanner

Mechanically Rotating Mirrors

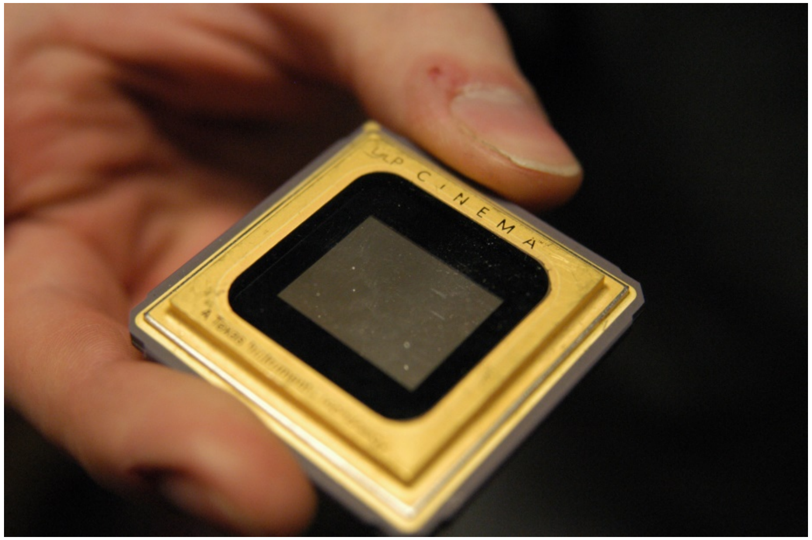
Scan Rate: 40 SPM

Unit Cost: ~$100

Used in Retail

Optical Beam Steering Applications

Digital μ-Mirror Device



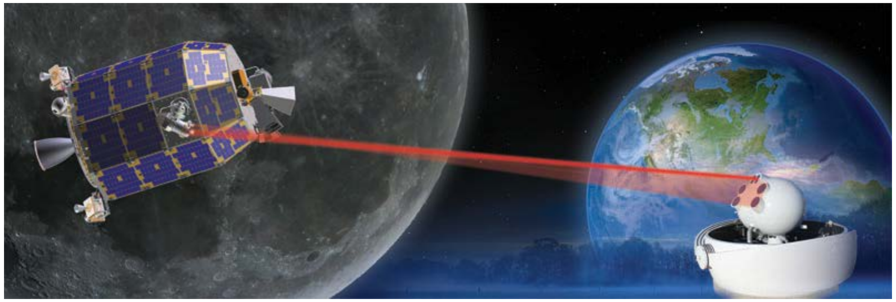
> 10^6 Rotatable Micro-Mirrors

ON/OFF Switching Speed: ~ 50 KHz

Unit Cost: ~$50

Used in Digital Light Processors (DLP)

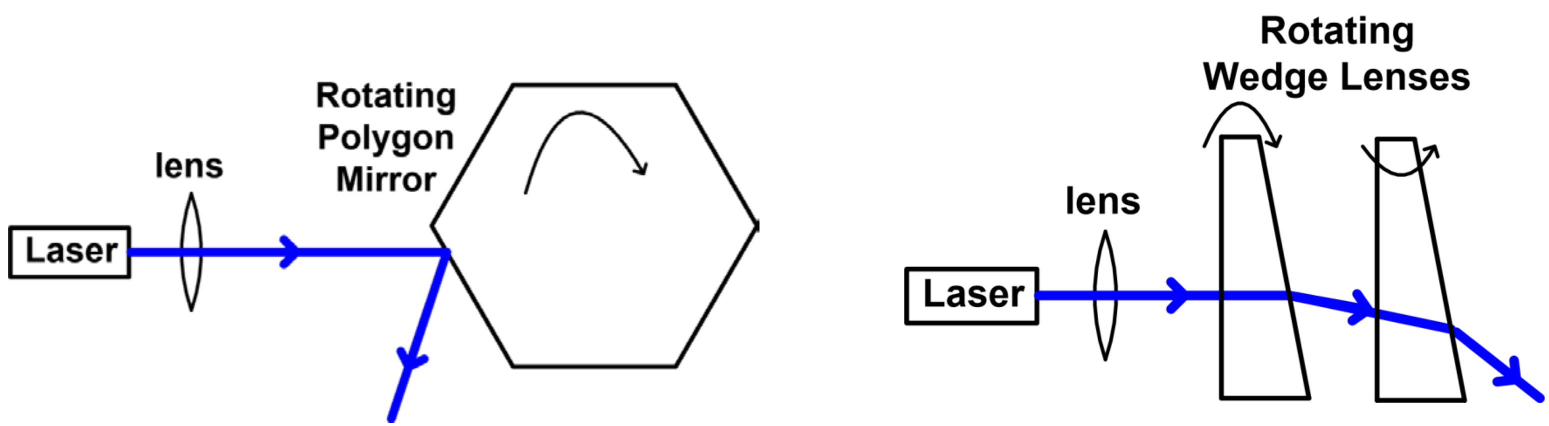
Free Space Optical Communications



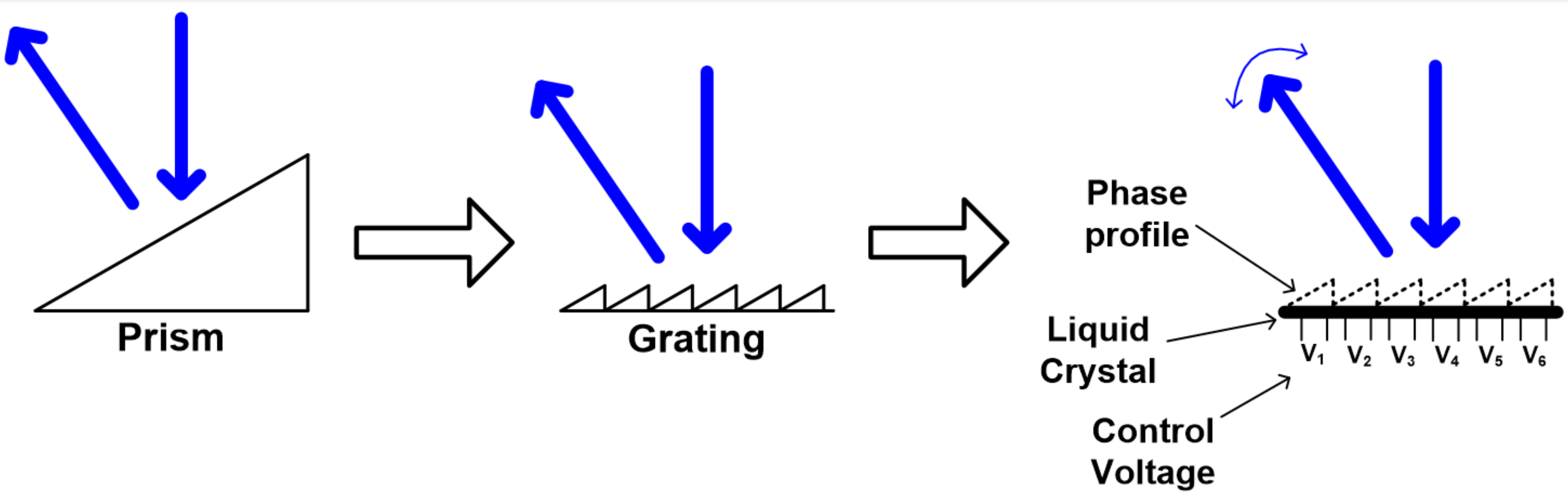
Mechanically steerable mirrors for automatic tracking

Conventional Optical Steering Methods

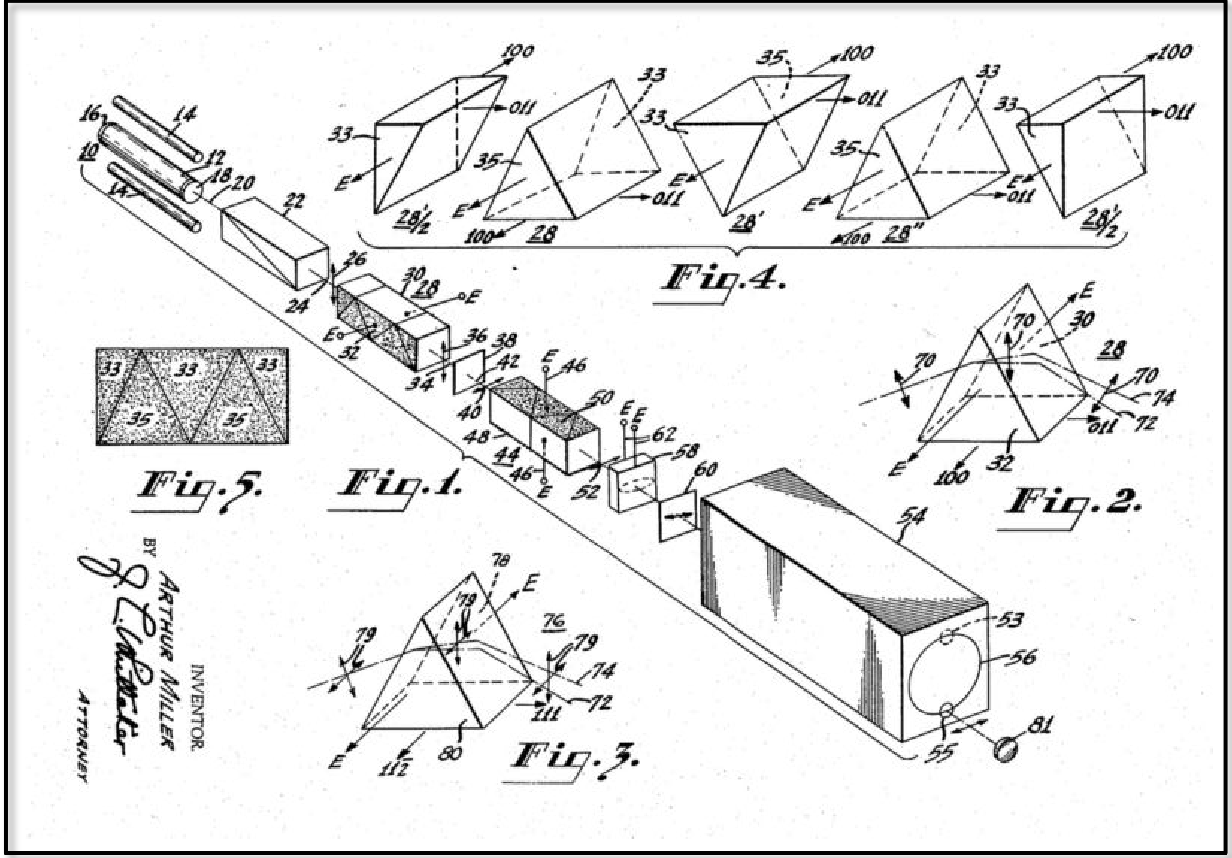
Rotating Optics



Liquid Crystal



Non-Mechanical Laser Beam-Steering
RCA Corp., 1963



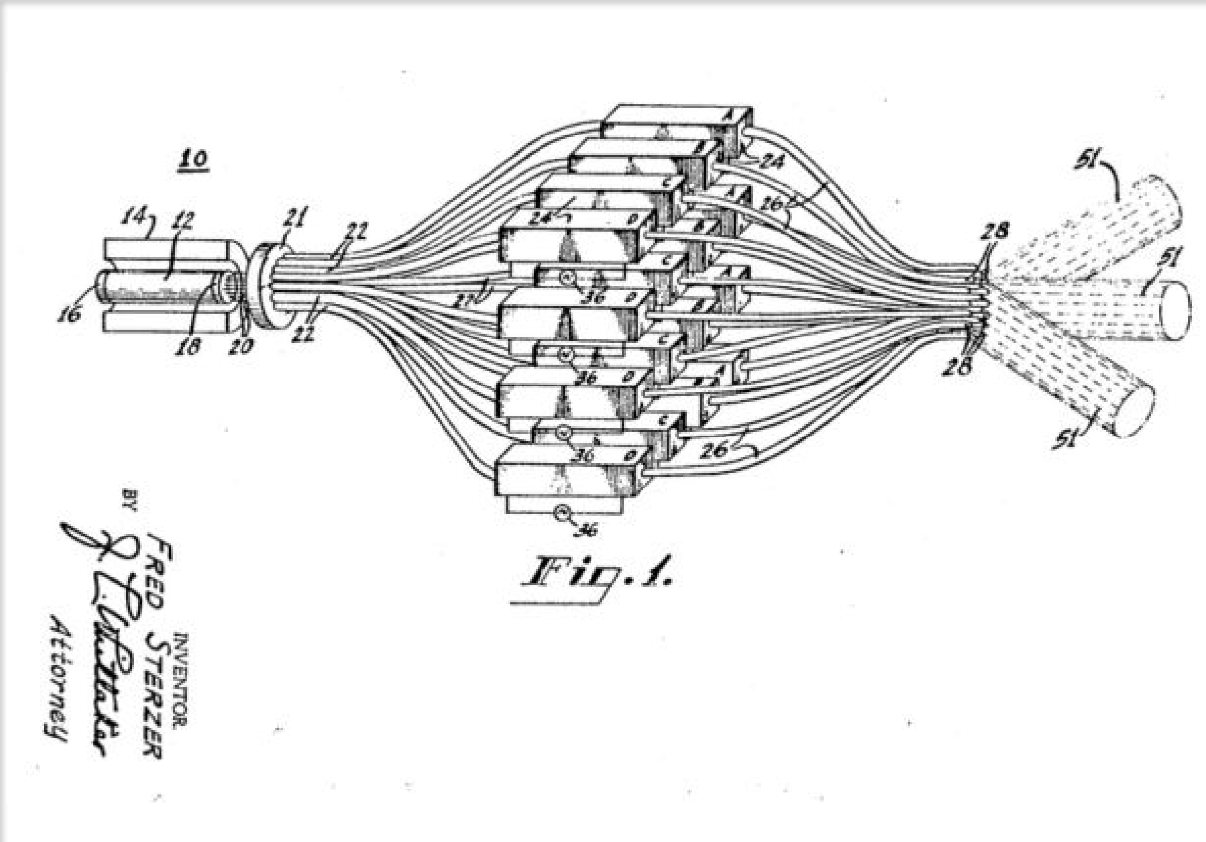
It has been suggested that a collimated light beam, such as that obtained from a laser could be used for many things if the beam could be spatially deflected.

For example, the light beam could be modulated and used as a projection TV display device if it could be efficiently deflected.

Also, the laser beam could be used for steerable optical transmitting and receiving antennas which are desirable in certain types of optical radar.

A. Miller, "Light deflecting device," US 3305292 A, 1967 (filed 1963).

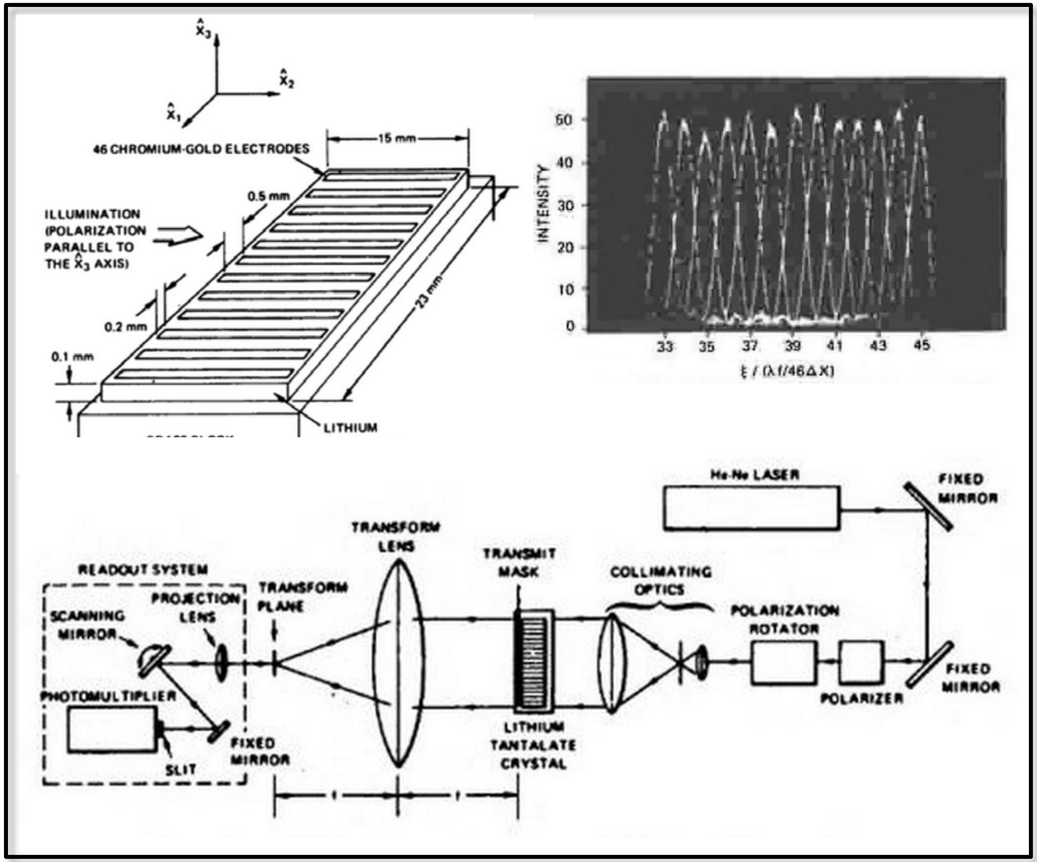
Laser Phased Array
RCA Corp., 1963



For example, an *electronically steerable laser beam* is useful in an optical radar system, in an optical communication system wherein either the transmitter or receiver is in motion, in ultra high speed printing systems, in machining devices that are controlled by means of electronically directing the laser, beam, and in ultra high speed logic circuits.

F. Sterzer, "Phased array light deflecting system," US 3331651 A, 1967 (filed 1963).

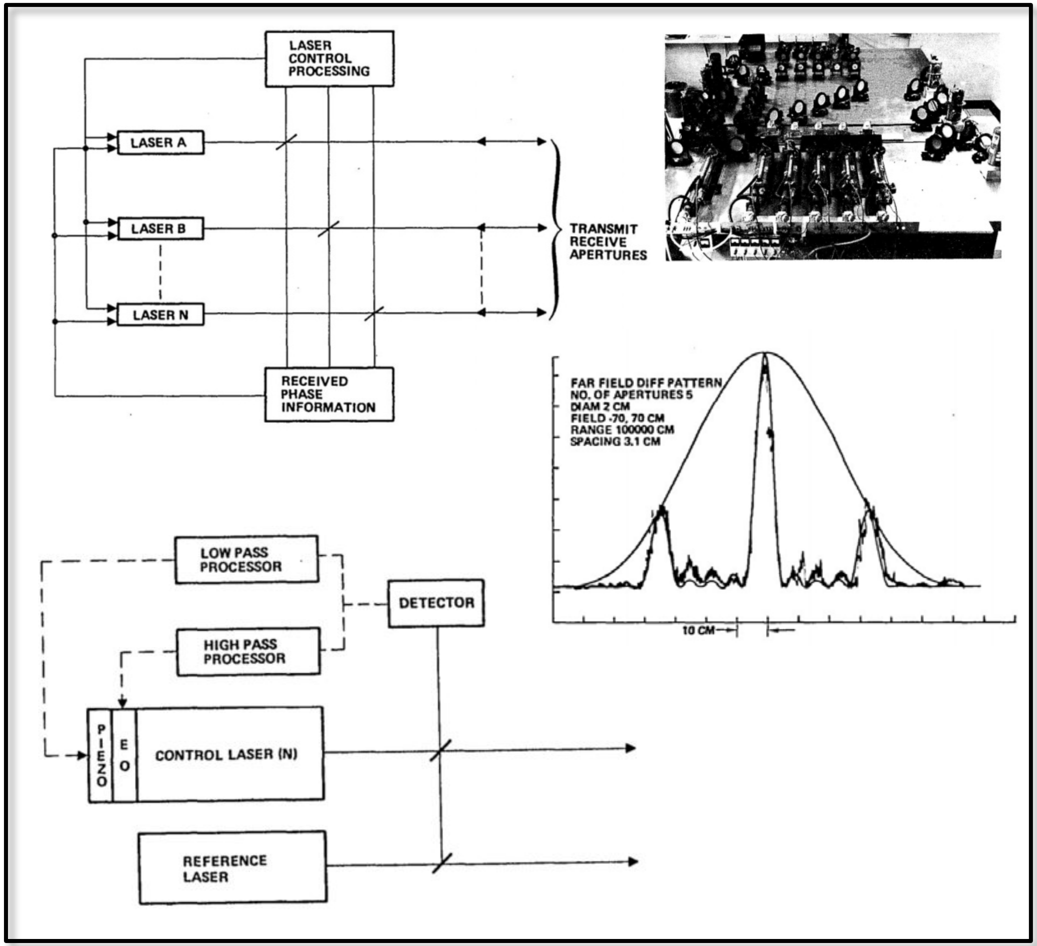
Beam-Steering via Phase Modulators
JHU APL, 1972



- ✓ Lithium Tantalate phase shifter
  - ✓ 27 V for 2π phase shift
- ✓ 46 Channels
  - ✓ 633 nm
- ✓ Linear phase progression
- × Free-space optics
- × No amplitude control
- × Only transmit function (no RX)

R. Meyer, "Optical beam steering using a multichannel Lithium Tantalate crystal," *Applied Optics,* 11(3), pp. 613 – 616, 1972.

Phased Array using Locked Lasers
Rockwell, 1979



- ✓ CO_2 lasers, 5 W, 10 μm
- ✓ 5 Channels
- ✓ Phase adjustment through PLL (no optical phase shifter needed)
- × Free-space optics
- × Complicated control algorithm
- × No amplitude control
- × Only transmit function (no RX)

C. Hayes and W. Davis, "High-power-laser adaptive phased arrays," *Applied Optics,* 18(24), pp. 4106 – 4111, Dec 1979.

Monolithic Laser Scanning Device
XEROX, 1982

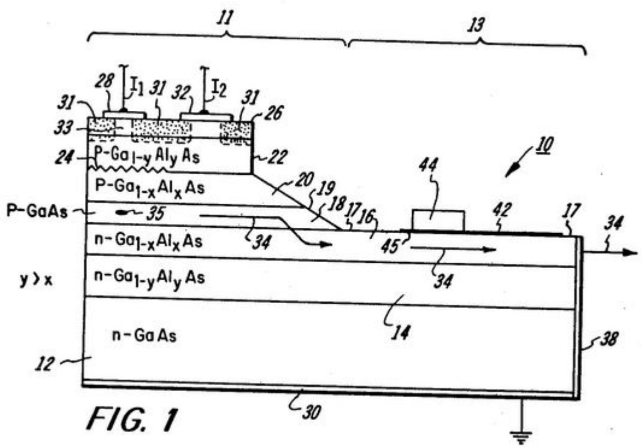


FIG. 1

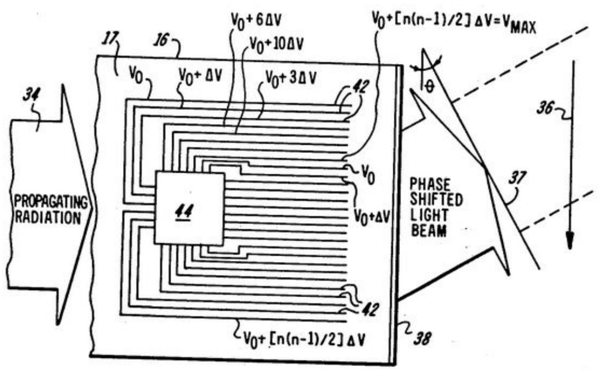


FIG. 11

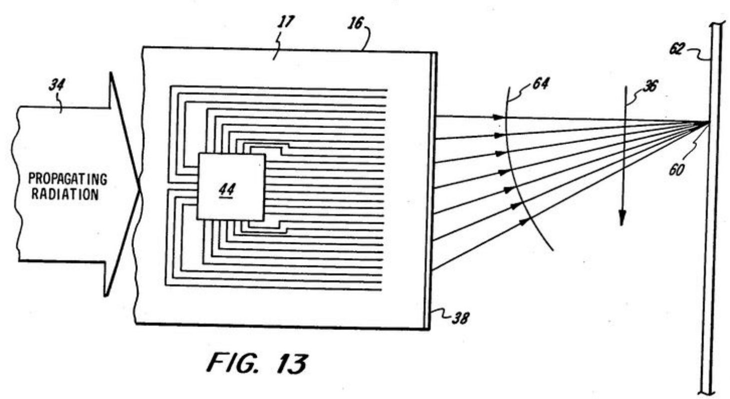
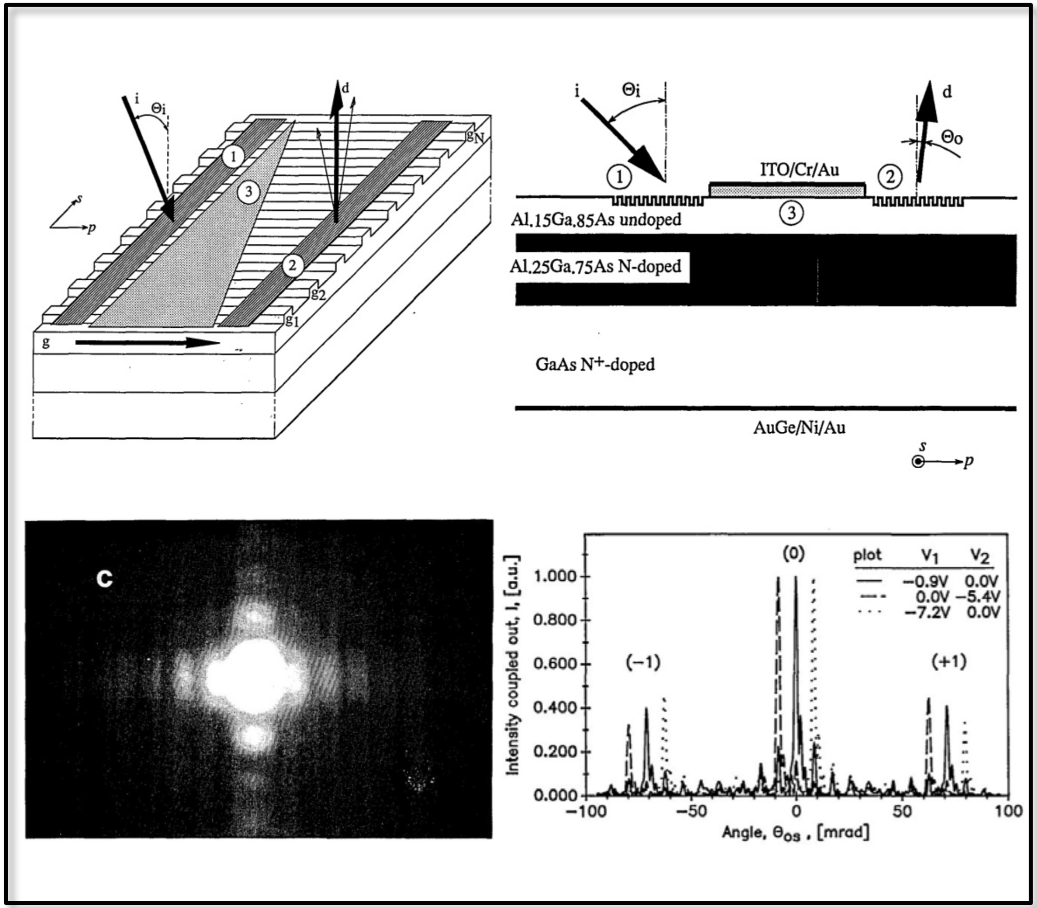


FIG. 13

- ✓ Hetero-structure injection laser region & optical scanning region
- ✓ Element-level phase control
- ✓ Fully monolithic
- × No amplitude control
- × Only transmit function (no RX)

D. Scifres, R. Burnham, W. Streifer, "Monolithic laser scanning device," US Patent 4360921, Nov 1982.

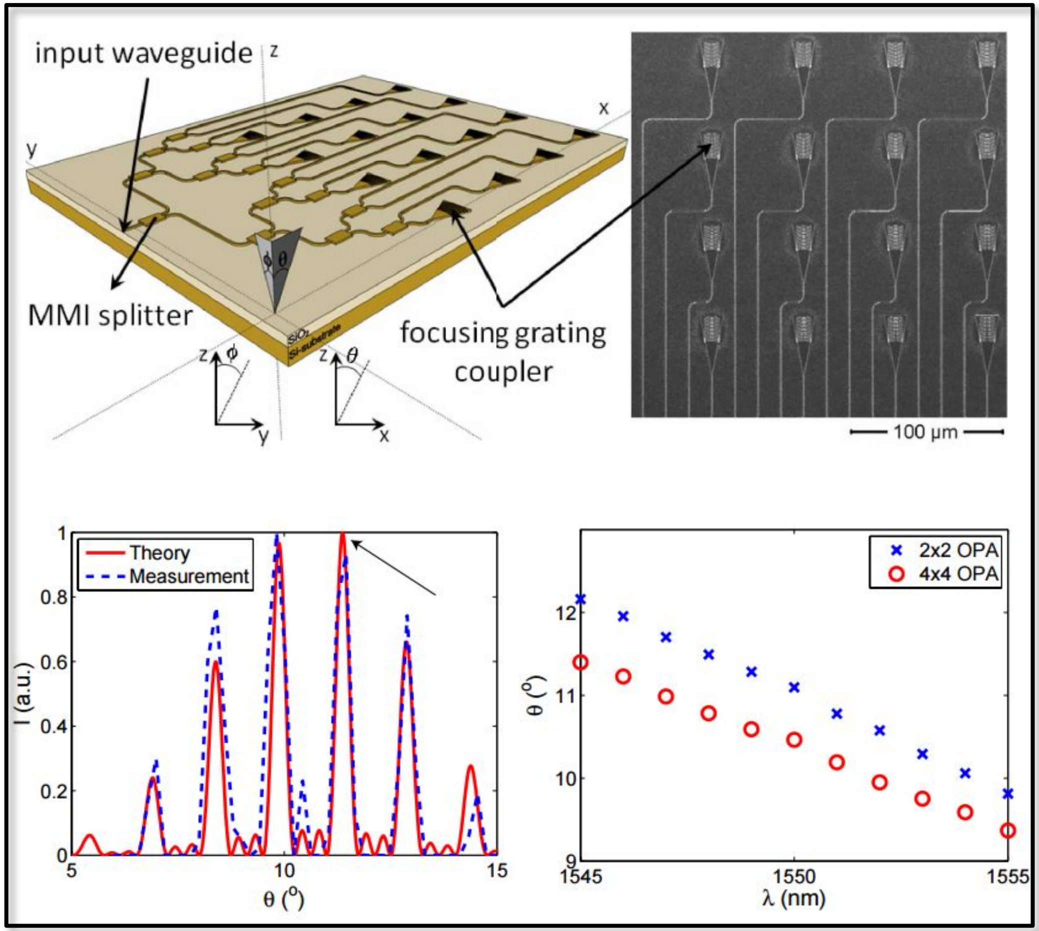
Beam-Steering via Wavelength Tuning
ETH, 1993



- ✓ AlGaAs Process
  - ✓ Waveguide: 3-µm $Al_{0.25}Ga_{0.75}$
  - ✓ Substrate: N^+ 001 GaAs wafer
- ✓ 43 Channels
  - ✓ 900 nm
- ✓ Electro-optical phase shifters based on indium tin oxide/AlGaAs Shottky junctions
- × No amplitude control
- × Only transmit function (no RX)

F. Vasey, F. Reinhart, R. Houdré, and J. Stauffer, "Spatial optical beam steering with an AlGaAs integrated phased array," *Applied Optics,* 32(18), pp. 3220 – 3232, 1993.

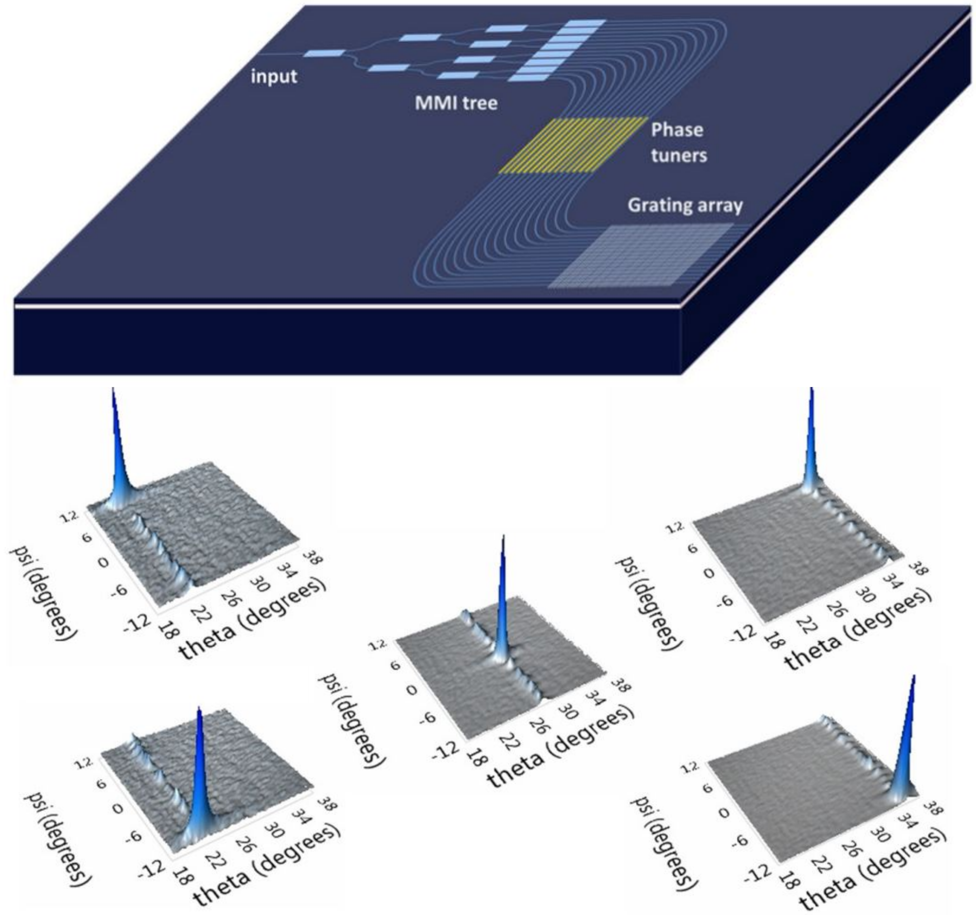
Beam-Steering via λ-tuning in Silicon
IMEC, 2010



- ✓ Silicon Photonics Process
  - ✓ Silicon thickness: 220 nm
  - ✓ Buried oxide thickness: 2 μm
- ✓ 4 x 4 Channels
  - ✓ 1550 nm
- × Beam steering via wavelength tuning only in one direction.
- × No independent phase control
- × No amplitude control
- × Only transmit function (no RX)

K. Van Acoleyen, H. Rogier, and R. Baets, "Two-dimensional optical phased array antenna on silicon-on-insulator," *Optics Express*, 18(13), 13655–13660, June 2010.

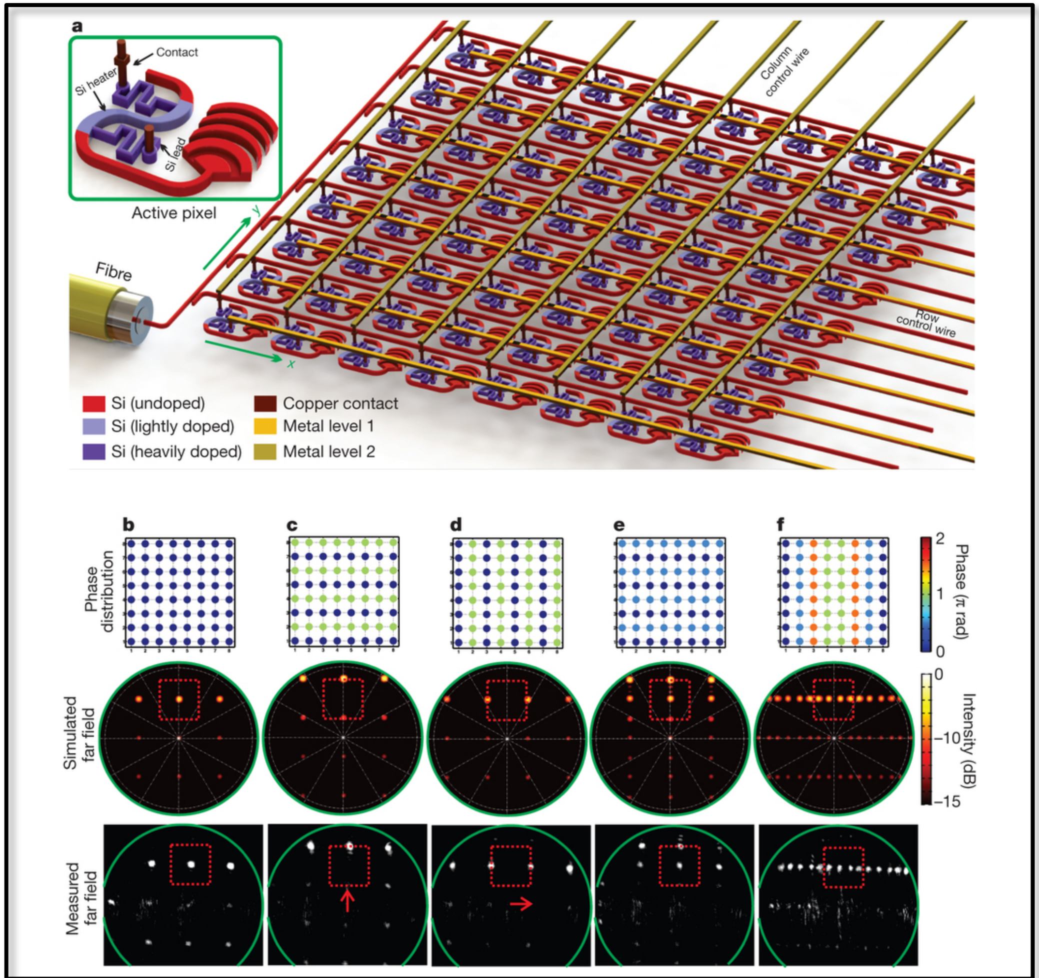
2D Beam-Steering via ϕ-shift & λ-tuning
UCSB, 2011



- ✓ Silicon Photonics Process
  - ✓ Silicon thickness: 500 nm
  - ✓ Buried oxide thickness: 1 μm
- ✓ 4 x 4 Channels
  - ✓ 1550 nm
- ✓ Thermal phase shifters for beam steering in the lateral axis ψ
- × Beam steering in the longitudinal axis θ via wavelength tuning.
- × No amplitude control
- × Only transmit function (no RX)

J. Doylend, M. Heck, J. Bovington, J. Peters, L. Coldren, and J. Bowers, "Two-dimensional free-space beam steering with an optical phased array on silicon-on-insulator," *Optics Express*, Oct 2011.

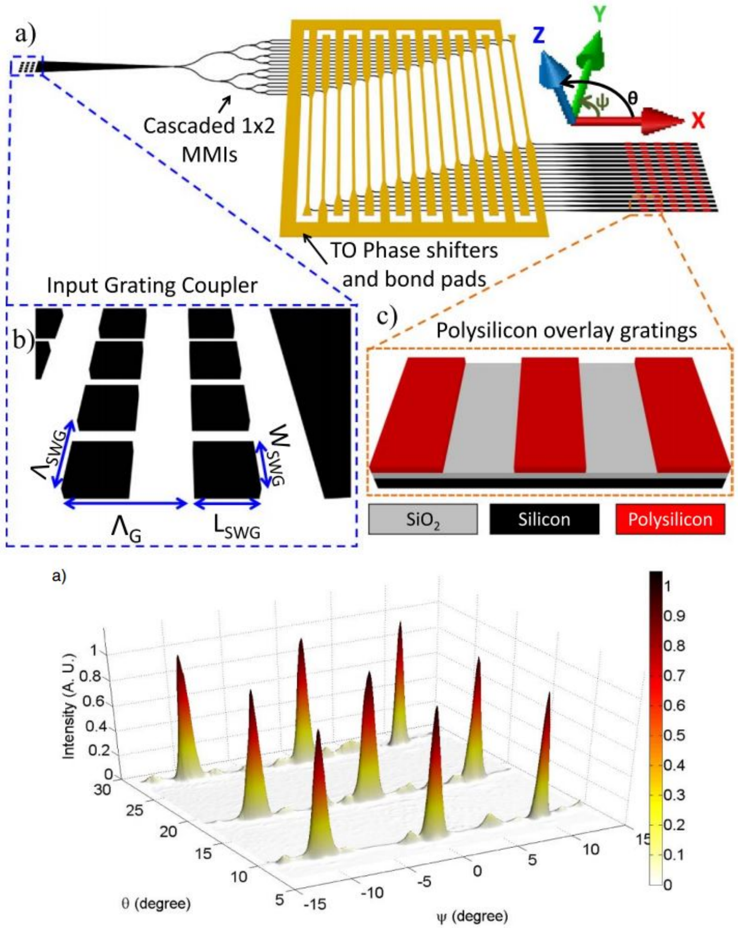
Large-Scale Nanophotonic Phased Array
MIT, 2013



- ✓ Silicon Photonics Process
  - ✓ 300 mm, 65 nm CMOS foundry
  - ✓ Silicon thickness: 220 nm
  - ✓ Buried oxide thickness: 2 μm
- ✓ 8 x 8 Channels
  - ✓ 1550 nm
  - ✓ Unit cell size: 9 μm x 9 μm
- ✓ Thermal phase shifters
  - ✓ Independent for each channel
  - ✓ 8.5 mW for 180° phase shift
- × No amplitude control
- × An entire row/column has the same phase control signal
- × Only transmit function (no RX)

J. Sun, E. Timurogan, A. Yaacobi, E. Shah Hosseini, and M. Watts, "Large-scale nanophotonic phased array," *Nature*, pp. 195 – 199, Jan 2013.

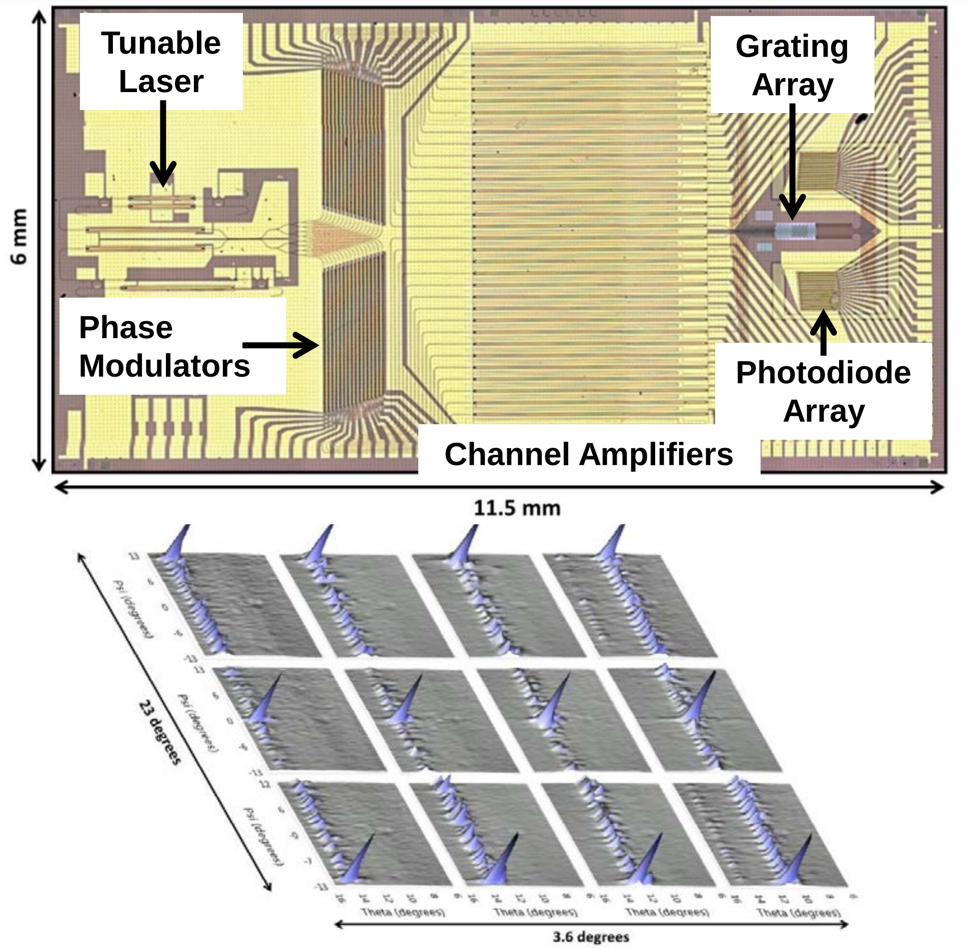
2D Beam-Steering via ϕ-shift & λ-tuning UT, 2014



- ✓ Silicon Photonics Process
  - ✓ Silicon thickness: 250 nm
  - ✓ Buried oxide thickness: 3 μm
- ✓ 16 Channels
  - ✓ 1550 nm
- ✓ Thermal phase shifters for beam steering in the lateral axis ψ
- × Beam steering in the longitudinal axis θ via wavelength tuning
- × No amplitude control
- × Only transmit function (no RX)

D. Kwong, A. Hosseini, J. Covey, Y. Zhang, X. Xu, H. Subbaraman, and R. Chen, "On-chip silicon optical phased array for two-dimensional beam steering," *Optics Letters,* 39(4) 941-944, Feb. 2014.

2D Beam-Steering via ϕ-shift & λ-tuning
UCSB, 2015



- ✓ SOI + III-V Photonics Process
  - ✓ Si / BOX thickness: 0.5 / 1 μm
  - ✓ III-V epitaxial growth on silicon
- ✓ 32 Channels
- ✓ Thermal phase shifters for beam steering in the lateral axis ψ
- ✓ Amplitude control at each channel
- ✓ On-chip photo-detector array for on-chip array test & calibration
- × Beam steering in the longitudinal axis θ via wavelength tuning (on-chip tunable laser).
- × Only transmit function (no RX)

J. Hulme, J. Doylend, M. Heck, J. Peters, M. Davenport, J. Bovington, L. Coldren, and J. Bowers, "Fully integrated hybrid silicon two dimensional beam scanner," *Optics Express*, 23 (5), March 2015.

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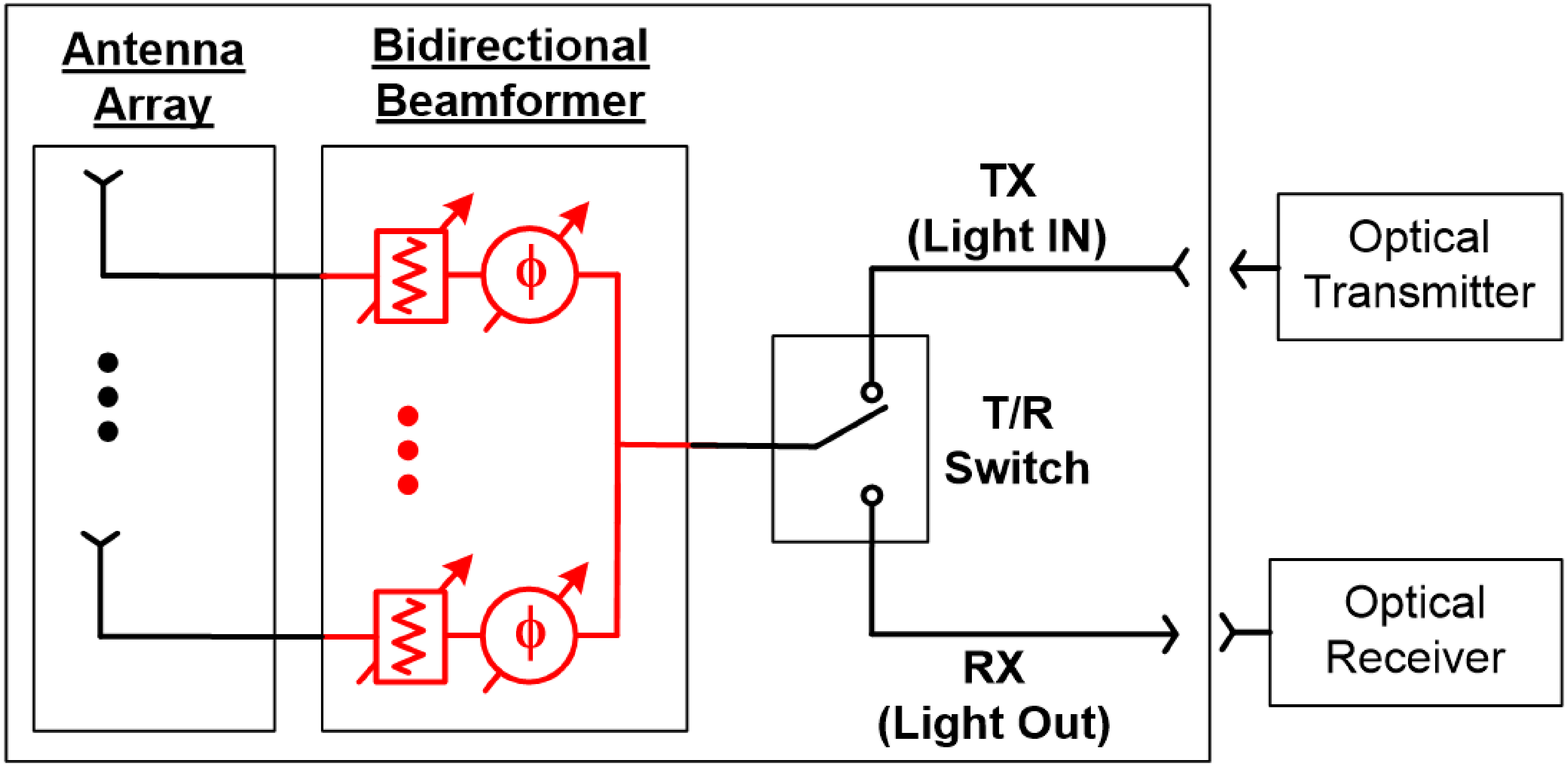
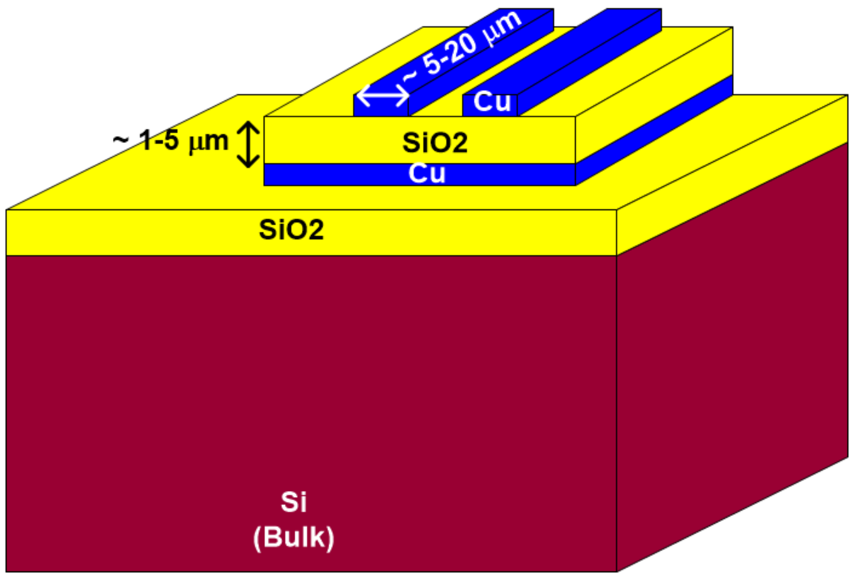
Optical Phased Array Transceiver



- ✓ Bidirectional passive beam-forming works in transmit and receive modes.
- ✓ The entire optical beam-former and control electronics can be realized in a monolithic silicon chip.

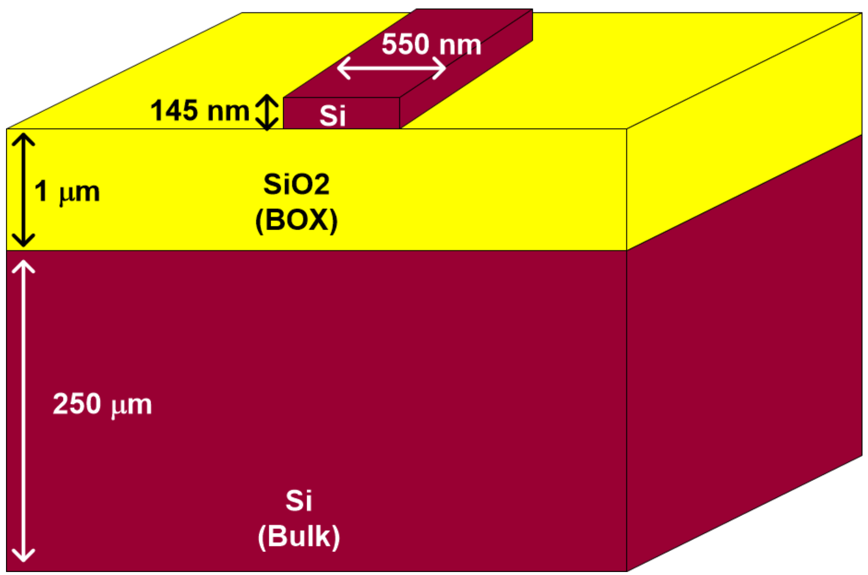
Routing On-Chip Electromagnetic Signals

RF Transmission Line



Frequency	Typical Loss
1 GHz	0.15 dB/mm
10 GHz	0.3 dB/mm
100 GHz	1 dB/mm

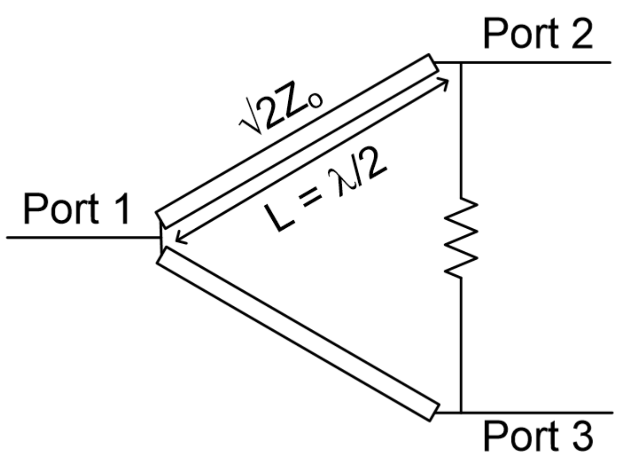
Optical Dielectric Waveguide



Performance Metric @ λ = 1550nm	Measured Performance
Straight Waveguide Loss	1.27 dB/mm
U-Turn Loss (turn radius = 2 μm)	0.7 dB
U-Turn Loss (turn radius = 5 μm)	0.2 dB

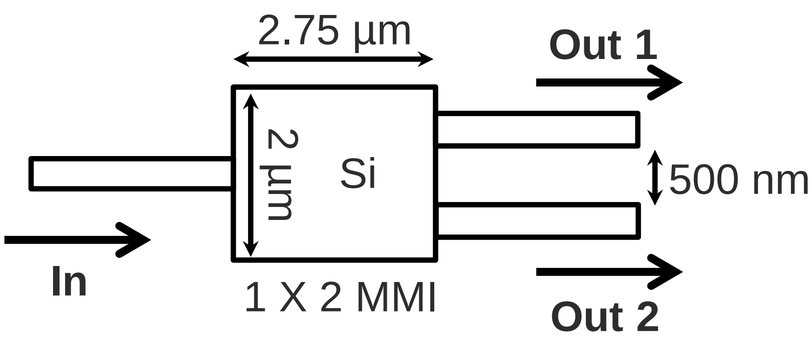
On-Chip Electromagnetic Splitters

RF Wilkinson Splitter/Combiner



Frequency	Insertion Loss	Footprint
24 GHz	1.4 dB	120 μm x 290 μm
45 GHz	0.6 dB	250 μm x 960 μm
95 GHz	0.6 dB	250 μm x 340 μm

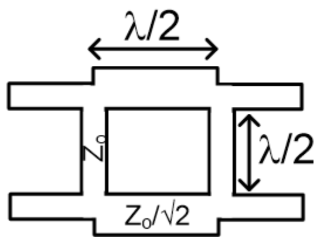
Optical Multi-Mode Interferometer



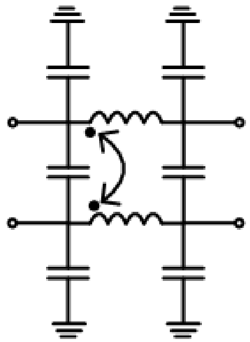
Performance Metric @ λ = 1550nm	Measured Performance
Insertion loss	0.3 dB
Footprint	2 μm X 2.75 μm

On-Chip Electromagnetic Couplers

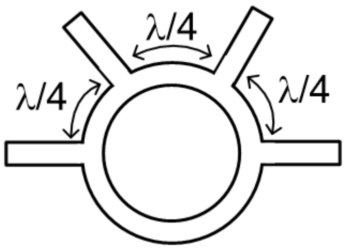
RF Directional Couplers



Branch Line Coupler



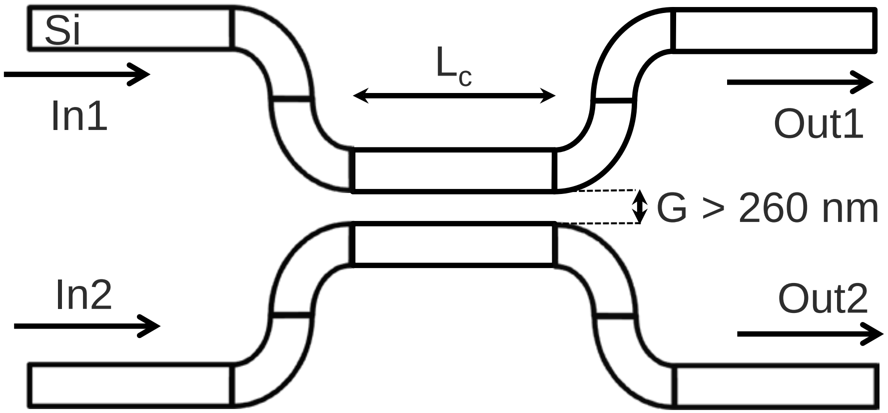
Lange Coupler



Rat Race Coupler

Frequency	Insertion Loss	Footprint
2.4 GHz	1.7 dB	380 μm x 390 μm
10 GHz	1 dB	840 μm x 960 μm
60 GHz	1 dB	120 μm x 160 μm

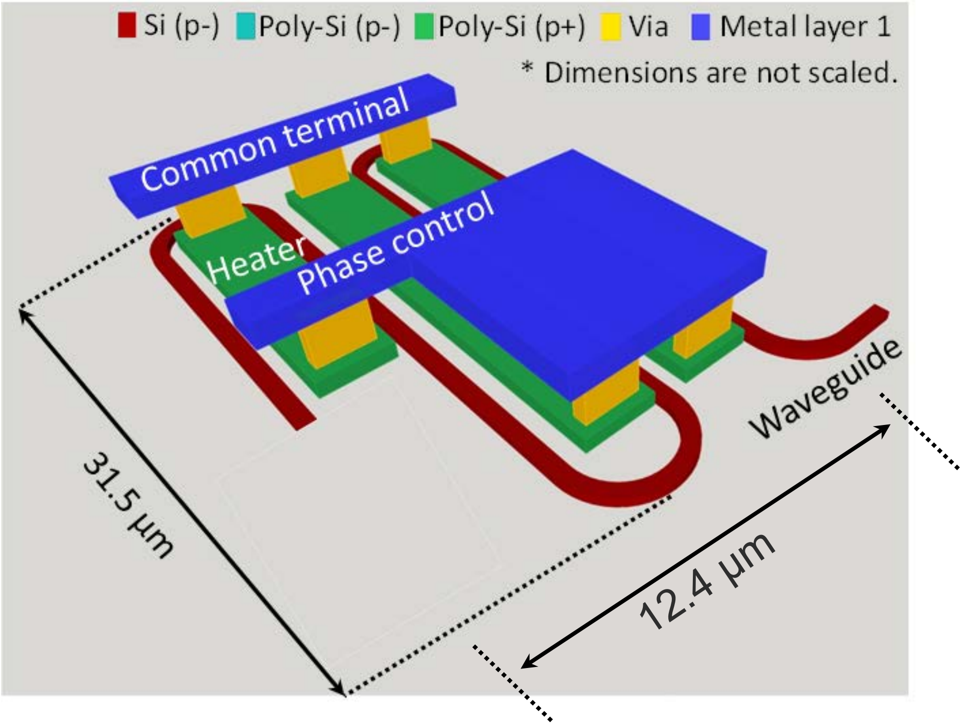
Optical Directional Coupler

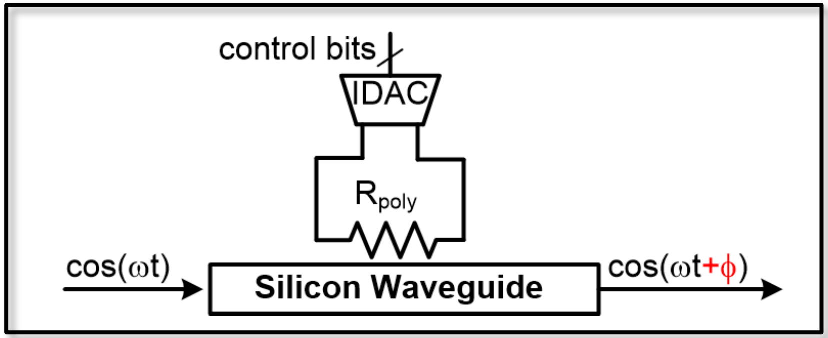


L_π for G = 260 nm & R = 5 μm is 36.4 μm

Performance Metric @ λ = 1550nm	Measured Performance
L_c for 10% coupling	6.1 μm
L_c for 50% coupling	18.2 μm

Bidirectional Optical Variable Phase Shifter

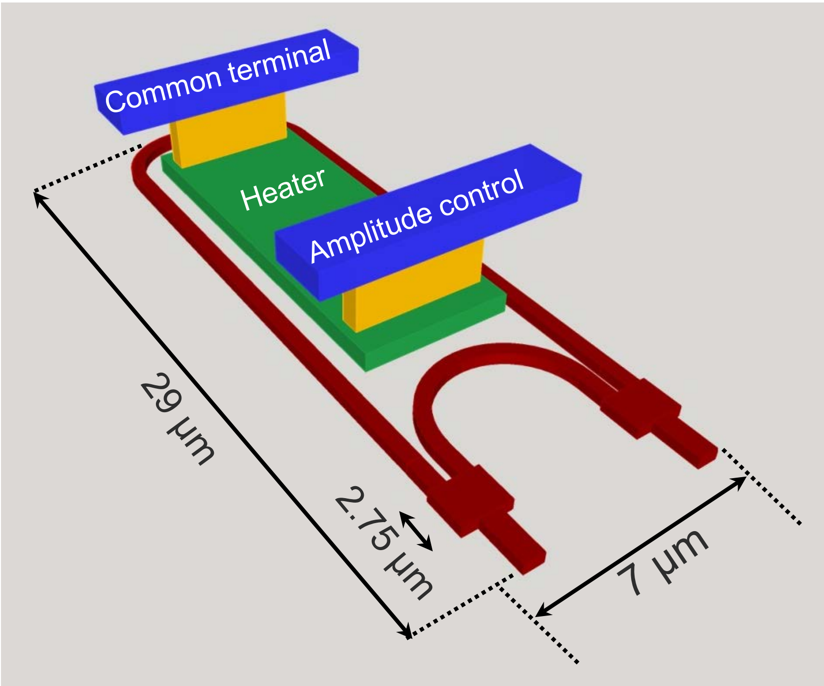


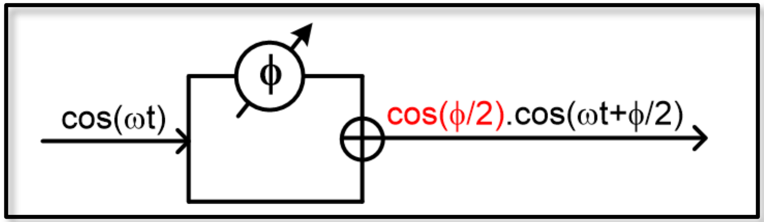


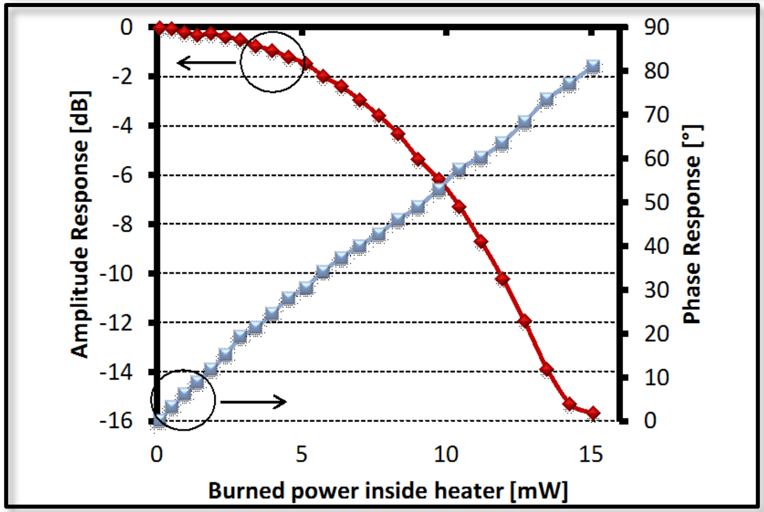
Performance Metric @ λ = 1550nm	Measured Performance
Overall phase shifter length	94.4 µm
$P_{2\pi}$	27.2 mW
$\Delta T_{2\pi}$	105 °C
Insertion loss	2.2 dB
Heater resistance	1 kΩ

- ✓ Propagation velocity is modified by changing the local temperature (adjusting current passing through an adjacent polysilicon).
- ✓ Optical waveguide and heater are meandered to reduce footprint.
- ✓ Variable phase shifter can cover 360° phase shift with 27.2 mW power.

Bidirectional Optical Variable Attenuator

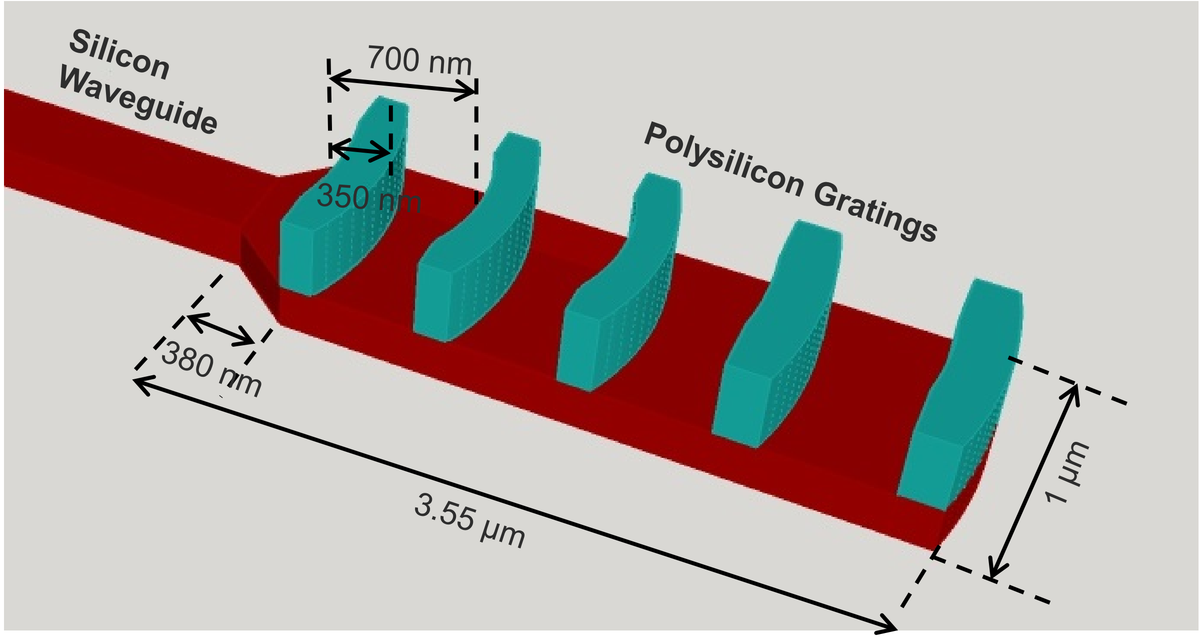




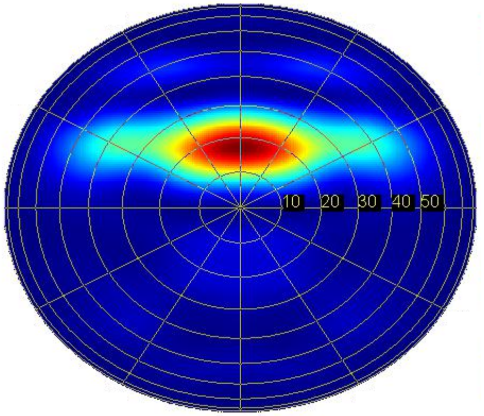


- ✓ Attenuation is set by adjusting relative phases of two added signals
  - ✓ 0° relative phase shift corresponds to zero attenuation
  - ✓ 180° relative phase shift corresponds to infinite attenuation
- ✓ Relative phase shift is adjusted thermally between optical waveguides of different lengths.

Optical Antenna (Grating Coupler)

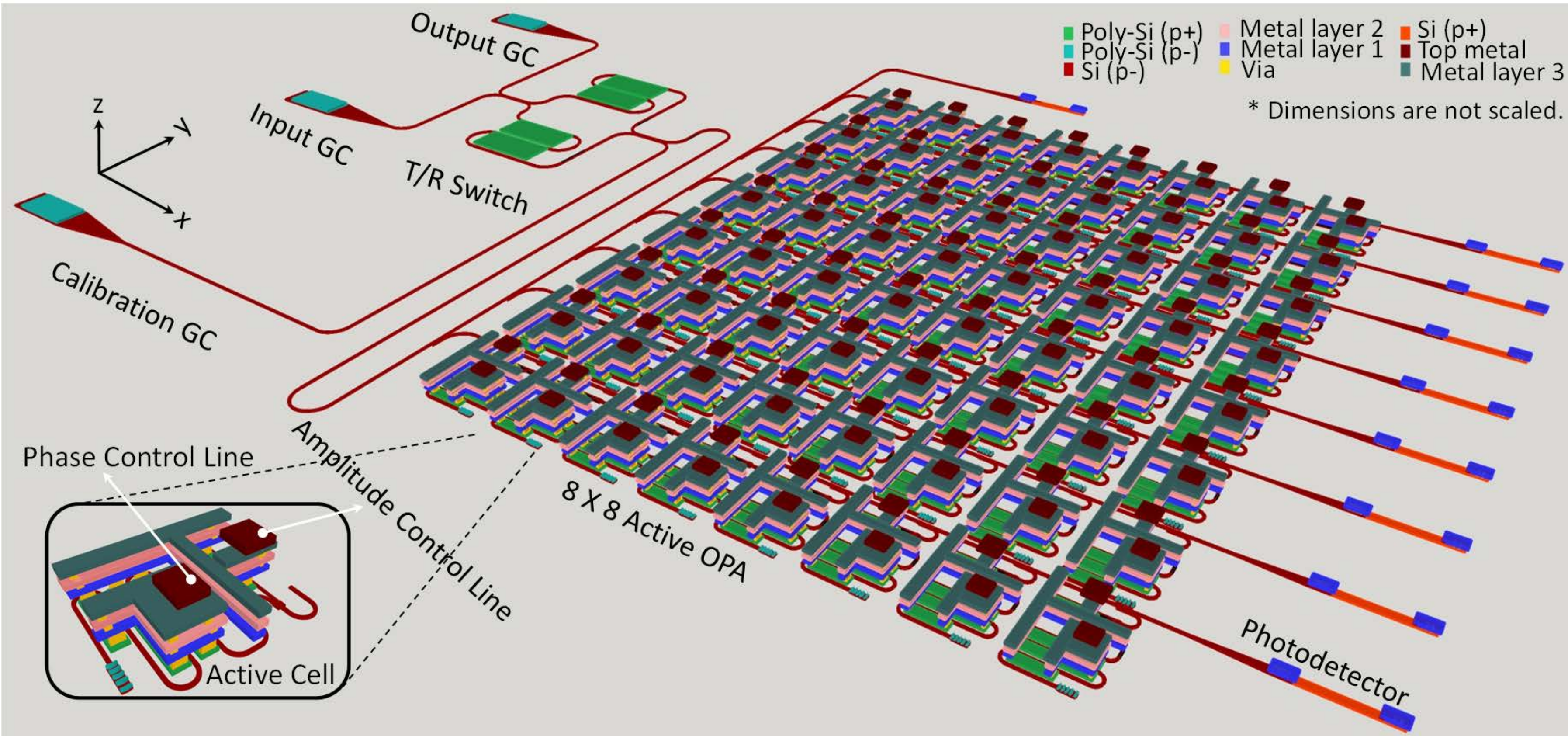


FDTD simulation of far-field radiation pattern



- ✓ Simulated radiation efficiency = 50%
- ✓ Peak radiation for single optical antenna occurs at around 20°
- ✓ Larger grating couplers are used for TX and RX ports.

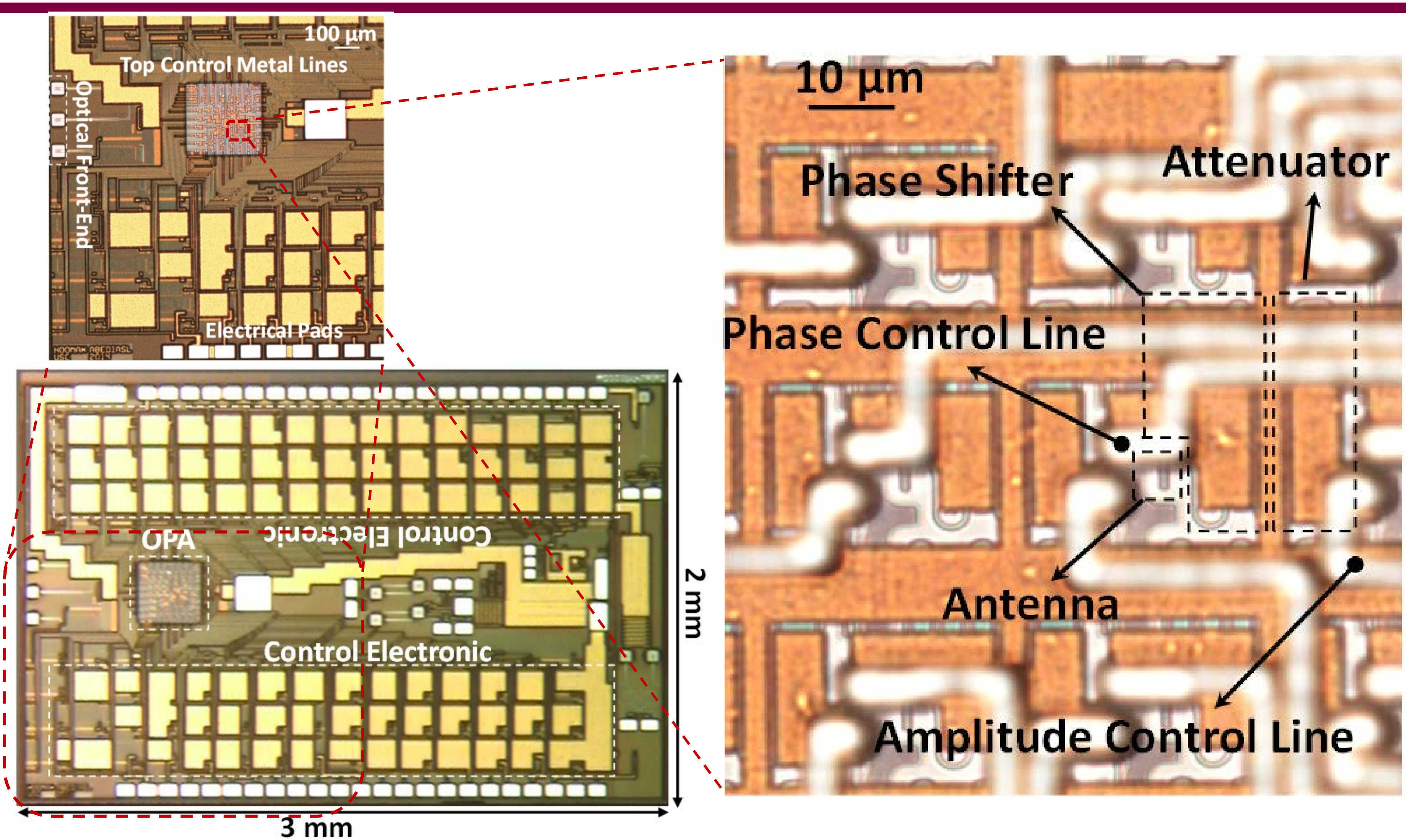
Monolithic Optical Phased Array Transceiver



H. Abediasl and H. Hashemi, "Monolithic optical phased-array transceiver in a standard SO CMOS process," *Optics Express*, vol. 23, no. 5, pp. 6509-6519, March 2015.

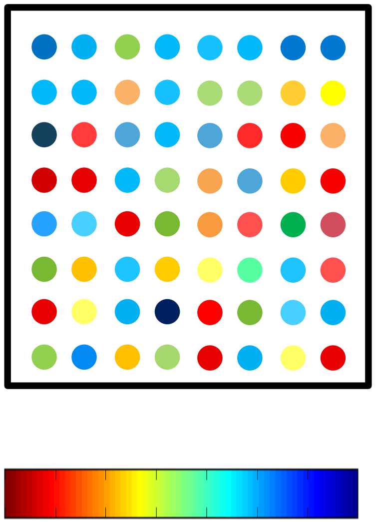
Monolithic Optical Phased Array Transceiver

Chip Microphotograph

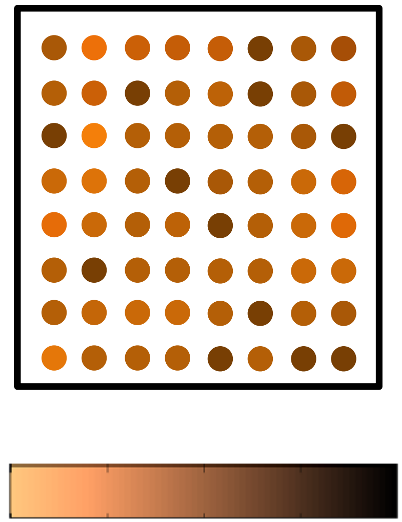


Measured Array Performance without Calibration

Phase Profile



Amplitude Profile

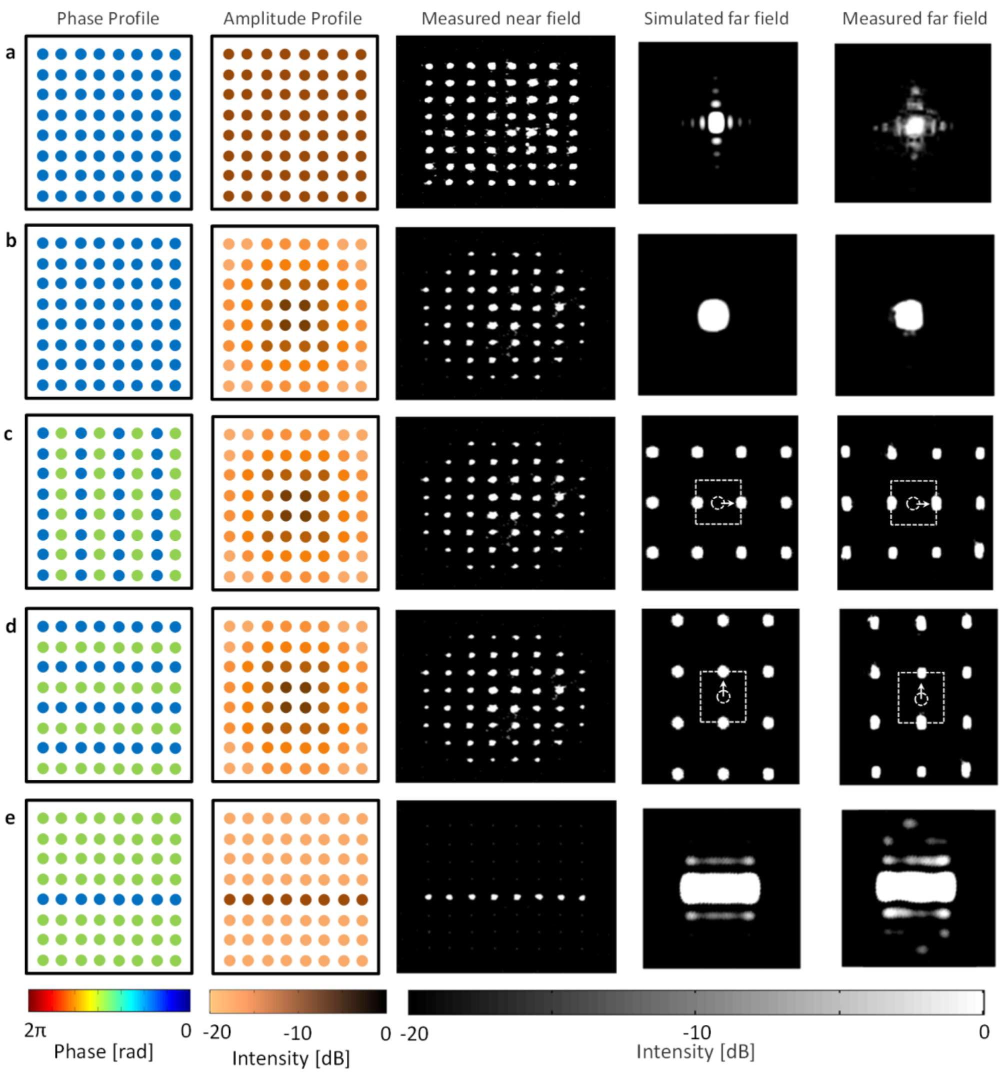


Far-Field Pattern

× Phase & amplitude mismatches due to process mismatches even when all channels have the same setting.

✓ All arrays must get calibrated during start-up.

Optical Phased Array TX Measurements After Calibration



Uniform amplitude distribution
Uniform phase distribution

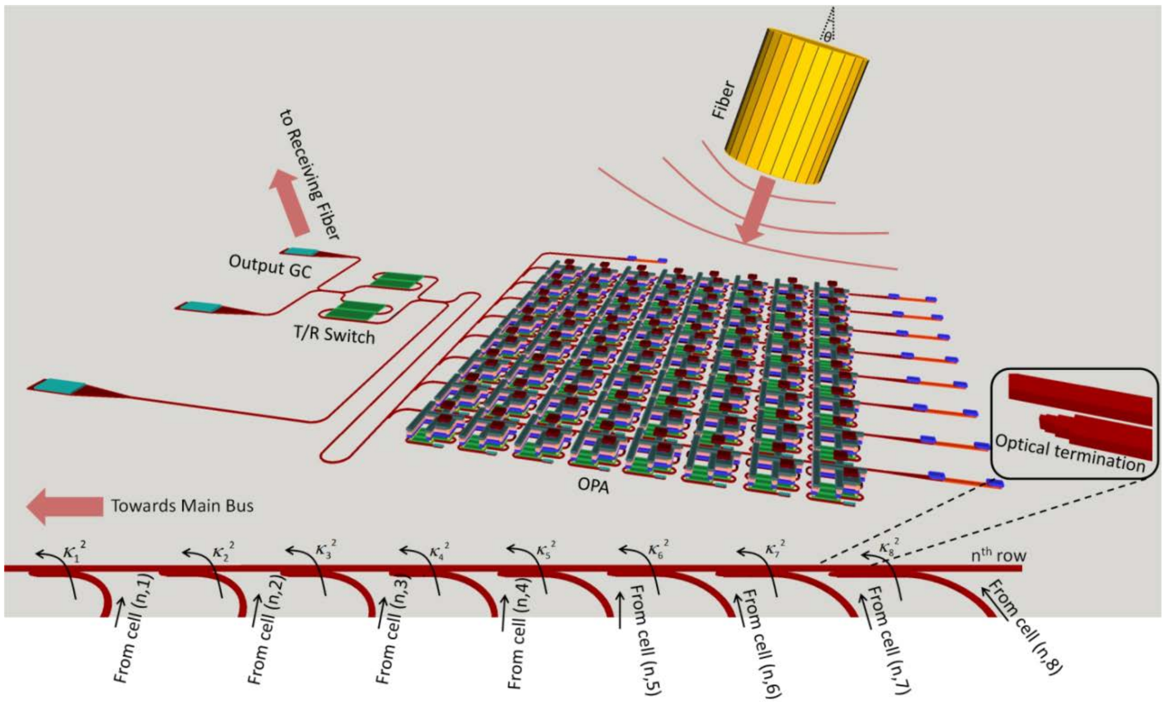
Gaussian amplitude distribution
Identical phase settings

Gaussian amplitude distribution
0° / 180° phase in alternate columns

Gaussian amplitude distribution
0° / 180° phase in alternate rows

Non-uniform amplitude distribution
Non-uniform phase distribution

Optical Phased Array RX Measurements
After Calibration



- ✓ Maximum received power is achieved when all the antennas contribute to the total collected field with the same phase and amplitude.
- ✓ Minimum received power is achieved when the phase of half of the antennas shifted 180°respect to the other half.
- ✓ 14.5 dB maximum to minimum ratio was measured (peak to null ratio).

Outline

- Radio Frequency Phased Arrays
- Optical Beam Steering
- Monolithic Optical Phased Array Transceiver in SOI CMOS
- Conclusions

Phased Array Advancements

- ✓ Radio frequency phased arrays
  - ✓ Concept: 1900s
  - ✓ Discrete demonstrations: 1940s
  - ✓ Monolithic demonstrations: 2000s
  - ✓ Applications: electronically scanning radar, wireless communications, etc.
- ✓ Optical phased arrays
  - ✓ Early demonstrations: 1970s
  - ✓ Monolithic demonstrations: 1980s
  - ✓ Silicon monolithic demonstrations: 2010s
  - ✓ Applications: lidar, projection, display, holography, optical communications, etc.

Monolithic phased arrays have been proposed/demonstrated for high-speed interconnects (inter-chip, intra-chip, backhaul, etc.), touchless gesture sensing, endoscopic laser surgery, etc.

Future

Opportunity to use

1 billion, *nano-scale transistors* with cut-off frequencies reaching *1 THz*

and

ability to manipulate *electrons* **and** *photons* on the same chip

enables

complex integrated systems, such as phased arrays,

with

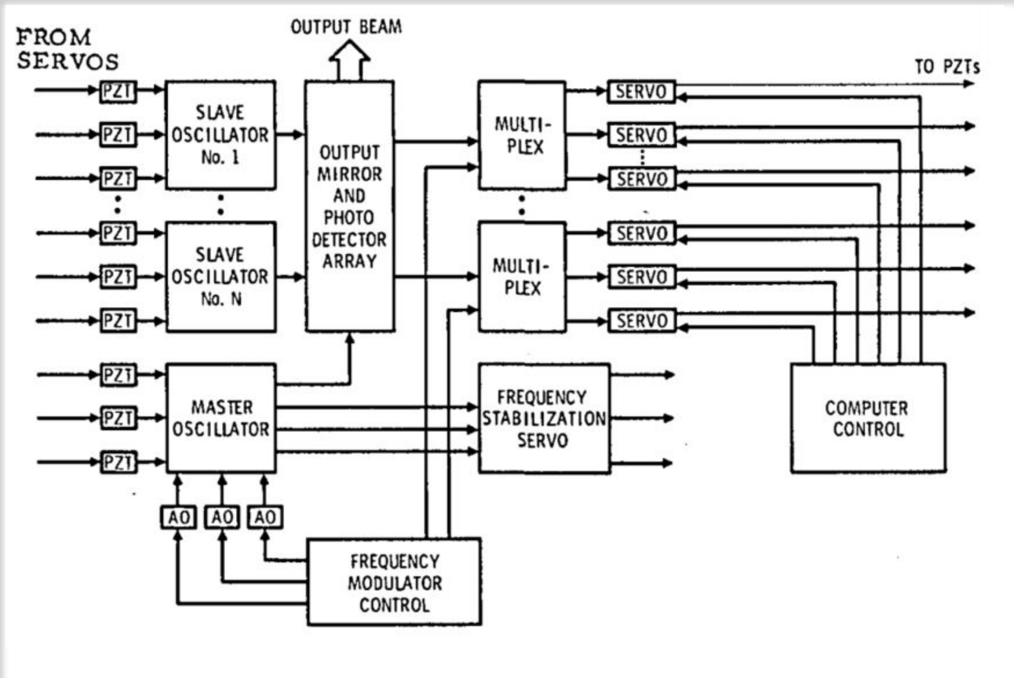
unprecedented functionality and performance

for

unforeseen applications.

Appendix

Phased Array using Locked Lasers
Aerospace Corporation, 1978



- ✓ Phase locking all frequencies of multi-frequency lasers
- ✓ Phase adjustment through PLL (no optical phase shifter needed)
- × Free-space optics
- × No amplitude control
- × Only transmit function (no RX)

C. Wang, "Master and slave oscillator array system for very large multiline lasers," *Applied Optics*, 17(1), pp. 83 – 86, Jan 1978.

Acoustic Phased Arrays

# of Elements: 16 – 128

Frequency: 2 – 10 MHz

Used for Human Imaging