Optical True Time Delay Based on a Recirculating (White) Cell and Micromirror Technology

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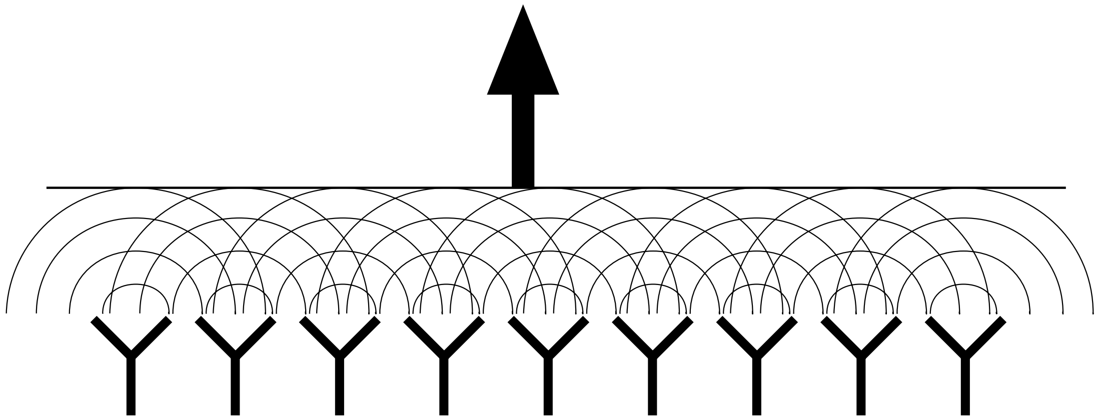
Acknowledgments

- Stuart A. Collins, Jr.
- Also graduate students toiling selflessly in the lab:
  - » Brad Stone
  - » Niru Nahar
  - » Rashmi Mital

Organization

- The problem we're trying to solve
- Our approach: The White cell
- Various designs to date
- Our current apparatus
- The MEMS device to do it
- Experimental results
- Other propaganda

Consider an array of antennas



- One element alone produces a broad pattern
- Their signals add coherently to produce a highly directional beam
- Beam emitted perpendicular to the array

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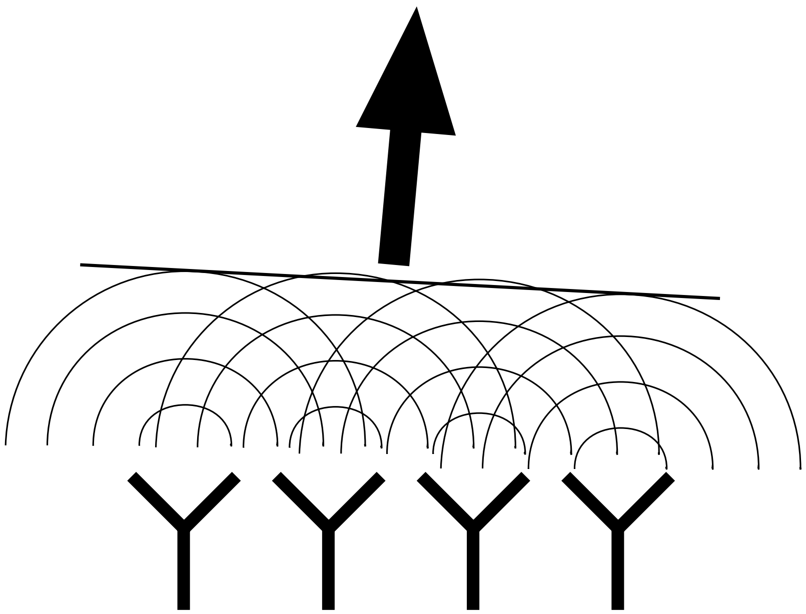
Phase shifting

- In phase shifting, 3π is the same as π
- Will only get the right phase shift for one frequency
- Different frequencies go in different directions (beam squint)
- Lousy for broadband antennas



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True-time delay

- A delay of 6π corresponds to some actual time
- If delay all the signals by the right times instead of phases, works at all frequencies
- Great for broadband antennas

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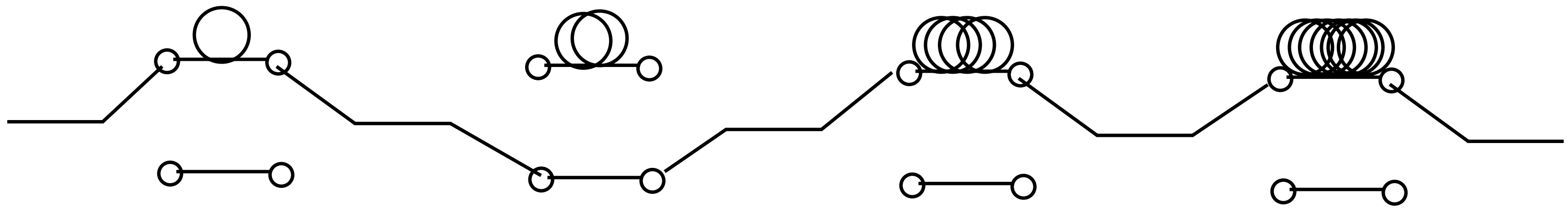
Our task

- To provide LOTS of delays (thousands),
  - » Makes for very accurate steering
- To provide those delays for LOTS of antenna elements (hundreds or thousands)
  - » Makes for very narrow beam shape
  - » Can null out distracting stuff

One approach



- This could be switches and lengths of coax
  - » (Or optical switches and lengths of fiber)
- Need one set like the above for every antenna element

There is a snag…

- Some delays may be as long as 100’s of ns
- That’s meters of coax or stripline
- Heavy, expensive, and temperature sensitive
- Naturally we want to do this optically…

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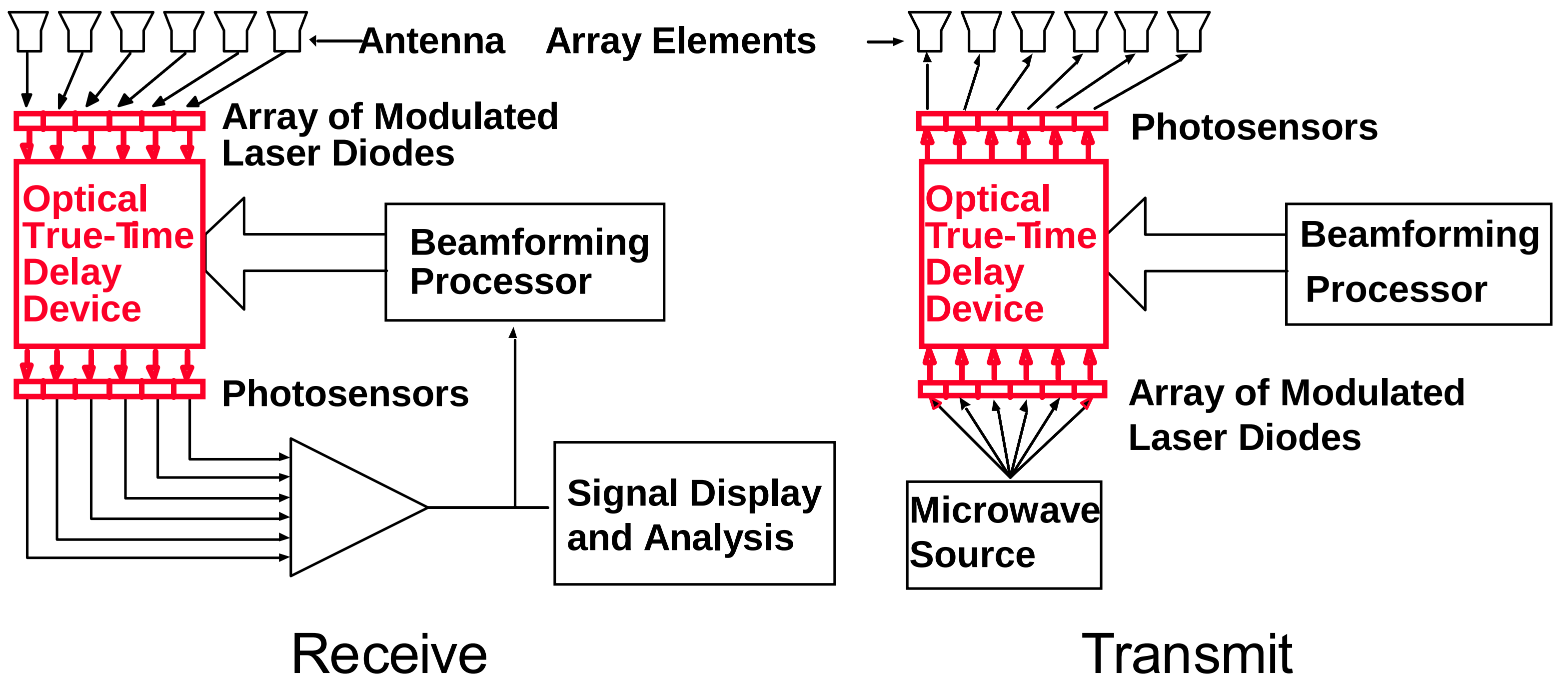
Here’s how…

- One light beam for every antenna element (or subarray)
- Modulate RF signal onto light beam
- Delay light beam
- Convert back to RF at the end- delays intact

The big, big picture



Reciprocal Device

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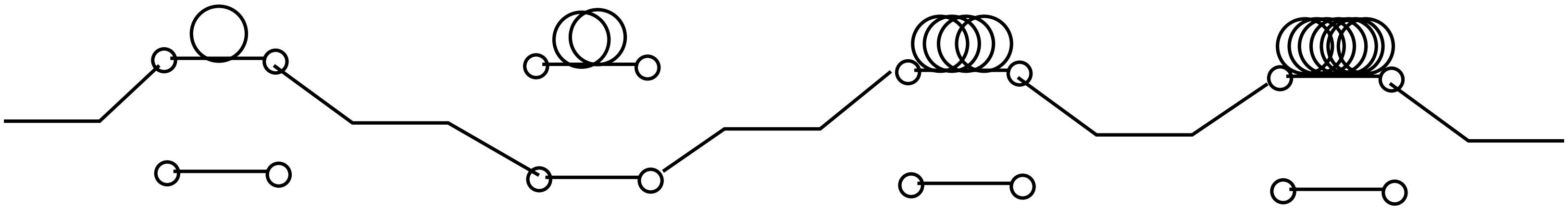
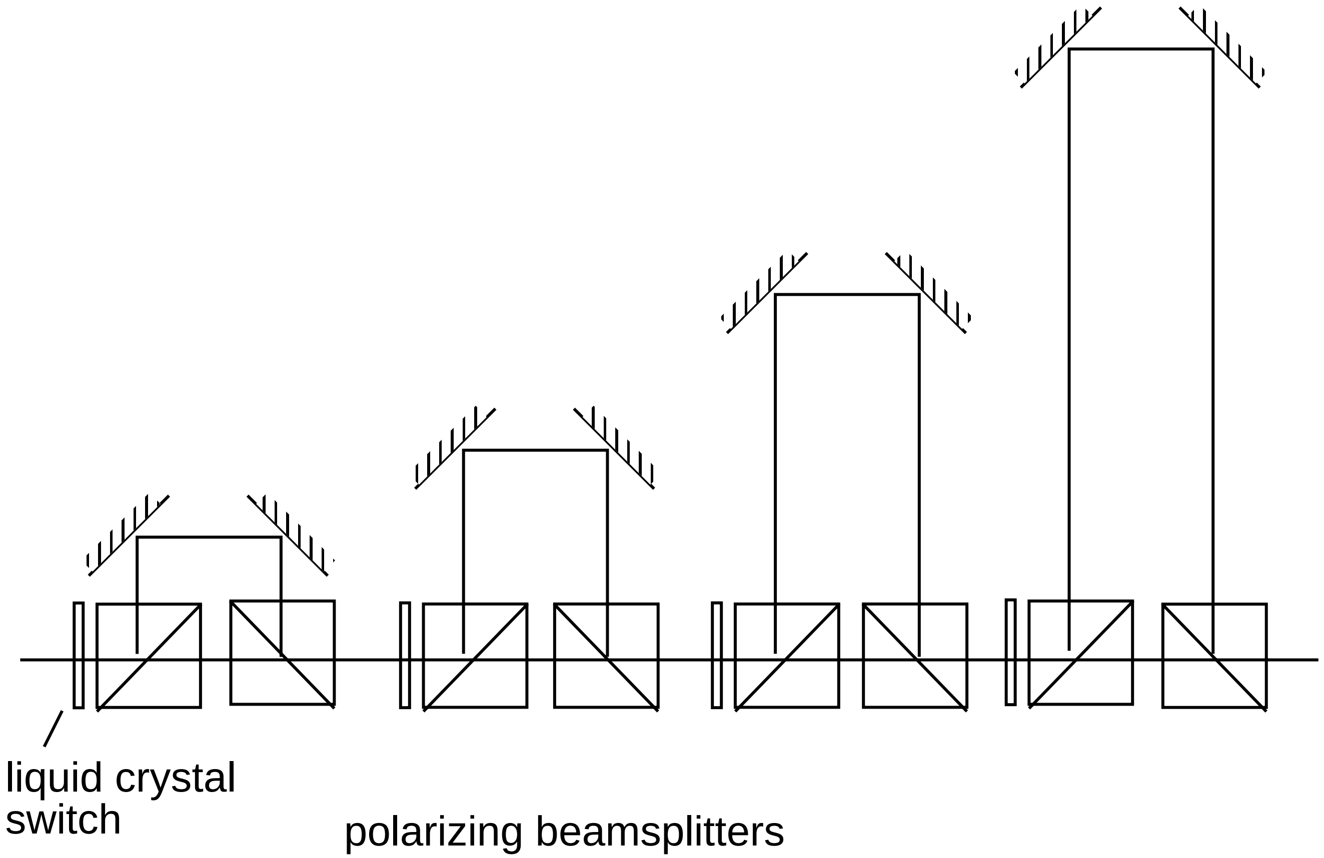
Recall switching fiber approach



- Need a string like this for every antenna element
- Gets to be a lot of hardware even using fiber if antenna array is large

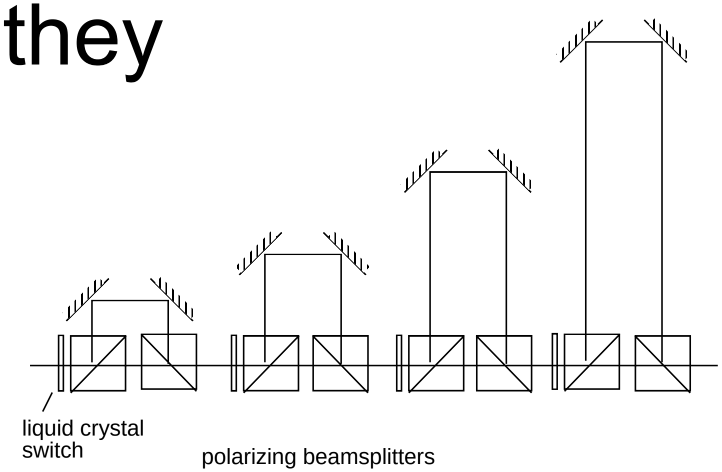
Here's a (previous) free space approach



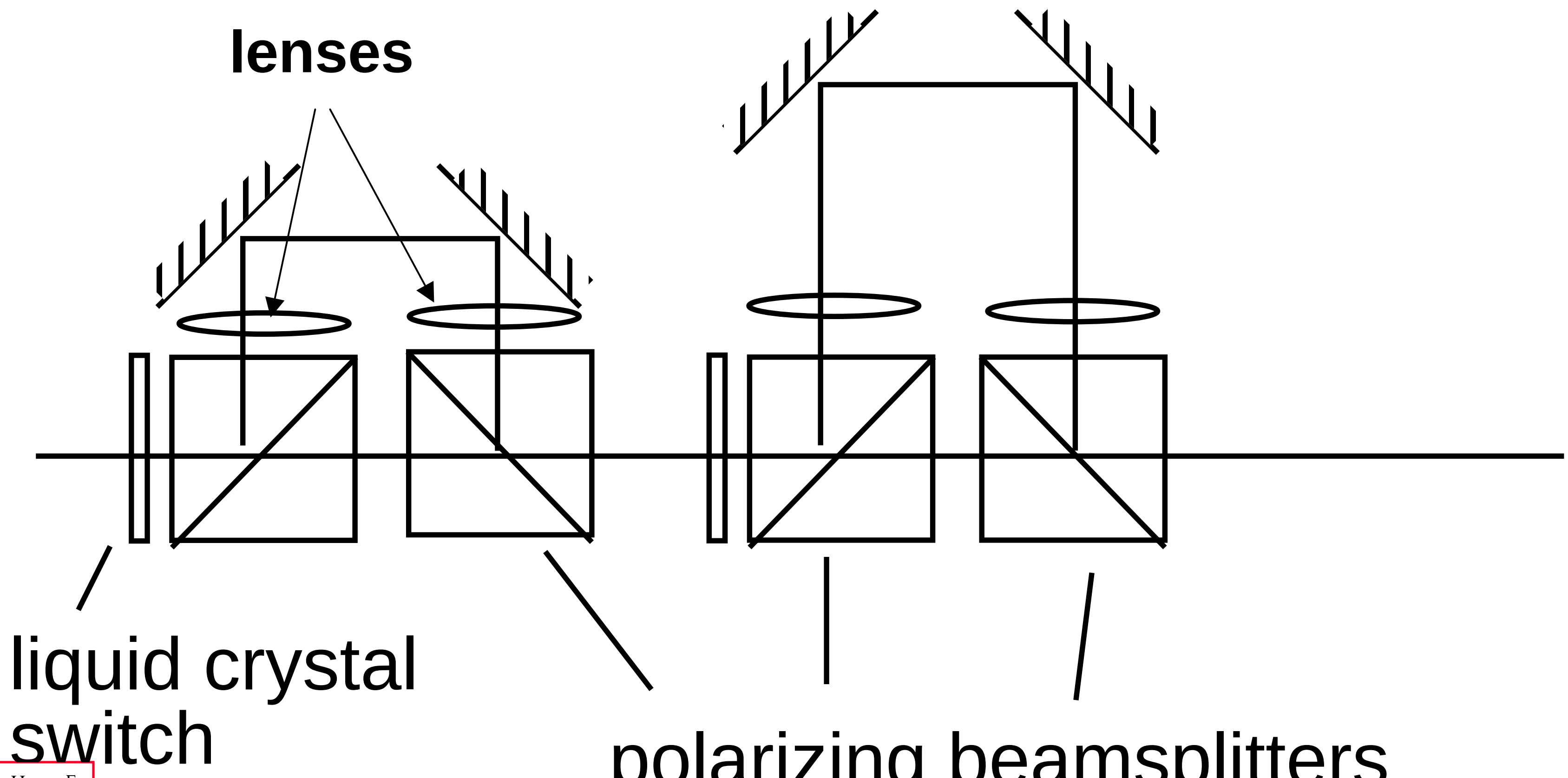
See, for example, Riza, J. Lightwave Tech.. **12**(6), pp. 1440-1447, 1994

Features

- Free space doesn't weigh much
- Each switch can be a spatial light modulator, so can run multiple beams in parallel
- But, beams diverge as they propagate
- Makes SLM awfully big



Add lenses to refocus the beams



Waveguides vs. Free Space

- Hard to do short delays in fiber
- Could use integrated optics, but then hard to do long delays

- Free space can do long or short
- Offers parallelism since beams can overlap in space
- Have to solve divergence problem

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Our approach

- Also uses free space
- Also uses a spatial light modulator
  - » (in our case a MEM micromirror array)
- Still have zillions of switches but they're all on one chip, not distributed all over the place
- Based on the White cell

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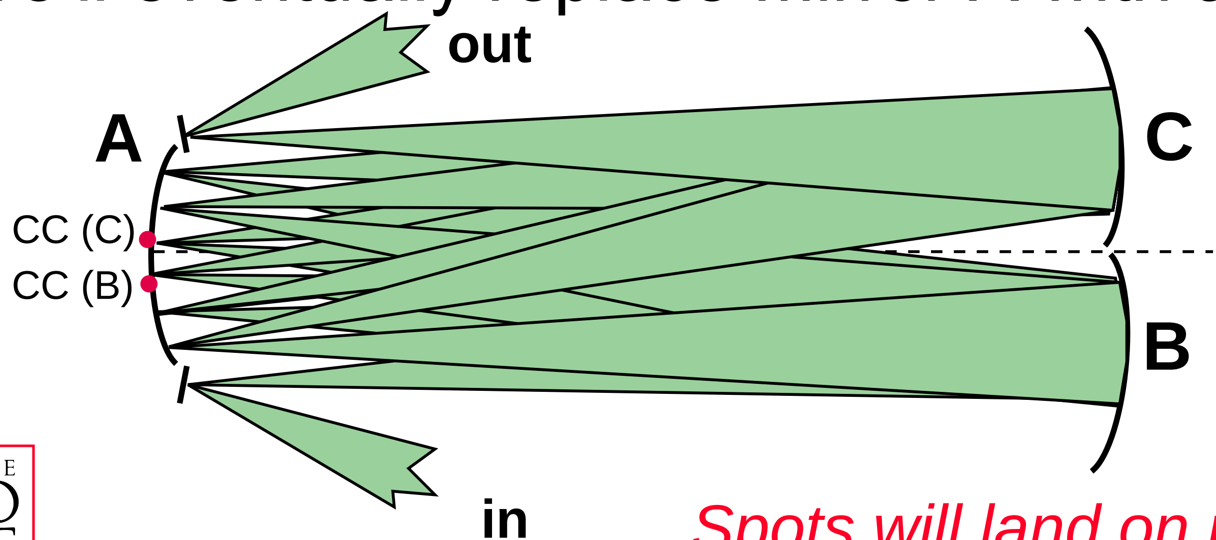
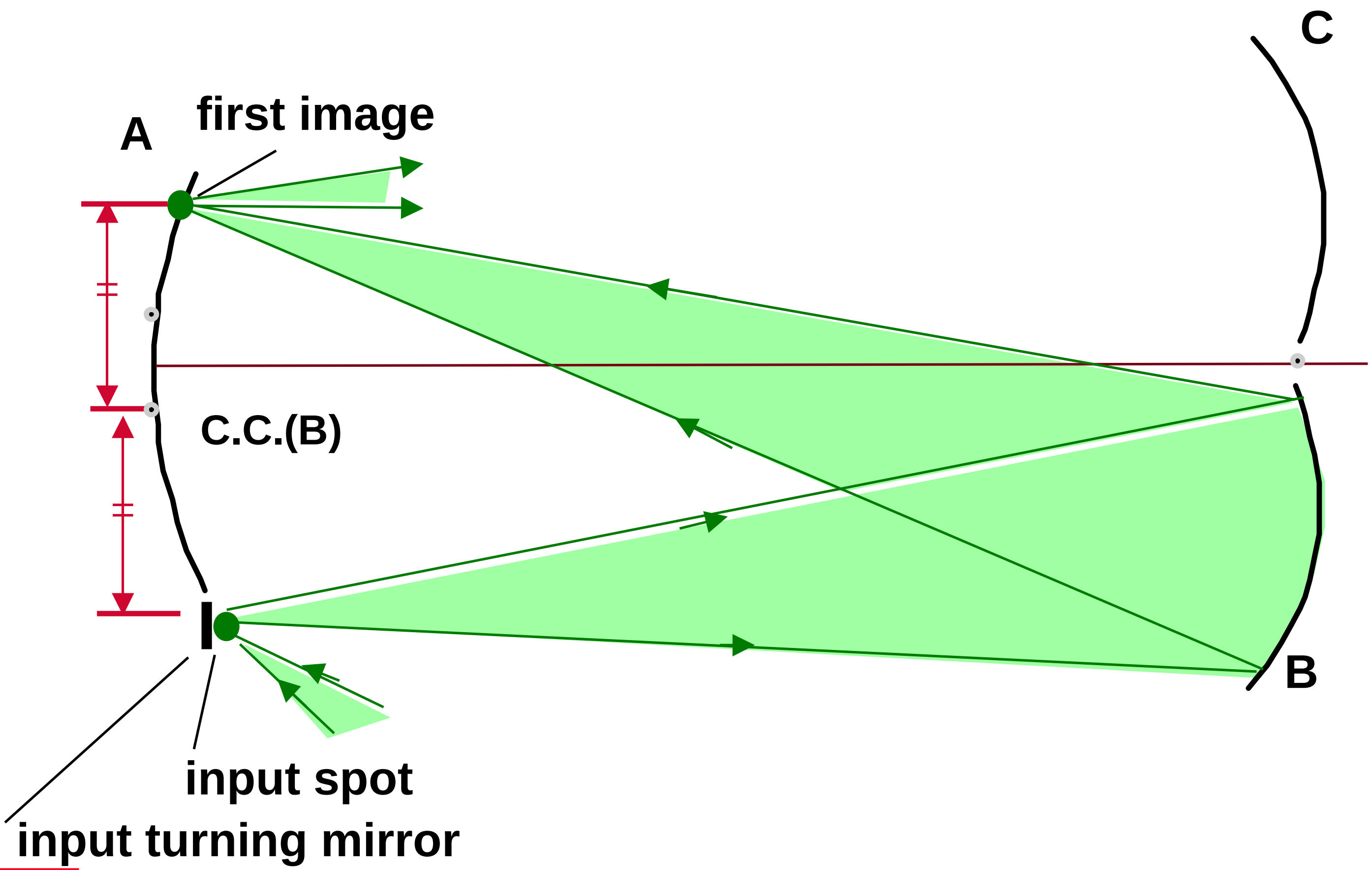
The (original) White cell

- Three spherical mirrors- all identical
- Light bounces back and forth repeatedly
- Light focused to a new spot on every bounce
- We'll eventually replace Mirror A with a MEM



Spots will land on pixels

White Cell - Operation



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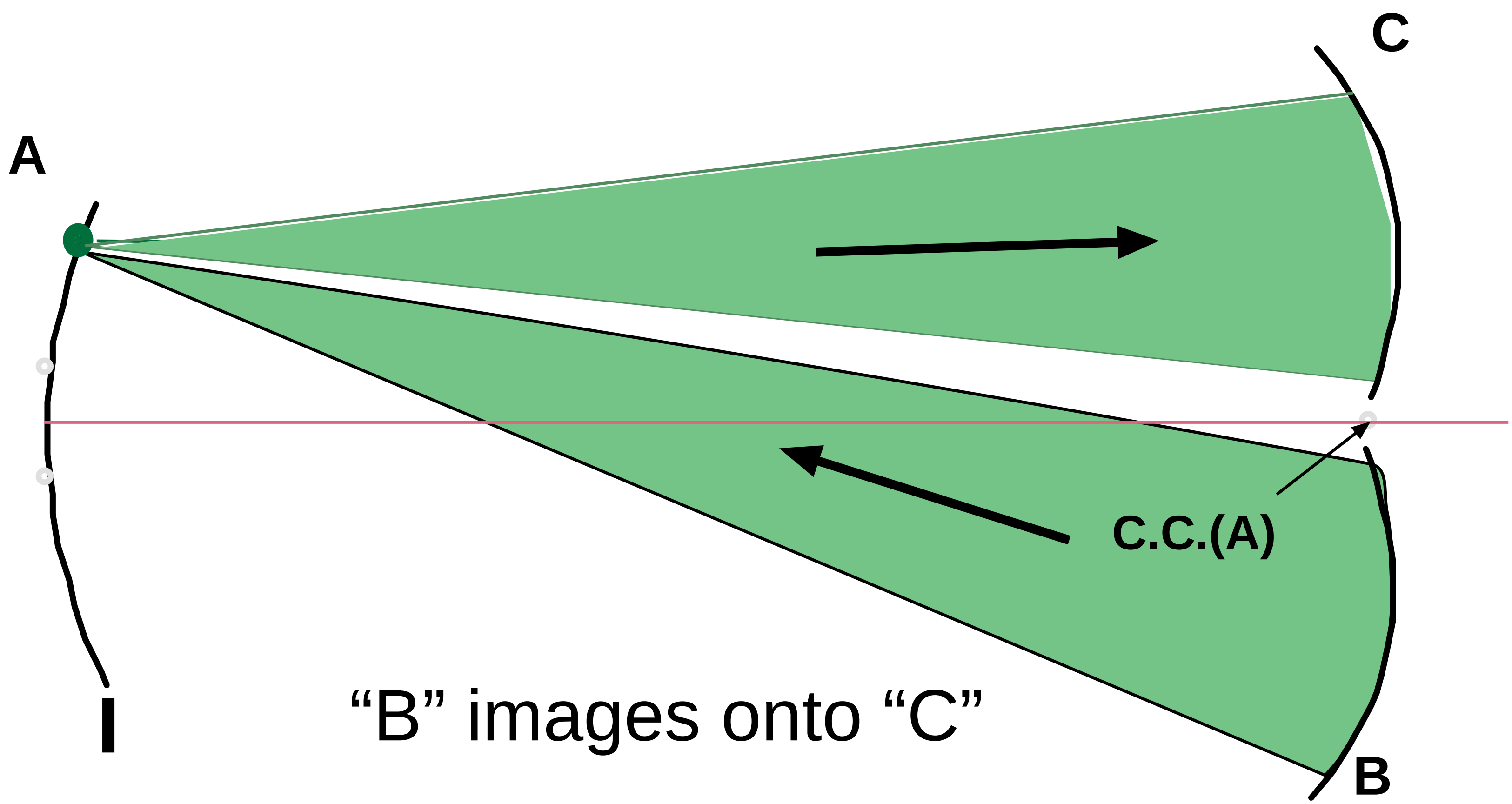
Second White cell imaging condition



“B” images onto “C”

Thus no diffraction losses

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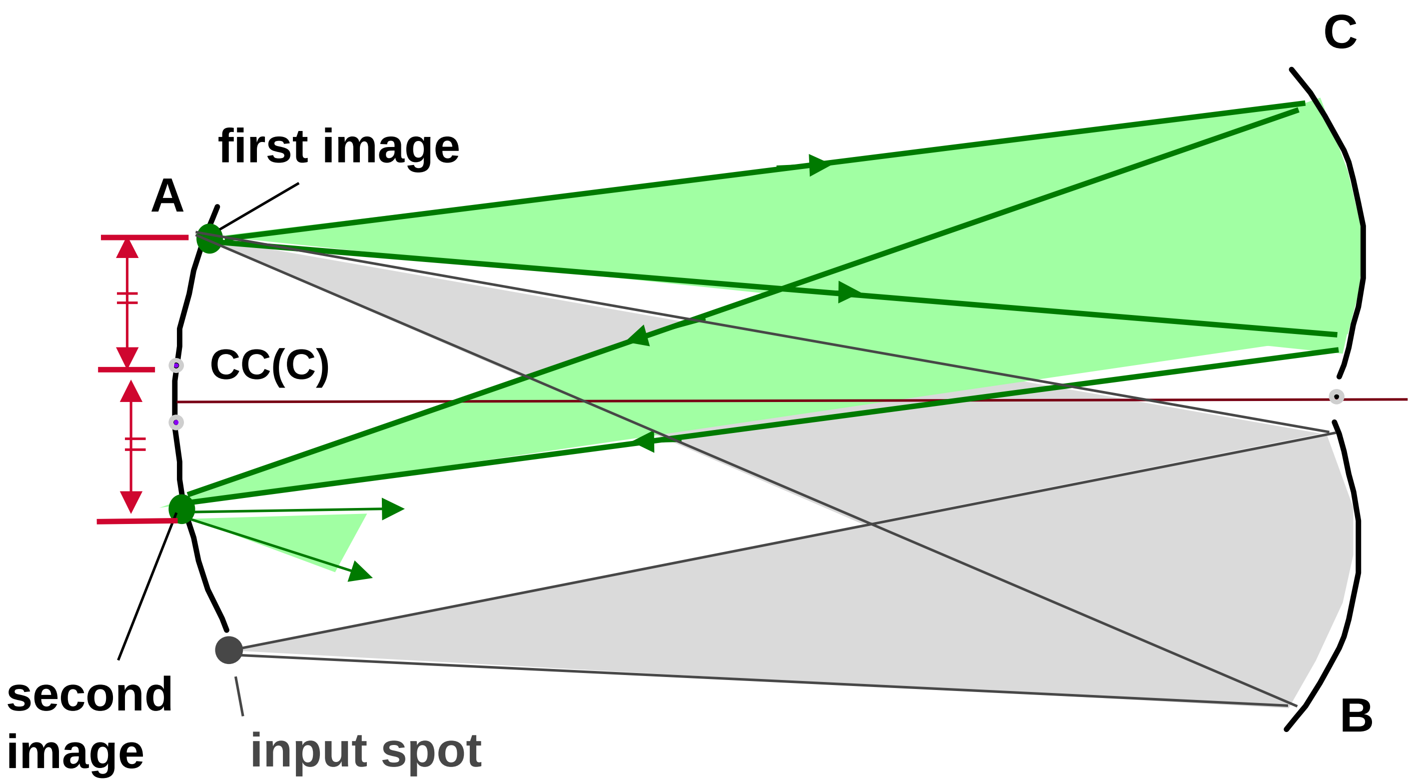
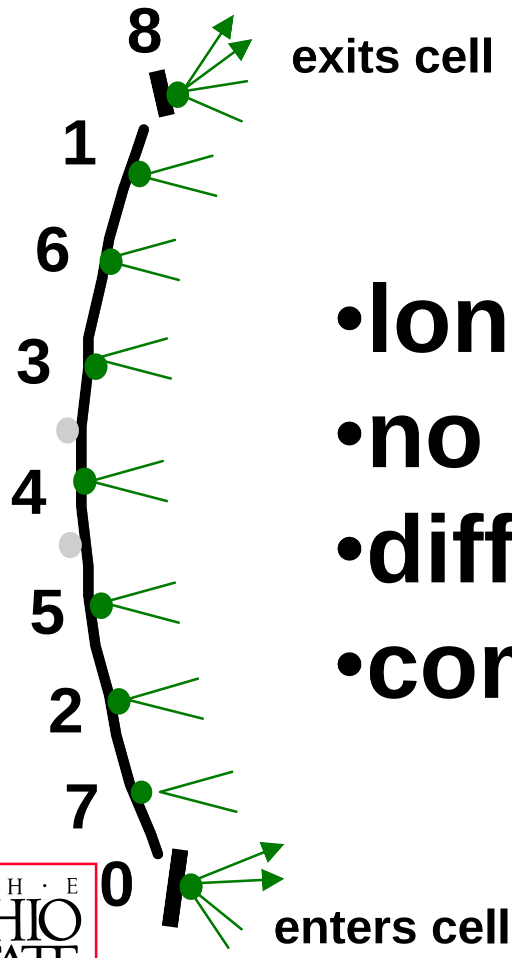
White Cell - continued

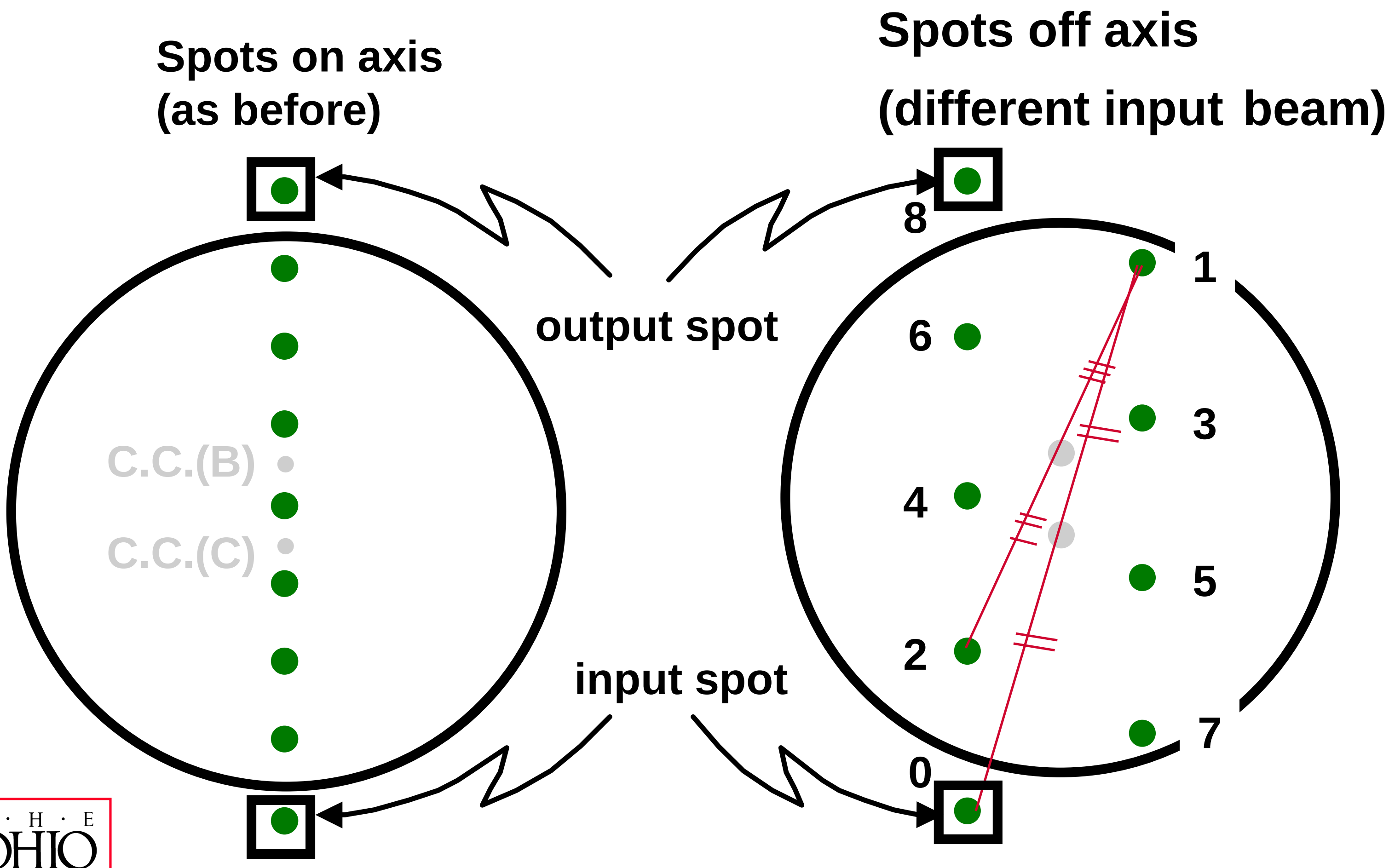


Sequence of Spot Images
(for one input beam)

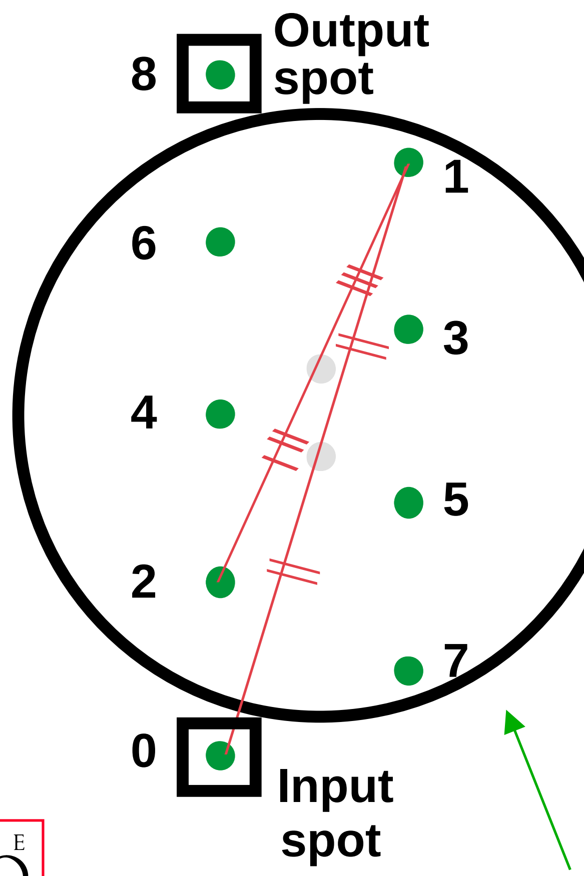


- long optical path possible
- no divergence
- diffraction limited
- compact

End View of Mirror



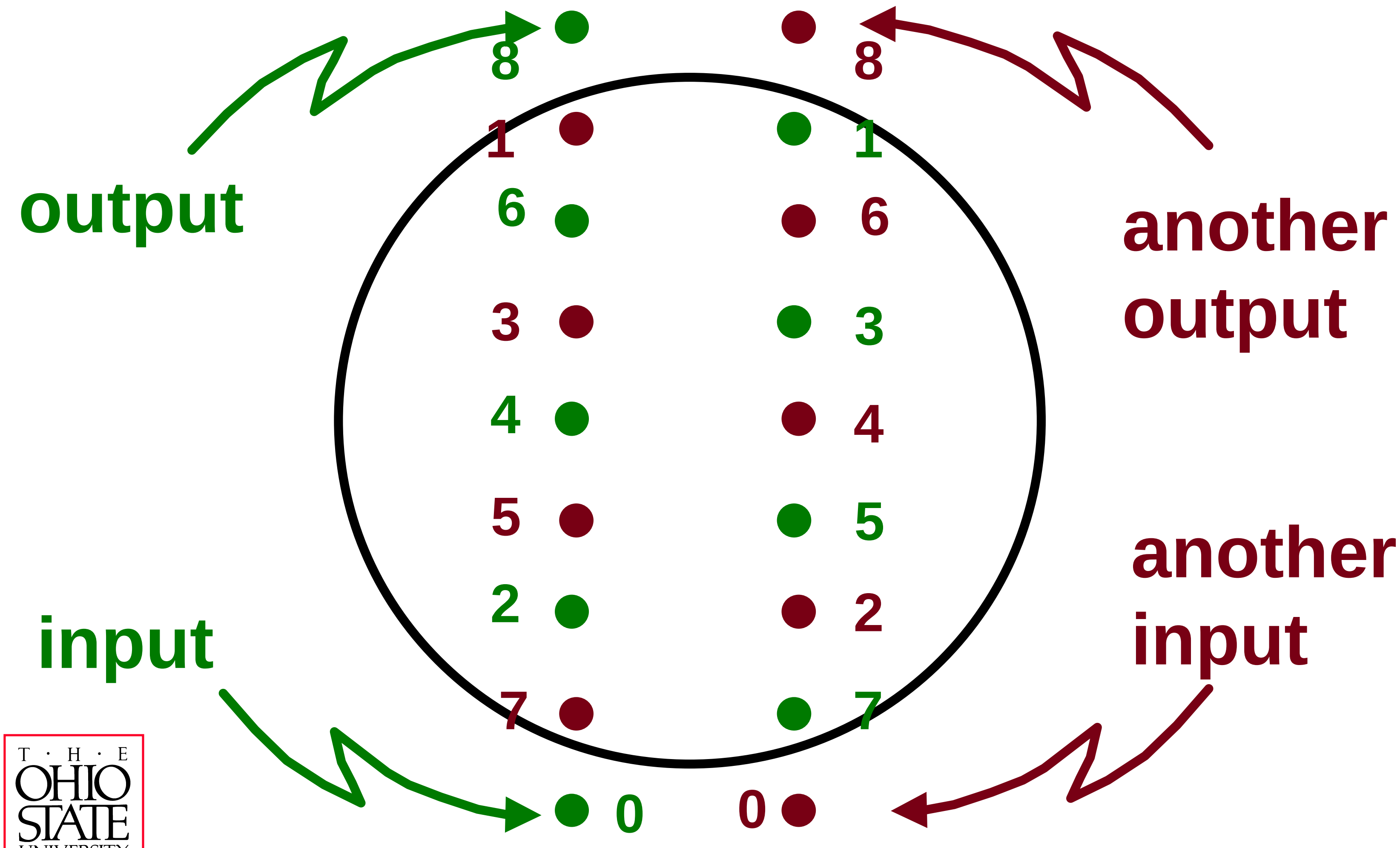
Significance of spots



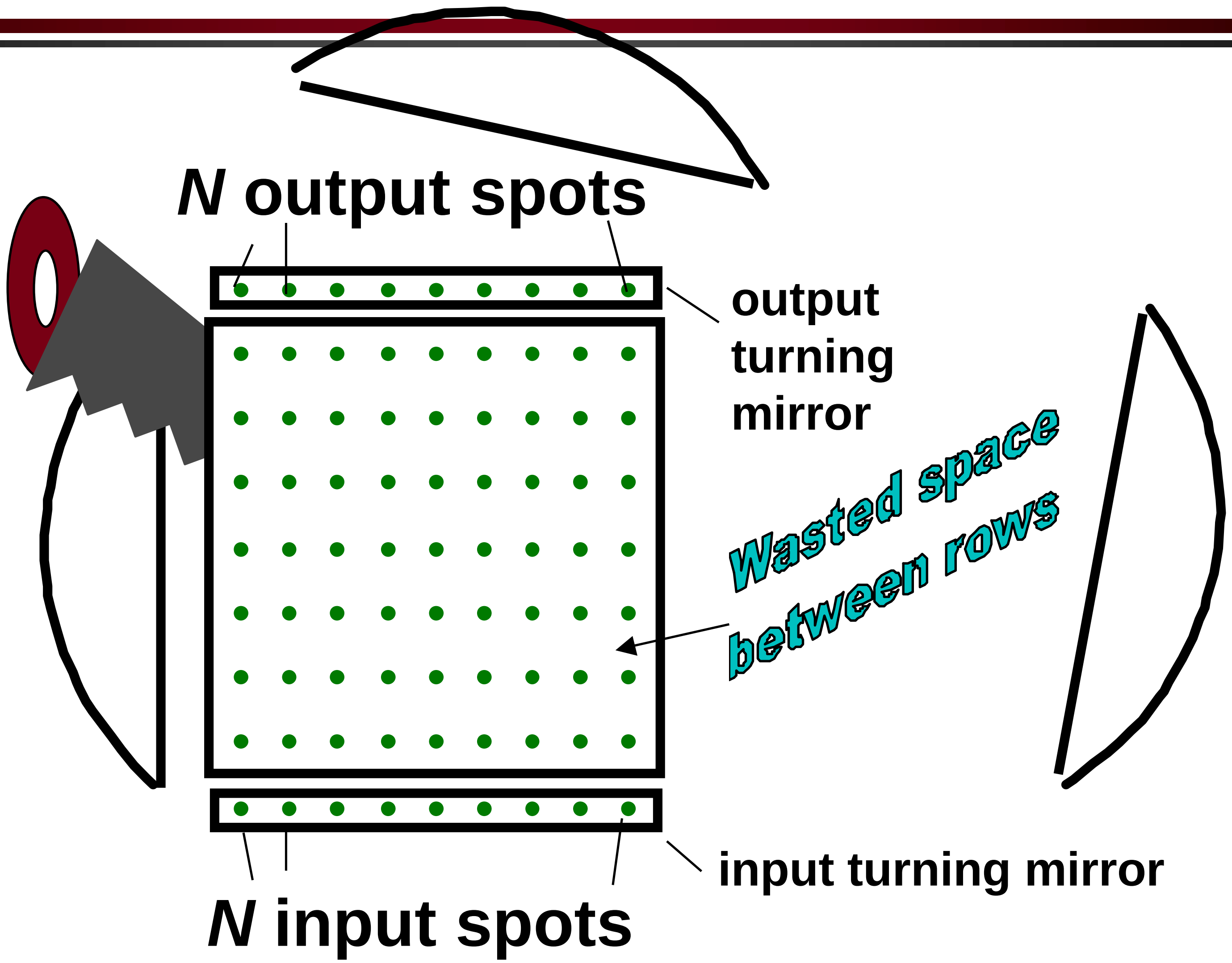
- Spot pattern depends on input location and Mirror B,C alignment
- Will map spots to pixels on MEM
- Emphasize spot pattern not determined by MEM

Mirror A soon to be a MEM

Bring in a second light beam



Complete Spot Set



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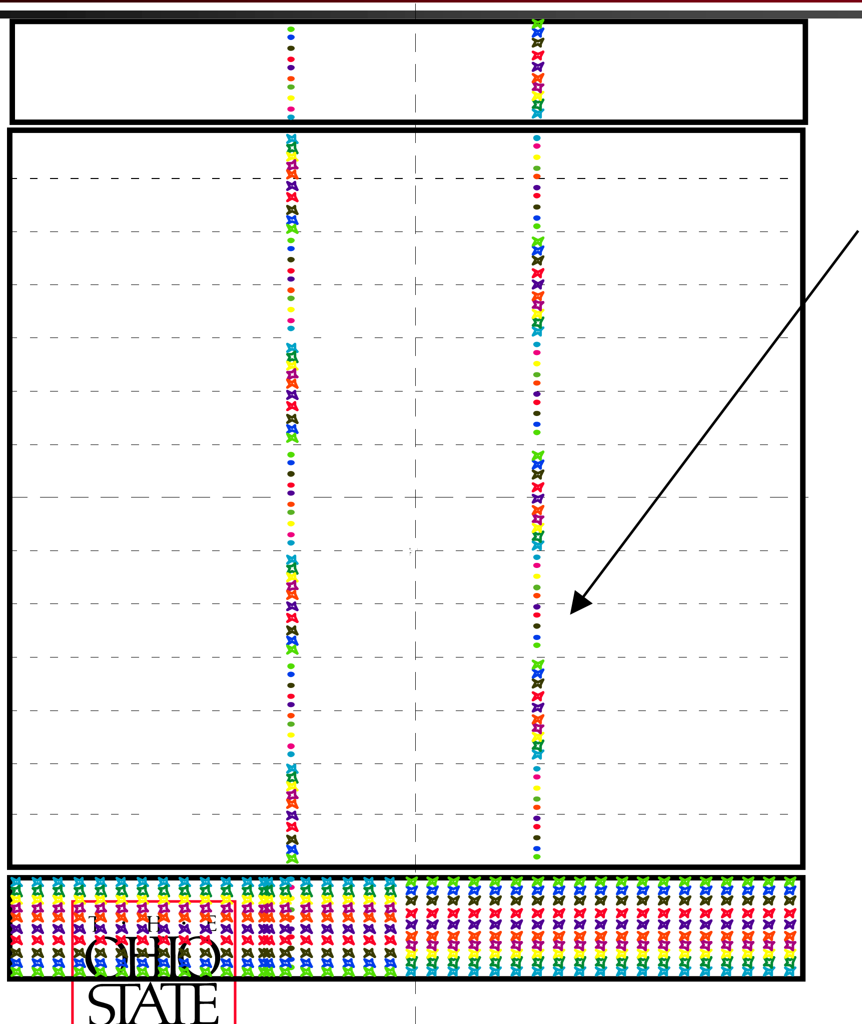
Can add even more spots...



The whole group bounces around, still striking unique pixels

- **One light beam per antenna element**

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Summary of White cell

- Beams bounce back and forth a set number of times *m*
- Alignment of B and C determine *m,* not Mirror A (or future MEM)
- Many beams can circulate through cell at same time
- Now, to adapt it to switchable delays

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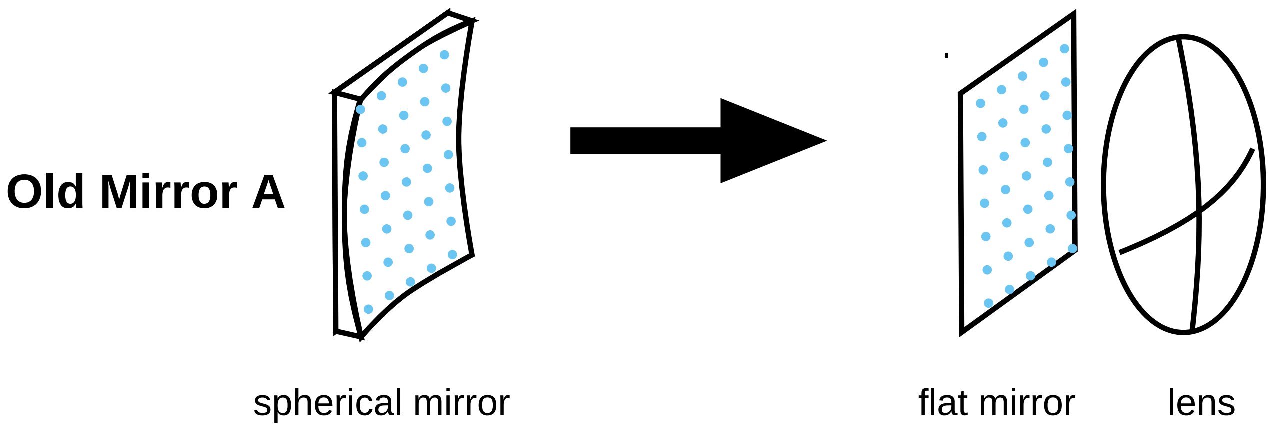
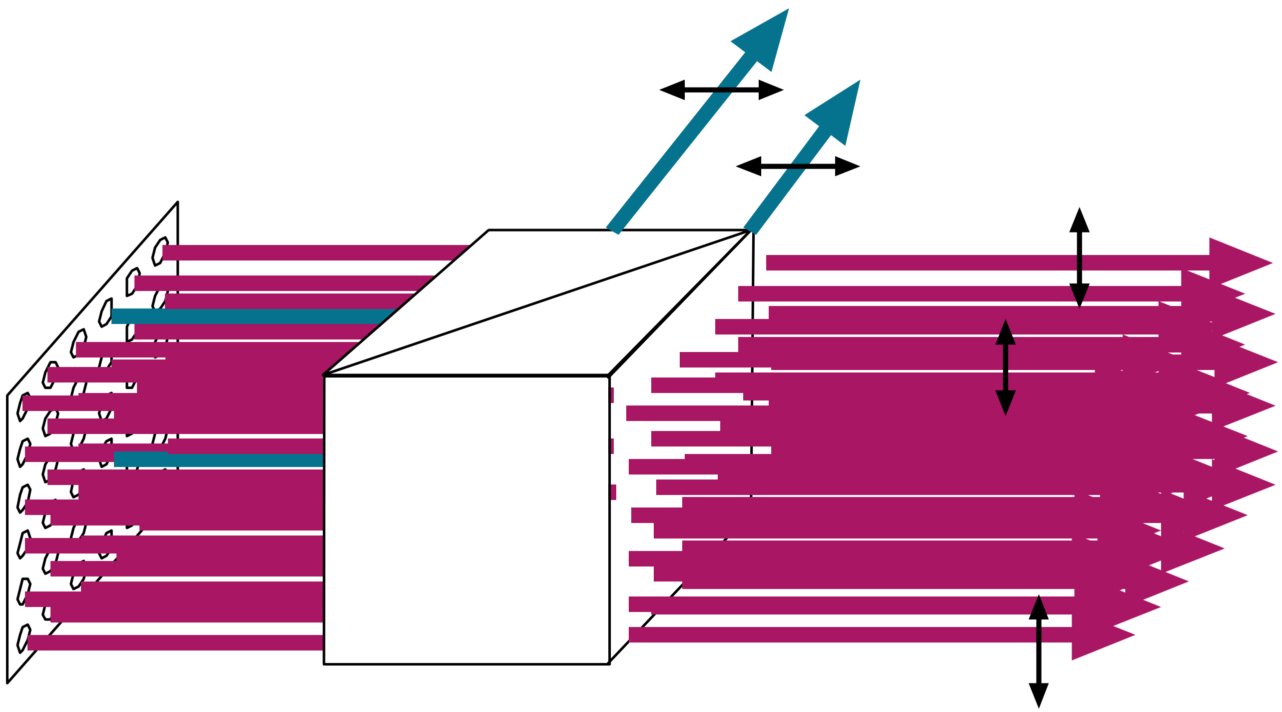
Replace Mirror A with an SLM



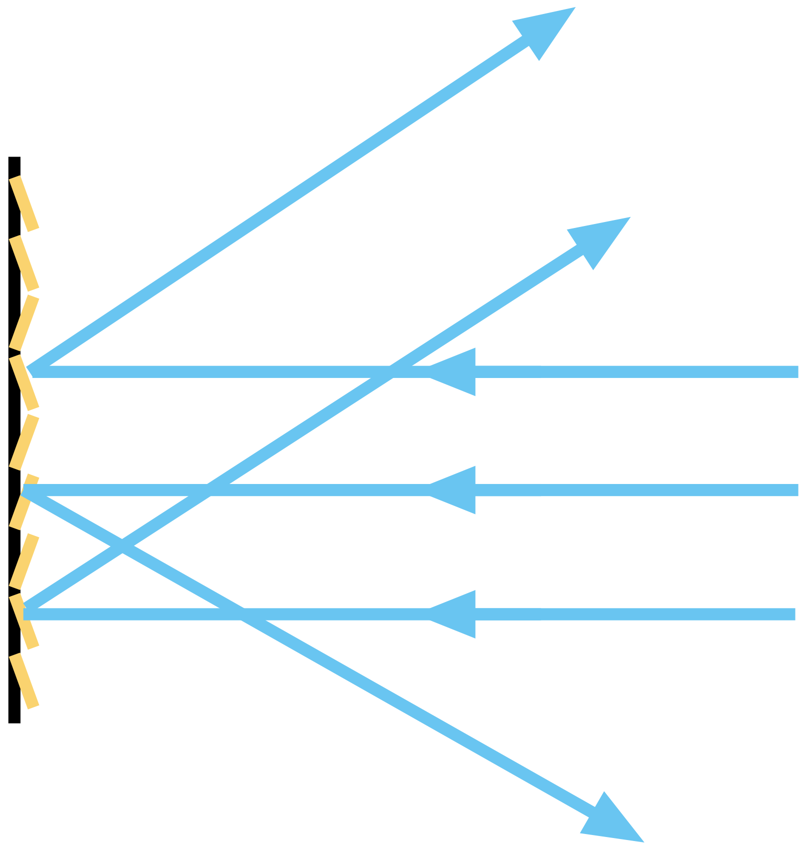
- Operation is the same optically
- Then replace flat mirror with a spatial light modulator
- SLM can be liquid crystal or microelectromechanical (MEM) device

The SLM controls the path

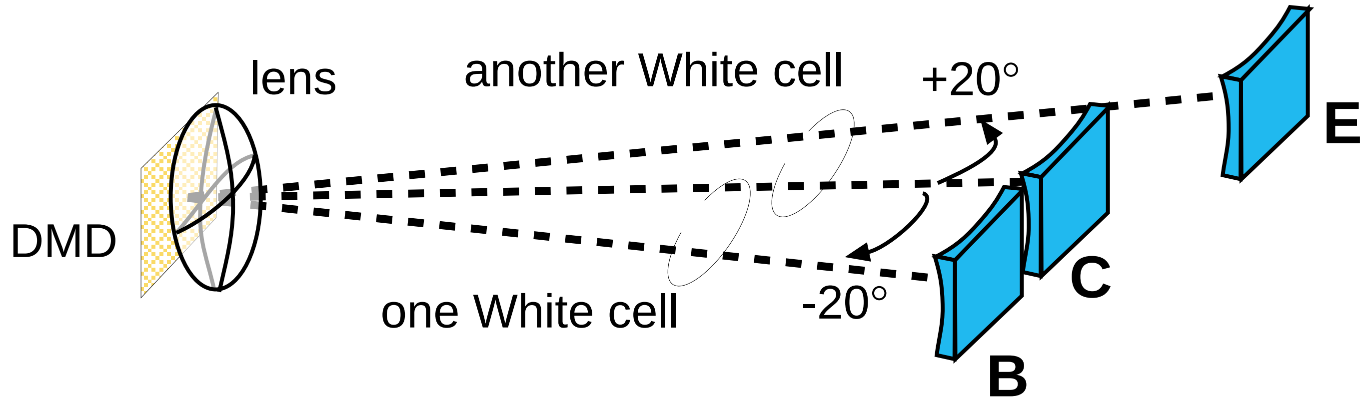


Or using a MEM

- Micromirrors tip to (suppose) two angles
- Beams can be deflected in different directions
- Put this into a White cell



Replace Mirror A with MEM and lens



- Let MEM first be two-state (e.g., TI DMD)
- Can form two White cells
- Path length different for White cells but spot pattern is the same regardless of path

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We call this a linear TTD cell

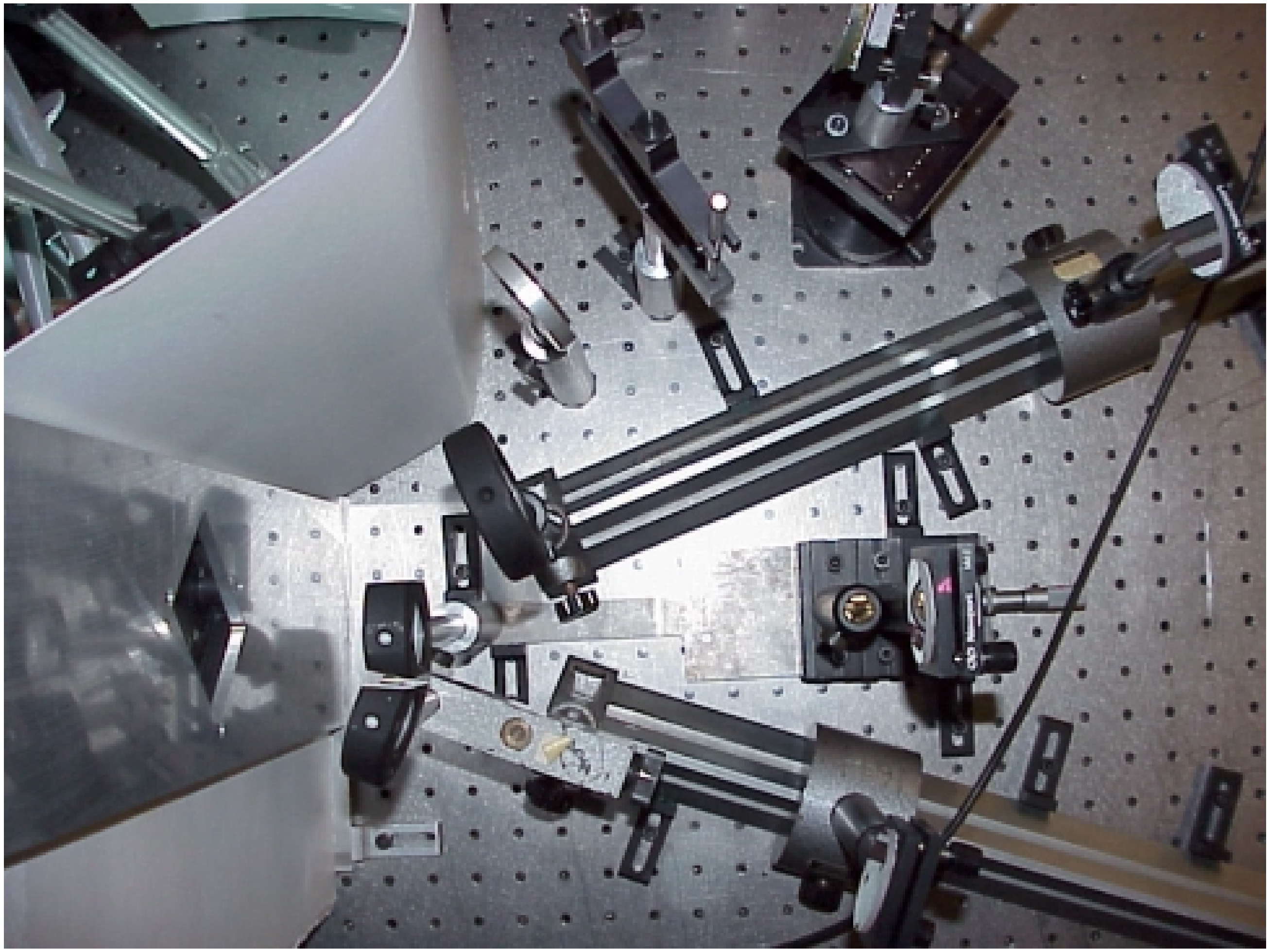
- Number of delays is proportional to *m:*

$$N = \frac{m}{4}$$

where *m* is the number of bounces

- Note number of bounces is fixed- set by spherical mirrors

Linear cell apparatus



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Details of linear cell

- Time increment was 1 ns
- Used pulsed laser (green) to measure delays
- Loss ≈ 1.2 dB/bounce
  - » Diffraction a big problem
    - – Pixels smaller (16 μm) than our beam
    - – We used a 50x50 pixel "macropixel"
    - – Get diffraction off interpixel gaps and holes in mirrors
  - » Mirrors are aluminum (gold has higher reflectivity)

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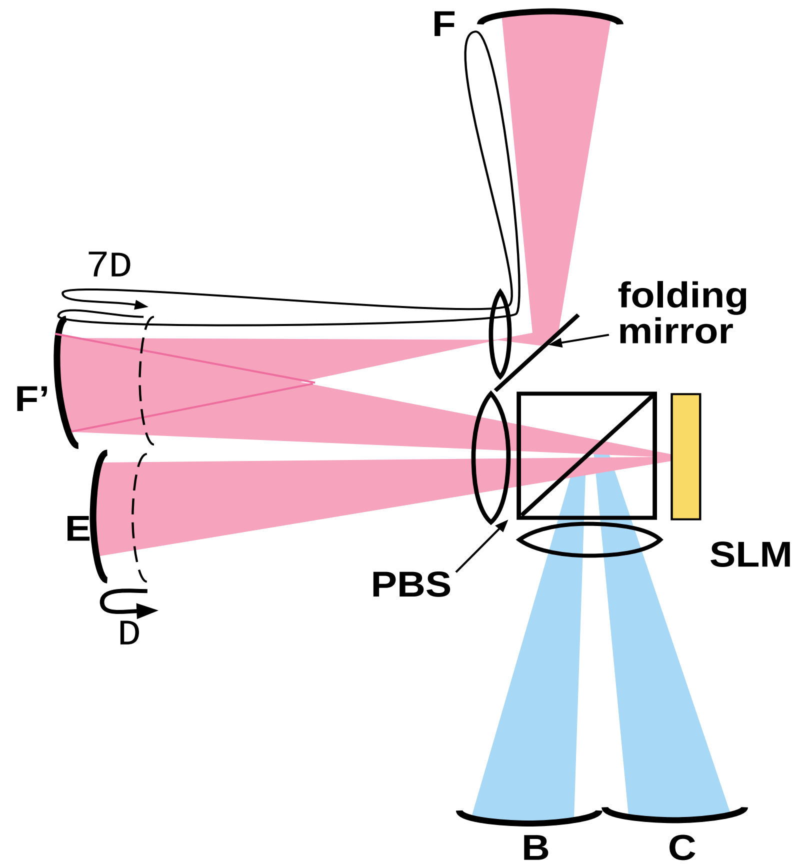
Next design (using an LC)

- "E" is the one's place
- Can count up to *m/2* by going to E (say, 6 in 12 bounces)
- Make "F" longer by 1 (the 7's place)
- Can go there up to six times



Here we're counting in base "6"

This is a quadratic cell

- Number of delays goes as

$$N = \left(\frac{m}{2}\right)\left(\frac{m}{2}+1\right) + \left(\frac{m}{2}\right)(1) = \left(\frac{m}{2}\right)^2 + 2\left(\frac{m}{2}\right)$$

Number of possible visits to F

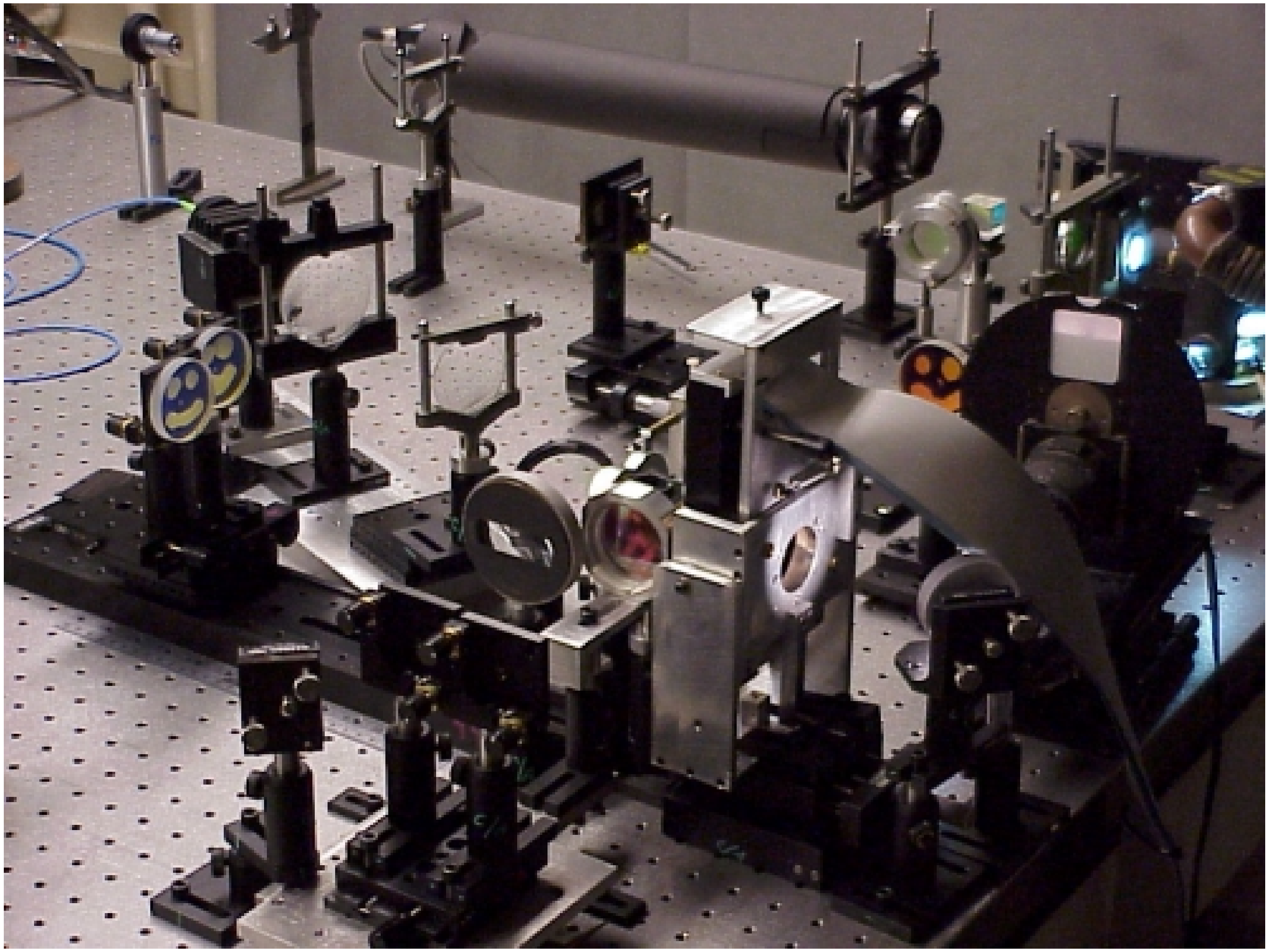
Delay of F

Number of possible visits to E

Delay of E

- Quadratic in *m/2*

Quadratic cell apparatus



Details of quadratic cell

- Used diode-pumped Nd:YAG laser (1319 nm)
- Time delay increment 1 ns
- Had four input spots
  - » Fiber array in silicon V-groove
- Losses about 1 dB/bounce
  - » Almost all of it was due to SLM and PBS
- Crosstalk was lousy (SLM was designed wrong)

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Loss is a problem

- Both designs had worse than 1dB loss per bounce
- Liquid crystals are about as good as they are going to get
- MEMS are going to get LOTS better
- Industry prediction is <0.1dB/bounce
- Still have to keep number of bounces low- certainly to fewer than 20

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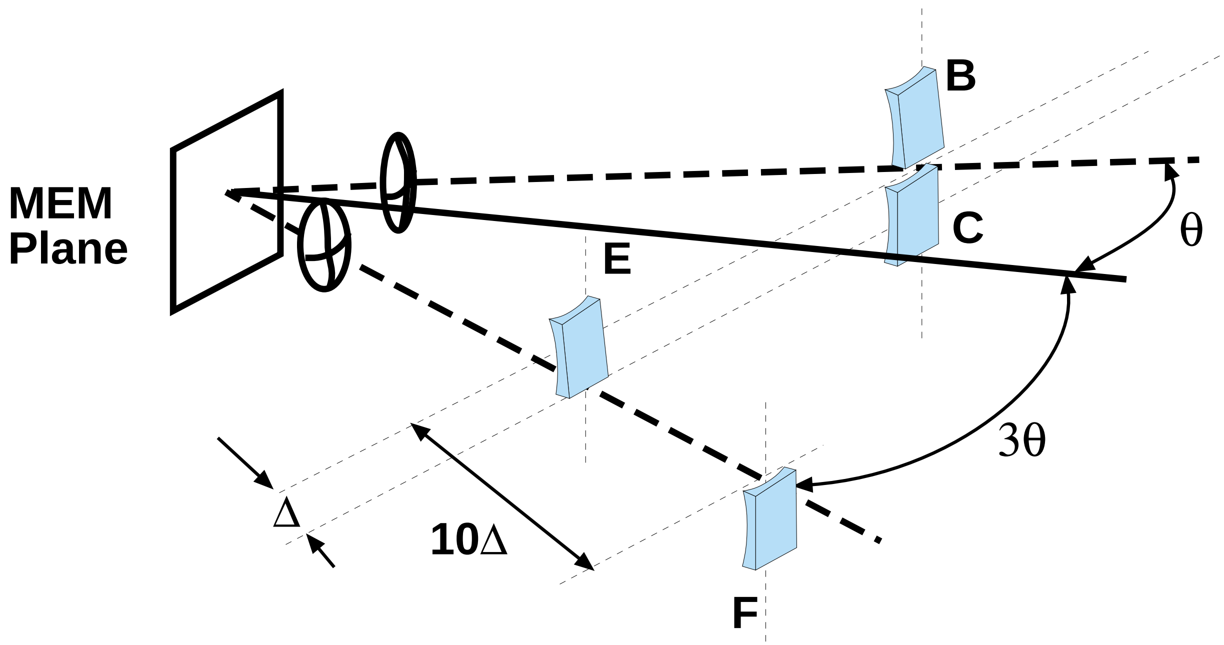
How to do quadratic with a MEM?



- One White cell along $+\theta°$ axis
- Two more mirrors along $-3\theta°$

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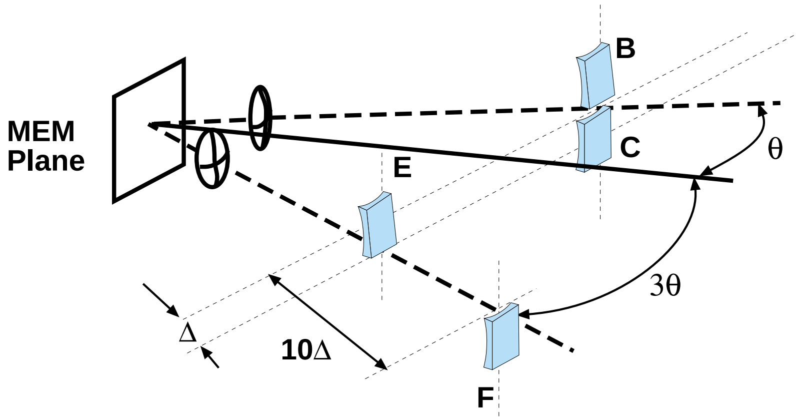
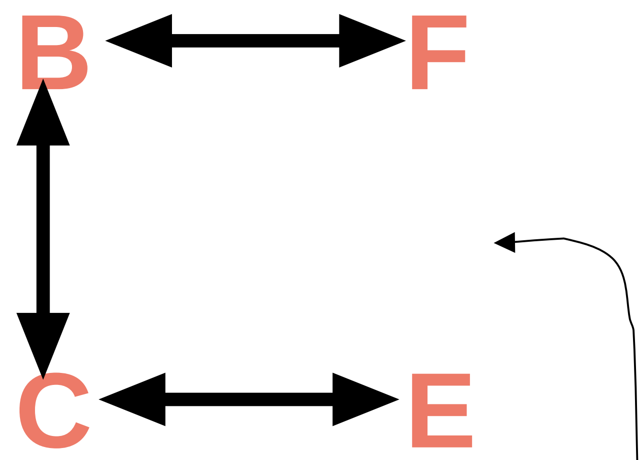
Transitions





- Always go from upper to lower mirror
- Light can go from
  - » B to C
  - » B to F
  - » C to E

This transition not possible ☹

As a result

- This one is quadratic, but in *m*/4 instead of *m/2*

$$N == \left(\frac{m}{4}\right)^2 + 2\left(\frac{m}{4}\right)$$

But with 20 bounces…

- Linear MEMS-based cell could do 5 delays 😝
- Quadratic MEMS-based cell could do 25 delays ☹
- Have to do better…

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Suppose MEM had *three* states

- Can add another axis
- Allows for two more White cell mirrors
- Now have a 1’s, 10’s, 100’s, and 1000’s mirror
- Number of delays goes as number of bounces to the fourth

Quartic cell

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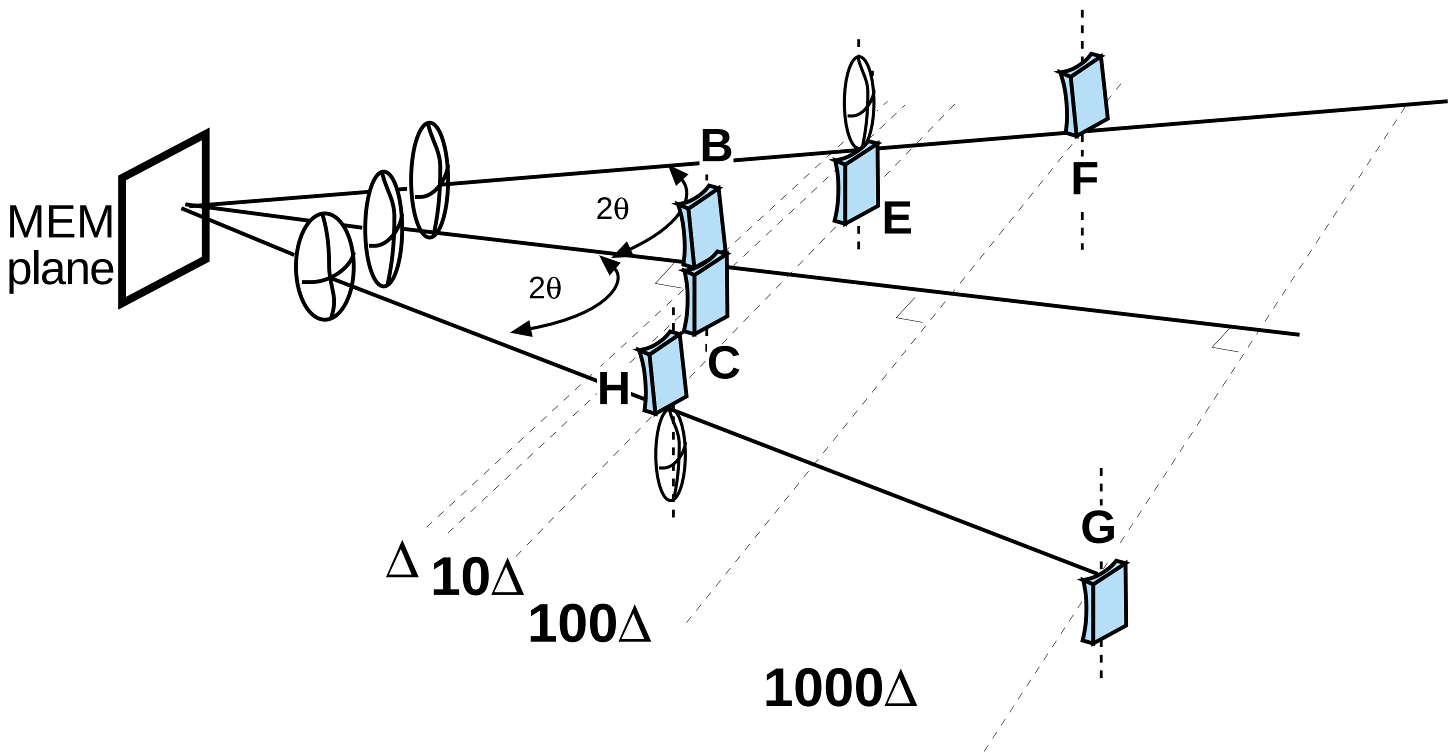
Layout of 3-state quartic cell



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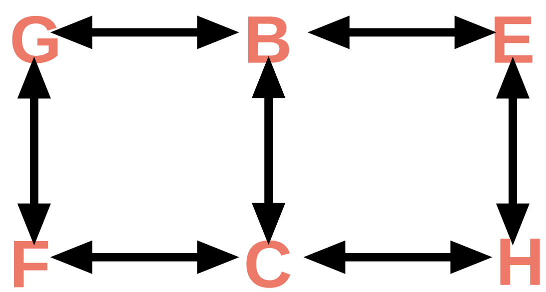
Connectivity diagram



Closed loops!

- Means more delays for fewer bounces
- More flexibility

Meaning:

- Quadratic cell
  - » Open loop (2-state MEM) $N \propto (m/4)^2$
  - » Closed loop (liquid crystal) $N \propto (m/2)^2$
- Quartic cell
  - » Open loops (hypothetical) $N \propto (m/8)^4$
  - » Closed loops (3-state MEM) $N \propto (m/4)^4$

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Number of delays

$$N=\left(\frac{m-2}{4}\right)^4+4\left(\frac{m-2}{4}\right)^3+6\left(\frac{m-2}{4}\right)^2+4\left(\frac{m-2}{4}\right)-1$$

- Suppose have 18 bounces
  - » Build arms *Δ, 5Δ, 25Δ, 125Δ…*
  - » Count in base 5 not base 10
- Can have 611 delays 😐
- Not enough for greedy radar guys

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Suppose MEM had more states

- For each additional state can add two White cell mirrors
- That adds two significant digits to total number of delays (in whatever base you're counting in)
- Five states: "octic" cell (if that's a word)
- Of course, still have to get loss down to get *m* up

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Suppose…

- The five states were East, West, North, South, and flat
- Put two White cell mirrors in each of those directions
- Two mirrors (B and C) form a null cell
  - » No net delay if just go to these
- Rest are delay arms

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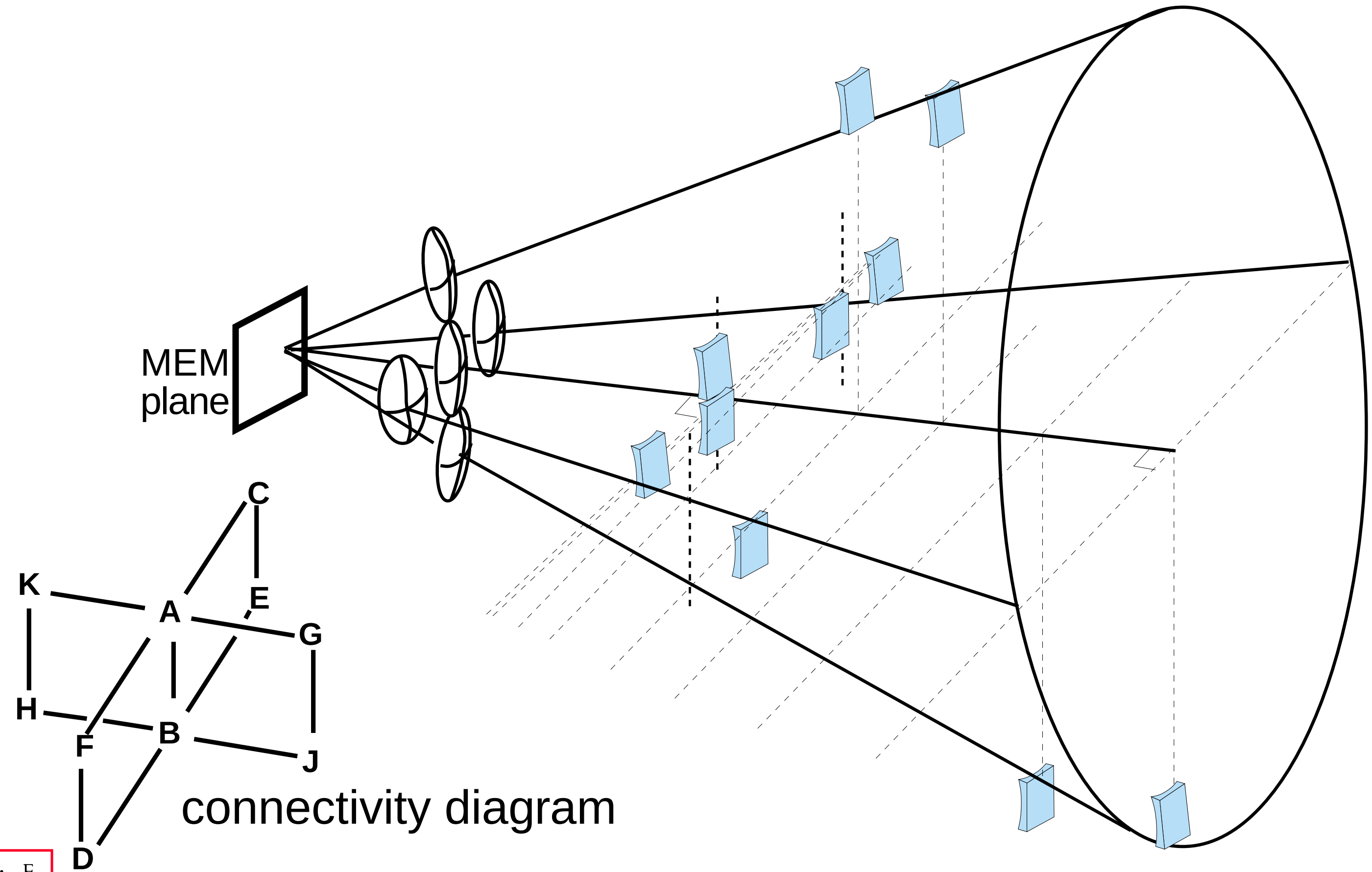
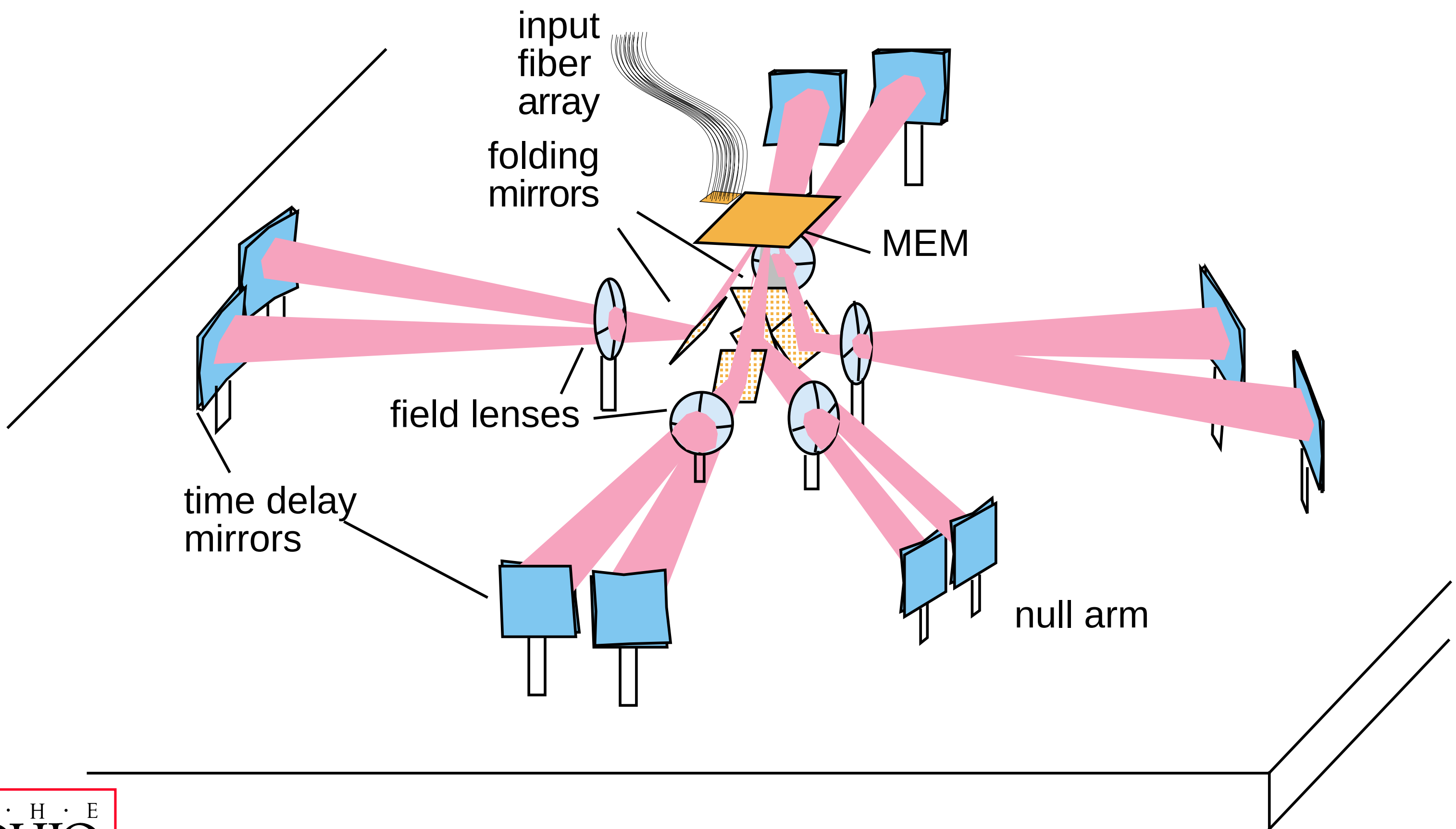
The “Octic” cell



In the lab, we'll do this…



Number of delays

$$N = \left(\frac{m-1}{8}\right)^8 + 8\left(\frac{m-1}{8}\right)^7 + 28\left(\frac{m-1}{8}\right)^6 + 56\left(\frac{m-1}{8}\right)^5 + 68\left(\frac{m-1}{8}\right)^4 + $$
$$+ 48\left(\frac{m-1}{8}\right)^3 + 16\left(\frac{m-1}{8}\right)^2 + 0\left(\frac{m-1}{8}\right) - 1$$

- Or, in 17 bounces, can have 6,399 delays.☺

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But, hey, it turns out…

- Some micromirrors only *ever* tilt north and south
- Other mirrors only ever tilt east and west
- So really only have to build a 3-state MEM
- Just rotate half of them!

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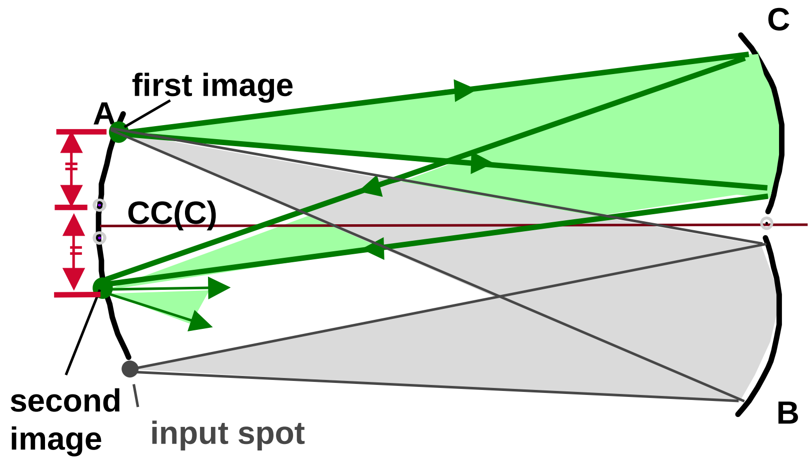
What about analog mirrors?

- Sure, they exist
- They have infinity states
- Overkill for us
- We need at least 10° between positions
  - » Because beams diverge
  - » Can't have beams overlapping
  - » We have to use 1.5μm

•Current analog MEMS only have a range on the order of 10° anyway

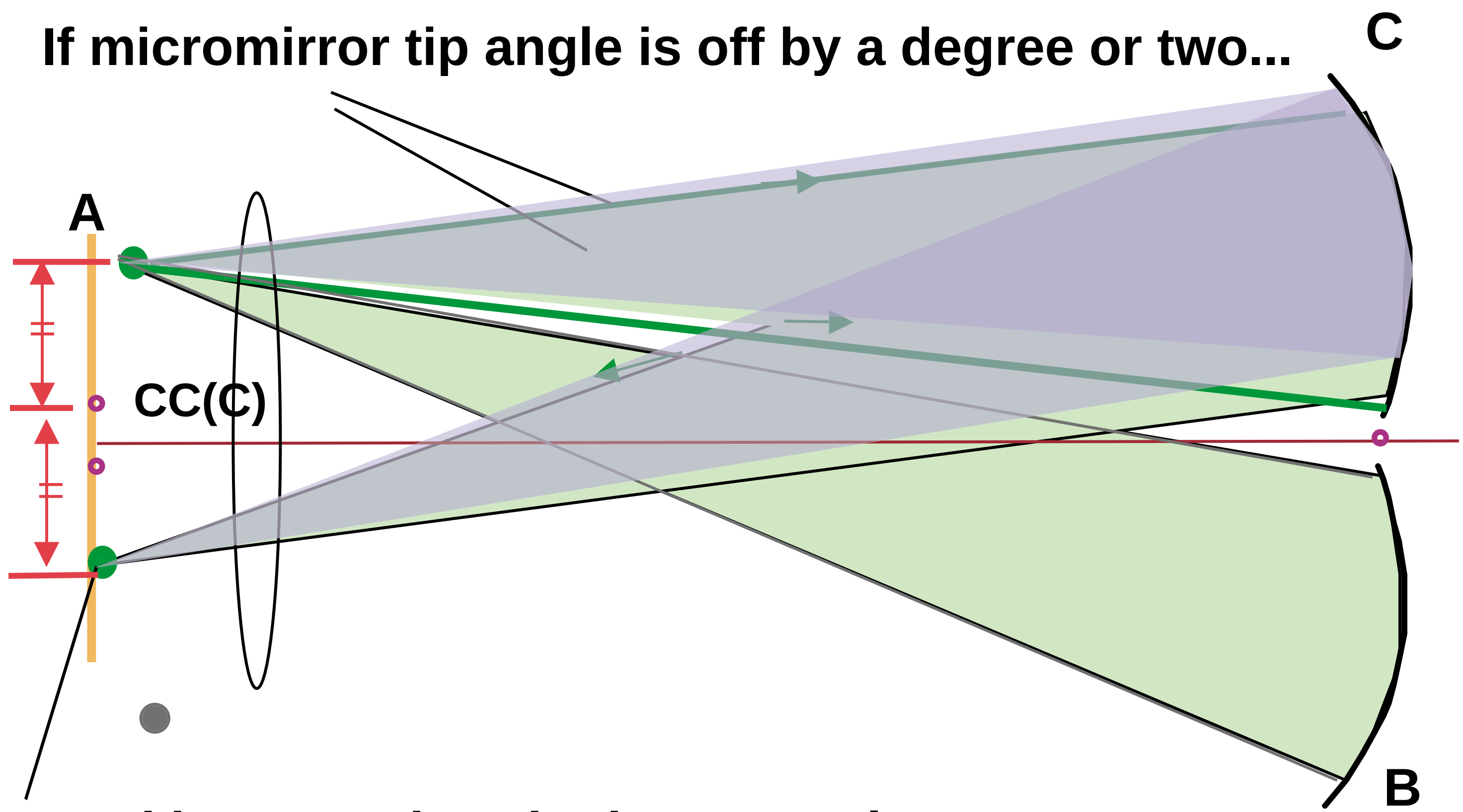
Tilt angle accuracy not a big deal

- Recall operation of White cell
- Spot returns to A because of imaging of B and C
- "A" replaced by MEM…



MEM just sends light to correct White Cell mirror

If micromirror tip angle is off by a degree or two...



...second image arrives in the same place anyway

Simplifies MEM

- Don't need precise aiming
- Don't need optical feedback to keep micromirrors pointed
- Don't have to worry about micromirror drift
- Don't need dual gimbal construction

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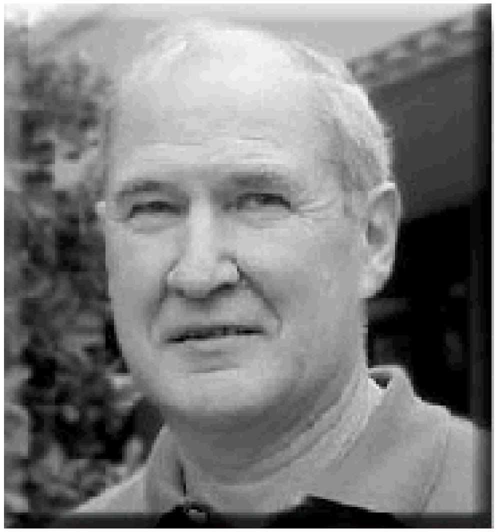
MEMS Micromirror Array

Being developed by:

Noel C. MacDonald

University of California
Santa Barbara



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Key goals

- 1-D mirror arrays
  - » Mirrors can tip to three angles along one axis
- Optical quality good enough for communications
  - » Very low loss
- Packaging large arrays
- Demonstrate large arrays

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New facility at UCSB

- Class 1000 clean room
- Process line for 8” wafers
  - » 3 ICP etching stations
    - – includes100nm Bromine chemistry Silicon/InP etcher - great for optically flat sidewalls
  - » 3 tube, 8”wafer-size oxidation furnace
  - » 8” optical Lithography tool
- Can do everything in single crystal silicon
- Also have access to National Nanofabrication Users Network (NUNN) facility at UC Santa Barbara

Uniqueness

- New actuator design
- New mirror integration concepts
- High fill factor
- Double sided wafer processing

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Key issues

- How to make a very large array
- How to address thousands of mirrors
- How to get large tilt angles
- How to package such a device

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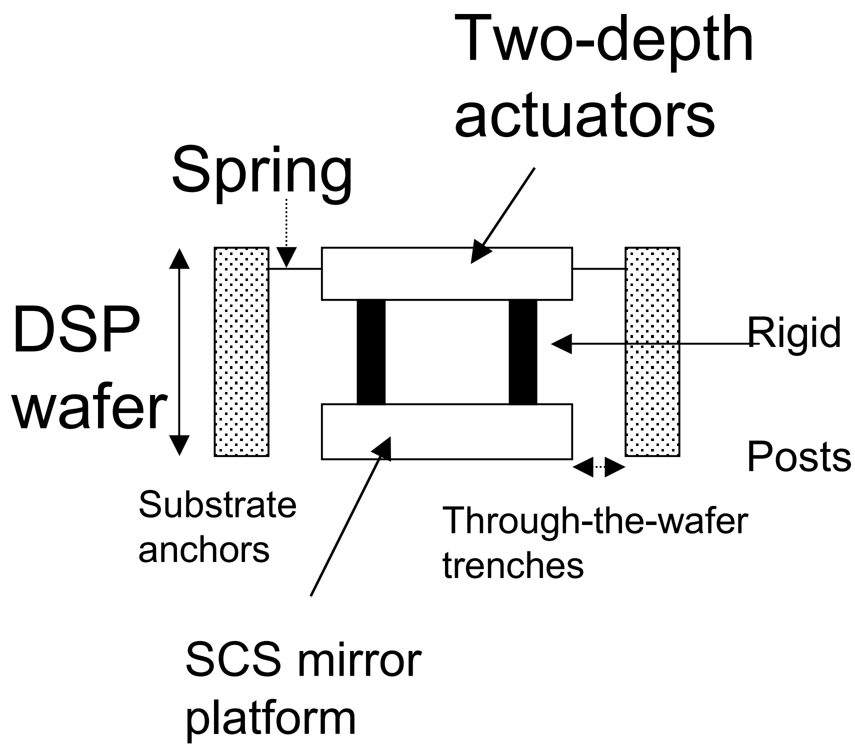
Approach

- Mount actuator behind the mirror
  - » (instead of around the outside)
  - » Actuator on front of chip, mirrors applied to back
  - » Use a through-the-wafer etch



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Will investigate

- Wafer bonding approaches to facilitate
  - » Large angle mirror tilt
  - » Improved access to interconnects
- Integration of multi layer thin-film mirror stacks
  - » Improve mirror reflectivity
- Control stress in MEMS (causes bowing)
- Fatigue and fracture of large-array chips

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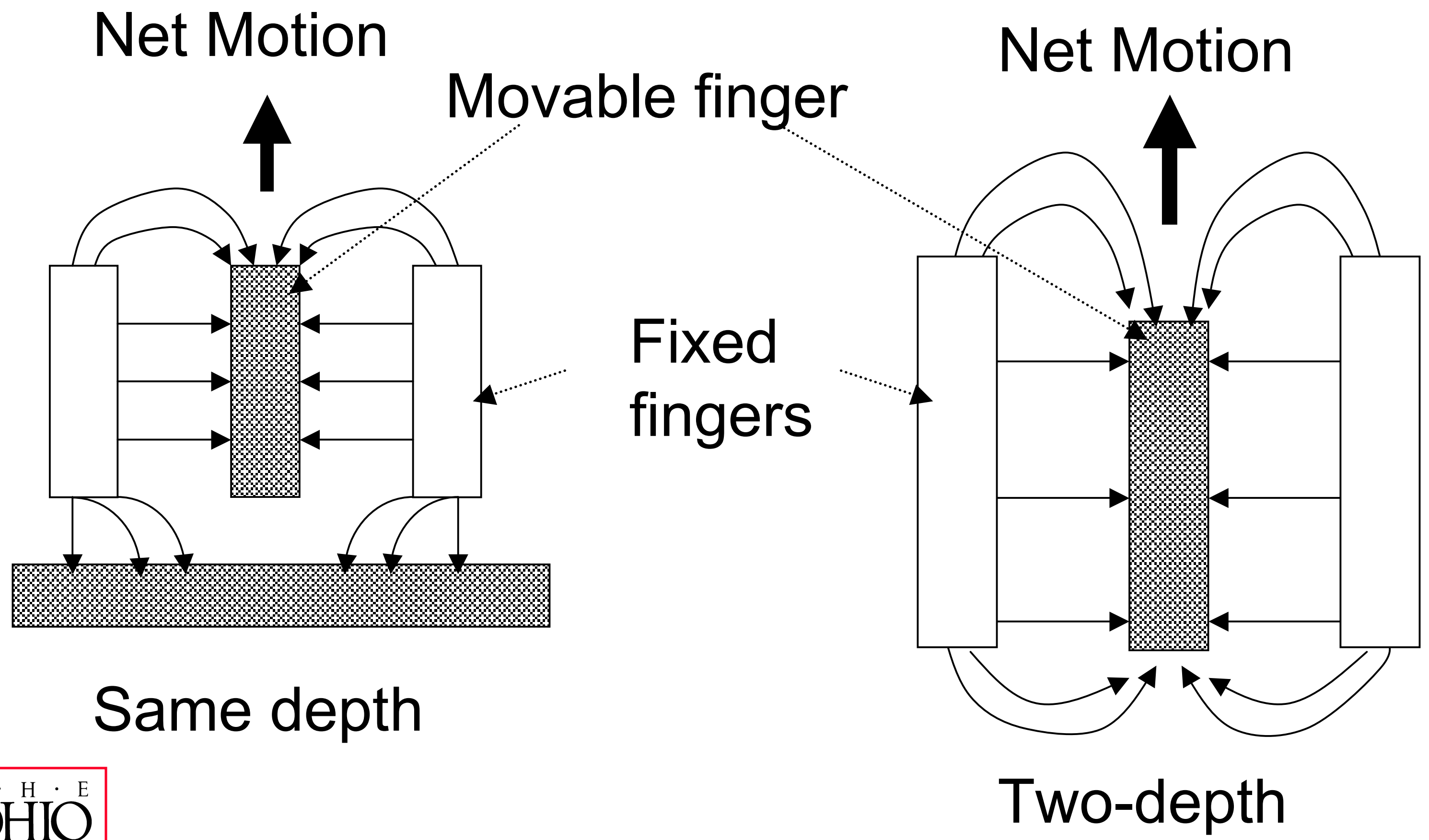
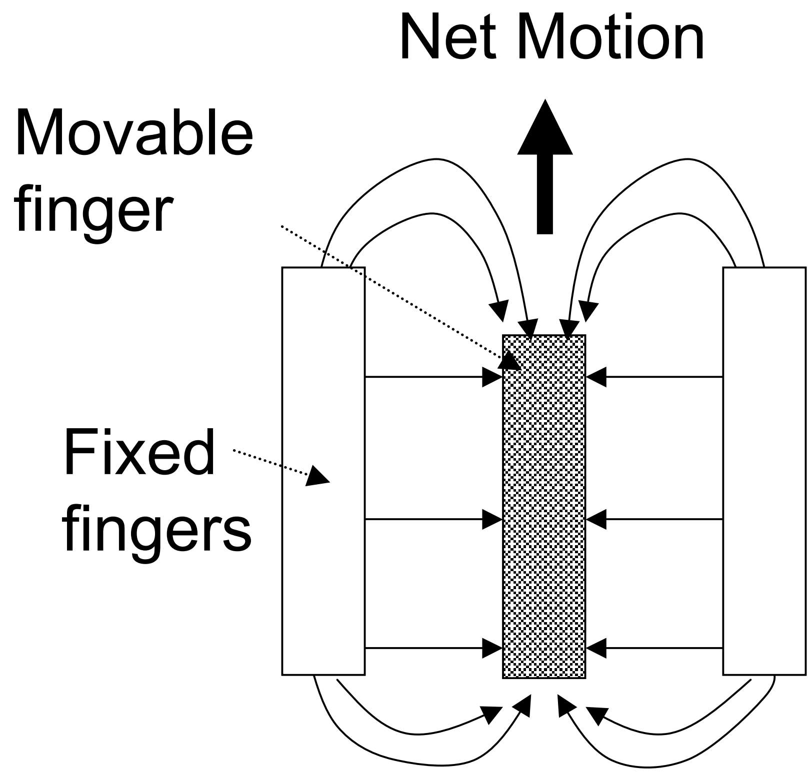
Big piece: Two-Depth Actuators



Advantage

- Increase vertical asymmetry in electric field
- Grounded substrate far away
- Asymmetrical metal coverage in SCREAM* process increases field
- Asymmetry produces vertical motion



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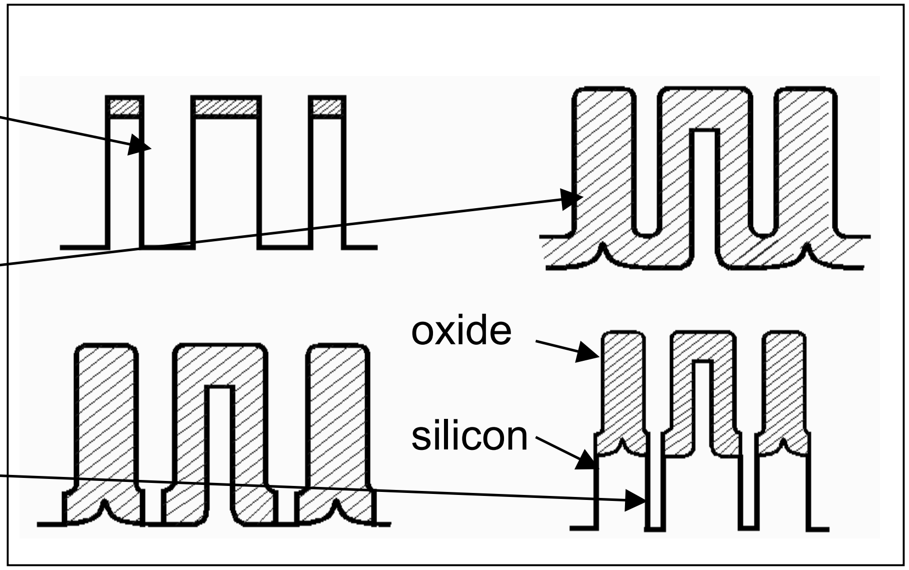
*Single Crystal Silicon Reactive Etch and Metallization

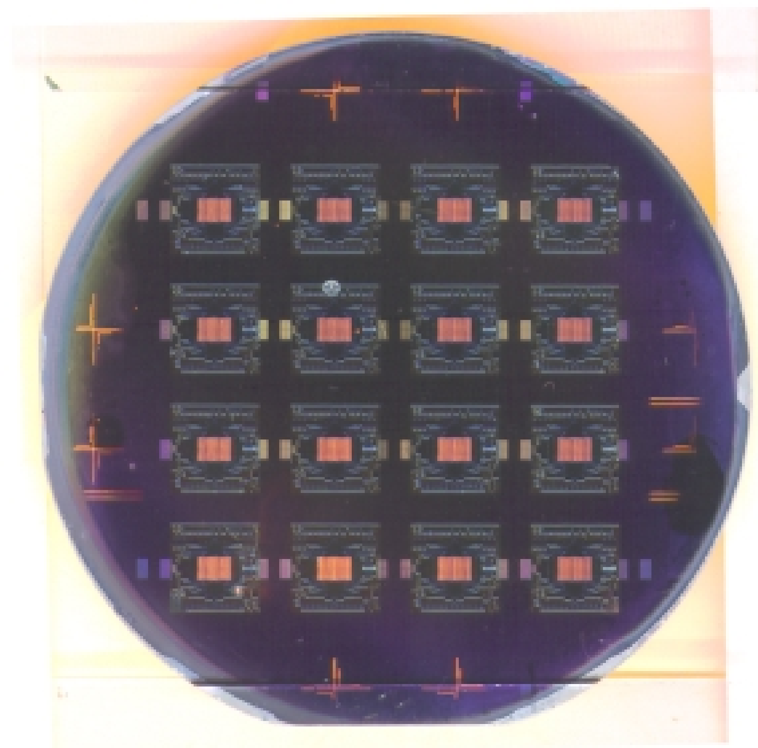
How to get that two-depth electrode?

- Make lines of different widths
- Vertical RIE etch
- Thermal oxidation consumes narrow lines
- Etch again to make trenches deeper
- Release from wafer (not shown)



A wafer

- Three inch wafer
- Sixteen mirror arrays
- Each chip has 25 mirrors



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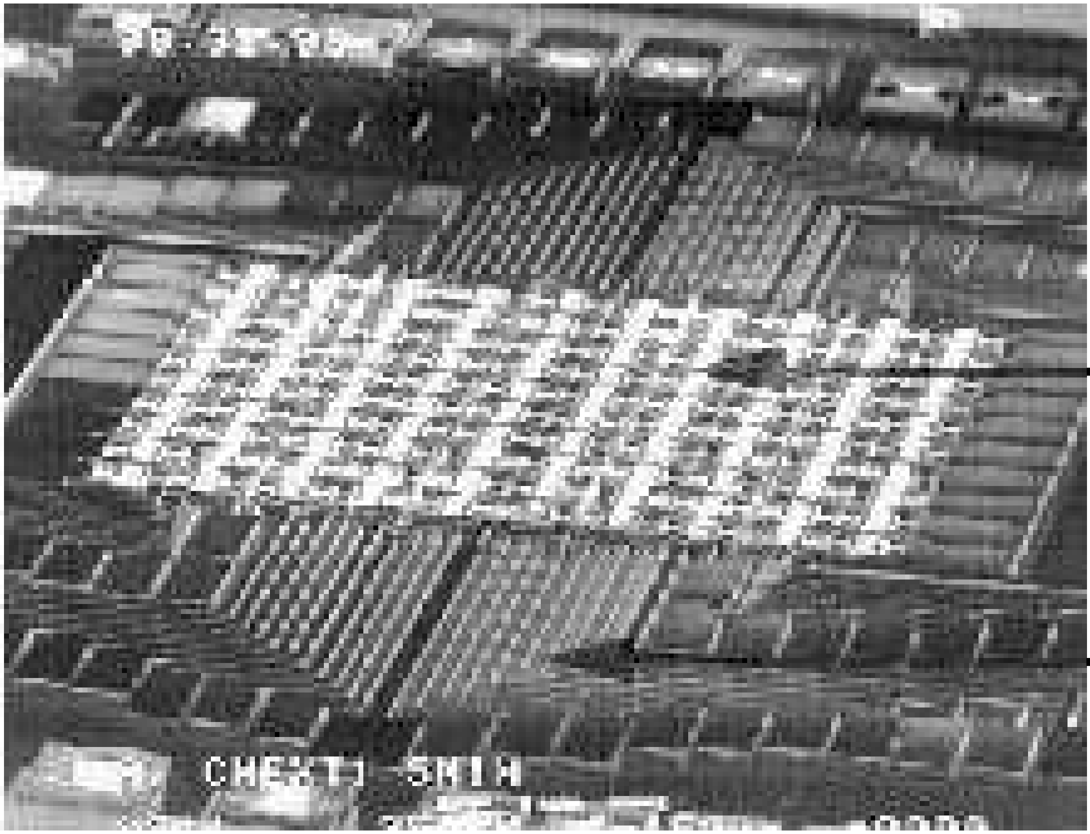
A 10x10 array: back side



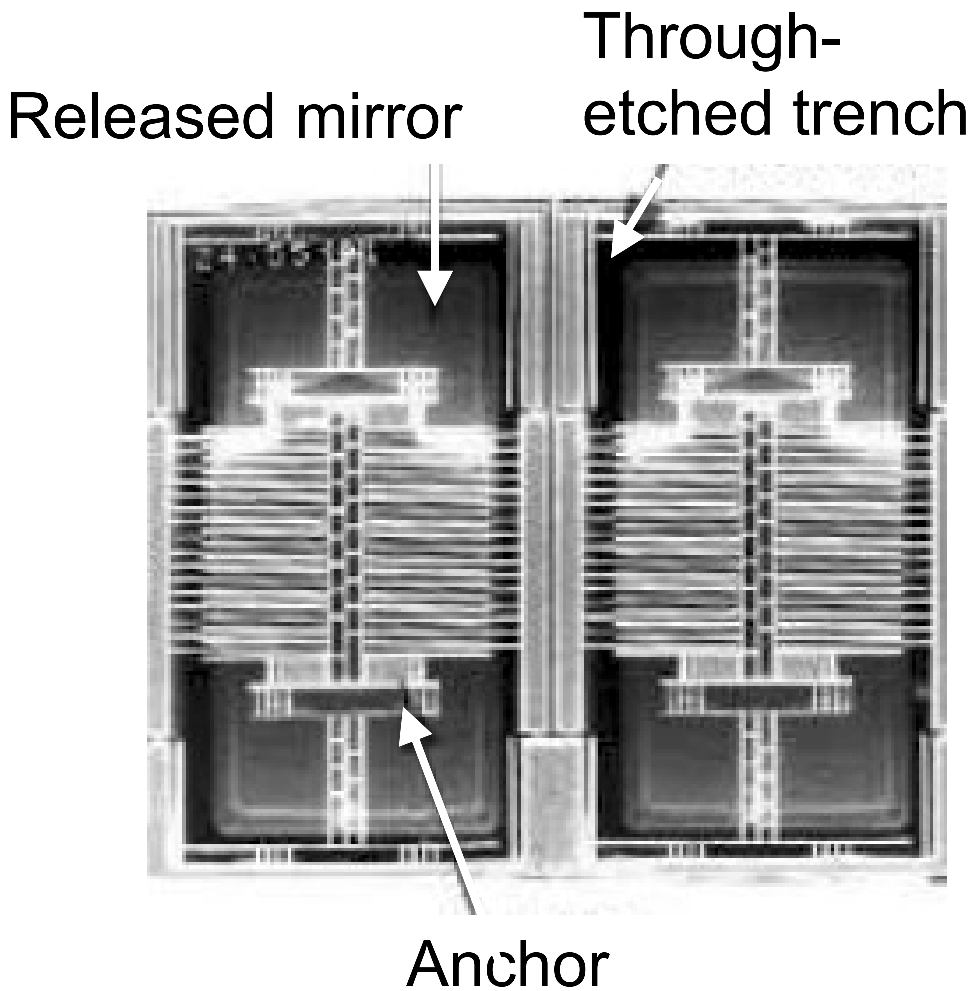
10x10 mirror array

(fill factor 85%)

Individually addressable contact pads

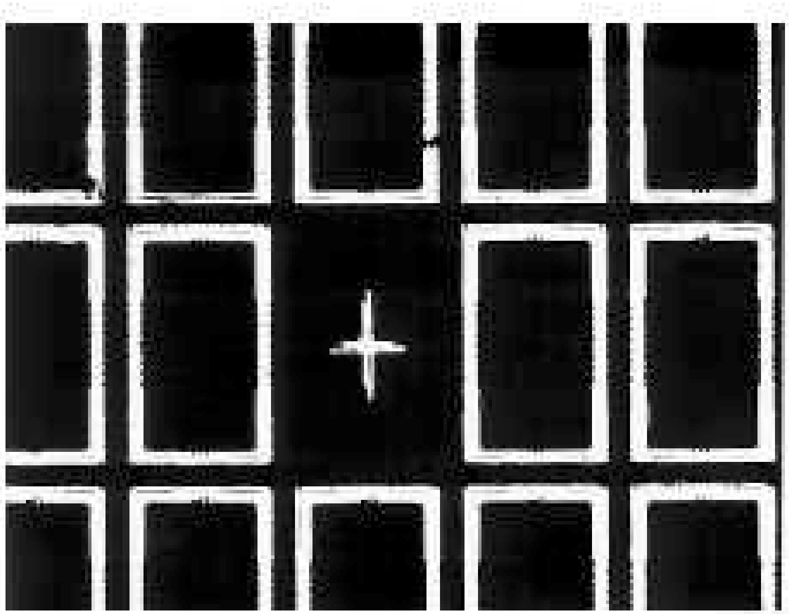
Two mirrors

- SCS comb drive actuator
- Torsion bar to support the mirror
- Mirror visible in background
- Back side



Front side

- Lighted from the back
- Light coming through trenches shows mirrors are fully released and suspended



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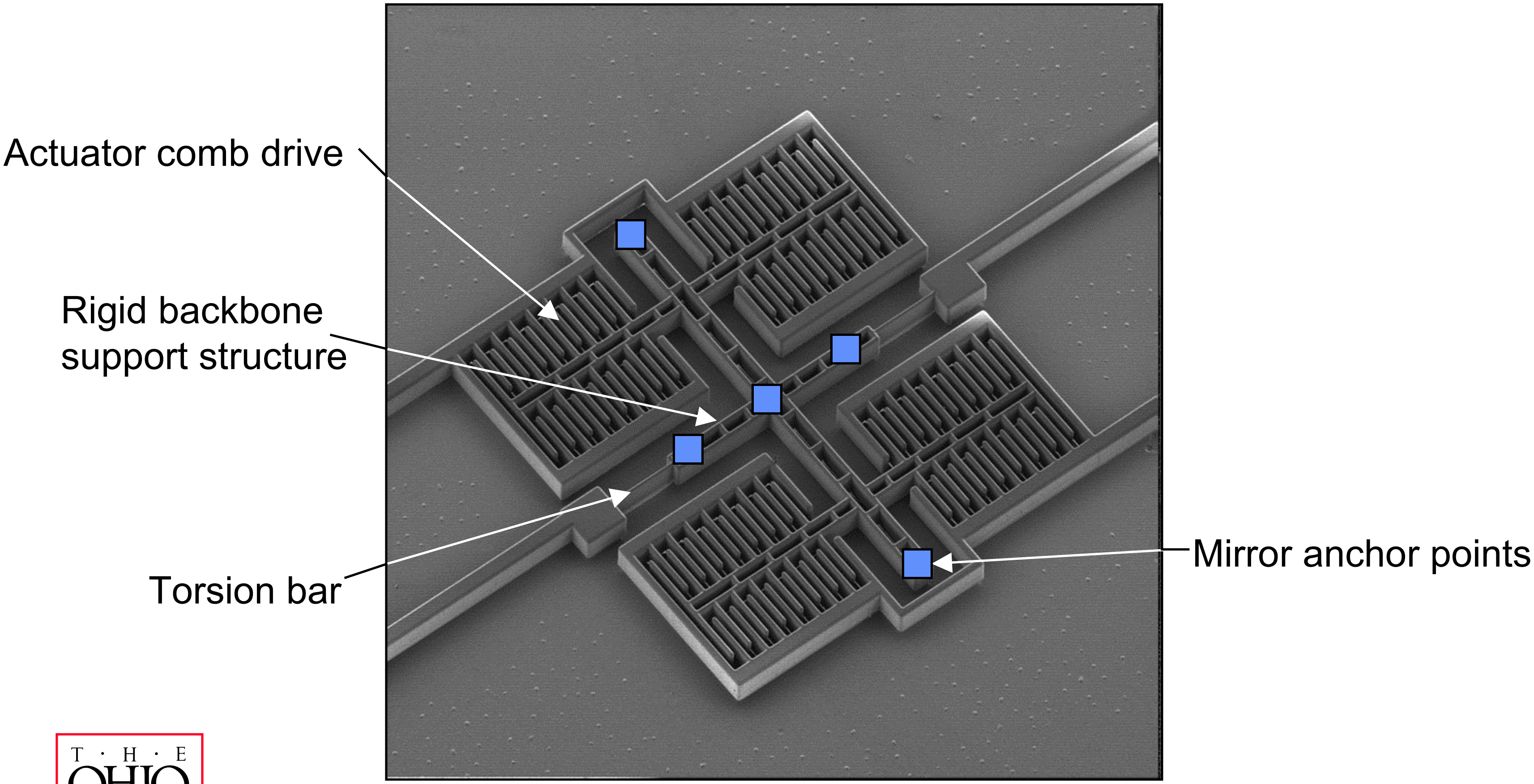
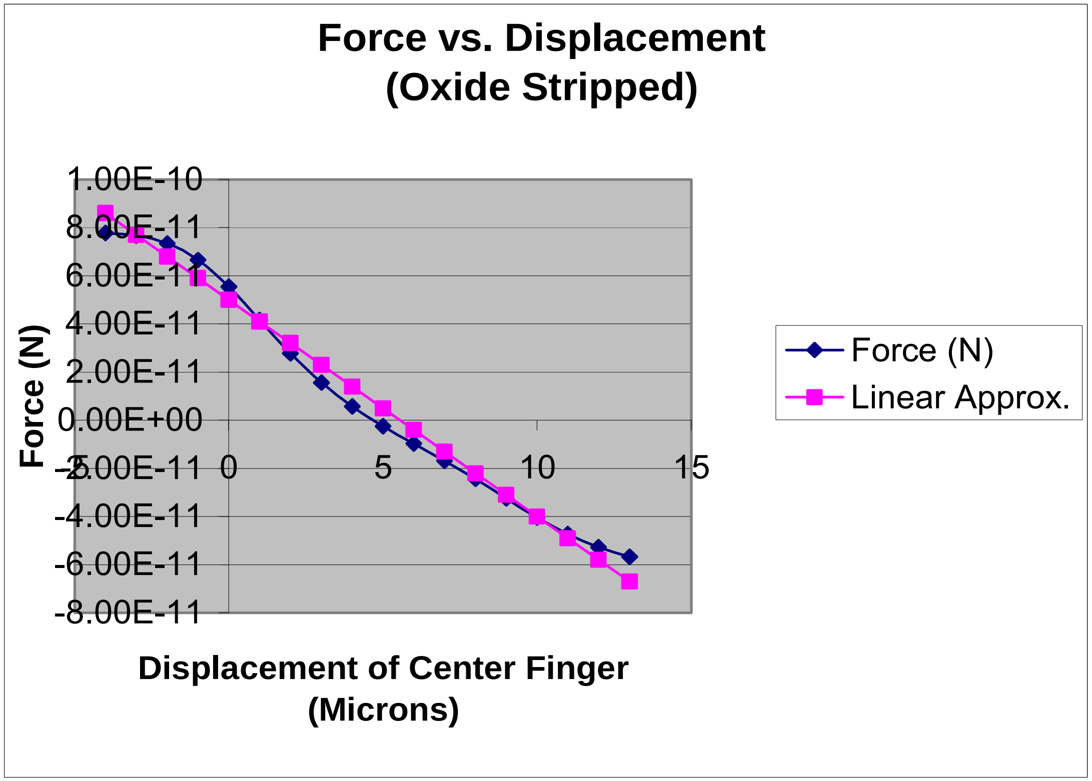
Here is a 1-level design



Force vs. displacement



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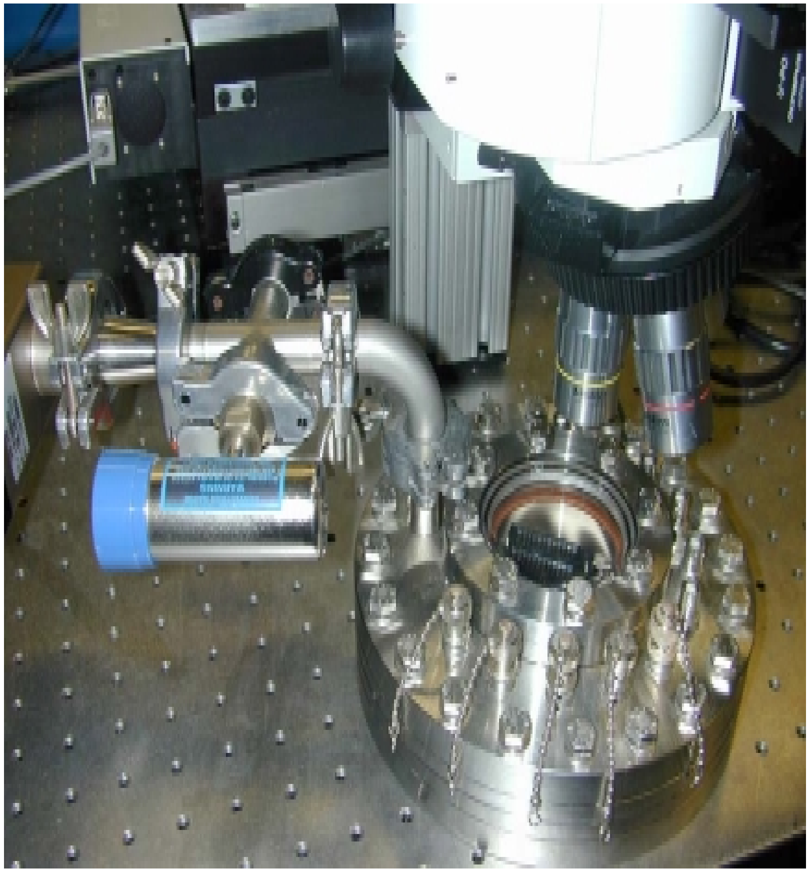
Package

- Ultra High Vacuum (UHV) package
- Optically flat window provides optical access to the MEMS chip
- Computer-controlled robot arm with an attached optical microscope



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So, we’re anxiously awaiting…

Meanwhile…

Our goals

- Provide 6,399 different delays
- Minimum delay increment 3 ps
- Maximum sequential delay 19 ns
- Can do longer delays by extra visits to longer arms
- Accuracy must be to ±0.5ps

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How many antenna elements?

- Will have a 128x128 array=16,384 pixels
- Each beam makes 17 bounces
- 16,384 pixels divided by 17 bounces = 963 beams
- Can support 963 antenna elements with one MEM

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How will we control accuracy?

- Need accuracy ±0.5ps
- That's 75 μm in free space
- Must tune each arm to 75 μm accuracy?
- But wait, it's worse! We can't accumulate more than 0.5 ps error in 17 bounces!

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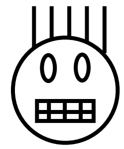
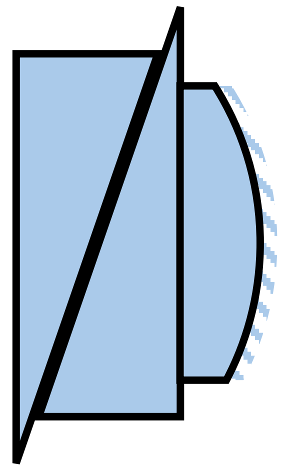
No, wait, it's worse than that!

- Each beam passes through each arm twice on one round trip
- Therefore in 17 bounces, or 34 passes, cannot accumulate more than 0.5 ps error
- That's 4μm per path in free space (2.9 μm in glass)

2.9 µm!



- So we insert two prisms
- As prisms translate, effective thickness increases
- That increases or decreases time of travel



But it's not that simple

- Want to change time of flight
- Imaging conditions must also be maintained- keep White cell in focus
- As glass gets thicker, back mirror must recede
- Naturally, not at equal rates…

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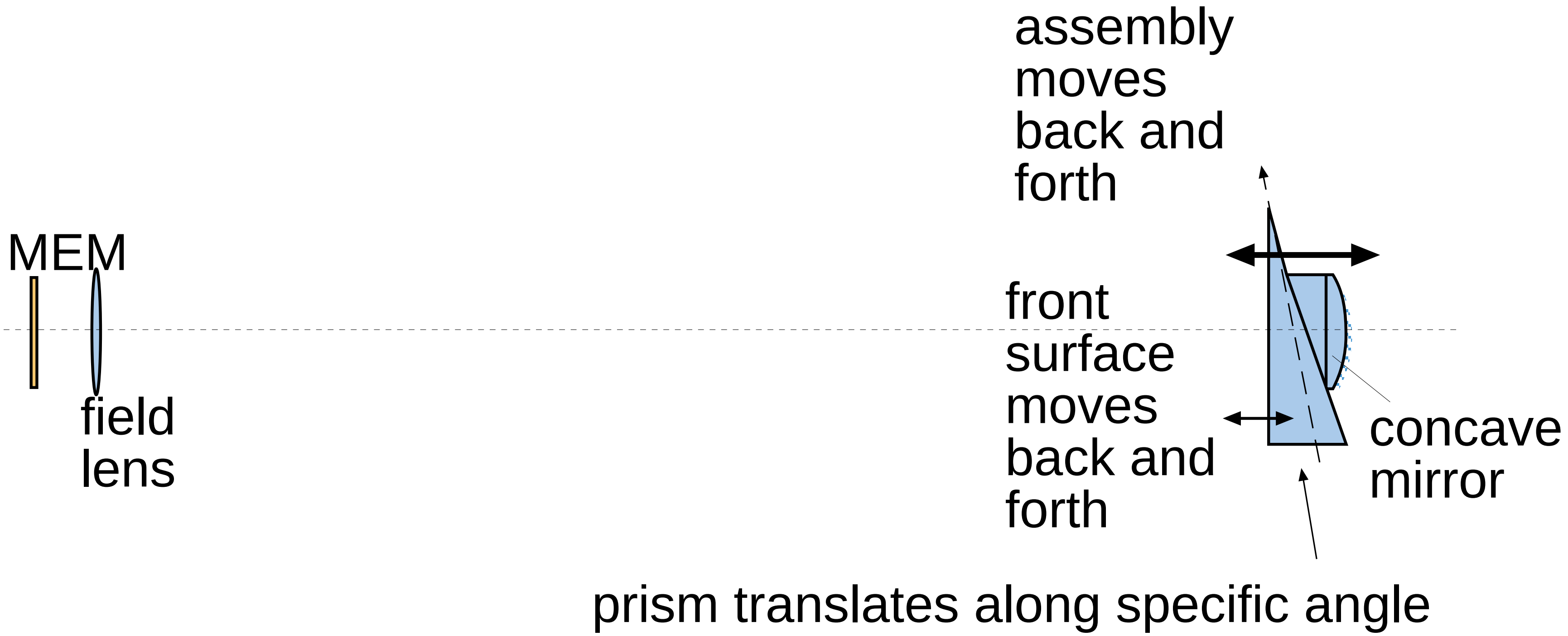
Solution


MEM
field lens
assembly moves back and forth
front surface moves back and forth
concave mirror
prism translates along specific angle

What about overall size of apparatus?

- Affected by
  - » Wavelength
  - » Spot size
  - » Pixel size
  - » Pixel pitch
  - » Overall MEM size

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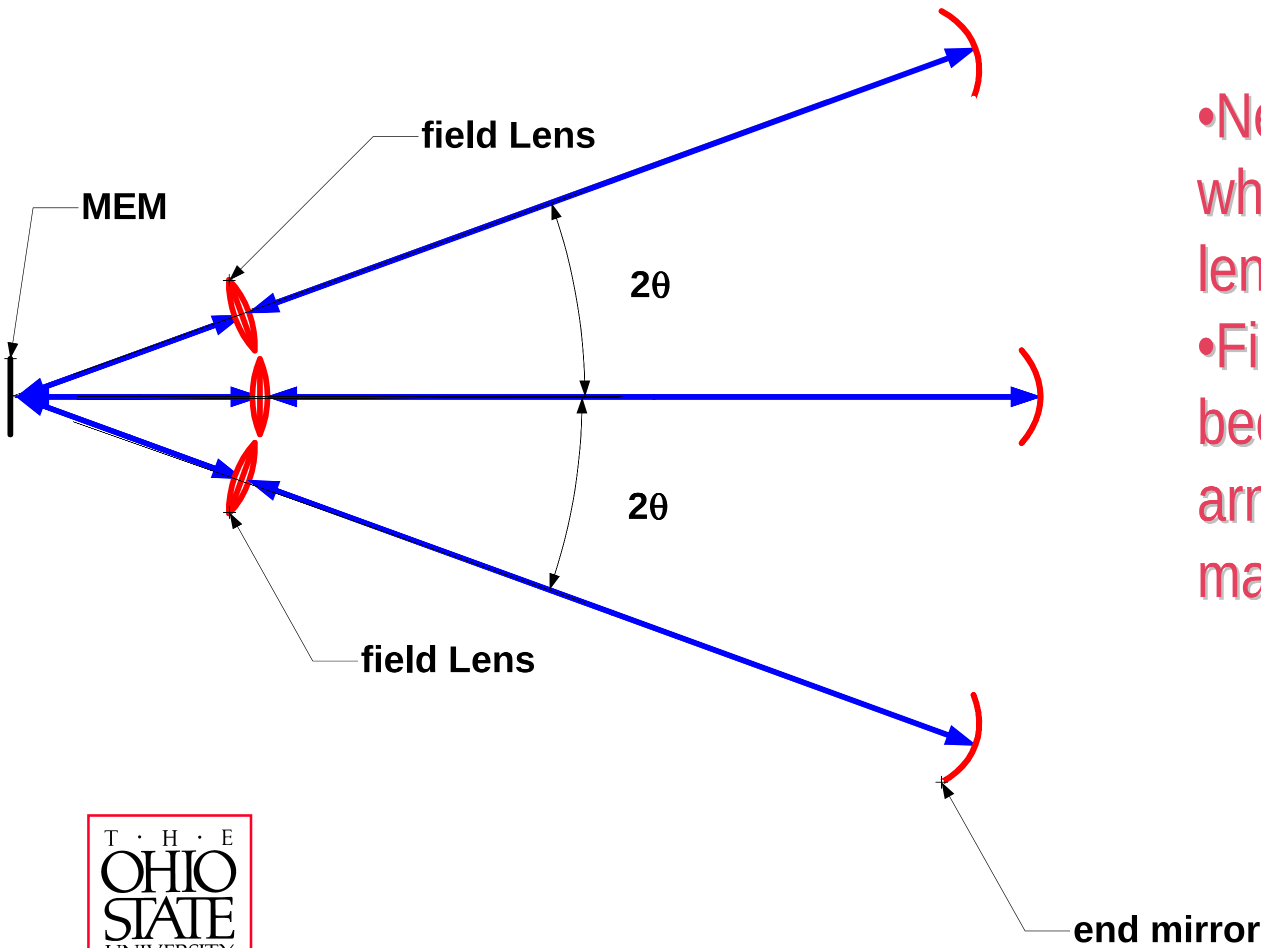
Set-up (in one plane)



- Need to determine where to place field lenses
- Field lenses different because lengths or arms different (have to maintain imaging)

Tradeoffs

- Want small divergence angle
  - Short wavelength
  - Large spots
- Want small MEM
  - Small spots
  - Small pitch

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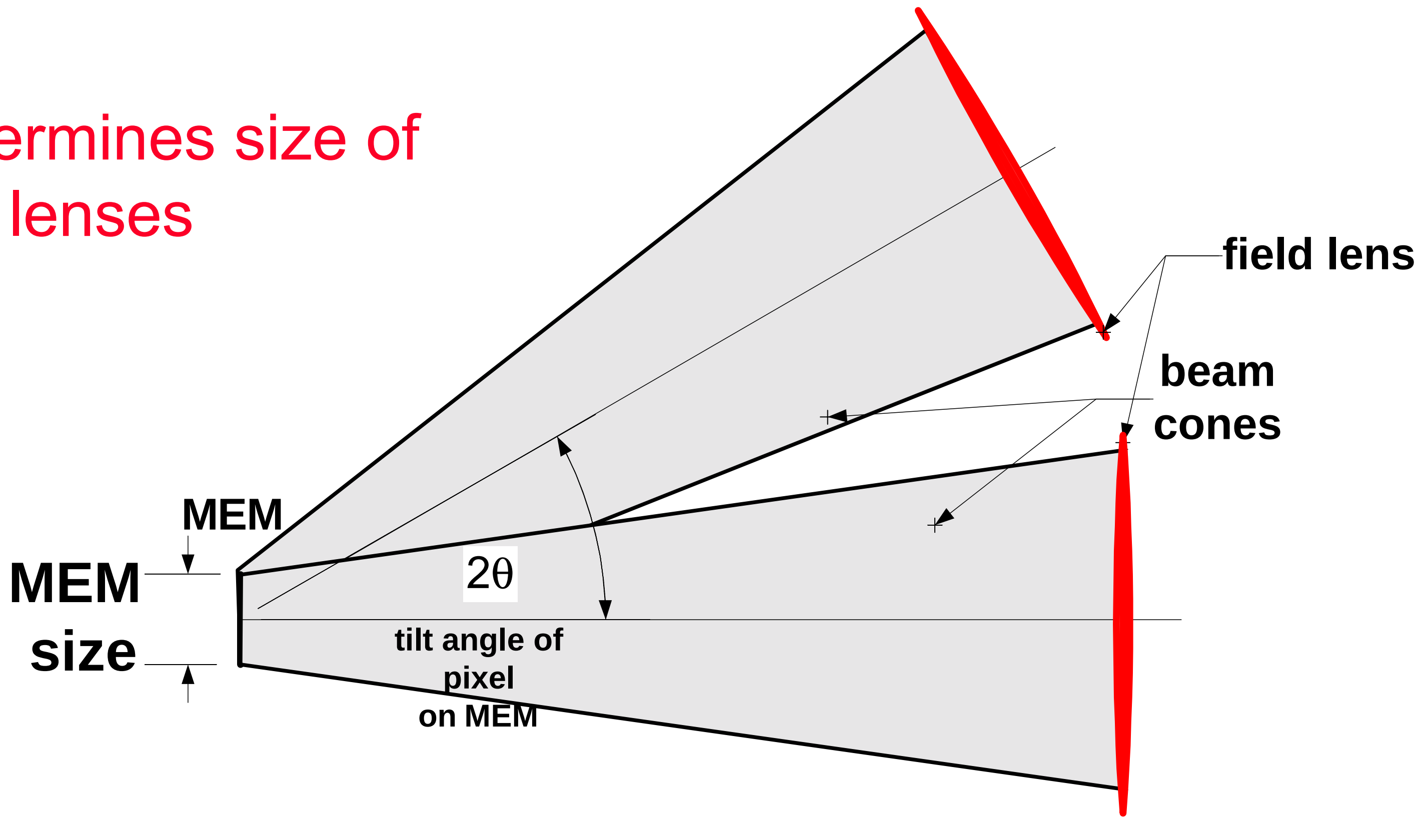
Because

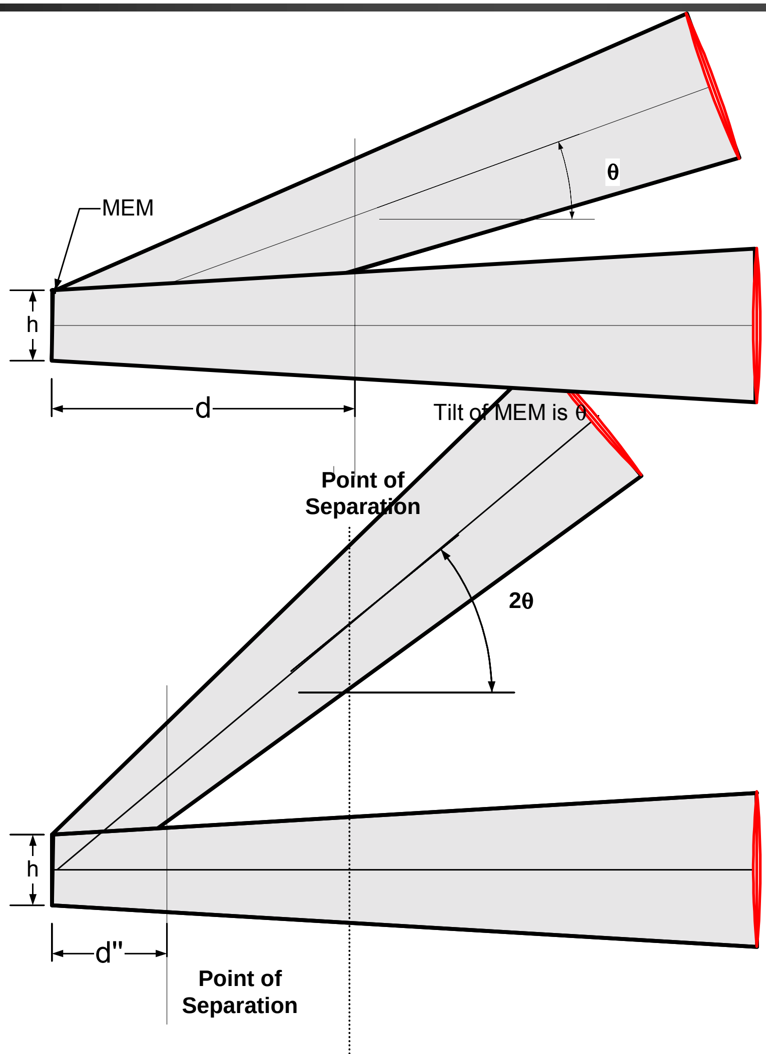
- Small divergence angle=> smaller field lenses
  - » Smaller beams
  - » Smaller end mirrors
- Large tilt angle
  - » Smaller distance to first lens
  - » Thus smaller lenses
  - » Thus smaller end mirrors…

Where do beams separate?

Determines size of first lenses

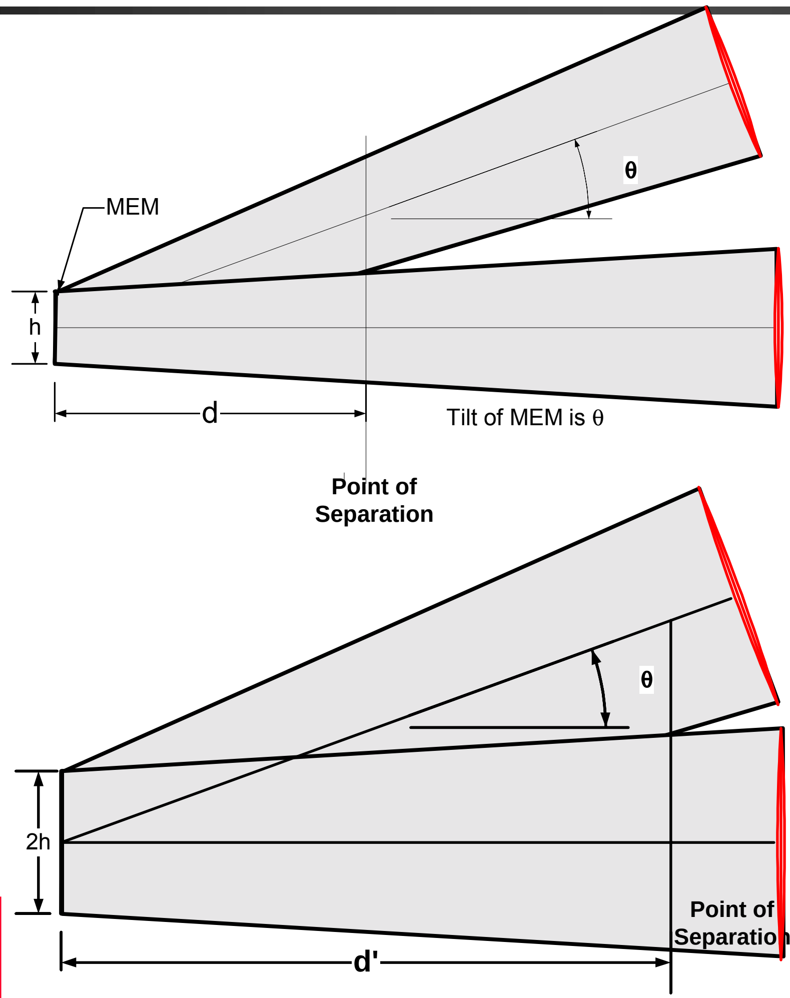


Effect of tilt angle



Large Tilt Angle
➔Shorter Separation Distance

Overall size of MEM



Larger MEM → Larger Separation Distance

- Means want few pixels
- Small pixels
- Small pitch

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Current design

- Arms are
  - 3 ps
  - 9 ps
  - 27 ps
  - 81ps
  - 240ps
  - 720 ps
  - 2160 ps
  - 6480 ps

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Sizes (paraxial design)

- Null arm is about 800mm long
- Longest arm is ≈1.8m
- Field lens is 2” diameter
- End mirrors are 4” diameter
- Way too big

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With non-paraxial optics

- Can relax f/10 condition
- Will use compound lenses
- Makes everything shorter
- May be able to deduce size to 2” end mirrors or smaller
- Reduce overall lengths by better than factor of 2

Also

- Can fold paths for more compactness
- Paths can cross each other
  - » Allows even smaller volume.

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Overall approach

- Build a paraxial octic cell
  - » Use singlet lenses
  - » Maintain f/10 imaging conditions
  - » Start by building a single quartic cell, then add the rest
  - » Use "static MEM" until real MEM available
  - » A few input beams (4 or 8) to start with

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What is a "static MEM?"

- An unchanging array of micro-mirrors
  - » Simulates the MEM in one fixed state
  - » Constructed of mirror-coated micro-prisms
  - » Larger than anticipated 1st-generation MEM device (allows for more functionality)
    - "Larger" means more pixels
    - Same pixel pitch
    - Same pixel size

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Why a Static MEM?

- Temporarily Replaces the MEM for optical alignment
  - An optical device with MEM properties is necessary in order to align all the wings
- Allows *some* flexibility if MEM delivery is delayed
- Allows us to shorten the “Critical Path” on our project Gantt Chart

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Features of the SMEM

- 1760 micro-mirrors in a 44x40 array
- Allows for ten *complete* delay sets for eight inputs
  - » Four sets dedicated to optical alignment and calibration (tuning)
  - » Four sets dedicated to demonstration of broadband steering
  - » Two sets dedicated to the demonstration of both long (>19 ns) and short (~3 ps) delays.

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Then, non-paraxial design

- Use compound lenses
- Go to f/4 or even better
- Build new, improved octic cell
  - » We're learning some optical design software now to get ready
  - » Must do sequential and non-sequential ray tracing
  - » Correct aberrations (primarily astigmatism)
  - » Reduce physical size big time

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Where we are

- White cell design is complete, parts being ordered
- Tuning prism design complete
- Algorithm for choosing mirror progressions complete
- Design for “static MEM” complete
- Alignment procedure worked out

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Milestones

- March 2003:
  - First quartic cell built and demonstrated
  - Aligned with SMEM, then operated using active MEM
  - First MEM 10x10, with drive electronics, packaged, delivered and installed
  - Losses and aberrations predicted
  - Demonstrate viability of tuning prisms

Then..

- Phase II:
  - » Complete paraxial octic cell- add other quartic cell
  - » Provide accurate tuning for all arms
  - » Measure delays, loss, crosstalk
  - » Increase size of MEM to 40 x40, reduce number of connections

Phase III

- Design non-paraxial octic cell
  - » Minimize size
  - » Use compound lenses and toroidal optics where necessary to minimize aberrations
  - » Fold paths for compactness
- Begin building non-paraxial apparatus
- MEMS work continues, including drive electronics and larger array

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Phase IV

- Complete non-paraxial octic cell
- Demonstrate with 128x128 MEM
- Measure delays, loss, crosstalk
- Demonstrate complete range of delays for at least eight input beams

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Other applications of switchable White cells

- Tapped delay lines with thousands of taps
  - » Really big matched filter
  - » Optical code-division multiple access with a boatload of users
  - » Encryption with some serious code lengths

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Optical Correlation

- Correlation with very high resolution
- Monitor health of optical link by correlating received signal with nice, crispy clean new bit
  - » Reveals attenuation, dispersion, etc
  - » Much more information than “is there light?”
- Can do in time scale of two bits (e.g. 50ps)

Optical circulator

- Optical circulator with hundreds of ports
  - » (Does anyone need that?)
- No polarization components (no waveplates or expensive optically active crystals)

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Optical switch

- Just like time delay device, except:
  - » Different paths all the same length (latency the same)
  - » Different White cells aligned differently
  - » Spots return to different locations depending on which White cells a given beam goes to

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Challenges to White cell approach

- Got to get the loss down on the MEM
- Have to produce a truly large MEM array *and* address all the pixels
- Have to get physical size down
  - » Use non-paraxial optics
  - » Fold paths

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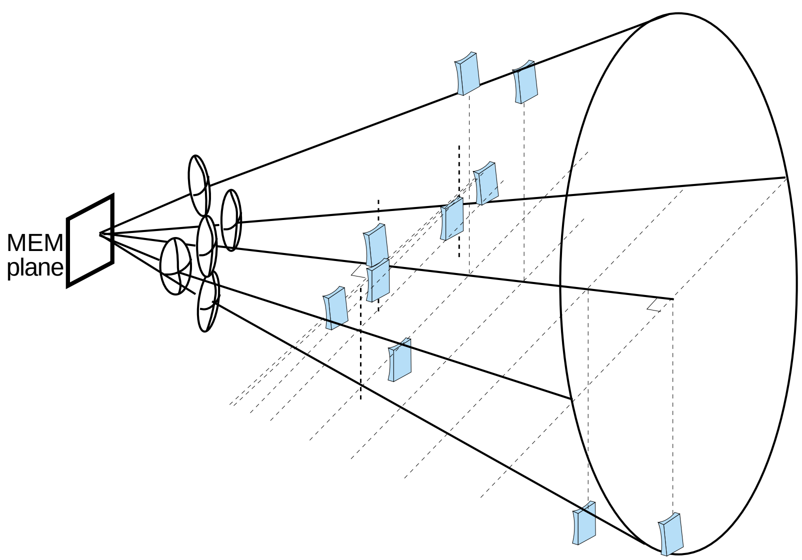
Summary



- Free-space optical true time delay device for phased array antennas
- Massively parallel
  - » 6399 delays
  - » 900 light beams (antenna elements)
- Two-depth design and two-sided construction for MEM makes it possible

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