Micro Scale Mirrors For Optical Communication

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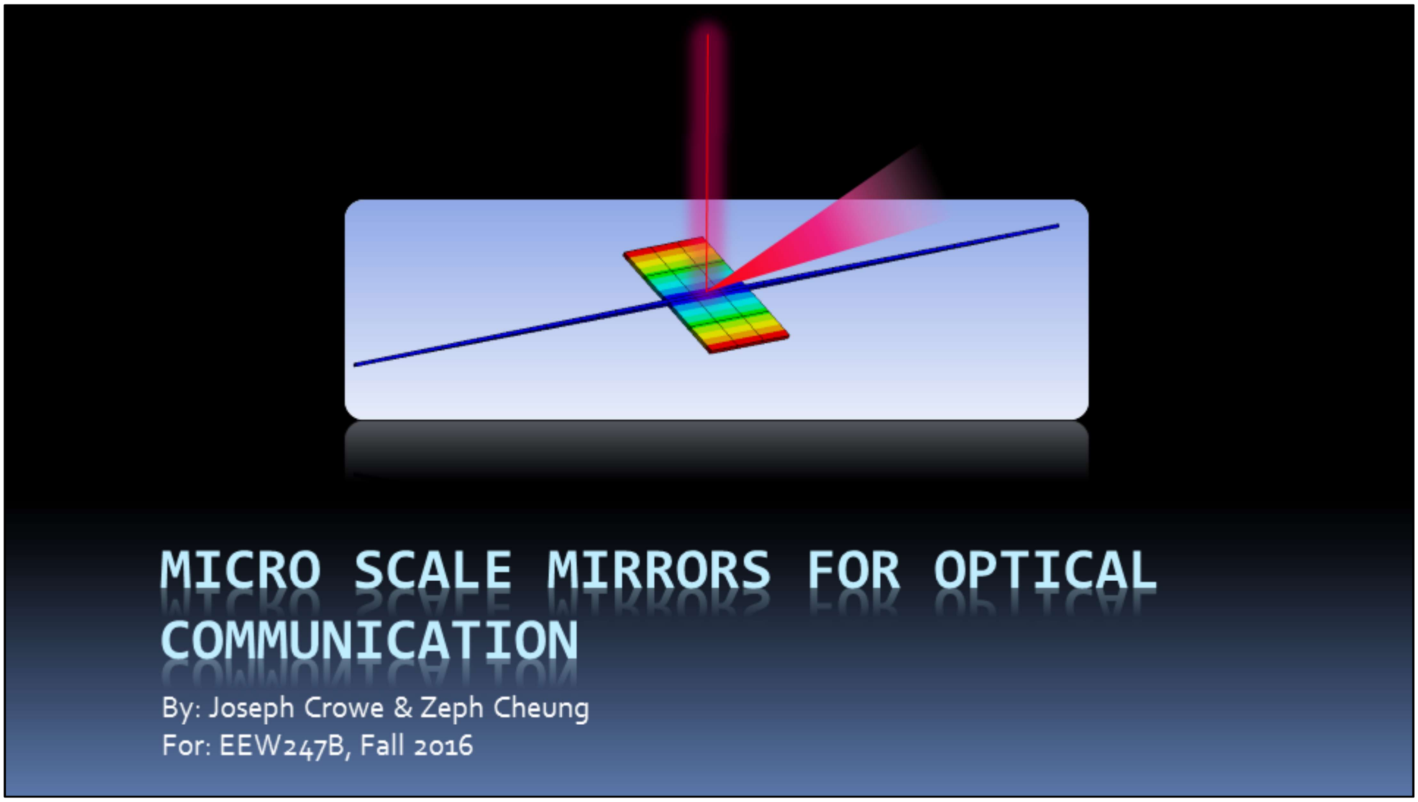
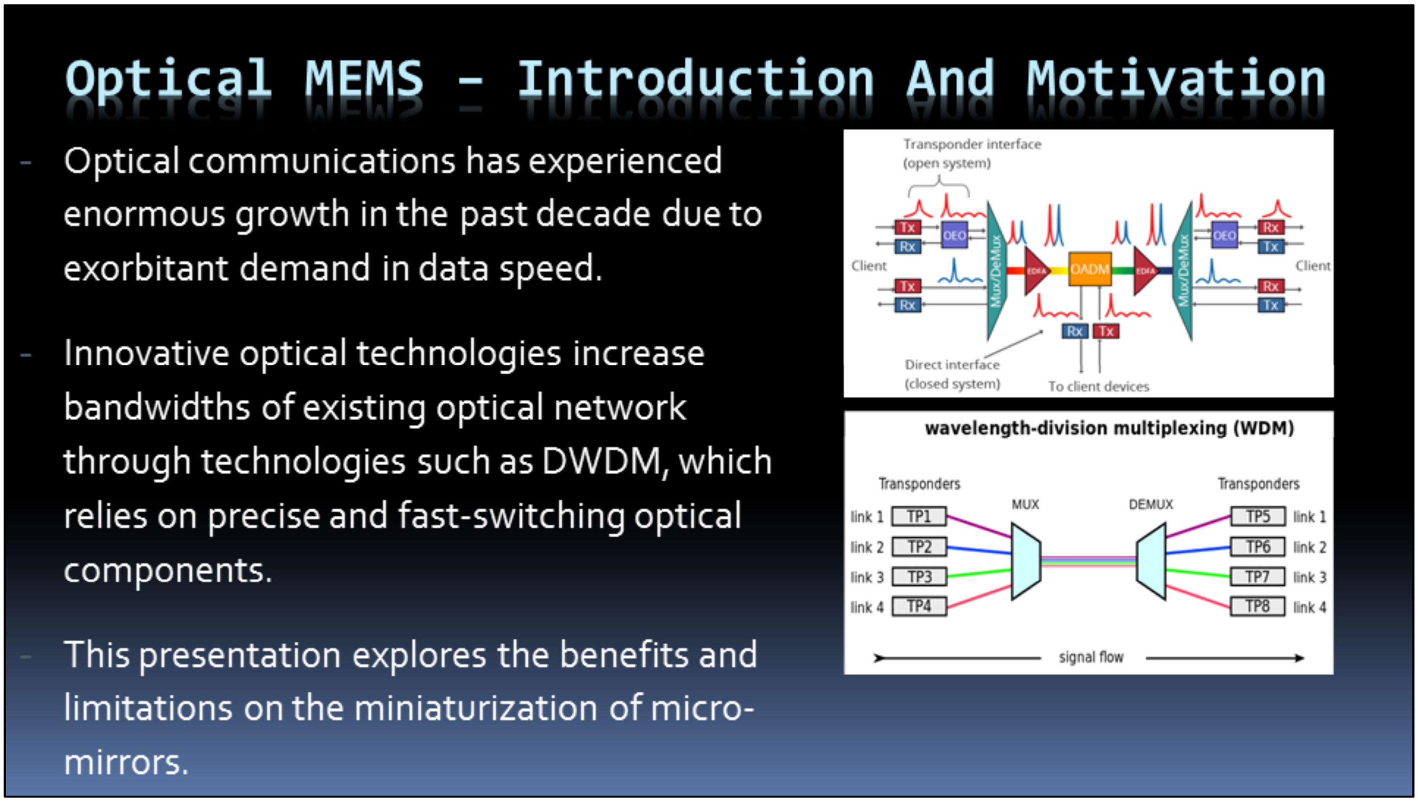


MICRO SCALE MIRRORS FOR OPTICAL COMMUNICATION

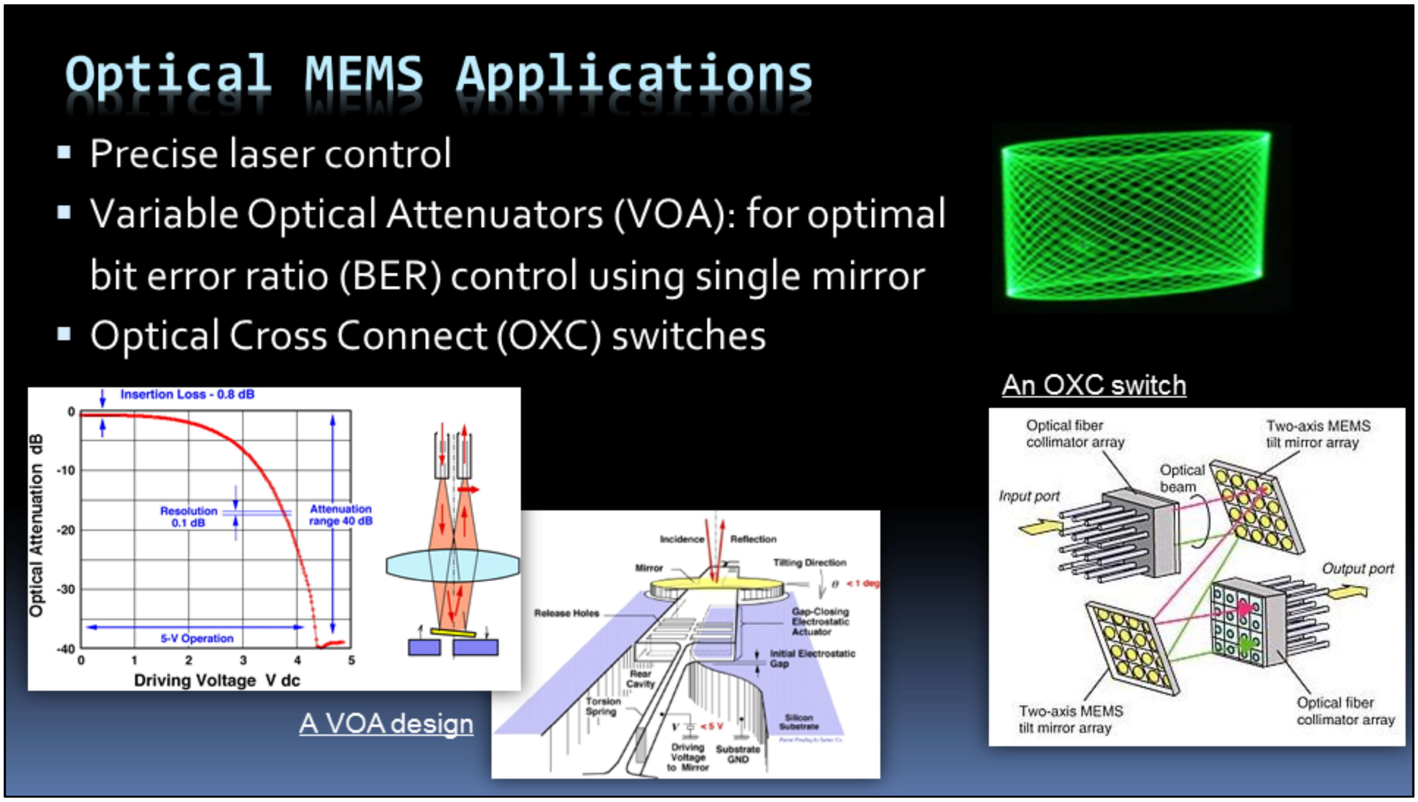
By: Joseph Crowe & Zeph Cheung
For: EEW247B, Fall 2016



Optical MEMS – Introduction And Motivation

- Optical communications has experienced enormous growth in the past decade due to exorbitant demand in data speed.
- Innovative optical technologies increase bandwidths of existing optical network through technologies such as DWDM, which relies on precise and fast-switching optical components.
- This presentation explores the benefits and limitations on the miniaturization of micro-mirrors.

There has been a strong motivation on faster data rate in telecommunications in the past few decades. In particular, the explosion of mobile devices leads to a demand for higher speed for data transfer in the field of optical communications. Fiber optics telecommunications is based upon the ability to transfer data in a low loss environment, while at the same time transferring it at high speeds.



Optical MEMS Applications

- Precise laser control
- Variable Optical Attenuators (VOA): for optimal bit error ratio (BER) control using single mirror
- Optical Cross Connect (OXC) switches

A VOA design

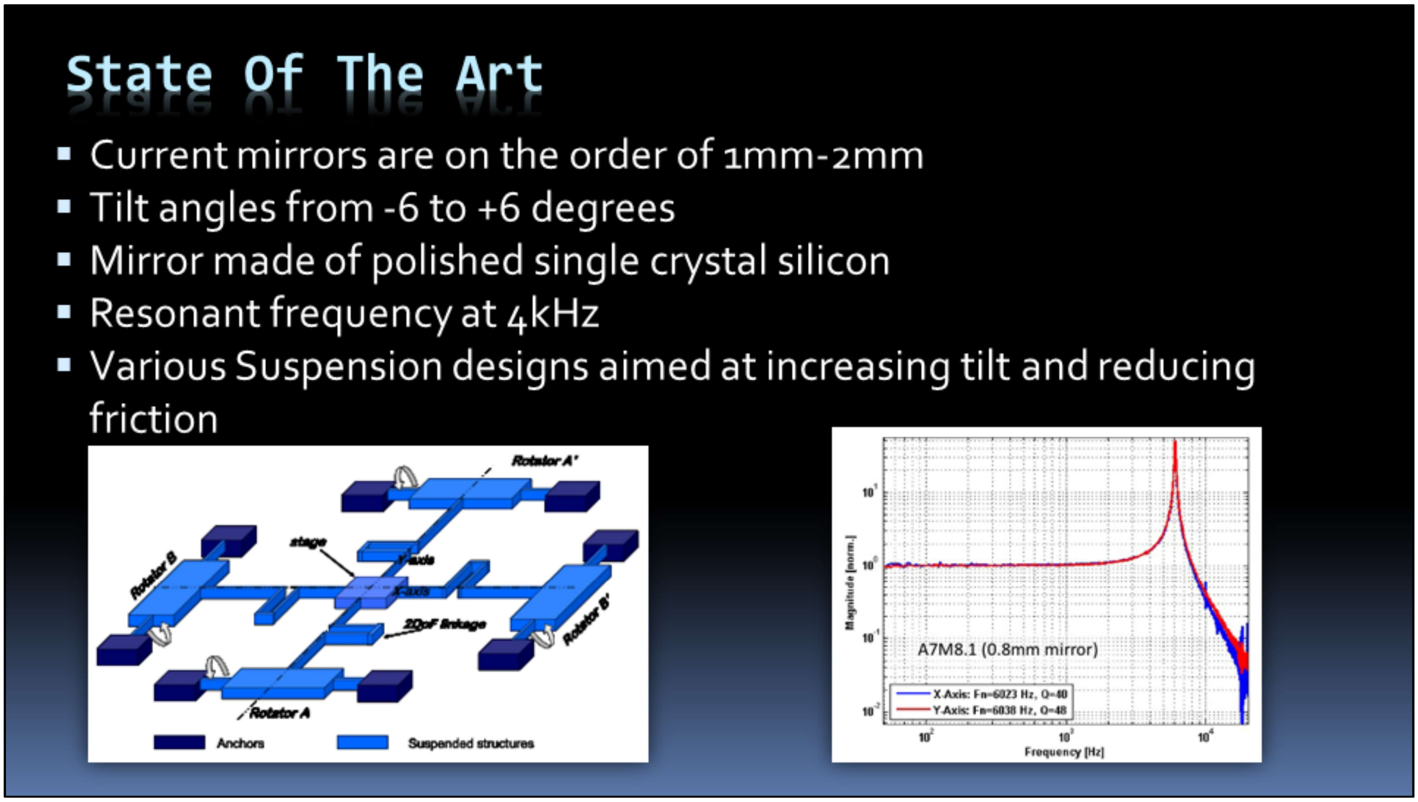
An OXC switch

MEMS mirrors have a wide ranging field of applcations. Essentially, the optical mirror controls the direction of an incoming laser, and redirect it.

An optical attenuator attenuates an incoming signal’s power level. This is necessary as the incoming optical signal can be so strong that it would overload a fiber optic receiver and degrade the bit error ratio (BER). Alternatively, in a WDM system, the optical channel strength wil need to be optimized to achieve similar power levels. In a fixed attenuator type device, a connector can be used to connect to regular FO connectors to attenuate light. But in a VOA device, one of the designs utilizes a MEMS mirror actuated by an electrostatic comb drive, to redirect to a path that is designed to have a variable attenuation power. Such devices operates on driving voltage between 5V and 12V, and can attenuate signals by as much as 40dB, at an open loop resolution of 0.1dB.

Ref:

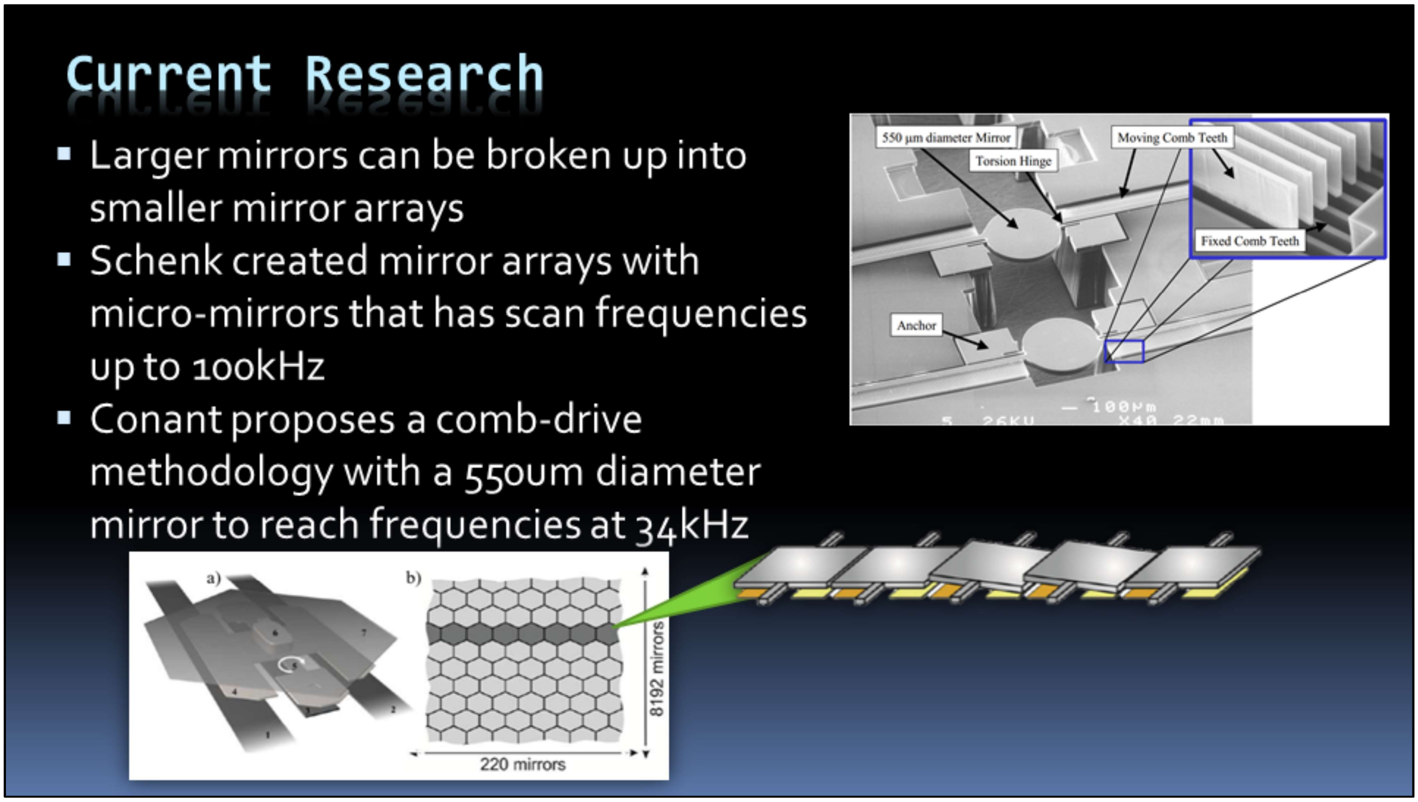
1. “Fiber Optic Attenuator Solution Aid”, http://www.fs.com/fiber-optic-attenuator-solution-aid-344.html
2. “Attenuator with Parallel Plate Tilt Mirror”, http://toshi.iis.u-tokyo.ac.jp/toshilab/?Research%2FMEMS%20Variable%20Optical%20Attenuator%20with%20Parallel-Plate%20Tilt%20Mirror
3. Ch. 10 “Optical Cross Connect”



State Of The Art

- Current mirrors are on the order of 1mm-2mm
- Tilt angles from -6 to +6 degrees
- Mirror made of polished single crystal silicon
- Resonant frequency at 4kHz
- Various Suspension designs aimed at increasing tilt and reducing friction

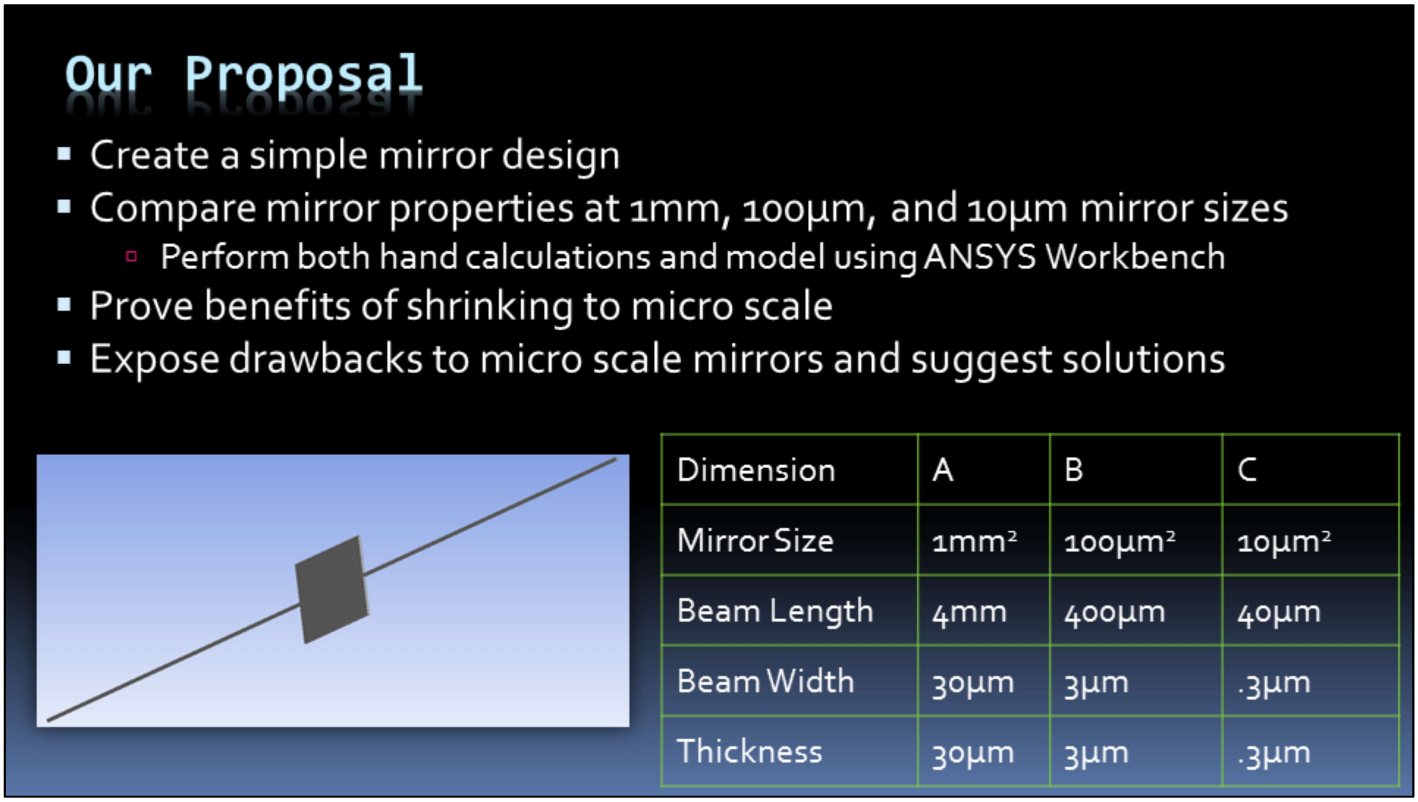
Mirrorcle technologies is a company leading in MEMS mirror design. They produce mirrors on the order of 1mm-2mm in diameter which have resonant frequencies of around 4kHz. Mirrorcle creates their mirrors from single crystal silicon without any special metal coating for reflection. They polish the silicon surface itself using chemical mechanical processing (CMP) steps to provide the reflective surface. Their suspension designs are unique in that they are a gimble-less two axis design which allows for maximal tilt while reducing drive power and eliminating friction from moving joints. The mirrors produced by Mirrorcle are predominantly used for optical scanning purposes such as laser manipulation for visual effects.



Current Research

- Larger mirrors can be broken up into smaller mirror arrays
- Schenk created mirror arrays with micro-mirrors that has scan frequencies up to 100kHz
- Conant proposes a comb-drive methodology with a 550um diameter mirror to reach frequencies at 34kHz

One issue with shrinking mirror size is that the light beam can actually be larger than what the small mirror can reflect. Therefore larger mirrors can be broken up into an array of micro-sized mirrorss to reflect the entire beam at much higher switching speeds without sacrificing brightness or definition. In Schenk's research it was found that the micro mirror arrays provided scan frequencies up to 100kHz[7]. Another creative micro-mirror design is proposed by Conant who introduces a Staggered Torsional Electrostatic Combdrive (STEC) micro-mirror[8]. This mirror, as seen above, operates on the comb drive principle which functions by providing a voltage between the top and the bottom layers of the mirrors. This voltage creates a force which attracts the moving comb teeth to the fixed teeth and thus tilting the mirror. This simple design doesn't rely on a normal electrostatic-actuator design and provides devices with resonant frequencies that reach 34kHz. The design provided by Conant consists of a 550 um diameter mirror, it will be later proposed to shrink the mirror further to increase the resonant frequency even further.

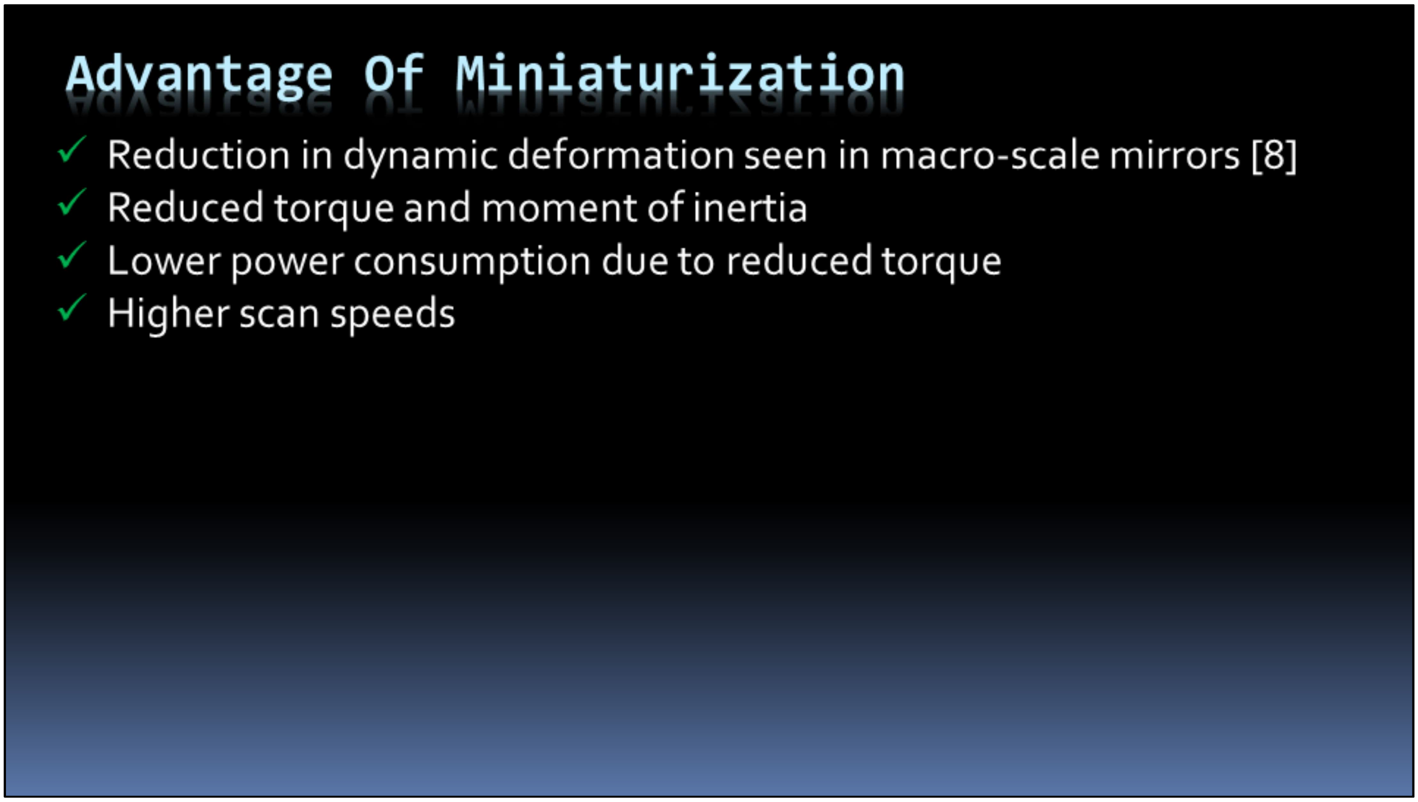


Our Proposal

- Create a simple mirror design
- Compare mirror properties at 1mm, 100µm, and 10µm mirror sizes
  - Perform both hand calculations and model using ANSYS Workbench
- Prove benefits of shrinking to micro scale
- Expose drawbacks to micro scale mirrors and suggest solutions

Dimension	A	B	C
Mirror Size	1mm^2	100µm^2	10µm^2
Beam Length	4mm	400µm	40µm
Beam Width	30µm	3µm	.3µm
Thickness	30µm	3µm	.3µm

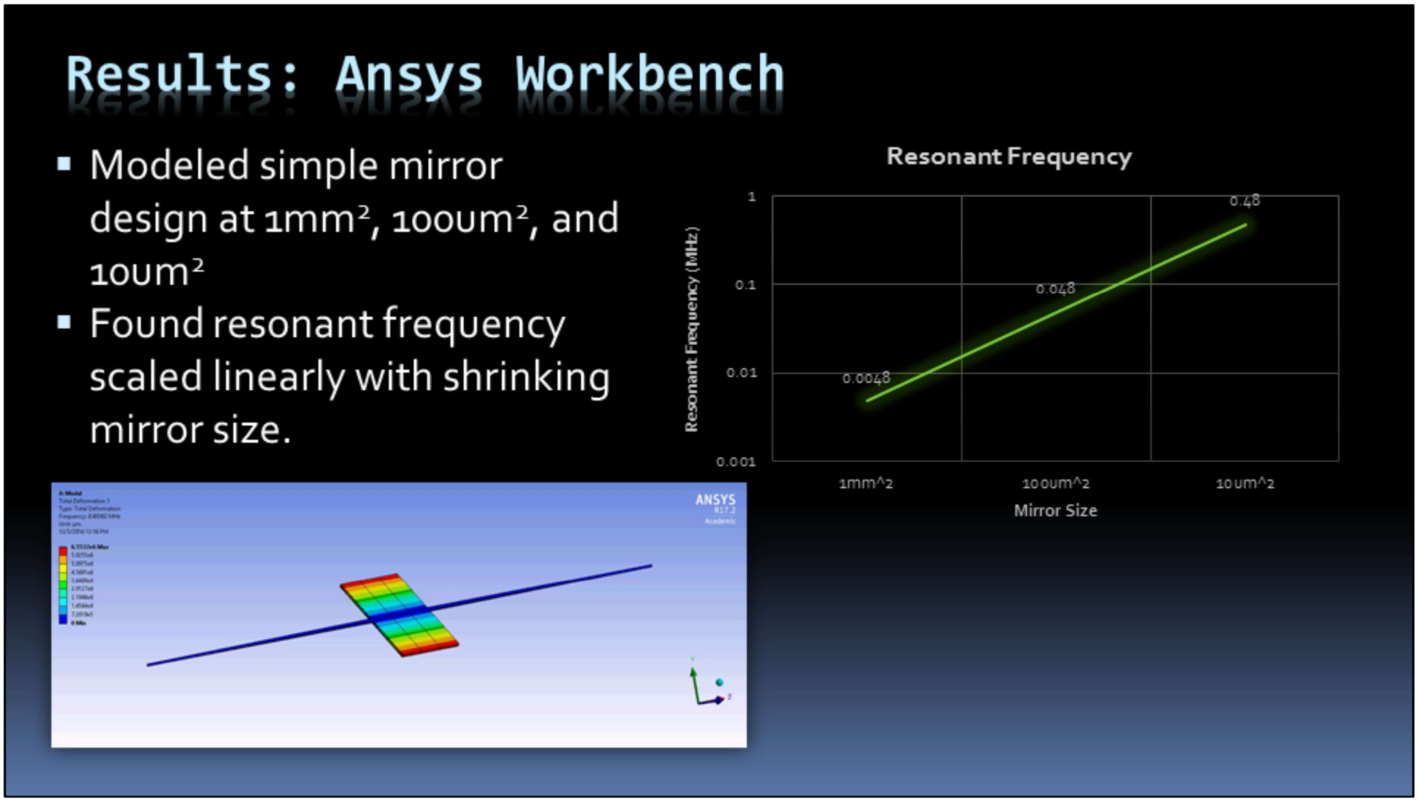
For our project we look to start with a simple mirror design consisting of a single mirror being supported by two straight beams. The mirror will rotate about the beam axis to provide the switching capabilities desired by optical switching mirrors. With this design we will compare mirror properties such as inertial forces, tilt angle, and resonant frequency to prove that scaling improves each of these properties. We will use both hand calculations as well as computational models to gather the data for mirror lengths of 1mm^2, 100um^2, and 10um^2. From these calculations and models we hope to both prove the benefits of scaling mirrors to the micro scale as well as expose any drawbacks that can be seen due to such scaling. For any drawbacks seen, we will provide explanations and offer possible solutions for alleviating these issues.



Advantage Of Miniaturization

- ✓ Reduction in dynamic deformation seen in macro-scale mirrors [8]
- ✓ Reduced torque and moment of inertia
- ✓ Lower power consumption due to reduced torque
- ✓ Higher scan speeds

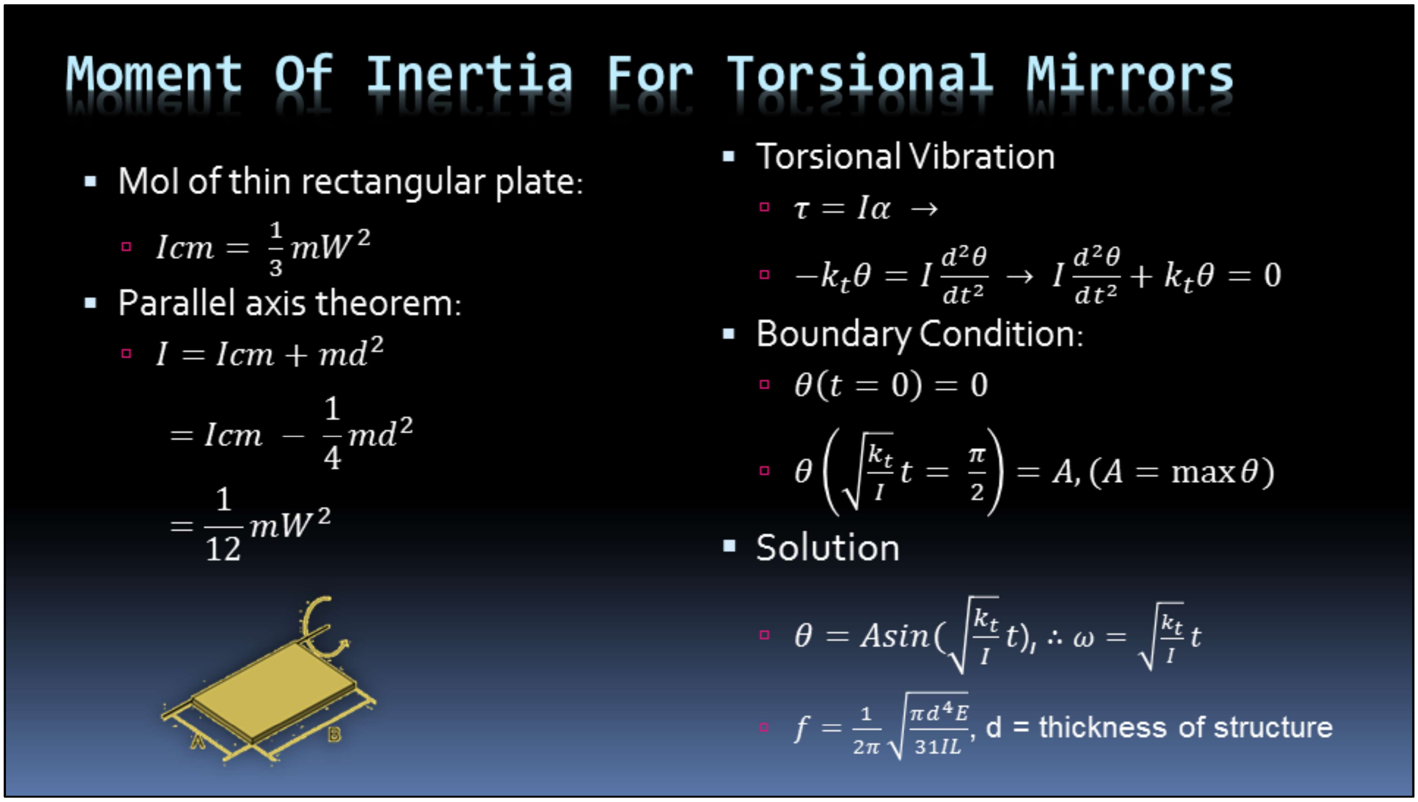
We found several advantages to using micro-mirrors, these advantages will be discussed in the following slides.



Results: Ansys Workbench

- Modeled simple mirror design at 1mm², 100um², and 10um²
- Found resonant frequency scaled linearly with shrinking mirror size.

Using Ansys Workbench we were able to model the simple mirror and beam design mentioned earlier. In Ansys we used single crystal silicon as the material to ensure that the properties such as stiffness and elasticity matched those that we would be using for hand analysis. In order to replicate the fixed-fixed design of normal mirror designs we set each beam end to be fixed while the rest of the beam and center mass were able to freely move. Once the designs at each mirror size were created, simulations were run to determine the resonant frequency achieved by each mirror. The results from the simulations can be seen in the table above. It can be seen that by shrinking the device by a factor of 10, the resonant frequency increases accordingly by a factor of 10. Another useful observation from the resulting data is that the 1mm^2 mirror design has a resonant frequency of 4.8kHz, which very closely matches the 4kHz that was achieved by the current state of the art mirrors at .8mm that were discussed earlier.



Moment Of Inertia For Torsional Mirrors

- MoI of thin rectangular plate:
  - $Icm = \frac{1}{3}mW^2$
- Parallel axis theorem:
  - $I = Icm + md^2$

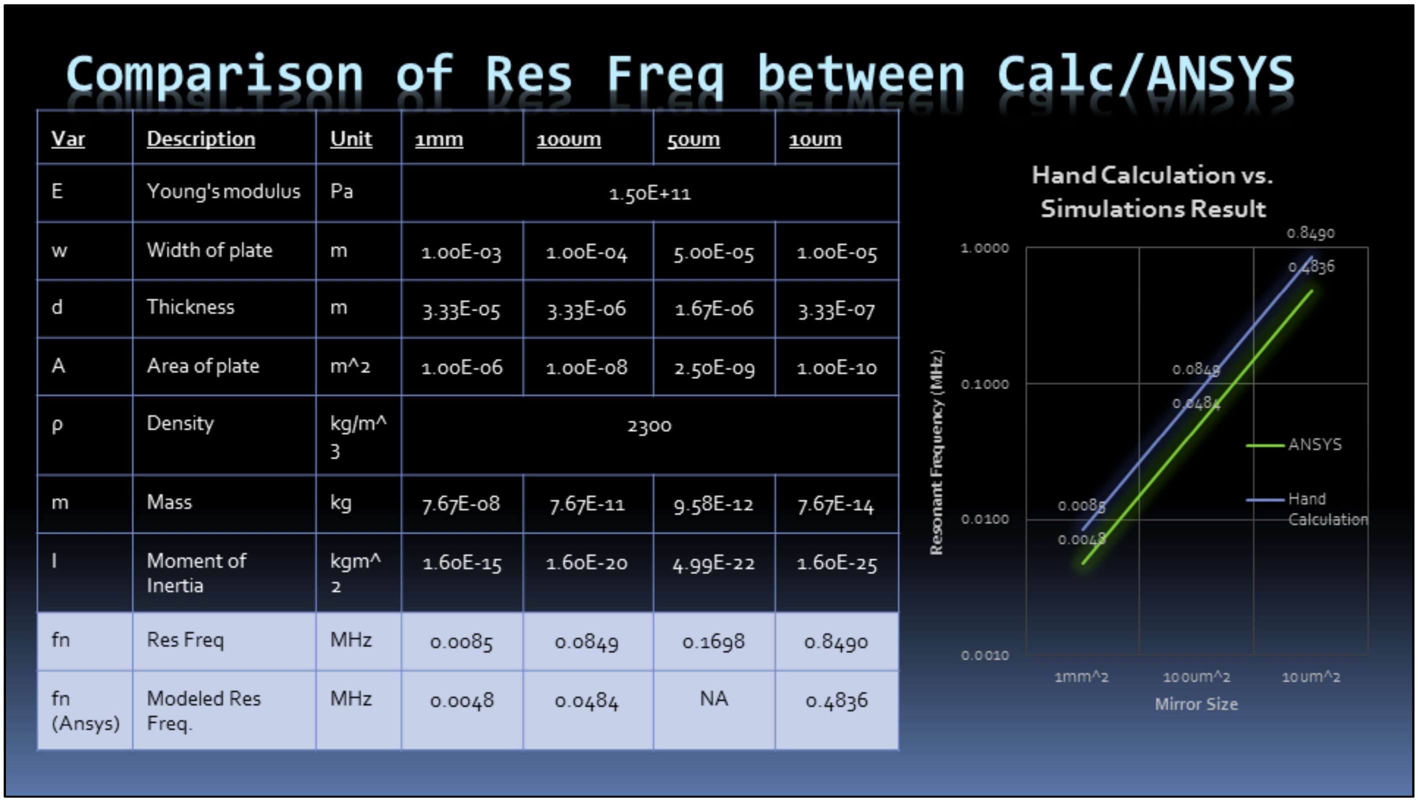
$$= Icm - \frac{1}{4}md^2$$

$$= \frac{1}{12}mW^2$$

- Torsional Vibration
  - $\tau = I\alpha \rightarrow$
  - $-k_t\theta = I\frac{d^2\theta}{dt^2} \rightarrow I\frac{d^2\theta}{dt^2} + k_t\theta = 0$
- Boundary Condition:
  - $\theta(t = 0) = 0$
  - $\theta\left(\sqrt{\frac{k_t}{I}}t = \frac{\pi}{2}\right) = A, (A = \max\theta)$
- Solution
  - $\theta = Asin(\sqrt{\frac{k_t}{I}}t), \therefore \omega = \sqrt{\frac{k_t}{I}}t$
  - $f = \frac{1}{2\pi}\sqrt{\frac{\pi d^4 E}{31IL}}$, d = thickness of structure

Our proposal is based on the design of a torsionally vibrating system. In order to analyze the system, we first calculated the moment of inertia (MOI) of a thin rectangular plate, and by using the parallel axis theorem, the total moment of inertia is determined to be 1/12 multiplied by the mass and the square of the width of the plate.

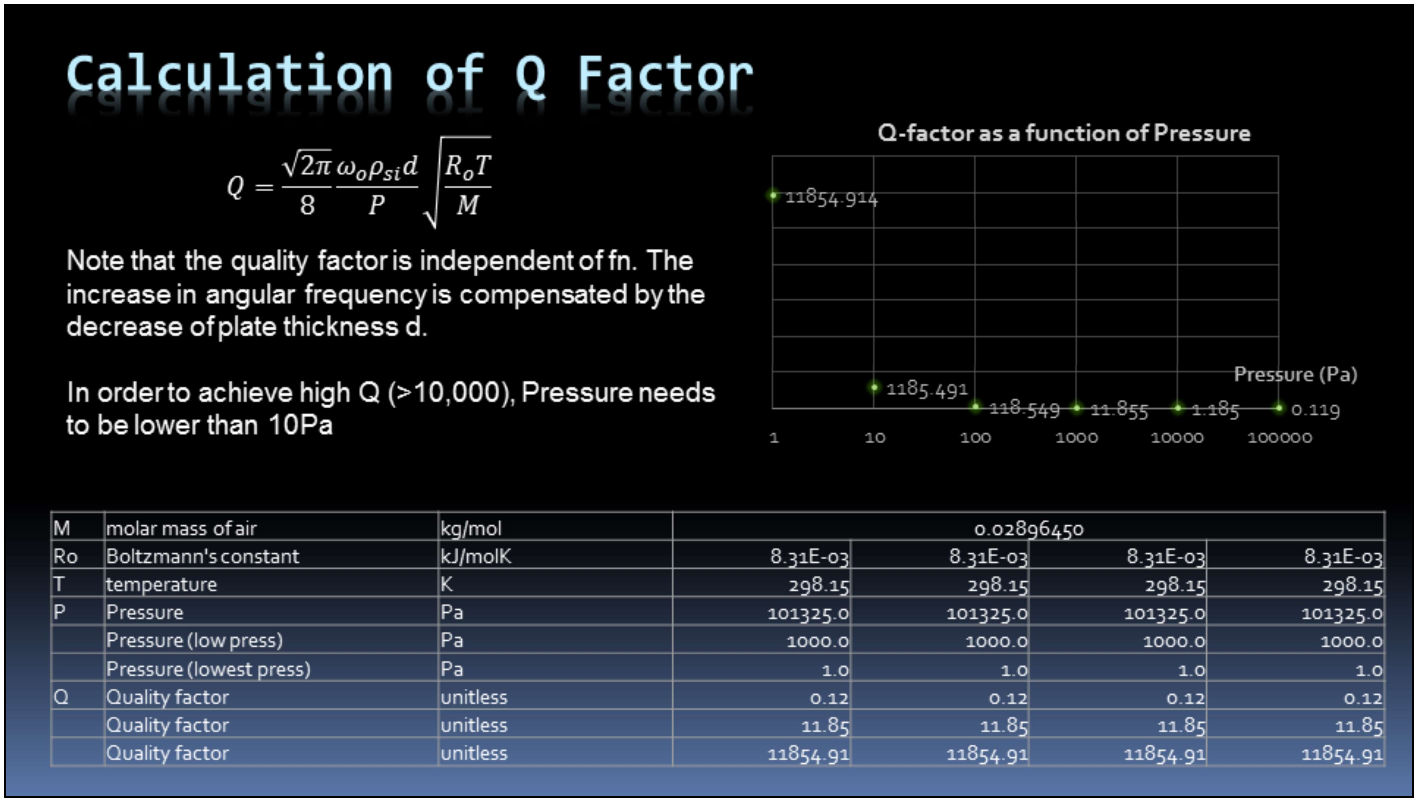
Once this was found, we moved on to calculate for the natural frequency of a torsionally vibrating plate. We accomplished this by identifying that the torque of a spinning system is the product of the MOI and its corresponding angular acceleration, and by solving the corresponding homogenous differential equation. By applying the proper boundary equations, we identified the radian frequency to be the square root of kt/I multiplied by time. And with proper geometrical substitution, the equation resonant frequency (fn) is identified.



Comparison of Res Freq between Calc/ANSYS

Var	Description	Unit	1mm	100um	50um	10um
E	Young's modulus	Pa	1.50E+11			
w	Width of plate	m	1.00E-03	1.00E-04	5.00E-05	1.00E-05
d	Thickness	m	3.33E-05	3.33E-06	1.67E-06	3.33E-07
A	Area of plate	m^2	1.00E-06	1.00E-08	2.50E-09	1.00E-10
ρ	Density	kg/m^3	2300			
m	Mass	kg	7.67E-08	7.67E-11	9.58E-12	7.67E-14
I	Moment of Inertia	kgm^2	1.60E-15	1.60E-20	4.99E-22	1.60E-25
fn	Res Freq	MHz	0.0085	0.0849	0.1698	0.8490
fn (Ansys)	Modeled Res Freq.	MHz	0.0048	0.0484	NA	0.4836

As can be seen in the graph above, the results from our hand calculations and modeling are very close. The small amount of variation can be accounted for in a few minor differences and assumptions that were made in the hand calculations versus the computational model. One example is that the weight of the beams in the hand calculations were ignored in the calculation of resonant frequency and moment of inertia. Even though the beam's mass is relatively small in comparison to the mass of the mirror, it does effect the behavior of the device in the end.



Calculation of Q Factor

$$Q = \frac{\sqrt{2\pi}}{8} \frac{\omega_o \rho_{si} d}{P} \sqrt{\frac{R_o T}{M}}$$

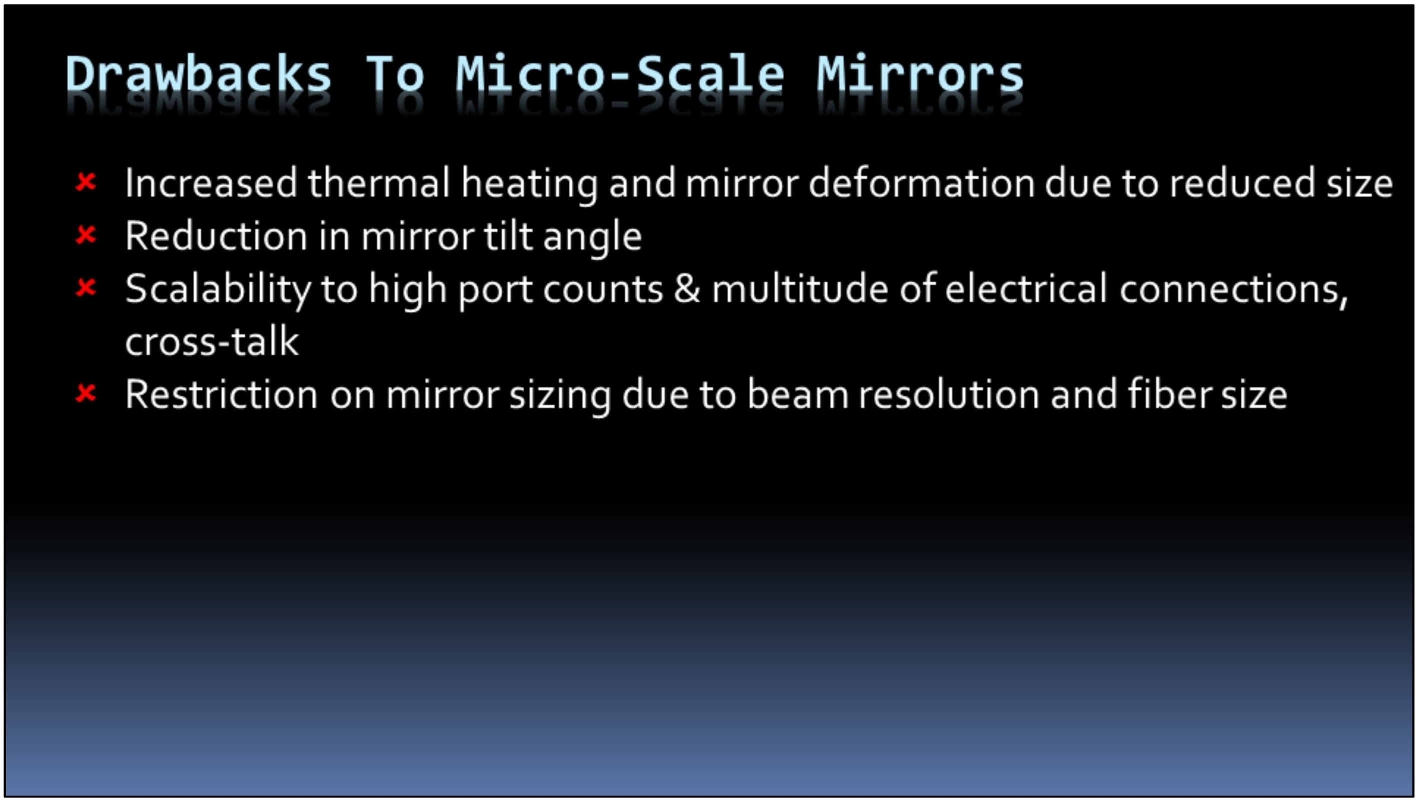
Note that the quality factor is independent of fn. The increase in angular frequency is compensated by the decrease of plate thickness d.

In order to achieve high Q (>10,000), Pressure needs to be lower than 10Pa

M	molar mass of air	kg/mol	0.02896450			
Ro	Boltzmann's constant	kJ/molK	8.31E-03	8.31E-03	8.31E-03	8.31E-03
T	temperature	K	298.15	298.15	298.15	298.15
P	Pressure	Pa	101325.0	101325.0	101325.0	101325.0
	Pressure (low press)	Pa	1000.0	1000.0	1000.0	1000.0
	Pressure (lowest press)	Pa	1.0	1.0	1.0	1.0
Q	Quality factor	unitless	0.12	0.12	0.12	0.12
	Quality factor	unitless	11.85	11.85	11.85	11.85
	Quality factor	unitless	11854.91	11854.91	11854.91	11854.91

We originally figured that the Quality factor would be closely tied with the resonant frequency's response to scaling, but upon further inspection of the formula it can be seen that the Quality factor is actually independent from the scaling responses of the resonant frequency. Since the resonant frequency is calculated with the plate thickness 'd' in its denominator, the 'd' in the numerator of the Quality factor equation cancels out with this 'd' to make the Q factor independent of the gains made by scaling fn. Therefore, in order to improve the quality factor in our micro-mirror case, the best solution is to lower the pressure and put the device in a vacuum.

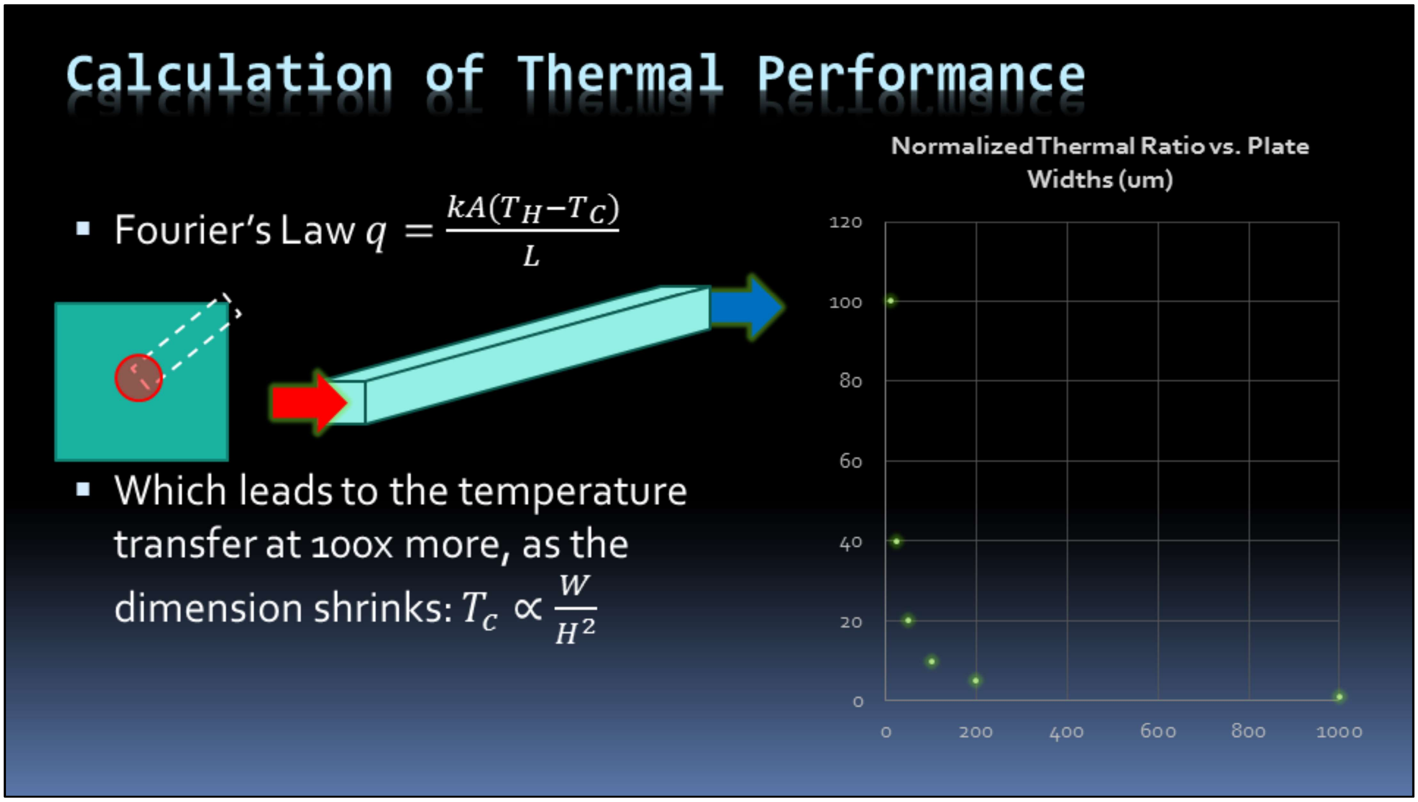
Ref: Kadar, "CALCULATION OF THE QUALITY FACTOR OF TORSIONAL RESONATORS IN THE LOW-PRESSURE REGION"



Drawbacks To Micro-Scale Mirrors

- Increased thermal heating and mirror deformation due to reduced size
- Reduction in mirror tilt angle
- Scalability to high port counts & multitude of electrical connections, cross-talk
- Restriction on mirror sizing due to beam resolution and fiber size

We found several drawbacks to micro-scale mirrors including increased thermal heating and mirror deformation as well as a reduction in mirror tilt angle. These issues will be described and possible solutions will be provided in the following slides.

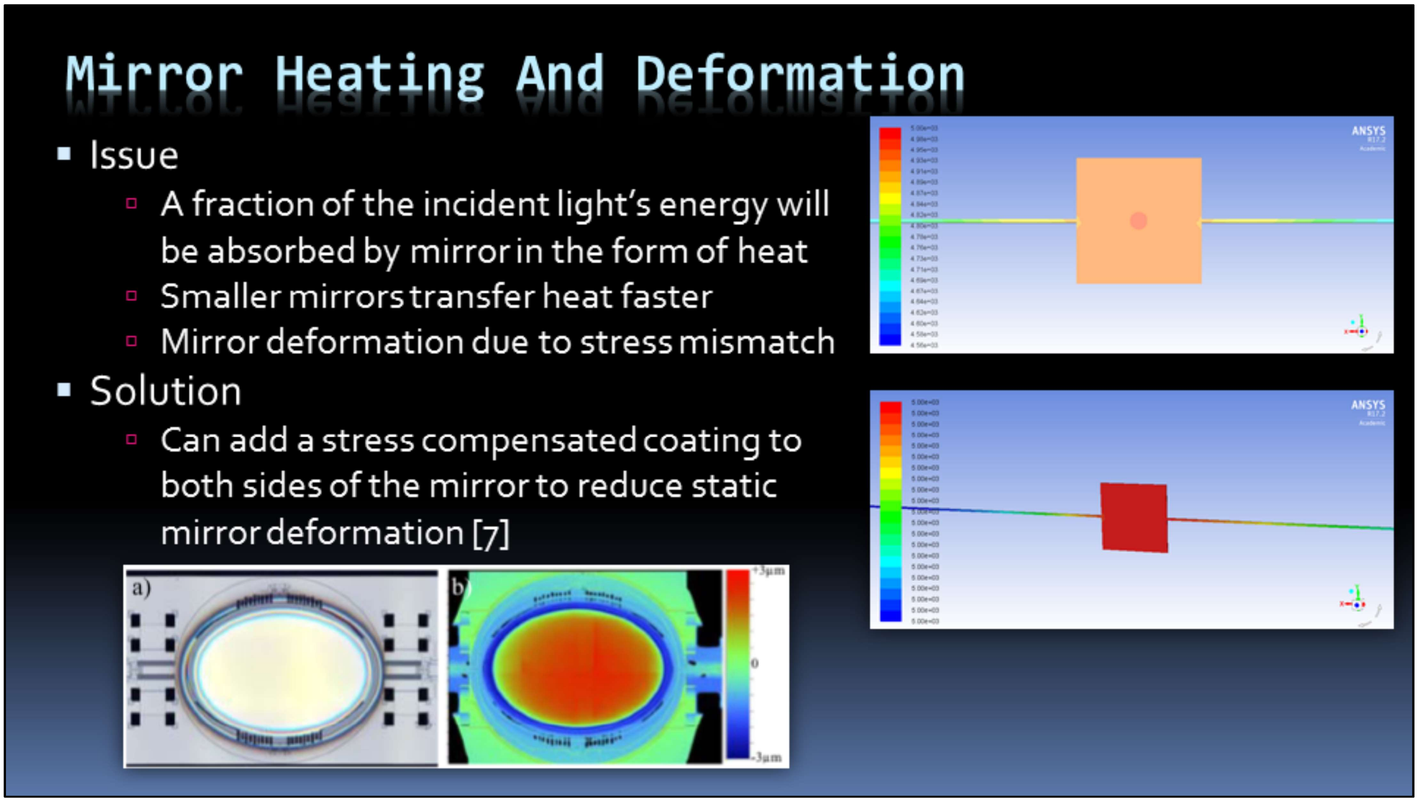


Calculation of Thermal Performance

- Fourier's Law $q = \frac{kA(T_H - T_C)}{L}$
- Which leads to the temperature transfer at 100x more, as the dimension shrinks: $T_c \propto \frac{W}{H^2}$

In calculating the thermal performance during miniaturization, a simple model in which the center is subjected to a high thermal input is used. Assuming radial symmetry in thermal conduction, and that the thickness is small relative to the width of the mirror, we applied a simple mathematical model by extracting one sliver of the plate from the center to the edge.

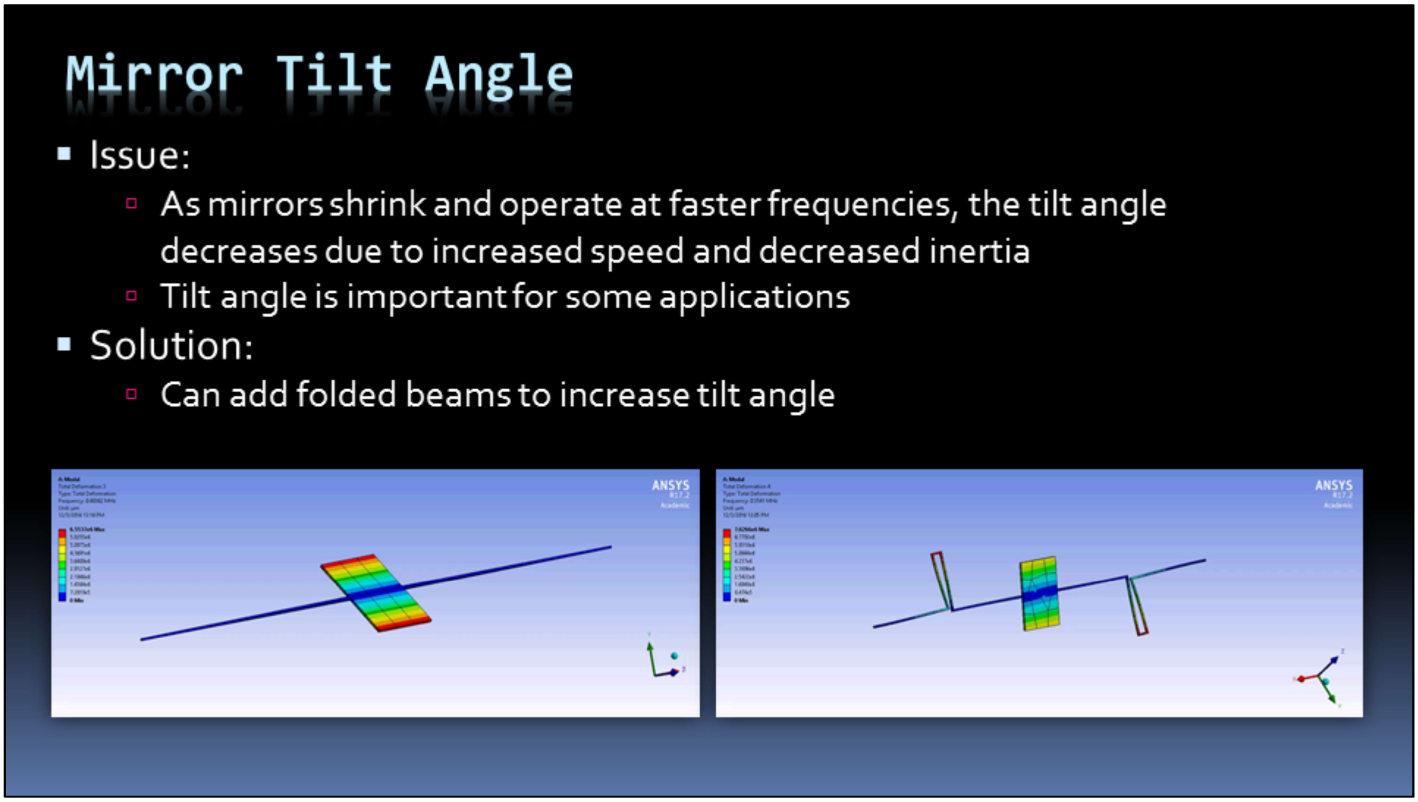
By applying Fourier's Law of thermal propagation, we observe that the temperature of the far end of the structure is proportional to the ratio of width of the mirror, over the square of the thickness of the structure. As we shrink the width of the mirror from 1mm to 10 um, the corresponding temperature increases at the same rate as the reduction (100x).



Mirror Heating And Deformation

- Issue
  - A fraction of the incident light’s energy will be absorbed by mirror in the form of heat
  - Smaller mirrors transfer heat faster
  - Mirror deformation due to stress mismatch
- Solution
  - Can add a stress compensated coating to both sides of the mirror to reduce static mirror deformation [7]

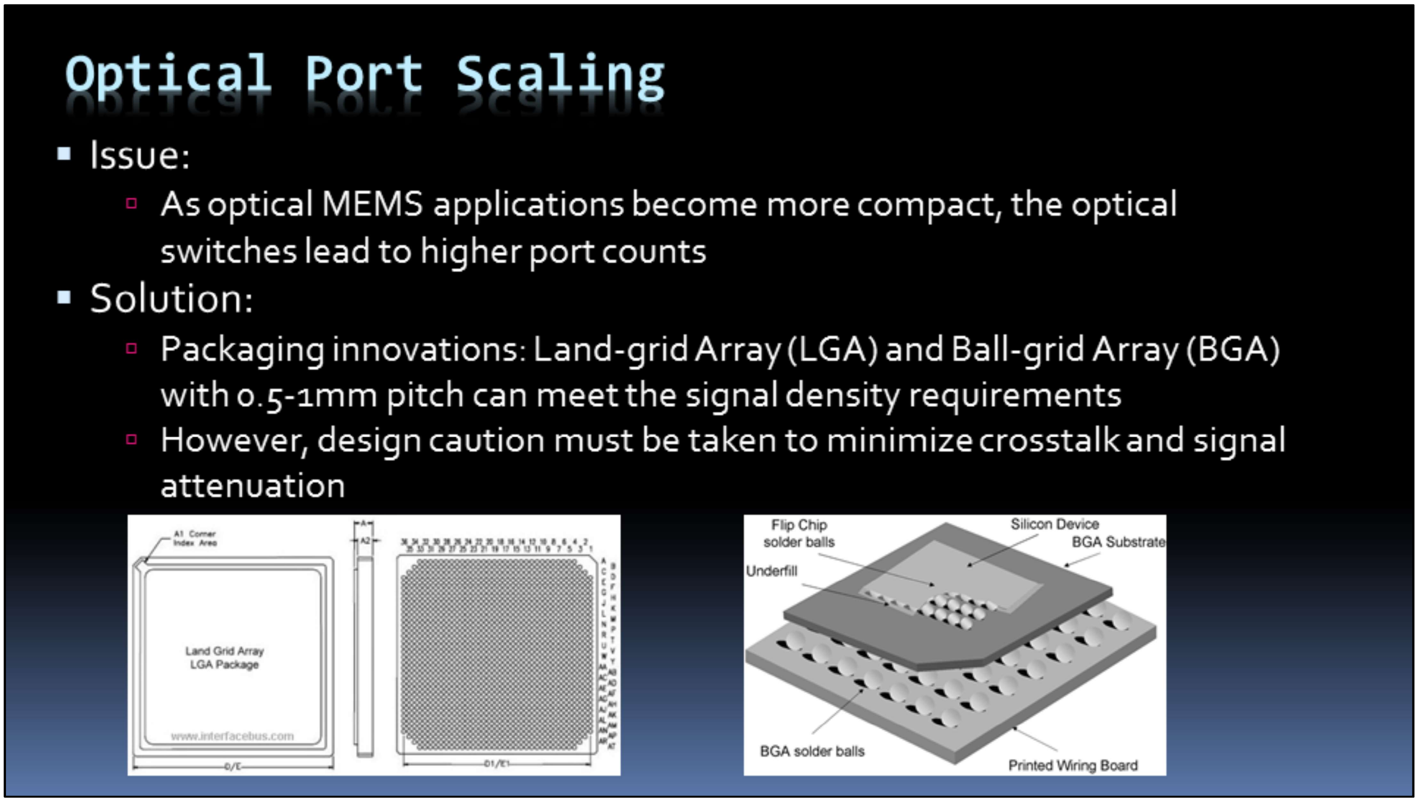
Since all metals are imperfect reflectors, the mirror will absorb a fraction of the incident light’s energy and will therefore begin to heat up[9]. With the scaling of the mirror, this heat will transfer more quickly throughout the device and cause deformation which can affect the integrity of the optical switch. As you can see above in the heat flow diagrams on the right, the amount that the heat dissipates per unit time in the 1mm^2 mirror versus the 10um^2 mirror is significant therefore a significant increase in mirror deformation can be expected. Typically reflective metals are only deposited on a single side of the mirror apparatus, therefore when the metal heats up, a stress mismatch is created between the mirror metal and the underlying metal creating this deformation. One method to alleviate this deformation is to employ a double sided metalization method so that the stress will be relatively equal on both sides. This is not a perfect solution as light won’t be hitting the underneath metal and the added weight will reduce the goodness acquired due to the original scaling of the mirror. Another solution is to add a stress compensated coating to both sides of the mirror plate which will reduce this statis mirror deflection[7]. As seen in the interferometric measurement result of deformation topography in the lower figure the heat resistant coating prevents deformation quite well.



Mirror Tilt Angle

- Issue:
  - As mirrors shrink and operate at faster frequencies, the tilt angle decreases due to increased speed and decreased inertia
  - Tilt angle is important for some applications
- Solution:
  - Can add folded beams to increase tilt angle

As mirrors shrink the tilt angle decreases due to the increased operating speed and decreased inertia of the mirror. This can be a problem if the application requires a large tilt angle such as visual optics in projectors or laser scanning, but for others such as optical switching, a smaller tilt angle can be desireable because the beam strikes the mirror at near-normal incidence which allows for yet smaller mirrors[9]. If a larger tilt angle is still desired, there are solutions to help alleviate this. One such solutions is to add folded beams into the design to increase the tilt angle as modeled above. This added folded beam can be designed according to the tilt angle required. The drawback to adding folded beams is that the resonant frequency will slightly decrease due to the added beam mass, but this trade off can be tuned to give the results that are desired.



Optical Port Scaling

- Issue:
  - As optical MEMS applications become more compact, the optical switches lead to higher port counts
- Solution:
  - Packaging innovations: Land-grid Array (LGA) and Ball-grid Array (BGA) with 0.5-1mm pitch can meet the signal density requirements
  - However, design caution must be taken to minimize crosstalk and signal attenuation

Another potential problem for MEMS optical switches is the electrical connections for the micro-mirrors. By one count, it'll take at least four connections to rotate a mirror along two axes. Integrating all the addressing, control and drive electronics will be difficult, especially when high-voltage and precise analog circuitry is required. With current packaging development (LGA/BGA), the problem is alleviated, but attention must be paid to the unwanted cross-talk among electrical connections in order to avoid errors in controlling the movement of the micro-mirrors.

Ref:
1. Tung, “An Introduction to MEMS Optical Switches” https://courses.cit.cornell.edu/engrwords/final_reports/Tung_MF_issue_1.pdf
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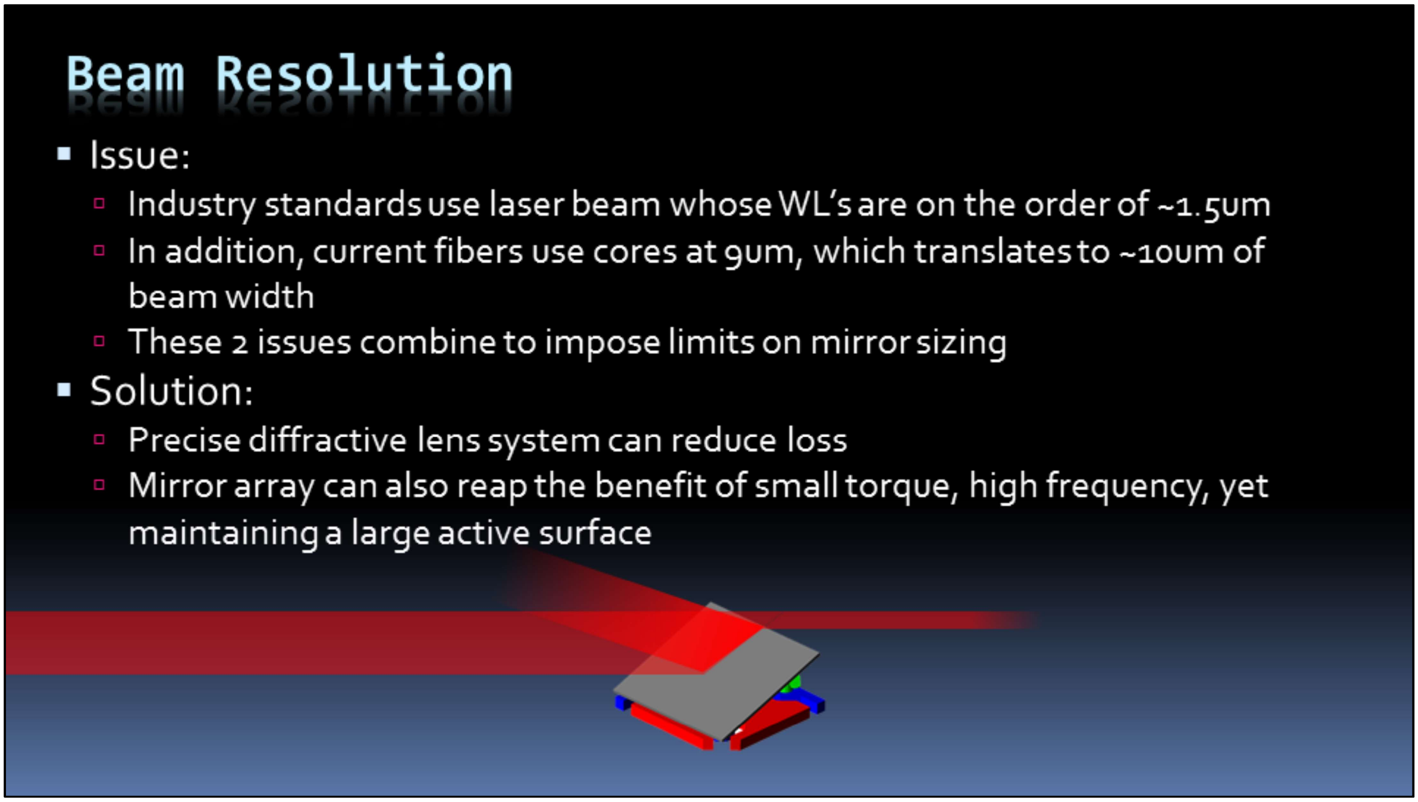
3. https://www.scribd.com/doc/147201322/What-s-LGA-BGA-PGA-DIP-Chip-Carrieres

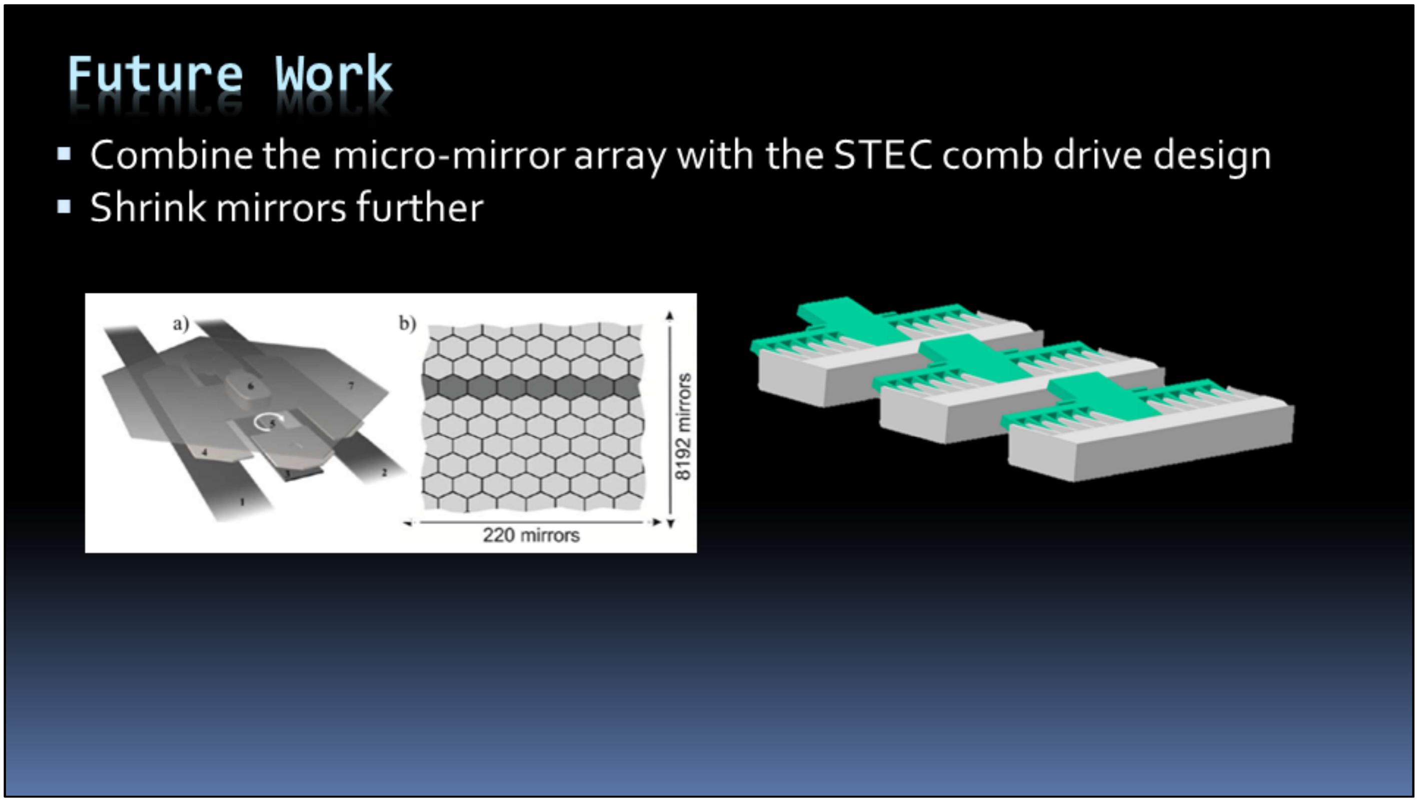


Beam Resolution

- Issue:
  - Industry standards use laser beam whose WL's are on the order of ~1.5um
  - In addition, current fibers use cores at 9um, which translates to ~10um of beam width
  - These 2 issues combine to impose limits on mirror sizing
- Solution:
  - Precise diffractive lens system can reduce loss
  - Mirror array can also reap the benefit of small torque, high frequency, yet maintaining a large active surface

One last issue is that the telecom industry uses laser beam whose wavelength is at roughly 1550nm. At such resolution, the mirror is expected to be at least 1 order of magnitude bigger to prevent loss due to misalignment/coupling. In addition, the industry standard uses fiber cores that are 9um in diameter. Provided that the light is not guided through metal, we'd expect a light beam diameter of roughly 10um across, and this can be an issue for miniaturizing a single mirror.

In order to counter this shortfall, there will be a need to develop precise diffractive lens system to minimize power loss. However, this is not enough, eventually we will have to address the issue that there's a physical minima to reflect light of width that corresponds to the width of a single mirror. Another solution is presented in one of the papers by Schenk, where an array of mirrors is joined together to form a bigger surface.



Future Work

- Combine the micro-mirror array with the STEC comb drive design
- Shrink mirrors further

For future work we propose that a valuable design could come in the form of combining both the STEC comb drive design proposed by Conant and the micro-mirror array design proposed by Schenk. This new design would provide the benefits of both designs which we saw earlier to create an array of high frequency mirrors that can be used for visual optics as well as optical switching. Further shrinking the mirrors that were proposed in the STEC design would also further improve the operating frequency of this design and would make it even more appealing for several applications.

Conclusions

- Scaling mirrors to the micro scale has many benefits
    - Higher resonant frequency and scan speed
    - Reduced mirror deformation
    - Reduced energy to operate device
    - Reduced torsion and inertial forces
- But this doesn't come for free
    - Faster thermal heating
    - Reduced tilt angle
    - Increased complexity due to higher density

In conclusion, there are several benefits to scaling mirrors to the micrometer scale. However, like most scientific solutions, this scaling introduces several issues that must be overcome in order to make these devices feasible and advantageous. The most notable benefits of scaling mirrors to the micrometer scale is the increased resonant frequency and reduced inertial forces. These factors allow for the mirrors to operate at higher scan frequencies and function with reduced energy to power the devices. The drawbacks to shrinking the mirrors include faster thermal heating due to the decreased volume as well as reduced tilt angle due to the increased operating speeds and reduced torque. We have proposed solutions to these in earlier slides that will help alleviate some of these issue, however, these solutions will halter some of the goodness that comes from the mirror scaling in the first place. A balance needs to be found based on the application being used to find the correct scaling factor that provides a mirror design with the desired scan speeds while minimizing the tradeoffs that would most hinder the success of the device in such an application. Overall the scaling of mirrors to the micrometer scale can be a powerful tool for some of the applications we have described and should definitely be considered as a viable option when building a new design.

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