21.6 Microelectromechanical Scanning Devices for Optical Networking Applications

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M. Wu

The state-of-the-art of optical MEMS devices for optical networking applications is reviewed, and a scanning micromirror with angular vertical comb (AVC) actuators is introduced. The AVC scanner uses a single etching process and is completely self-aligned. It has 50% larger scan angle than conventional vertical comb devices. Resonant frequency is 630Hz.

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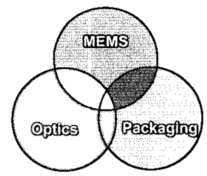
OUTLINE

- Introduction
- 2D MEMS optical switches – Lessons learned
- 3D MEMS optical switches
  - Critical issues for MEMS scanners
  - New scanner using angular vertical comb drive actuators
- Conclusion

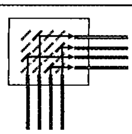
Critical Issues of 2D MEMS Switches



- Concurrent engineering of MEMS, Optics and Packaging
  - MEMS:
    - Mirror angle accuracy, uniformity, repeatability; Fill factor; Stiction
  - Optics:
    - Fiber collimator array; Optical alignment (active)
  - Packaging
    - Fix and maintain alignment (for 20 years); Hermetic sealing; Resistance to temperature variation; Reliability

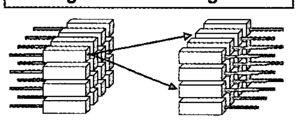
MEMS Optical Switch Architectures

2-D MEMS Digital Crossbar Switch



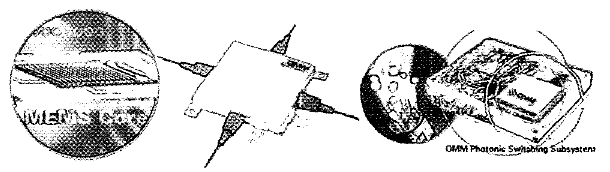
- N^2 digital micromirrors
- Digital switch, easy to control
- Maximum size of the switch limited by diffraction (32x32)
  - Multi-stage network (e.g., Clos) needed to large OXC

3-D MEMS Analog Beam-Steering Switch



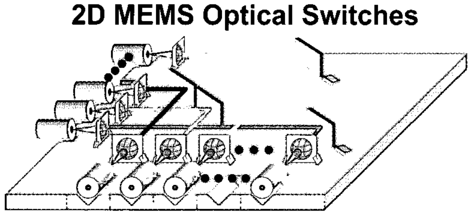
- 2N analog scanners (2 DOF)
- Close-loop control for each scanner
- Scalable to large port count (> 1000)

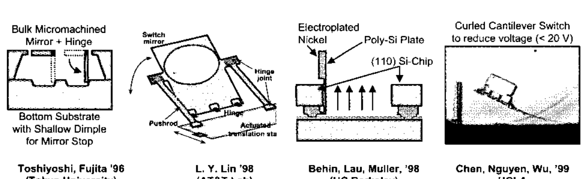
Current Status of 2D MEMS Optical Switch



- 2-D MEMS optical switch has been successfully commercialized
- 4x4, 8x8, 16x16, and 32x32 are now commercially available in quantities
- Telcordia qualifications (GR-1073-CORE, GR-1221-CORE and GR-468-CORE) passed
- Automation in assembly, packaging, and testing is key to volume production

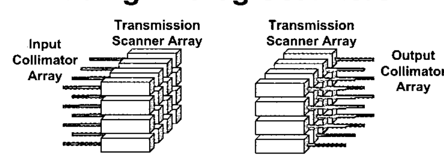
2D MEMS Optical Switches





3-D Switch using Analog Scanners

1. Transmission type with Scanning Microlenses



2. Reflection type with Scanning Micromirrors

3-D Switch using Analog Scanners

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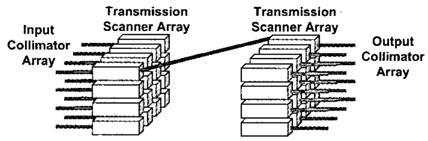

2. Reflection type with Scanning Micromirrors

3-D Switch using Analog Scanners

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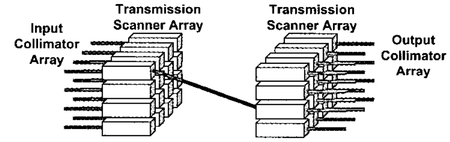

2. Reflection type with Scanning Micromirrors

3-D Switch using Analog Scanners

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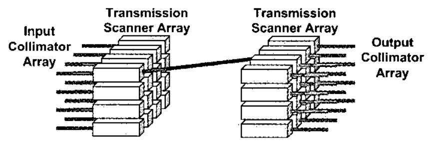

2. Reflection type with Scanning Micromirrors

3-D Switch using Analog Scanners

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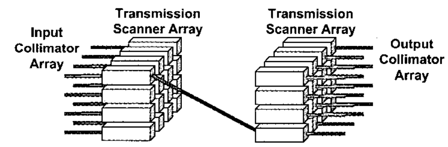

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3-D Switch using Analog Scanners

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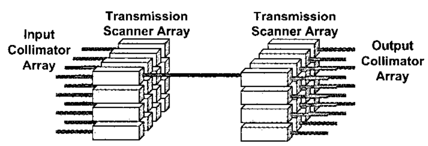

2. Reflection type with Scanning Micromirrors

3-D Switch using Analog Scanners

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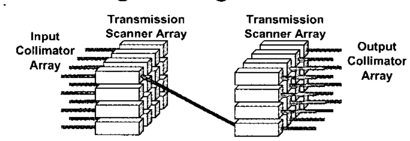
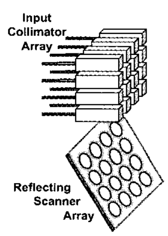


2. Reflection type with Scanning Micromirrors



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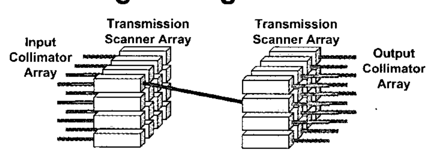

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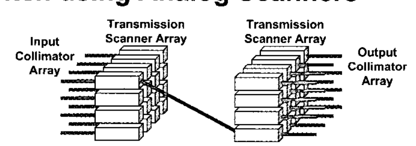

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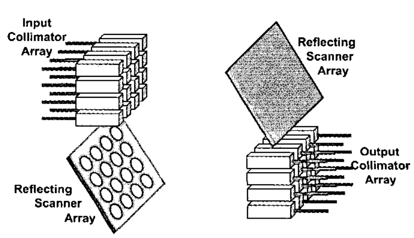

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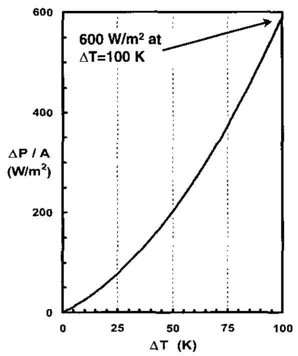
Measurement of Chip Cooling with E-jet

- Heat transfer capacity increases to 600 W/m² at ΔT = 100 K
- Stable operation: >6B cycles
- Typical human cooling requirement is 360-700 W/m²
- Mobile Pentium III (0.5-1 GHz) cooling requirement: 10-50 kW/m²



Power Consumption and Efficiency

- Consumed power in the 25 resonator MACE by device and parasitic capacitances is ~300mW.
- A high voltage source of ~100V is needed since MACE. This is not a major issue since charge-pump circuits can be used to accommodate this higher voltage.
- Efficiency can be improved by recovering some of the energy currently wasted in charging and discharging the capacitors.
- Significant energy is used up in moving the air around and this depends on the flow rate and air volume needed for a particular application. This is the dominant power dissipation source and cannot be reduced.
- E-jet is expected to be at least as efficient as some of the standard fans used in portable systems.

Future Development

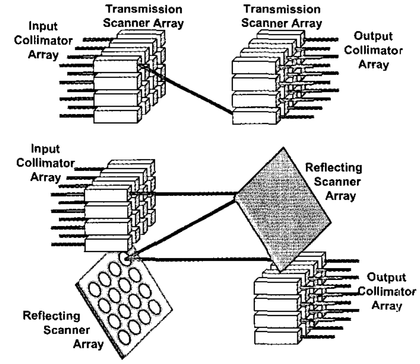
- Clearly the heat removal rate of the current devices is not sufficient for high-power electronic devices.
- The e-jet velocity needs to be increased.
- New designs are in development that can increase the jet velocity by a factor of about 10x
- The total volume of pumped air can be increased by using a larger number of devices.
- Further work is necessary to optimize the assembly and attachment of e-jets to the IC chip.
- Further long-term stability and reliability tests are needed.
- Active Pin-Fin heat sink should provide a higher efficiency.

Conclusions and Summary

- A stand-alone micromachined electronic jet capable of producing air flow velocity of 0.5-1 m/sec has been developed.
- E-jet is fully integrated and does not require external components for its operation.
- E-jet is quiet (50-70kHz), and is electrostatically operated.
- E-jet is thin (<2mm), and small (few cm on a side) and can be mounted directly over the IC chip package, without interfering with the manufacturing of the IC chip.
- E-jet can be used for air pumping and cooling applications in a variety of portable electronic devices.

3-D Switch using Analog Scanners

1. Transmission type with Scanning Microlenses
2. Reflection type with Scanning Micromirrors



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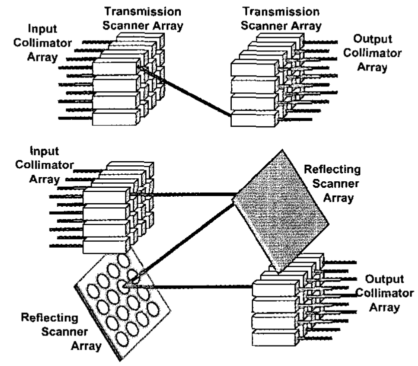

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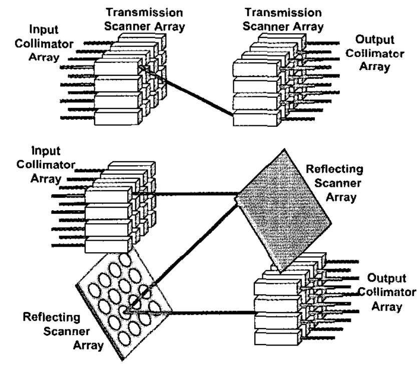

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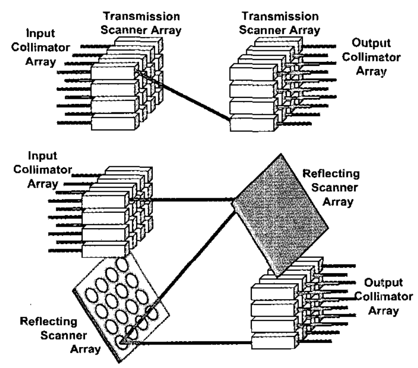
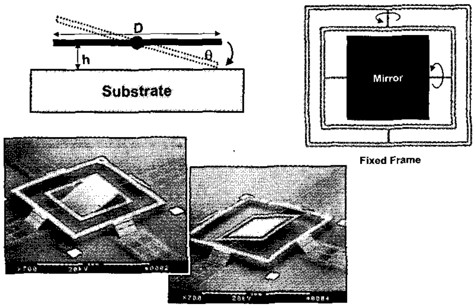
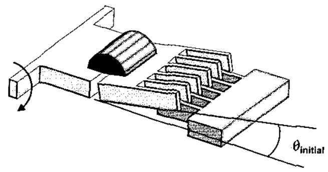


Surface-Micromachined 2-D Scanning Micromirrors



L. Fan, M. C. Wu, Optical MEMS 1998

New Angular Vertical Comb Drive Actuator

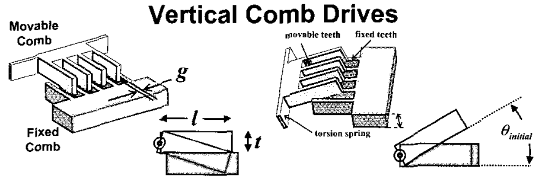


- Movable comb is tilted by an initial angle
- Offers many advantages over staggered vertical combs:
  - Simpler fabrication process; need only a single-layer SOI
  - Self-aligned, both movable and fixed combs are pattered and etched at the same time
    → Increased threshold for lateral instability
  - Larger scan angle (determined by the initial tilt angle)

Critical Issues for 2D Scanners

- Flat mirror surface over wide temperature range
- Large mirror area, large scan angle
- Low actuation voltage (or energy)
- Reasonably high resonant frequency
- High fill factor
- Low crosstalk among scanners
- Good repeatability
- Low drift

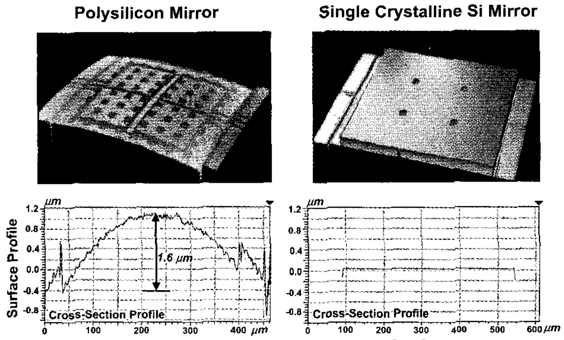
Comparison of Staggered and Angular Vertical Comb Drives



	Staggered Vertical Comb (SVC)	Angular Vertical Comb (AVC)
Torque per Gap	$\tau = \frac{\varepsilon \cdot l^2}{2g}$	$\tau = \frac{\varepsilon \cdot l^2}{2g}$
Maximum Scan Angle	$\theta_{\max} = \frac{l}{t}$	$\theta_{\max} = \theta_{initial} > \frac{l}{t}$

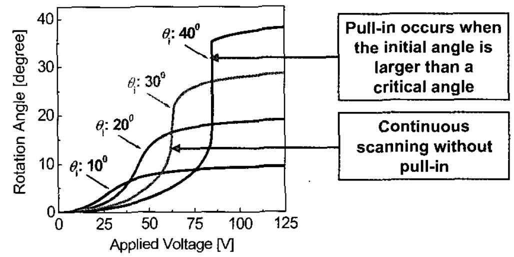
Micromirror Flatness

Polysilicon Mirror | Single Crystalline Si Mirror



R = 1.8 cm | R = 265 cm

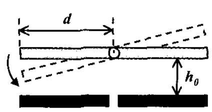
Calculated Scanning Characteristics of AVC Scanner



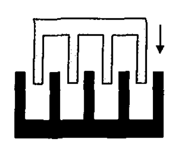
The maximum angle without pull-in is 50% larger than SVC scanner with same comb dimensions

Considerations for Actuators (Electrostatic)

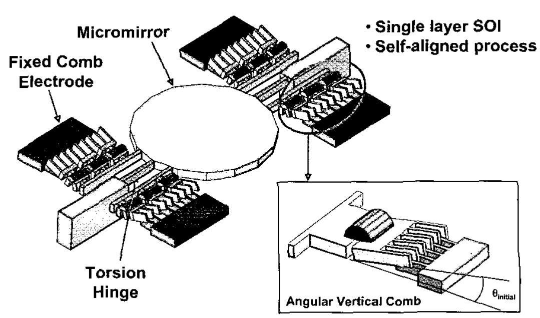
- Parallel plate actuators
  - Large, flat single-crystalline micromirrors with large scan angle has been demonstrated [Blackstone, 2001; Sawada, 2001]
  - Issues: High voltage; Usable angle reduced by pull-in bistability



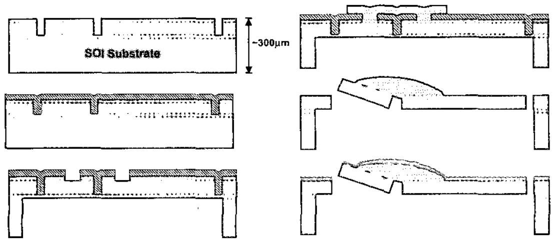
- Vertical comb actuators
  - Large force density
  - Low voltage, large scan range, high resonant frequency
  - Initially demonstrated by surface/bulk-micromachining [Selvakumar, 1995]
  - Staggered vertical comb using double-



Schematic of Micromirror with Angular Vertical Comb (AVC) Actuator

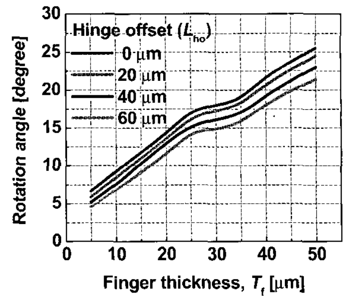


Fabrication Process for AVC Scanner



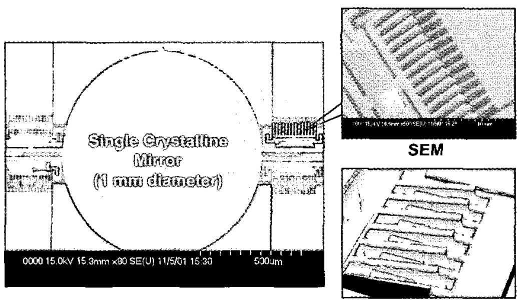
- One-step DRIE on SOI wafer
- Self-aligned fixed and movable comb fingers
- Use reflow of photoresist for 3D assembly (after Syms)

Maximum Scan Angle versus Thickness of SOI



- Bias voltage kept constant at 100 V
- Finger length and initial tilt angle are optimized for maximum angle

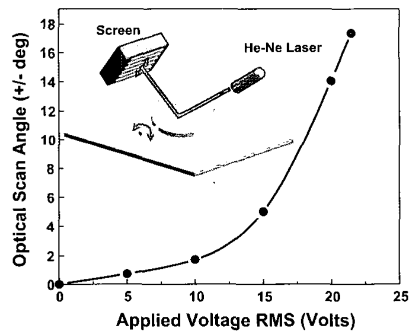
Scanning Electron Micrograph of AVC Scanner



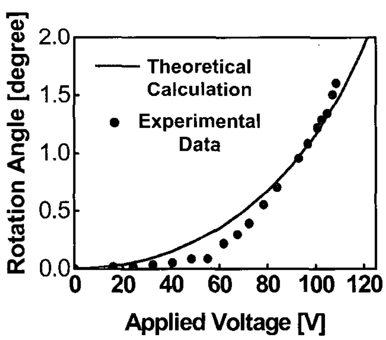
SEM

Optical Interferometric Image

Resonant Scanning Angle at 1.4 kHz



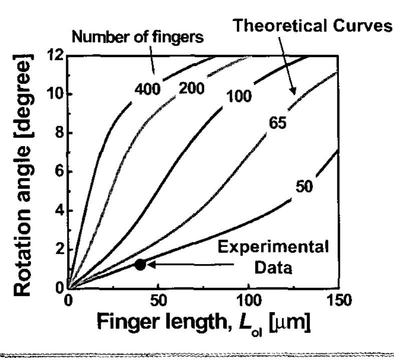
Measured Scanning Characteristics



Conclusion

- MEMS is a disruptive technology for optical systems
- Attractive for dynamic all-optical functions
- Successful commercialization Optical MEMS products requires concurrent engineering of
  - MEMS, Optics, Packaging
- Reviewed status of 2D and 3D MEMS optical switches
- Discussed angular vertical comb (AVC) actuator for scanning mirrors that is promising for large area, large scan angle micromirrors

Optimization of AVC Scanner



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