Microphotonics Devices for Space Applications

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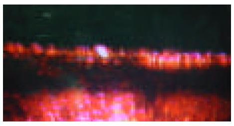

Outline

- Project Motivation and Objectives
- Advantages of Micro-optics
- Material Systems for Micro Photonic Integrated Circuits (PIC)
- Micro-PIC Technologies
- MPB Technology Demonstrator
- Conclusions

Motivation

- **High penalty mass-cost during the launch of payloads (€ 200,000 /kg)**
- **Miniaturization advantages**
  - **higher functional densities.**
  - **higher frequency of missions,**
  - **More scientific or commercial benefit per mission.**
- **Optical systems in particular:**
  - **High data transmission and processing rates (GHz);**
  - **Immunity to EM interference;**
  - **Significant mass savings for signal harnesses (1/20 electrical)**
  - **Simplified signal routing and protection from ESD damage**
  - **Low high-frequency signal attenuation**

Specific Space Applications for Microphotonics

- **Optical processor for multi-channel optical sensor systems**
- **Optical high capacity downlinks (hyper-spectral missions)**
- **Optical WDM inter-satellite links**
- **Multi-channel configurable optical RF signal distribution and processing (programmable true-time delay, filtering)**
- **Satellite optical attitude control (optical gyroscope, sun sensor, earth sensor)**

Advantages of SOI System

- **Two material systems for micro PICs:**

  Silicon on Insulator (SOI) and InGaAsP (InP)

SOI Advantages:

- Large-area, low-cost substrates (> 20 cm O.D.)
- Compatible with CMOS integrated electronics
- Well-established wafer processing and micro machining due to Si I.C. technologies
- Good thermal stability
- Low-cost native thermal SiO_2
- High-index Si waveguides or low-index SiON waveguides
- Possibility of Er or Yb-doped active silica waveguides for light amplification and waveguide tunable lasers

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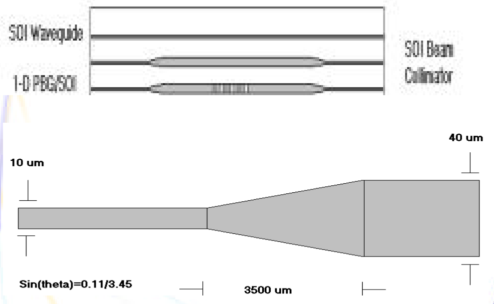
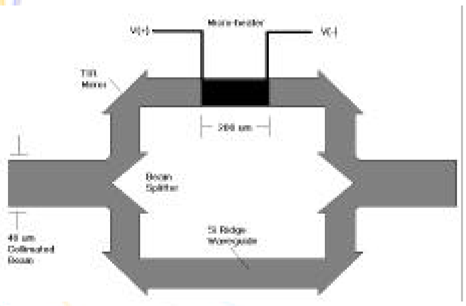
Basic parts: tapered waveguide and collimator



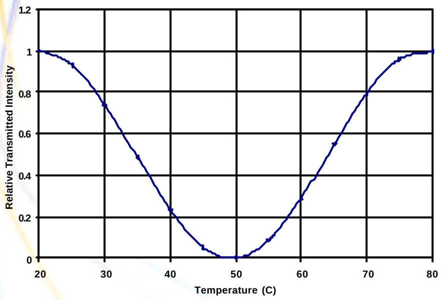
Tuning/Switching Mechanisms for SOI Platform

- Thermo-optic (n = 3.38(1+ 3.9 10^{5}T), T in K)
- MEMS micro-actuators
- pressure/strain
- Photonic Bandgap structure
- VOn smart materials (Metal – Insulator transition)
    - Thermochromic (ms to µs)
    - Electrochromic (µs to ps)

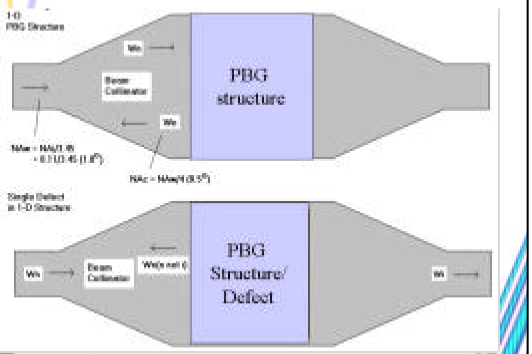
Device 1: TIR Mach Zehnder Interferometer



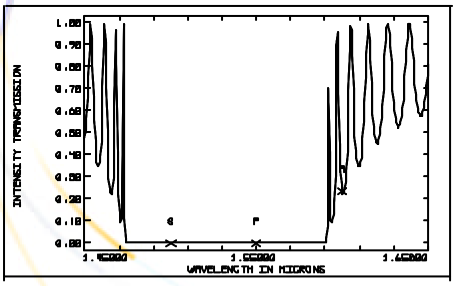
Transmitted intensity at 1550 nm versus micro-heater temperature:



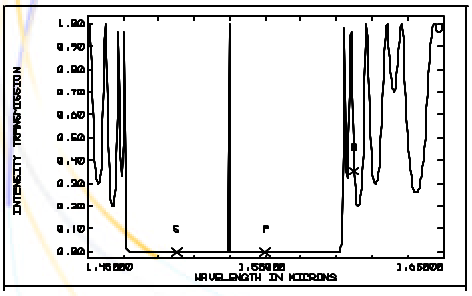
Device 2: WDM PBG Structure

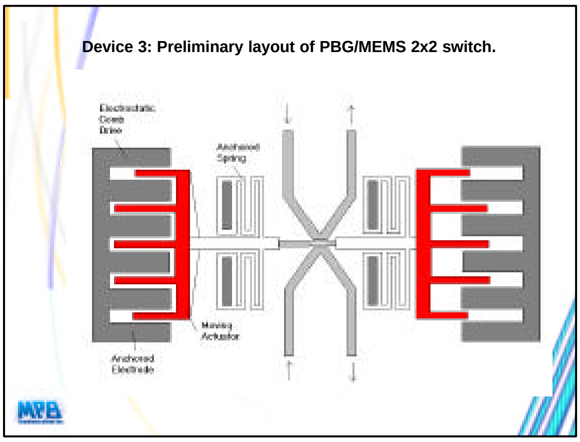


PBG 1-D Structure Transmittance

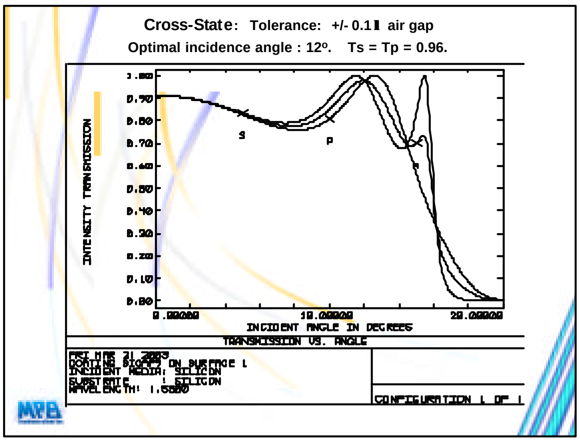


Reflected narrow line due to Single Defect in 1-D PBG Structure



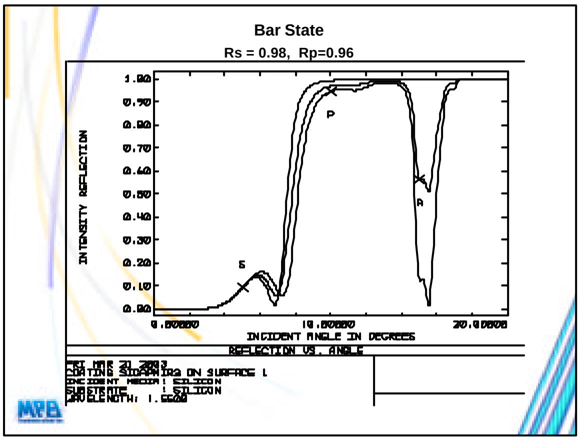


Device 3: Preliminary layout of PBG/MEMS 2x2 switch.



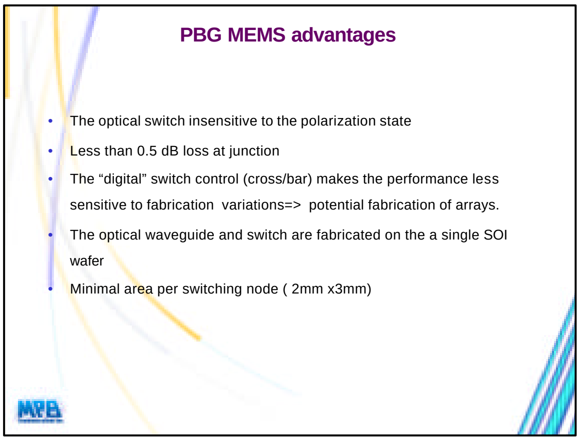
Cross-State: Tolerance: +/- 0.1▮ air gap

Optimal incidence angle : 12º. Ts = Tp = 0.96.



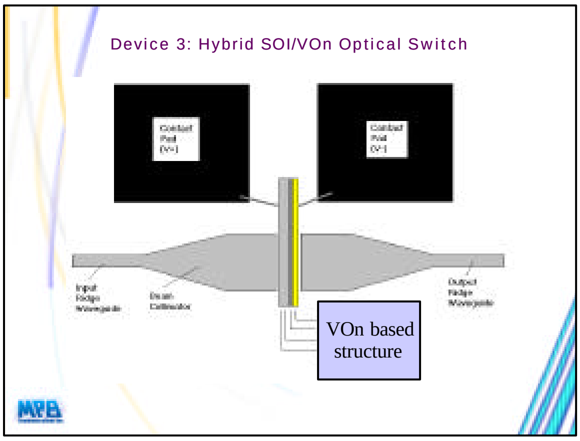
Bar State

Rs = 0.98, Rp=0.96

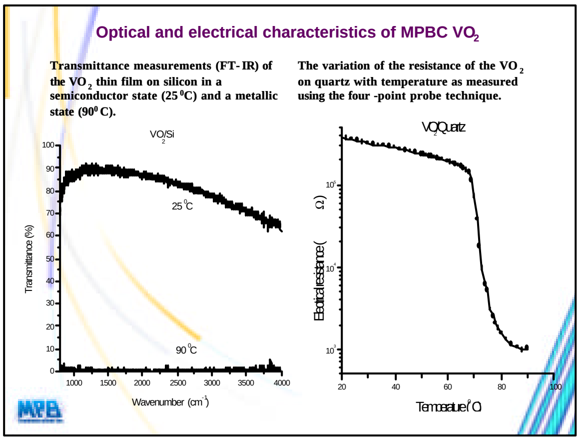


PBG MEMS advantages

- The optical switch insensitive to the polarization state
- Less than 0.5 dB loss at junction
- The “digital” switch control (cross/bar) makes the performance less sensitive to fabrication variations=> potential fabrication of arrays.
- The optical waveguide and switch are fabricated on the a single SOI wafer
- Minimal area per switching node (2mm x3mm)



Device 3: Hybrid SOI/VOn Optical Switch

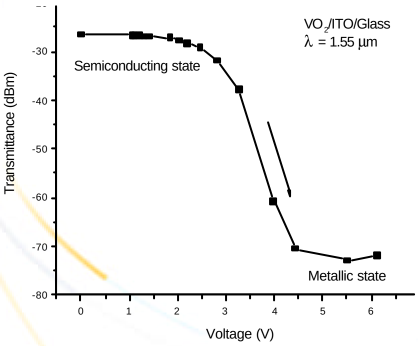


Optical and electrical characteristics of MPBC VO_2

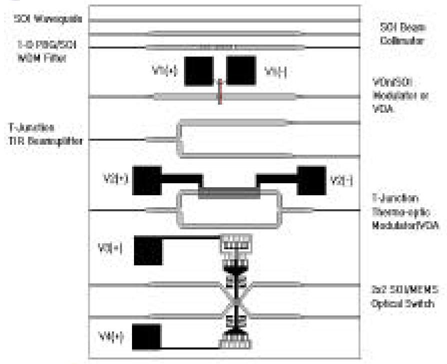
Transmittance measurements (FT- IR) of the VO_2 thin film on silicon in a semiconductor state (25 ^{0}C) and a metallic state (90^0 C).

The variation of the resistance of the VO_2 on quartz with temperature as measured using the four -point probe technique.

Preliminary Electrochromic Device Results



Schematic of Technology Demonstrator



Micro-PIC Technology Demonstrator

- SOI platform (5-6 µm Si/1 µm SiO$_2$/ Si)
- Integration of several different active and passive components on a single substrate
- Employs several different miniaturization technologies on a single substrate: TIR waveguides, 1-D PBG concepts, thin-film electrochromic active optics, MEMS
- Novel 1-D PBG wavelength selector for WDM systems
- Novel T-junction beamsplitter - 160 x 200 µm
- Novel VOn/SOI optical switch
- Novel polarization-independent SOI/MEMS optical switch

Summary of different technologies for NxM integrated-optic switches

Switch Technology	Substrate	Switching Speed	Channel Capacity	Size	Functional Density
				(cm^2)	(channels/cm^2)
Electro-optic	LiNbO3	<nsec	6 x 6	350	0.03
Amplification Switch	III-V	nsec	4 x 4	0.04	400
Thermo-optic	Silica, SOI	2 msec	16 x 16	110	2.4
Total Internal Reflection	Silica, SOI	5 to 10 msec	32 x 32	6	171
MPB 2x2 MEMS	SOI	ms to ms		2 x 3 mm	120 (limited by MEMS actuator size)
MPB VOn	SOI	ms to ps		0.2 x 0.2 mm	> 2000

Comparison to Traditional Integrated-Optic Devices

Traditional SOI Device	Device area (cm^2)	New MPB Device	Device area (cm^2)
2x2 Thermo-optic Switch	0.4	2x2 MEMS/PBG Device	0.06-junction + MEMS , 0.02 (junction only)
1x2 silica splitter	0.3	TIR Beam splitter	0.0002
LiNBO3 high speed device	2	Von SOI high speed switch	<0.05
WDM linear Bragg grating	>10 cm long for 1 pm resolution	PBG linear Defect	< 50 ìm long

Conclusions

- Novel passive and active components have been formulated for the SOI platform
- Proposed methodology employs TIR, PBG, MEMS and smart-coating concepts to improve device performance and significantly reduce device substrate area.
- Concepts for novel PBG structures for WDM filtering have been developed that offer significantly greater feasibility for fabrication.
- Proposed technology demonstrator incorporates new, advanced-technology concepts for miniaturization of optical devices on SOI platform

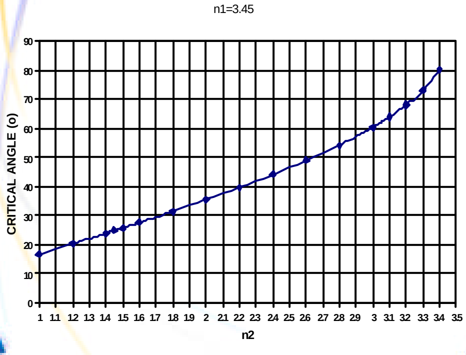
ANNEXES

- Examples comparison RF/Microphotonics
- MEMS and ANSYS simulations

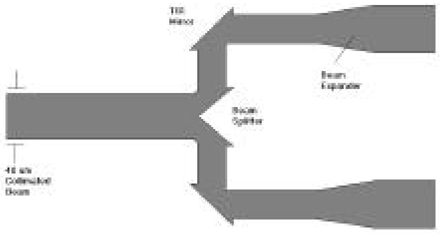
Miniaturization Technologies for SOI micro-PICS

- **Total-Internal Reflection (TIR)**
- **Tunable 50 to 100 nm-thick smart materials (VOn)**
- **Photonic band-gap concepts (1-D, 2-D)**
- **3-D structures using silica on SOI and vertical couplers**
- **MEMS actuators (1 x 1 mm)**

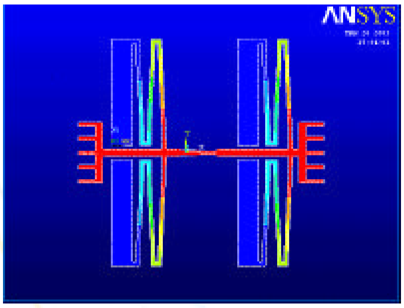
Critical angle for Total Internal Reflection



TIR Y-junction



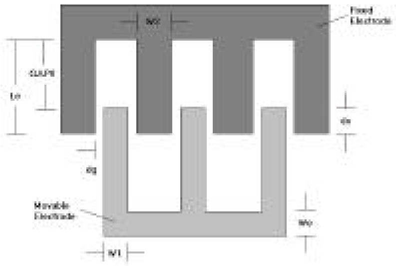
MEMS Flexure Structure



Ansys mechanical simulation of MEMS actuator.

Spring Length	Number of Spring Elements	Restoring Force	Max Stress (50 mm displacement)	Maximum Force (50 mm displacement)
(μm)		(μN/μm)		(μN)
300	3	34.7		1562
500	3	7.7	132	384
700	3	2.8	68	141
750	3	2.3	59	115
500	4	5.78	101	289
700	4	2.4	58	120
750	4	1.95	51	97
1000	4	0.825	29	41

Electrostatic Comb Transducer

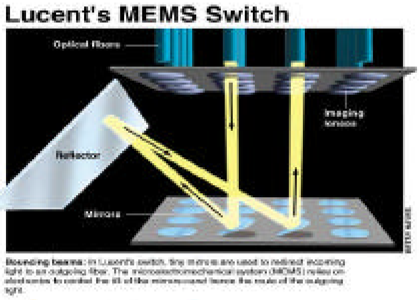


Dependence of Comb force on dg and V as simulated using Ansys.

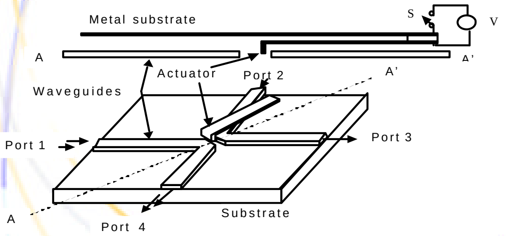
Ls = 750 µm

Comb Drive Gap (dg)	V	F	Nc
(µm)	(V)	(µN)	
1	100	0.89	130
1	150	1.33	87
1.5	100	0.6	192
1.5	150	0.89	130
2	100	0.30	383
2	150	0.67	172

Traditional MEMS micro-Mirror



MEMS-based 2x2 optical cross-connect (after K. Hogari and T. Matsumoto).

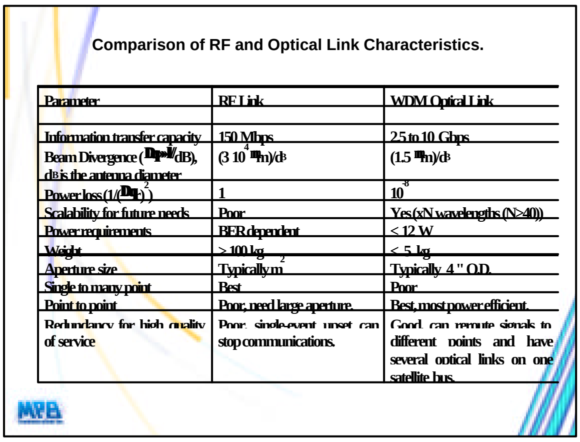


Specifications of optical switching characteristics for different applications in Space.

Application	Switch Type	Switching Speed
Optical Bus Network	N x M	msec
Transponders, OADM	2x2 cross-bar	msec
Optical Beam-forming (Beam Steering)	2x2 cross-bar arrays	msec to µsec
OTDM	1 x N	ns to ps (bit interleaving) µs to ps (packet switching)
Optical D/A	1 x N	ns to ps (signal interleaving)
Multi-channel Sensor Systems	1 x N	ms
Optical integrated gyroscope.	1x2 crossbar	ns

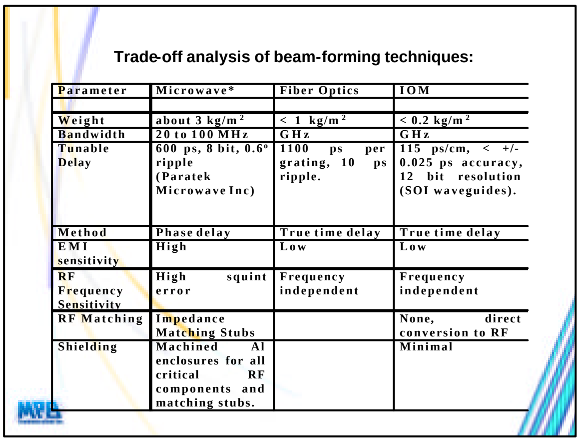
Comparison of electrical and optical box-to-box links.

Parameter	Electrical harness	Optical Ring Bus
Typical weight	10 kg	<0.2 kg
EMI concerns	Yes: requires special routing and shiedling.	No
Ground loop problems	Yes	No
System integration	Time-consuming and costly	Safer, considerably simplified system integration.
Data rates	MHz	> 1 GHz
Scalability	No. requires change in architecture	WDM - can add extra capacity using multiple wavelengths on single fiber.
Signal integrity	Low. requires significant shielding and data coding.	High. enables high data transfers



Comparison of RF and Optical Link Characteristics.

Parameter	RF Link	WDM Optical Link
Information transfer capacity	150 Mbps	2.5 to 10 Gbps
Beam Divergence ($\Delta\theta \approx \lambda/d_B$), d_B is the antenna diameter	$(3\ 10^4\ \mu m)/d_B$	$(1.5\ \mu m)/d_B$
Power loss $(1/(\Delta\theta)^2)$	1	10^{-8}
Scalability for future needs	Poor	Yes (xN wavelengths (N>40))
Power requirements	BER dependent	< 12 W
Weight	> 100 kg	< 5 kg
Aperture size	Typically m^2	Typically 4 " O.D.
Single to many point	Best	Poor
Point to point	Poor, need large aperture.	Best, most power efficient.
Redundancy for high quality of service	Poor, single-event upset can stop communications.	Good, can reroute signals to different points and have several optical links on one satellite bus.



Trade-off analysis of beam-forming techniques:

Parameter	Microwave*	Fiber Optics	IOM
Weight	about 3 kg/m^2	< 1 kg/m^2	< 0.2 kg/m^2
Bandwidth	20 to 100 MHz	GHz	GHz
Tunable Delay	600 ps, 8 bit, 0.6° ripple (Paratek Microwave Inc)	1100 ps per grating, 10 ps ripple.	115 ps/cm, < +/- 0.025 ps accuracy, 12 bit resolution (SOI waveguides).
Method	Phase delay	True time delay	True time delay
EMI sensitivity	High	Low	Low
RF Frequency Sensitivity	High squint error	Frequency independent	Frequency independent
RF Matching	Impedance Matching Stubs		None, direct conversion to RF
Shielding	Machined Al enclosures for all critical RF components and matching stubs.		Minimal