YIQIS 2020

POLITECNICO MILANO 1863

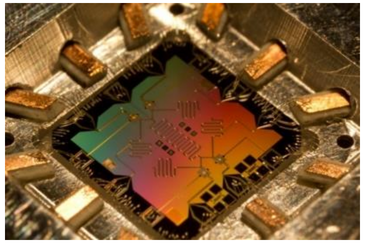
CNR IFN Istituto di Fotonica e Nanotecnologie

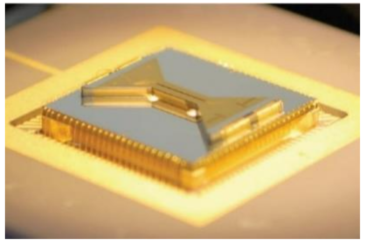
Structured glass for low power actuation of thermal phase shifters

ATZENI Simone

The quantum «race»

- ❑ Superconducting electronic circuits
- ❑ Single ions trapped by electromagnetic fields
- ❑ Spin states in quantum dots
- ❑ Single photons



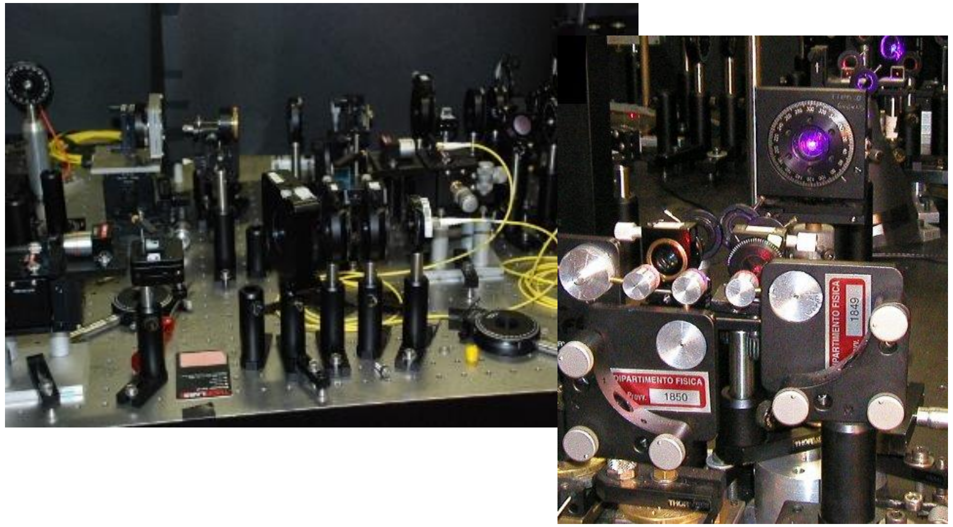


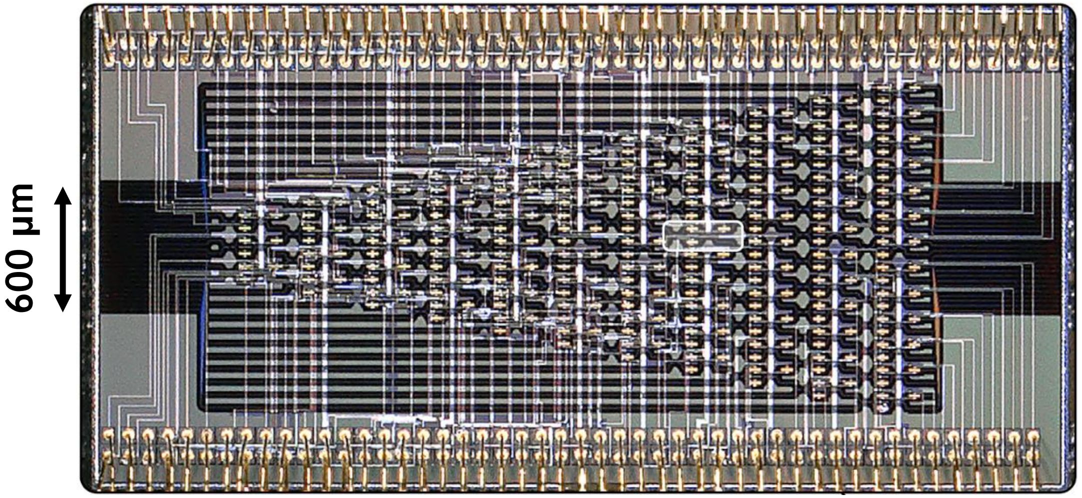
Strengths of single photons:

- ❑ Moderate cooling required
- ❑ Low decoherence
- ❑ Long distance transmission of the quantum information
- ❑ There exists a solid technological framework developed for optical communications

Integrated quantum photonics

Bulk optics implementations…





Harris et al., *Nat. Photonics* 11, 447-453 (2017).

Integrated circuits as enabling technology:

- Miniaturization and complexity
- Scalability and integration density
- Intrinsic optical stability among a high number of components

Femtosecond Laser Micromachining

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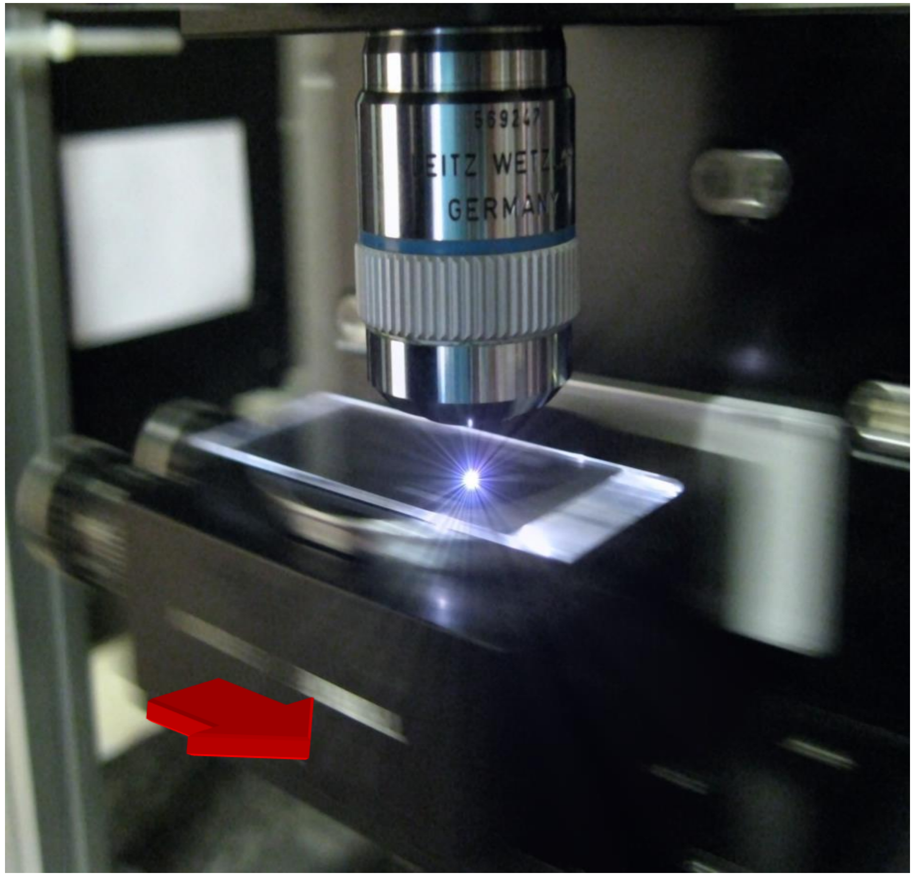

Femtosecond laser pulses are focused in the bulk of a transparent, dielectric material.

- **Nonlinear absorption** generates a seed of free electron, multiplied by avalanche ionization
- Energy transfer causes a **structural modification** of the substrate
- Translation of the substrate allows the fabrication of the device

According to laser – material interaction and energy deposition regime…

- Localized change of the refractive index
- Material ablation and microstructuration

Femtosecond Laser Micromachining

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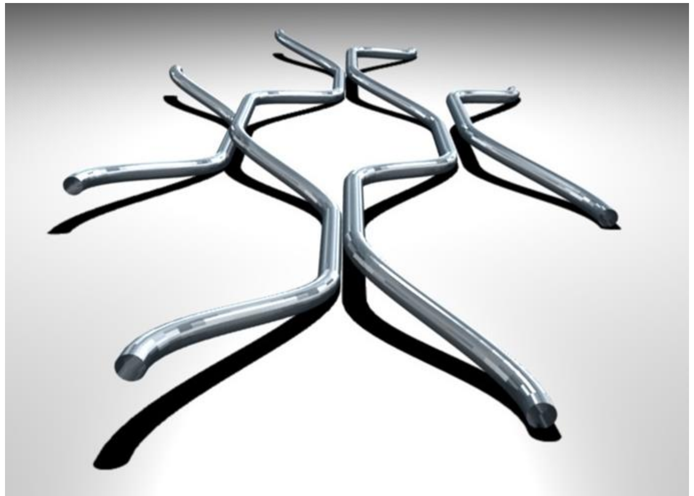
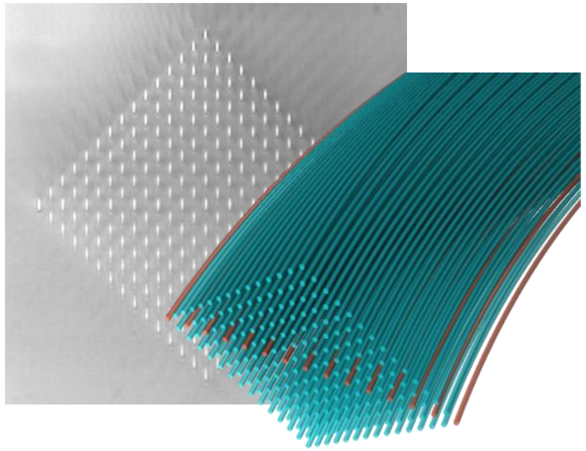
FLM PROVIDES A UNIQUE SET OF ADVANTAGES TO INTEGRATED QUANTUM PHOTONICS

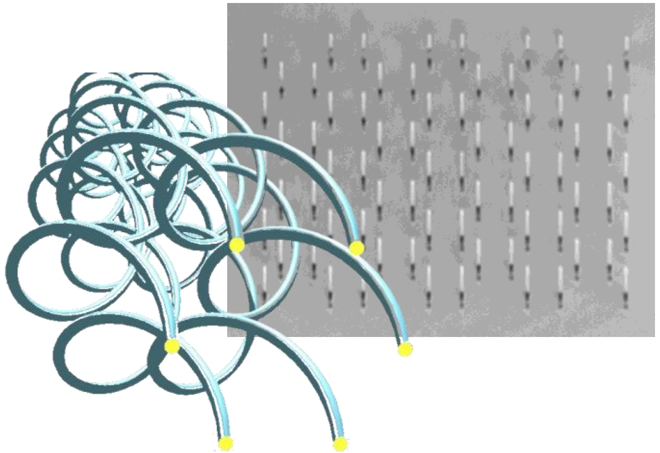
- Single-step maskless approach allows **fast prototyping** turnaround
- Nonlinear absorption can be exploited for the inscription of **complex 3D geometries**
- Low refractive index contrast enables **low coupling losses** with single-mode fibers



Sansoni et al., *Phys. Rev. Lett.* 108, 010502 (2012).



Corrielli et al., Nat. Commun. 4, 1555 (2013).

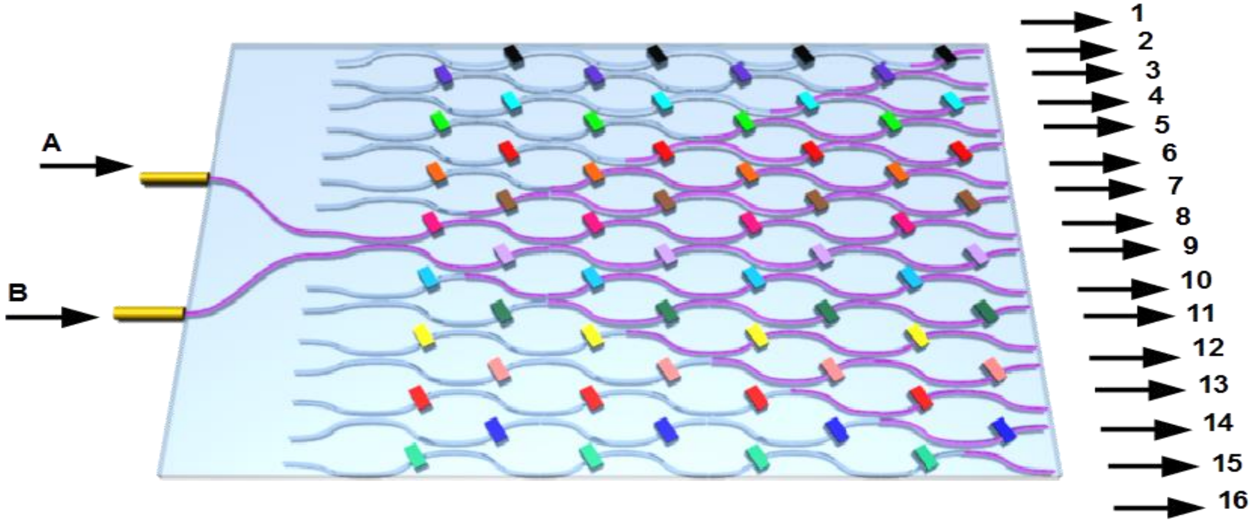


Crespi et al., New J. Phys. 15, 013012 (2013).

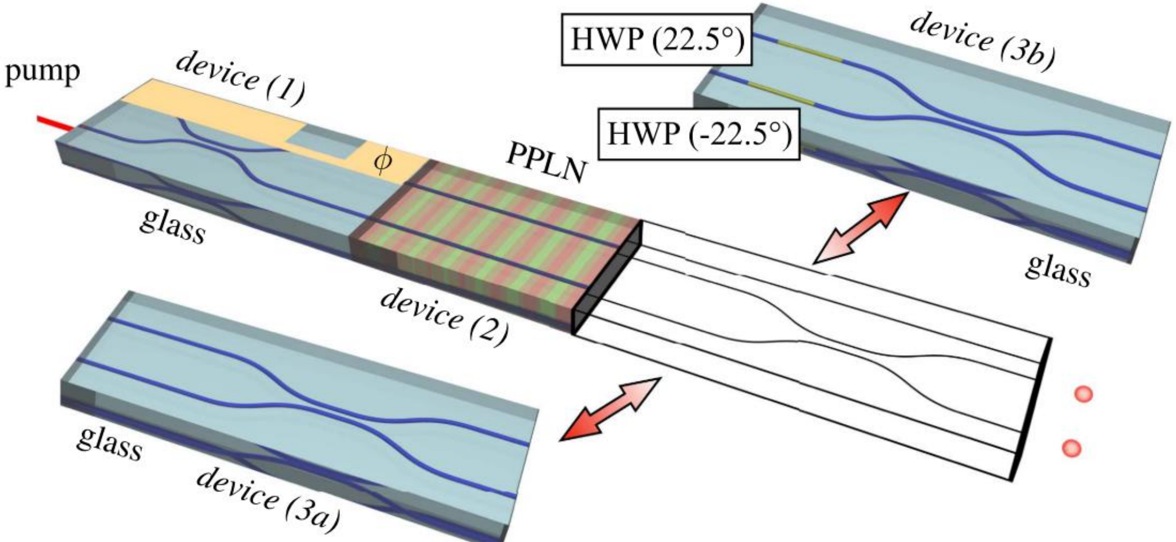
Femtosecond Laser Micromachining

FLM PROVIDES A UNIQUE SET OF ADVANTAGES TO INTEGRATED QUANTUM PHOTONICS

- **Low birefringence** ($b = 1 \times 10^{-6}$) allows the exploitation of FLM circuits in polarization-encoded applications
- By processing different materials we can investigate new functionalities in **composite platforms**



Sansoni et al., *Phys. Rev. Lett.* 108, 010502 (2012).
Crespi et al., *Nat. Photonics* 7, 322-328 (2013).

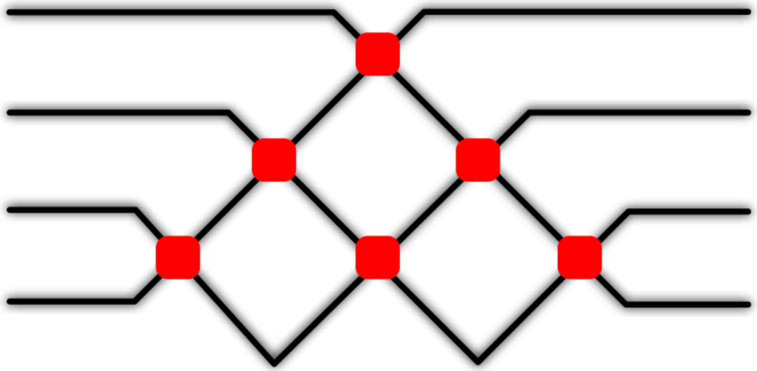


Atzeni et al., *Optica* 5, 311-314 (2018).
Seri et al., *Optica* 5, 934-941 (2018).

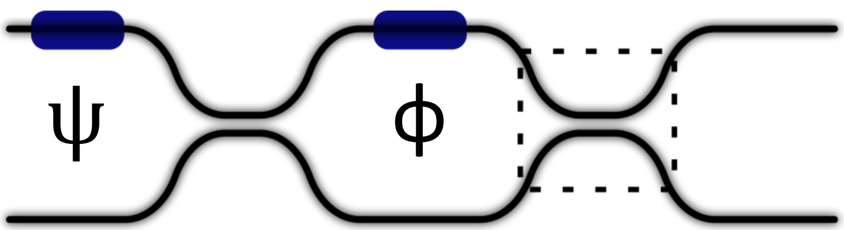
Optical processor: a general scheme

$|\psi_{out}\rangle = U|\psi_{in}\rangle$

IMPLEMENTATION THROUGH A MULTIPORT INTERFEROMETER



...IN WHICH THE BASIC CELL ( )

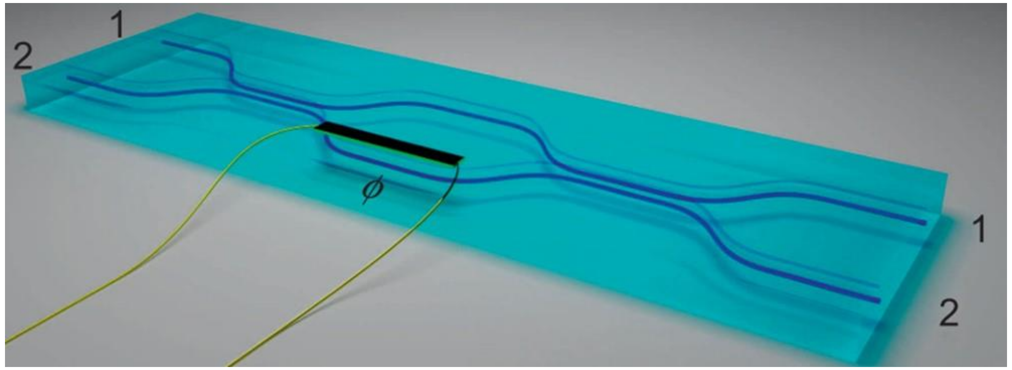


Reck et al., *Physical Review Letters*, 73(58), (1994)

FLM phase shifters implementation

Reconfigurable Mach – Zehnder interferometer

- A phase delay between the arms can be induced by a temperature difference
- Resistive microheater placed on one arm
- Transmission modulated by driving the voltage on the microheater



Flamini et al., *Light: Science & Applications* 4, e354 (2015).

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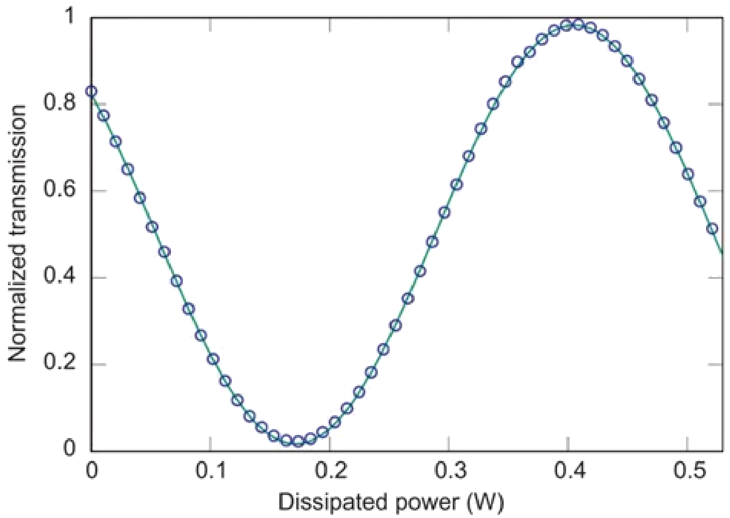
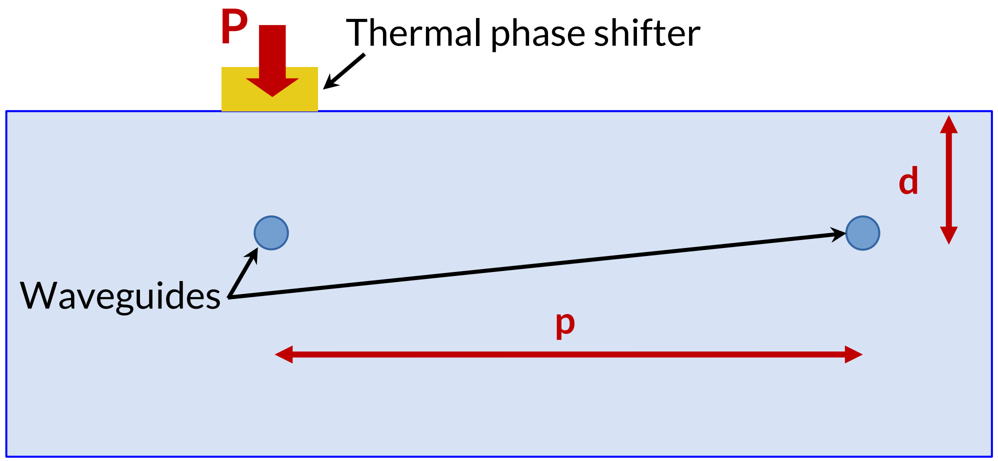


What's the bottleneck of this approach?

- Reconfiguration time ~ 100 ms
- High power dissipation (P > 500 mW for 2π)
- Thermal cross-talk

Power dissipation

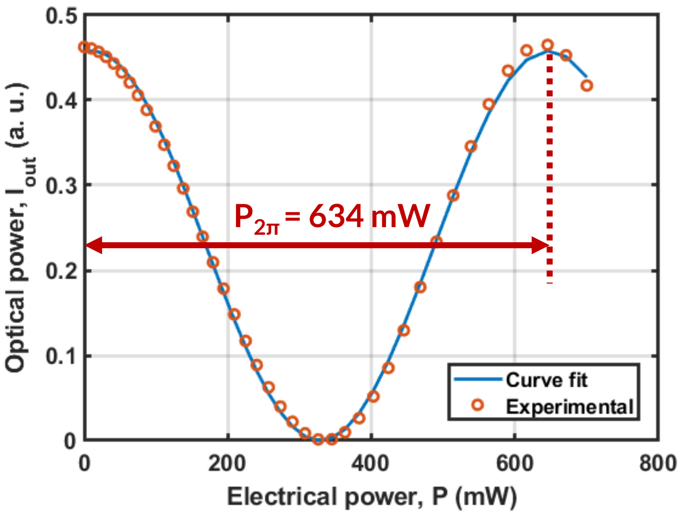


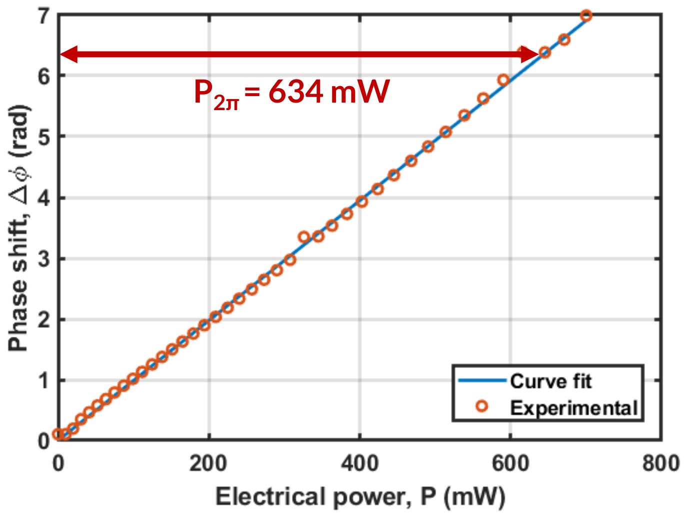
BASIC STRUCTURE OF THE DEVICE

- Corning Eagle XG (boro-aluminosilicate)
- d = 30 μm (minimum value for our FLW setup)
- p = 127 μm ≈ state of the art for FLW circuits
- λ = 1550 nm

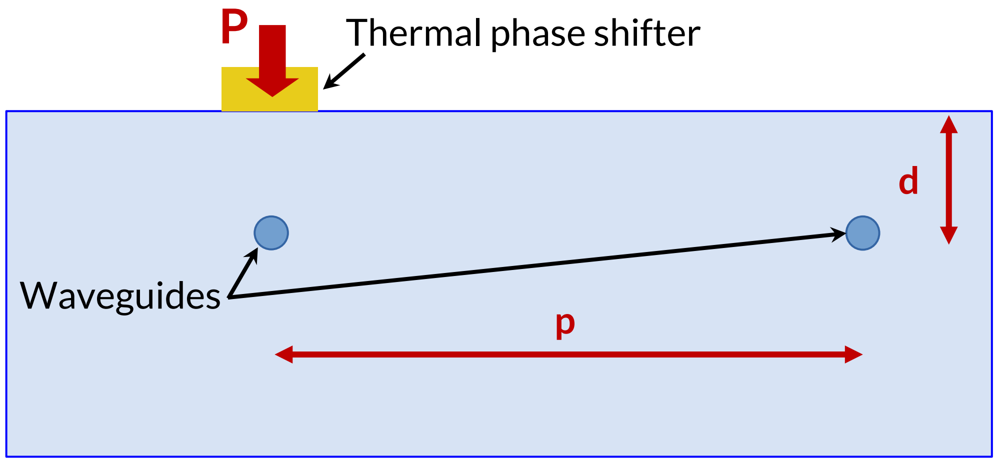
PHASE SHIFT OPERATION

$$\begin{cases} \Delta\phi = \alpha P \\ I_{out} = I_{max}[1 + \cos(\phi_0 + \alpha P)] \\ P_{2\pi} = \dfrac{2\pi}{\alpha} \end{cases}$$





Power dissipation



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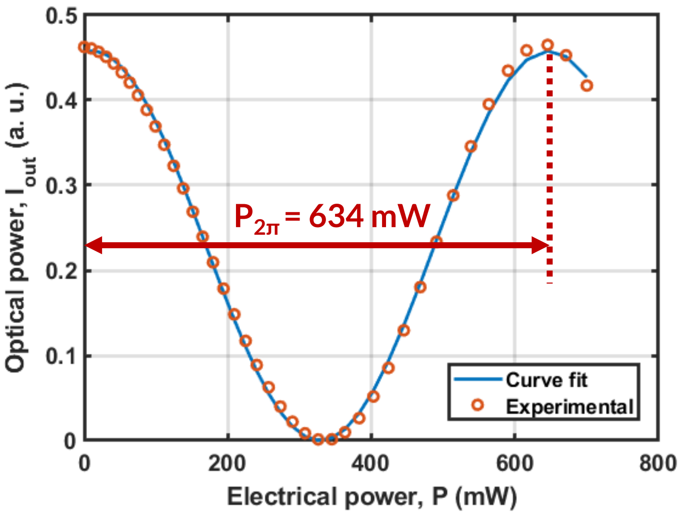
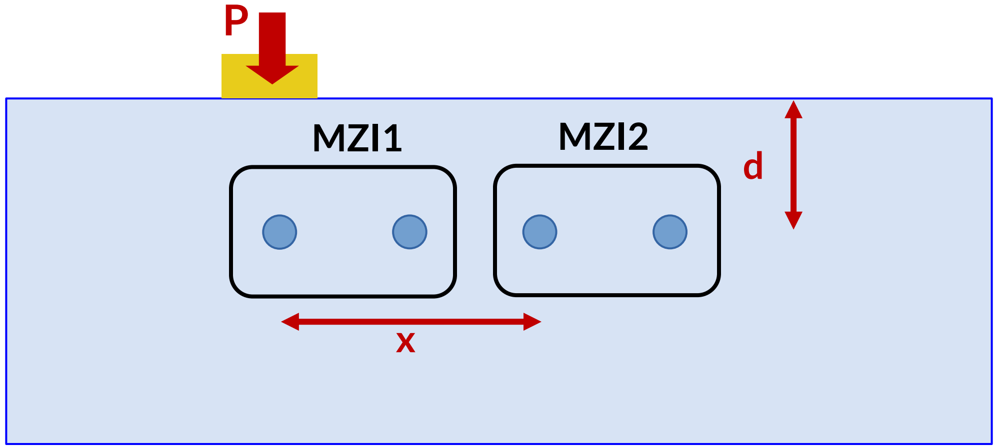
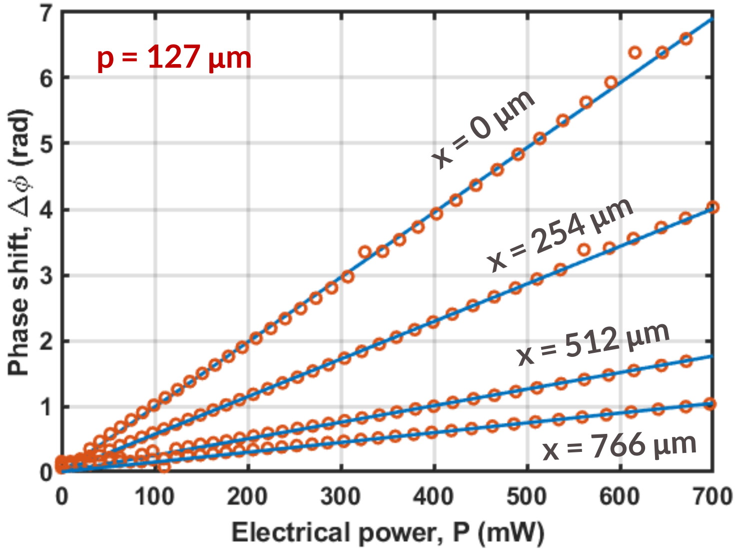
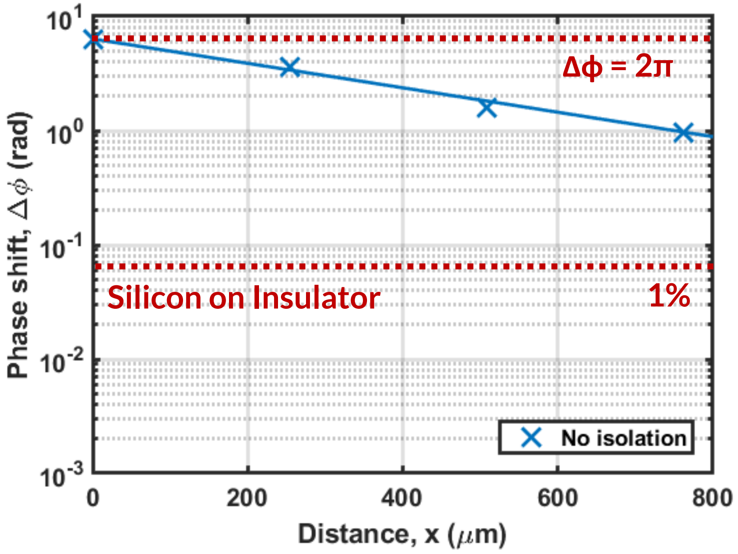


Silicon on Insulator	Si_3N_4	Silica on Silicon	FLW
50 mW	600 mW	800 mW	634 mW

Thermal cross-talk



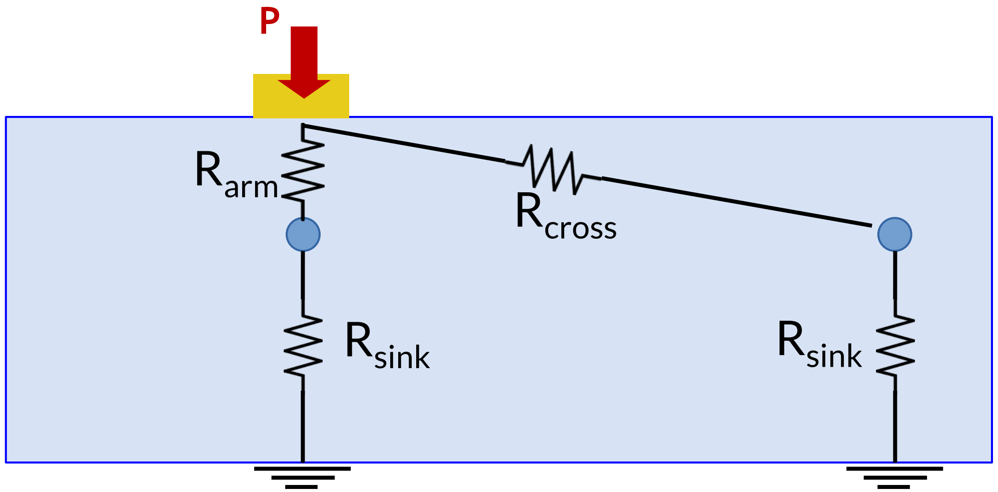




- First neighbour (x = 2p = 254 µm) thermal cross-talk is **58%**
- An effective calibration is not trivial in presence of cross-talk

How can we decrease $P_{2\pi}$ and thermal cross-talk?

Lumped circuit model



- Thermal isolation prevents the heat diffusion towards the rest of the circuit
- Both power dissipation and thermal cross-talk will benefit from this approach

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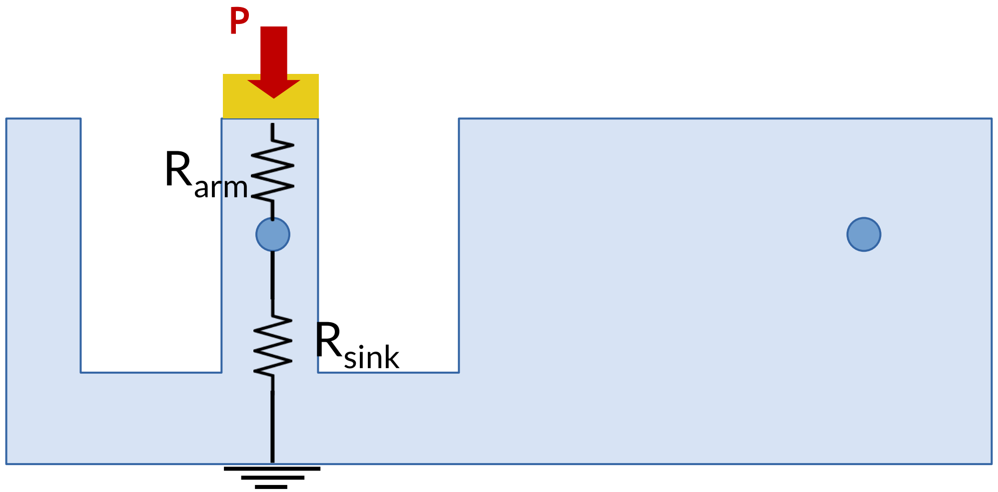

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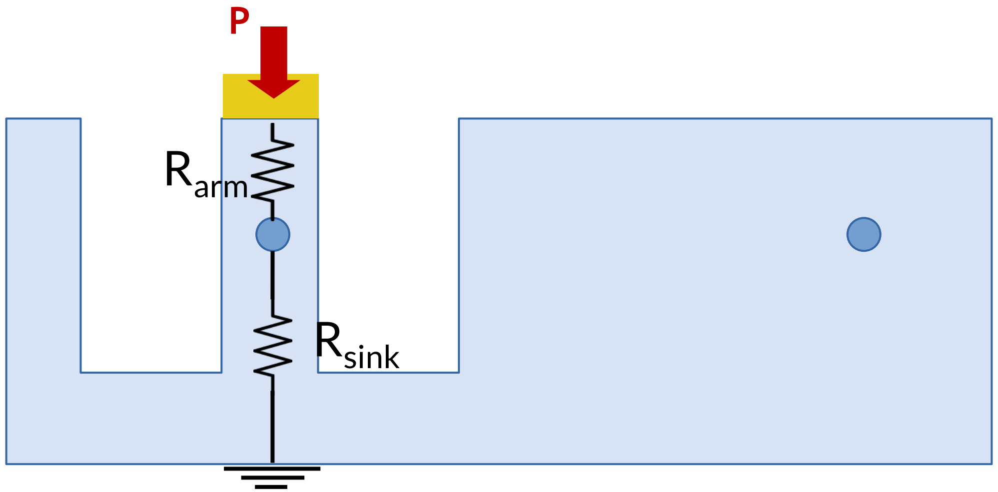

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TOWARDS FULL THERMAL ISOLATION…

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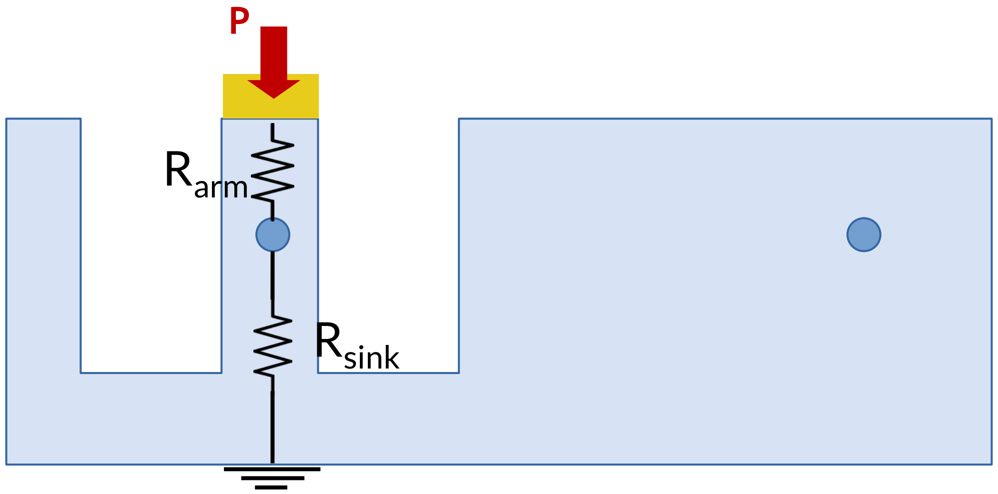

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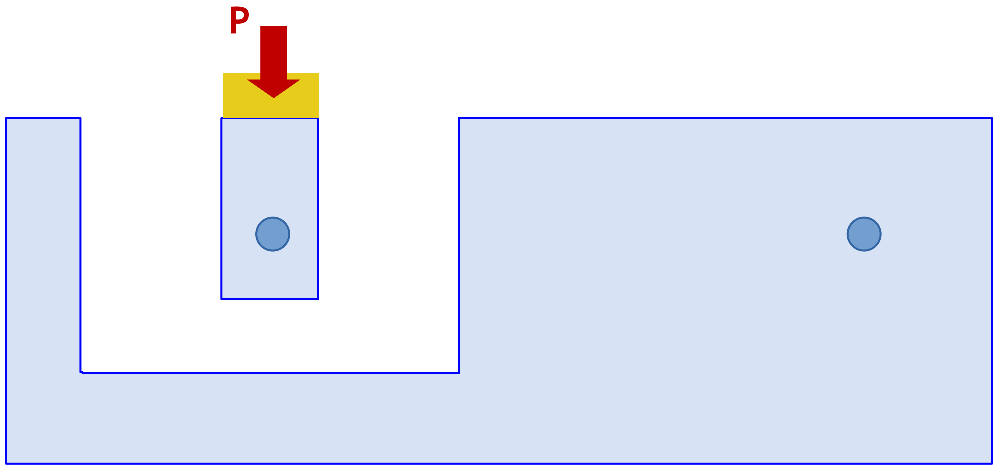
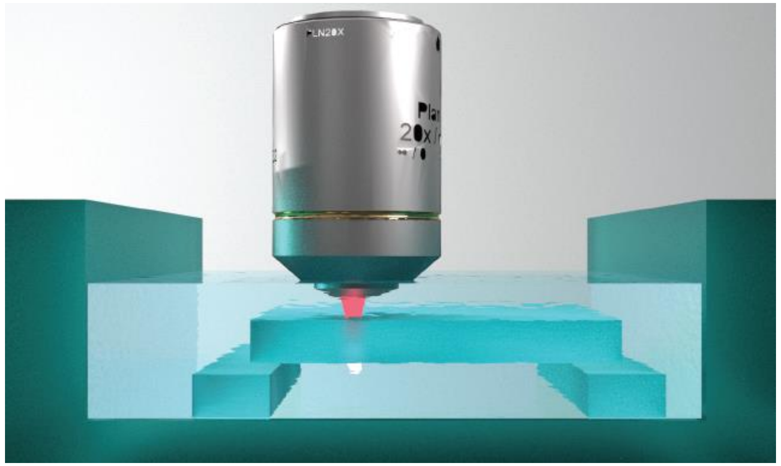
TOWARDS FULL THERMAL ISOLATION…



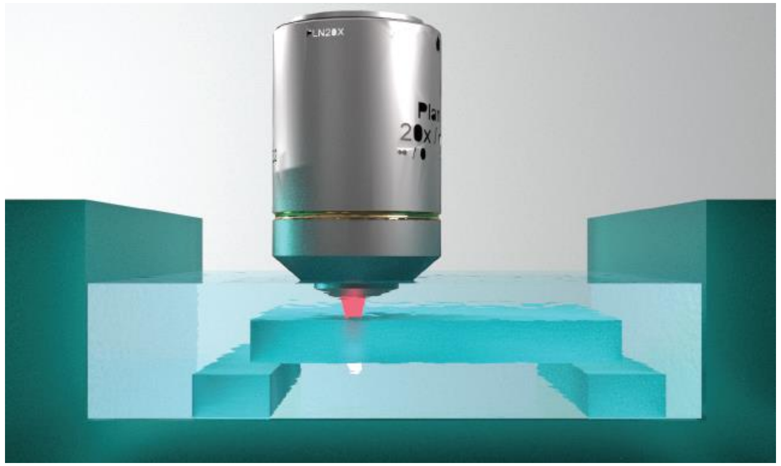
- Temperature increase limited only by the leakage towards the sink

Water-assisted laser ablation



- ❑ Water aids debris removal
- ❑ Ablated area does not affect focusing condition
- ❑ Low processing time

Water-assisted laser ablation



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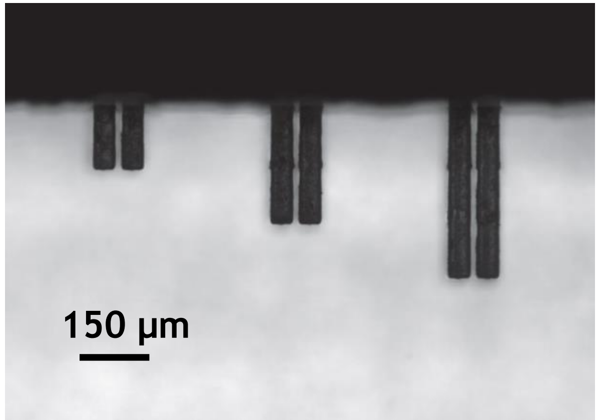
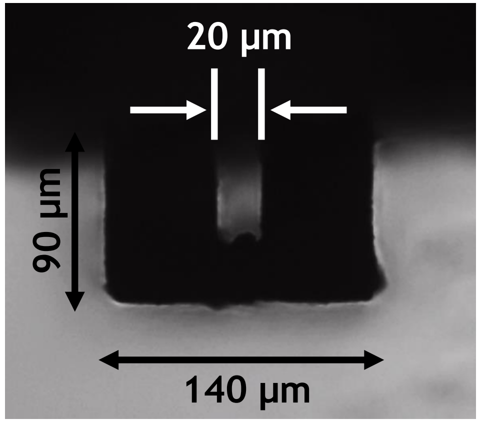
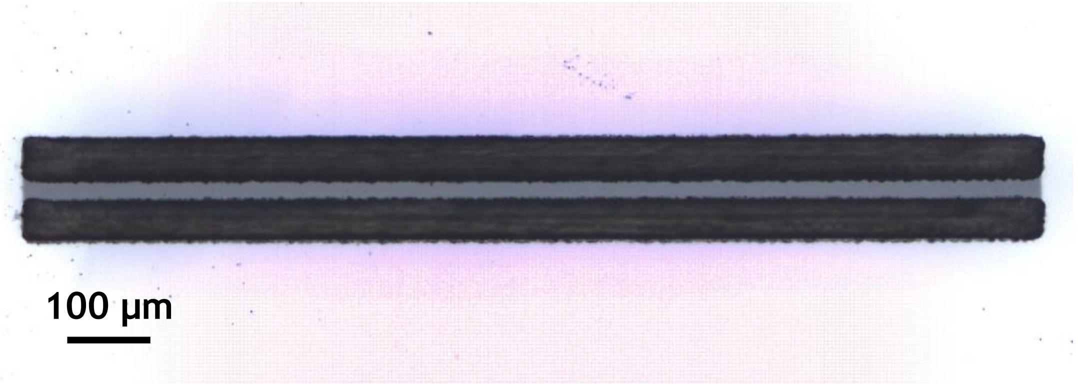
CROSS SECTION

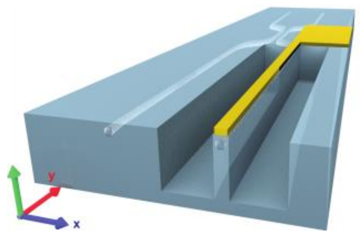




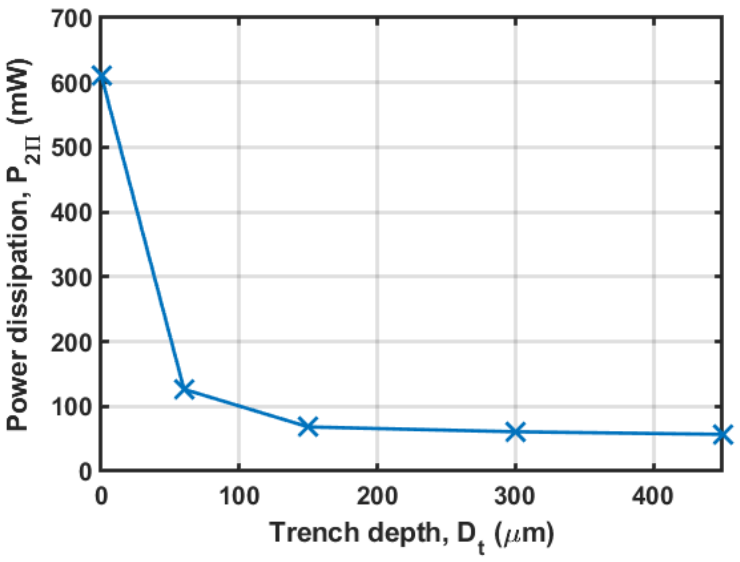
TOP VIEW

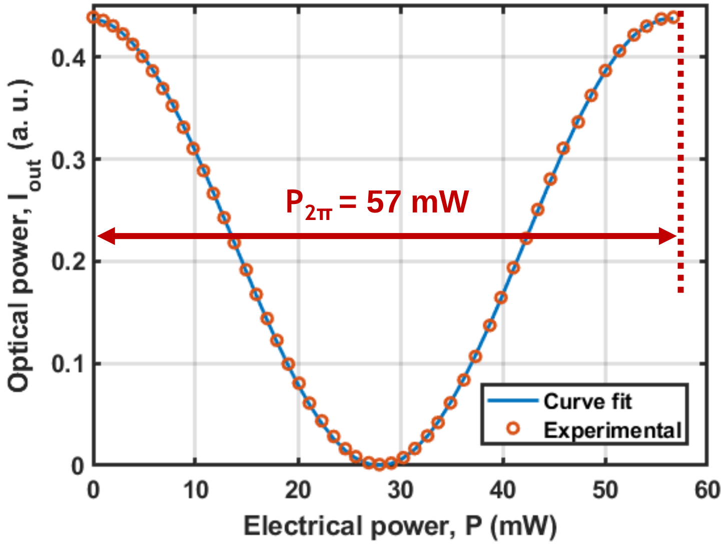


Reconfiguration performance: trenches



POWER DISSIPATION

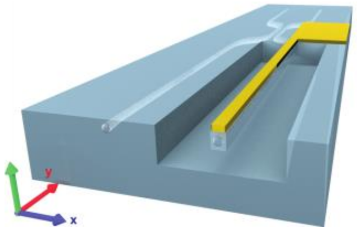




Silicon on Insulator	Si_3N_4	Silica on Silicon	This work
50 mW	600 mW	800 mW	**57 mW**

- ❑ Power dissipation is now comparable with SOI devices

Reconfiguration performance: bridge



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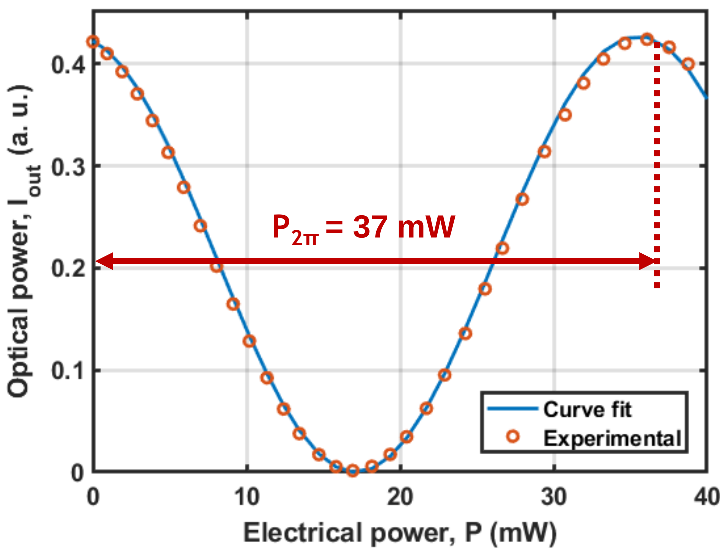

Silicon on Insulator	Si_3N_4	Silica on Silicon	This work
50 mW	600 mW	800 mW	**37 mW**

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Reconfiguration performance: bridge

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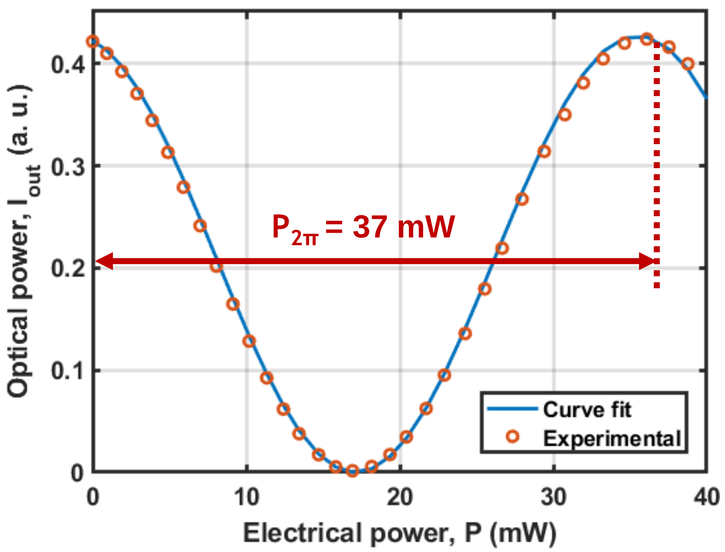
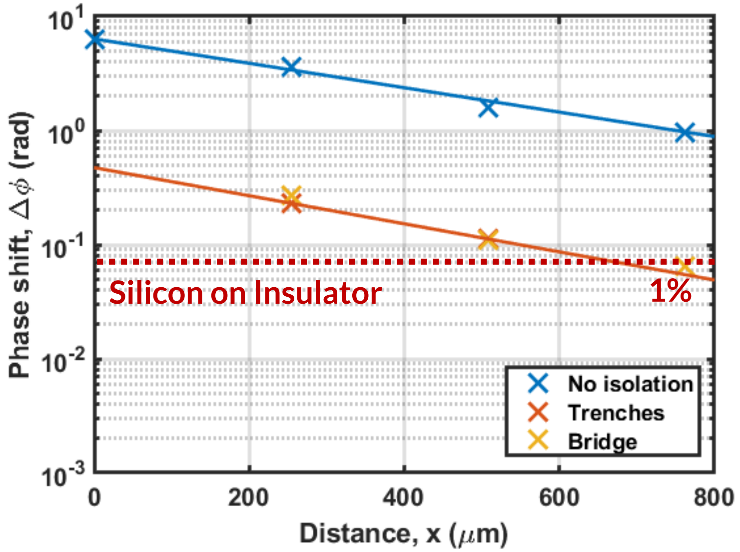
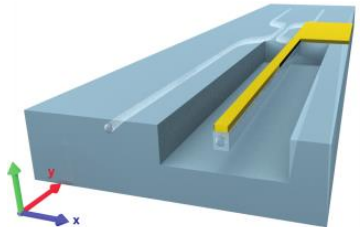


THERMAL CROSSTALK





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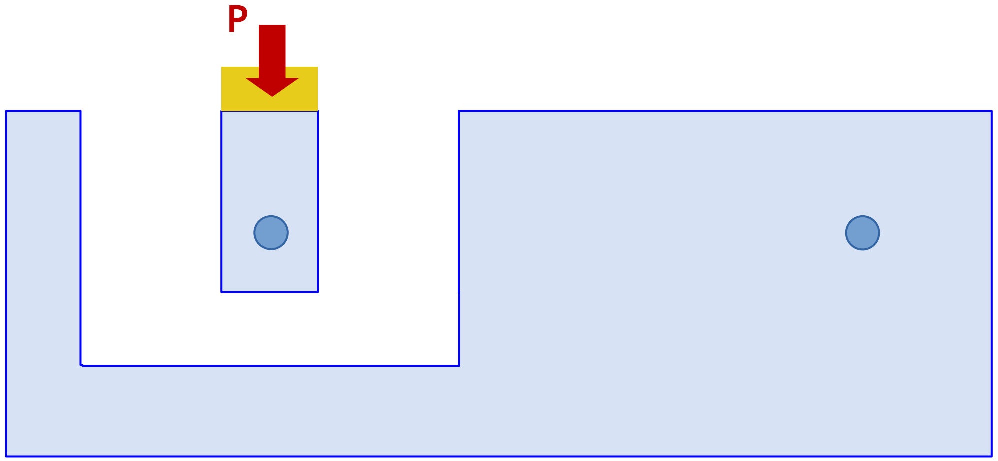
50 mW	600 mW	800 mW	**37 mW**

- Power dissipation is now comparable with SOI devices
- Thermal cross-talk (first neighbour) drops to 3.5 %

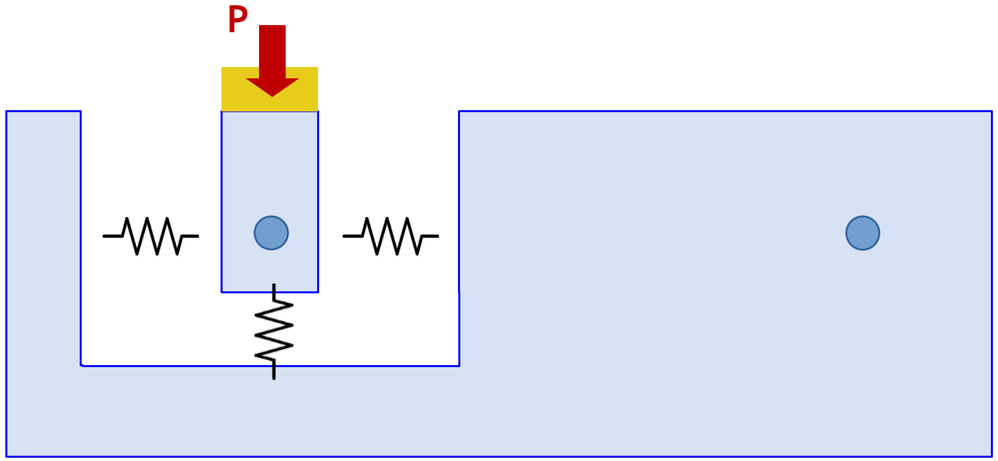
Modeling and FEM simulations



Bridge waveguide is fully isolated, but…

- Reduction in power dissipation is limited (down to 35%)
- Thermal cross-talk is unchanged

Modeling and FEM simulations



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a thermal leakage should be present

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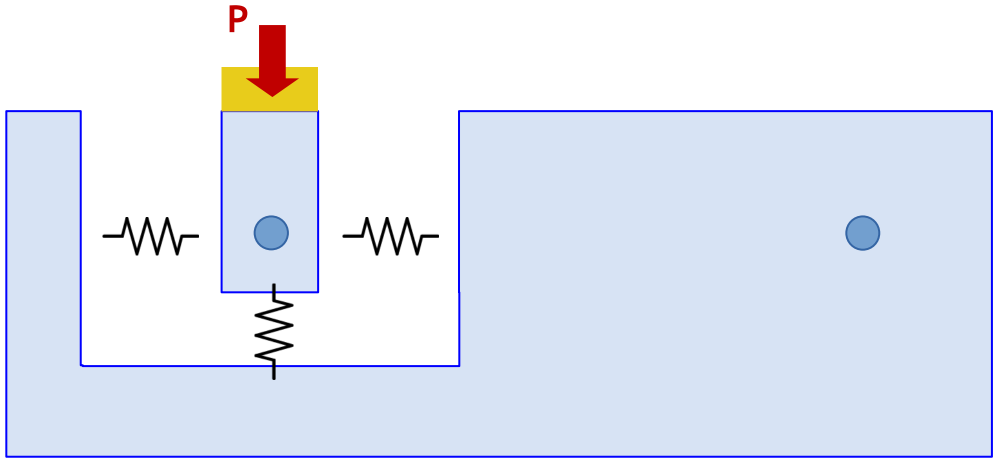

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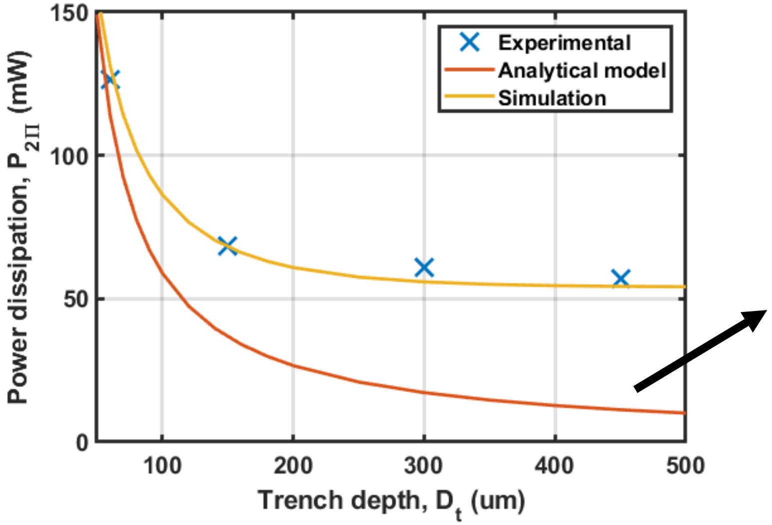


$$P_{2\pi} \propto \frac{1}{D_t}$$

Analytical study on trenches:

- Power dissipation should approach 0 mW when $D_t \rightarrow \infty$
- FEM simulations explain the experimental results by accounting for **air conduction**

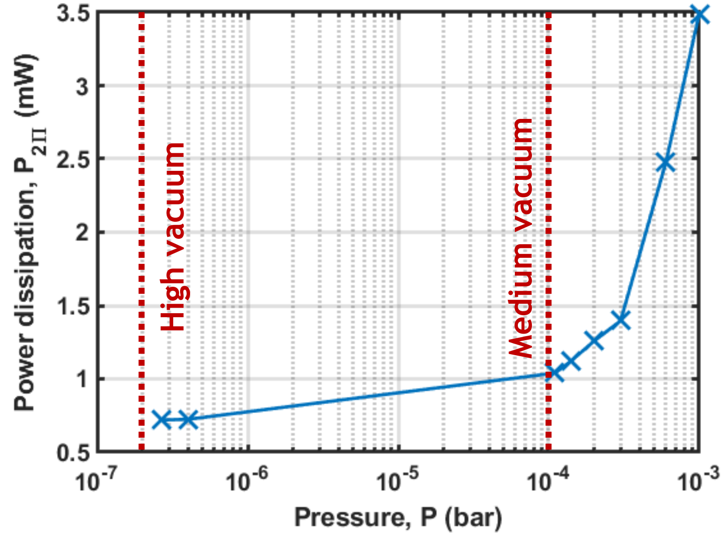
Performance in vacuum

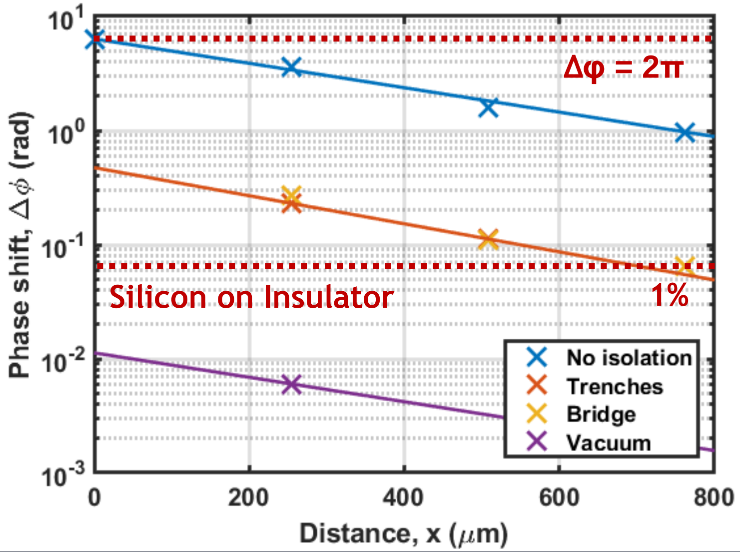
EXPERIMENTAL SETUP

- ❑ Bridge waveguide configuration
- ❑ Vacuum chamber featuring a two-stage pumping system:
  - ❑ Medium vacuum (10^{-4} bar)
  - ❑ High vacuum (10^{-7} bar)

RESULTS

- ❑ Power dissipation drops at:
  - ○ 1 mW in medium vacuum
  - ○ **0.72 mW at high vacuum**
- ❑ Thermal cross-talk **lower than 0.1 %** at high vacuum





Conclusions

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- Structuring glass allows one to achieve low power dissipation (37 mW) and thermal cross-talk (3.5%) for the actuation of thermal phase shifters
- Scaling up circuits complexity
- Further performance improvement for vacuum operation

F.Ceccarelli, S.Atzeni et al., *Laser and Photonics Reviews*, 2000024 (2020), https://doi.org/10.1002/lpor.202000024

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CNR – IFN, Milano


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VitreaLab GmbH, Wein

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