Thermostatic Fins for Spatially and Temporally Adaptive Microfluidic Cooling

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STREAMS
Smart Technologies for eneRgy Efficient Active cooling in Advanced Microelectronic Systems

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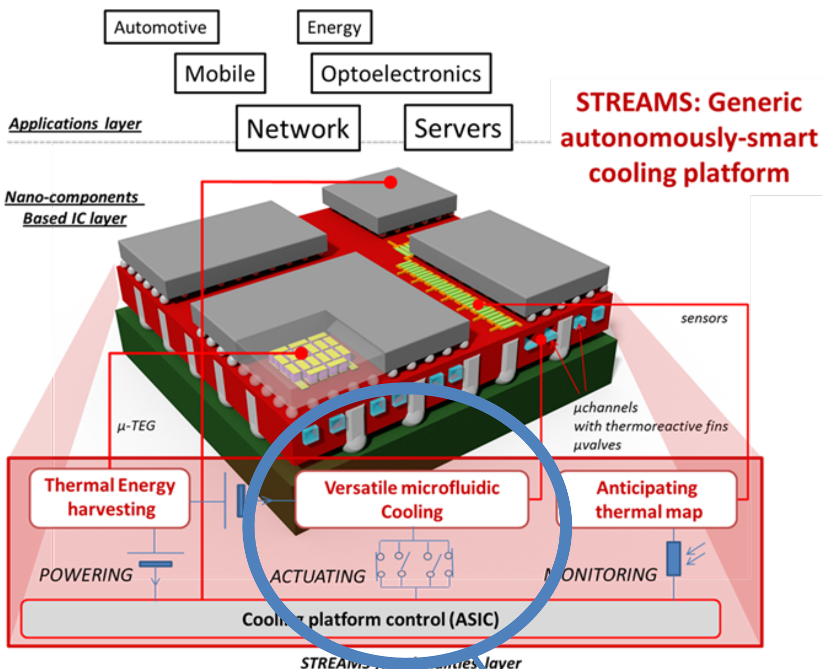
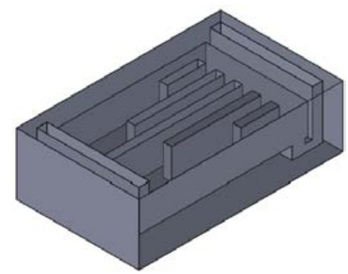
Introduction

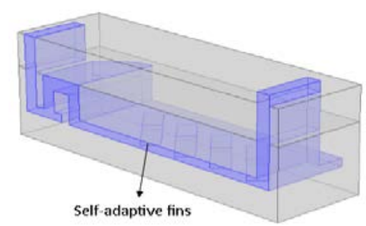


2 proposed solutions

Fixed geometry (array of microfluidic cells) [1].



Self-adaptive solution

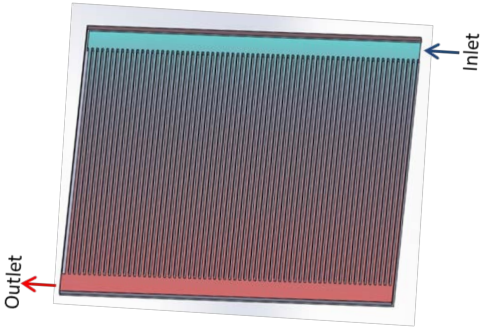


Main objectives: Pumping power reduction and more temperature uniformity.

[1] Laguna, G., Vilarrubí, M., Ibañez, M., Betancourt, Y., Illa, J., Azarkish, H., … Barrau, J. (2018). Numerical parametric study of a hotspot-targeted microfluidic cooling array for microelectronics. *Applied Thermal Engineering*, *144*, 71–80.

Introduction

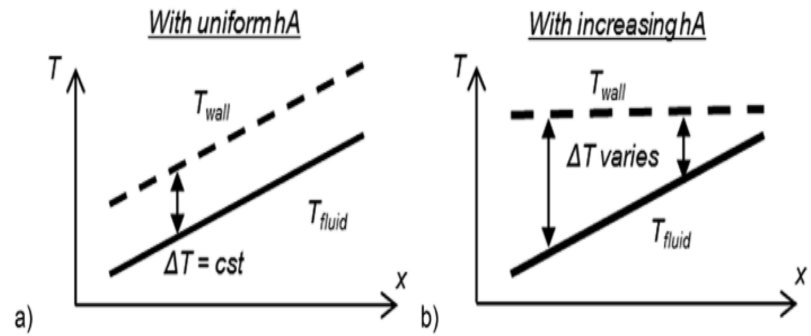
- High power densities on nowadays Integrated circuits → large heat dissipation → air cooling reached a limit of heat extraction.
- Electronic reliability:
  - Maximum chip temperature below a limit.
  - Low thermal gradients on the chip surface.
- Multicore processors and 3D-IC: hotspot regions and time-dependent power map distributions → challenge for isothermal junction temperature.



- Microchannel liquid cooling technology:
  - Low thermal resistances.
  - Large pressure drops (large P_{pump}) and poor temperature uniformity.

Introduction

- Optimum thermal management approach: target the coolant to the hotspot regions → isothermal chip condition, minimum pressure drop.
  - Some works [2-4] focused on specific heat flux distributions → oversized pumping powers due to constant flow rate distributions.



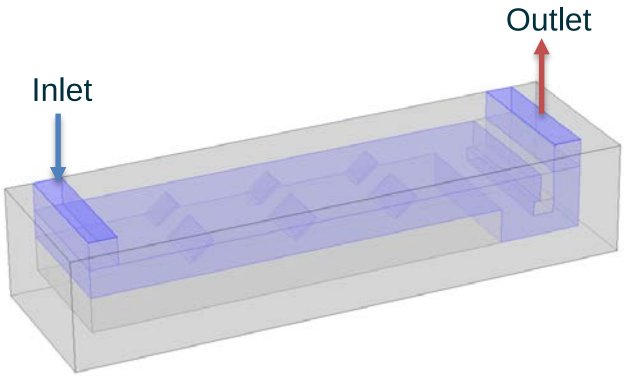
[5]

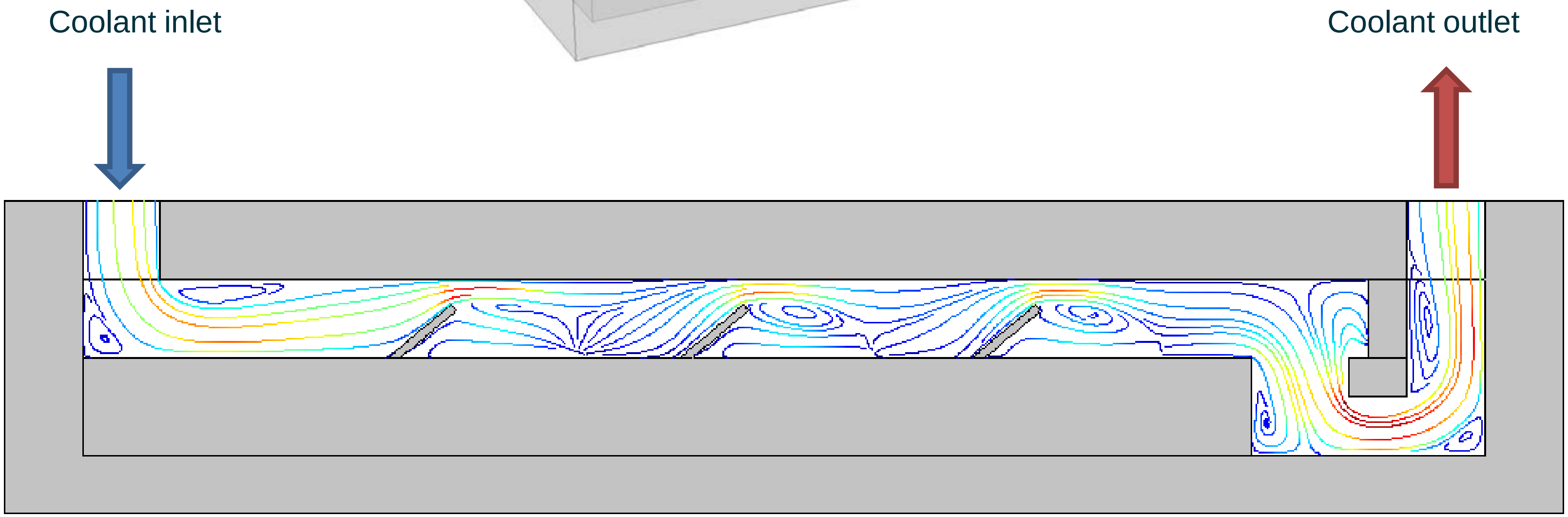
[2] C. S. Sharma et al., "Energy efficient hotspot-targeted embedded liquid cooling of electronics," Int. J. Heat Mass Transf., vol. 88, pp. 684–694, 2015.
[3] C. S. Sharma, G. Schlottig, T. Brunschwiler, M. K. Tiwari, B. Michel, and D. Poulikakos, "A novel method of energy efficient hotspot-targeted embedded liquid cooling for electronics: An experimental study," Int. J. Heat Mass Transf., vol. 88, pp. 684–694, Sep. 2015.
[4] L.-M. Collin et al., "Hot spot aware microchannel cooling add-on for microelectronic chips in mobile devices," 2017 16th IEEE Intersoc. Conf. Therm. Thermomechanical Phenom. Electron. Syst., pp. 460–464, May 2017.
[5] Vilarrubí, M., Riera, S., Ibañez, M., Omri, M., Laguna, G., Fréchette, L., & Barrau, J. (2018). Experimental and numerical study of micro-pin-fin heat sinks with variable density for increased temperature uniformity. *International Journal of Thermal Sciences*, *132*(June), 424–434.

Introduction

- Flow disruption techniques to enhance heat transfer → increase pressure drop

Microfluidic cell with fins inside acting as vortex generators



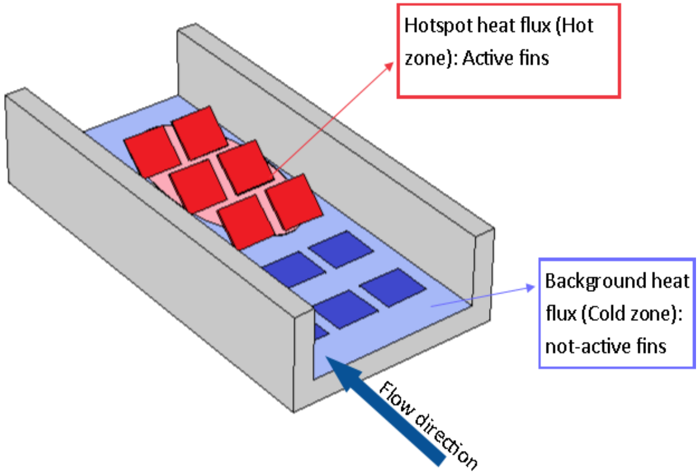


The streamlines indicate the velocity field.

Introduction

Self-adaptive fins

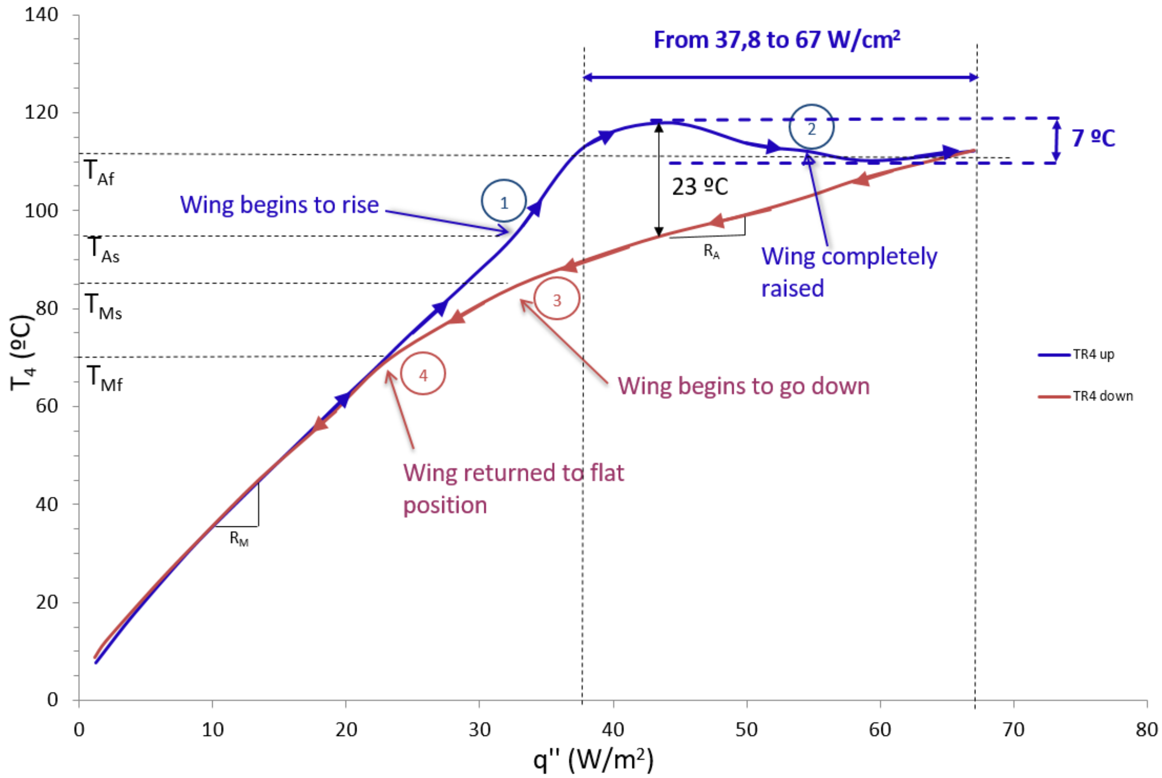
Adapt their shape to non-uniform and time dependent heat load scenarios → self-adaptive vortex generators.



Self-adaptive concept

Previous work → Shape memory alloy (SMA) wing [6]

- Based on Two Way Shape Memory Effect (TWSME) of a SMA wing

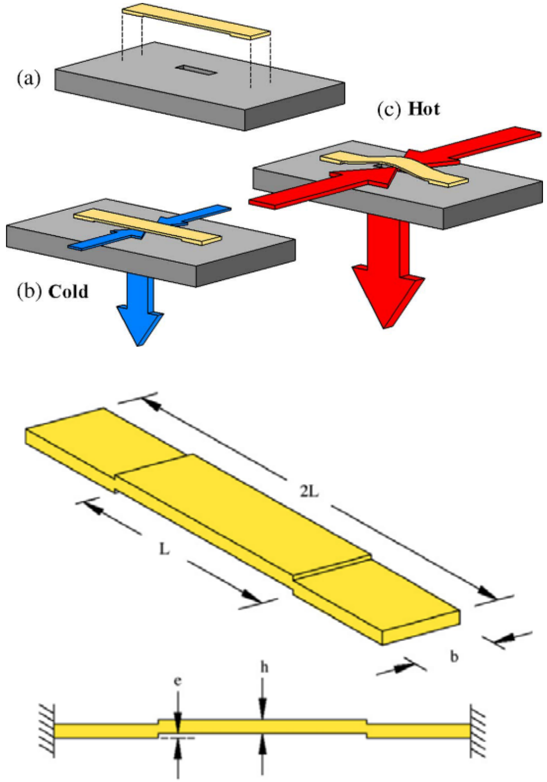


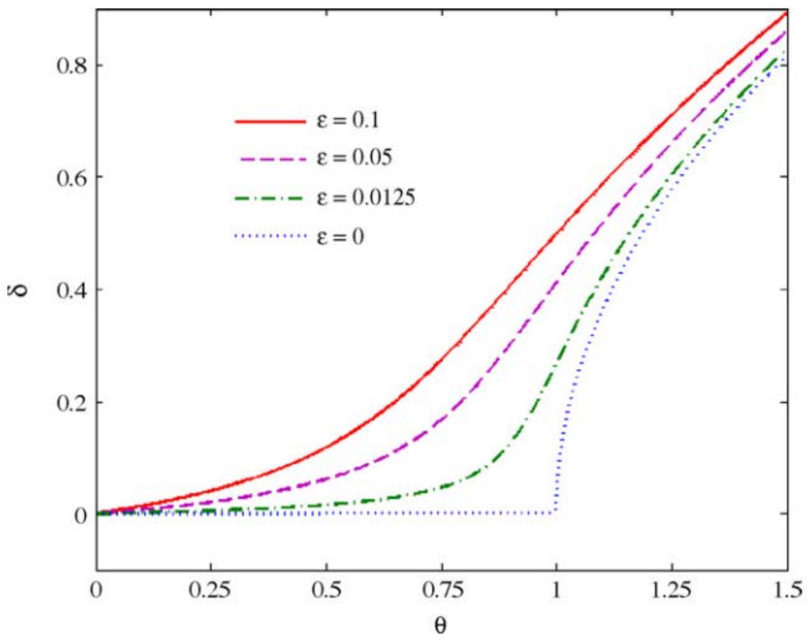
- Fixed inlet coolant temperature and flow rate
- Heat flux variation from 37,8 to 67 W/cm^2.
- Temperature uniformity within an interval of 7 ºC (expected of 85 ºC without self-adaptation).

[6] Provisional Application for Patent - U.S. Patent and Trademark Office (01/03/2018; Attorney Docket Number: 05202424-52USPR).

Self-adaptive concept

- Temperature regulated nonlinear microvalves [4].



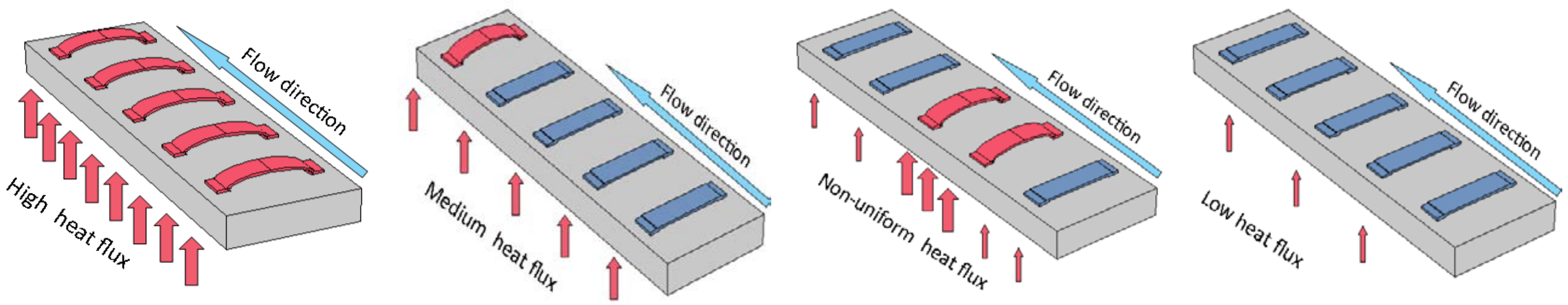


[4] M. McCarthy, N. Tiliakos, V. Modi, and L. G. Fréchette, "Temperature-regulated nonlinear microvalves for self-adaptive MEMS cooling," J. Microelectromechanical Syst., vol. 17, no. 4, pp. 998–1009, 2008.

Self-adaptive concept

Based on previous concepts:

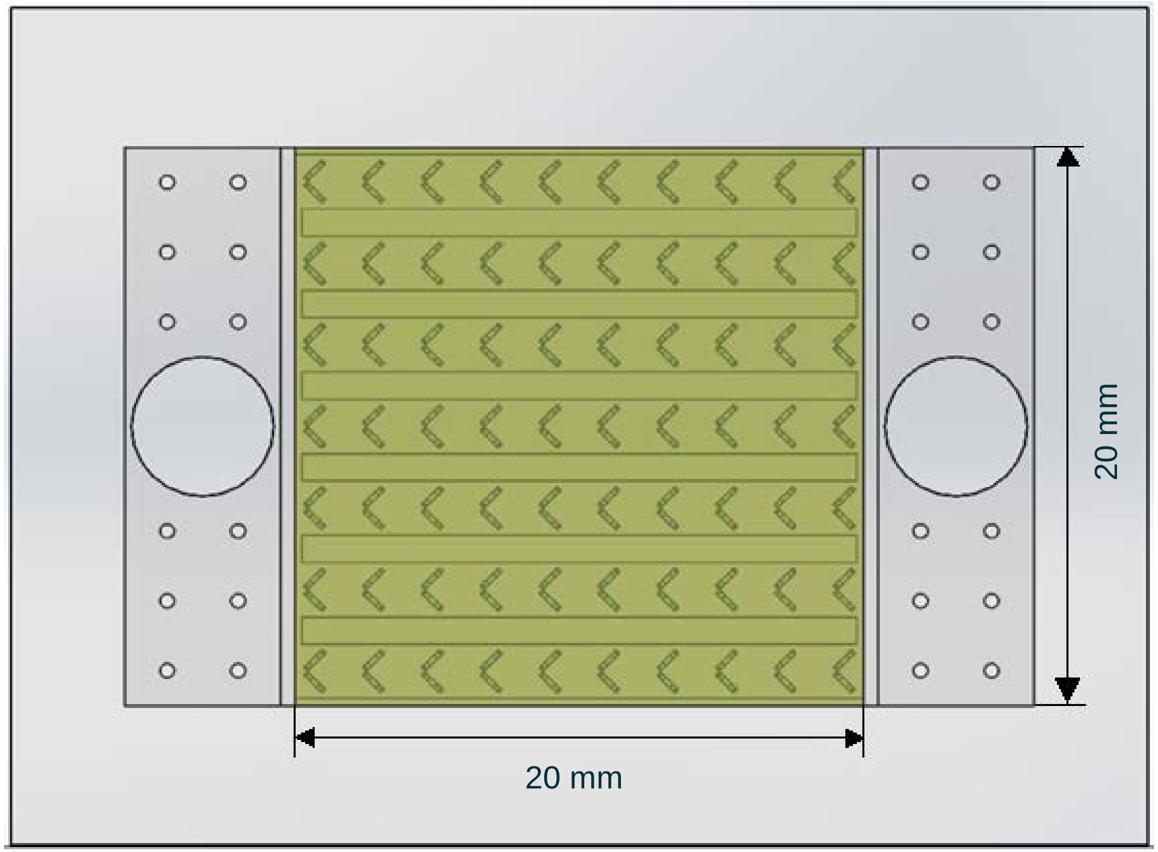
- Doubly clamped silver beams axially restrained to a material of low CTE (Si).
- Thermal buckling used as a passive actuator mechanism within microchannels → thermal adaptive vortex generators (VG).



(a) (b) (c) (d)

[4] M. McCarthy, N. Tiliakos, V. Modi, and L. G. Fréchette, “Temperature-regulated nonlinear microvalves for self-adaptive MEMS cooling,” J. Microelectromechanical Syst., vol. 17, no. 4, pp. 998–1009, 2008.

Final device concept



Array of 7 microchannels with 10 pairs of vortex generators.

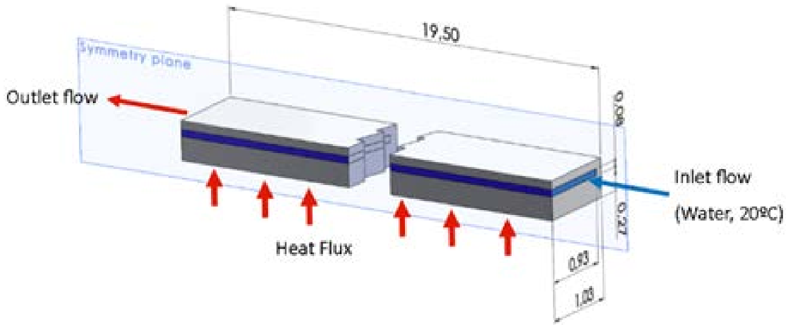
Channel dimensions

W = 1,86 mm

L = 19,5 mm

Numerical simulation

- Comparison between microchannel with fixed fins and microchannel with self-adaptive fins.



Numerical model:

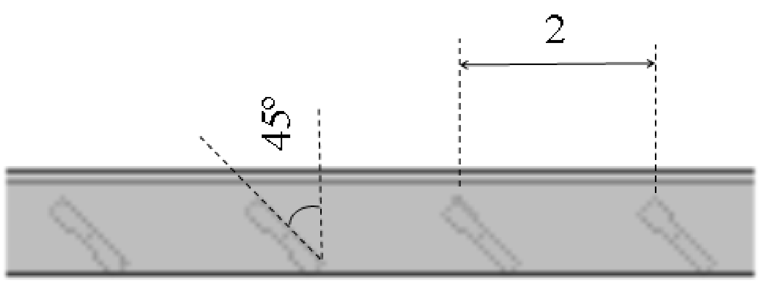
Si microchannel with 10 pairs of self-adaptive fins acting as VG.

Coolant fluid: water (T_{in} = 20ºC)

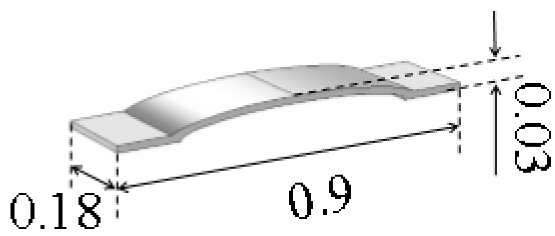
Q = $9{,}12 \cdot 10^{-8}$ m^3/s ($T_{chip,max}$ = 85 ºC)

Re = 90 → laminar flow

Grid independence test performed



a)

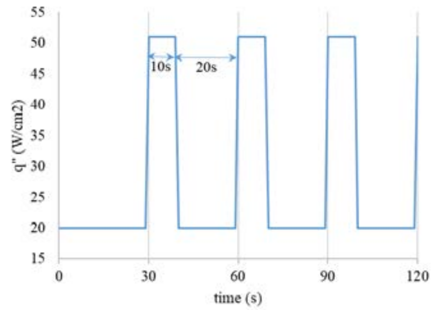


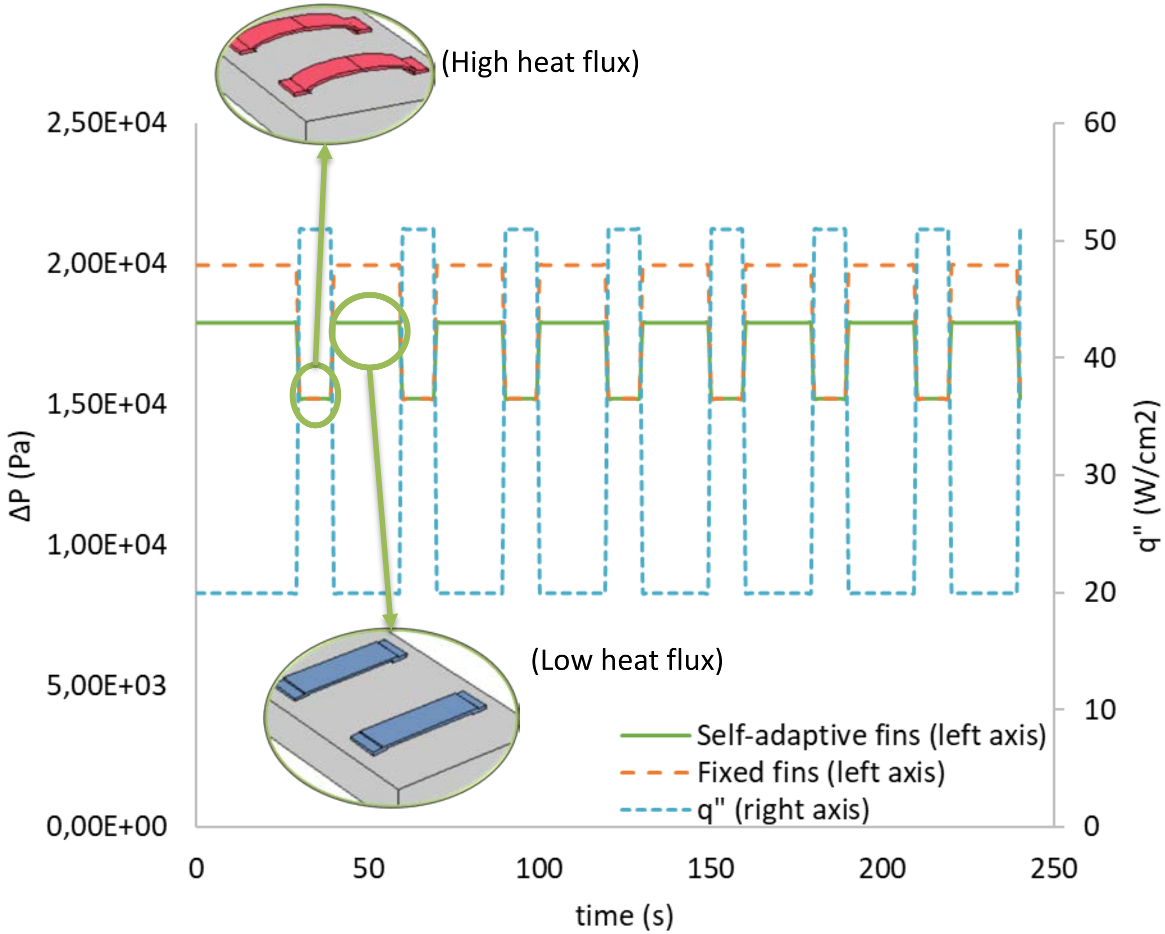
b)

All units in mm

Pumping power reduction

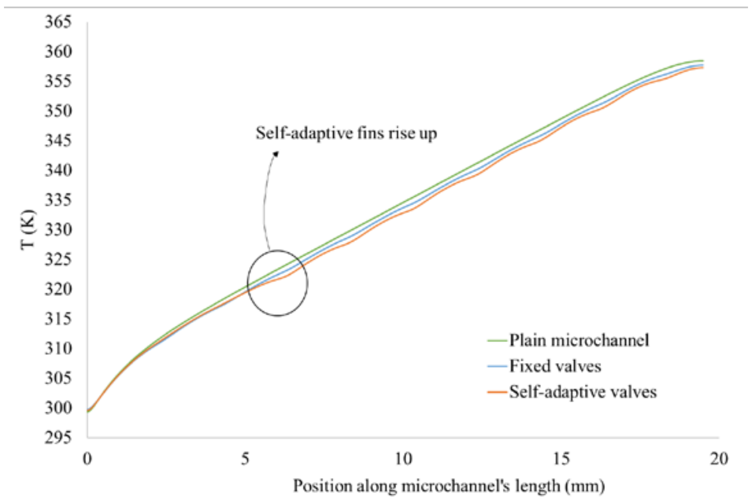
Heat load scenario



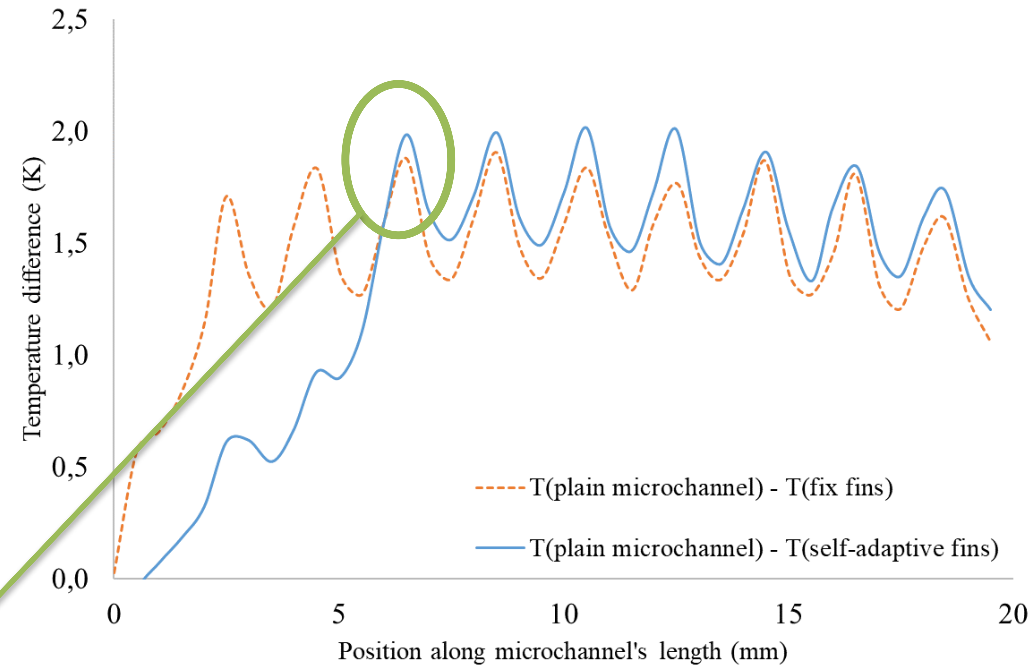


As a consequence: P_{pump} is reduced by an 8 %.

Temperature uniformity

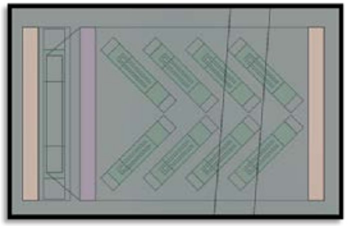


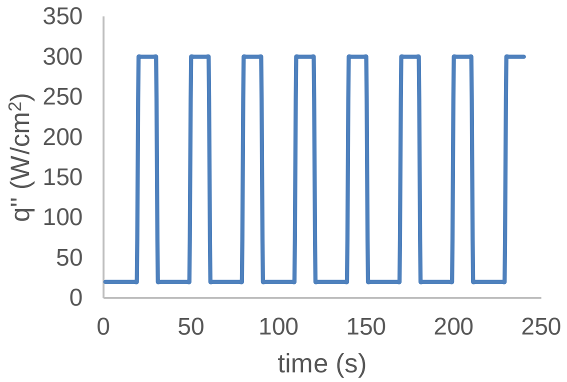
q'' = 51 W/cm²

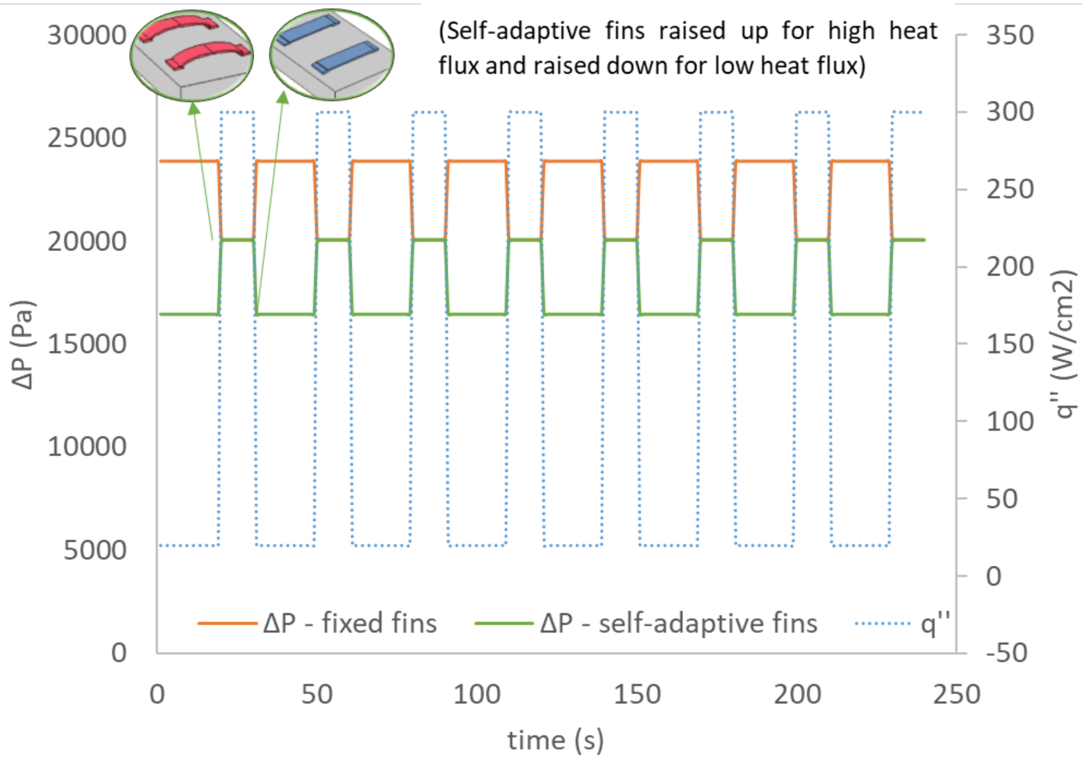


Below the fins the chip temperature is decreased → heat transfer improvement ($Nu/Nu_0 = 1{,}1$).

Impact of Self Adaptive fins within microfluidic cells







Coolant fluid: water (T_{in} = 20ºC)

Q = $2{,}01 \cdot 10^{-7}$ m³/s ($T_{chip,max}$ = 85 ºC)

Re = 220 → laminar flow

Grid independence test performed

P_{pump} is reduced by around 20 % for this heat load scenario

Impact of Self Adaptive fins within microfluidic cells

Fins inside a cell

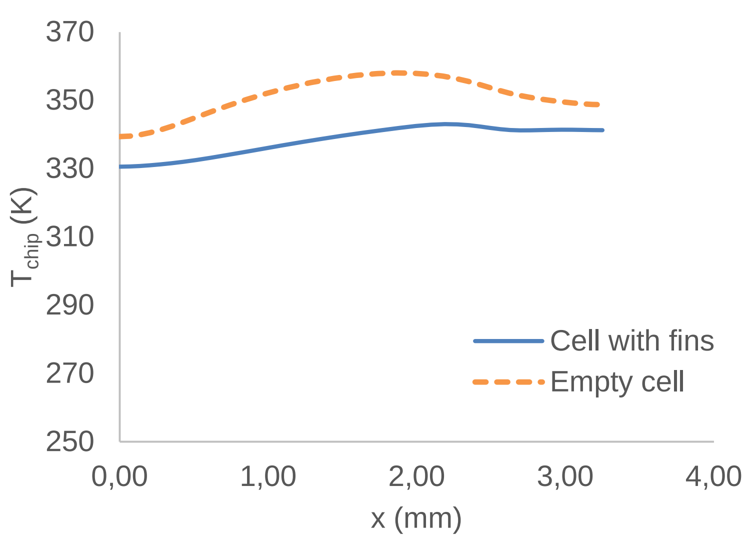
Temperature uniformity

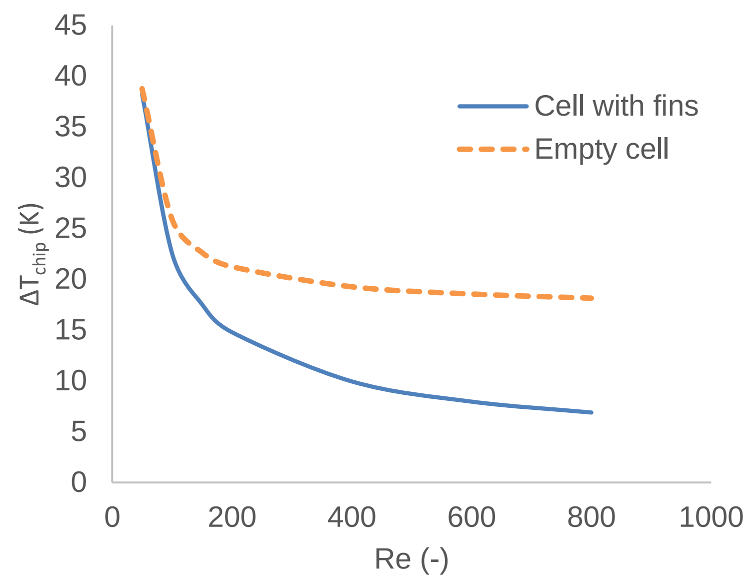
Re = 220

q" = 300 W/cm^2

$\Delta T_{empty\ cell}$ = 21 K

$\Delta T_{cell\ with\ fins}$= 14 K (- 33 %)





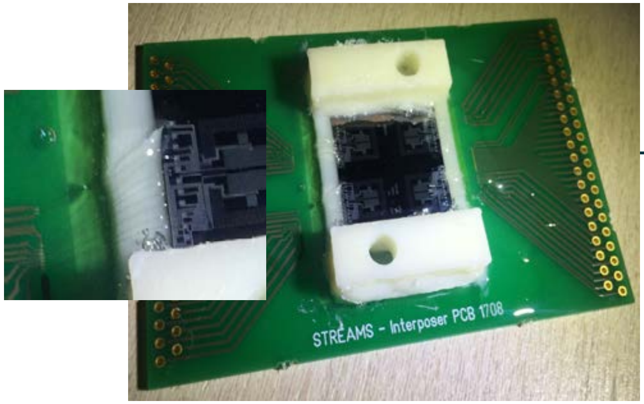
Conclusions

- **Thermally activated self-adaptive fins** acting as vortex generators demonstrate its capacity to reduce the pressure drop inside a microchannel compared to a cooling device with fixed vortex generators: ↓↓ **pumping power**.
  - For a given heat load scenario: **reduction of 8 %** compared with fixed fins.
- Further pumping power reduction can be achieved combining the solution with tailored flow rate and/or an array of microfluidic cells [5].

- Chip temperature uniformity similar to a plain microchannel but increased difference below the fins. More significant reduction achieved within an array of microfluidic cells.

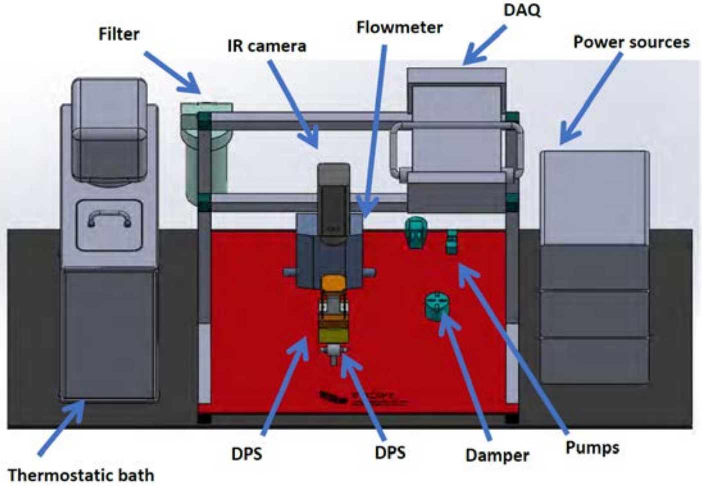
[5] G. Laguna et al., "Microfluidic cell cooling system for electronics," in THERMINIC 2017 - 23rd International Workshop on Thermal Investigations of ICs and Systems, 2017, vol. 2017–January.

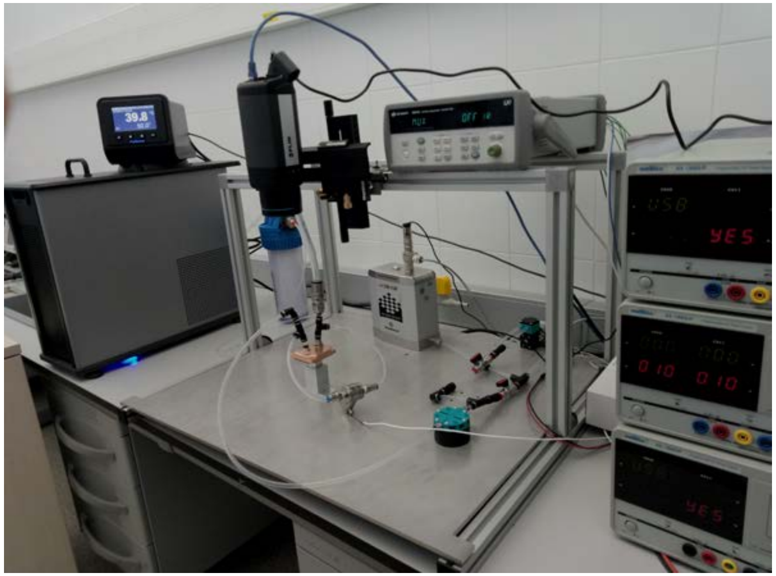
Ongoing work



The cooling device is under microfabrication process.

Test bench





Acknowledgments

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