6th ESA Round Table on Micro & Nano Technologies for Space Applications 2007

ESA-ESTEC
Noordwijk, The Netherlands

RF-MEMS technology, components and circuits

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[3] ESA-ESTEC, The Netherlands

Outline

- Switchable filters in mainstream RF-MEMS technology
  - Hybrid MCM-D/RF-MEMS
  - Fully integrated
- Electrostatic Fringing-Field Actuator (EFFA)
- Basic EFFA devices
  - Devices
  - Integration opportunities
  - Circuits for RF-applications
- Advanced EFFA devices: Relays
- Conclusions

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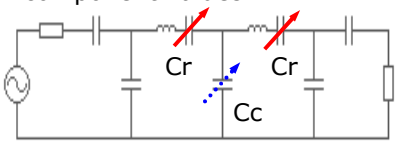
Design of a switchable filter for GPS/GALILEO

Technologies available

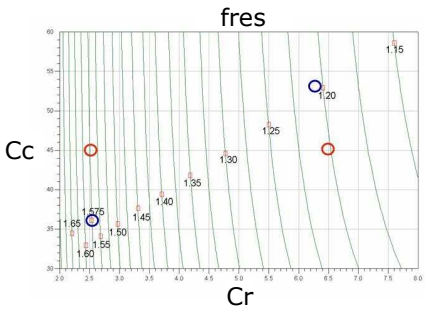
MCM-D	RF-MEMS
• Fixed passive components	• Tunable passive components
• Low loss substrate Glass	• Low loss substrate Glass
• Thick Cu traces • Low loss dielectric spacers 5µm BCB	• Thin Al traces • Air gap 3µm thick
• High capacitance density 300nm Ta_2O_5	• High capacitance density 300nm Ta_2O_5
• Resistors TaN 25Ω/□	• Resistors TaN 25Ω/□

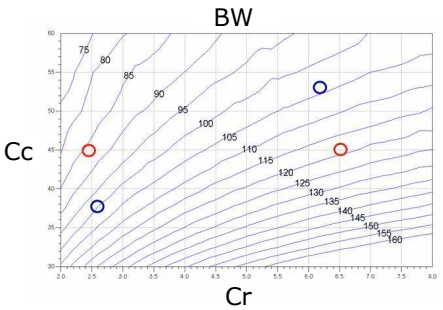
Filter specifications and architectures

The main target specifications, the passband frequencies and bandwidth, were translated in filter architectures and lumped component values.



	Galileo	GPS
Center frequency	1.2GHz	1.58GHz
Bandwidth	0.1GHz	0.1GHz





Filter schematics

	Galileo	GPS
Center frequency	1.2GHz	1.58GHz
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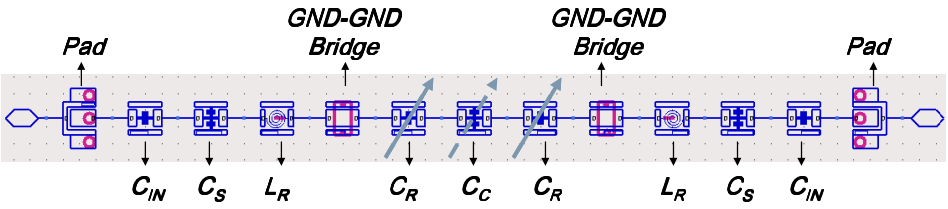


2 switches filter						3 switches filter				
C_{IN} [pF]	C_S [pF]	L_R [nH]	C_R [pF]	C_C [pF]		C_{IN} [pF]	C_S [pF]	L_R [nH]	C_R [pF]	C_C [pF]
2.00	5.56	5.34	6.60	45.00	GPS	2.00	5.56	5.34	6.45	53.70
			2.56		Galileo				2.58	38.90

Fixed

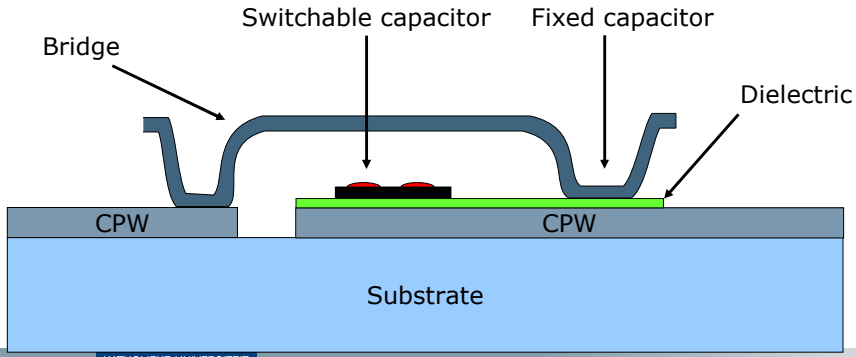
Variable

Switching capacitors building blocks

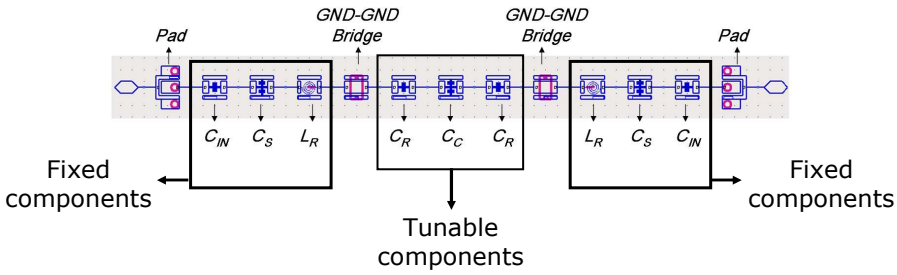
To produce a small but accurate capacitance contrast, we implemented:

- A fixed capacitor with value close to the capacitance required in idle-state
- A switchable capacitor with top floating metal and Pt contact in parallel

Series integrated implementation



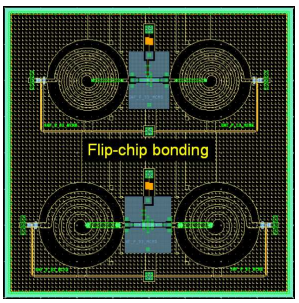
Hybrid integration – MCM-D / RF-MEMS

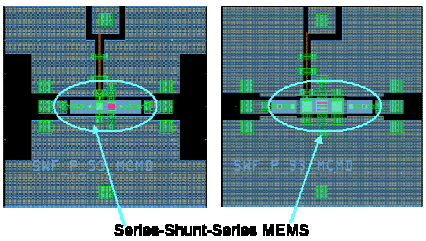


- Only the central core of the filter has to be in RF-MEMS technology.
- The feeding circuits and inductive stages of the resonators are fixed.

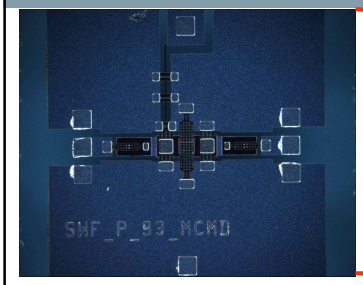
Hybrid integration – MCM-D / RF-MEMS

- Fixed feeding circuits and inductive stages of the resonators realized in MCM-D.
- Switchable capacitive stages of the resonators and switchable coupling capacitor in RF-MEMS.



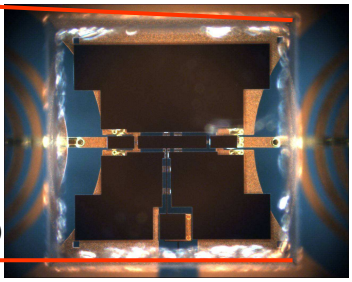


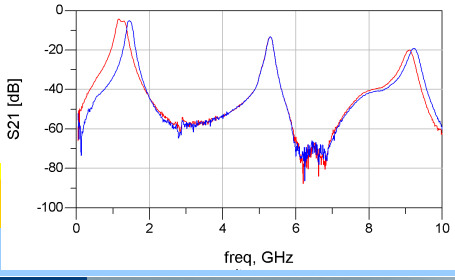
Hybrid integration
Switchable filter with MCM-D inductors



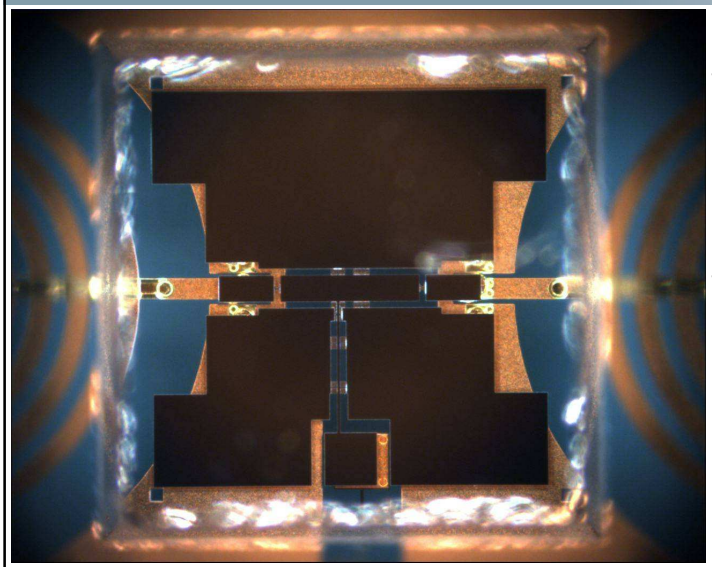
MEMS

MCM-D





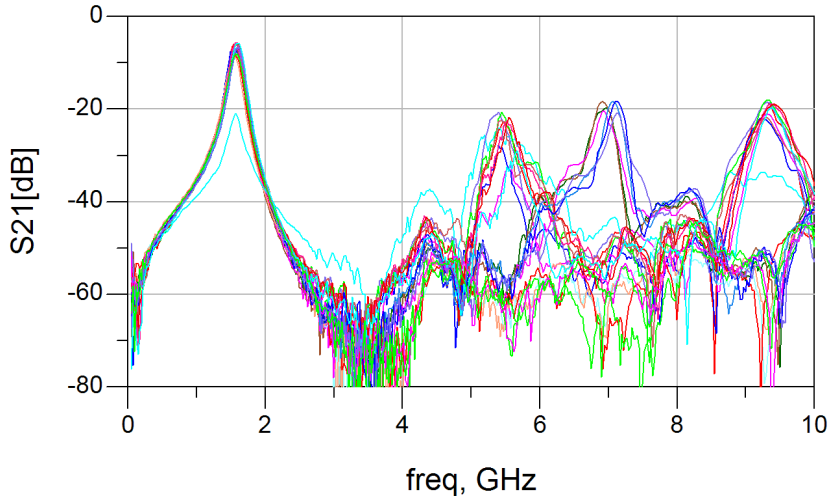
Hybrid integration - Conclusion



The performance of the hybrid filter come close to that of fixed filters in MCM-D technology.

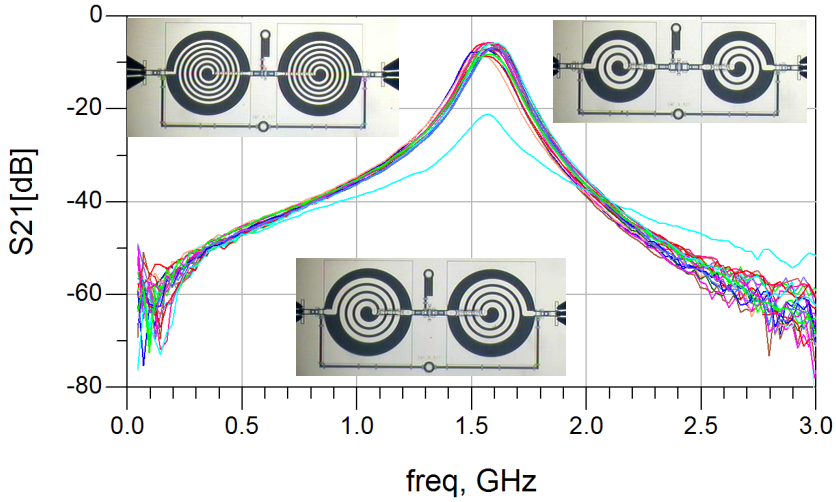
This approach however increases obviously the process complexity and introduces an unnecessary stress on the RF-MEMS devices.

Full integration – RF-MEMS process stability



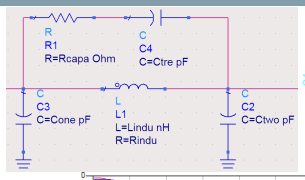
22 filters from 3 different wafers - 3 types of filters

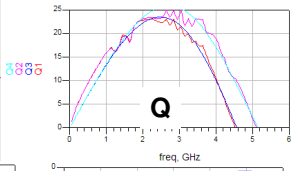
Full integration – RF-MEMS process stability



22 filters from 3 different wafers – Δf_{res} ~ 75MHz

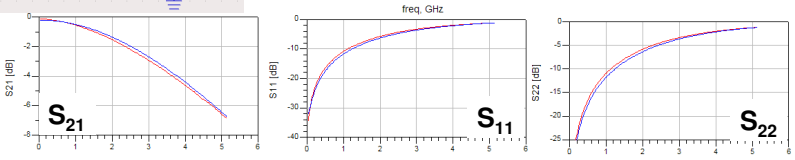
Summary of the RF-MEMS modeling a) Inductor stage

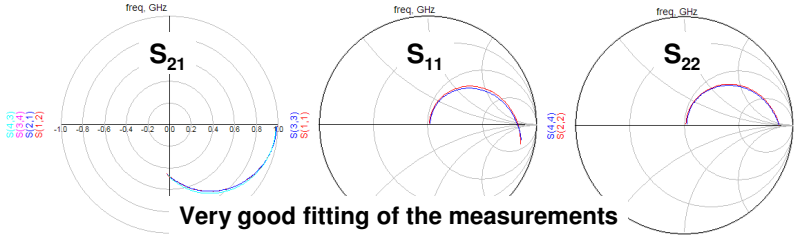




Eqn Q3=-imag(stoy(S)(3,3))/real(stoy(S)(3,3))

Eqn Q4=-imag(stoy(S)(4,4))/real(stoy(S)(4,4))

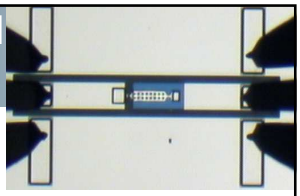


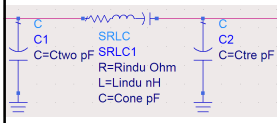


Very good fitting of the measurements

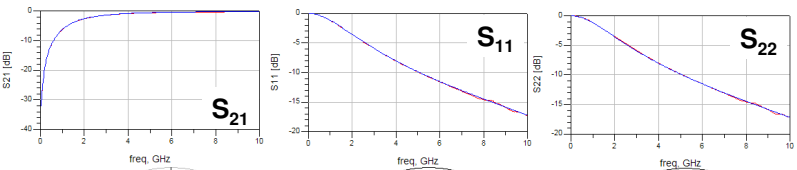
freq (45.00MHz to 5.150GHz) freq (45.00MHz to 5.150GHz) freq (45.00MHz to 5.150GHz)

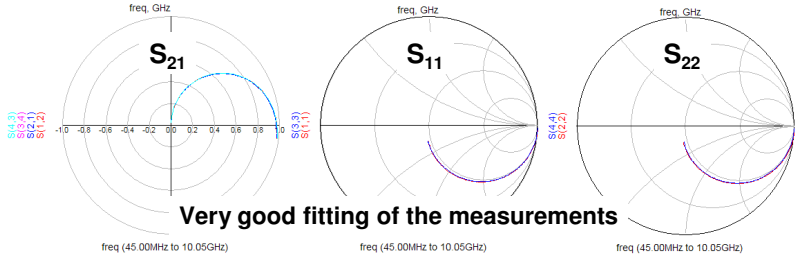
Summary of the RF-MEMS model b) Series capacitor stage





The proper definition of these capacitances is key for the proper definition of f_{res}.

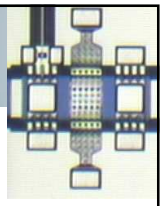


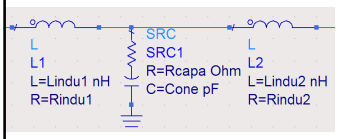


Very good fitting of the measurements

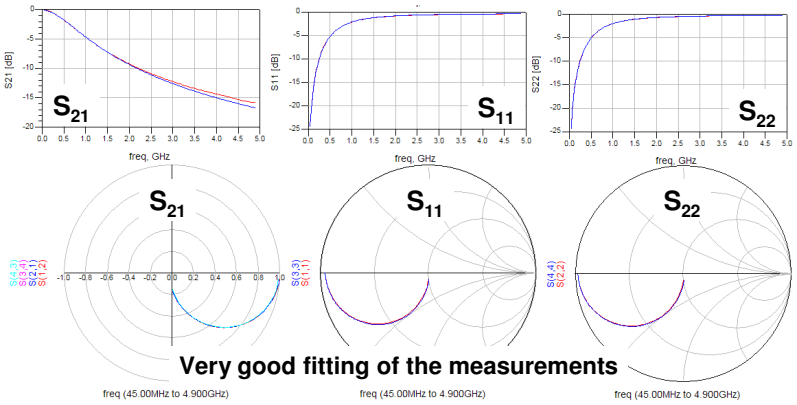
freq (45.00MHz to 10.05GHz) freq (45.00MHz to 10.05GHz) freq (45.00MHz to 10.05GHz)

Summary of the RF-MEMS modeling
c) Shunt capacitor stage





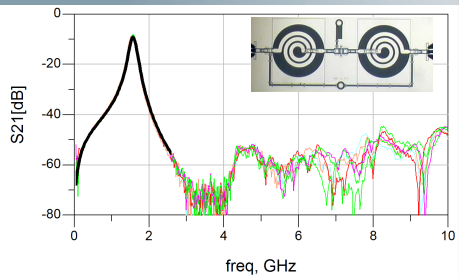
The proper definition of these capacitances is key to controlling the bandwidth of the filters.

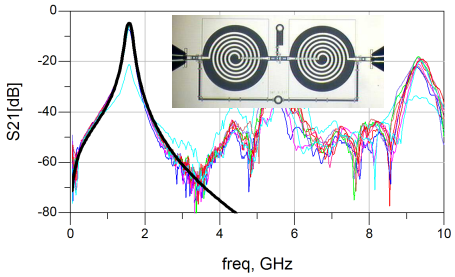


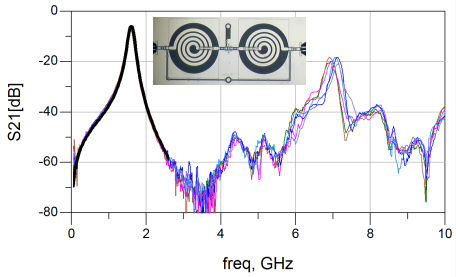
Very good fitting of the measurements

Full integration – RF-MEMS modeling

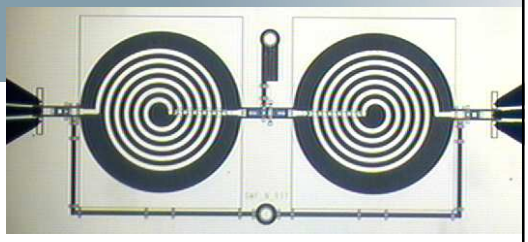
Filter re-simulation by cascading of the modeled elements in close agreement with the measurements below the first resonance.







Fully integrated RF-MEMS filter

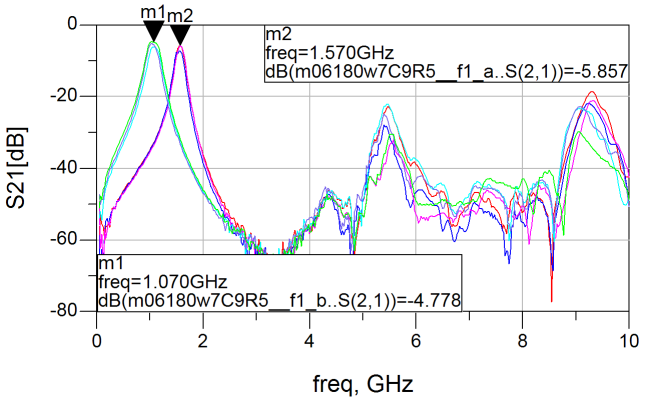


Comparison of the actuation of 3 switchable filters.

Good filter characteristic for the upper band.
Good definition of f_{res_up}

Good filter characteristic for the lower band.
Slight shift of f_{res_down}

Good in-band insertion loss in both states.



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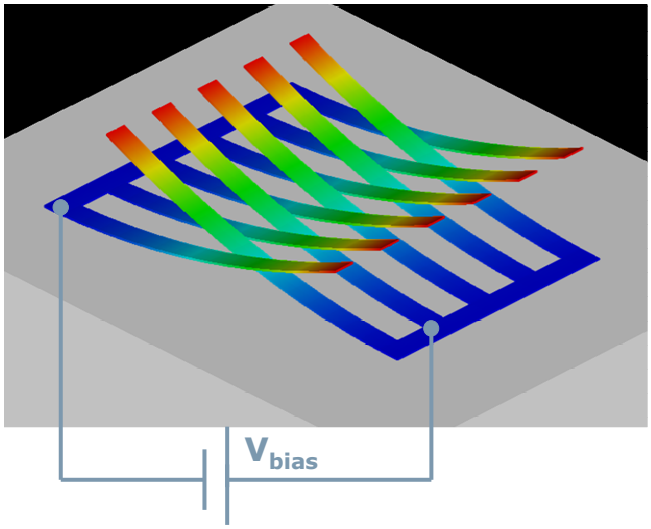
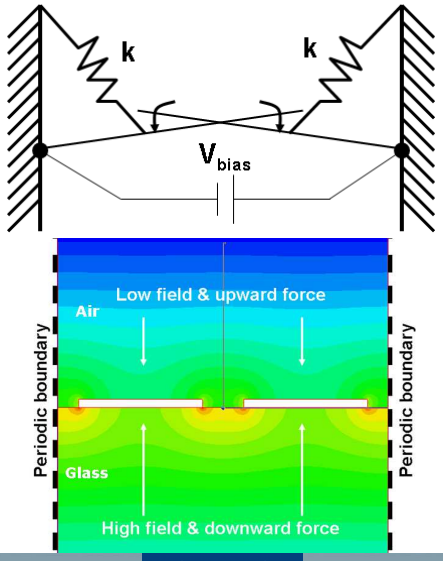
Interfacing Reliability, Process and Design

- Understanding the basic properties of materials used in Microsystems is key to improve their reliability.
- The relative complexity of the MEMS technologies hampers the optimal study of specific isolated reliability issues.
- Mimicking MEMS devices with fixed ones often yields only a partial information on actual devices
  - Dielectric charging: MIM capacitors vs. MEMS capacitors
  - Creep: Uniform films on substrate vs. patterned films on sacrificial layer
- There is a clear interest in defining a simple test device using a minimal but representative processing to provide a sound insight in the MEMS reliability

The electrostatic MEMS a RF-designer can process

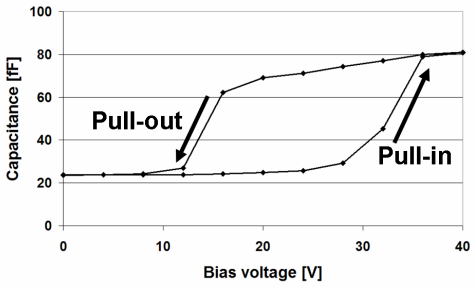


2 actuation principles in one device



First, the fingers tend to align.

As a result, they approach the substrate



Then, the fingers smash on the substrate due to an unbalance of the E-field distribution

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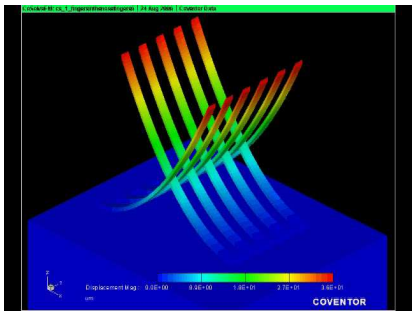
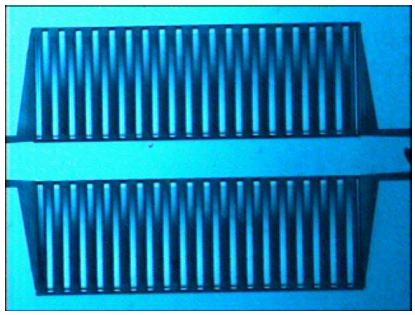
Actuation of the "finger in the nose" design

Coventorware simulation

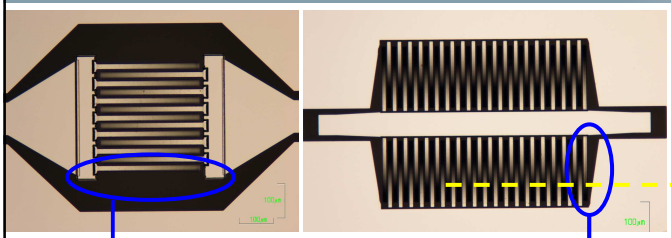


100Hz actuation, stroboscopic video capture



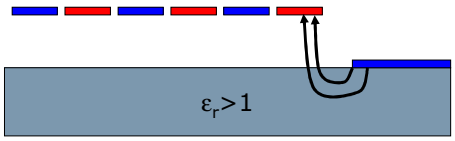
Remark the difference in periodicity breaking at the edges of the device.

Robust, versatile, integrable, …



Edge finger free.
Less electrostatic pressure.

Edge finger biased and in the proximity of the ground.
Enhanced electrostatic pressure.



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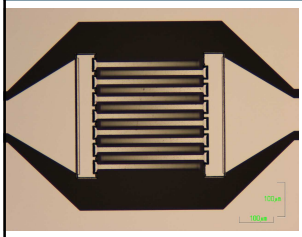
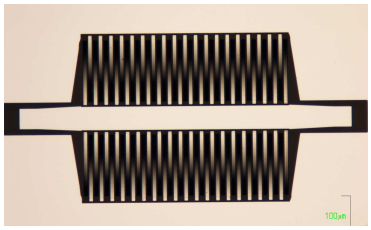
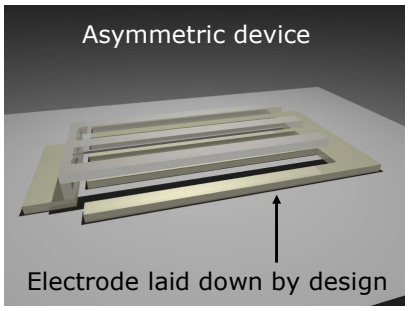
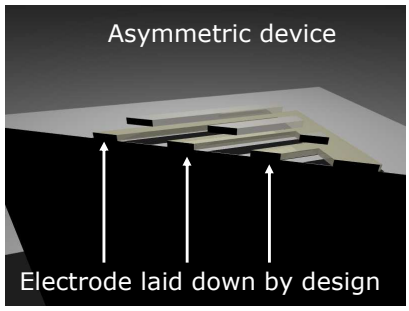




Using this symmetry breaking, we can define a device fully asymmetric, with lowered actuation voltage.





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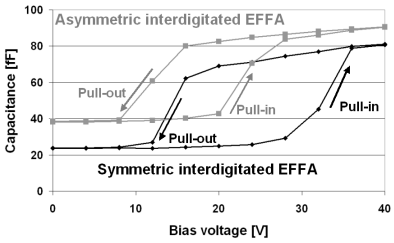

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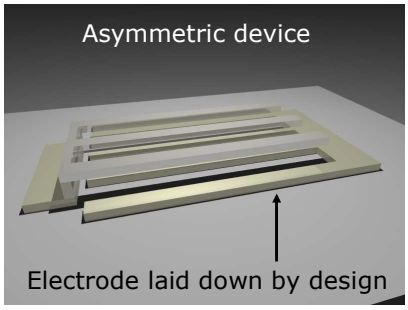

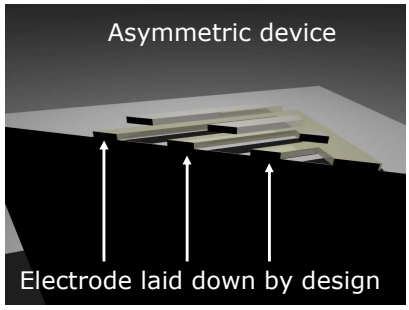

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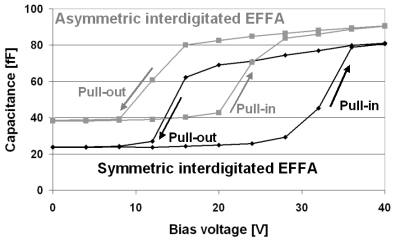
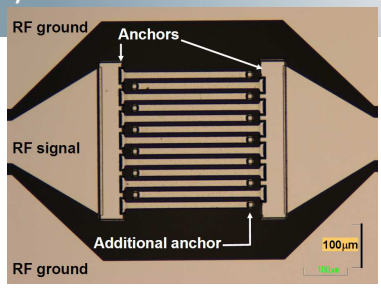
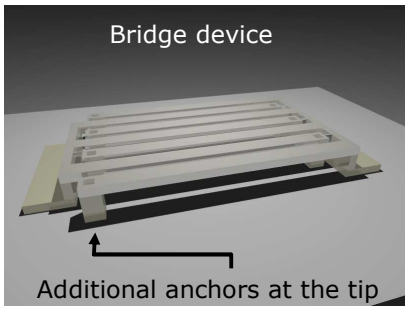
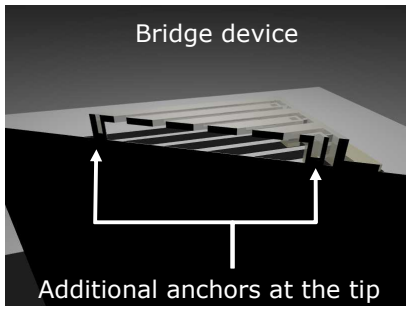
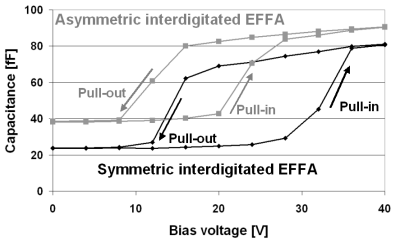


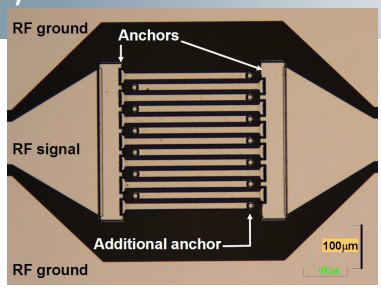


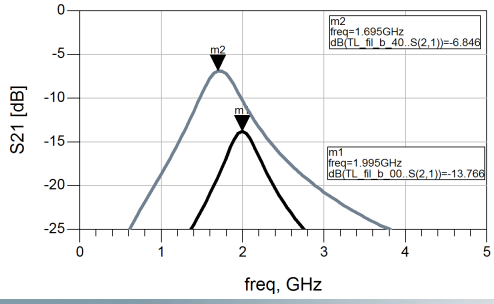




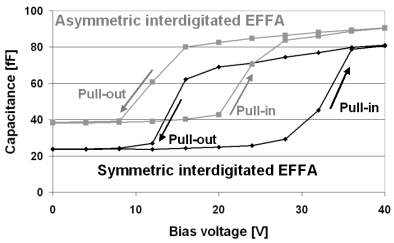
Robust, versatile, integrable, …

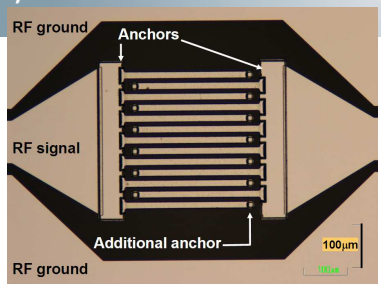


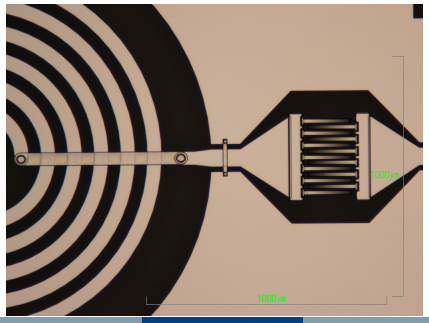


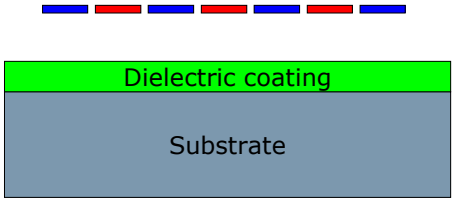


Robust, versatile, integrable, …

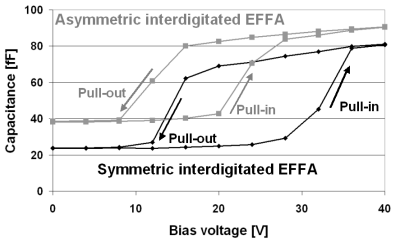


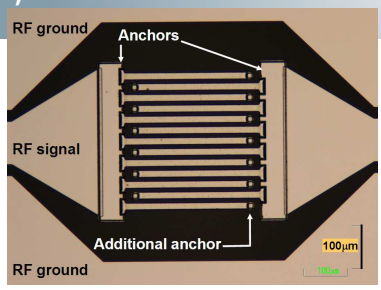


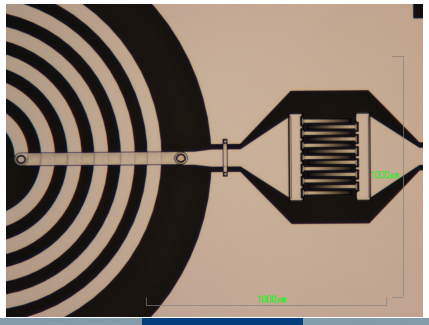




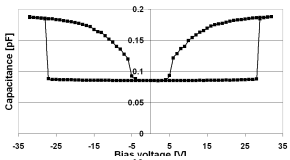
Robust, versatile, integrable, …



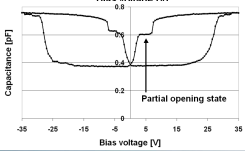




TaO coating

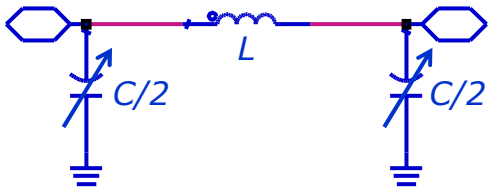


BCB coating

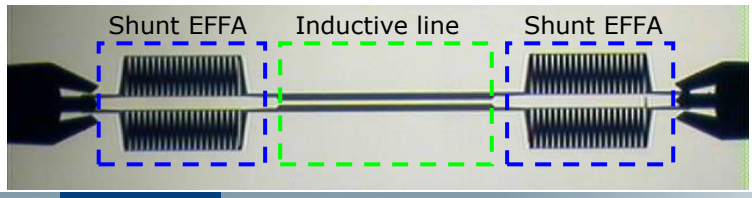


A 2-mask phase-shifter

Equivalent π-network of an element of transmission line

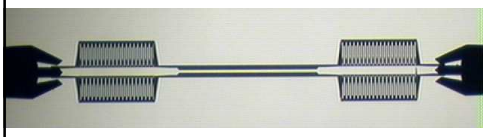


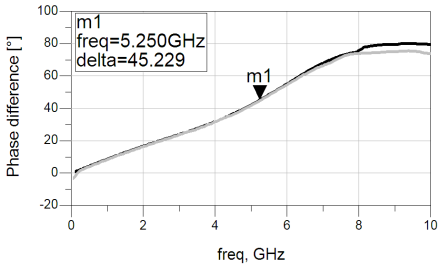
Switching the capacitances, the electrical length increases while the matching is preserved.

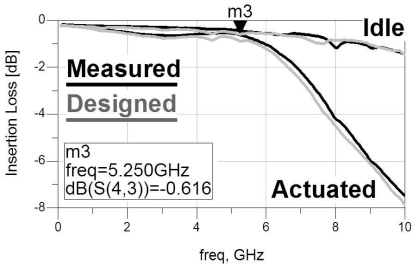


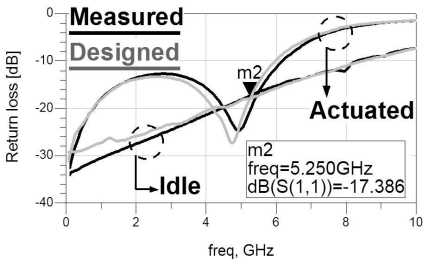
A 2-mask phase-shifter

Very good agreement between measurements and simulations.
45° phase shift @ 5.25GHz, 0.7dB IL



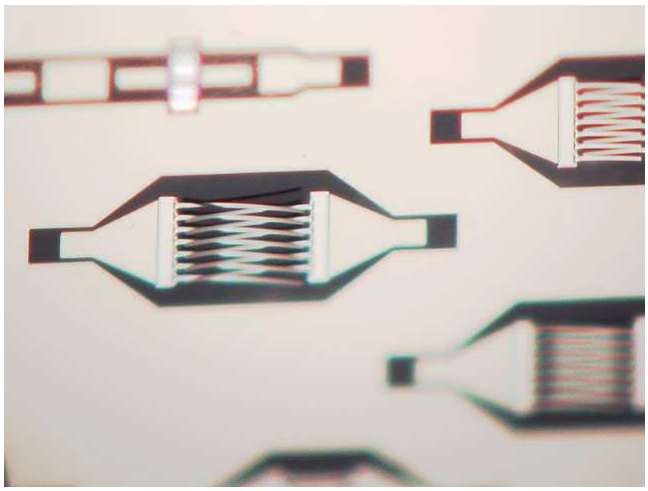






The electrostatic MEMS a RF-designer can process

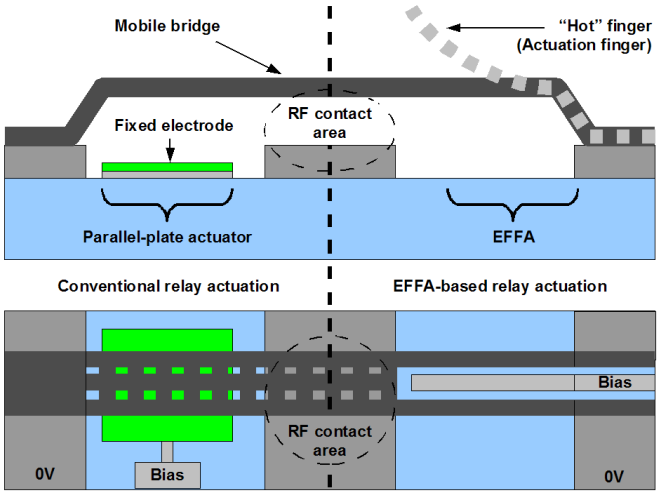
Sensing and actuating superposed



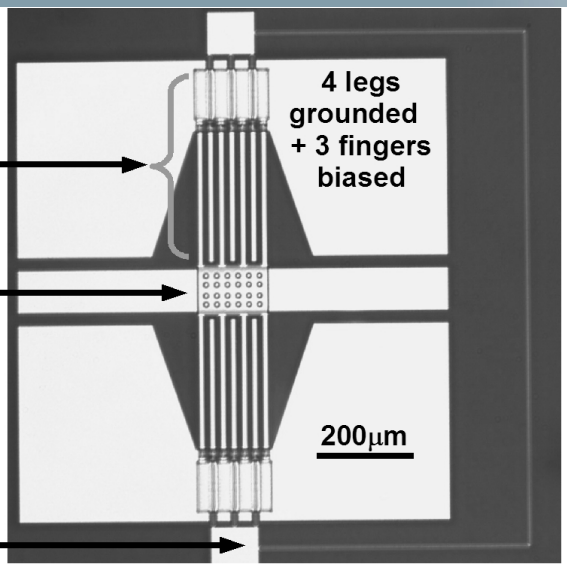
Outline

- Switchable filters in mainstream RF-MEMS technology
  - Hybrid MCM-D/RF-MEMS
  - Fully integrated
- Electrostatic Fringing-Field Actuator (EFFA)
- Basic EFFA devices
  - Devices
  - Integration opportunities
  - Circuits for RF-applications
- Advanced EFFA devices: Relays
- Conclusions

EFFA-based relay-actuation



EFFA-based shunt relay capacitor



No voltage on the "metal-metal" contact.

Native AlO_X prevents the ohmic contact.

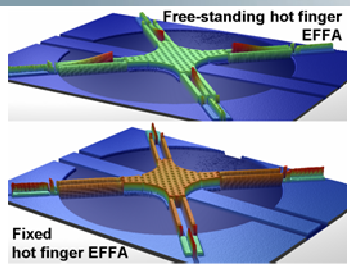
Improved capacitance ratio compared to the standard EFFA's.

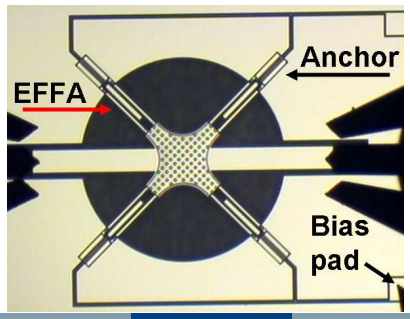
Limited by non-planar contact and AlO_X thickness.

EFFA-based relay: "the flat cow"

RF-design to amplify the still moderate capacitance ratio and produce a switching characteristic.

Various MEMS implementations with free-standing or fixed hot fingers.





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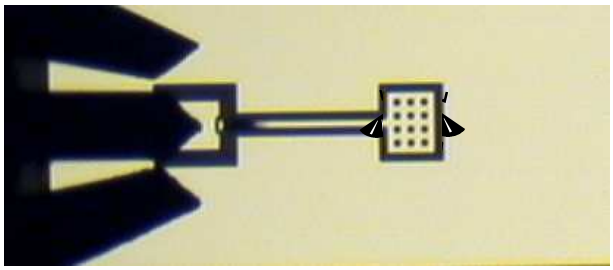
Conclusions: EFFA (Electrostatic Fringing-Field Actuator)

- In general a novel type of electrostatic actuators:
  Simple processing, low capacitances and maximal capacitance contrasts for the basic EFFA devices processed on glass with the current critical dimension.
- In a 2-mask process (1 day processing), we demonstrated:
  Switchable series and shunt capacitors, 45° phase-shifter @ 5.25GHz with IL< 0.6dB, finger- or bridge-based, mixed, with designed C-V characteristics, a test vehicle for dielectric charging
- In a 2-mask process, with coated substrate, we demonstrated:
  Enhanced C-V contrast by high-k coating of a glass substrate (TaO for example), meta-stable half-opened state by low-k coating of a glass substrate (BCB for example), integration possibilities with other technologies (MCM-D for example)
- In a 3-mask process, with a second metal, we demonstrated:
  Series tunable LC-tanks, series and shunt relay-actuated //-plate capacitors, relay-actuated capacitive switches, the principle of new relay-actuated ohmic switches

Acknowledgments

- Funding from ESA-ESTEC.

Questions ?



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