Dept. of Electrical & Computer Engineering • Aristotle University of Thessaloniki

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Computational Techniques for the Analysis and Design of Dielectric-Loaded Plasmonic Circuitry

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http://photonics.ee.auth.gr

Outline

- Introduction
  - Single Interface and SPPs
  - The DLSPP Waveguide
  - DLSPP-Based Components
- Microdisk/ring Filters
  - Layout and Operating Principle
  - 3D-FEM Implementation Details
  - Small Radii
  - Large Radii
  - Thermally-Tunable Add-Drop Filters
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  - Steady-State Response
  - Thermal Transient
  - Optical Transient
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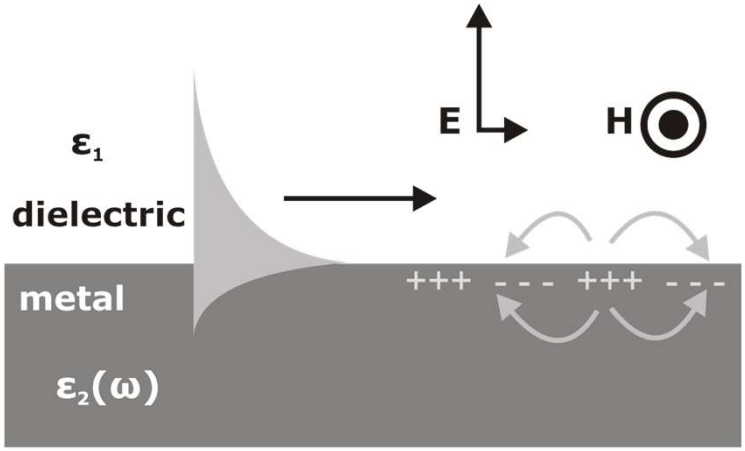
Introduction —Single Interface and SPPs

Surface Plasmon Polaritons (SPPs):

Electromagnetic surface waves coherently coupled to free electron oscillations.

- Propagate along a metal-dielectric interface.
- Fields decay exponentially away from the interface.
- Exhibit propagation losses due to resistive damping in the metallic film.
- Trade-off between propagation losses and lateral confinement.



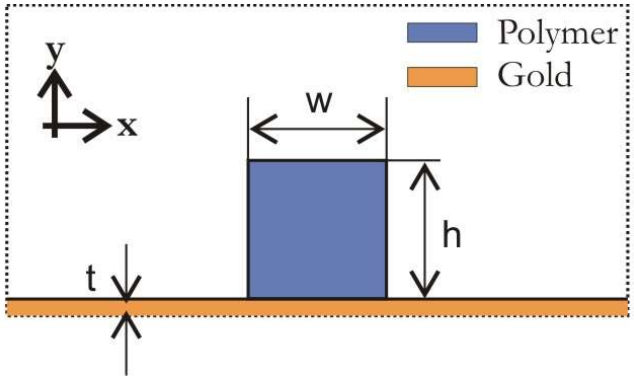
SPP at single metal-dielectric interface:
An elementary plasmonic waveguide.

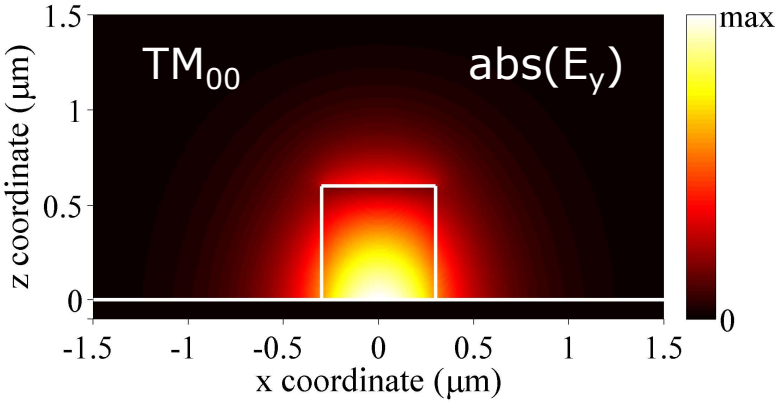
Introduction — The DLSPP Waveguide

Dielectric-loaded surface plasmon polariton (DLSPP) waveguide:

- ✓ Technologically simple
- ✓ (2D) Sub-wavelength confinement and strong guiding properties.
- ✓ Relatively low propagation losses (L_{prop} ~ 45 μm for TM_{00} mode)
- ✓ Readily accommodates diverse loadings → Dynamic components

T. Holmgaard, S.I. Bozhevolnyi, *Phys. Rev. B*, 75, 245405, 2006





$w \times h = 600 \times 600\ nm^2$ // $t_{Au} = 100\ nm$

$n_{pol} \sim 1.5$ // $\varepsilon_{r,Au} = -114 - j*11$ @ $\lambda = 1.55\ \mu m$

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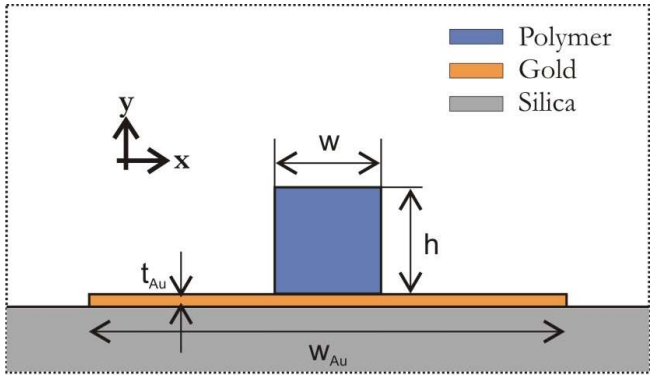
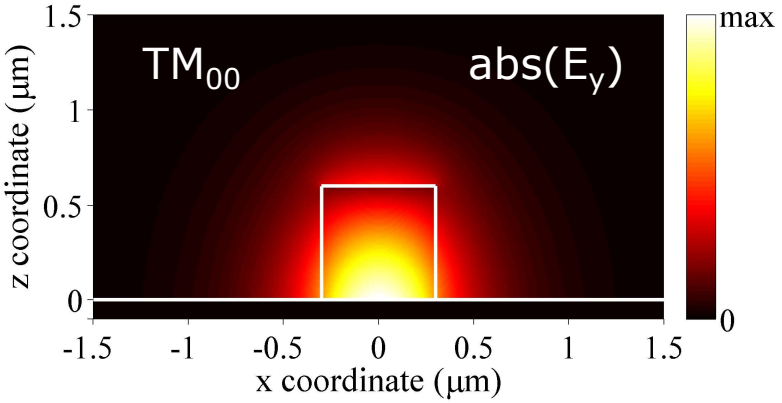


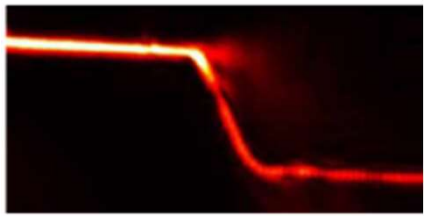


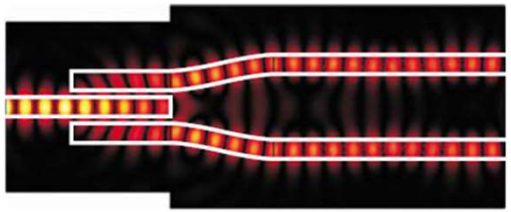
$w \times h$ = 600×600 nm^2 // t_{Au} = 100 nm
*n_{pol} ~ 1.5 // $\varepsilon_{r,Au}$ = -114 – j*11 @ λ = 1.55 μm*

Introduction — DLSPP-Based Components

Passive components:

- ✓Waveguide bends
- ✓Coupled lines
- ✓Splitters

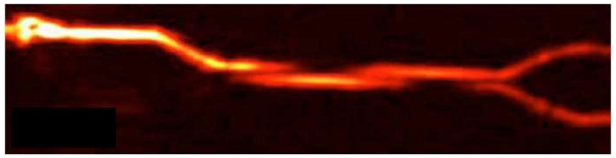


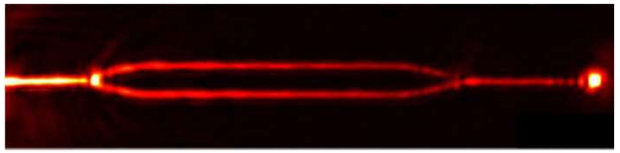


A.V. Krasavin, A.V. Zayats, *Phys. Rev. B*, 78, 045425, 2008
T. Holmgaard, et al., *Opt. Express*, 16, 13586, 2008

More recently, interest is focused on wavelength-selective components:

- ✓Bragg reflectors
- ✓Directional couplers
- ✓MZIs
- ✓Microring/disk resonator filters





T. Holmgaard, *et al.*, *Appl. Phys. Lett.*, 94, 051111, 2009
Z. Chen, *et al.*, *Opt. Lett.*, 34, 310, 2009

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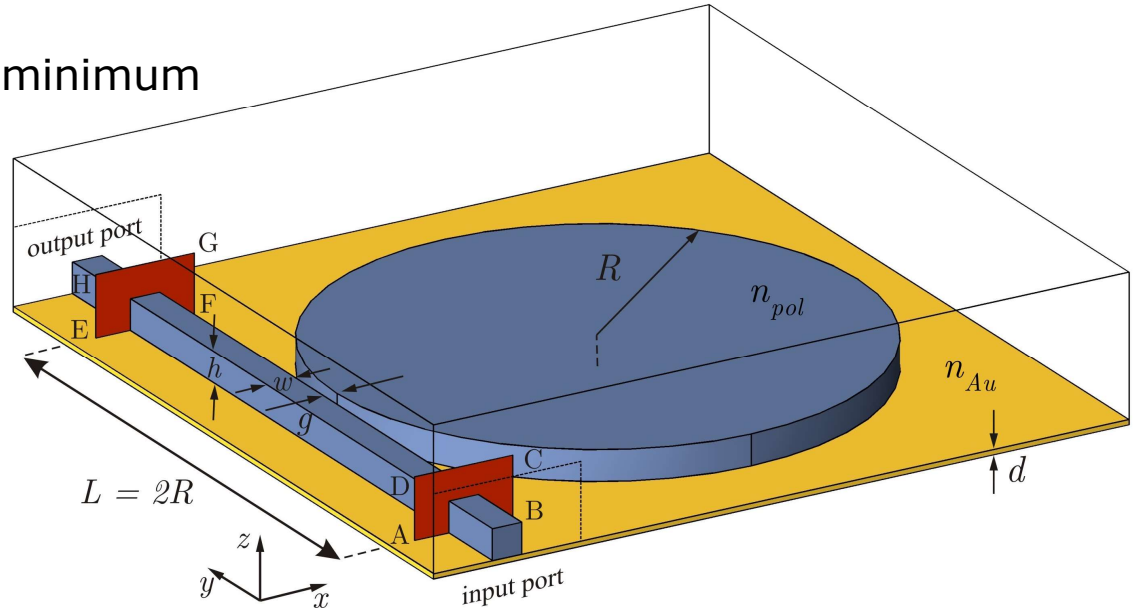
Microdisk/ring Filters – Layout and Operating Principle

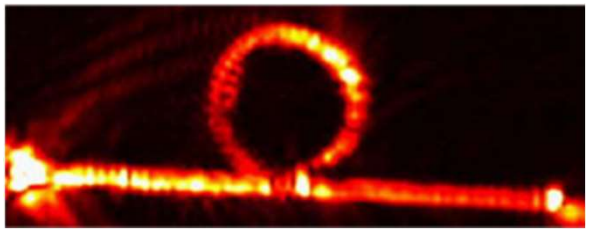
- ✓Wavelength selective component
- ✓Resonator coupled to bus w/g
- ✓On resonance transmission is minimum
- ✓Periodic response w.r.t. λ
- ✓Two loss mechanisms



Crucial Parameters:

- Resonator-w/g gap g (critical coupling - ER)
- Resonator radius *R* (FSR, loss per circulation)

Microring resonator filters have been experimentally and theoretically investigated.

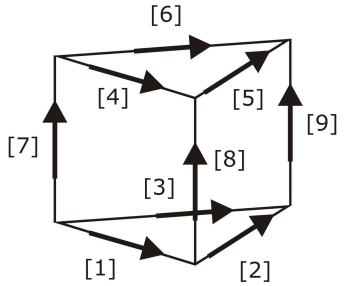


T. Holmgaard, *et al.*, *Opt. Express*, 17, 2968, 2009
O. Tsilipakos, *et al.*, J. Appl. Phys., 106, 093109, 2009

Microdisk/ring Filters – 3D-FEM Implementation Details

✓1st order triangular prisms

- 9 prism layers in total → 2(Au)+4(Pol.)+3(Air)



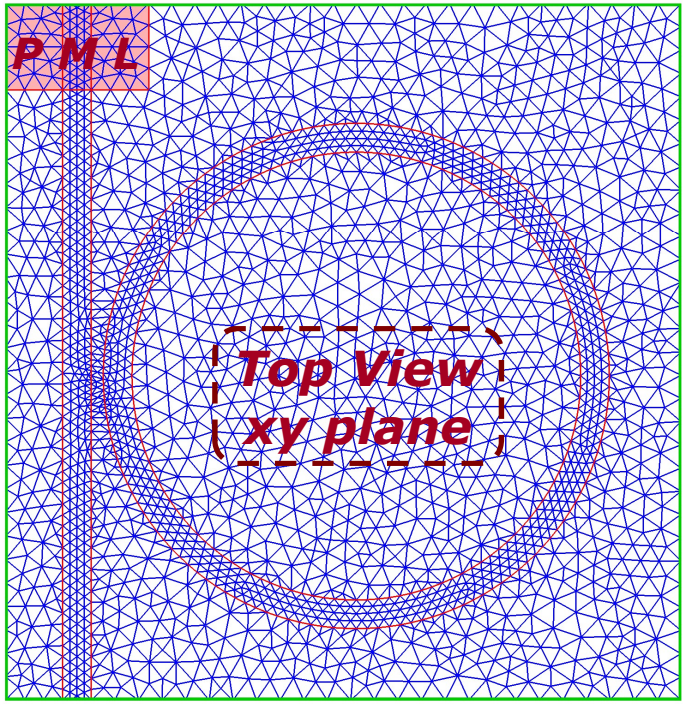
✓1st order absorbing boundary conditions (ABCs) on all sides and the top of the bounding box.

$$\hat{n}\times\left(\nabla\times\mathbf{E}\right)+jk_0\hat{n}\times\left(\hat{n}\times\mathbf{E}\right)=0$$

Modified for the I/O waveguide ports (hybrid mode)

Output: $$\hat{n}\times\left(\nabla\times\mathbf{E}\right)+j\beta\hat{n}\times\left(\hat{n}\times\mathbf{E}\right)=0$$

$$j\frac{\omega\mu_0}{Z_w^{TM}(x,z)},\ where\ \ Z_w^{TM}(x,z)=-\frac{E_z(x,z)}{H_x(x,z)}$$



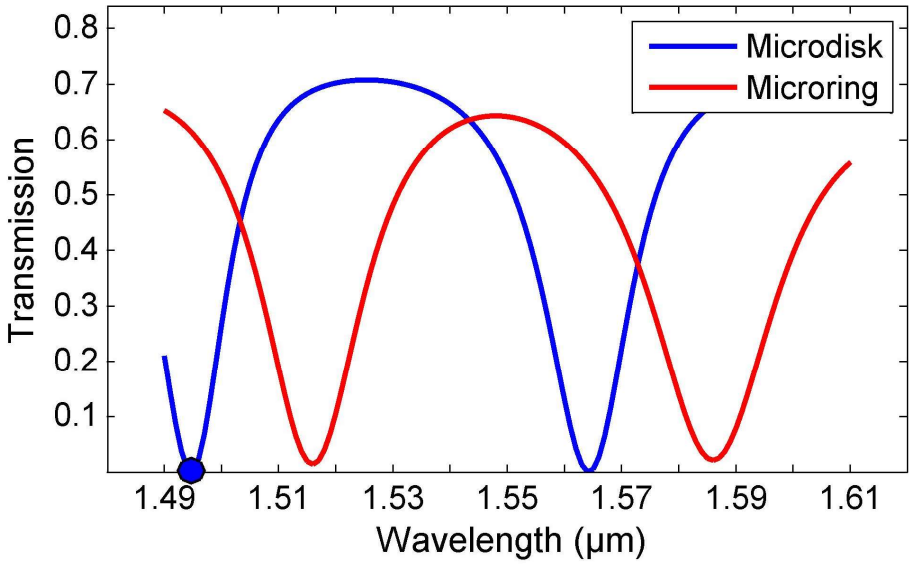
✓Perfectly matched layer (PML) for the reflectionless termination of the bus w/g.

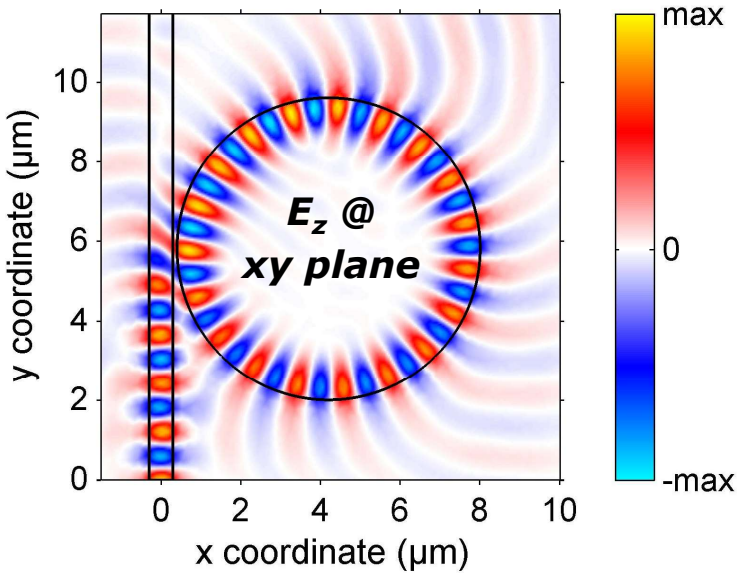
- Only ***locally*** employed. Global utilization → Increases DoFs & Degrades conditioning.

Microdisk/ring Filters – Small Radii

- Small radii → significant radiation losses (compared to resistive ones)
- Reduced radiation losses for the microdisk
  - Narrower minima linewidths
  - Eigenvalue simulations: $Q_D \sim 200$ vs $Q_R \sim 100$
  - Higher transmission maximum
- FSR ~ 70 nm // ER > 15 dB

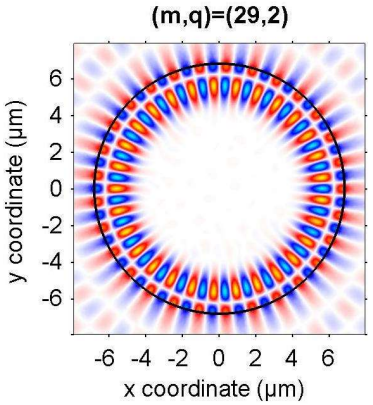
R = 3.8 μm
g = 0.1 μm
(critical coupling)

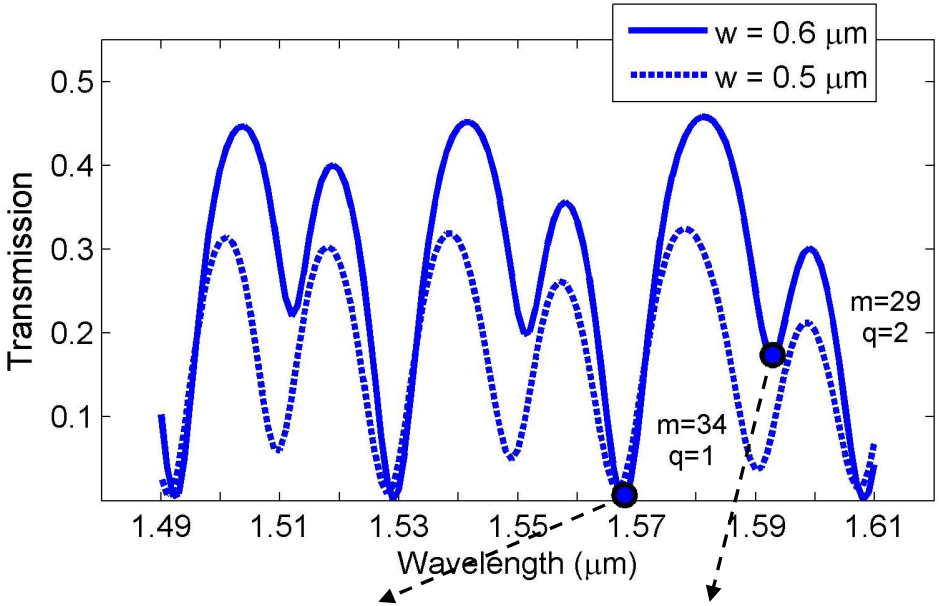




Microdisk/ring Filters – Large Radii

- ✓R = 6.8 μm, g = 0.1 μm
- ✓2nd radial order modes (q=2)

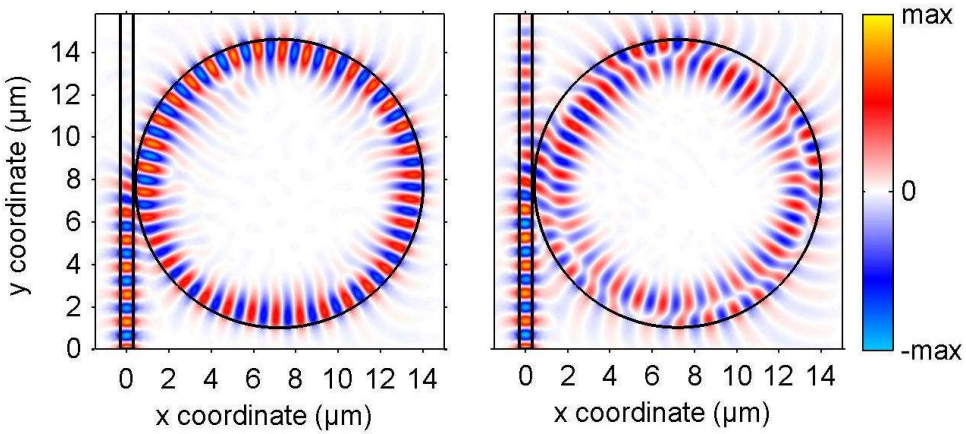




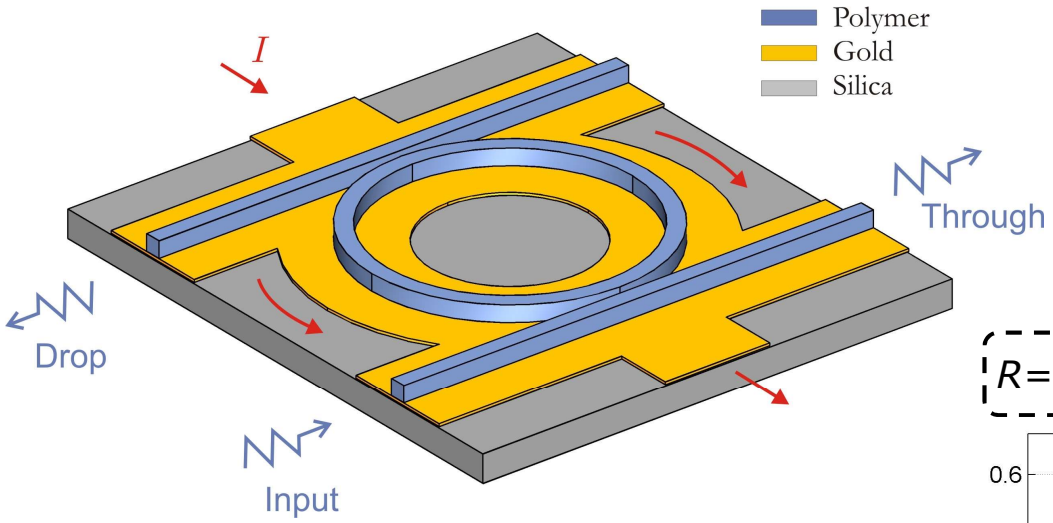
Excitation efficiency tuning:

- Waveguide width
- Disk radius

At λ=1.593 μm the E_z plot reveals a linear combination of modes (33,1) and (29,2)

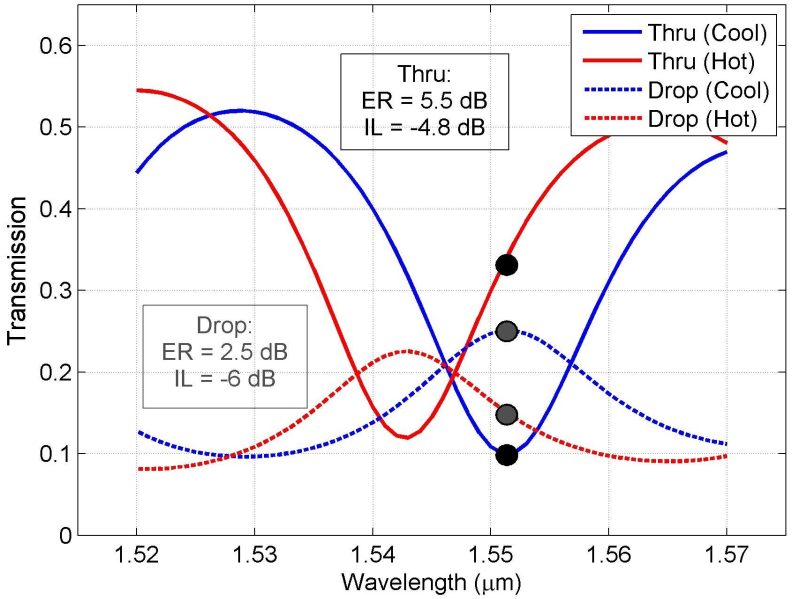


Microdisk/ring Filters – Thermally Tunable Add-Drop Filters



- ✓Two bus waveguides
- ✓Patterned metallic film
- ✓Possibly racetrack shape
- ✓SOI substrate

R=5.5 μm // L=0.5 μm // g1=g2=0.3 μm



- Operating w/l @ maximum of drop
- ~ 9 nm shift (TOC ~ 10^{-4}, ΔT = 100 K)
- Crosstalk ~ -4 dB for both states
- IL(drop) = -6 dB
- ER(drop) = 2.5 dB

More on thermo-optic DLSPP-based components:

J. Gosciniak, *et al.*, *Opt. Express*, 18, 1207, 2010
O. Tsilipakos, *et al.*, J. Appl. Phys., 106, 093109, 2009

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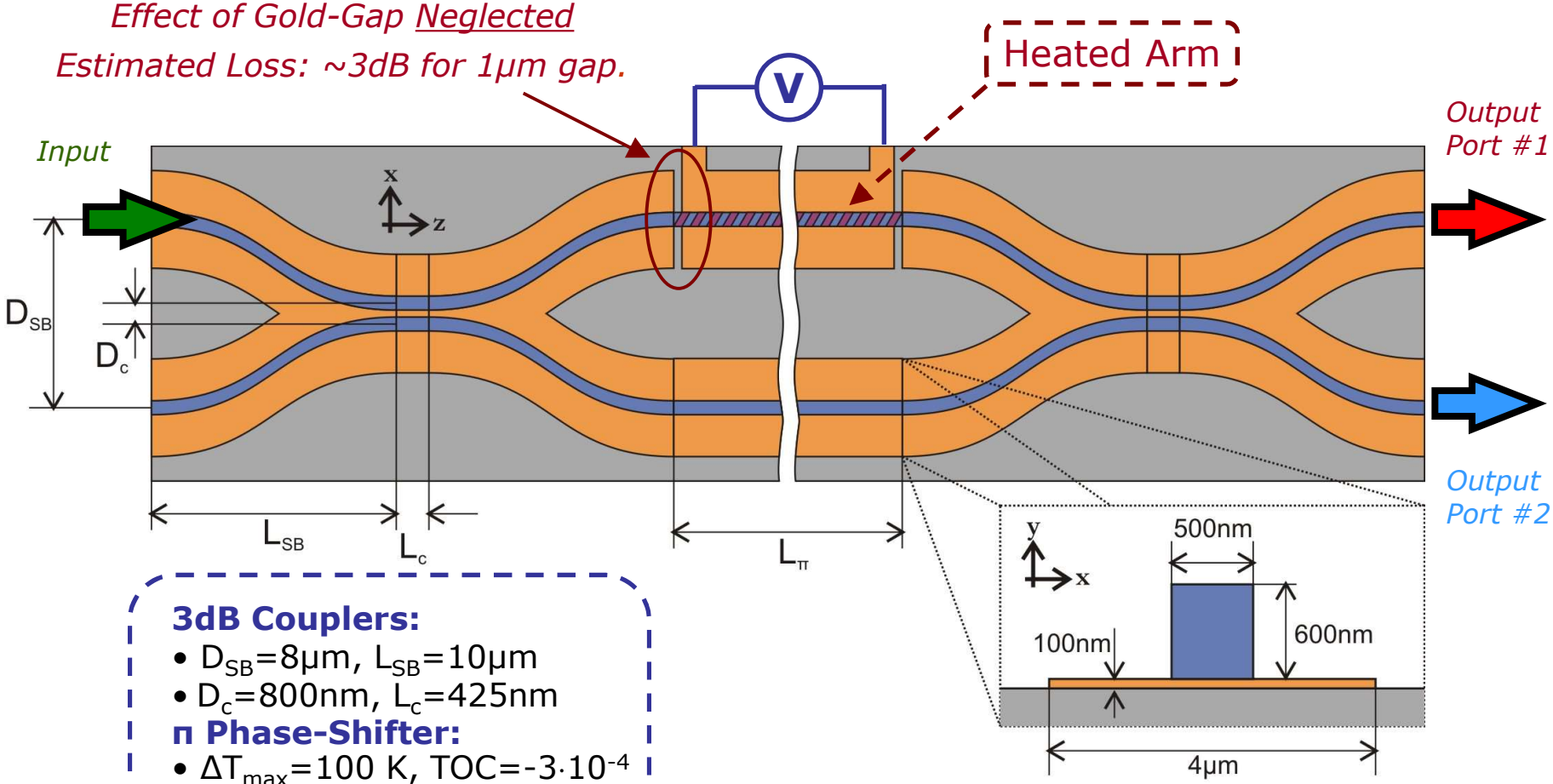
2x2 MZI Switch – Layout and Operating Principle

Effect of Gold-Gap Neglected

Estimated Loss: ~3dB for 1μm gap.



3dB Couplers:

- D_{SB}=8μm, L_{SB}=10μm
- D_c=800nm, L_c=425nm

π Phase-Shifter:

- ΔT_{max}=100 K, TOC=$-3 \cdot 10^{-4}$
- L_π=29,5μm

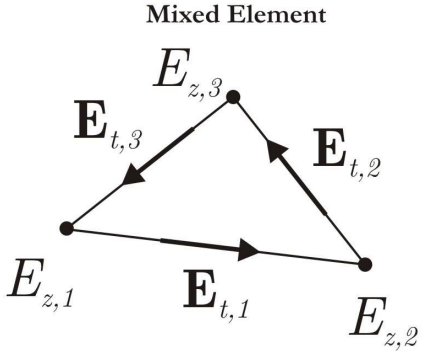
2x2 MZI Switch – 3D-BPM Implementation Details

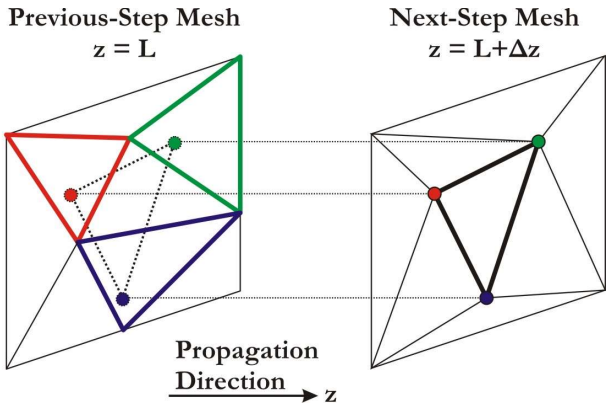
FD-BPM

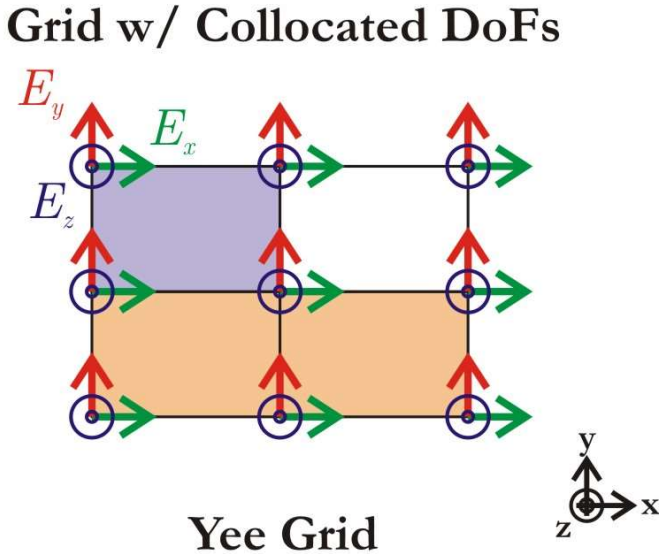
- Dramatic discontinuities on interfaces w/ Au
- Grid w/ Collocated DoFs
  - *The continuity of E_n is falsely imposed*
  - *Im{n_{eff}} is miscalculated*
- Yee grid gives fairly accurate results

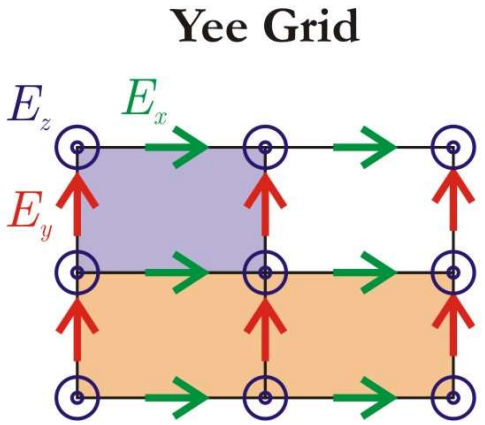
FE-BPM

- Mixed elements: edge ($\boldsymbol{E_t}$) + nodal (E_z)
- Effective index corrected (real and imag. part)
- Computational overhead for z-varying structures



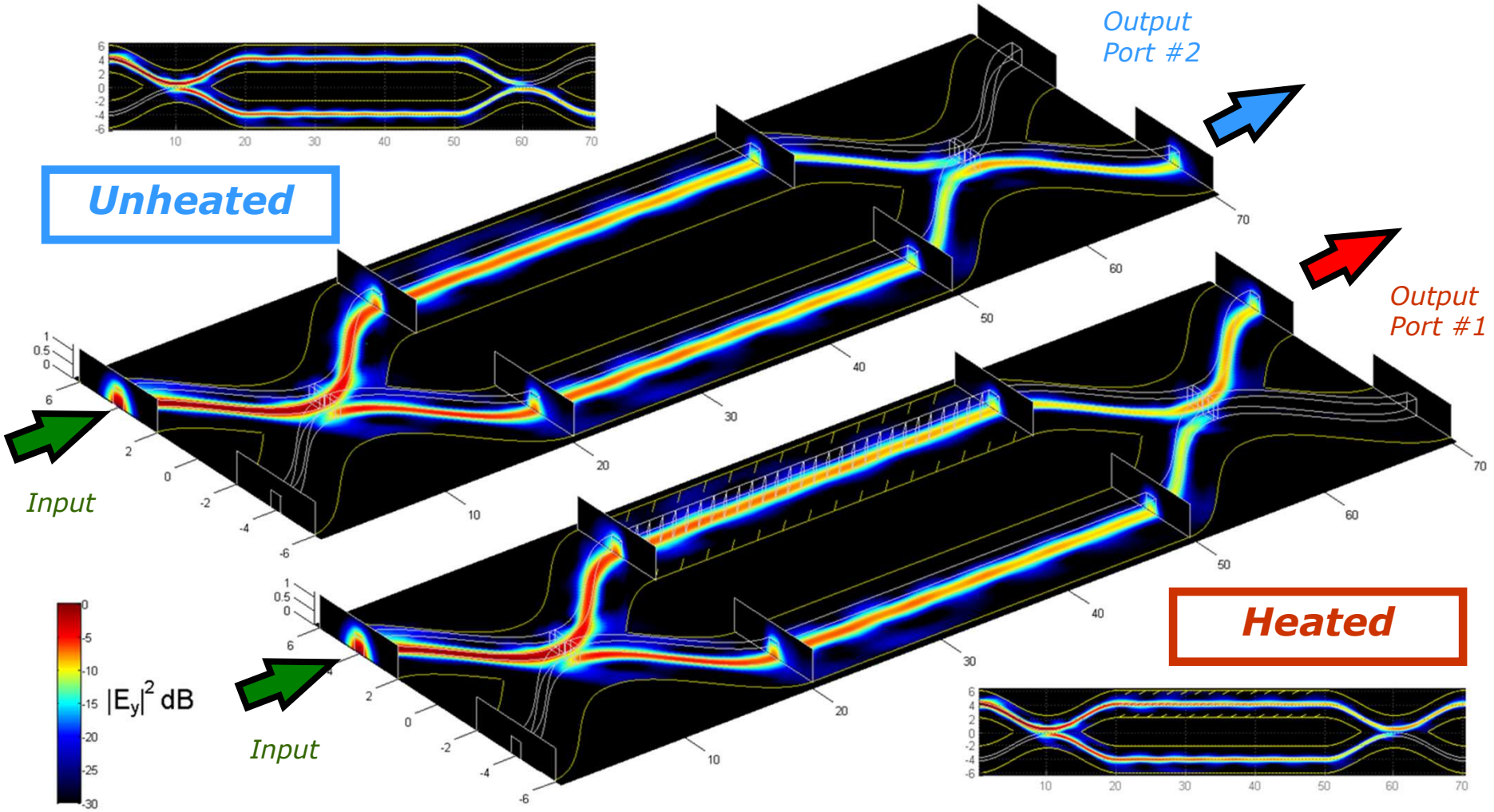






✓ The semi-vector TM BPM gives satisfactory results

2x2 MZI Switch – Steady State Response



2x2 MZI Switch – Thermal Transient

✓V = 1.2 V → **J = 100 GA/m²**

✓Temperature distribution calculated through → $\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-K \nabla T) = Q \equiv \frac{J^2}{\sigma}$

(time-stepping in increments of 0.1 μs up to 10 μs)

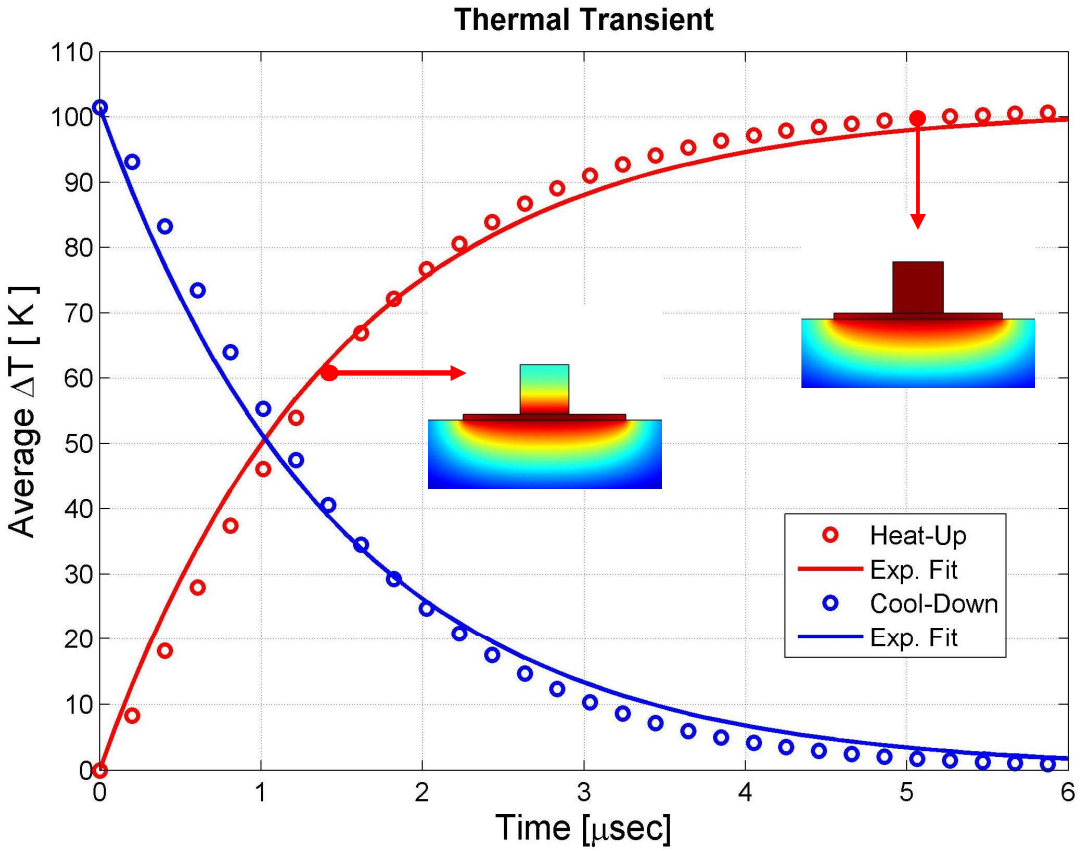
Exponential fits:

$$\Delta T_{av}(t) = \Delta T_{av}^{\infty}\left(1 - e^{-t/\tau_{rise}}\right)$$

$$\Delta T_{av}(t) = \Delta T_{av}^{\infty}\left(e^{-t/\tau_{fall}}\right)$$

$$\tau_{rise} = \tau_{fall} = 1.5\,\mu s$$

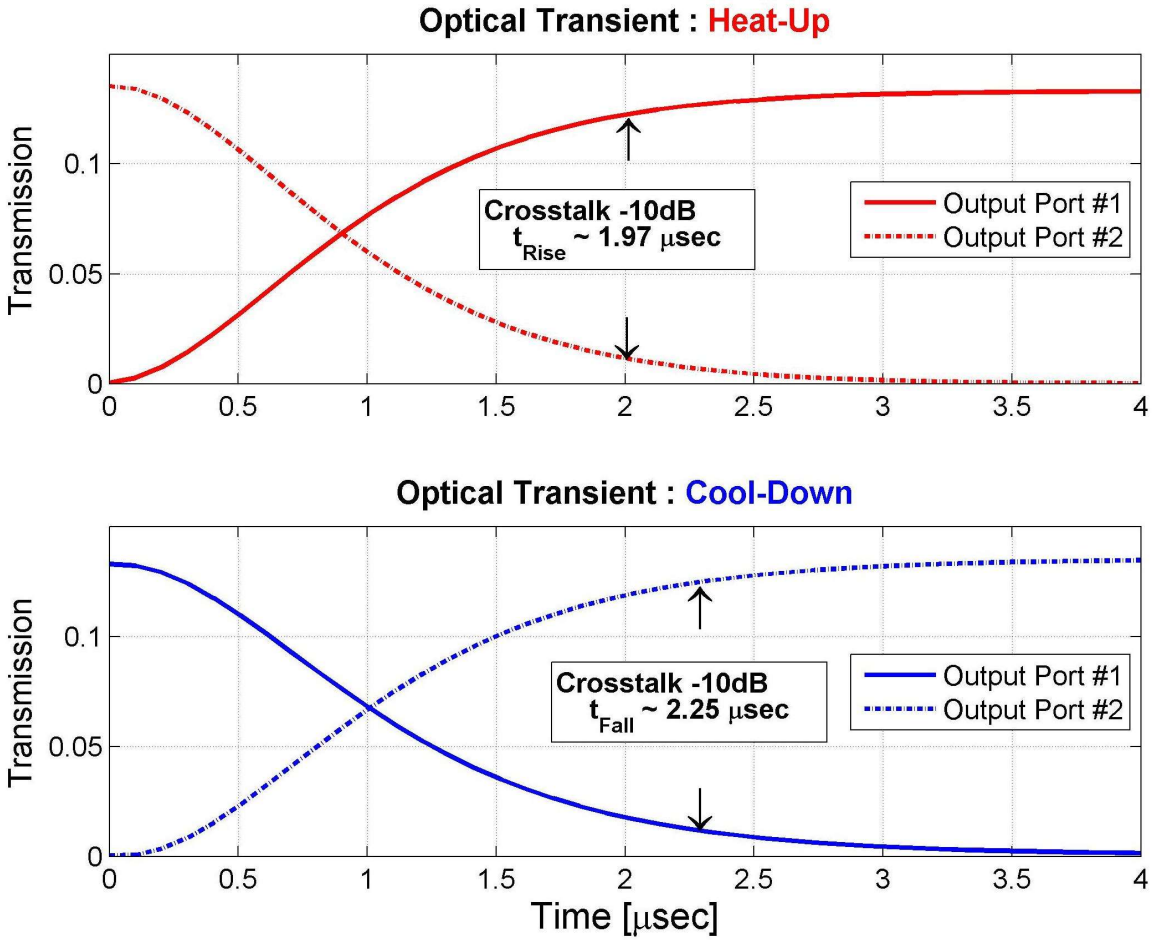
- ΔT is spatially constant in DL only in steady state
- Non-uniform distribution during transient



2x2 MZI Switch – Optical Transient

- **Switching Time: 1.97 μs (Heat-Up) and 2.25 μs (Cool-down)**
  (Assuming -10 dB crosstalk between output ports)

Insertion Loss: ~9dB
- Propagation Losses
(~ 0.1 dB/μm)
- S-Bend Losses
(~ 1 dB per coupler)



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Conclusions

- Thermally tunable DLSPP-based components
  - 3D-FEM for small resonant structures
  - 3D-BPM for large structures with clear propagation direction
- Other switching configurations possible
  - Directional coupler switch
  - MMI switch
- Polymers with higher TOC would be beneficial
- Other types of addressing for faster switching

This work was supported in part by the European FP7 project **PLATON** [Contract No. 249135]

http://www.ict-platon.eu