

Hybrid silicon-plasmonics: Efficient waveguide interfacing for low-loss integrated switching components

O. Tsilipakos, A. Pitilakis, and E. E. Kriezis

Session 10: Surface Plasmons and Devices III

Presentation Outline

□ **Introduction**

- Nanophotonic circuits
- The DLSPP waveguide
- DLSPP-based thermo-optic switches
- Aim and scope

□ **DLSPP to SOI Waveguide Transition**

- SOI waveguide
- DLSPP to Si-rib waveguide transition
- Coupling loss breakdown
- DLSPP to Si-wire waveguide transition

□ **Practical Considerations**

- Longitudinal metallic stripe gap
- Horizontal offset
- Experimental results

□ **Hybrid SOI-DLSPP Switches**

- All-DLSPP longitudinal 2x2 TO switches
- Hybrid SOI-DLSPP 2x2 TO switches
- SOI coupler design

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Nanophotonic circuits

Two prominent nanophotonics technologies

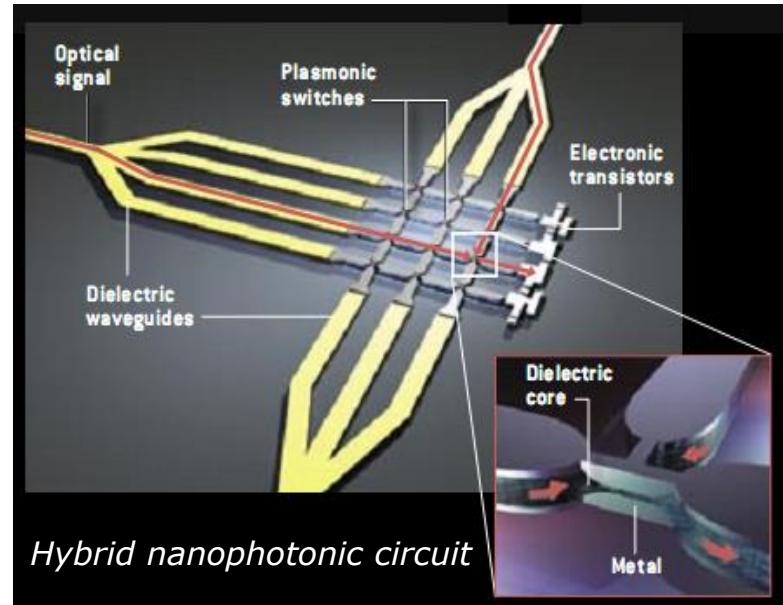
□ Silicon Photonics

- Ideal for passive circuitry
- Low-loss waveguides
- Compact w/g dimensions ($\sim 0.1 \mu\text{m}^2$)
- Strong waveguiding properties
- Mature technology

□ Plasmonics

- Promising for switching elements
- Can be very subwavelength
- Energy efficient
- ... but high propagation losses

H. Atwater, Scientific American, 2007

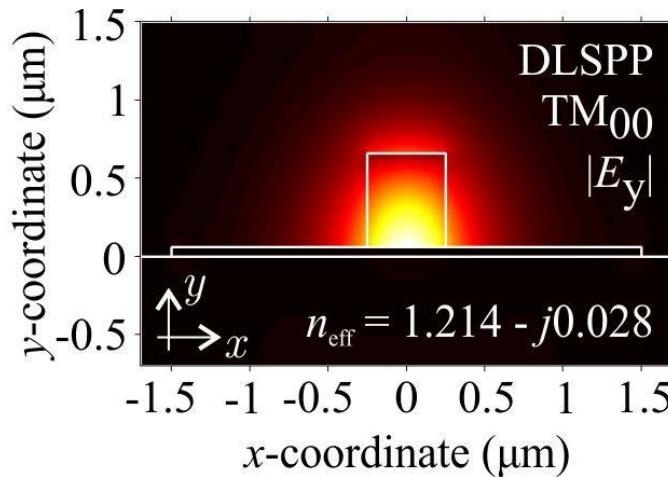
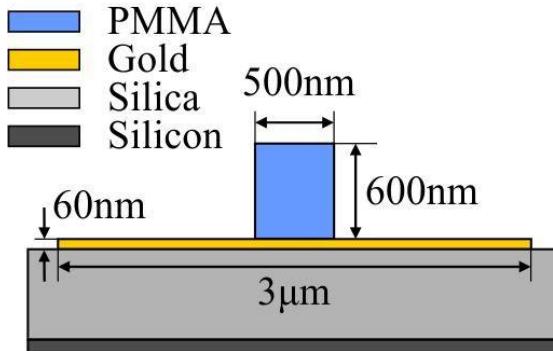


Hybrid silicon-plasmonic nanophotonic circuits can benefit from the distinct advantages of each technology!

The DLSPP waveguide

Dielectric-loaded surface plasmon polariton (DLSPP) waveguide:

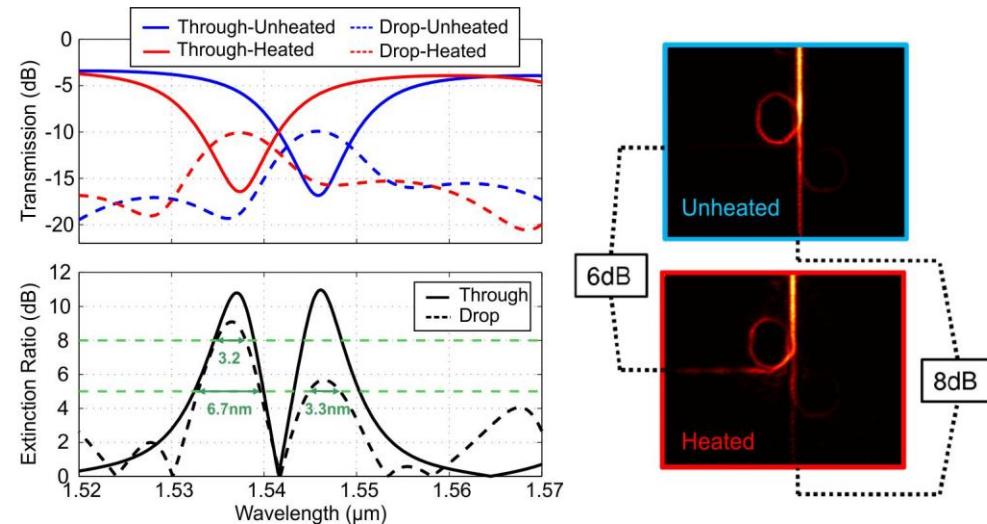
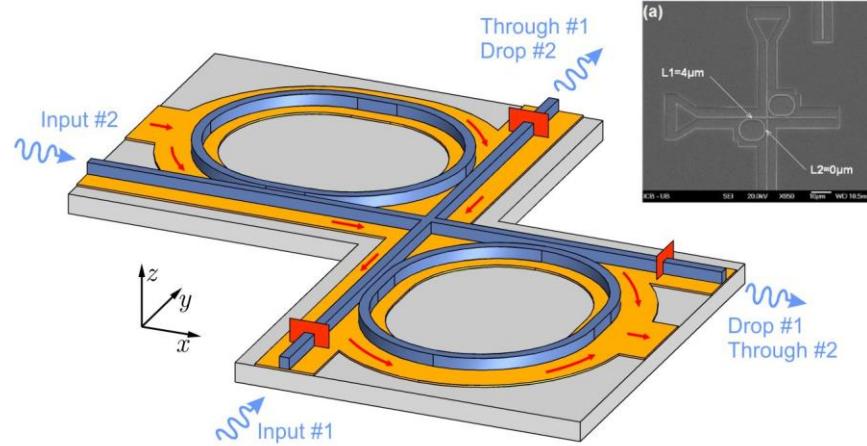
- ✓ Technologically simple
- ✓ Can be fabricated on an SOI wafer
- ✓ Sub-micron mode confinement
- ✓ Relatively low propagation losses ($L_{\text{prop}} \sim 45 \mu\text{m}$ or $0.1 \text{ dB}/\mu\text{m}$)
- ✓ Readily accommodates diverse loadings → diverse tuning mechanisms
- ✓ Energy-efficient thermo-optic tuning



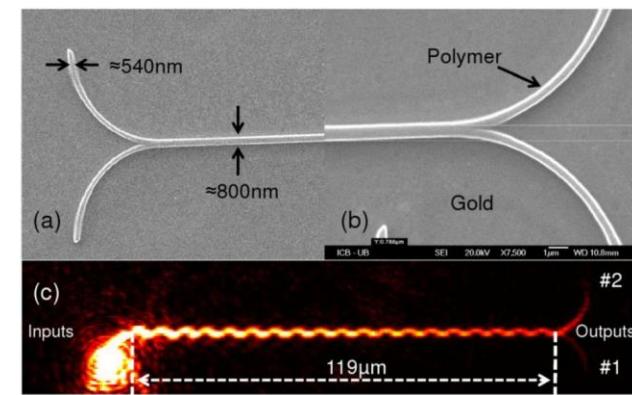
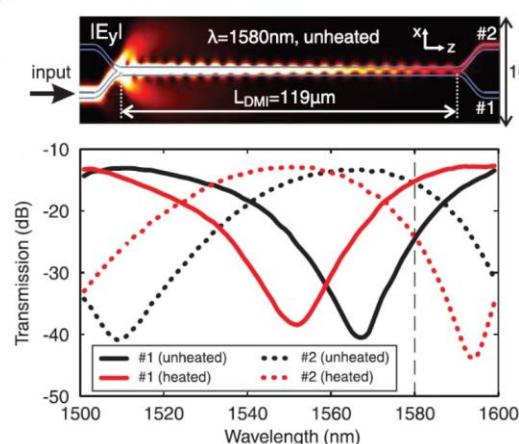
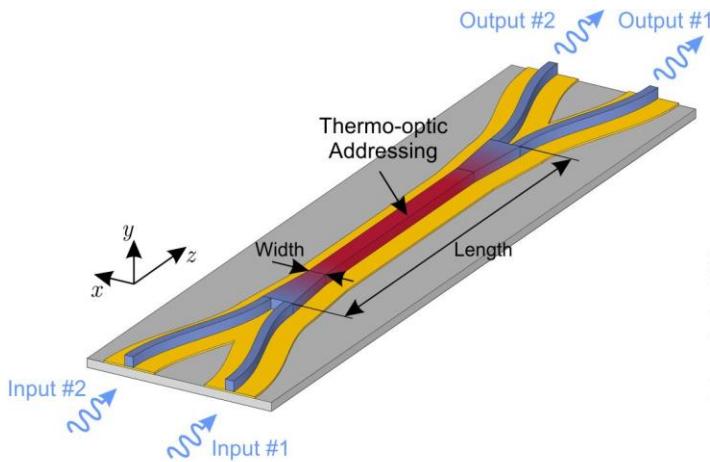
TOC _{PMMA}	$\sim 10^{-4} \text{ K}^{-1}$
n_{PMMA}	= 1.493
n_{Au}	= $0.55-j11.5$
n_{Si}	= 3.45
n_{SiO_2}	= 1.45

DLSPP-based thermo-optic switches

□ Dual-Resonator Switch

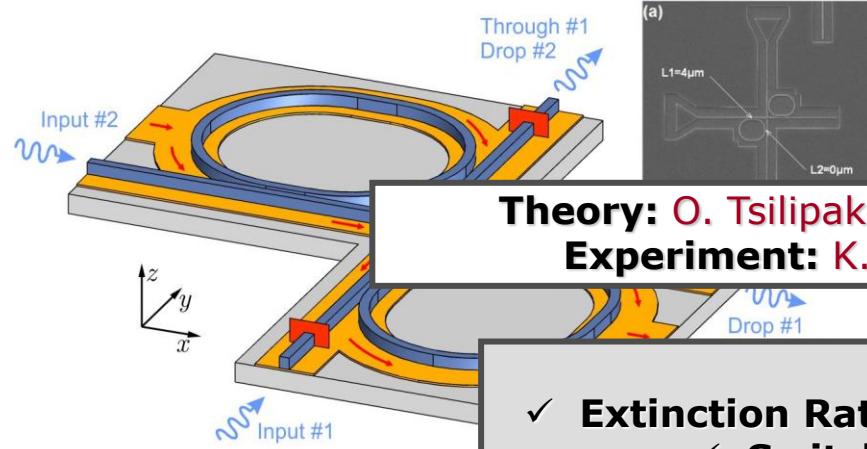


q Dual-Mode Interference Switch

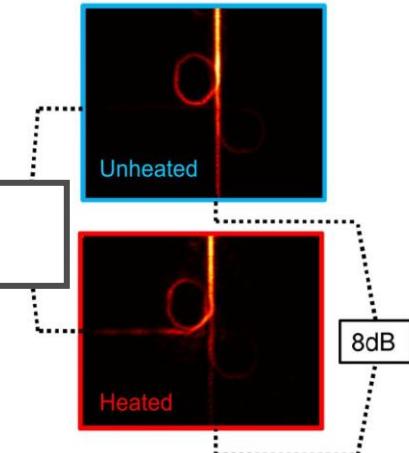
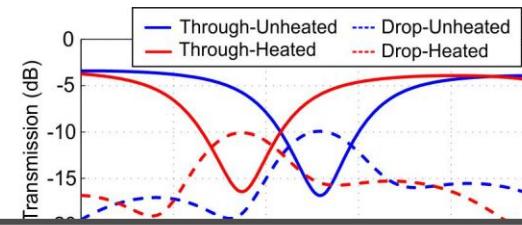


DLSPP-based thermo-optic switches

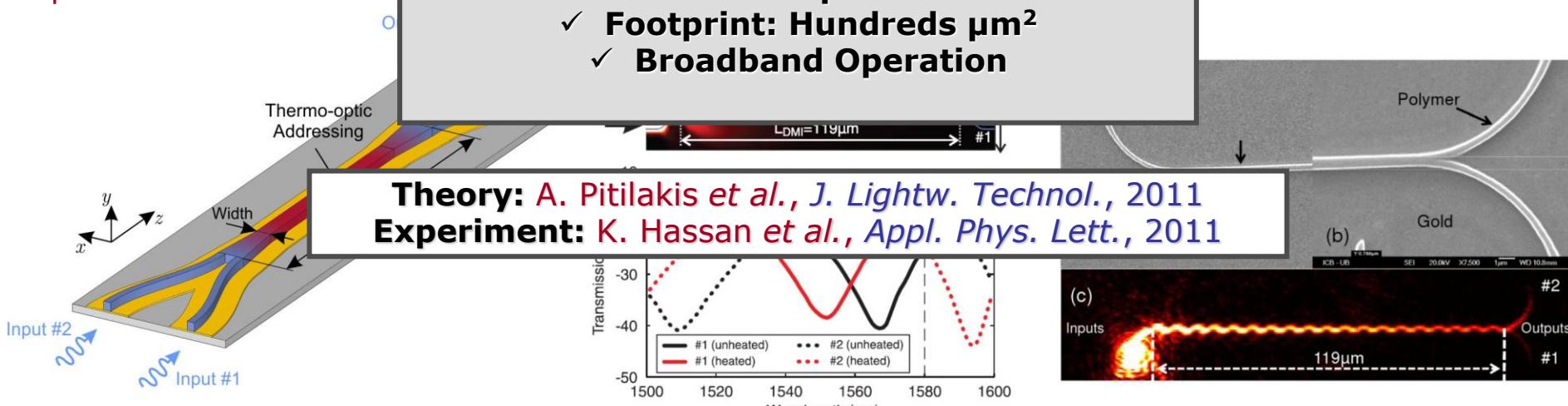
□ Dual-Resonator Switch



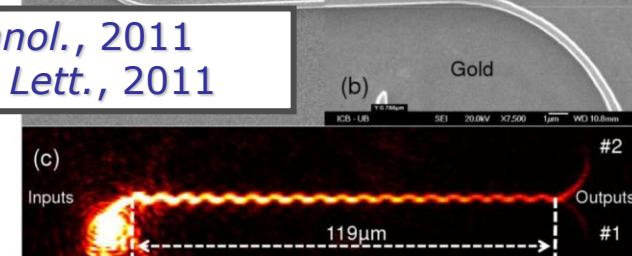
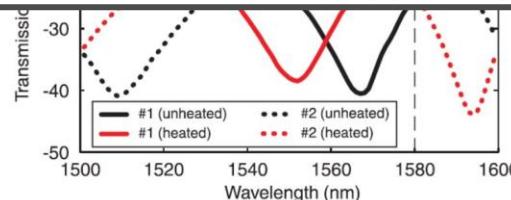
Theory: O. Tsilipakos *et al.*, *J. Appl. Phys.*, 2011
Experiment: K. Hassan *et al.*, *OFC*, 2012



q Dual-Mode Interf



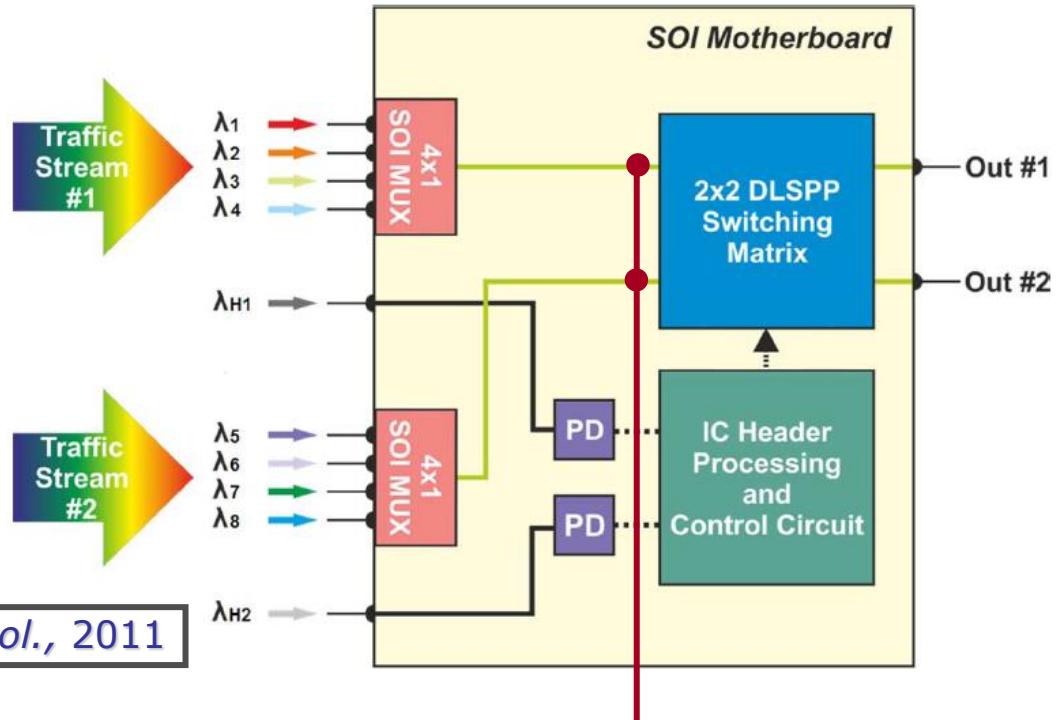
Theory: A. Pitilakis *et al.*, *J. Lightw. Technol.*, 2011
Experiment: K. Hassan *et al.*, *Appl. Phys. Lett.*, 2011



Aim and scope

2x2 Si-plasmonic router

- SOI filtering/mux stages
- DLSPP switching matrix
- Control circuit
- Photodiodes for O/E conversion



S. Papaioannou et al., J. Lightw. Technol., 2011

Efficient transition between the DLSPP and a compact SOI waveguide

- SOI waveguide must support a TM mode
- Compact and strongly guiding for small-footprint filtering/mux elements
- Butt-coupling approach since the plasmonic waveguide is lossy

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□ Practical Considerations

- Longitudinal metallic stripe gap
- Horizontal offset
- Experimental results

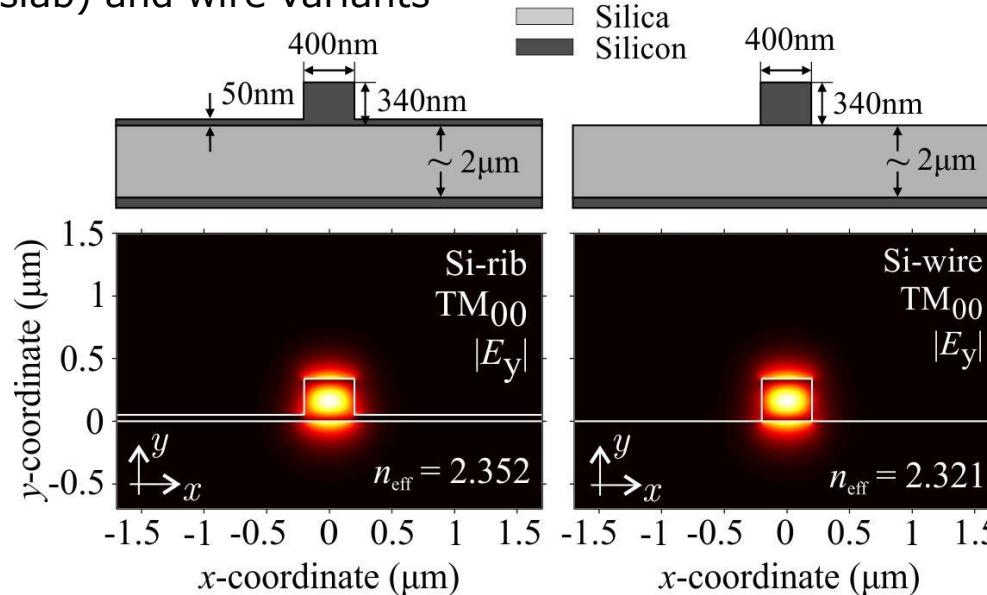
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SOI waveguide

Compact TM SOI Waveguide

- 400 nm × 340 nm silicon core
- Rib (50-nm slab) and wire variants
- 2-μm BOX

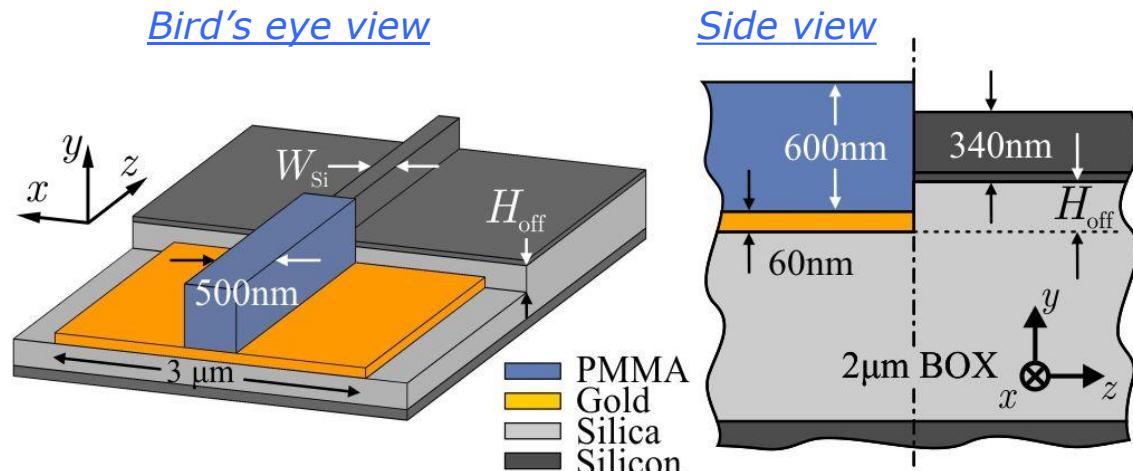


- Strongly confined TM_{00} mode
- Distributions for rib and wire variants are very similar for the nominal width
- **Spatial matching with the DLSPP is not particularly good**
 - x-extent of DLSPP almost double
 - Modes not centered along y-axis (lower part of rib mode cannot contribute to coupling)

DLSPP to Si-rib waveguide transition

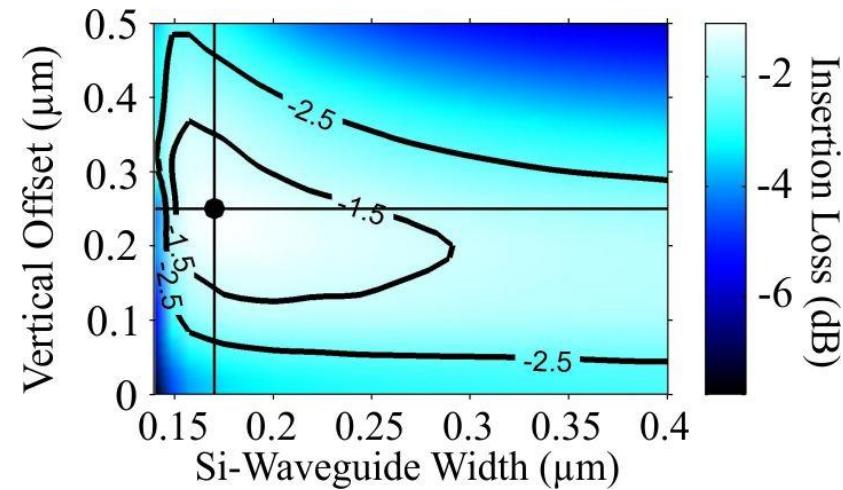
Design Parameters

- Vertical offset
(BOX etch-depth)
- Si-rib width @ interface
(adiabatic tapering
from nominal width)

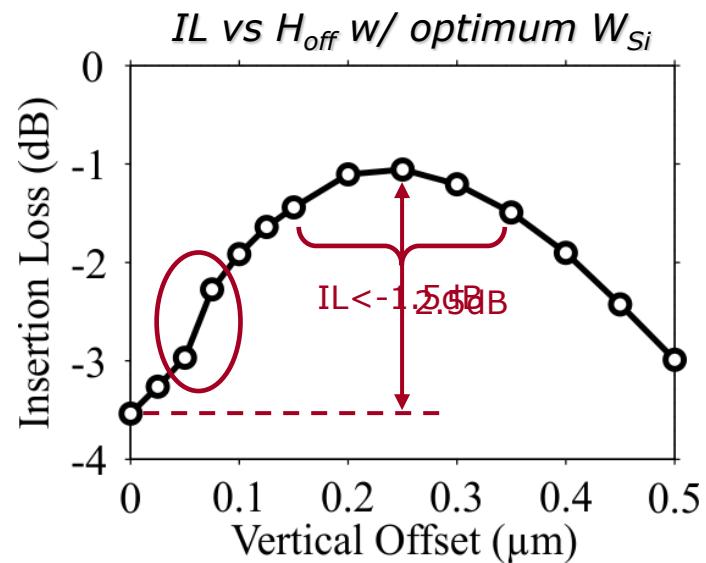
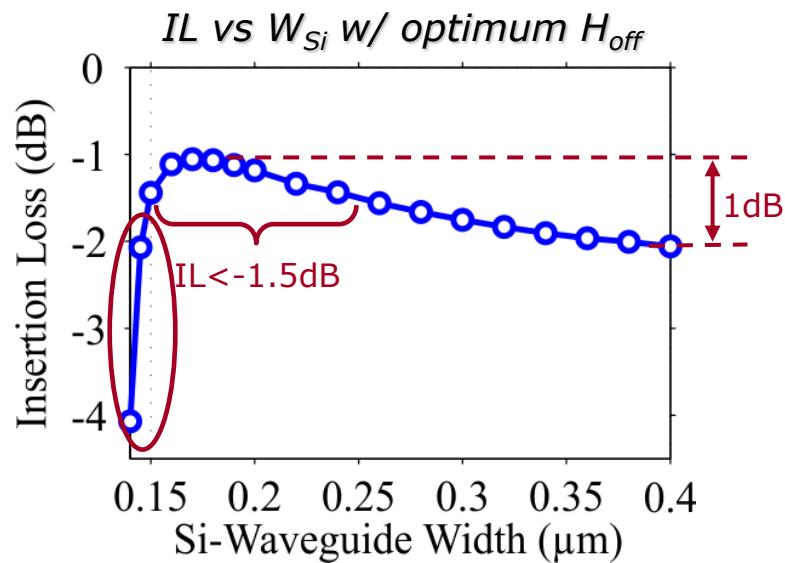


Analysis (3D-VFEM)

- Parametric analysis w.r.t. W_{Si} & H_{off}
- **Optimum:** IL = -1.05 dB
 $(W_{\text{Si}}, H_{\text{off}}) = (170 \text{ nm}, 250 \text{ nm})$
- Contours: ample fabrication tolerances
- IL < -1.5 dB
 - $150 \text{ nm} < W_{\text{Si}} < 250 \text{ nm}$
 - $150 \text{ nm} < H_{\text{off}} < 350 \text{ nm}$



DLSPP to Si-rib waveguide transition (cont'd)



- IL < -1.5 dB for $150 \text{ nm} < W_{Si} < 250 \text{ nm}$
- No-tapering penalty: 1 dB
- Steep IL increase for $W_{Si} < 145 \text{ nm}$

- IL < -1.5 dB for $150 \text{ nm} < H_{off} < 350 \text{ nm}$
- No-offset penalty: 2.5 dB
- Abrupt IL jump for $H_{off} = 60 \text{ nm}$

Coupling loss breakdown

1. Transmitted radiation modes

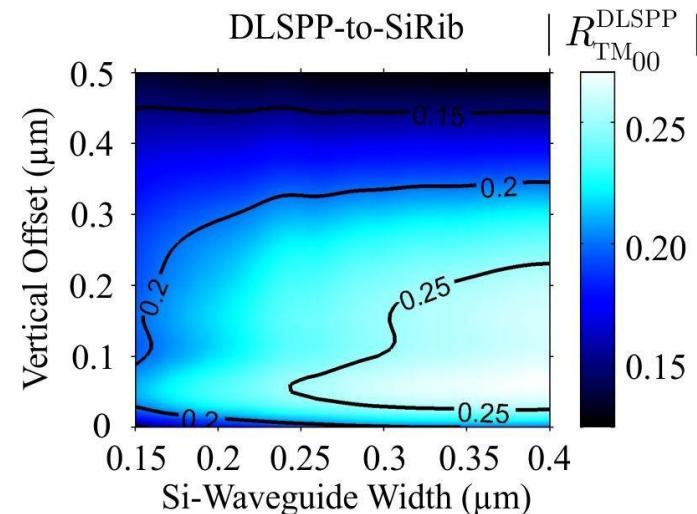
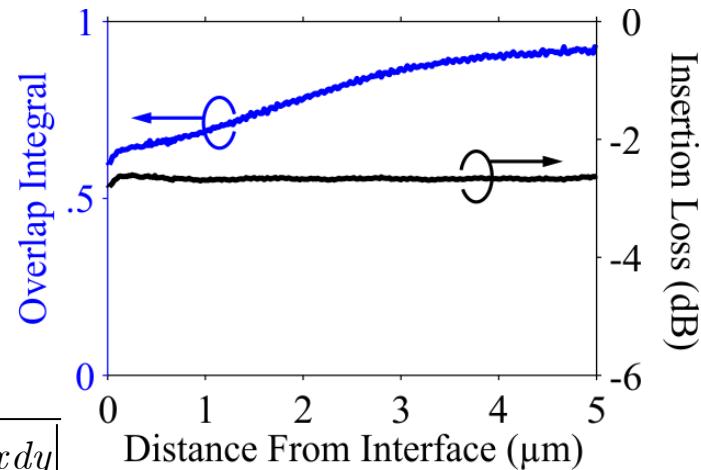
- Primary loss mechanism
- Procedure w/ overlap integral for IL calculation (example for nominal width and no offset)
- Little power coupled to reflected radiation modes

$$OI(z) = \frac{\left| \iint_A \mathbf{E}(x, y, z) \times \mathbf{H}_{\text{ref}}^*(x, y) \cdot \hat{\mathbf{z}} dx dy \right|^2}{\left| \iint_A \mathbf{E}(x, y, z) \times \mathbf{H}^*(x, y, z) \cdot \hat{\mathbf{z}} dx dy \right| \left| \iint_A \mathbf{E}_{\text{ref}}(x, y) \times \mathbf{H}_{\text{ref}}^*(x, y) \cdot \hat{\mathbf{z}} dx dy \right|}$$

2. Reflection in the form of the fundamental mode

- Amplitude reflection coefficient: **0.12 – 0.27** (1.5 – 7.5 % of input power)
- Max. reflection for nominal W_{Si} and small offsets
- Opposite propagation direction:
Higher reflection coefficients (up to 0.5)

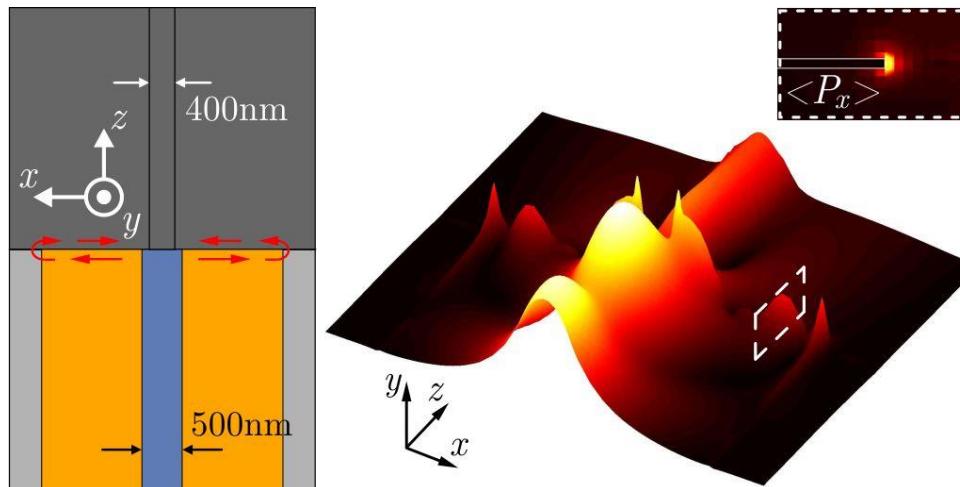
Return loss is not reciprocal



Coupling loss breakdown (cont'd)

3. Edge SPPs guided parallel to the interface

- Become noticeable for nominal width and small vertical offsets
- Finite stripe width: reflected at stripe corner
- Infinite stripe width: exit computational domain



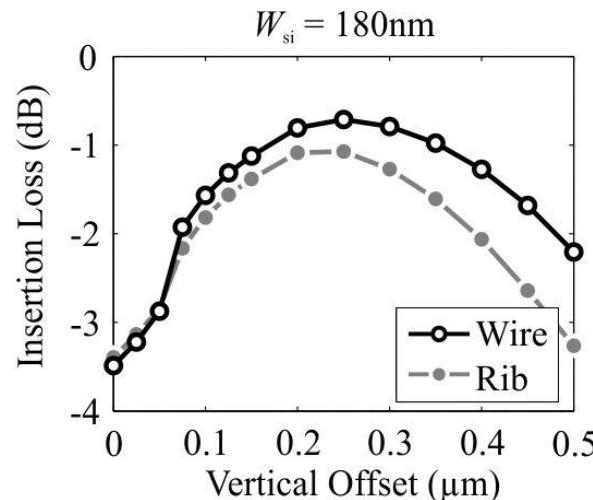
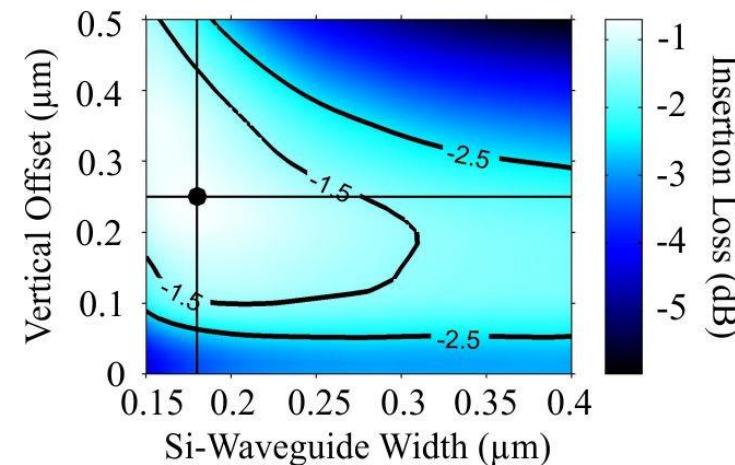
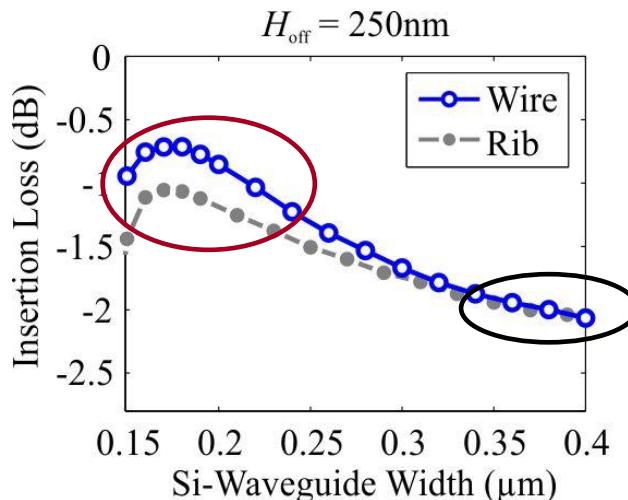
□ IL breakdown example: Optimum case (W_{Si} , H_{off}) = (170nm, 250nm)

- Coupling efficiency: **80 %**
- Reflection (fundamental mode): **4%**
- Transmitted radiation modes: ~ **16 %**
- Negligible power coupled to edge SPPs and reflected radiation modes

DLSPP to Si-wire waveguide transition

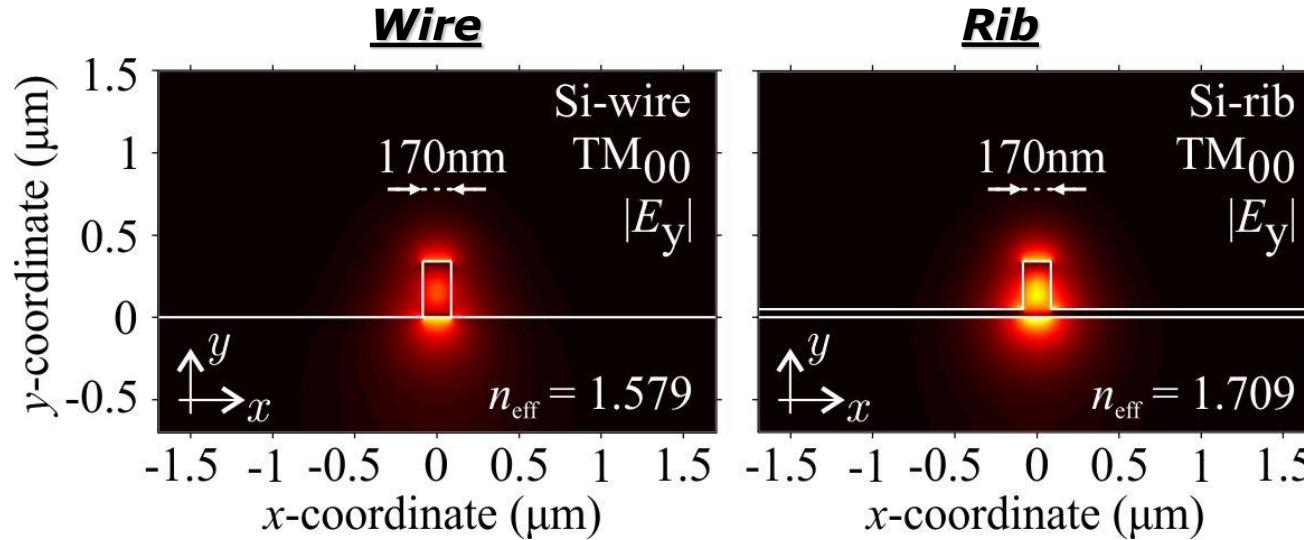
Results (3D-VFEM)

- **Optimum:** IL = -0.7 dB (180 nm, 250 nm)
- Contours indicate ample fabrication tolerances
- IL < -1.5 dB:
 - $150 \text{ nm} < W_{\text{Si}} < 280 \text{ nm}$
 - $100 \text{ nm} < H_{\text{off}} < 430 \text{ nm}$
- No-tapering penalty: 1.35 dB
- No-offset penalty: 2.8 dB
- Equivalent to rib for nominal width
- But for narrow SOI waveguides ...



DLSPP to Si-wire waveguide transition (cont'd)

- For small widths the TM₀₀ mode profile is quite different for wire/rib waveguides



Spatial matching with the DLSPP is better in the wire case.

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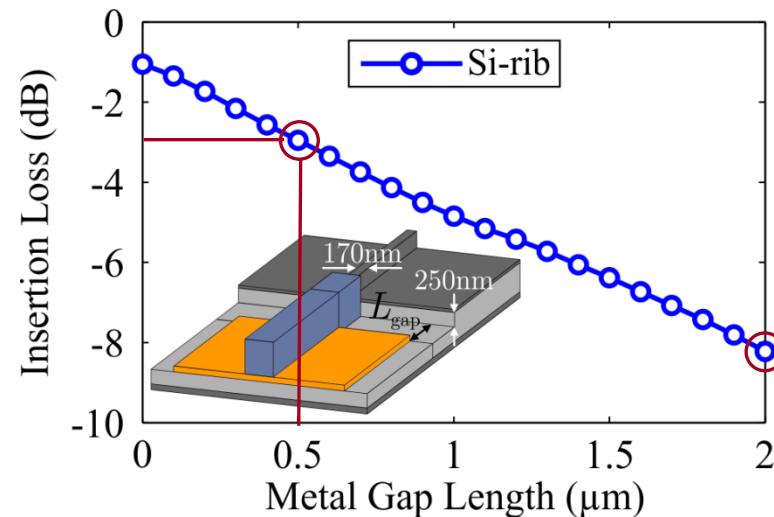
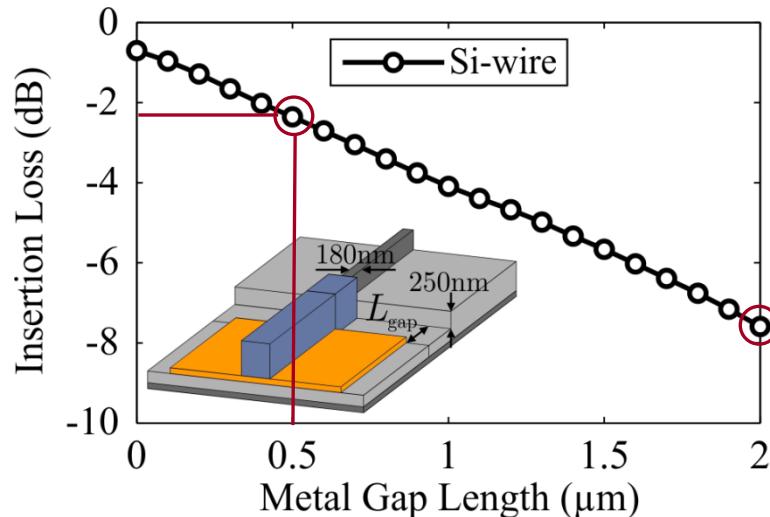
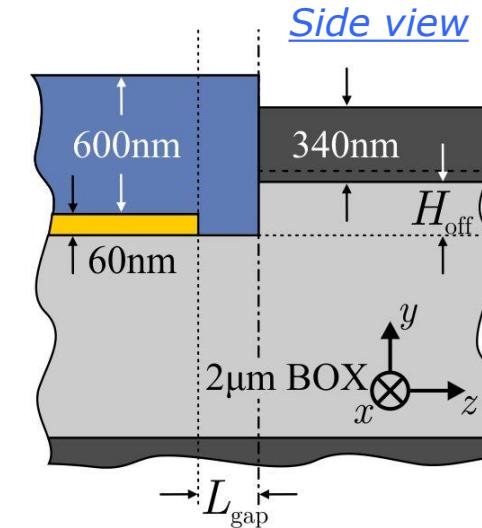
Longitudinal metallic stripe gap

Parameters

- Stripe stops a distance L_{gap} before interface
- Both rib and wire variants examined
- For optimum W_{Si} , H_{off} values

Results

- 0.5- μm gap → Rib: 2.95 dB // Wire: 2.35 dB
(2 // 1.5 dB IL penalty)
- 2- μm gap → IL > 8 dB
- 500x660 nm² polymer ridge → No guided mode!



Horizontal offset

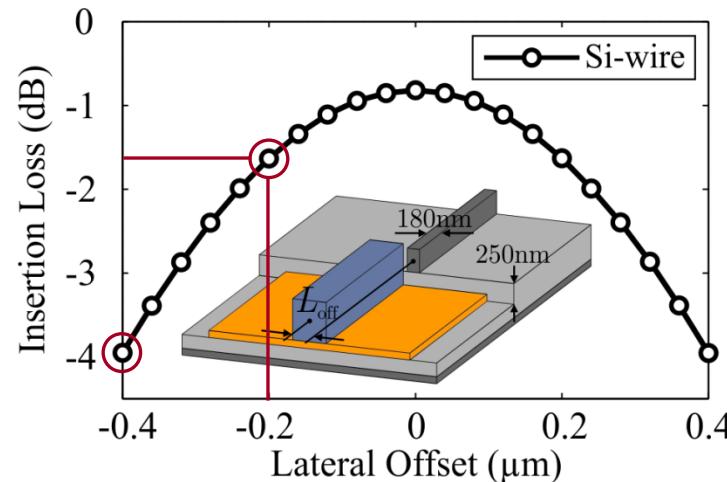
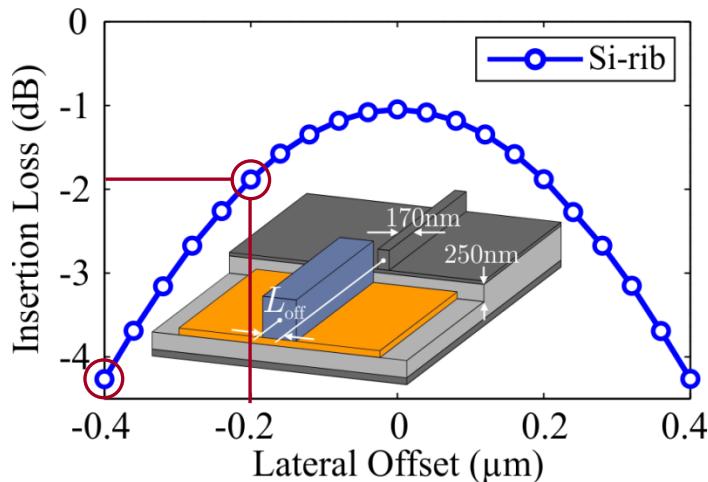
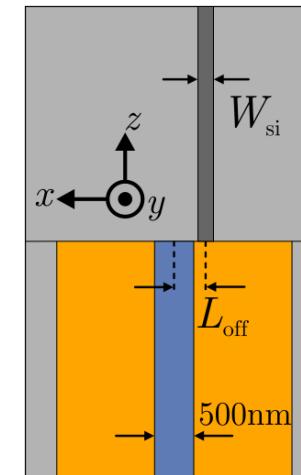
Parameters

- Horizontal offset L_{off} between guides
- Both rib and wire variants are examined
- For optimum W_{Si} , H_{off} values

Results

- Up to 50 nm → Negligible IL penalty
- 0.2- μm hor. offset → 1 dB penalty
- 0.4- μm hor. offset → 3 dB penalty

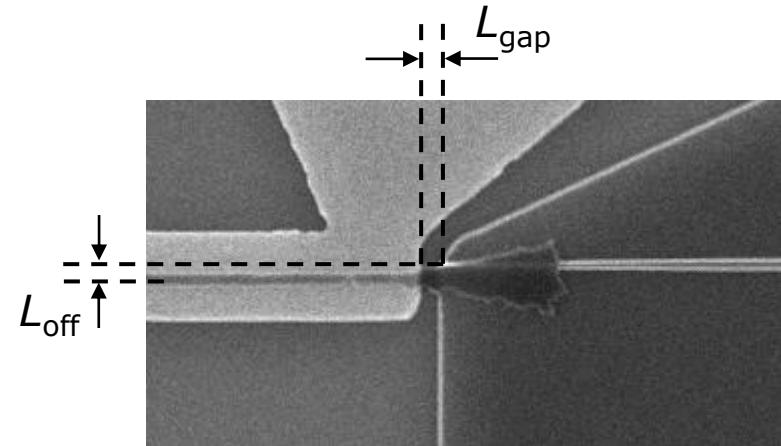
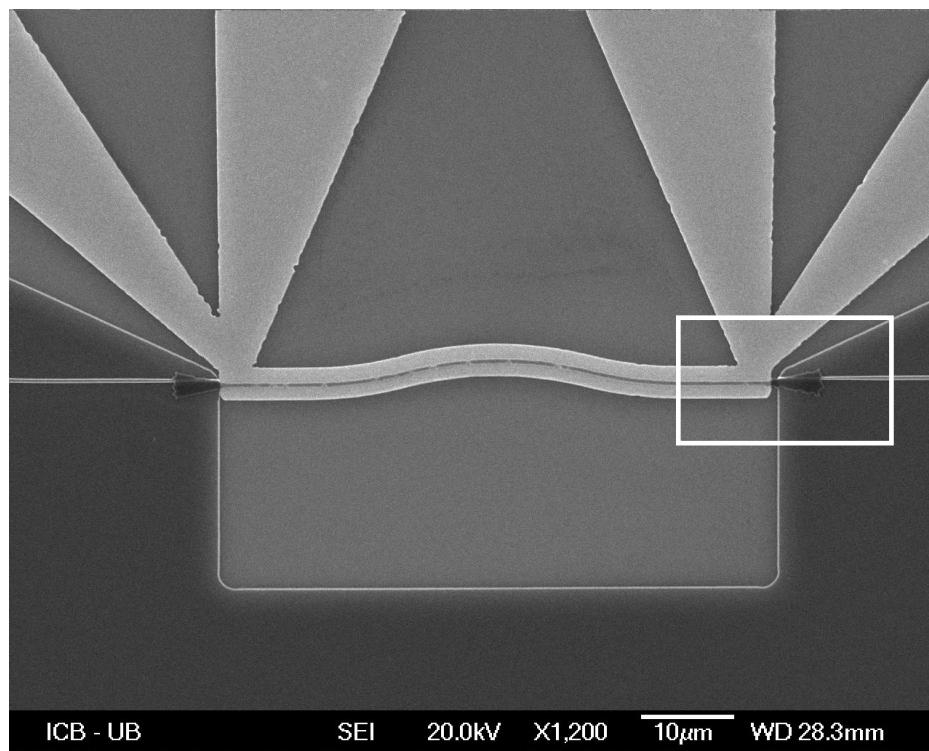
Top view



Experimental results

SEM image of bent DLSPP waveguide accessed with SOI WGs

- BOX cavity for providing vertical offset
- Contact pads for heating purposes

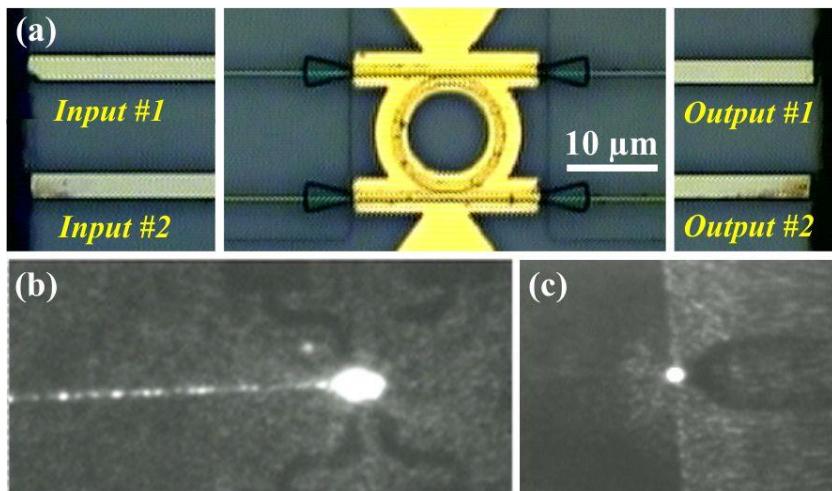


In certain transitions:

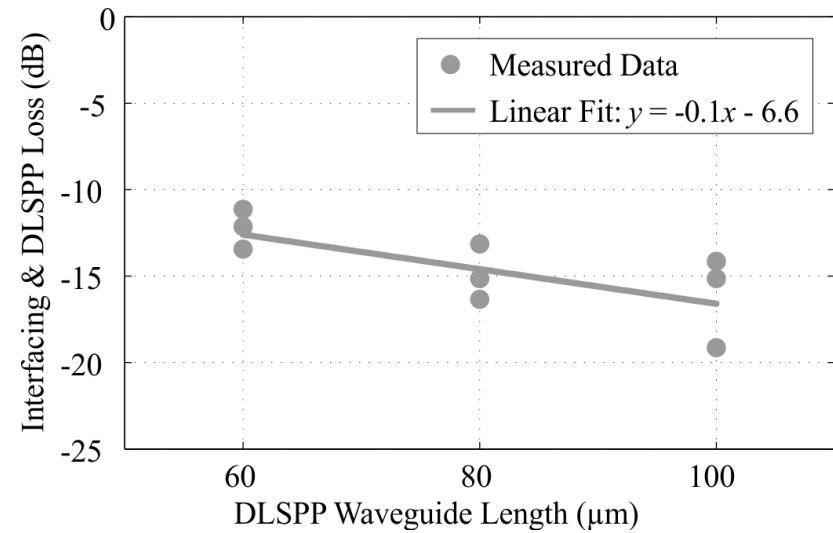
- Metallic stripe gap L_{gap}
- Horizontal offset L_{off}

Provided by K. Hassan, J.-C. Weeber, L. Markey, and A. Dereux:

Experimental results (cont'd)

Samples w/ Wire WGs

IL: 1.5 dB per interface

Samples w/ Rib WGs

IL: 2-4.5 dB per interface

O. Tsilipakos et al., IEEE J. Quantum Electron., 2012

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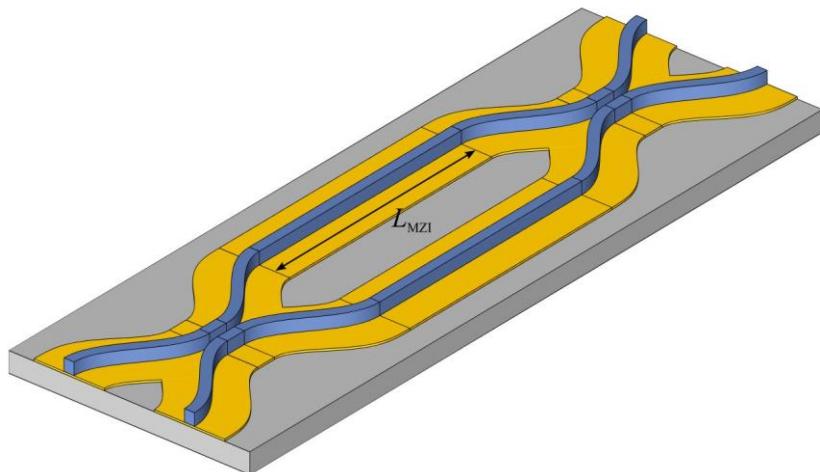
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□ Hybrid SOI-DLSPP Switches

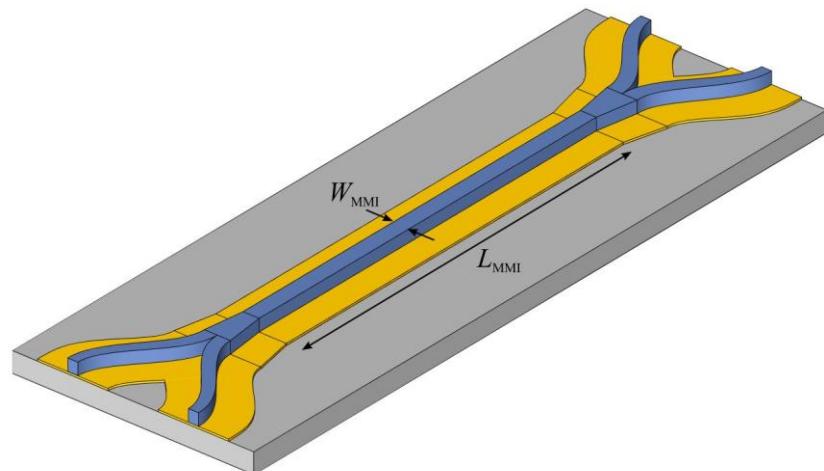
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All-DLSPP longitudinal 2x2 TO switches

Mach-Zehnder Interferometer



Multi-Mode Interference Switch



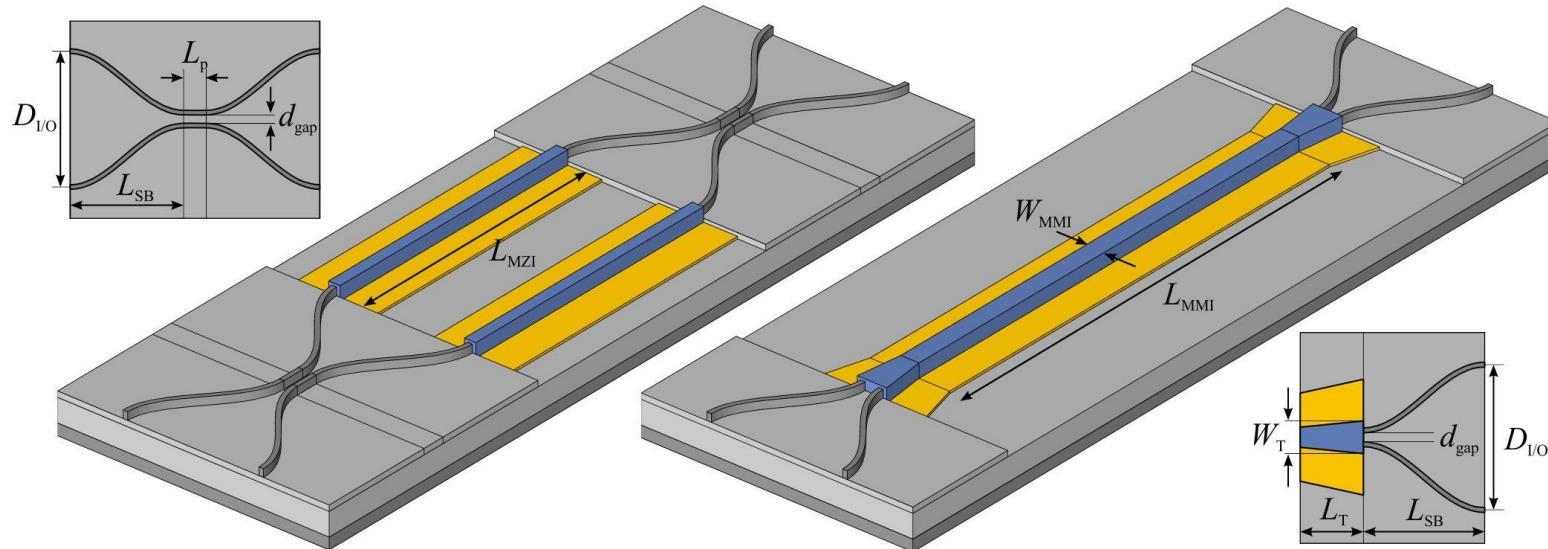
- Extinction Ratio: >30 dB
- Switching Time: $\sim 3 \mu\text{s}$
- Power Consumption: $\sim 10 \text{ mW}$
- Footprint: Hundreds μm^2
- Broadband Operation

A. Pitilakis *et al.*, *J. Lightw. Technol.*, 2011
D. Kalavrouziotis *et al.*, *IEEE Photon. Technol. Lett.*, 2012

But ... Increased Insertion Losses: $\sim 10 \text{ dB}$

Couplers / Y-junctions can be replaced by low-loss SOI counterparts!

Hybrid SOI-DLSPP 2x2 TO switches



- BOX cavity providing vertical offset
- S-bends with nominal or “interface” parameters
 - If nominal then tapering prior to interface
 - Smaller S-bend footprint
(SOI WG’s feature stronger confinement)

Hybrid MZI

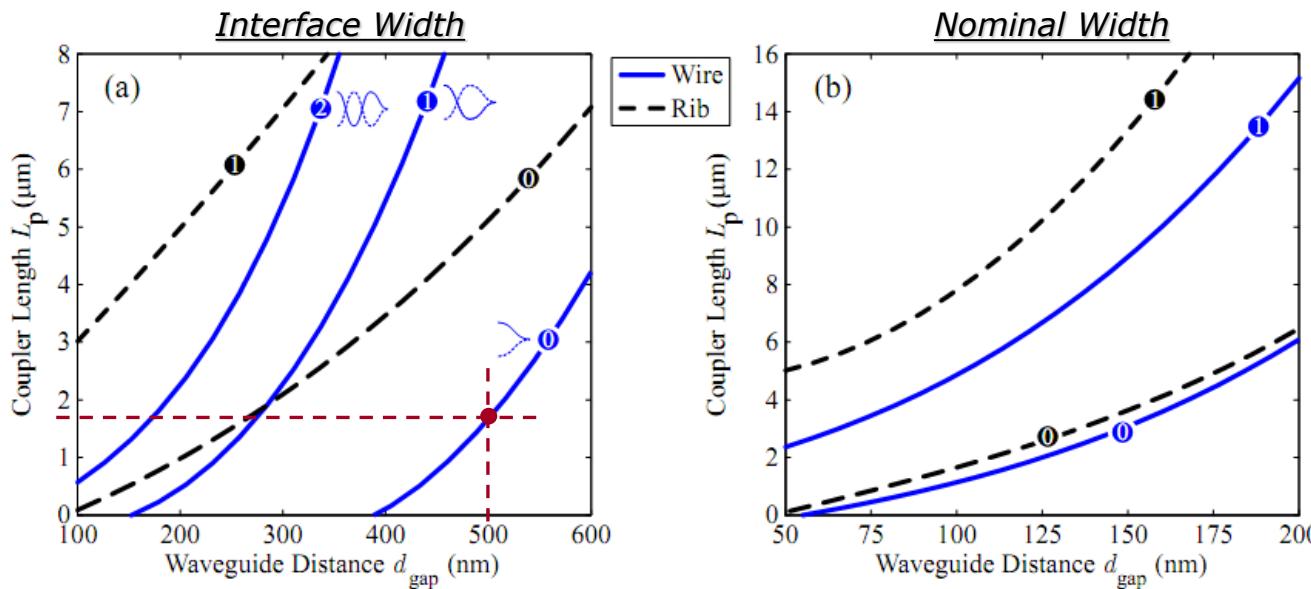
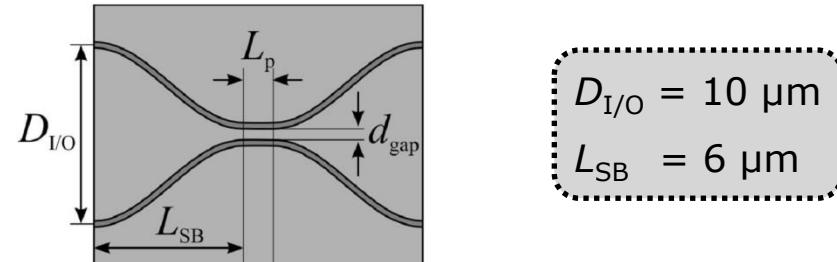
- **4.5-dB IL improvement:**
 - 6 dB loss for both 3-dB couplers
(2dB prop. & 1dB rad. per bend)
 - 1.5 dB aggregate interfacing loss (wire)

Asymmetric MZI w/ high-TOC ($3 \times 10^{-4} \text{ K}^{-1}$) polymer → IL of 3dB !
($L_{\text{MZI}} = 15 \mu\text{m}$ for $\Delta T = 100 \text{ K}$)

SOI coupler design

Design of 3-dB couplers (FE-BPM)

- Find L_p for given d_{gap} ($D_{\text{I/O}}$ & L_{SB} fixed)
- Both rib and wire variants
- Both nominal and “interface” WG widths
- For several coupling orders



- “Interface” widths → looser confinement → stronger coupling → smaller lengths needed
- The wire variant exhibits looser confinement than rib → smaller lengths needed

Design Example: Wire w/ “interface” width // $d_{\text{gap}} = 500 \text{ nm}$ // $L_p = 1.8 \mu\text{m}$

Conclusion

□ Efficient DLSPP-SOI Waveguide Interface

- IL = -1.05 dB for rib (W_{Si} , H_{off}) = (170 nm, 250 nm)
- IL = -0.70 dB for wire (W_{Si} , H_{off}) = (180 nm, 250 nm)

□ Coupling Loss Breakdown

- Transmitted radiation modes
- Reflection from interface (fundamental mode)
- “Edge” SPPs

□ Practical Considerations – Fabrication Tolerances

- 0.5-μm gap → 1.5/2 dB IL penalty for wire/rib
- 0.2-μm offset → 1 dB IL penalty

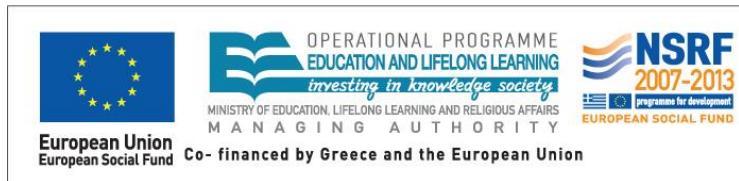
□ Hybrid SOI-DLSPP 2x2 TO Switching Elements

- 4.5-dB IL improvement for hybrid SOI-DLSPP MZI
- A-MZI w/ high-TOC polymer: Total IL = 3 dB !

Acknowledgements

Thank you!

*This work was supported in part by the European Union (European Social Fund — ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) — Research Funding Program: **Heracleitus II**. Investing in knowledge society through the European Social Fund.*



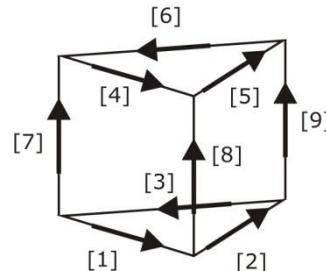
*This work was supported in part by the European FP7 ICT project **PLATON** [Contract No. 249135].
<http://www.ict-platon.eu>*



3D FEM implementation details

□ Triangular prism elements

- Curl-conforming basis functions
- > 20 prism layers



□ 1st order absorbing boundary conditions (ABCs) on all sides of the bounding box

$$\hat{\mathbf{n}} \times (\nabla \times \mathbf{E}) + jk\hat{\mathbf{n}} \times (\hat{\mathbf{n}} \times \mathbf{E}) = 0$$

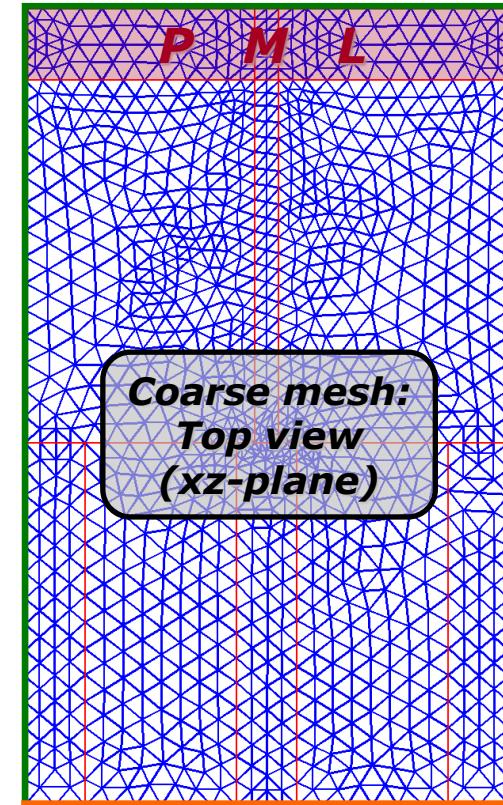
□ Modified input-port ABC

$$\hat{\mathbf{n}} \times \nabla \times \mathbf{E} + \bar{\gamma} \hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathbf{E} = 2\bar{\gamma} \hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathbf{E}^{\text{inc}}$$

$$\bar{\gamma} = \frac{j\omega\mu_0}{Z_w^{\text{TE}}(u, v)} \hat{\mathbf{u}}\hat{\mathbf{u}} + \frac{j\omega\mu_0}{Z_w^{\text{TM}}(u, v)} \hat{\mathbf{v}}\hat{\mathbf{v}}$$

Correct tensorial representation for hybrid modes

O. Tsilipakos *et al.*, *Microw. Opt. Technol. Lett.*, 2011



□ Perfectly matched layer (PML) for the reflectionless termination of output w/g.

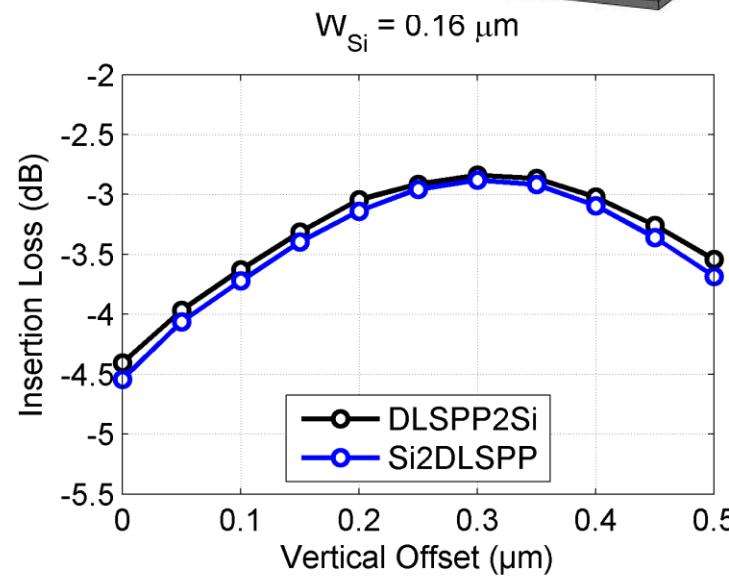
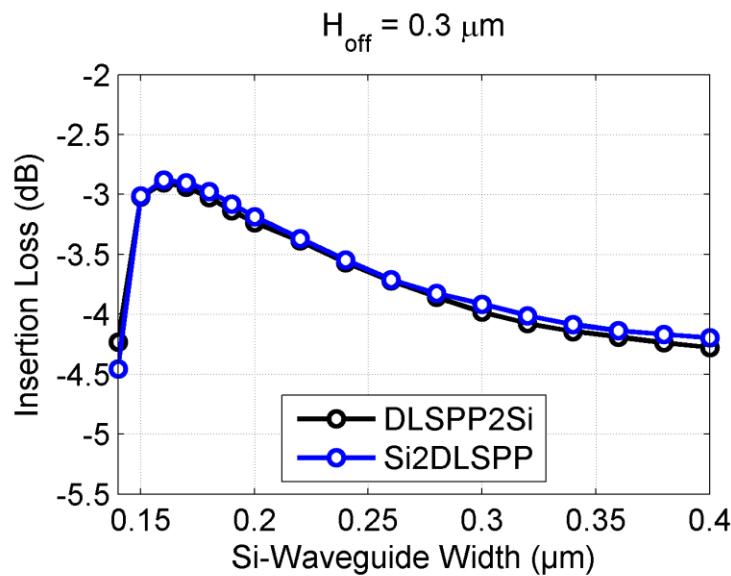
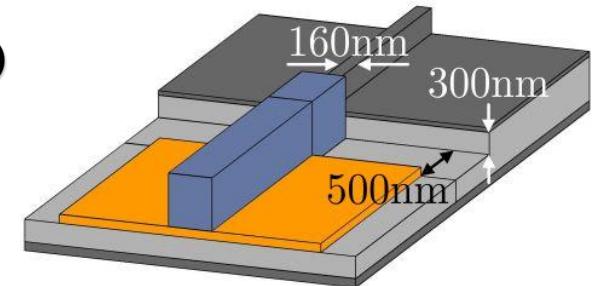
- ABC cannot properly absorb radiation modes excited at the interface
- Only locally employed. Global utilization would increase DoFs & degrade conditioning

Coupling efficiency reciprocity

DLSPP to Si-rib waveguide transition (0.5- μm -gap variant)

(Reciprocal WG junction problem)

- Optimum: $(W_{\text{Si}}, H_{\text{off}}) = (160 \text{ nm}, 300 \text{ nm})$
- Coupling efficiency between specific guided modes of the feed waveguides. Is it reciprocal?

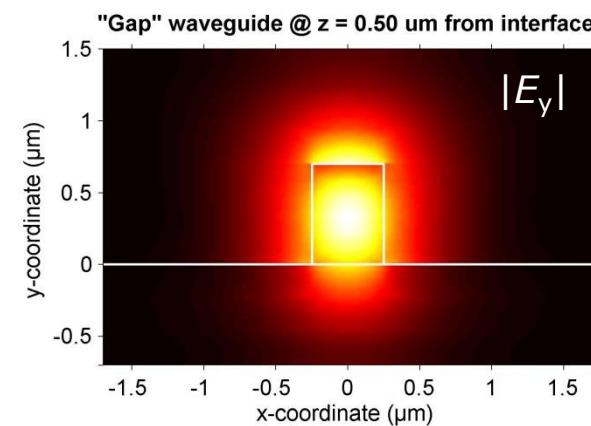
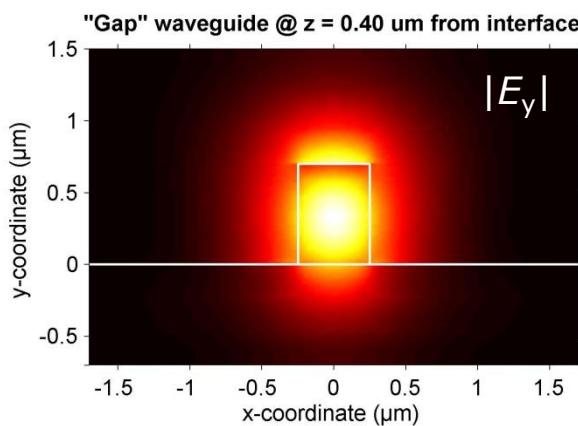
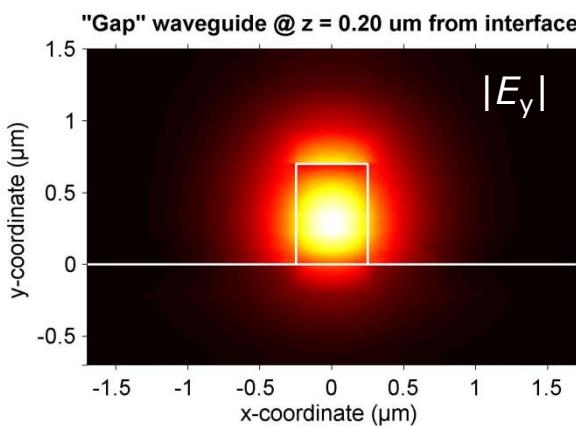
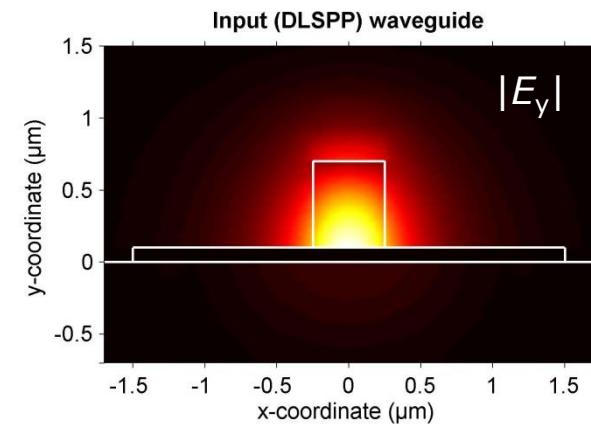


- Maximum discrepancy between prop. directions: 0.2-0.3 dB.
- Depends on discretization and computational domain dimensions
- Though not fully converged, coupling efficiency seems reciprocal despite of radiation modes!

G.-I. Kweon *et al.*, J. Lightw. Technol., 1999

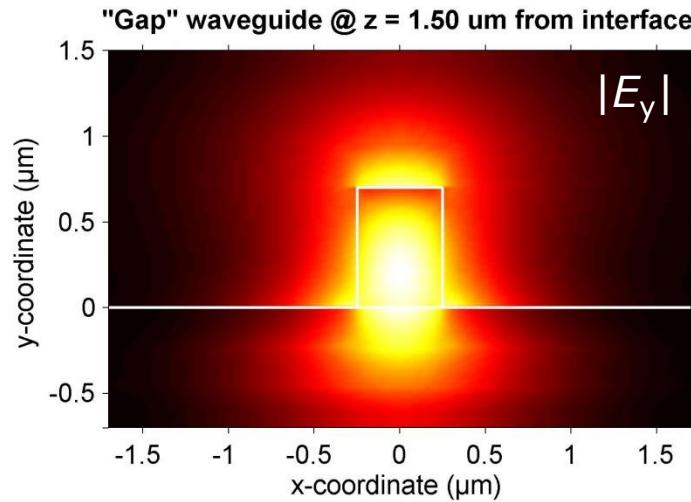
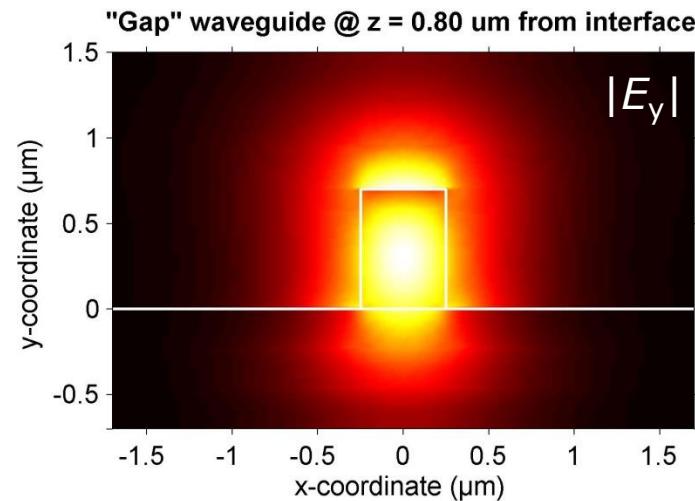
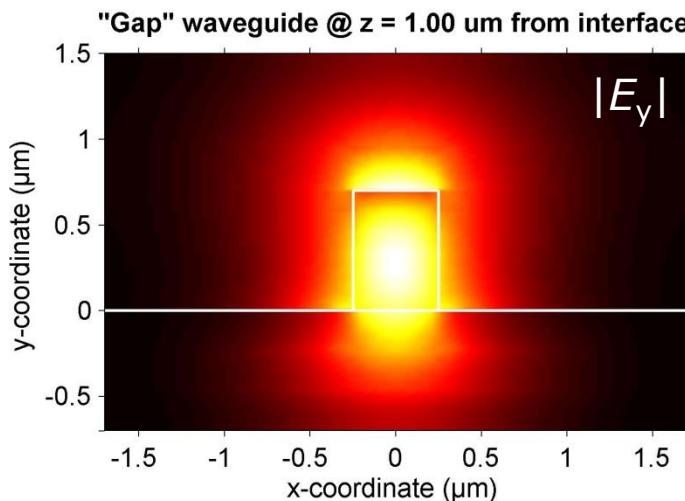
Mode evolution along gap

- ❑ "Gap" waveguide: 500x660 nm² polymer ridge on SiO₂ substrate → No guided mode!
- ❑ First 500 nm: Mode is gradually lifted from bottom of ridge (no metallic stripe present) and occupies its center.
- ❑ Field components spread in both lateral dimensions since no guided mode is supported.



Mode evolution along gap (cont'd)

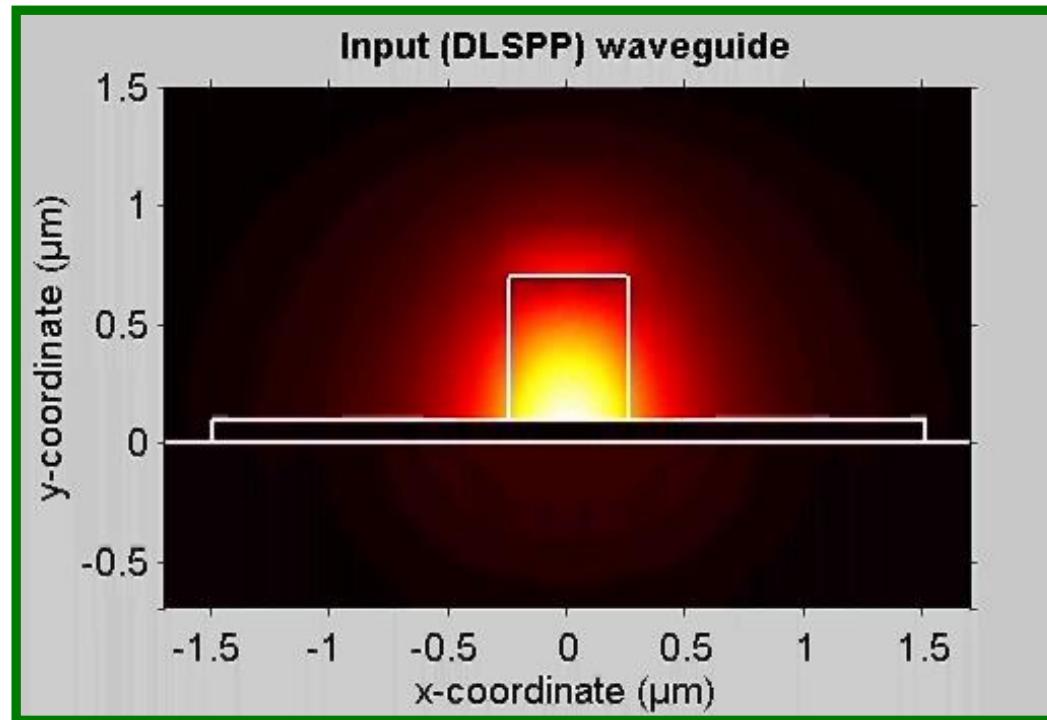
- ❑ After first 500 nm: Strong diffraction (spreading) of field components
- ❑ At 1 μm from interface: Fields extend more than 2 microns in both lateral dimensions.
- ❑ This behavior explains the large ILs associated with long gaps



Mode evolution along gap (cont'd)

❑ Video of E_y evolution (up to 1.5 μm into the “gap” w/g)

- Colormap re-normalized @ each frame – Note position of mode peak
- “Breathing” in input w/g due to reflection (met. stripe discontinuity)



Mode evolution along gap (cont'd)

❑ Video of E_y evolution (up to 1.5 μm into the “gap” w/g)

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