Towards Chip-scale Plasmonic Interconnect

Hassan Wassel[*], Mohit Tiwari[*], Jonathan Valamehr[+], Luke Theogarajan[+], Jennifer Dionne[^], Frederic Chong[*] and Timothy Sherwood[*]
[*]Computer Science @ UC Santa Barbara
[+]Electrical and Computer Engineering @ UC Santa Barbara
[^]Materials Science and Engineering @ Stanford

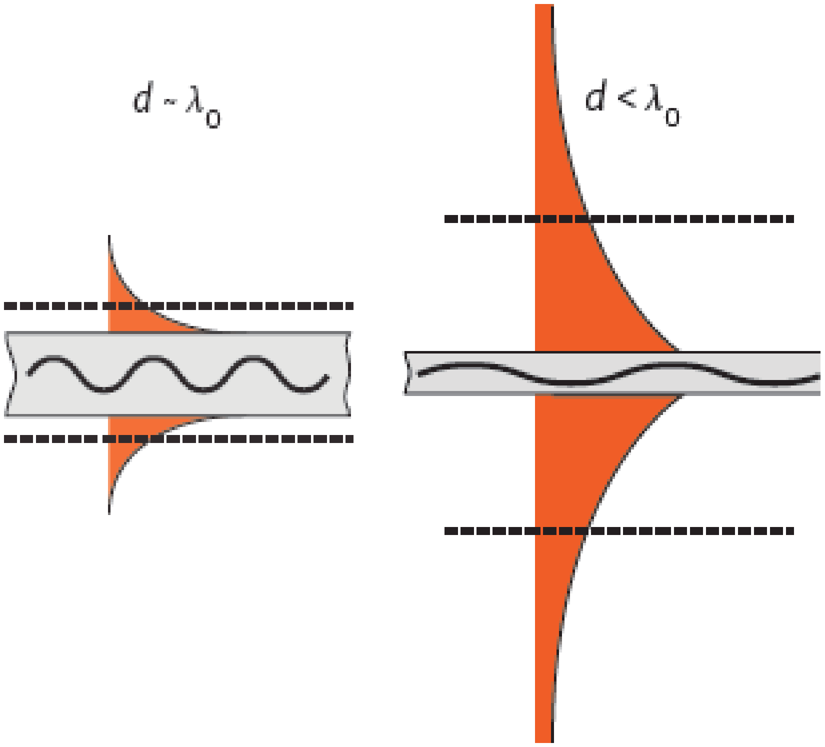
Why Plasmonics?

- Photonics is able to provide
  - ✓High bandwidth via WDM
  - ✓Low latency (no latching or buffering)
  - ✓Distance-independent energy consumption

- However,
  - ✗ Photonic component sizes are limited by the diffraction limit.

Diffraction limit

- Light cannot be confined in spaces less than $\lambda_0/2n$ where λ_0 is the free-space wavelength and n is the refractive index of the material.
- Micrometer sized components lead to high capacitances which limits bandwidth and increases latency and power consumption (best known is 50 fJ/bit)[2]

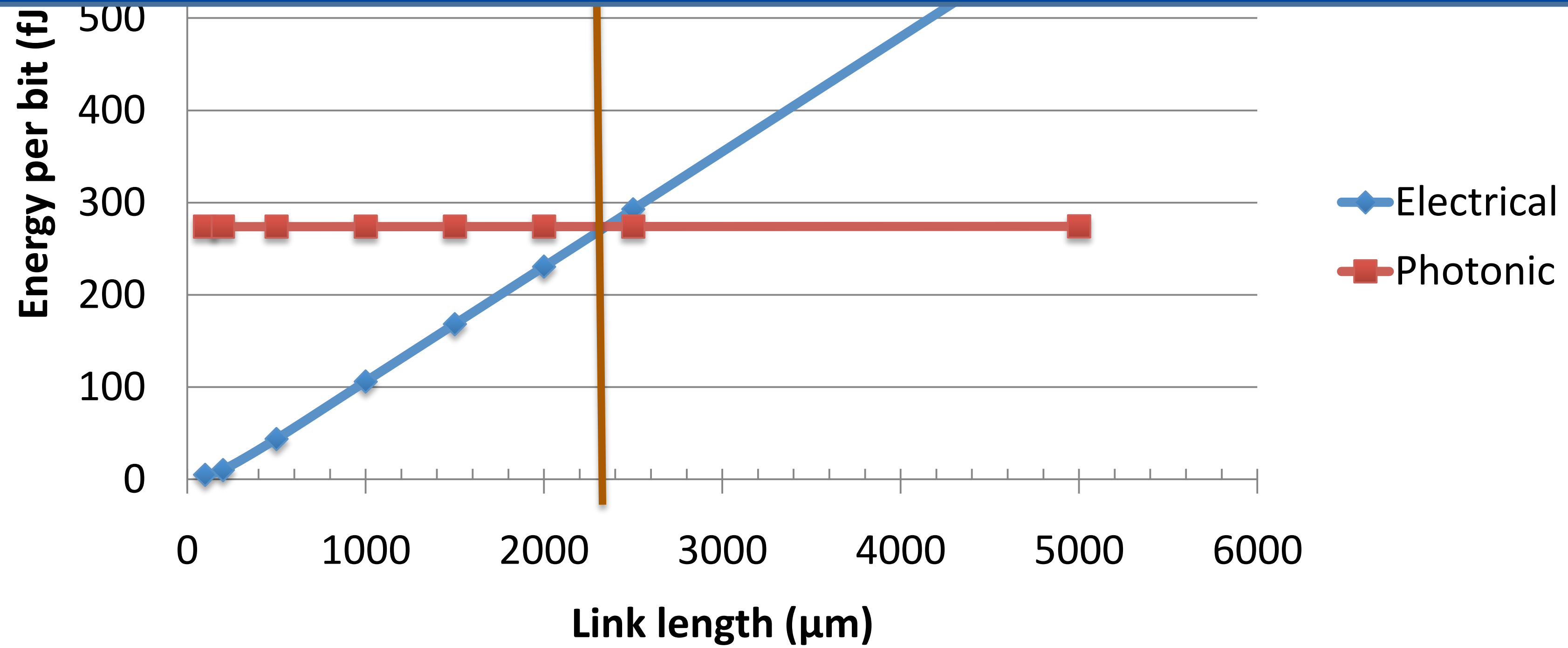


Images are taken from [1].

[1] Gramotnev et al, "Plasmonics beyond the diffraction limit," *Nature Photonics*, vol. 4, Jan 2010.
[2] Reed et al, "Silicon optical modulators," *Nature Photonics*, vol. 4, Jul. 2010.

Length vs. Energy Per Bit

Can plasmonics reduce the minimum distance at which photonic links are energy efficient?



Electrical results are obtained using Orion 2.0 for 32 nm (LVT)@ 3 GHz with V_{dd} = 1 V.

Photonic link is modeled using electrical components parameters from Batten et al [HOTI 2008] and ring modulators [Kirman et al, ASPLOS 2010]

Outline

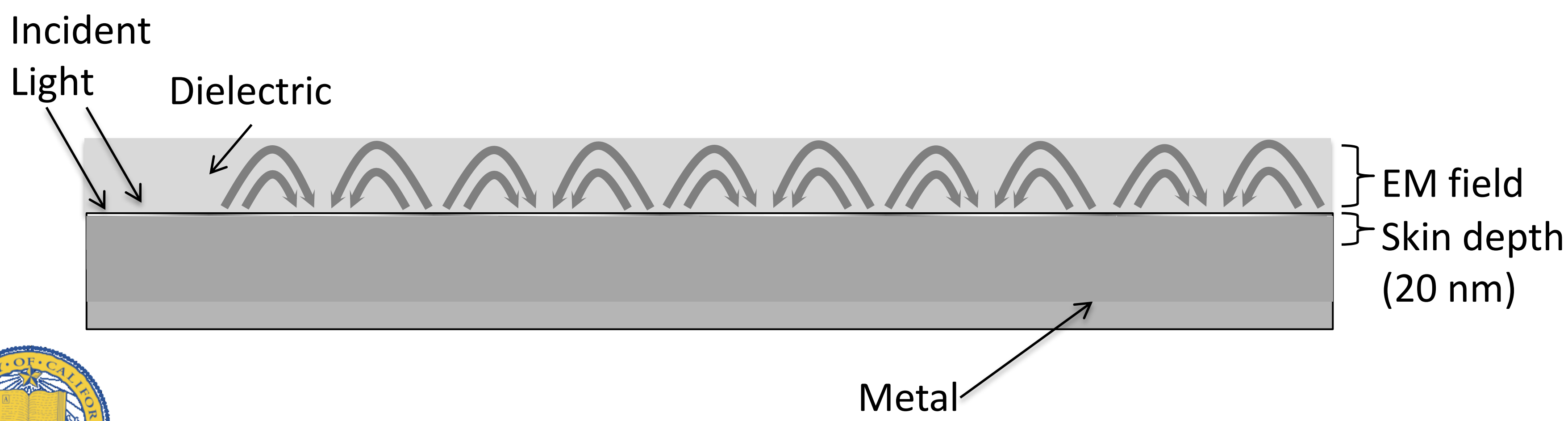
- Motivation
- Plasmonics
  - Surface Plasmon Polaritons
  - Sources
  - Waveguides
  - Modulators
  - Detectors
  - CMOS Compatibility
- Power Models & Results
- Conclusions

Surface Plasmon Polaritons

Surface plasmon polaritons (SPP) are electromagnetic waves that are coupled to free electron collective oscillations in a metal.

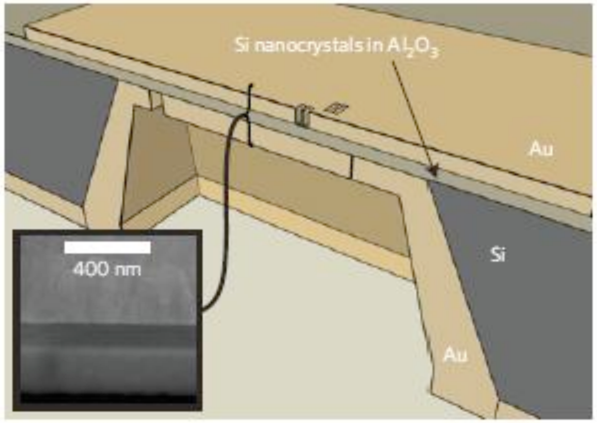
✔ Maintains the frequency of photonics at much shorter wavelength

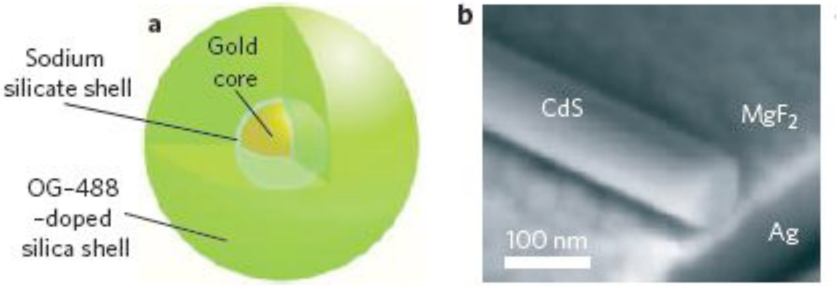
✗ Ohmic losses limit the propagation distances



SPP Source

- Electrical excitation
  - Not mature (16 mW for few μm propagation) [1]
- Optical Excitation
  - On-chip
    - Nanolaser has been demonstrated [2]
  - Off-chip laser source
    - CW laser is coupled to plasmonics with coupling losses of 1.1 dB per transition.



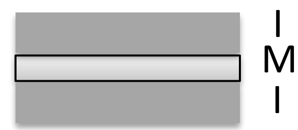


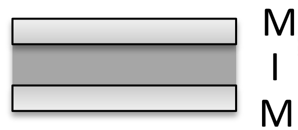
[1] Walters et. al, A silicon-based electrical source of surface plasmon polaritons. Nature Materials, 9(1):21–25, December 2009.

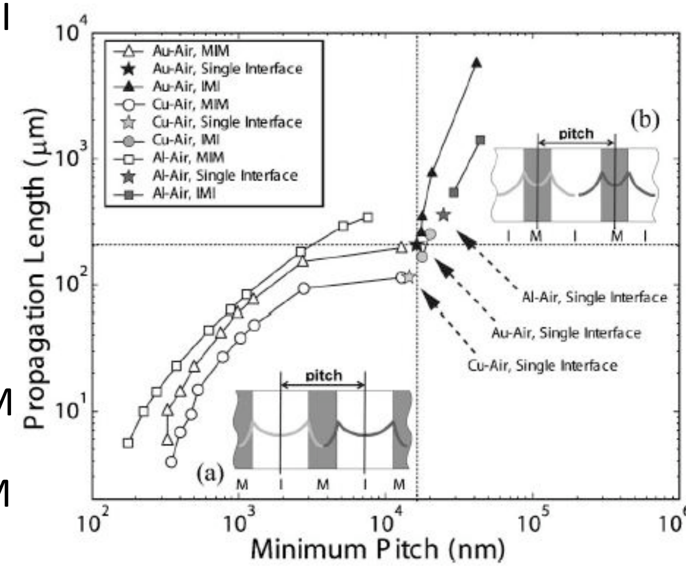
[2] M.T. Hill, "Nanophotonics: lasers go beyond diffraction limit.," *Nature nanotechnology*, vol. 4, Nov. 2009.

Plasmonic Waveguides

- Insulator-metal-insulator (IMI or LR-SPP)
  - Few cm range with similar confinement to photonic waveguides [1]
- Metal-insulator-metal (MIM or MDM)
  - For example, 80 μm range is achieved when the core thickness of silver/silica/silver waveguide is 250 nm.[2]





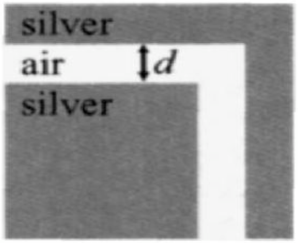


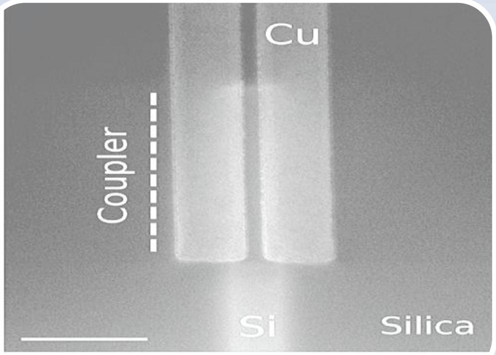
From [1]

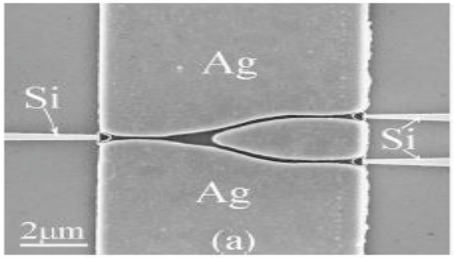
[1] Zia, et al, "Geometries and materials for subwavelength surface plasmon modes," J. Opt. Soc. Am. A 21, 2442-2446 (2004).

[2] Dionne et al, Plasmon slot waveguides: Towards chip-scale propagation with subwavelength-scale localization, Physical Review B, vol. 73, 2006.

Passive Devices







Bends are loss-free in MDM plasmonic waveguides [1]

High efficiency coupling from and two photonic waveguides

(1.1 dB per transition [2])

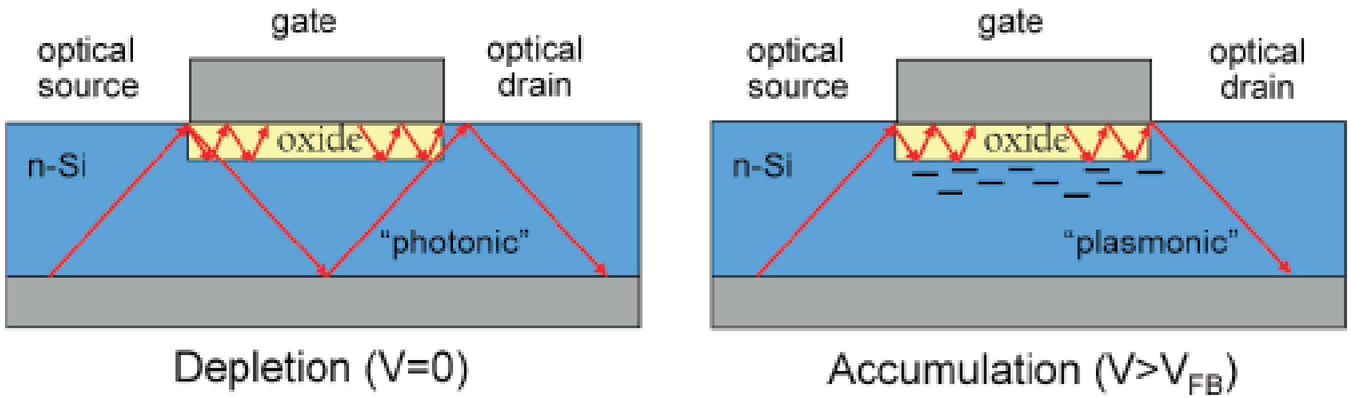
T-splitter and Y-Splitters has been proposed [50% loss].

[1] Veronis et al, "Bends and splitters in metal-dielectric-metal subwavelength plasmonic waveguides," *Applied Physics Letters*, vol. 87, 2005.

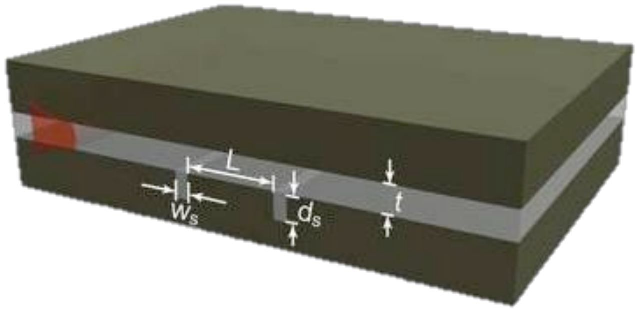
[2] Delacour et al, Efficient Directional Coupling between Silicon and Copper Plasmonic Nanoslot Waveguides: toward Metal−Oxide−Silicon Nanophotonics, *Nano Letters* 2010 *10* (8)

Plasmonic Modulators

- PlasMOStor [1]



- Compact Modulator[2]



[1] Dionne et al, PlasMOStor: a metal-oxide-Si field effect plasmonic modulator., Nano letters, vol. 9, Feb. 2009.
[2] Cai et al., "Compact, high-speed and power-efficient electrooptic plasmonic modulators.," *Nano letters*, vol. 9, Dec. 2009.

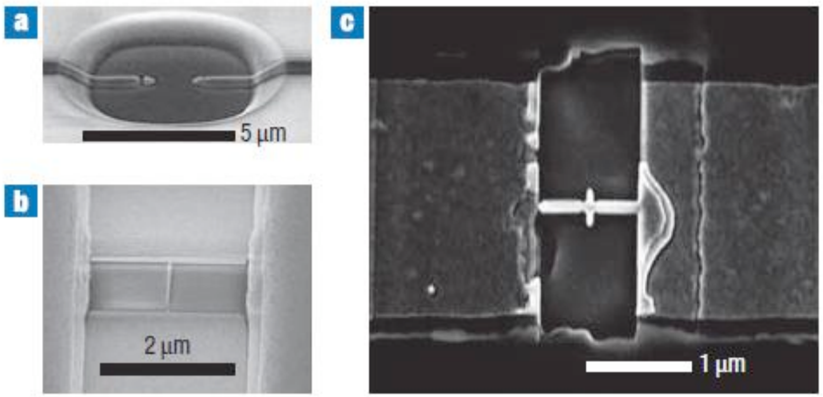
Plasmonic Modulators

Modulator	Photonic Ring Modulator [3]	PlasMOStor [1]	Compact Modulator [2]
Energy per bit (fJ)	50	6.8	1
Insertion loss (dB)	3	1.1	3
Modulation depth (dB)	12	>10	>3
Length X Width (μm X μm)	1000	2x2	1x0.5
Frequency (GHz)	11	> 40	> 100
Capacitance (fF)	50	14	1
Swing voltage (V)	2	0.7	1

[1] Dionne et al, PlasMOStor: a metal-oxide-Si field effect plasmonic modulator., Nano letters, vol. 9, Feb. 2009.
[2] Cai et al., "Compact, high-speed and power-efficient electrooptic plasmonic modulators.," *Nano letters*, vol. 9, Dec. 2009.
[3] Dong et al. "Low Vpp, ultralow-energy, compact, high-speed silicon electro-optic modulator," Opt. Express 17(2009).

Detectors

- SPP can be detected using photo-detectors.
- Plasmonics has been used to enhance the efficiency of photo-detector [1]
- Plasmonics is being proposed to develop phototransistors, leading to removal of the TIA.

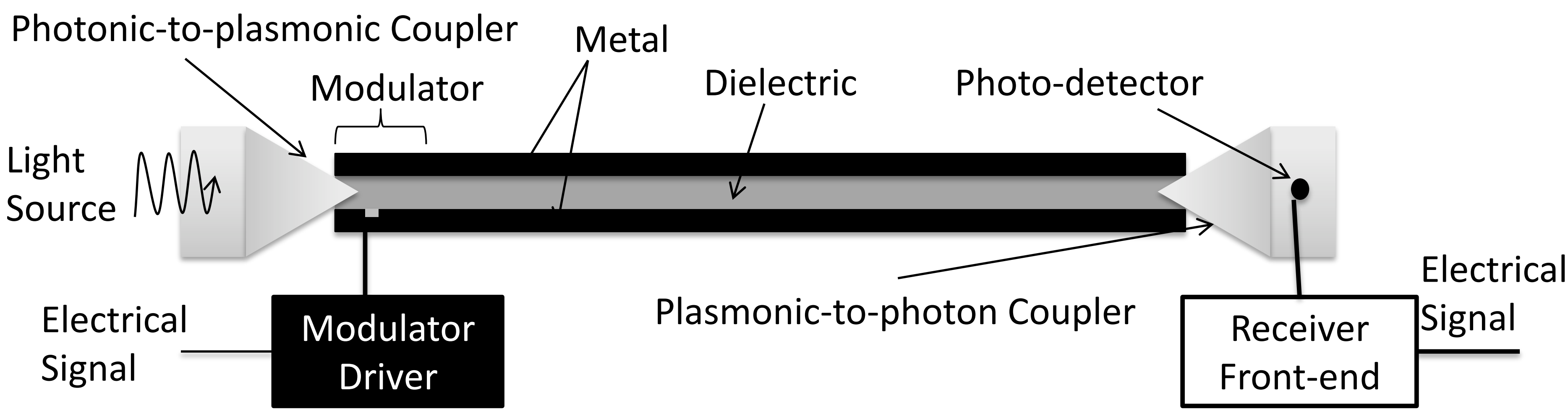


[1] Tang et al. "Nanometre-scale germanium photodetector enhanced by a near-infrared dipole antenna," *Nature Photonics*, vol. 2, Mar. 2008.

CMOS Compatibility

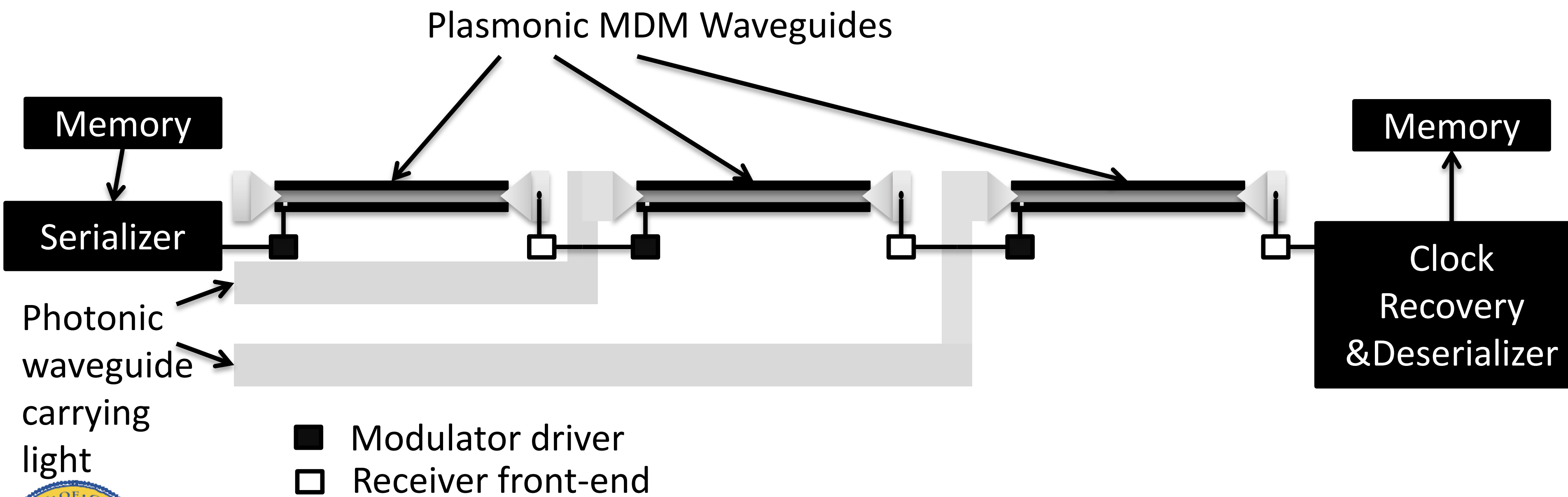
- Best plasmonic matels are gold and silver. However, aluminum and copper are also good plasmonic materials.
- The dielectric can be silicon, silicon oxide, silicon nitride or air.

Plasmonic Link

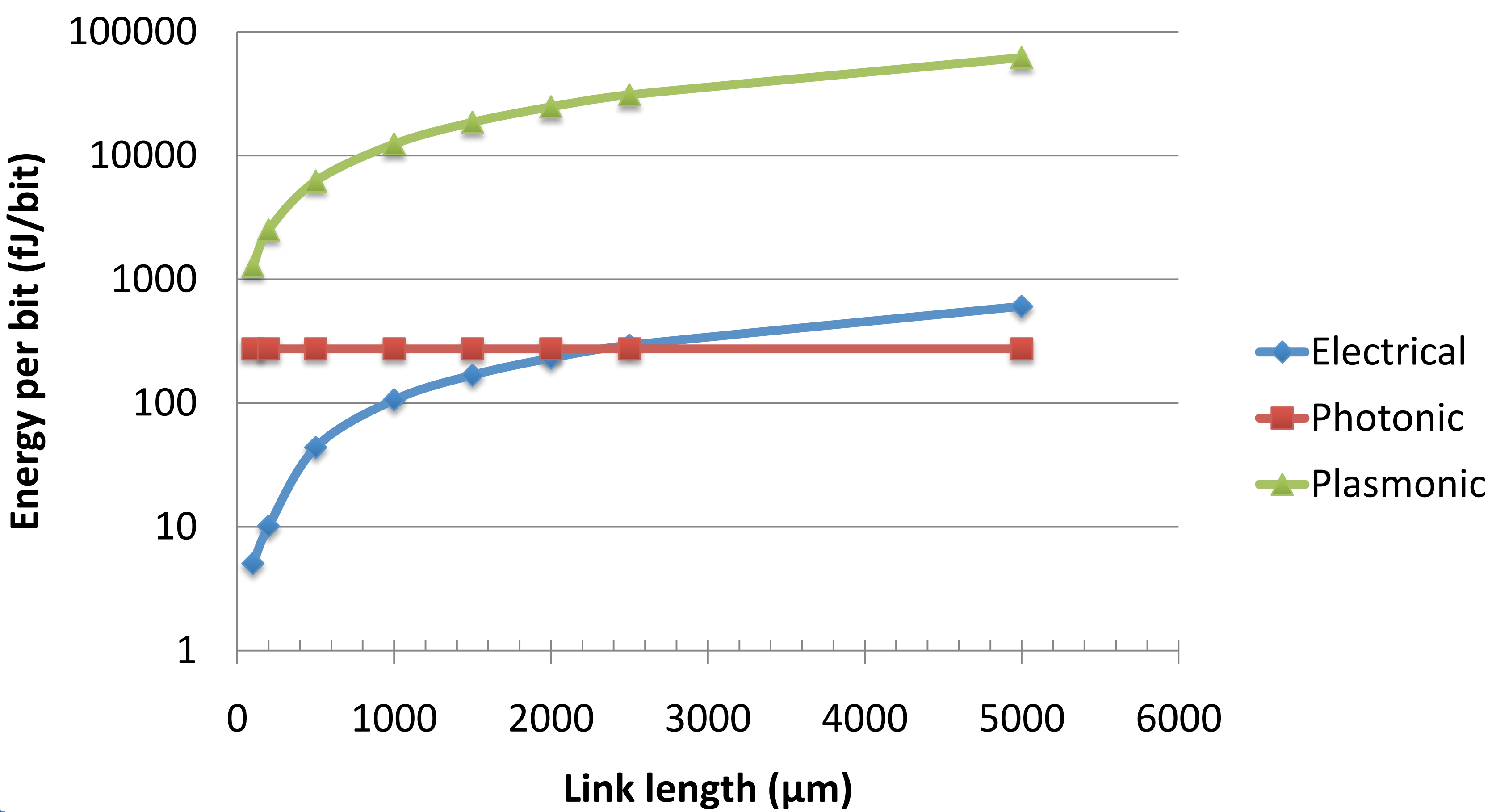


Plasmonic Link Power Model

- Static power = Segments * f(coupler loss, propagation loss, modulator insertion loss)
- Dynamic power = Segments * activity factor* EPB * Bandwidth
- Coupler loss = 1.1 dB/ transition
- Propagation loss = 0.2 dB/μm



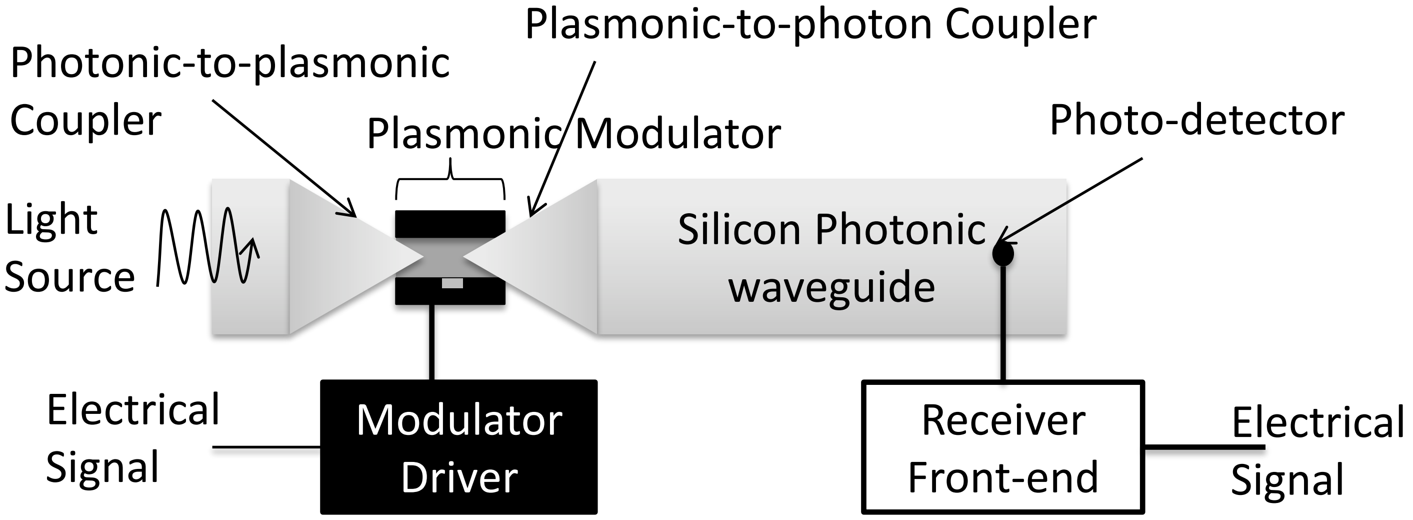
Results



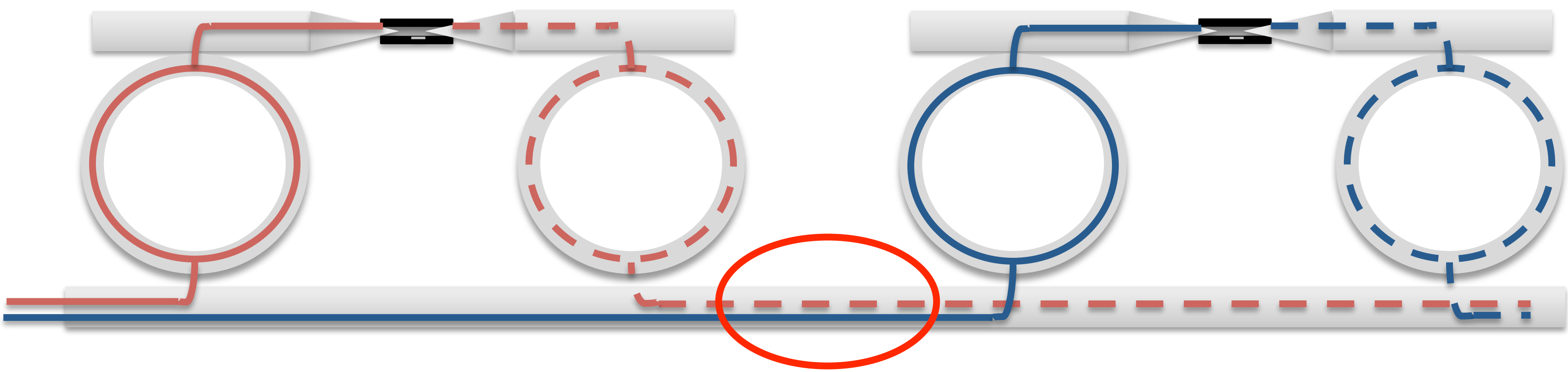
Energy per bit (fJ/bit)
100000
10000
1000
100
10
1
0
1000
2000
3000
4000
5000
6000
Link length (µm)
Electrical
Photonic
Plasmonic

Hybrid Link Power Model

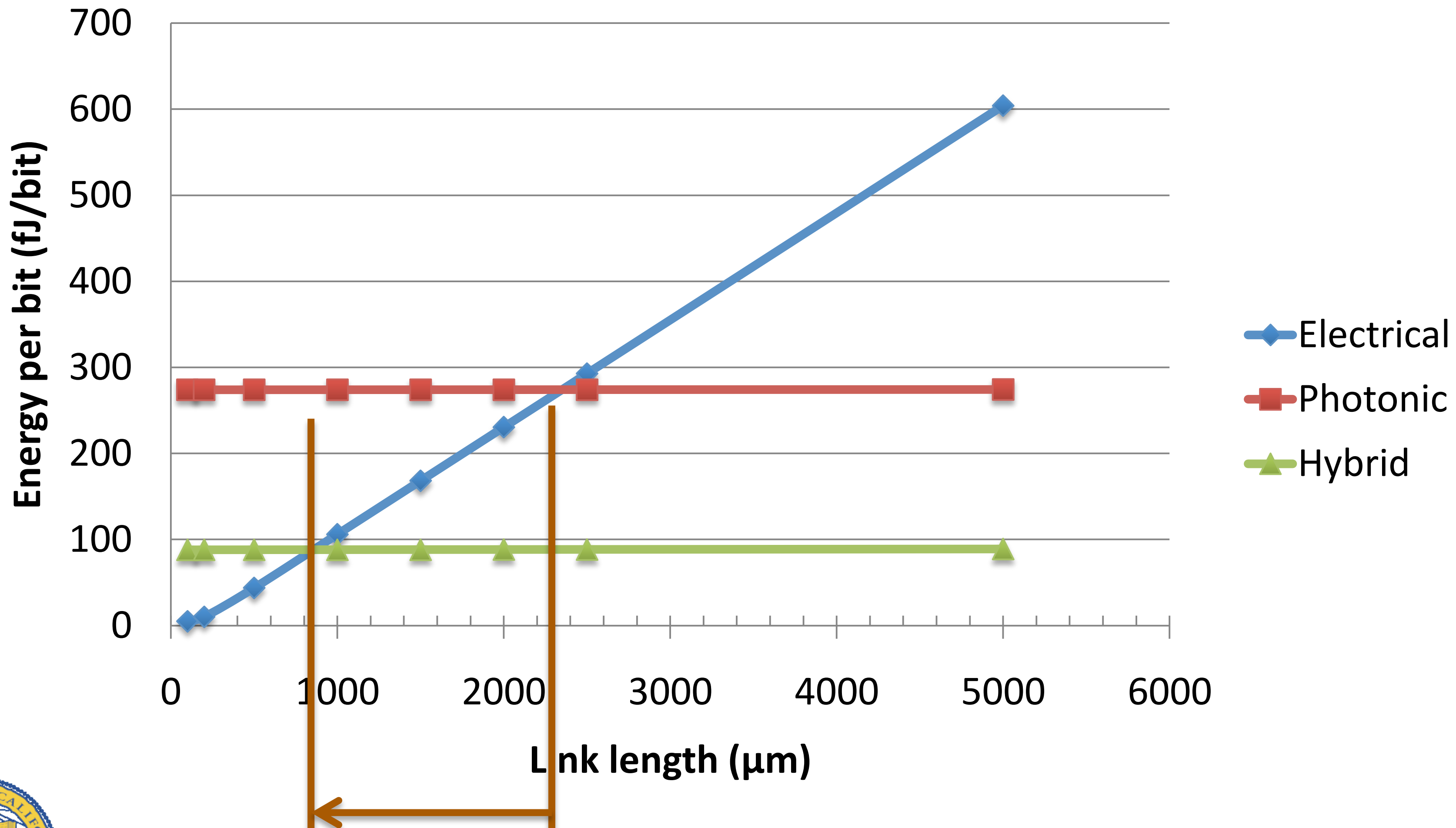
- Static power = f(coupler loss, propagation loss, modulator insertion loss)
- Dynamic power = activity factor * EPB * Bandwidth
- Coupler loss = 1.1 dB/ transition
- Propagation loss = 0.1 dB/mm



WDM Hybrid Link



Results



Energy per bit (fJ/bit)
700
600
500
400
300
200
100
0
0
1000
2000
3000
4000
5000
6000
Link length (µm)
Electrical
Photonic
Hybrid

Conclusions

- Plasmonics cannot be used for wave guiding.
- Plasmonics can improve the viability of on-chip photonics, via energy efficient detectors and modulators.
- It provides a potential of reducing the minimum distance at which photonics is more energy efficient than electrical signaling.

Thank you!