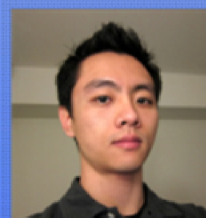
Jincy Jose
OPTIS North America, USA

Peter B. Catrysse
Stanford University, USA

Pablo Aitor Postigo
Consejo Sup Inverstigaciones Cientificas, Spain

Nadir Dagli
University of California, Santa Barbara, USA

Lin Zhang
Tianjin University, China



Jung Soo Park
Aurrion Inc., USA

Cheng Zhang
University Of Michigan, USA

Sachin Kumar Srivastava
Nanyang Technological University, Singapore

OSA Nanophotonics Technical Group

Welcomes
You!

What we do?

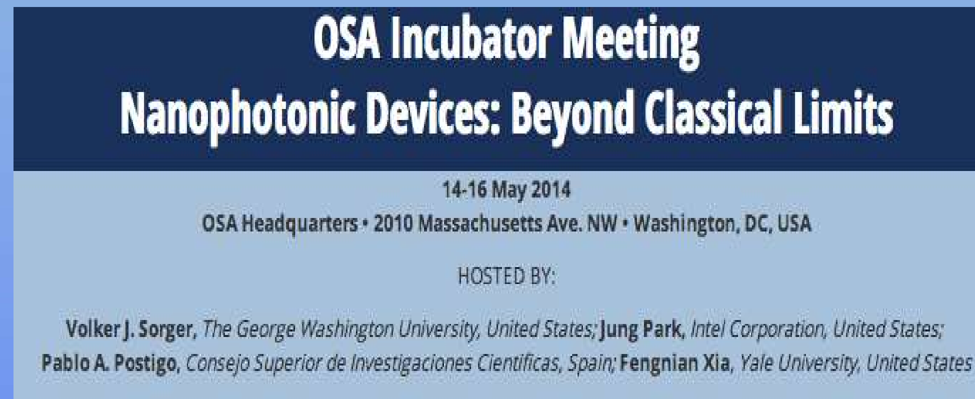
- Organize Incubators

- Webinars

  (Quarterly, Featuring prominent speakers)

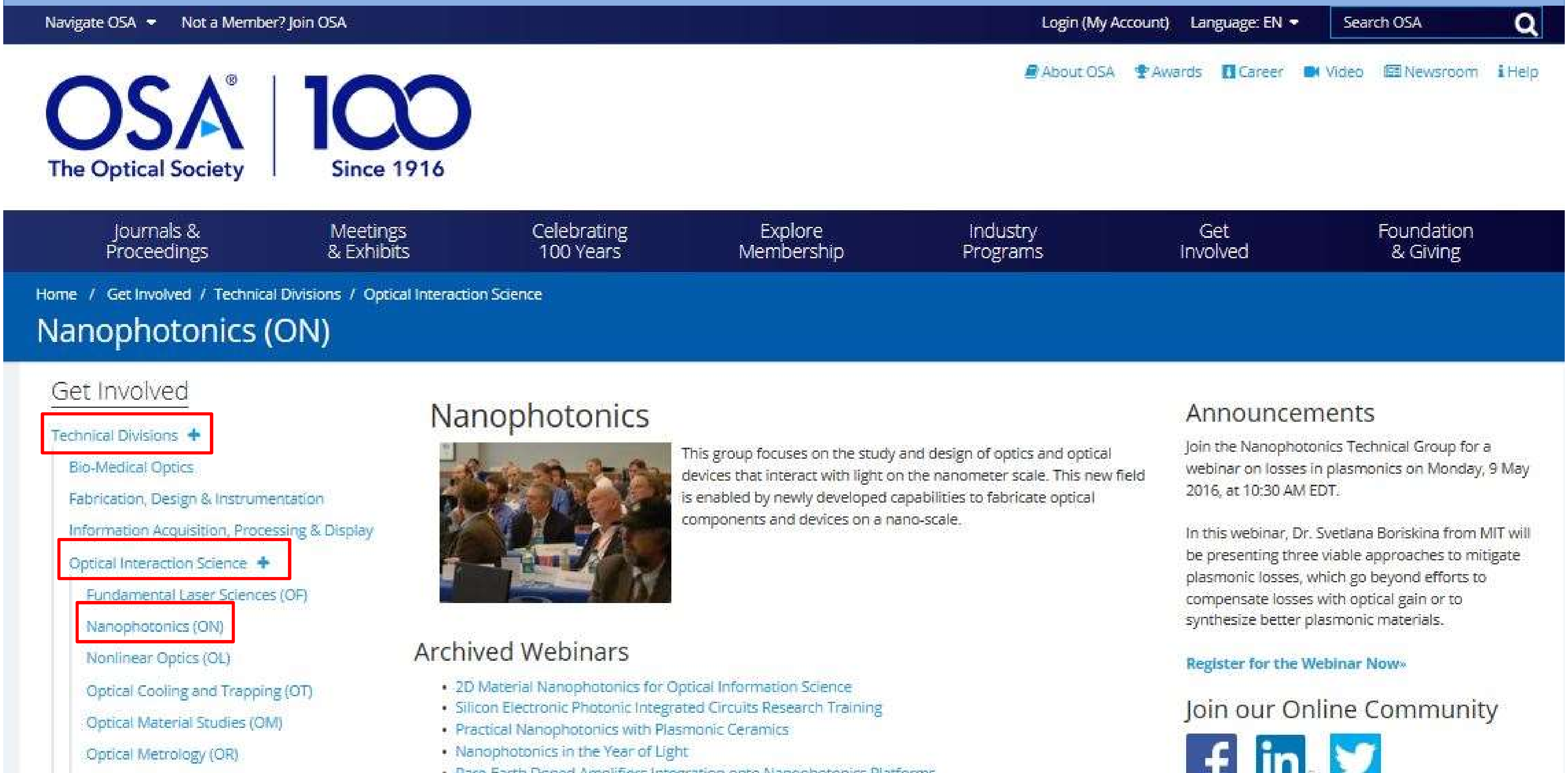
- Special Activities

  (@Conferences: Poster Sessions, Dine & Discover, Blogging)



Poster session at CLEO in San Jose (2016)

Where to find us?



http://www.osa.org/en-us/get_involved/technical_communities/ois/nanophotonics_(on)_(1)/

Creating a Community

- Do you like to blog?
- Organize an event?
- Interact with colleagues?

@Nano_OSA

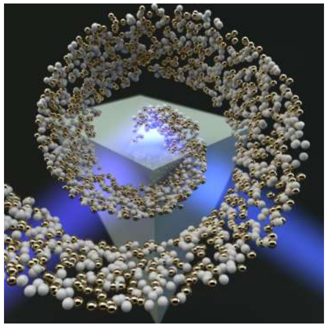
facebook.com/nanophotonicsosa

The Optical Society

osa.org/communities

Surprises from Nanophotonics

PHOTONIC SKIN-DEPTH ENGINEERING FOR SUB-DIFFRACTION CONFINEMENT



UNIVERSAL SPIN-MOMENTUM LOCKING OF LIGHT

Zubin Jacob

Purdue University, U.S.A.

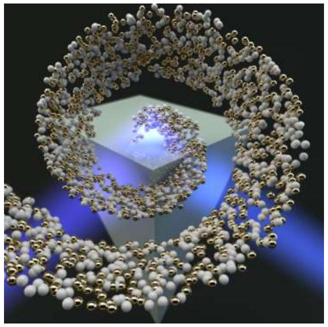
University of Alberta, Canada

Twitter: @zjresearchgroup

www.zjresearchgroup.org

Surprises from Nanophotonics

PHOTONIC SKIN-DEPTH ENGINEERING FOR SUB-DIFFRACTION CONFINEMENT



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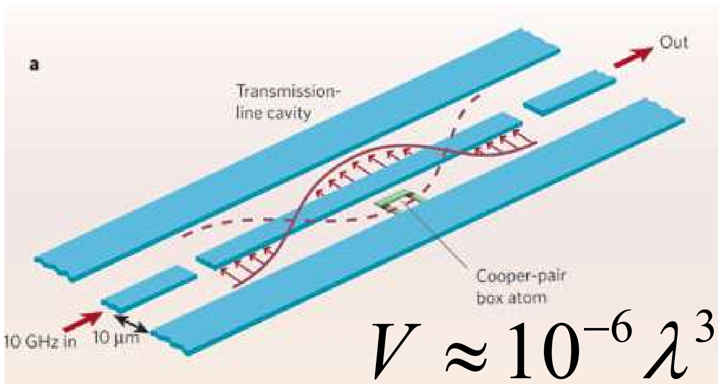
Mode Volume: Microwave to Optics

$$g \propto \sqrt{\frac{\hbar\omega}{V}}$$

1D Transmission Line Resonator

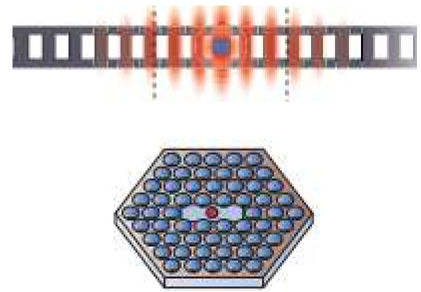


$$V \approx 10^{-6}\lambda^3$$

Circuit QED Regime

$$k_B T_{room} >> \hbar\omega_{microwave}$$

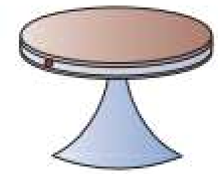
(Yale, ETH Zurich)



$$V \approx 0.5(\lambda / n)^3$$

Photonic Crystals

(Harvard, MIT, Caltech, Stanford)



$$V \approx 15(\lambda / n)^3$$

Microdisk

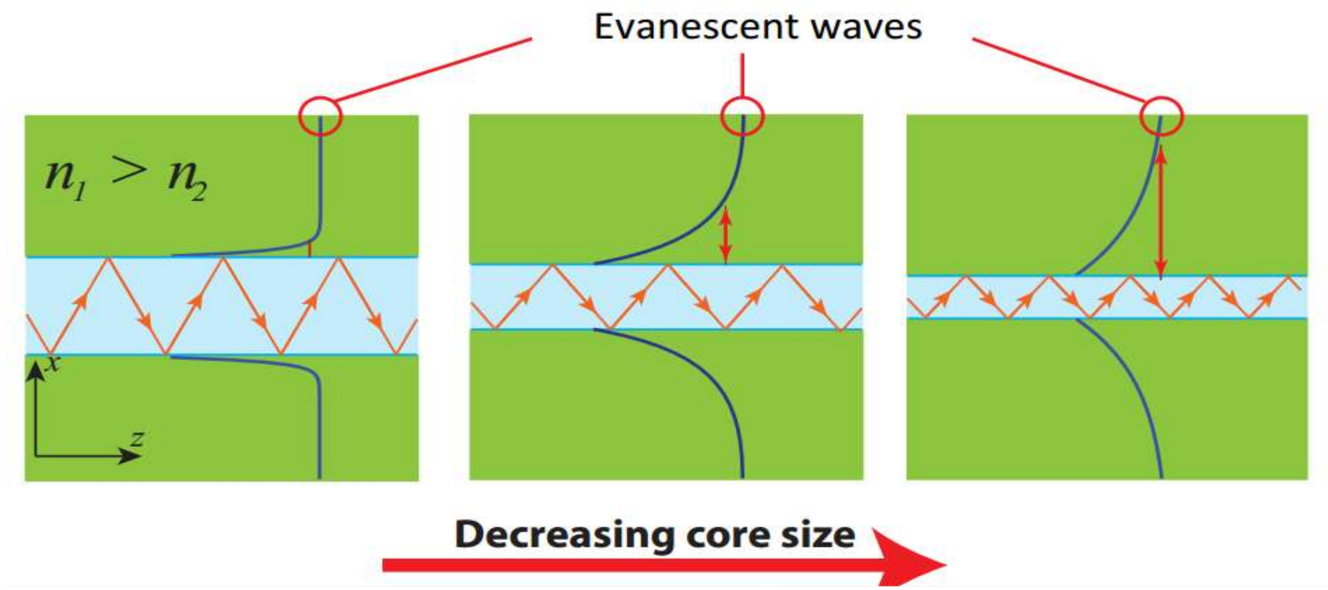
(Stanford, Caltech)

$$V \sim (\lambda / n)^3$$

Always considered fundamental for photonic mode

Plasmonic modes are sub-diffraction but inherently lossy

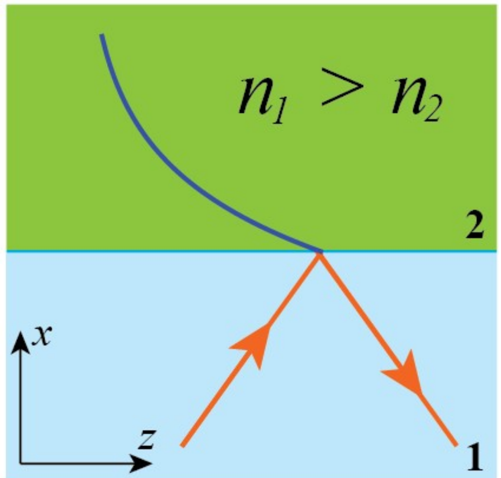
What is the challenge?

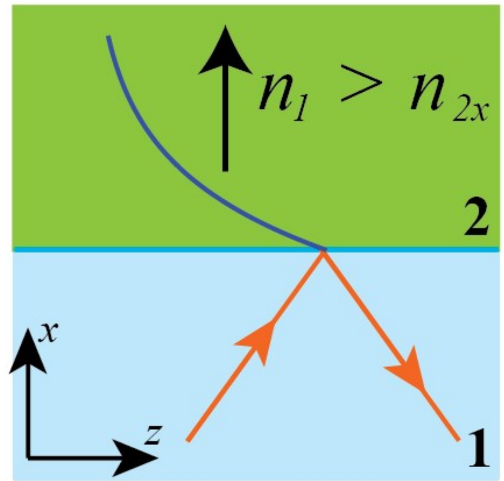


Symmetric waveguide
- No cut-off to lowest order mode

Evanescent waves spread out causing a fundamental limitation to mode volume

Relaxed Total Internal Reflection



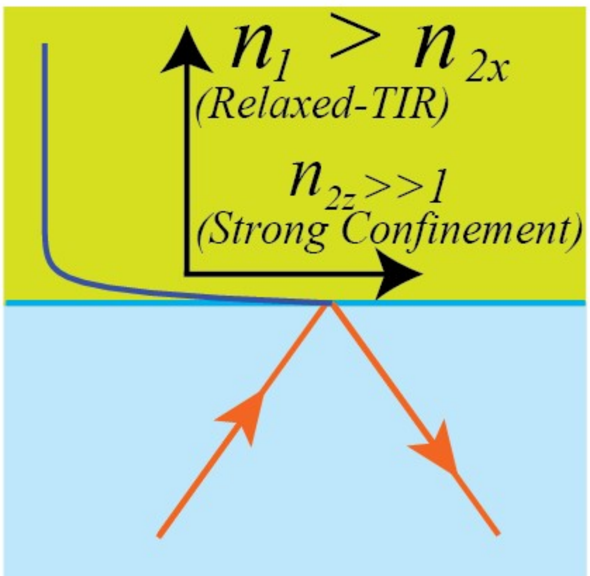


Relaxed-TIR: Contrary to popular assumption, the necessary and sufficient condition for total internal reflection of **TM modes** is:

New condition $$n_1 > n_{2x}$$

S. Jahani and Z. Jacob "Transparent sub-diffraction optics: nanoscale light confinement without metal. *Optica*, *1*(2), 96-100, (2014).
S. Jahani and Z. Jacob. "LIGHT CONFINING DEVICES USING ALL-DIELECTRIC METAMATERIAL CLADDING." U.S. Patent No. 20,140,355,930, (2014).
S. Jahani and Z. Jacob "Breakthroughs in photonics 2014: Relaxed total internal reflection," *IEEE Photonics Journal*, 7(3), 1-5, (2015)
S. Jahani and Z. Jacob "Photonic skin-depth engineering," JOSA B 32 (7), 1346-1353 (2015)

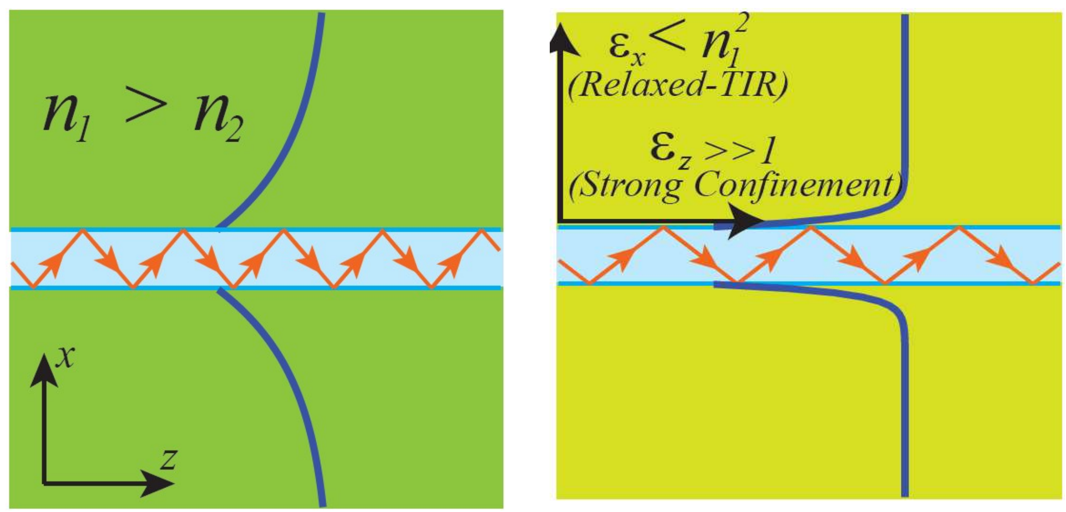
Controlling the momentum of evanescent waves



$$k_x^{\perp} = \frac{n_z}{n_x}\sqrt{(n_x k_0)^2 - (k_z^{||})^2}$$

There is one degree of freedom to choose n_z. We can control the momentum of the evanescent wave to decrease the skin depth if:

$$n_{2z} \gg 1$$



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S. Jahani and Z. Jacob. "LIGHT CONFINING DEVICES USING ALL-DIELECTRIC METAMATERIAL CLADDING." U.S. Patent No. 20,140,355,930, (2014).
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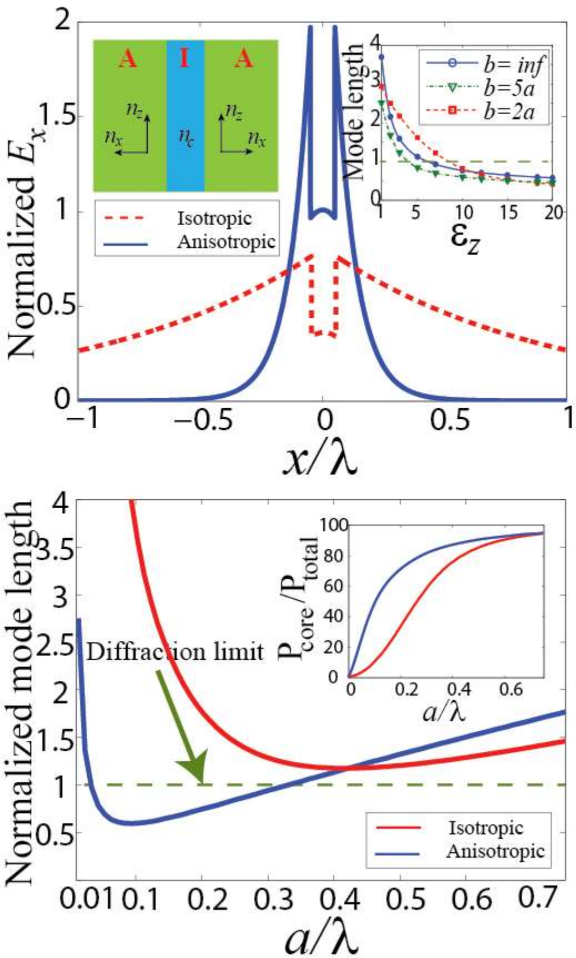
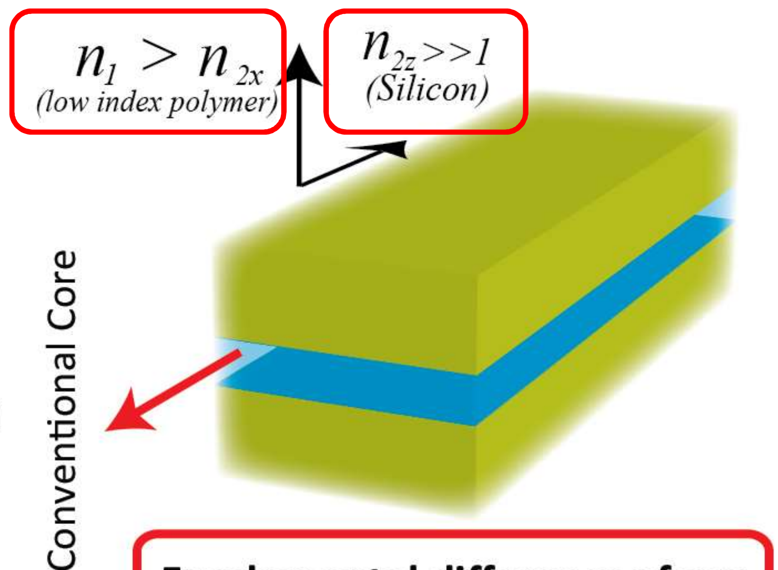
Extreme skin-depth waveguide



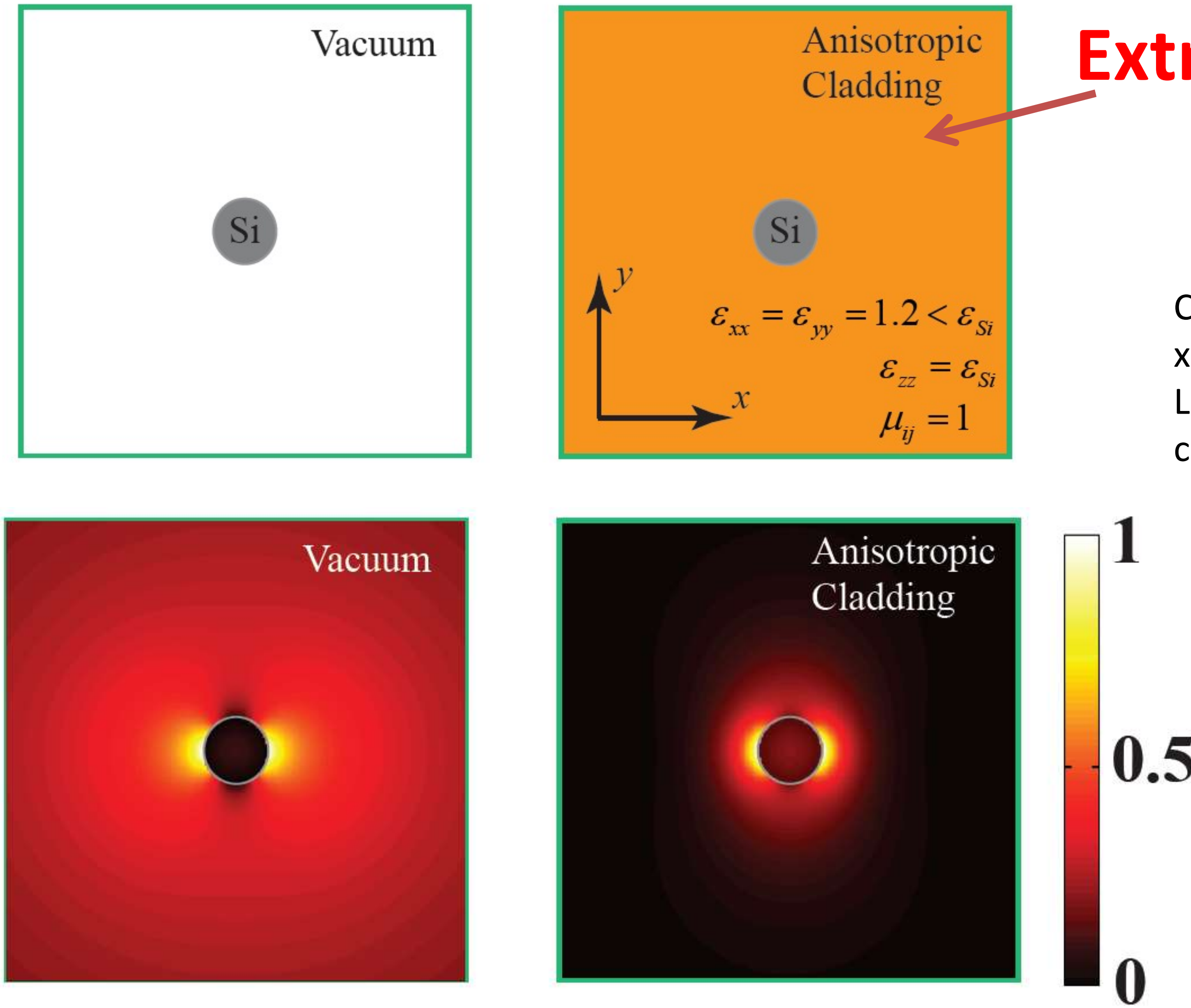


Fundamental differences from conventional waveguides:

- Controlling evanescent decay outside the core.
- All-dielectric sub-diffraction confinement

S. Jahani and Z. Jacob “Transparent sub-diffraction optics: nanoscale light confinement without metal. *Optica*, *1*(2), 96-100, (2014).
S. Jahani and Z. Jacob “Photonic skin-depth engineering,” JOSA B 32 (7), 1346-1353 (2015)

Better than vacuum?



Extreme skin-depth waveguides

Core average radius: 0.07λ
x-component of Electric Field
Lowest order mode (**HE_{11}**) – no cut-off

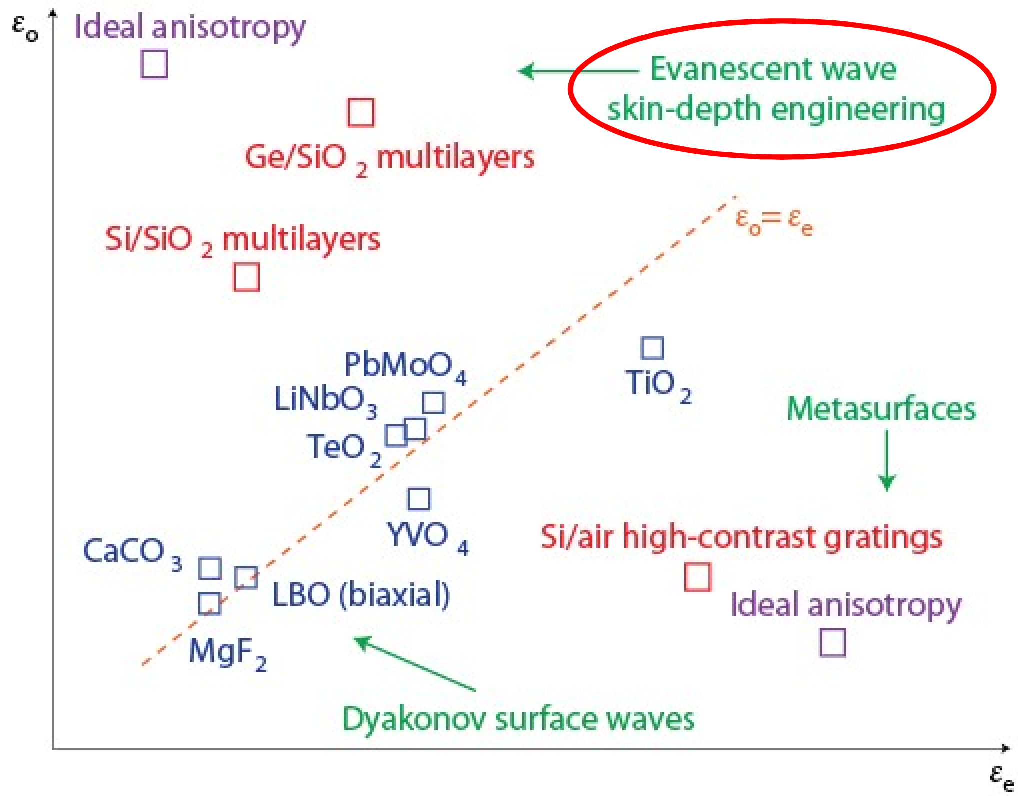
Mode area decreases 20 times !

Material like silicon in one direction, like air in the perpendicular direction!

S. Jahani & Z. Jacob, Nature Nanotech. 11, 23-36, (2016)
S. Jahani & Z. Jacob, Optica 1(2), 96-100, (2014)

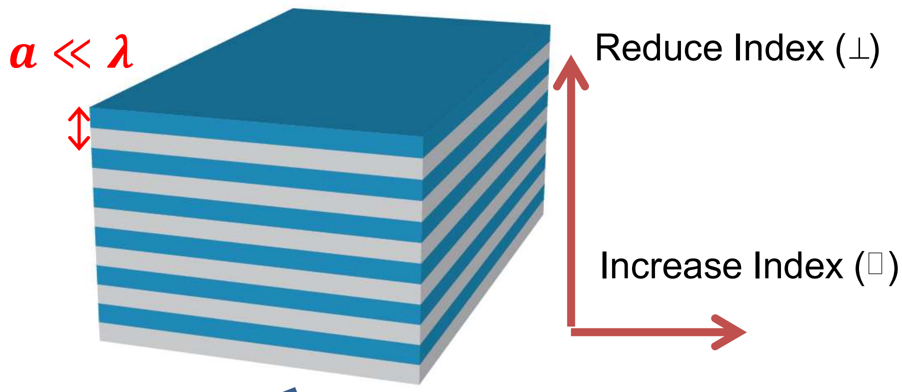
Need for All-Dielectric Metamaterials

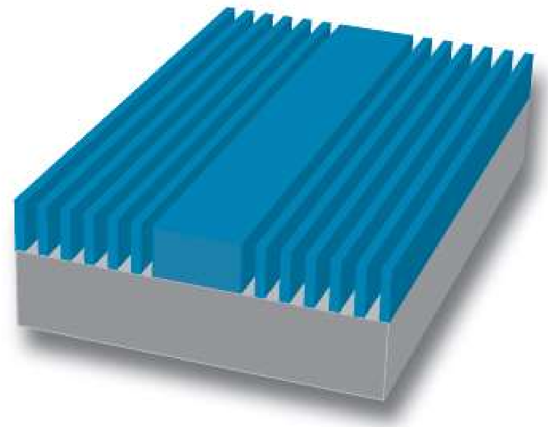
$\varepsilon > 1$



S. Jahani and Z. Jacob "All-dielectric metamaterials," Nature nanotechnology, 11, 23-36, (2016).

Practical realization



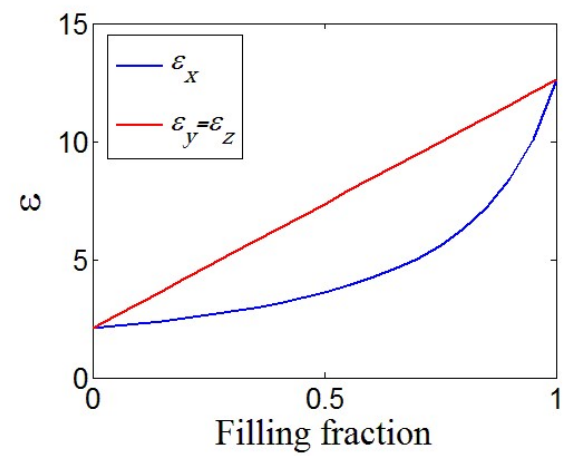


Collaboration with Prof. R. Decorby, Prof. V. Van, Prof. L. Christowski (UBC)

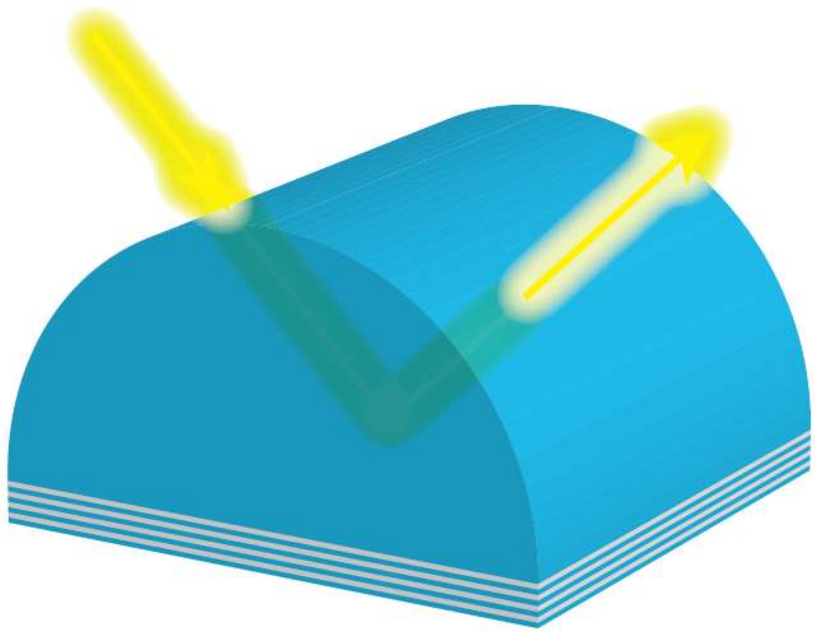
Effective medium theory (EMT):

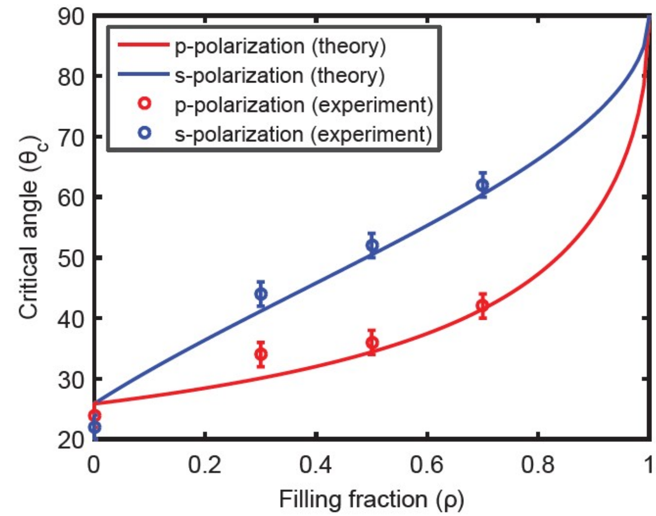
$$\varepsilon_{\parallel} = \varepsilon_y = \varepsilon_z = \rho\varepsilon_d + (1-\rho)\varepsilon_h$$

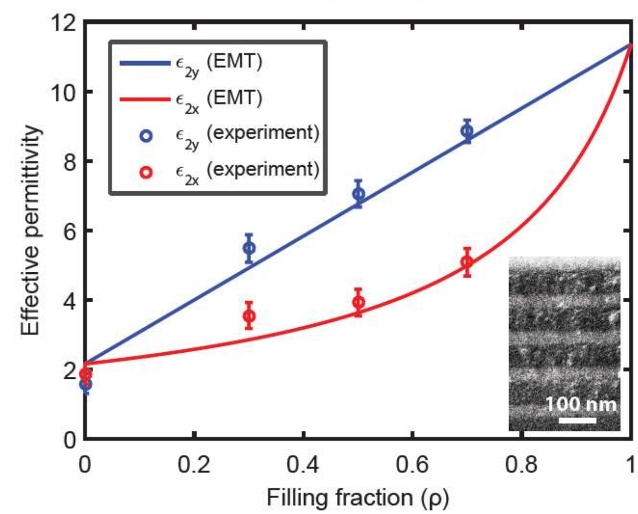
$$\varepsilon_{\perp} = \varepsilon_x = \frac{\varepsilon_d \varepsilon_h}{(1-\rho)\varepsilon_d + \rho\varepsilon_h}$$



Experimental verification of relaxed-total internal reflection





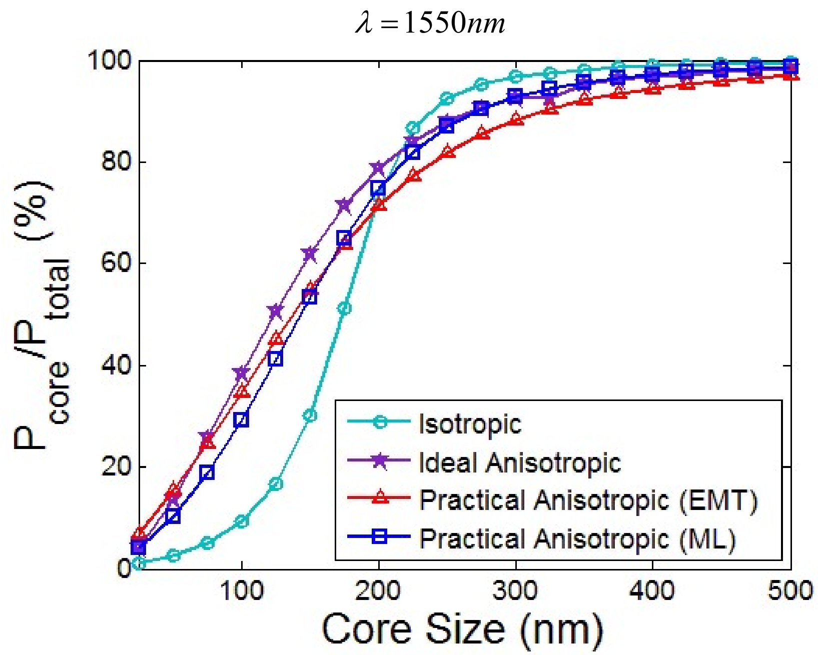


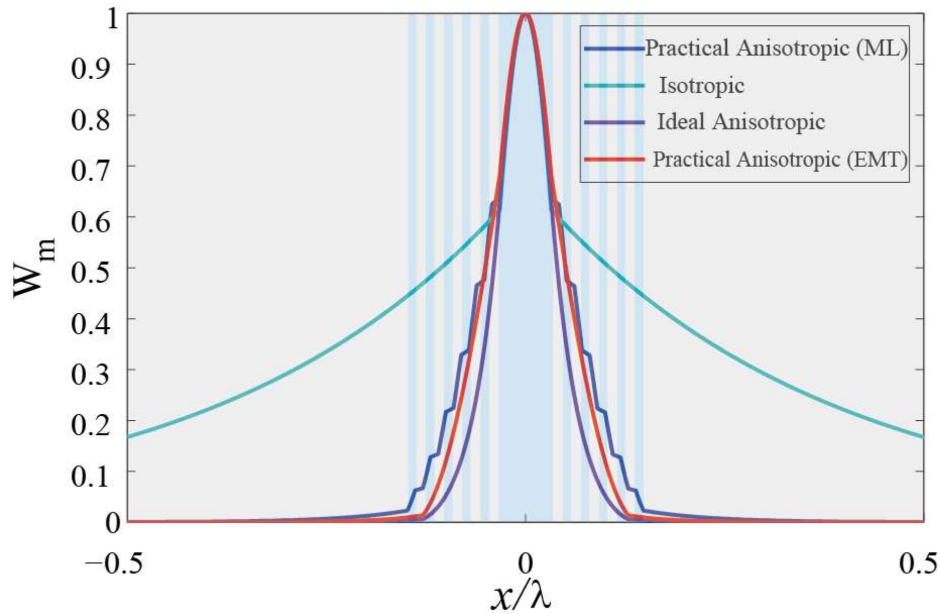
Collaboration with Prof. R. Decorby's lab
Fabricated by Jonathan Atkinson

$$\begin{cases} n_1 > \sqrt{\varepsilon_y}, & s-polarization \\ n_1 > \sqrt{\varepsilon_x}, & p-polarization \end{cases}$$

S. Jahani and Z. Jacob "Breakthroughs in photonics 2014: Relaxed total internal reflection," *IEEE Photonics Journal*, 7(3), 1-5, (2015)
S. Jahani et. al. "Experimental photonic skin-depth engineering on a silicon chip using all-dielectric metamaterials," (Preparing to submit)

Practical e-skid waveguides





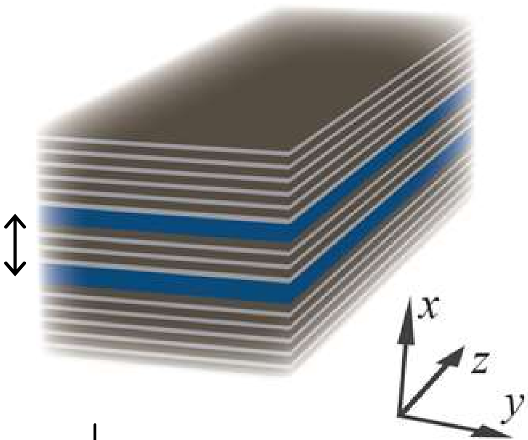
Mode area decreases 5 times!

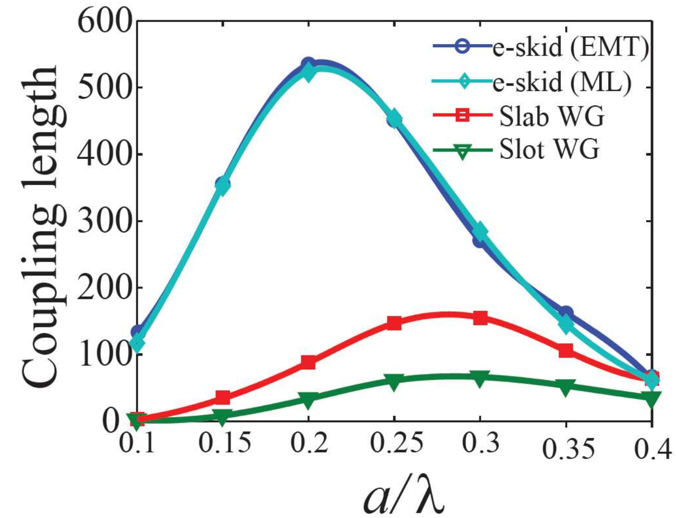
In ideal case, $\varepsilon_x = 1.2$ and $\varepsilon_z = 12$

In practical case, the cladding is Si/SiO_2 multilayer with Si filling fraction of 0.5.

Cross-talk reduction

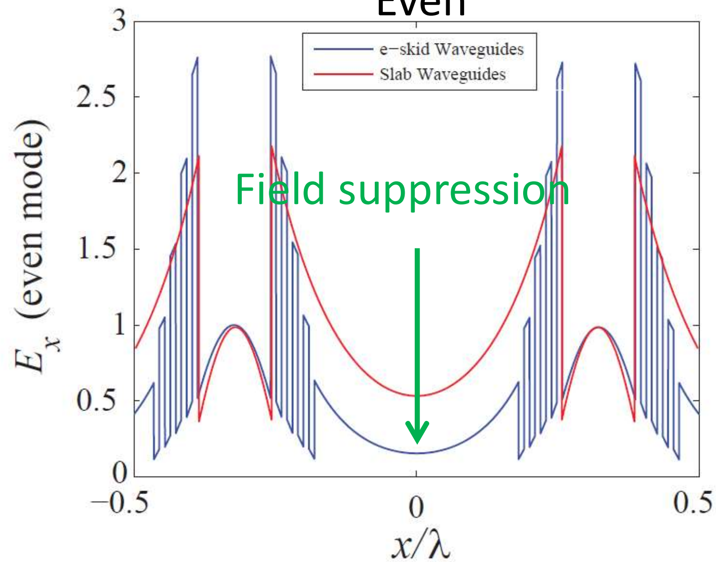
$s = 0.7\lambda$



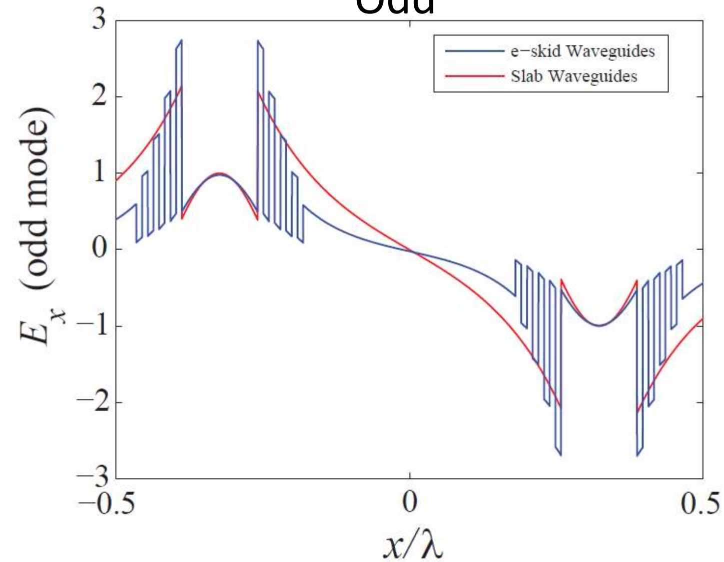


$$L_c \equiv \pi / \left|\beta^e - \beta^o\right|$$

Even



Odd



S. Jahani and Z. Jacob "Transparent sub-diffraction optics: nanoscale light confinement without metal. *Optica*, *1*(2), 96-100, (2014).
Almeida, Vilson R., et al. "Guiding and confining light in void nanostructure."*Optics letters* 29.11 (2004).

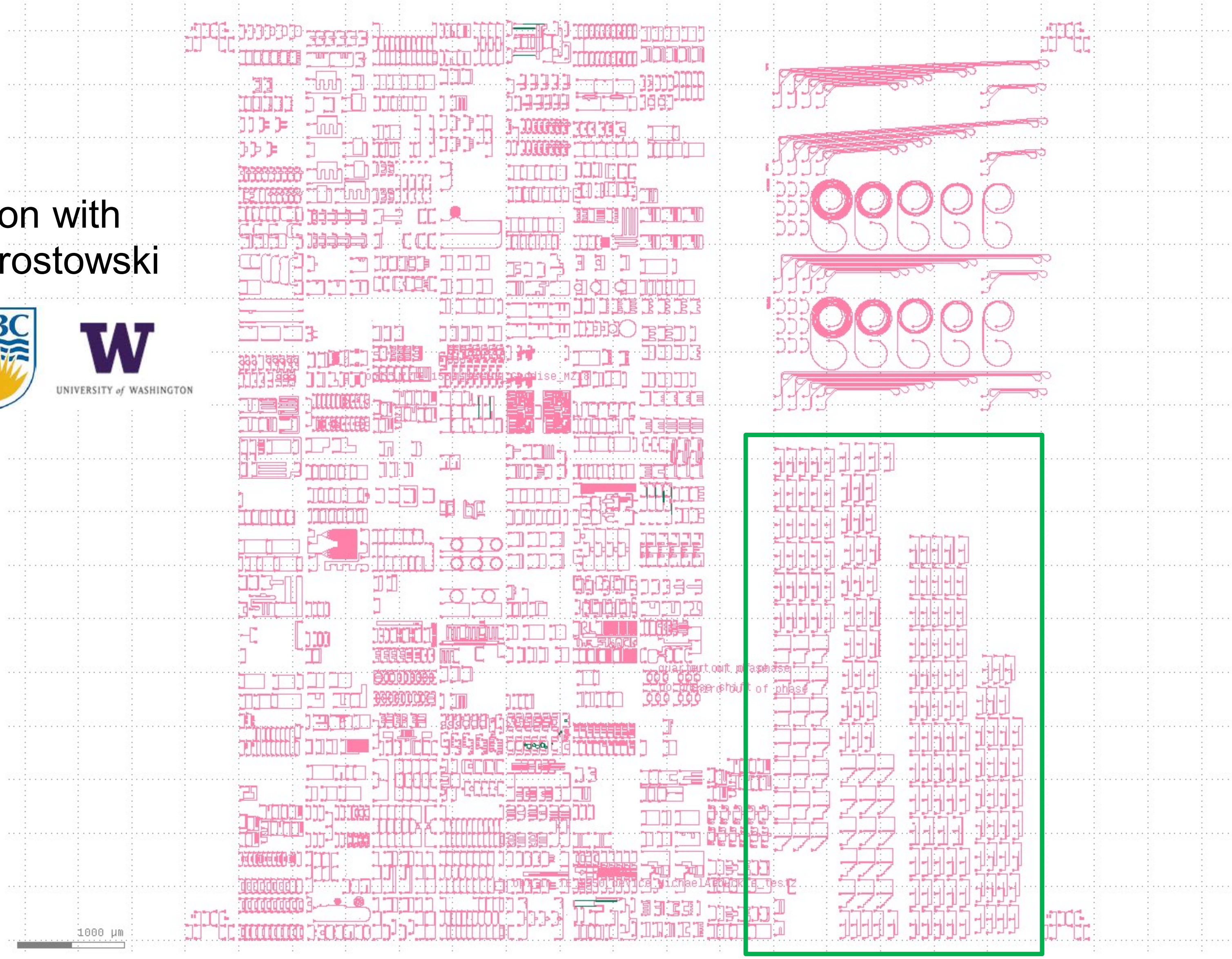
Waveguides on SOI platform

Collaboration with
Prof. L. Chrostowski

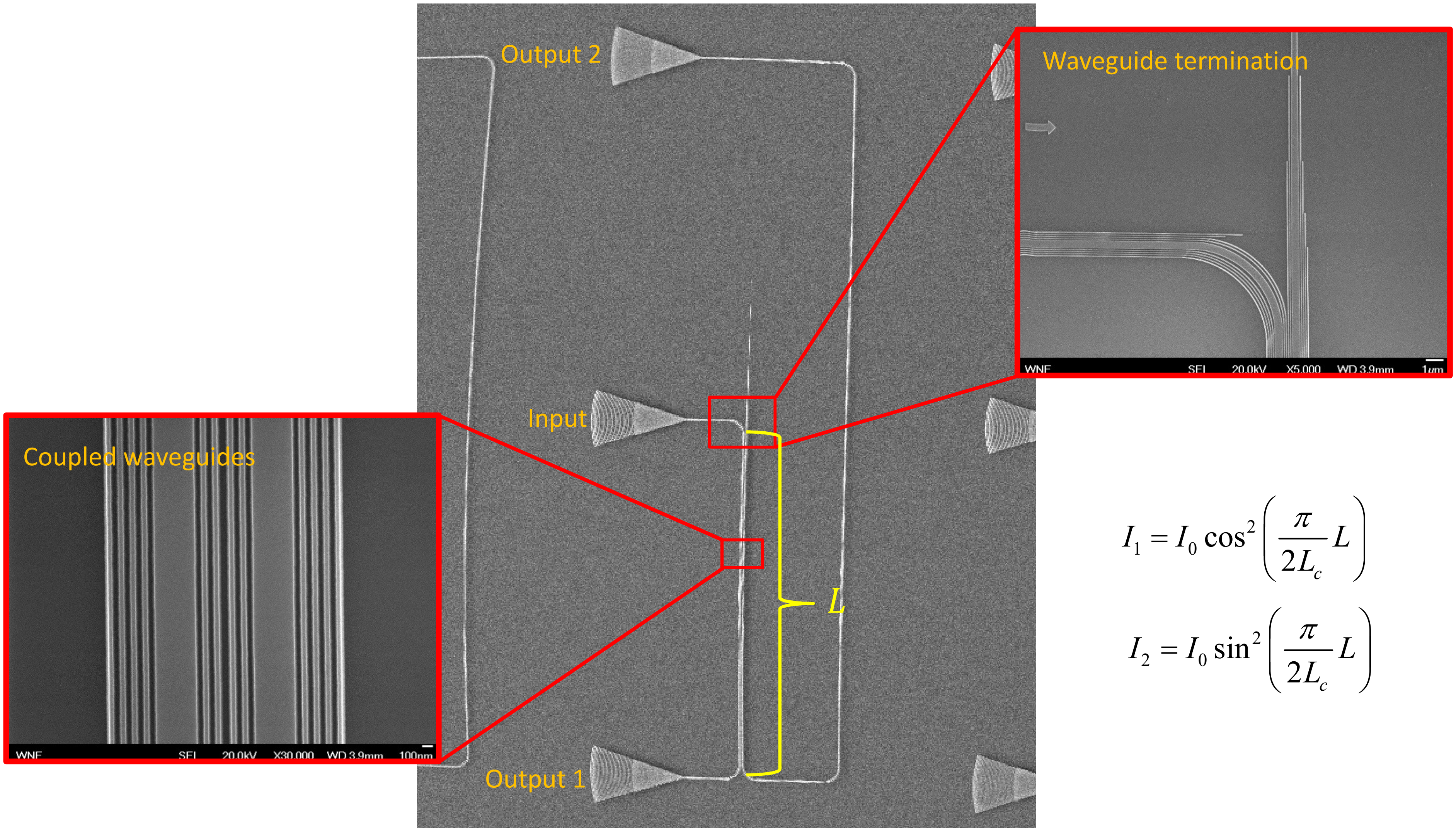
NSERC CRSNG
Si-EPIC CREATE

UBC

W
UNIVERSITY of WASHINGTON



Experimental set-up to measure cross-talk



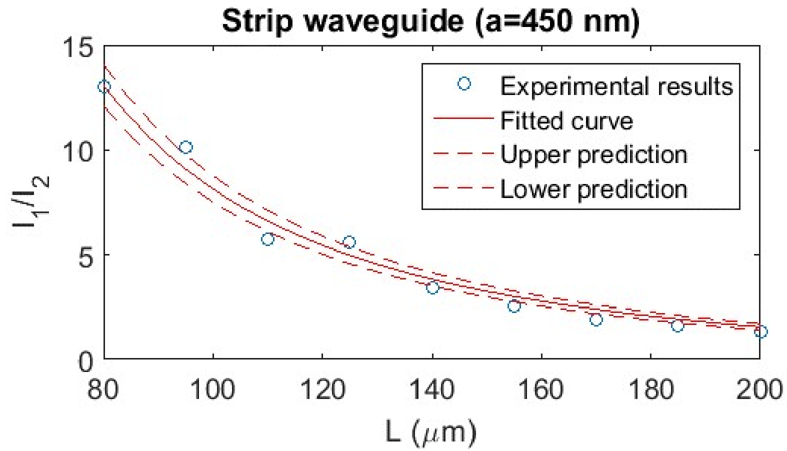
$$I_1 = I_0 \cos^2\left(\frac{\pi}{2L_c}L\right)$$

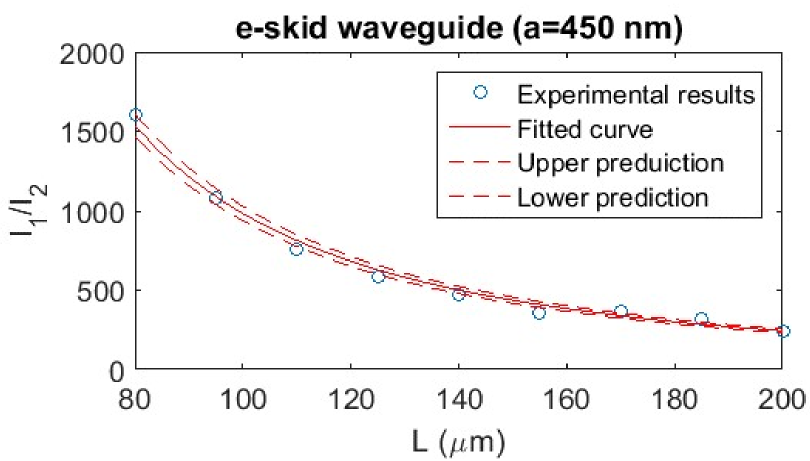
$$I_2 = I_0 \sin^2\left(\frac{\pi}{2L_c}L\right)$$

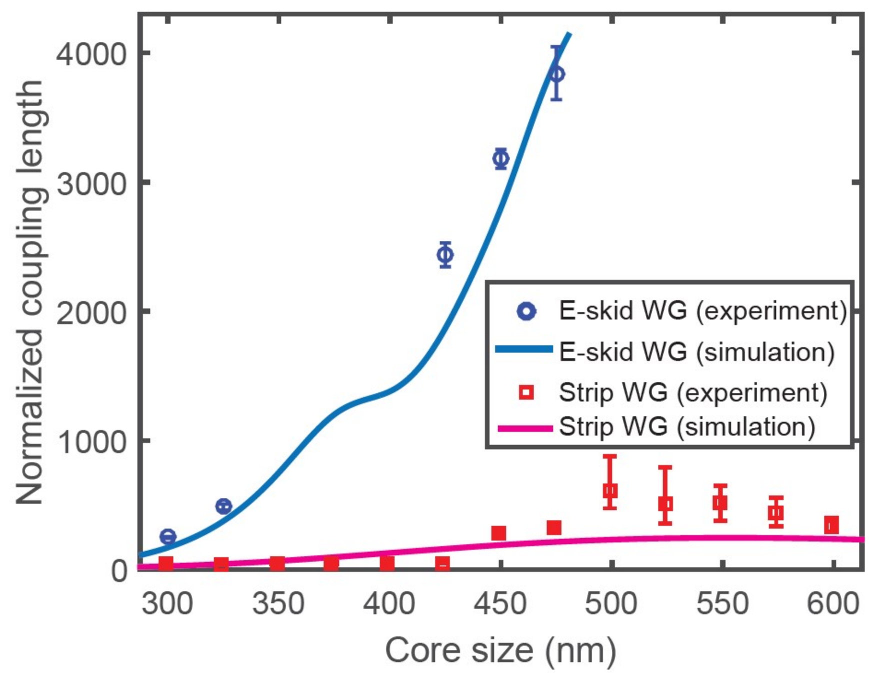
S. Jahani et. al. “Experimental photonic skin-depth engineering on a silicon chip using all-dielectric metamaterials,” (in preparation)

Demonstration of reduced cross-talk

Collaboration with Dr. Sangsik Kim and Prof. Minghao Qi (Purdue)







$$\frac{I_1}{I_2} = \cot^2\left(\frac{\pi}{2L_c}L\right)$$

S. Jahani et. al. "Experimental photonic skin-depth engineering on a silicon chip using all-dielectric metamaterials," (in preparation)

Our recent review

nature nanotechnology

FOCUS | REVIEW ARTICLE

PUBLISHED ONLINE: 7 JANUARY 2016 | DOI: 10.1038/NNANO.2015.304

All-dielectric metamaterials

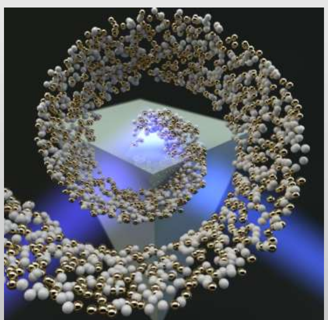
Saman Jahani[1] and Zubin Jacob[1,2]*

The ideal material for nanophotonic applications will have a large refractive index at optical frequencies, respond to both the electric and magnetic fields of light, support large optical chirality and anisotropy, confine and guide light at the nanoscale, and be able to modify the phase and amplitude of incoming radiation in a fraction of a wavelength. Artificial electromagnetic media, or metamaterials, based on metallic or polar dielectric nanostructures can provide many of these properties by coupling light to free electrons (plasmons) or phonons (phonon polaritons), respectively, but at the inevitable cost of significant energy dissipation and reduced device efficiency. Recently, however, there has been a shift in the approach to nanophotonics. Low-loss electromagnetic responses covering all four quadrants of possible permittivities and permeabilities have been achieved using completely transparent and high-refractive-index dielectric building blocks. Moreover, an emerging class of all-dielectric metamaterials consisting of anisotropic crystals has been shown to support large refractive index contrast between orthogonal polarizations of light. These advances have revived the exciting prospect of integrating exotic electromagnetic effects in practical photonic devices, to achieve, for example, ultrathin and efficient optical elements, and realize the long-standing goal of subdiffraction confinement and guiding of light without metals. In this Review, we present a broad outline of the whole range of electromagnetic effects observed using all-dielectric metamaterials: high-refractive-index nanoresonators, metasurfaces, zero-index metamaterials and anisotropic metamaterials. Finally, we discuss current challenges and future goals for the field at the intersection with quantum, thermal and silicon photonics, as well as biomimetic metasurfaces.

S. Jahani & Z. Jacob,
Nature Nanotechnology 11, 23-36, (2016)

Surprises from Nanophotonics

PHOTONIC SKIN-DEPTH ENGINEERING FOR SUB-DIFFRACTION CONFINEMENT



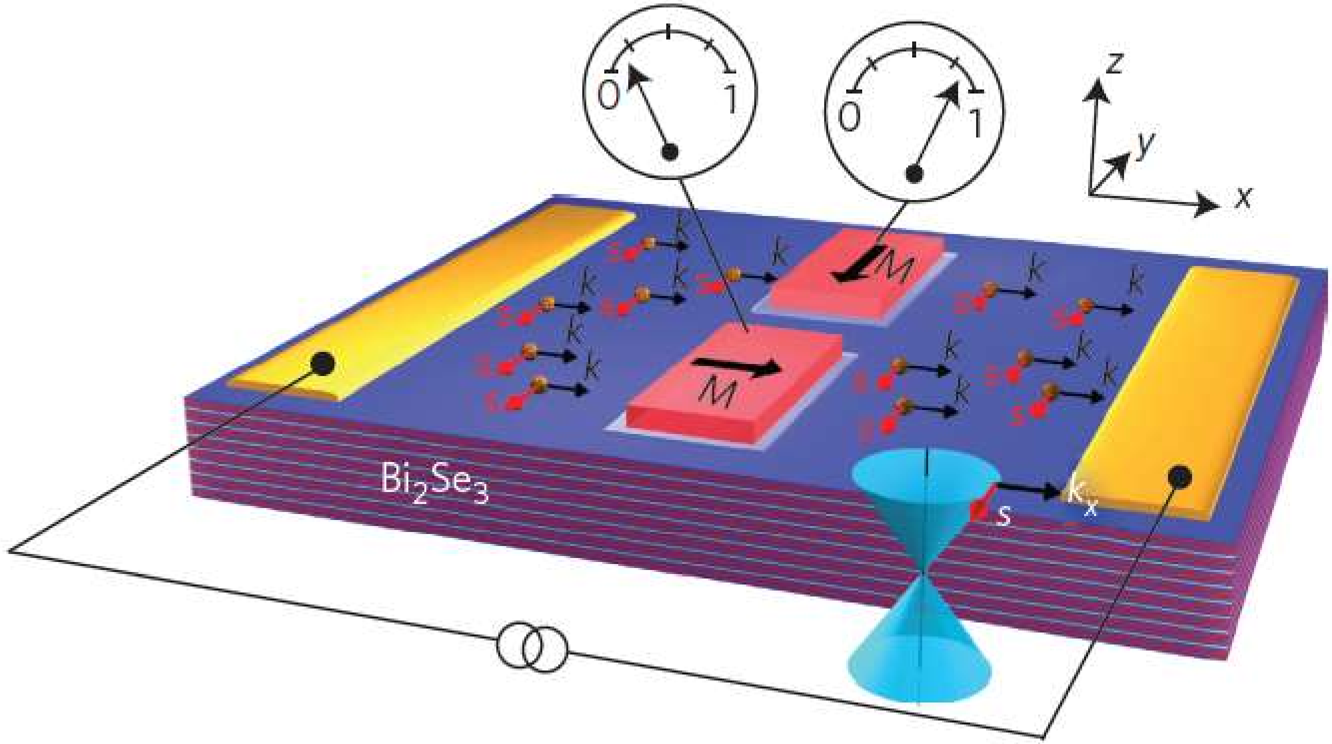
UNIVERSAL SPIN-MOMENTUM LOCKING of LIGHT

Zubin Jacob

ECE, Purdue University, U.S.A.

ECE, University of Alberta, Canada

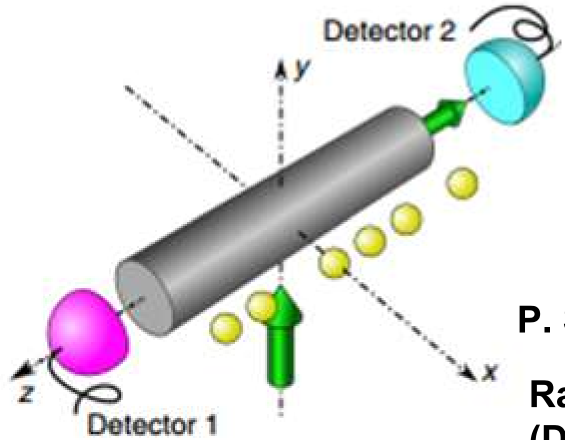
Spin-Momentum Locking: Electrons



Nat. Nanotechnology **9**, 218 (2014)

Topological Insulators: Bismuth Selenide
Quantum spin-hall state: Mercury Cadmium Telleride quantum wells

Spin-Momentum Locking: Light



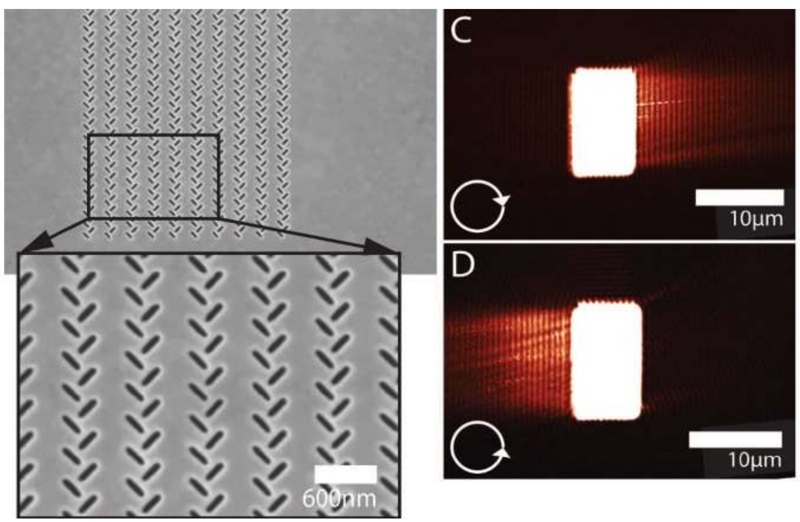
P. Schneeweiss

Rauschenbeutel Group
(Dec 2014, Nat. Comm.)

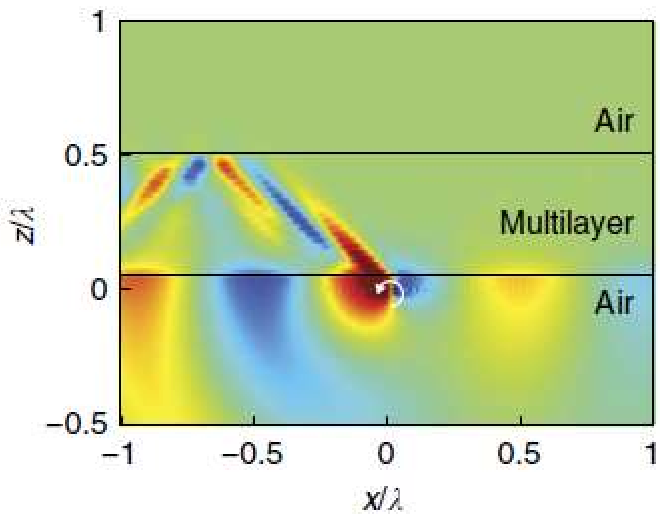
Cold atoms trapped near a nano-fiber

HE 11 mode

Emission in only one direction!



Cappasso Group



Zayats Group

See also:
G. Leuchs Group
Kuippers Group
Zheludev Group
Giessen Group
Lukin Group

Our claim: Fundamental origin of the above phenomena are properties of evanescent waves

What is the origin?

2 recent independent interpretations

Science

REPORT

Quantum spin Hall effect of light

Konstantin Y. Bliokh[1,2,*], Daria Smirnova[2], Franco Nori[1,3,*]

+ Author Affiliations

*Corresponding author. E-mail: k.bliokh@gmail.com (K.Y.B.); fnori@riken.jp (F.N.)

Science 26 Jun 2015:
Vol. 348, Issue 6242, pp. 1448-1451

Topology?

optica

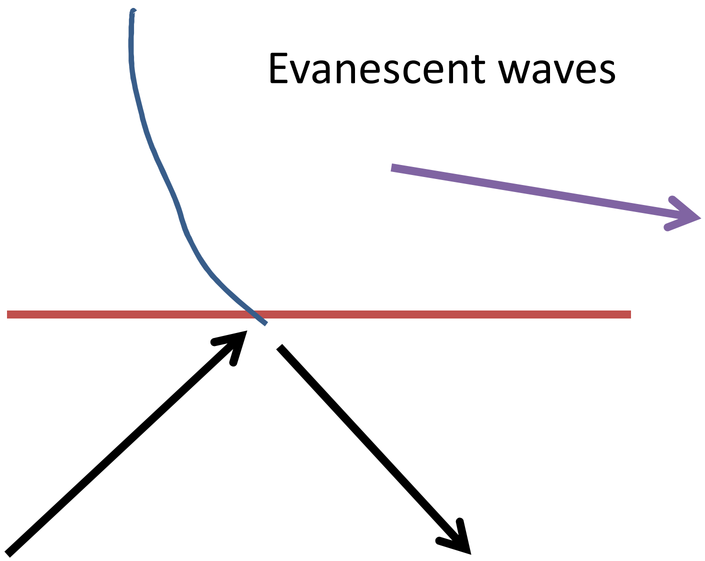
Universal spin-momentum locking of evanescent waves

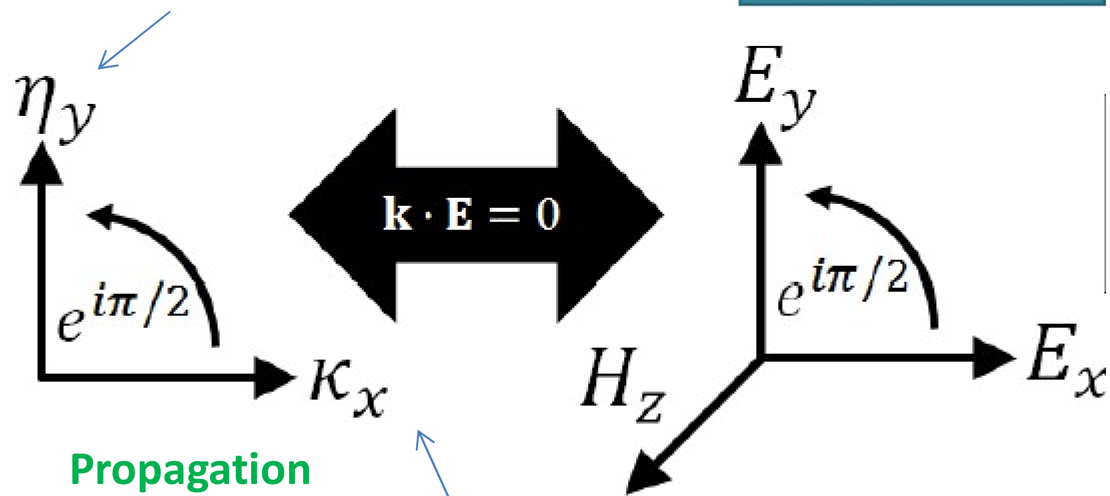
TODD VAN MECHELEN AND ZUBIN JACOB*

Vol. 3, No. 2 / February 2016 / Optica

Causality!

Total Internal Reflection



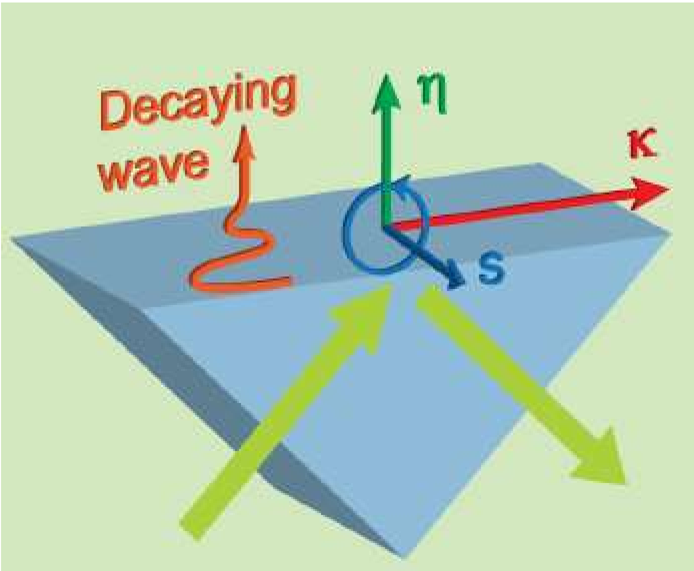


Intrinsic phase Difference: π/2

Incident: TM or (p)-polarized, linearly polarized plane wave

Similar arguments for the magnetic field in case of (s)-polarized incident waves

Intrinsic local polarization



Stokes parameters in terms of the pauli matrices

$$S_0 = \langle \psi | I | \psi \rangle$$

$$S_1 = \langle \psi | \sigma_z | \psi \rangle$$

$$S_2 = \langle \psi | \sigma_x | \psi \rangle$$

$$S_3 = \langle \psi | \sigma_y | \psi \rangle$$

Degree of
Circular polarization

$$\psi = \begin{bmatrix} E_x \\ E_y \end{bmatrix}$$

Electric Spin
(p)-polarized wave

$$\psi = \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

Magnetic Spin
(s)-polarized wave

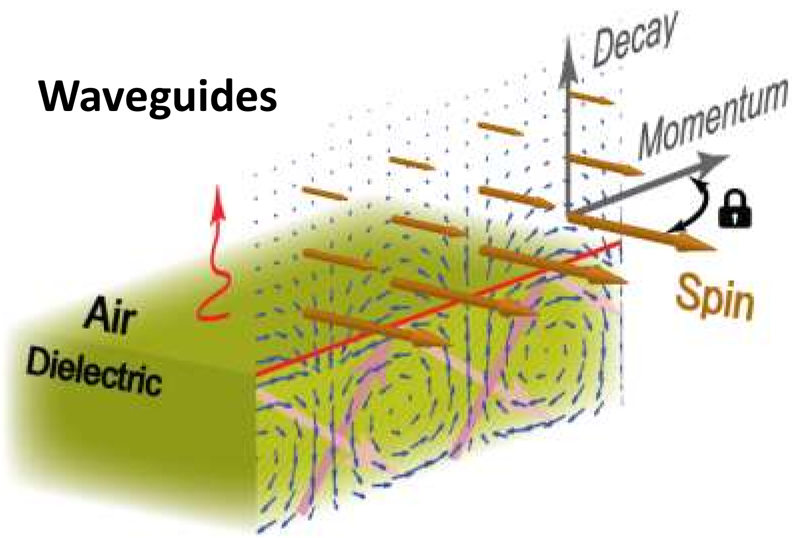
Defined at a fixed point in space near the interface

T. V. Mechelen & Z. Jacob, Optica 3 (2), 118-126 (2016)
F. Kalhor & Z. Jacob Appl. Phys. Lett. 108, 061102 (2016)

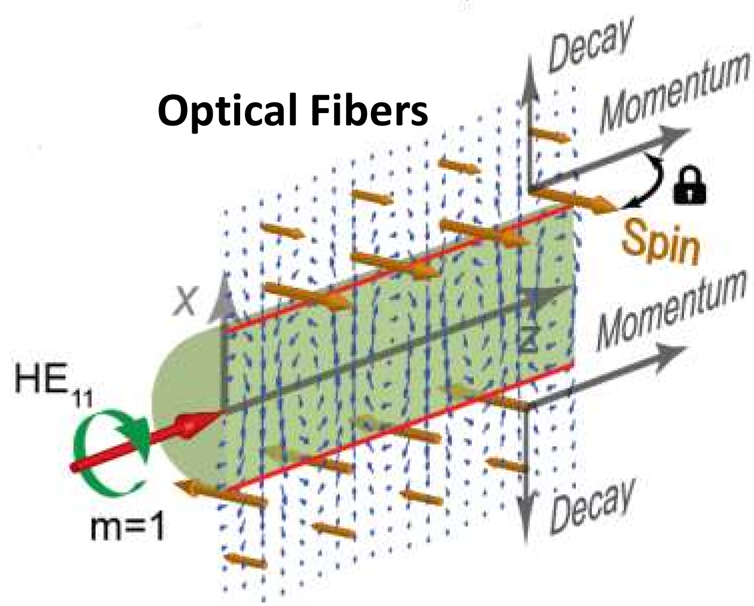
See also work from :
K. Bliokh (Japan), S. Barnett (U.K.)

New EM Triplet: Decay, Momentum, Spin

Waveguides

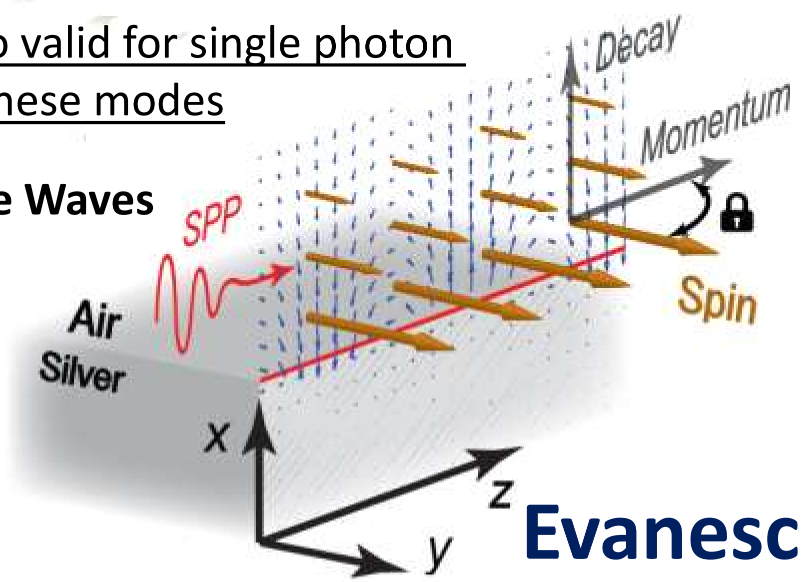


Optical Fibers



<u>Also valid for single photon in these modes</u>

Surface Waves

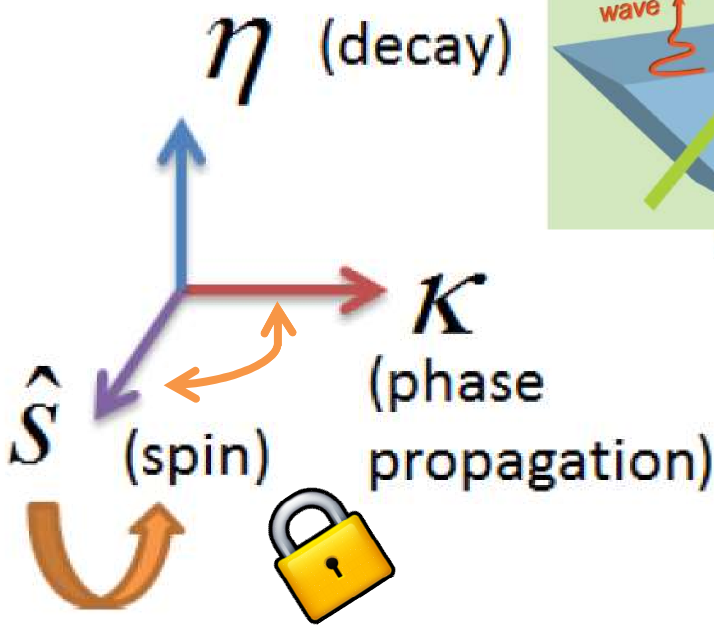


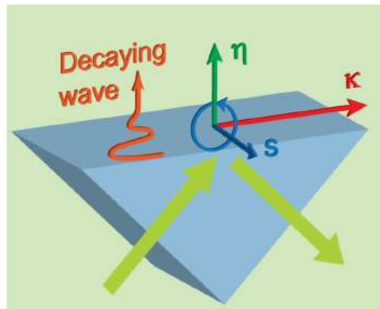
Evanescent Waves

Intrinsic Polarization axis — Momentum — Decay

$$\hat{s} = \frac{\mathrm{Re}\,\vec{k} \times \mathrm{Im}\,\vec{k}}{|\,\mathrm{Re}\,\vec{k} \times \mathrm{Im}\,\vec{k}\,|}$$

Why is the locking universal?

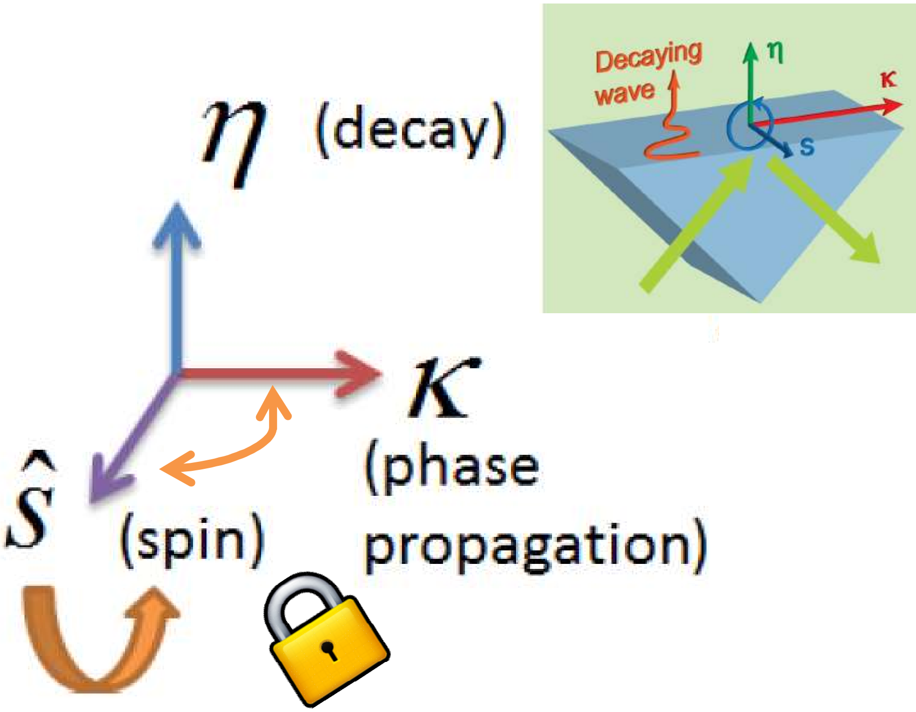


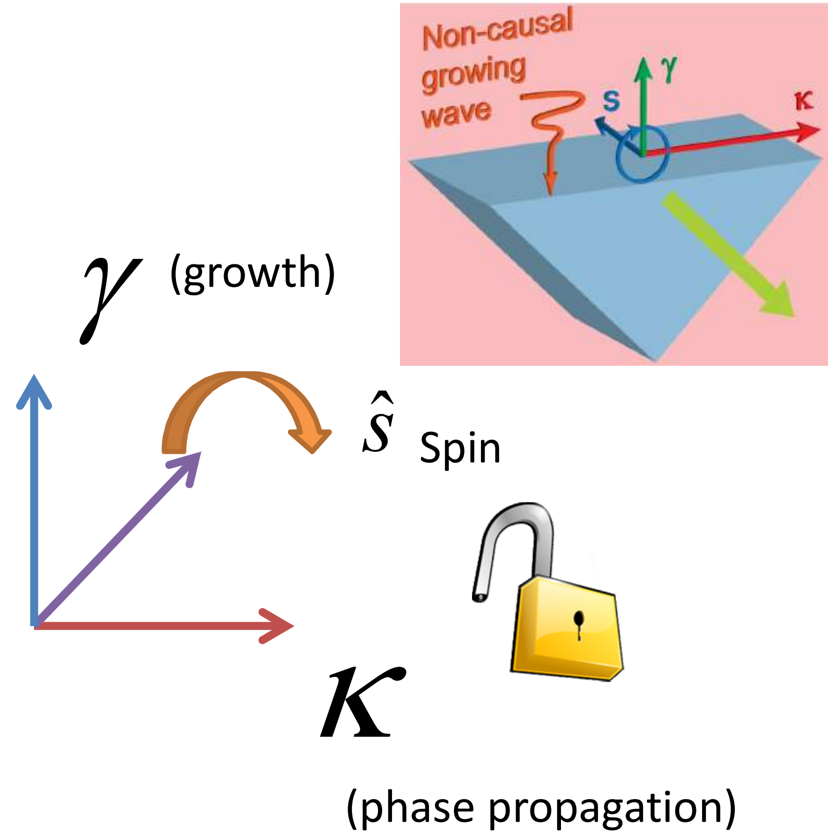


(Label evanescent waves with transverse spin)

T. V. Mechelen & Z. Jacob, Optica 3 (2), 118-126 (2016)
F. Kalhor & Z. Jacob Appl. Phys. Lett. 108, 061102 (2016)

Why is the locking universal?



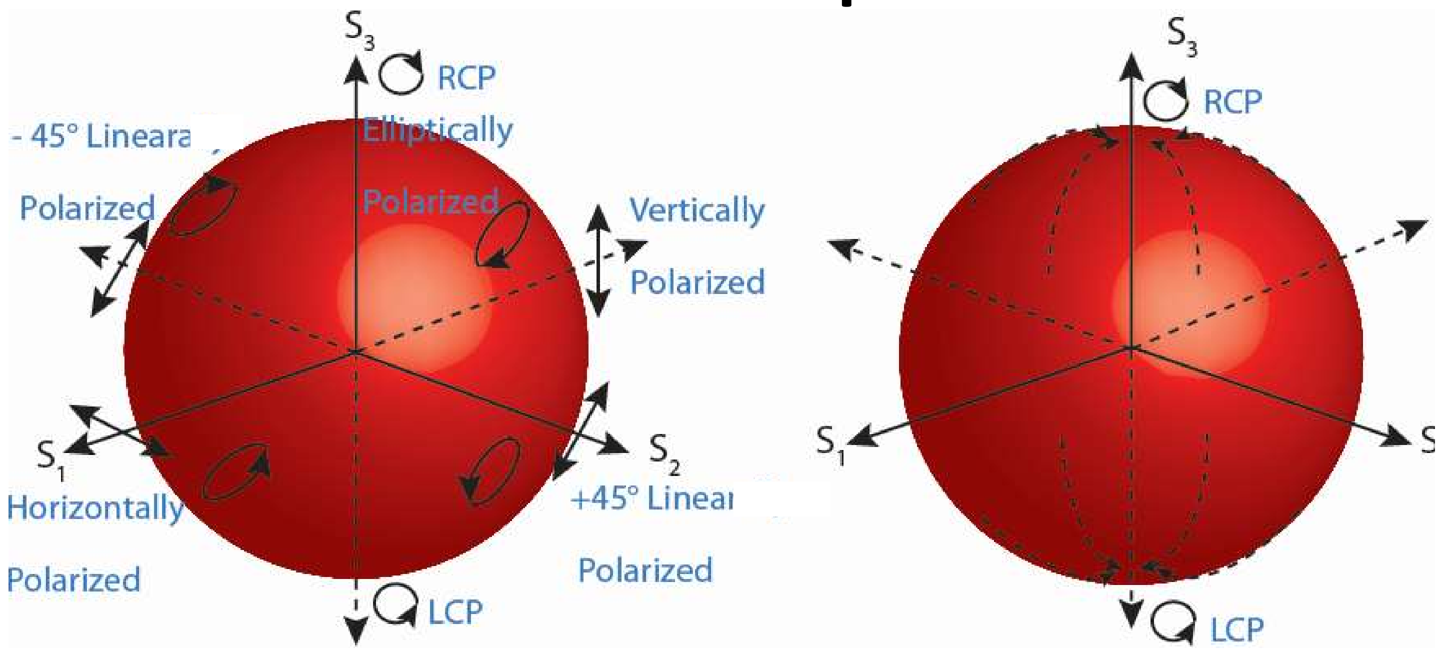


(Label evanescent waves with transverse spin)

Growing evanescent wave (not allowed by causal boundary conditions!)

T. V. Mechelen & Z. Jacob, Optica 3 (2), 118-126 (2016)
F. Kalhor & Z. Jacob Appl. Phys. Lett. 108, 061102 (2016)

Poincare sphere



Propagating Waves **Evanescent Waves**

T. V. Mechelen & Z. Jacob, Optica 3 (2), 118-126 (2016)
F. Kalhor, & Z. Jacob Appl. Phys. Lett. 108, 061102 (2016)

$$S^3 \to \pm 1$$

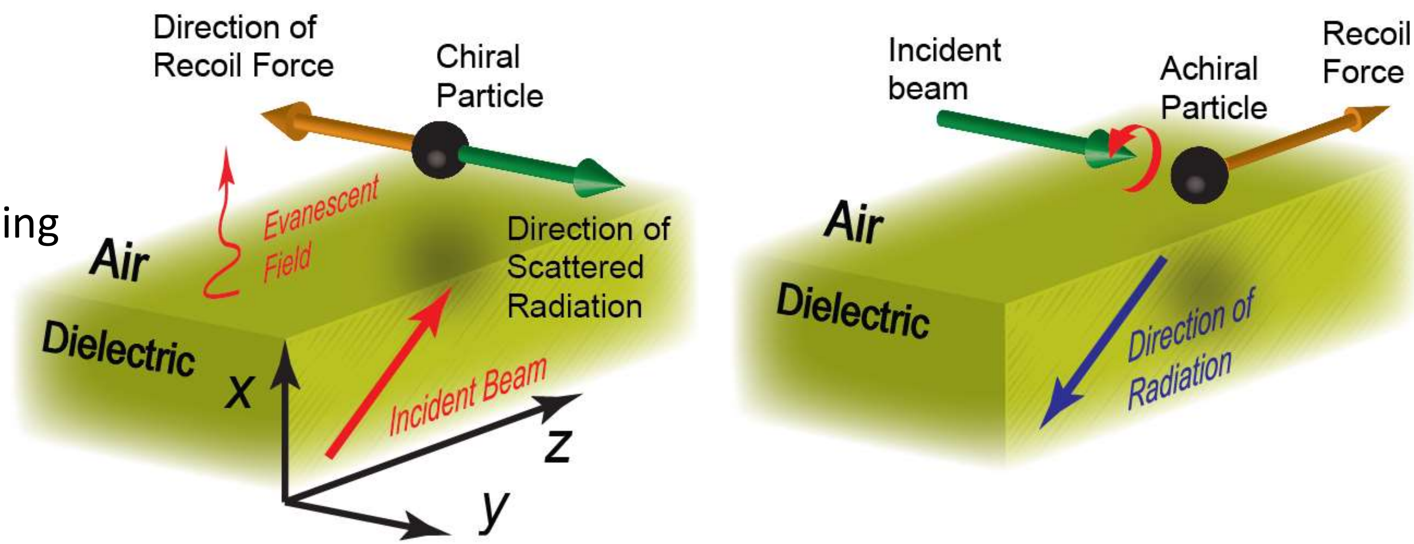
(defined locally,
generalization to evanescent waves)

Comes from causality hence is fundamental for all evanescent waves !

Spin-momentum locked optical forces

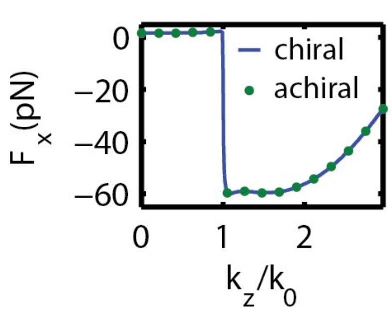
EM
Stress Tensor
Carries Information
About
Spin-momentum locking

$$\begin{bmatrix}\vec{p}\\ \vec{m}\end{bmatrix} = \begin{bmatrix}\alpha_{ee} & i\alpha_{em}\\ -i\alpha_{em} & \alpha_{mm}\end{bmatrix}\begin{bmatrix}\vec{E}\\ \vec{H}\end{bmatrix}$$

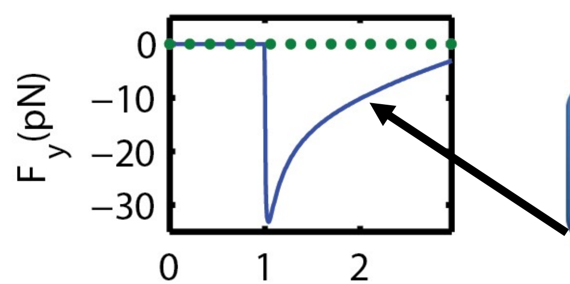


Force in unique transverse direction (explained by spin-momentum locking)

$p = 50mW/mm^2$



Conventional optical force (x-axis)

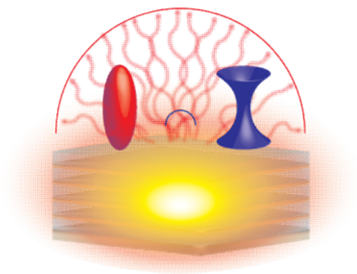


Only occurs beyond the TIR angle

Unique lateral direction force (y-axis)

Kalhor, F., Thundat, T. & Jacob, Z. Universal spin-momentum locked optical forces. *Applied Physics Letters* **108,** 061102 (2016).
See also recent work on optical forces on chiral particles: Bliokh, Cappasso, Zayats, Barnett, C.T. Chan, Ebbesen

RECENT RESEARCH HIGHLIGHTS



THERMAL METAMATERIALS

Nature Communications 7, 11809, (2016)

NEGATIVE FREQUENCY RESONANCE

Y. Guo and Z. Jacob
Opt. Ex., Vol. 22,
Issue 21, pp. 26193-26202 (2014)

SUPER-COULOMBIC DIPOLE-DIPOLE INTERACTIONS

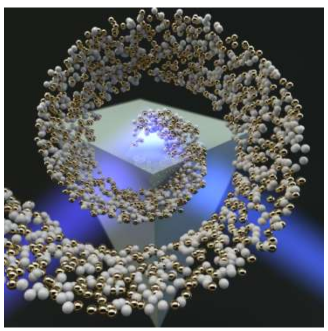
C. Cortes & Z. Jacob
arXiv:1601.04013 (2016)
[physics.atom-ph]

www.zjresearchgroup.org

SUMMARY

PHOTONIC SKIN-DEPTH ENGINEERING FOR SUB-DIFFRACTION CONFINEMENT

S. Jahani & Z. Jacob, Nature Nanotech. 11, 23-36, (2016)
S. Jahani & Z. Jacob, Optica 1(2), 96-100, (2014)



UNIVERSAL SPIN-MOMENTUM LOCKING of LIGHT

T. V. Mechelen & Z. Jacob, Optica 3 (2), 118-126 (2016)
F. Kalhor & Z. Jacob Appl. Phys. Lett. 108, 061102 (2016)

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