São Paulo School of Advanced Science on Nanophotonics

Class 2: Nonlinear optics in nanophotonic structures

Paulo Dainese, Assistant Professor
"Gleb Wataghin" Physics Institute
University of Campinas

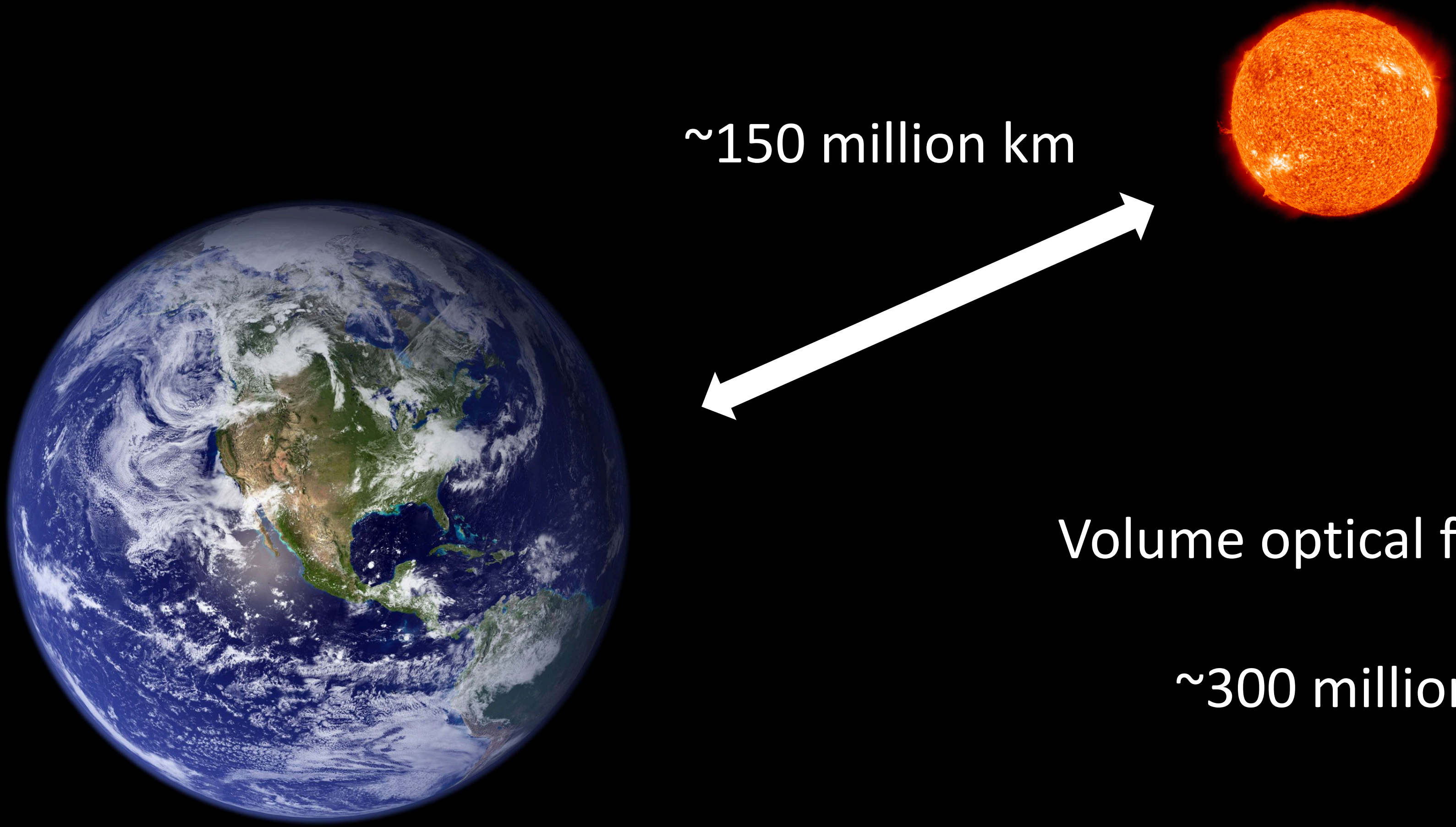
Instituto de Física "Gleb Wataghin"

UNICAMP

Outline

- Future of Optical Communications
- Why are we interested in photon-phonon interaction?
- **Our work: Brillouin scattering self-cancellation effect**
- what else is going on in our lab…
  - Free-carriers dispersion and thermal phase shift in silicon waveguides
  - High-order modes in photonics bandgap fibers and tapers
  - Broadband & small footprint dielectric antenna

Photonics is widely implemented in long-distance communications



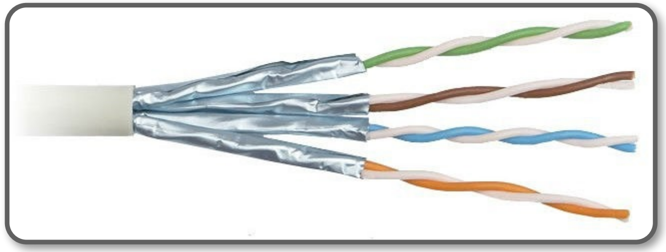
Volume optical fiber sold:

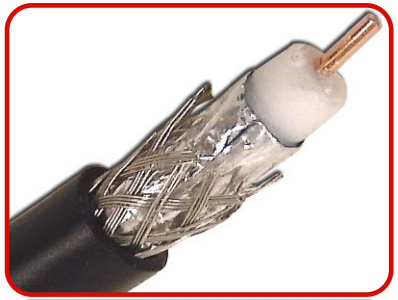
~300 million km

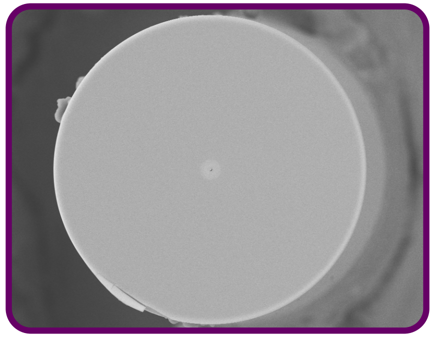
…every year

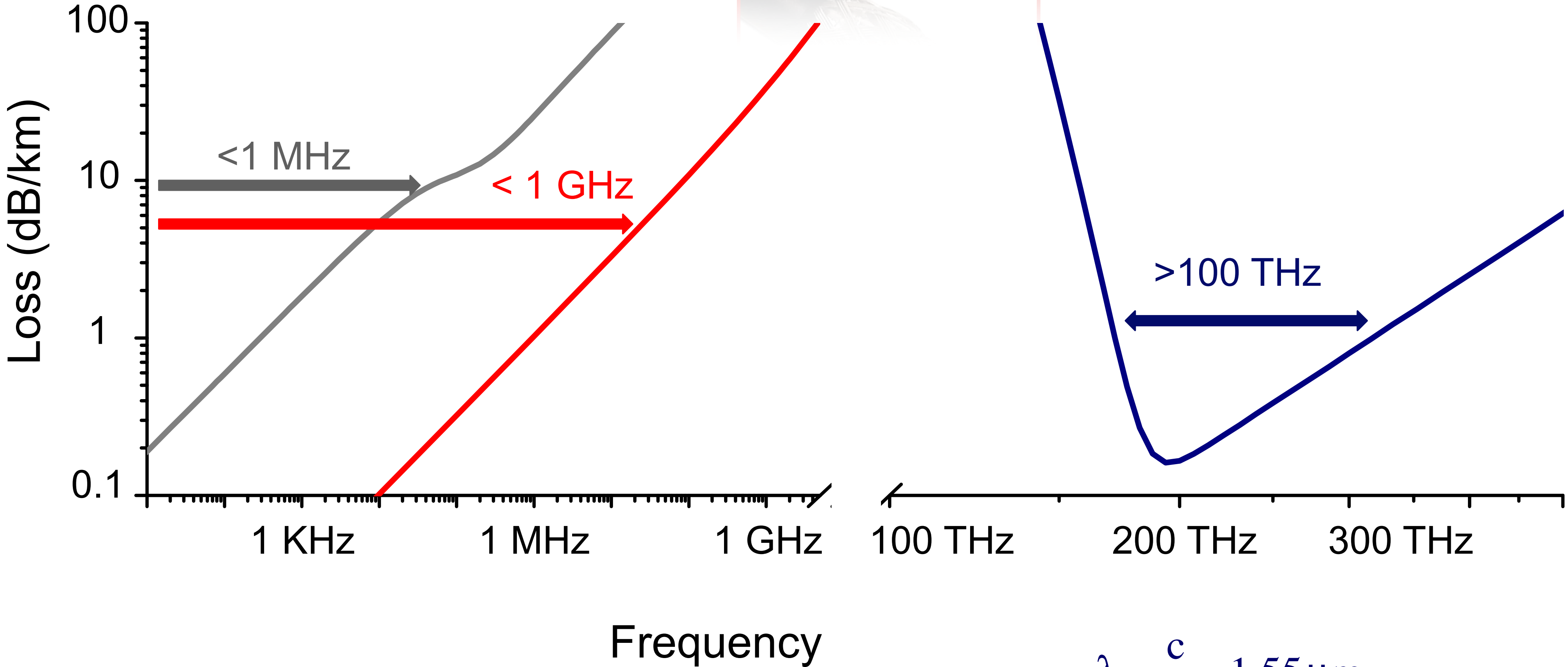
(or 7.500 turns around earth)

Transmission bandwidth



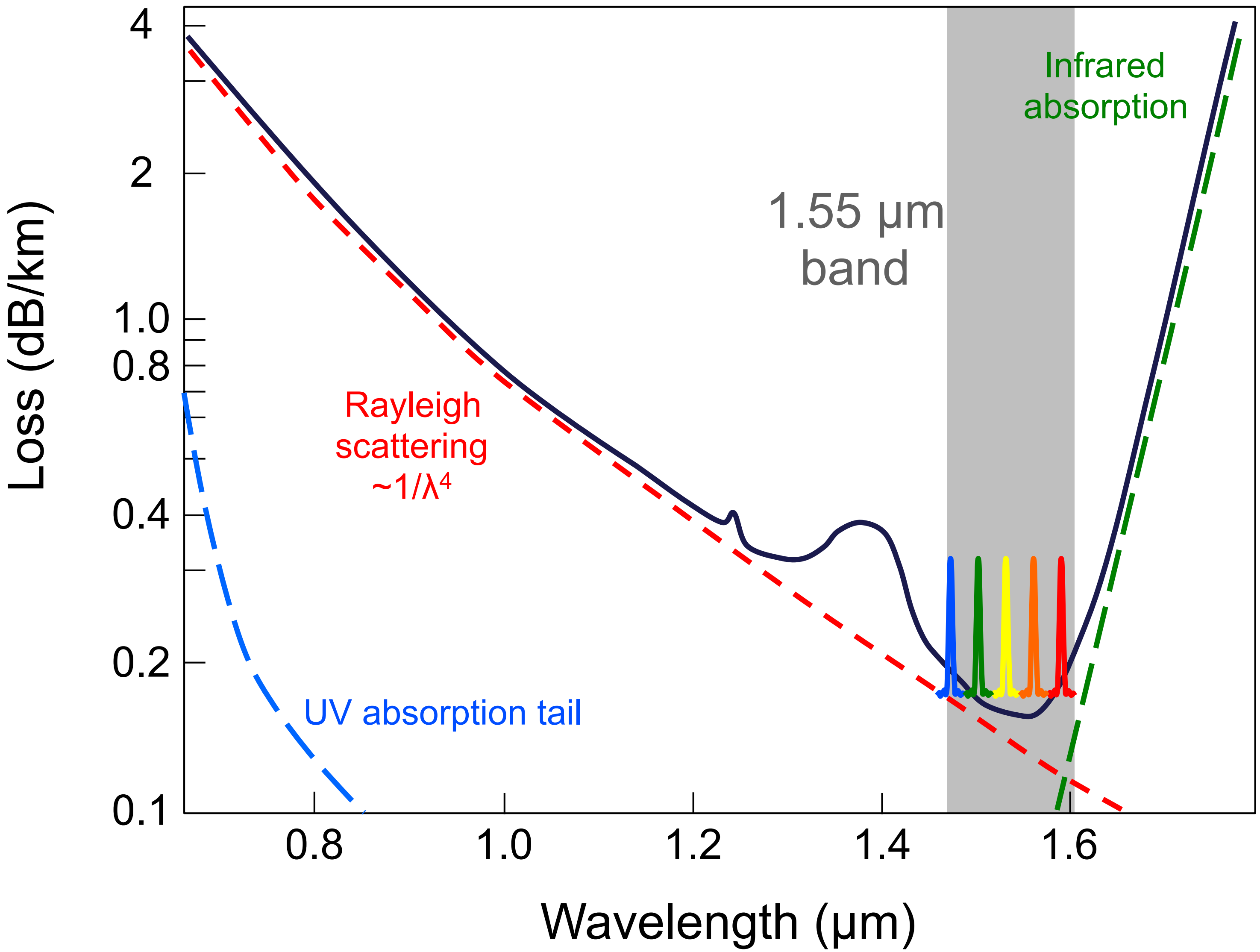




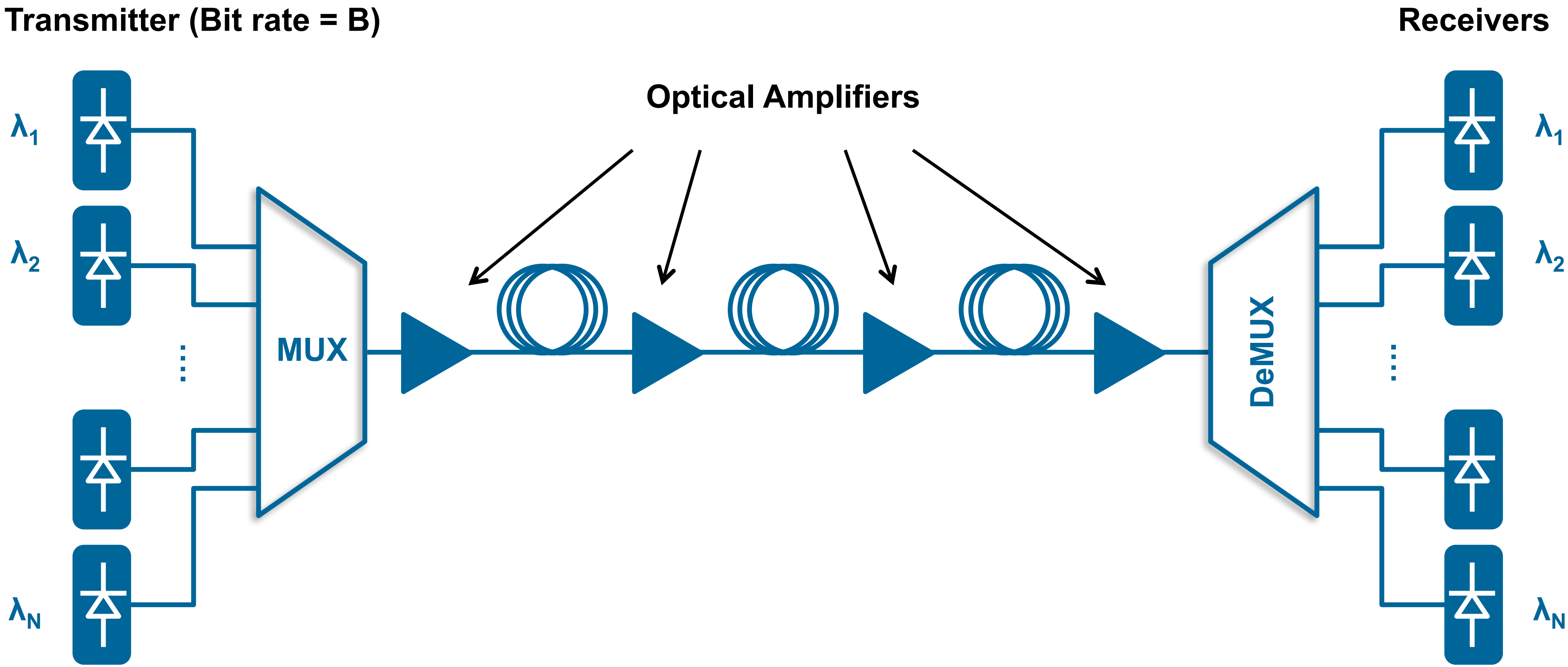


$$\lambda = \frac{c}{\nu} = 1.55\,\mu m$$

Wavelength Division Multiplexing (WDM) Systems



Wavelength Division Multiplexing (WDM) Systems



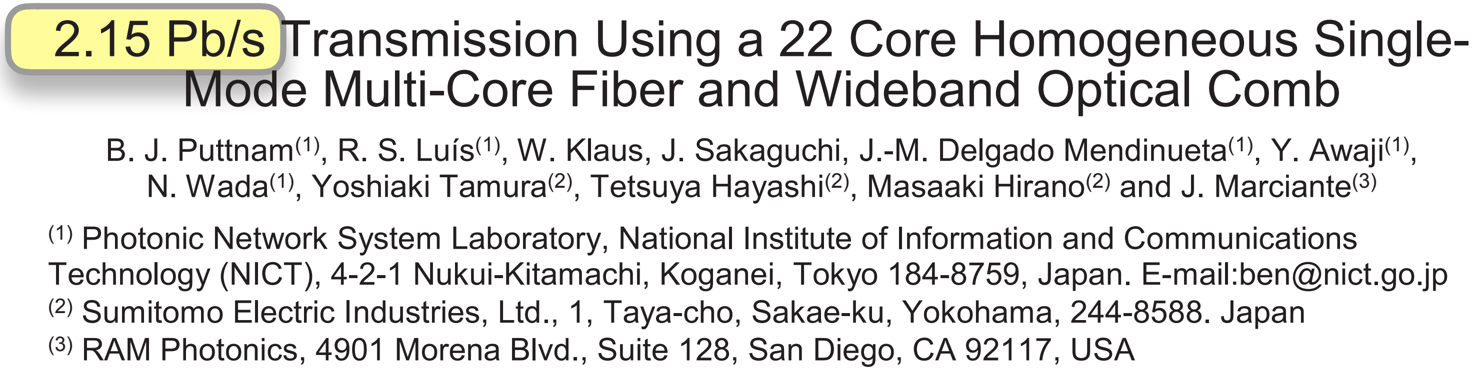
- Example: 40 lasers, 25 Gb/s each (x2 polarizations): 2 Tb/s
- 80 km spans

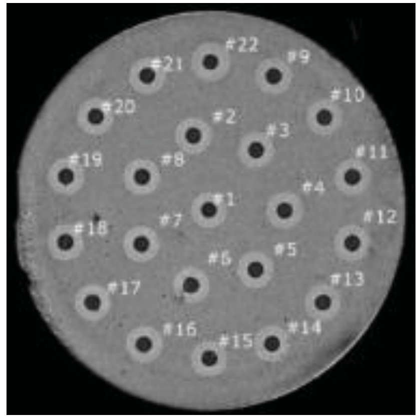
Commercial system

Padtec

Space-division multiplex: how much data can a fiber transmit?

European Conference on Optical Communications 2015





22 cores (~97 Tb/s per core)

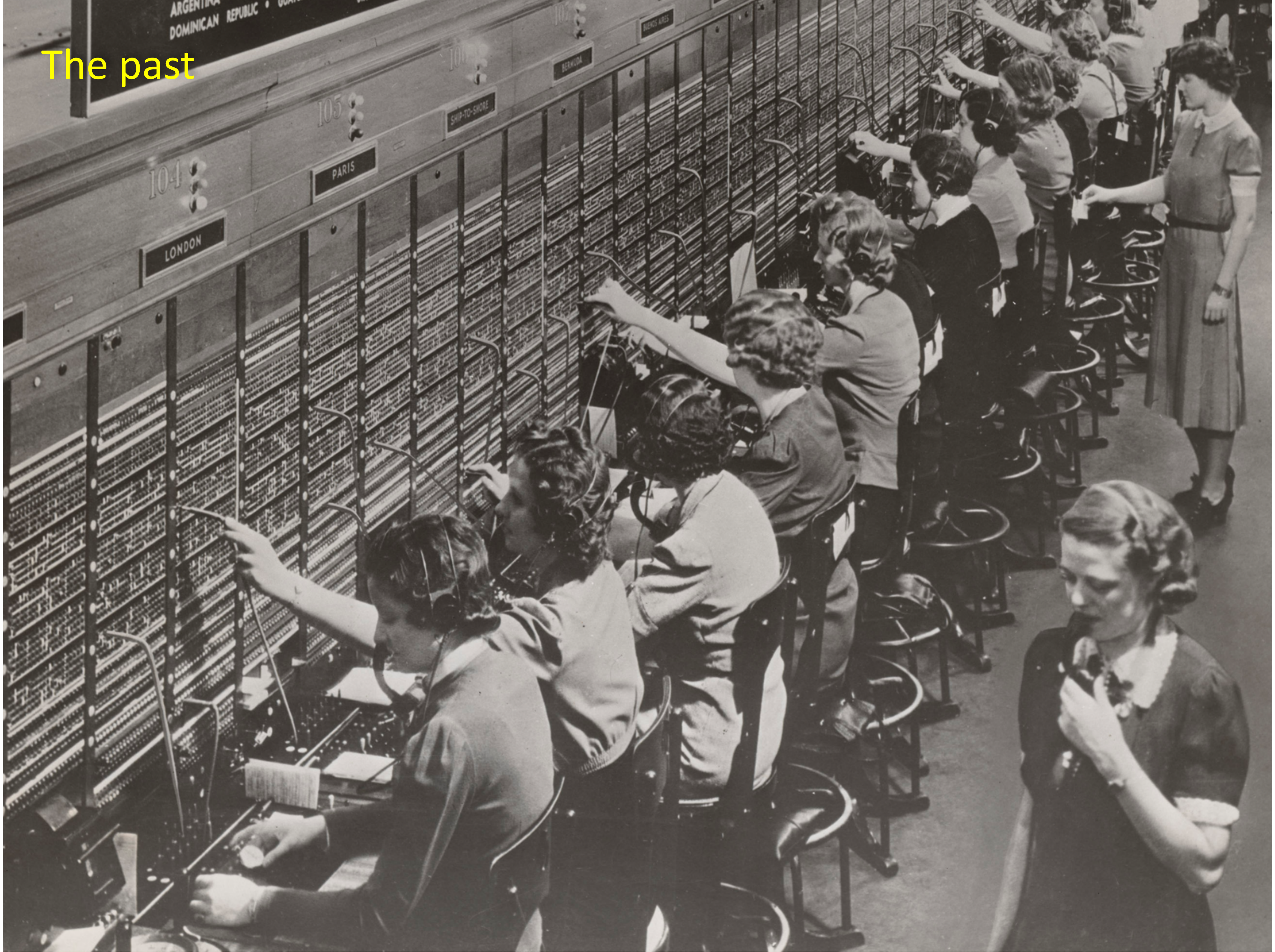
1 high-speed 10 Mb/s internet connection for each Brazilian (~200 million)

+ 15 million spare

<u>in one fiber</u>

Where do we go from here?

The past


ARGENTINA
DOMINICAN REPUBLIC
105
SHIP-TO-SHORE
BERMUDA
104
PARIS
LONDON

The past

The present

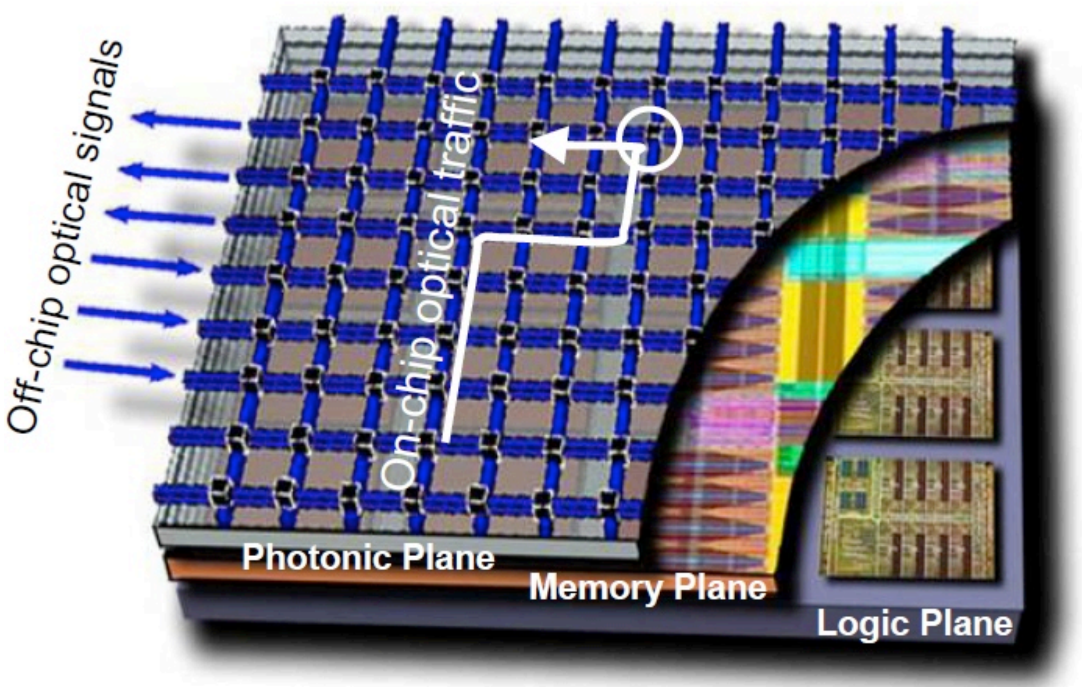
google.com/datacenters

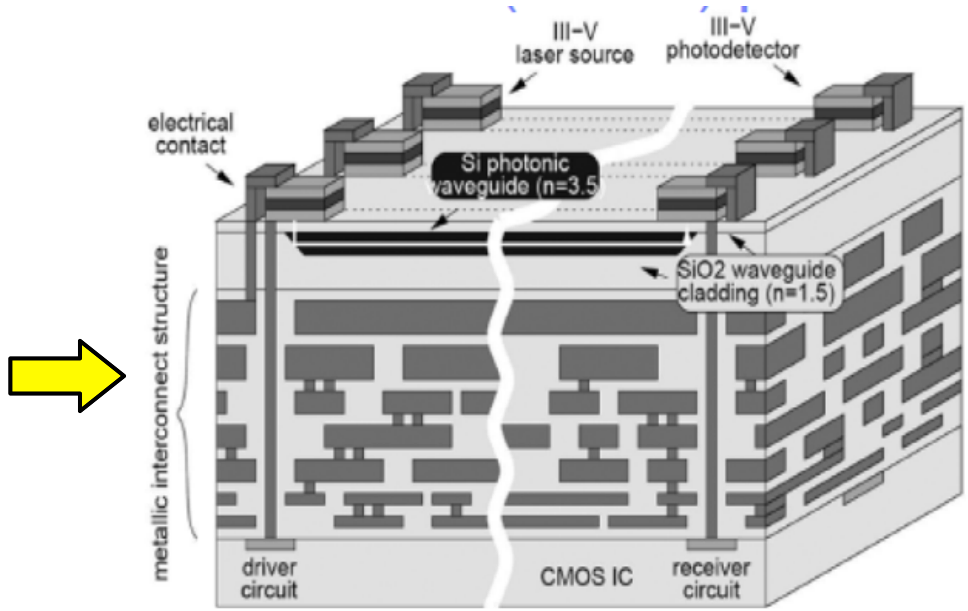
The present

The present

The future

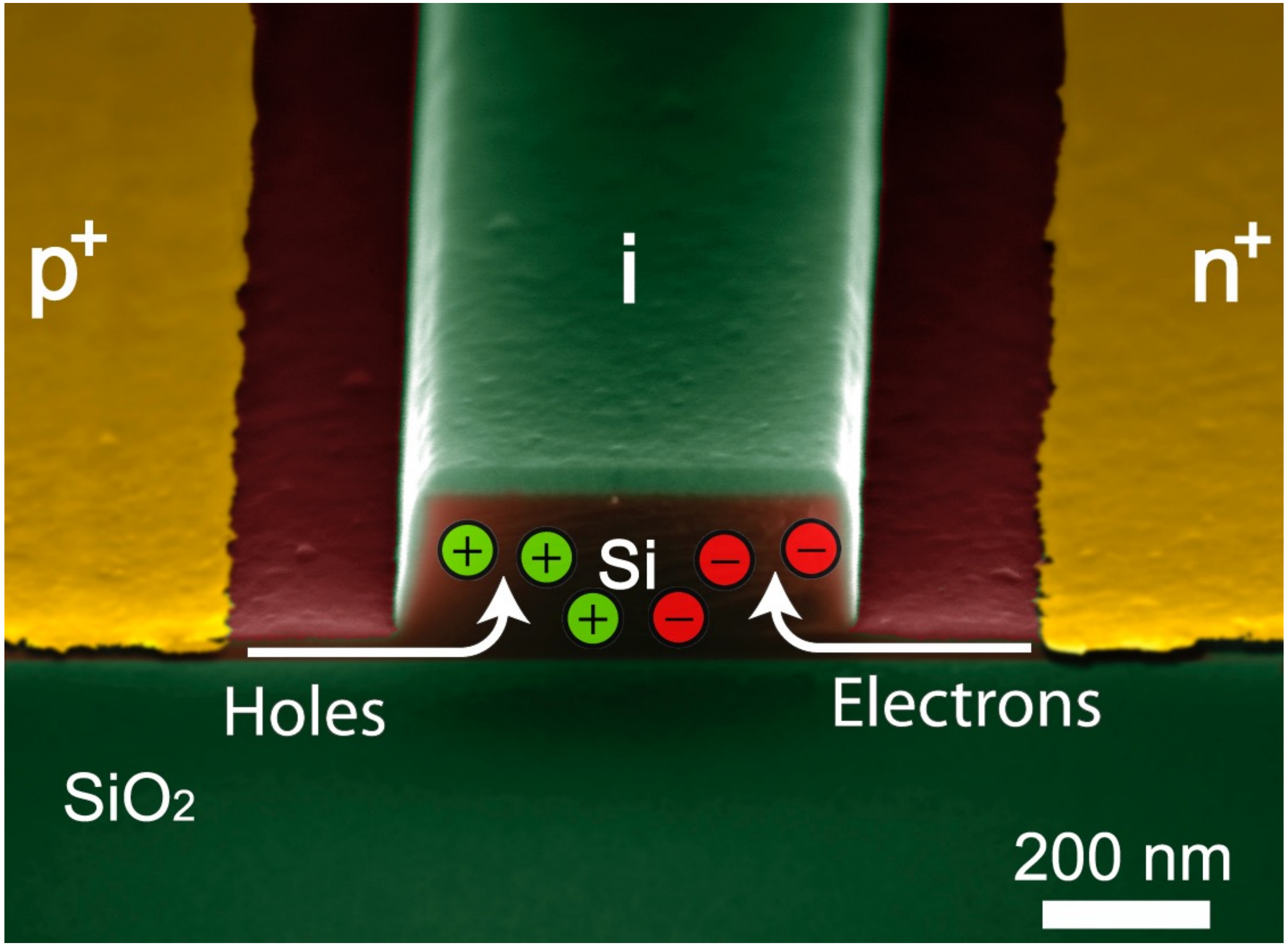
- Photonic technologies integrated into electronic chips





ibm.com

Silicon as an optical material

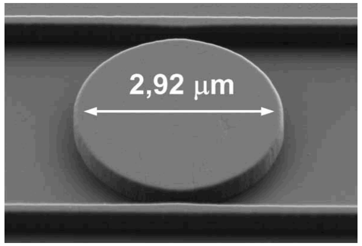


ibm.com

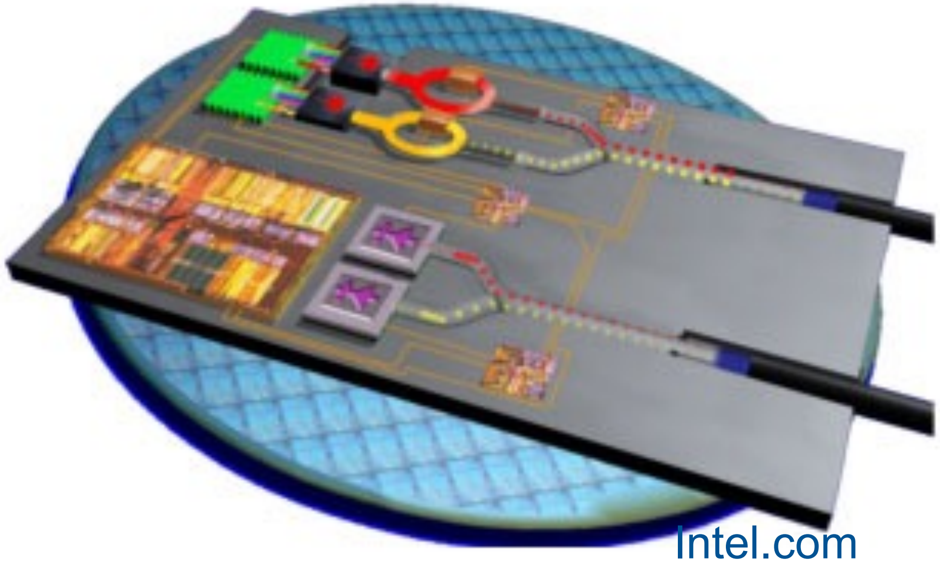
- Silicon waveguide
  - Silicon is transparent at long wavelengths (>1.1 μm)
  - WG dimensions much larger than electrical lines limited by optical wavelength
  - Electron injection can be used to alter optical properties

Basic building blocks

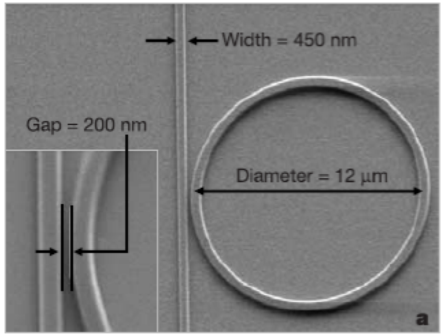
- Electronics and photonics on the same chip
- Multiple optical functions integrated (laser, waveguide, modulators, mux/demux…)
- Extensive research: most building blocks have been demonstrated but challenges remain



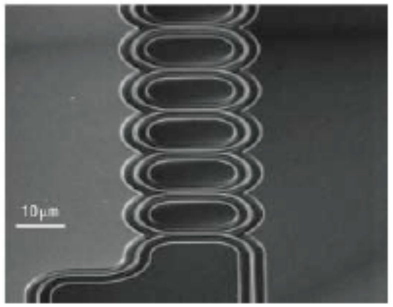
Add-drop filters
Optics Express 14, 12814 (2006)



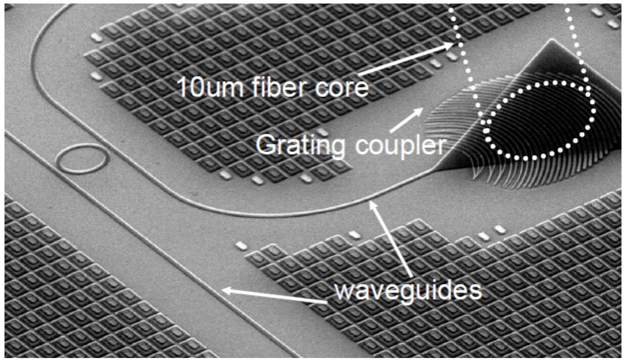
Intel.com



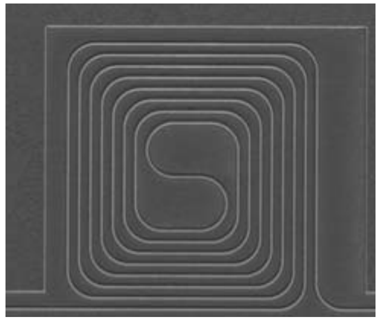
Nature 435, 325 (2005)



Optical delay line
Nature Photonics 1, 65 (2007)



Grating coupler, Luxtera



Bends
JSTQE 16, 33 (2010)

Photonic Integrated Circuits (PICs)

- The dream

THE BELL SYSTEM

TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING ASPECTS OF ELECTRICAL COMMUNICATION

Volume 48 September 1969 Number 7

Copyright © 1969 American Telephone and Telegraph Company

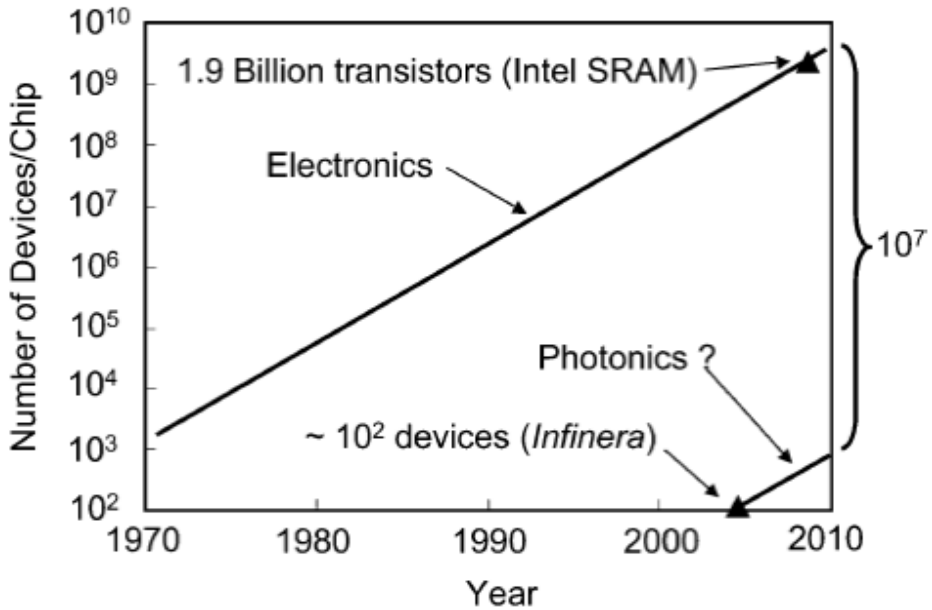
Integrated Optics: An Introduction

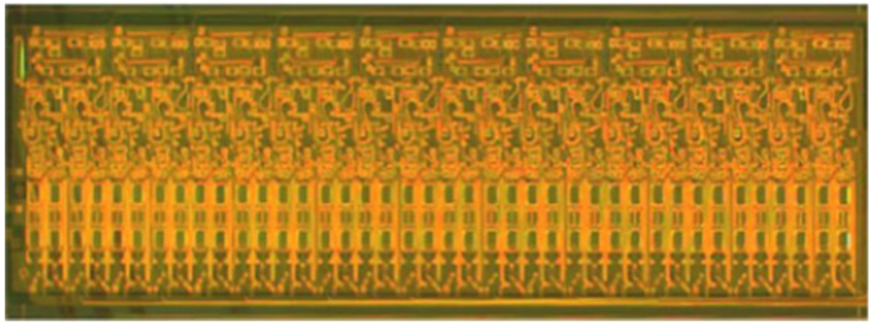
By STEWART E. MILLER

(Manuscript received January 29, 1969)

This paper outlines a proposal for a miniature form of laser beam circuitry. Index of refraction changes of the order of 10^{-2} or 10^{-3} in a substrate such as glass allow guided laser beams of width near 10 microns. Photolithographic techniques may permit simultaneous construction of complex circuit patterns. This paper also indicates possible miniature forms for a laser, modulator, and hybrids. If realized, this new art would facilitate isolating the laser circuit assembly from thermal, mechanical, and acoustic ambient changes through small overall size; economy should ultimately result.

- The reality





Infinera's 500-Gb/s PIC transmitter (InP): 10 tunable DFBs (bottom), 40 MZMs (top) and all sense and control functions required

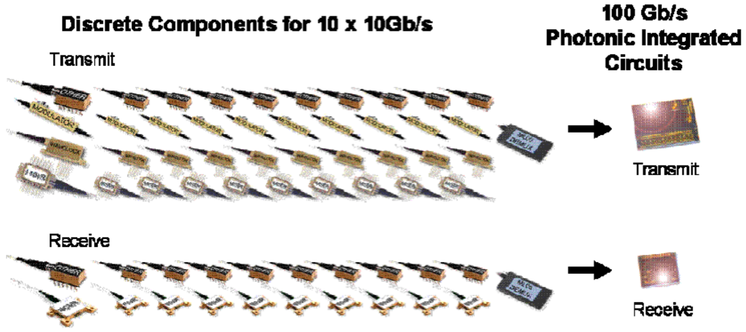
Why **EIC** is so successful and **PIC** has been harder to do?

Electronic Integrated Circuits	Photonic Integrated Circuits
• Planar FET – the building block;	• Require a wide variety of different devices (e.g., lasers, detectors, modulators, multiplexers, attenuators);
• Ideal materials: single-element silicon substrate, silica insulator, and aluminum wiring;	• Based on binary, ternary and quaternary materials that are much harder to control than Si;
• Scalable circuit (CMOS): cost per transistor drops as density increases;	• Photonic device sizes are limited by the optical wavelength (micron), much larger than the electron size limit;
• Real applications (e.g., memory and microprocessors) that need continuous progress of integration;	• Few applications that require both large-scale integration and high volume, with attendant low cost, have been identified.

(I. Kaminow, 2008)

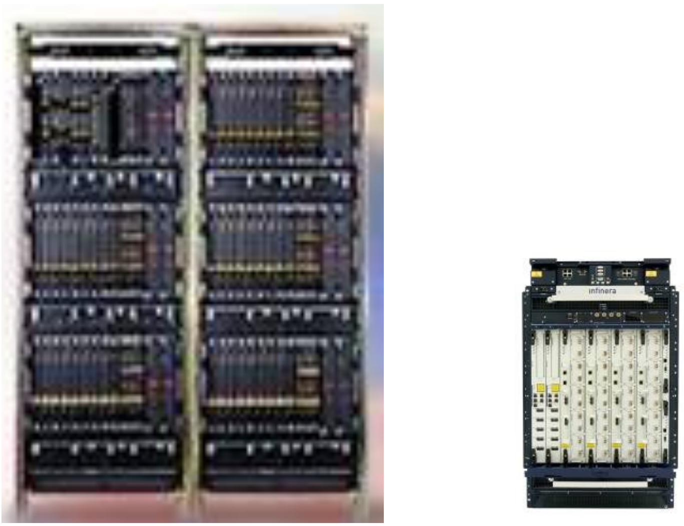
Discrete vs. Integrated Photonic Circuit

Card level



Tx Count	10G NRZ-OOK Discrete (40 X 10G)	NRZ-DQPSK Discrete (10 X 40G)	NRZ-PM-DQPSK Discrete (10 X 40G)	DQPSK PIC (1 X 400G)
Optical Components	DFB, MOD, VOA, AWG	DFB, SMZ, VOA, AWG	DFB, PBS, 2xSMZ, 2xVOA, PBC, AWG	PIC
# of Optical Components for 400G	121	31	71	1
# of Fiber Couplings for 400G	241	61	161	1

System level



Components	Discrete	Integrated
Size	2 bays (40×10Gb/s) 3-4 bays (80×10Gb/s)	Half-bay (40 × 10 Gb/s) 1 bay (80 × 10 Gb/s)
Line Card Capacity	10 Gb/s	100 Gb/s
# Orderable Parts	≈ 200	≈ 20
Line-Side Fibers (400G)	≈ 50	5

Infinera.com

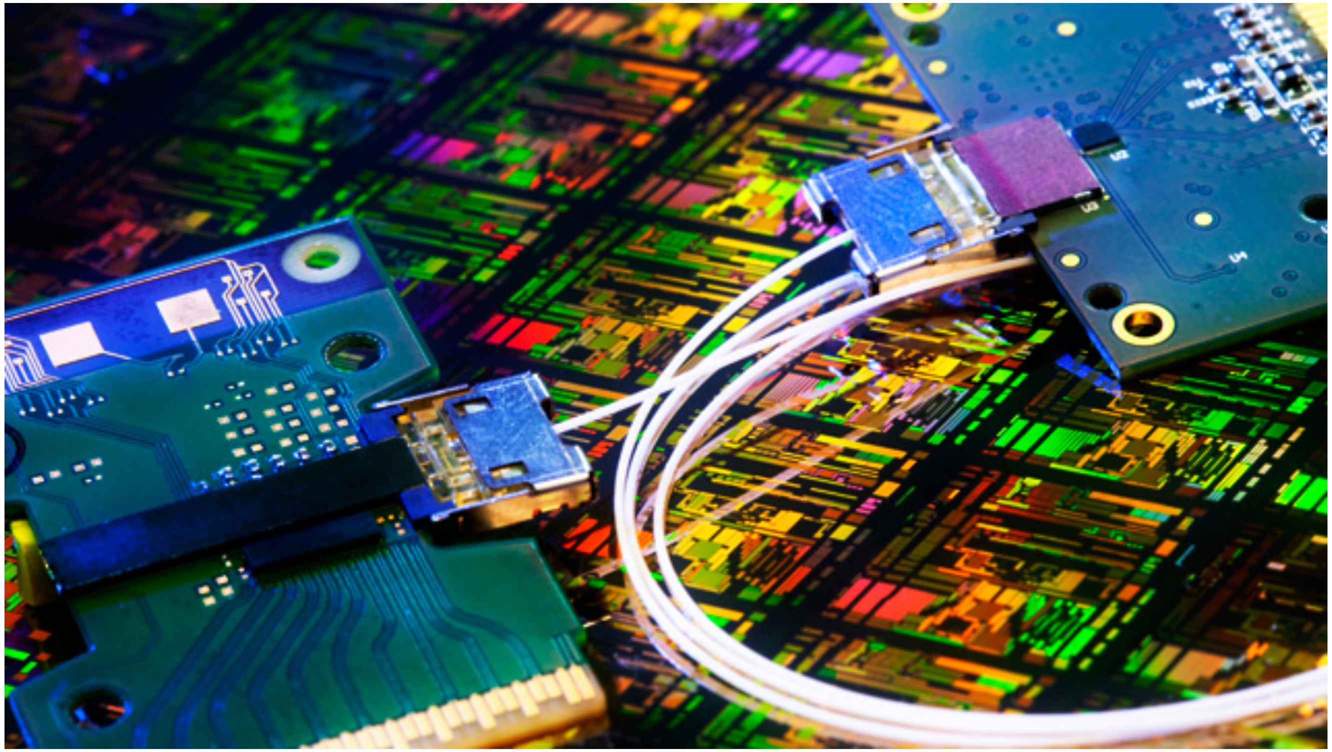
The future

- New's room: IBM's Silicon Photonics Technology Ready to Speed up Cloud and Big Data Applications (2015)

100 Gb/s silicon photonics transceiver

The future

- Intel's silicon photonics 100 Gb/s prototype chips



Outline

- Future of Optical Communications
- Why are we interested in photon-phonon interaction?
- **Our work: Brillouin scattering self-cancellation effect**
- what else is going on in our lab…
  - Free-carriers dispersion and thermal phase shift in silicon waveguides
  - High-order modes in photonics bandgap fibers and tapers
  - Broadband & small footprint dielectric antenna

Why do we care?

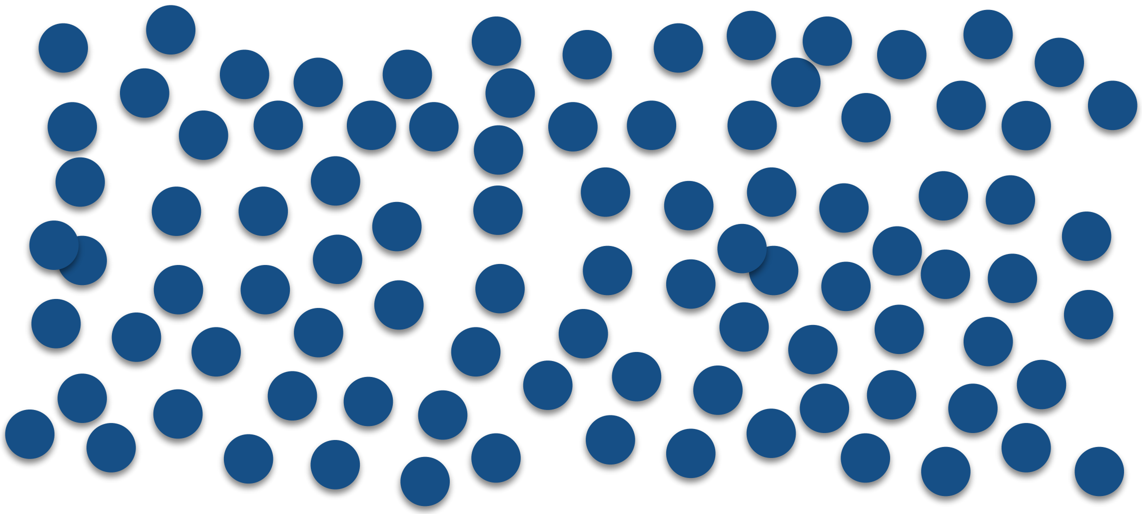
Light fields generate elastic waves

↔

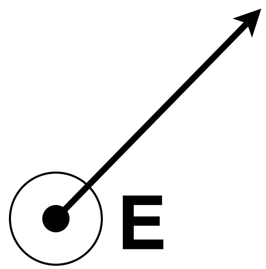
Elastic waves alter the propagation of light

we can use this interaction to build devices!

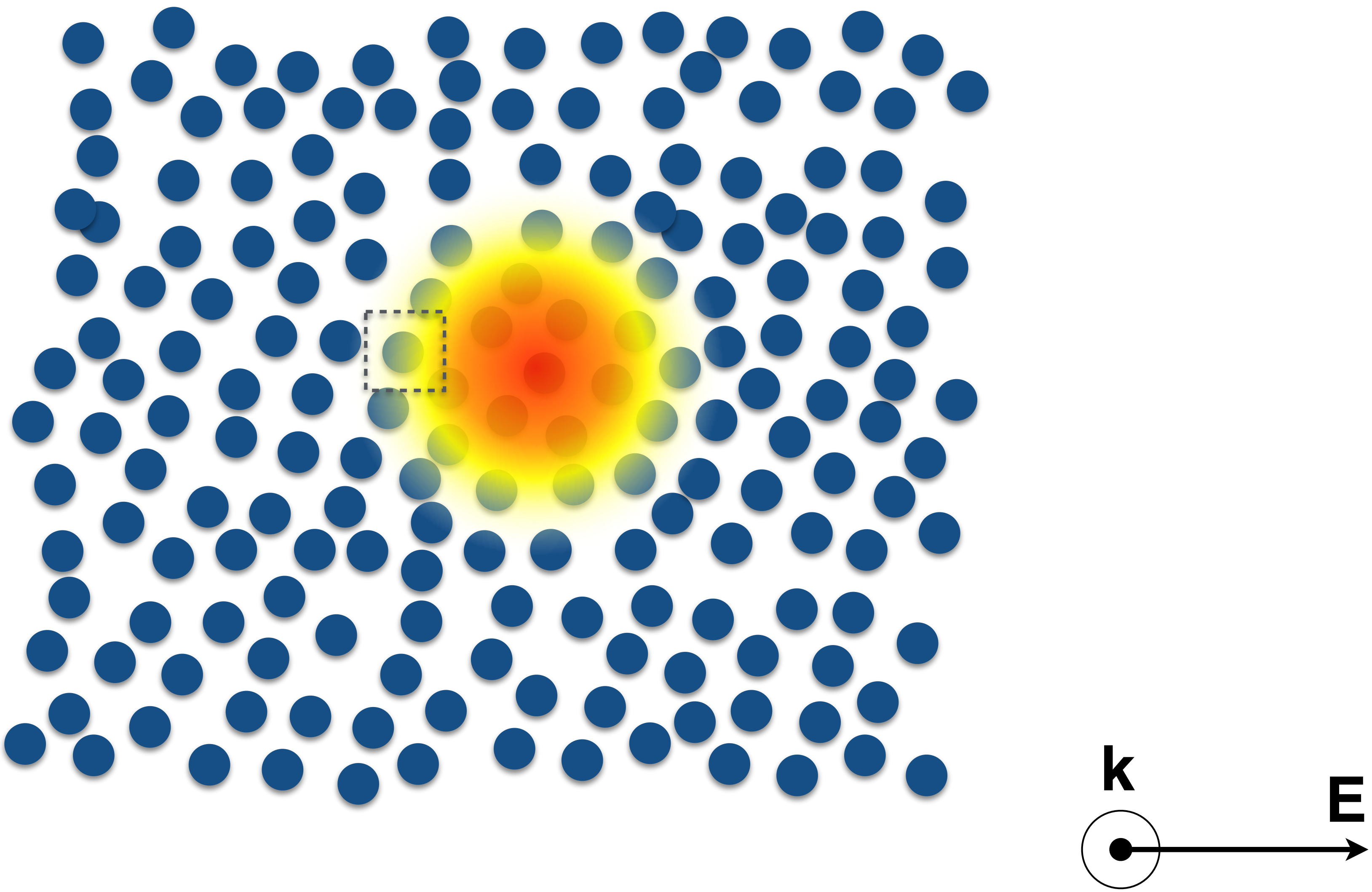
Radiation pressure



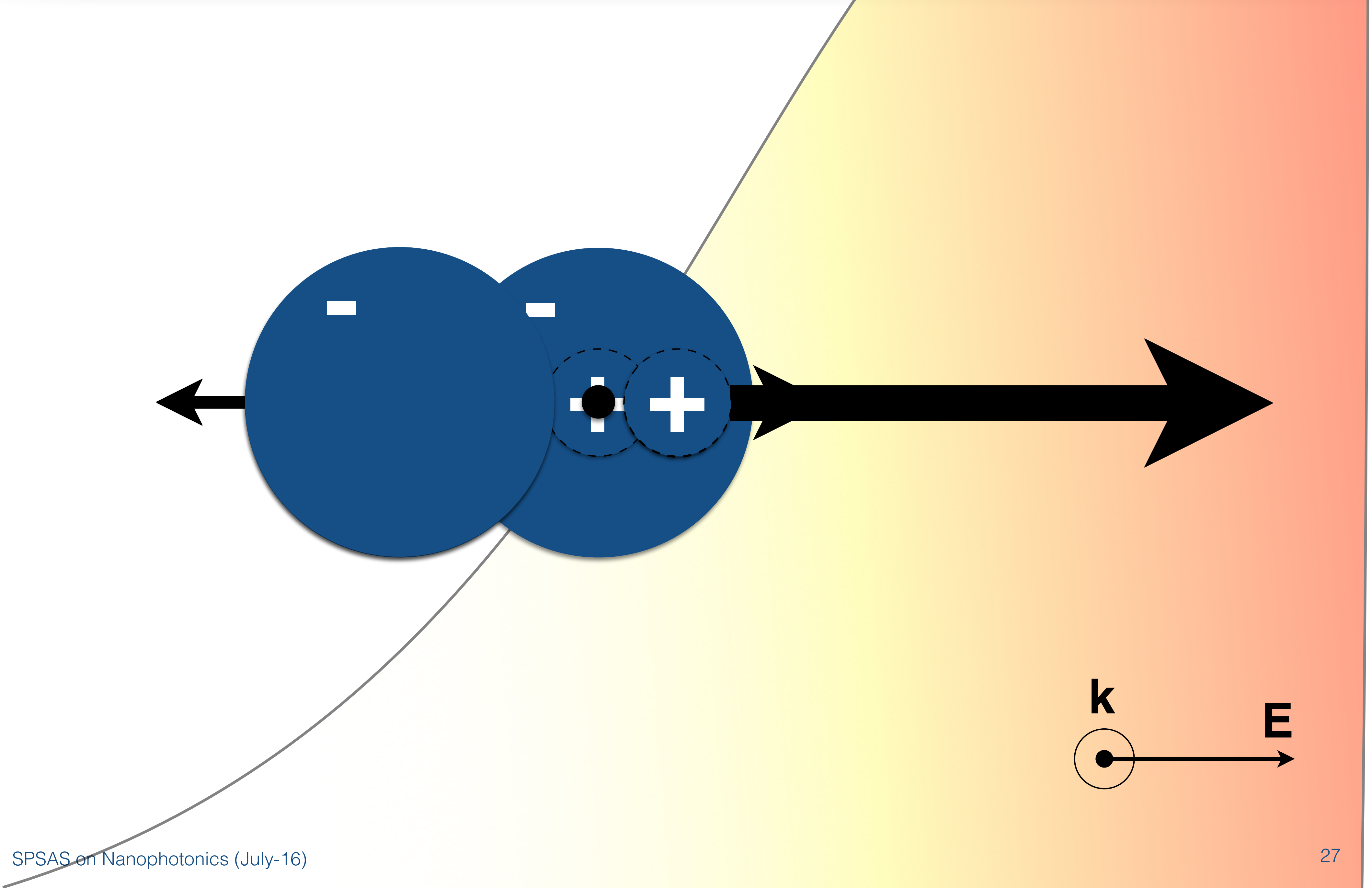
Time varying perturbation in the materials refractive index
➠ Emission of radiation



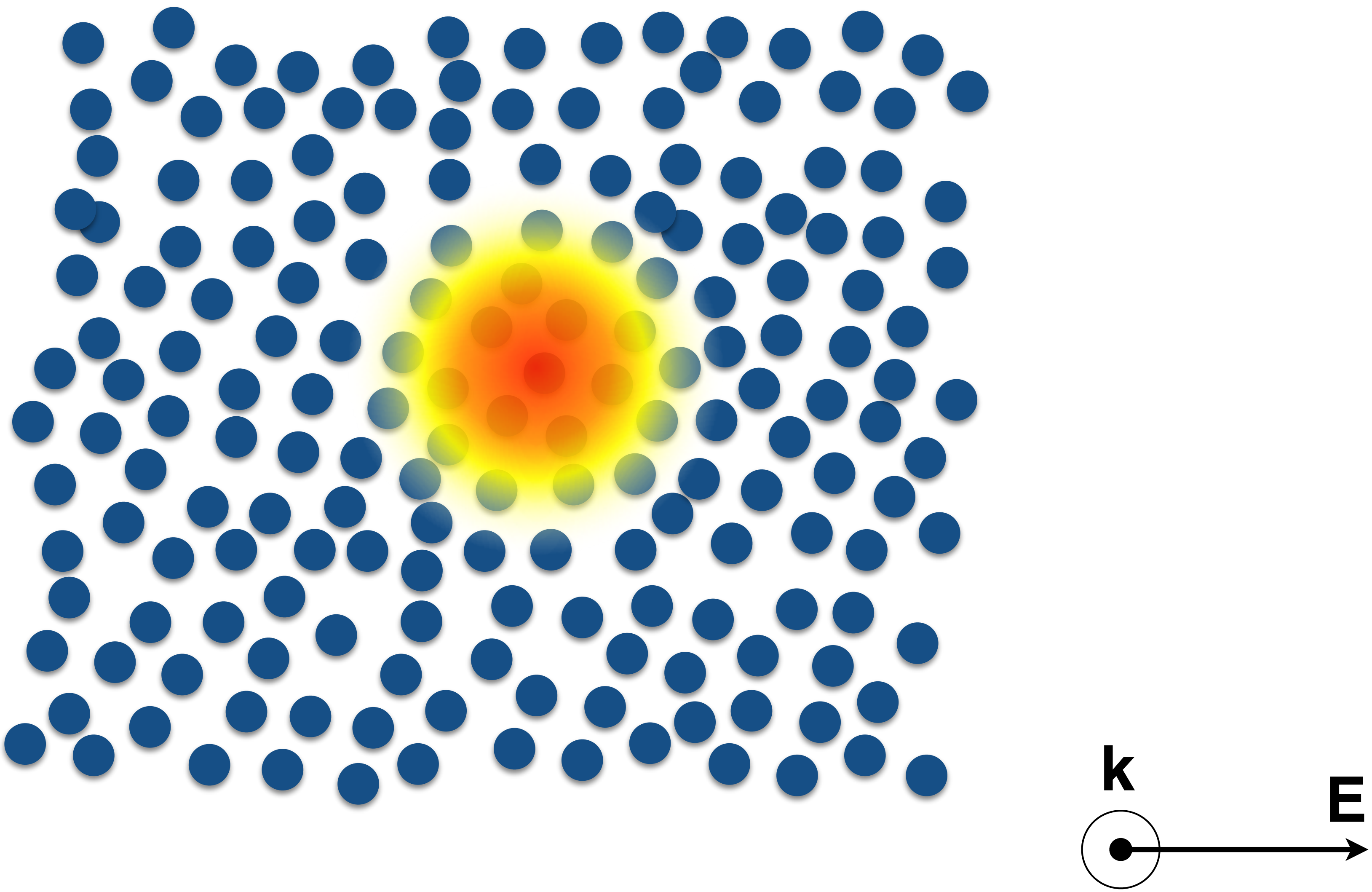
Electrostriction force



Electrostriction force

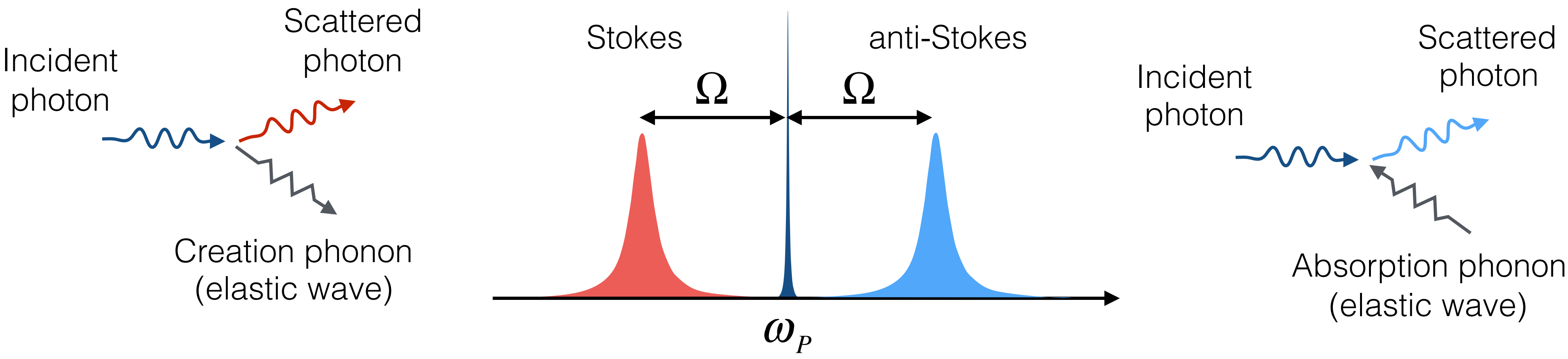


Electrostriction force

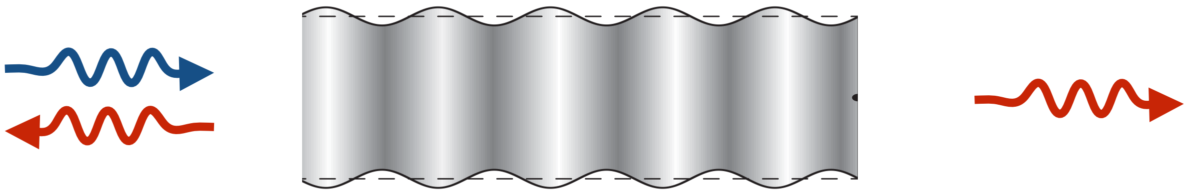


Brillouin scattering

- Energy conservation: creation or absorption of an acoustic phonon (elastic wave)



- Momentum conservation: in waveguides and cavities, only backward and forward directions are allowed



Backward Brillouin scattering: $\beta = \pm(\beta_P + \beta_S) \simeq \pm 2\beta_P$ Propagating elastic wave

Forward Brillouin scattering: $\beta = \pm(\beta_P - \beta_S) \simeq 0$ Cut-off elastic wave

Fundamental & Practical applications

nature physics

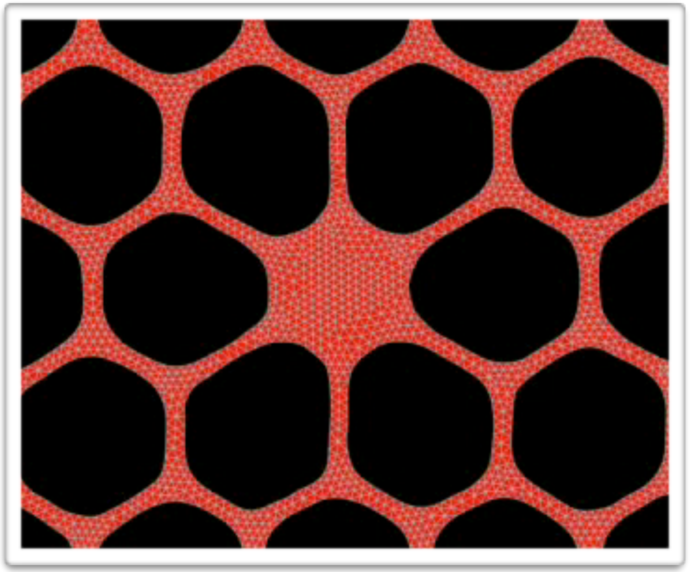
LETTERS

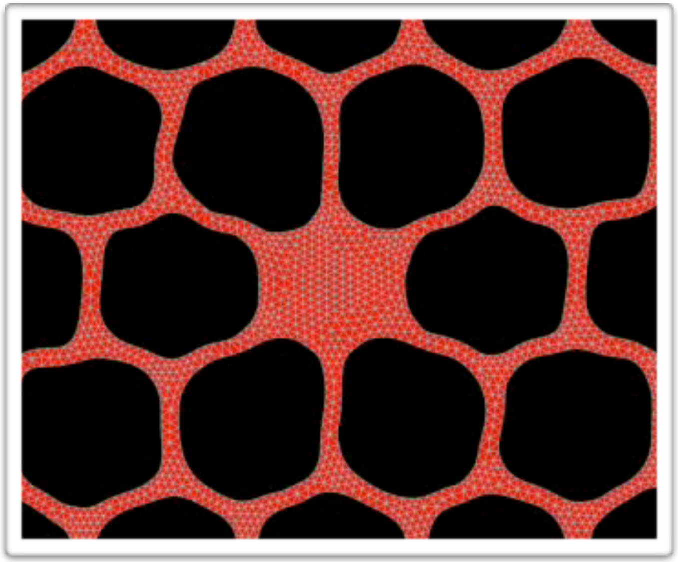
Stimulated Brillouin scattering from multi-GHz-guided acoustic phonons in nanostructured photonic crystal fibres

P. DAINESE[1,2], P. ST. J. RUSSELL[1,3]*, N. JOLY[1,3], J. C. KNIGHT[1], G. S. WIEDERHECKER[2], H. L. FRAGNITO[2], V. LAUDE[4] AND A. KHELIF[4]

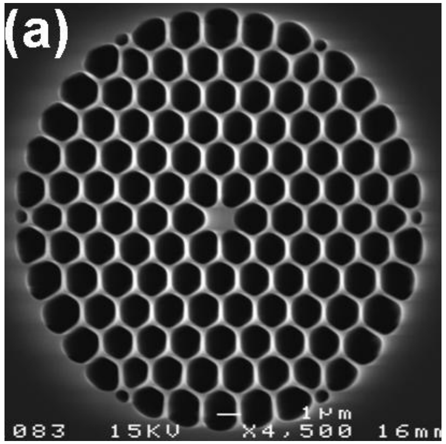
[1]Photonics & Photonic Materials Group, Department of Physics, University of Bath, Bath BA2 7AY, UK
[2]CePOF, Instituto de Física, Universidade Estadual de Campinas, 13.083-970 Campinas SP, Brazil
[3]Max-Planck Research Group (IOIP), University of Erlangen-Nuremberg, Guenther-Scharowsky-Str., 1/Bau 24, 91058 Erlangen, Germany
[4]Département LPMO, Institut FEMTO-ST, 32 avenue de l'Observatoire, F-25044 Besançon cedex, France
*e-mail: russell@optik.uni-erlangen.de

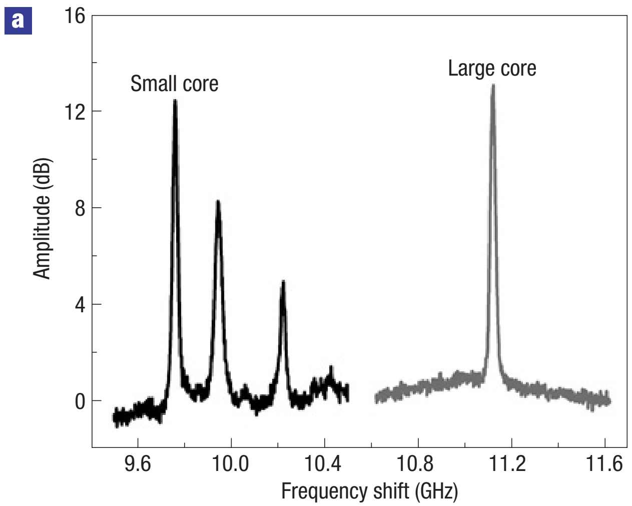
nature physics | VOL 2 | JUNE 2006 | www.nature.com/naturephysics





Photon-phonon confinement in sub-wavelength structures





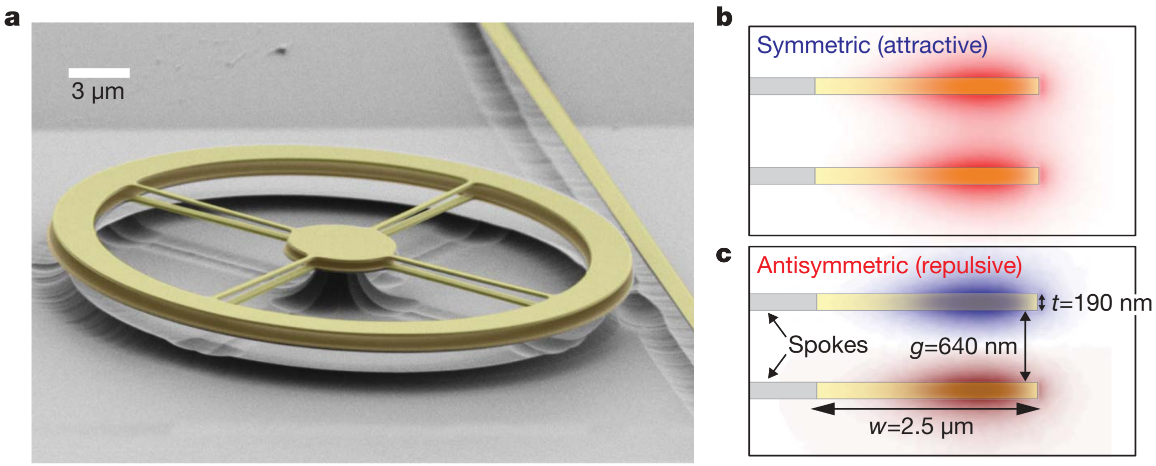
Fundamental & Practical applications

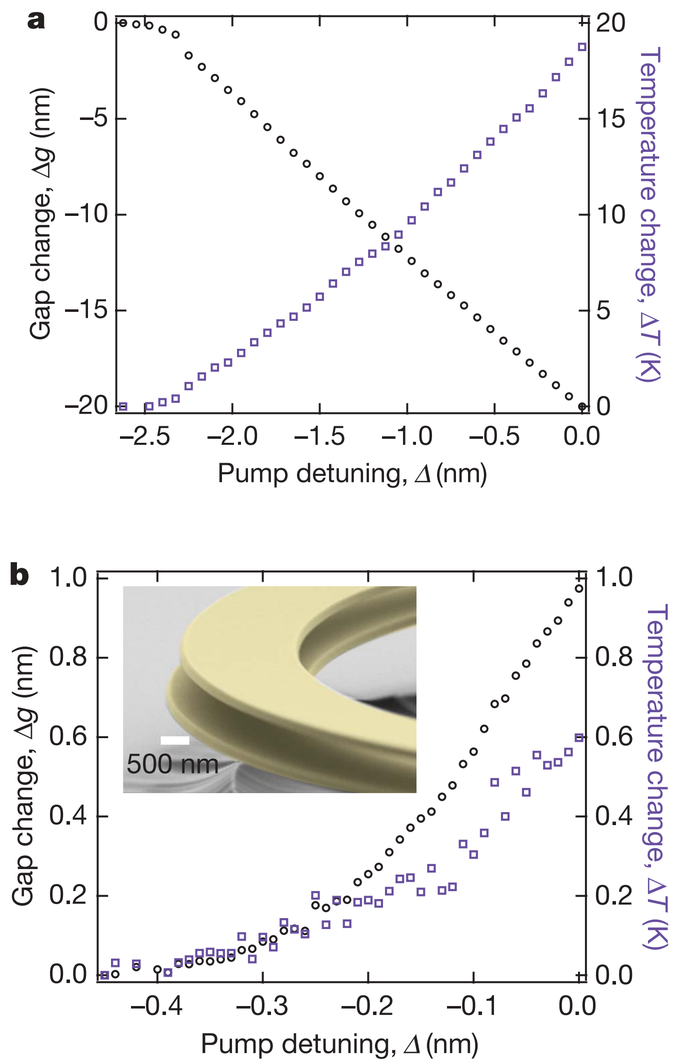
Vol 462|3 December 2009|**doi:10.1038/nature08584** nature

LETTERS

Controlling photonic structures using optical forces

Gustavo S. Wiederhecker[1], Long Chen[1], Alexander Gondarenko[1] & Michal Lipson[1]





Fundamental & Practical applications

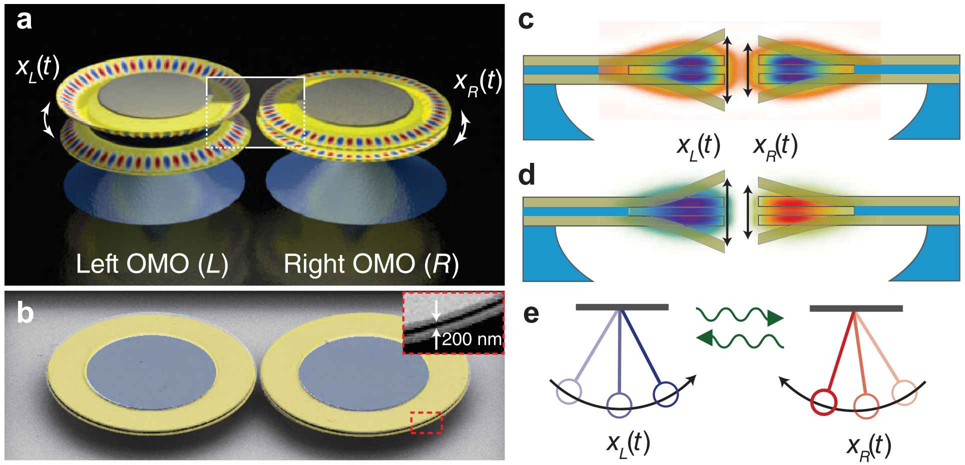
PRL 109, 233906 (2012) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2012

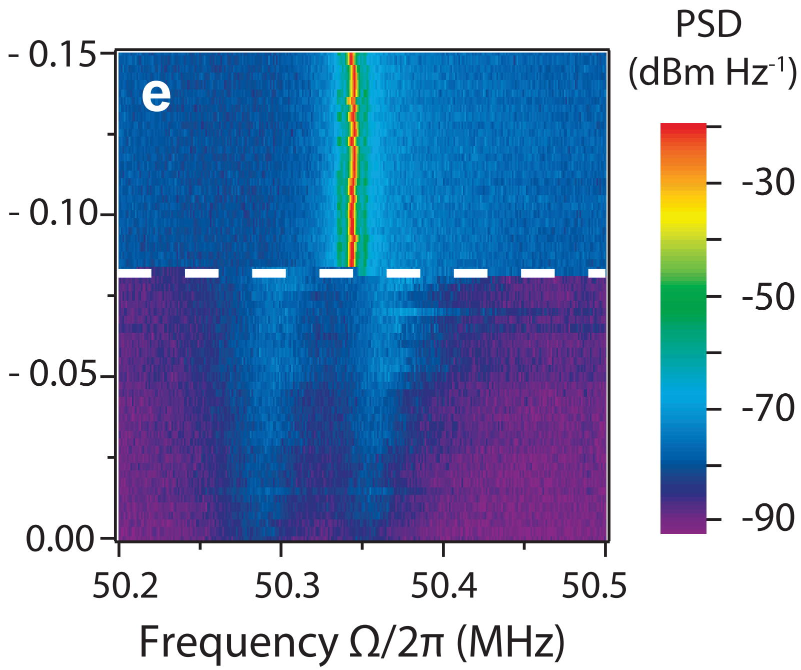
Synchronization of Micromechanical Oscillators Using Light

Mian Zhang,[1] Gustavo S. Wiederhecker,[1,2] Sasikanth Manipatruni,[1] Arthur Barnard,[3]
Paul McEuen,[3,4] and Michal Lipson[1,4]

[1]*School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853, USA*
[2]*Instituto de Física, Universidade Estadual de Campinas, 13083-970 Campinas, SP, Brazil*
[3]*Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853, USA*
[4]*Kavli Institute at Cornell for Nanoscale Science, Ithaca, New York 14853, USA*

Synchronization of mechanical oscillators





Fundamental & Practical applications

REVIEW ARTICLE | FOCUS

Slow and fast light in optical fibres

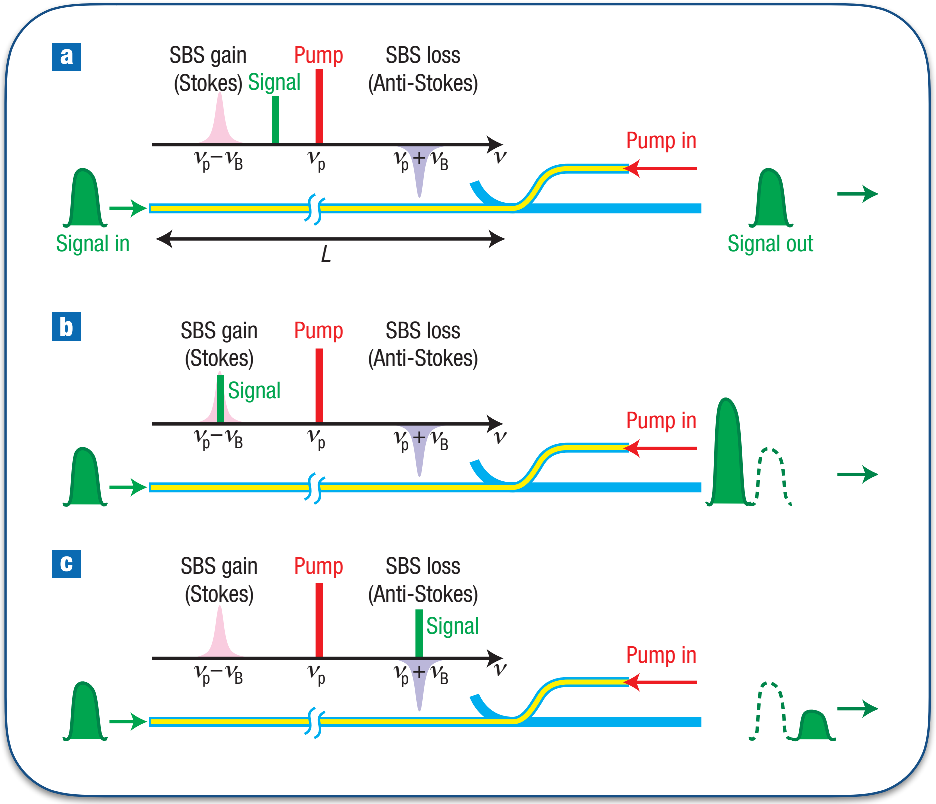
LUC THÉVENAZ
Swiss Federal Institute of Technology, École Polytechnique Fédérale de Lausanne (EPFL), Institute of Electrical Engineering, Station 11, 1015 Lausanne, Switzerland
e-mail: Luc.Thevenaz@epfl.ch

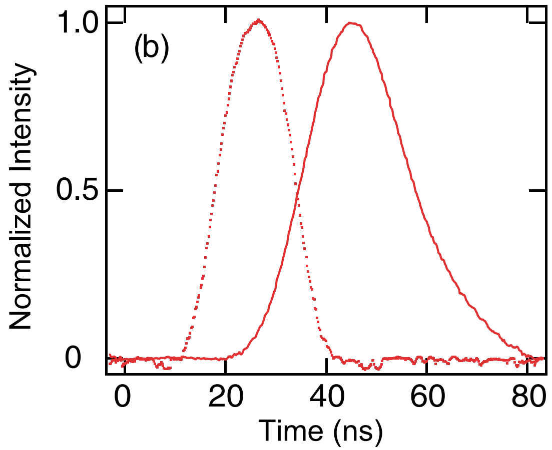
nature photonics | VOL 2 | AUGUST 2008 | www.nature.com/naturephotonics

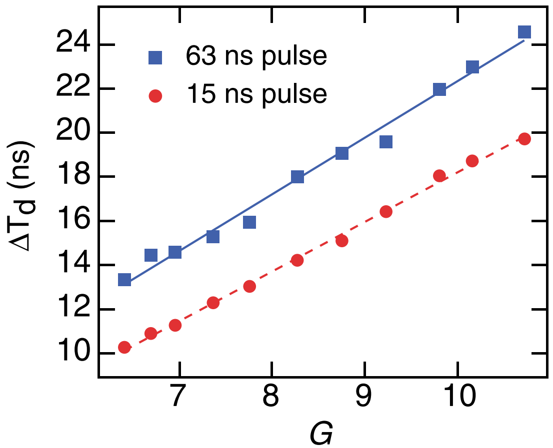
PRL 94, 153902 (2005) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2005

Tunable All-Optical Delays via Brillouin Slow Light in an Optical Fiber

Yoshitomo Okawachi,[1] Matthew S. Bigelow,[2] Jay E. Sharping,[1] Zhaoming Zhu,[3] Aaron Schweinsberg,[2] Daniel J. Gauthier,[3] Robert W. Boyd,[2] and Alexander L. Gaeta[1]
[1]School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA
[2]The Institute of Optics, University of Rochester, Rochester, New York 14627, USA
[3]Department of Physics, Duke University, Durham, North Carolina 27708, USA
(Received 7 January 2005; published 18 April 2005)





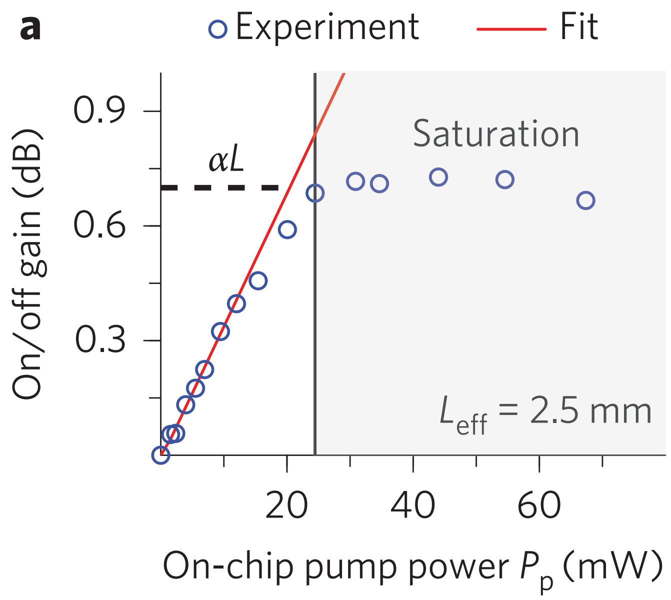


Fundamental & Practical applications

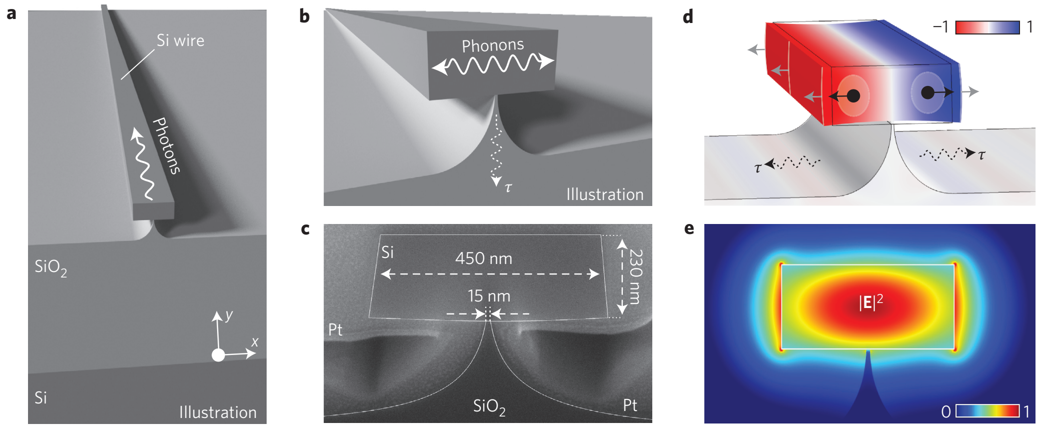
nature photonics | ARTICLES
PUBLISHED ONLINE: 16 FEBRUARY 2015 | DOI: 10.1038/NPHOTON.2015.11

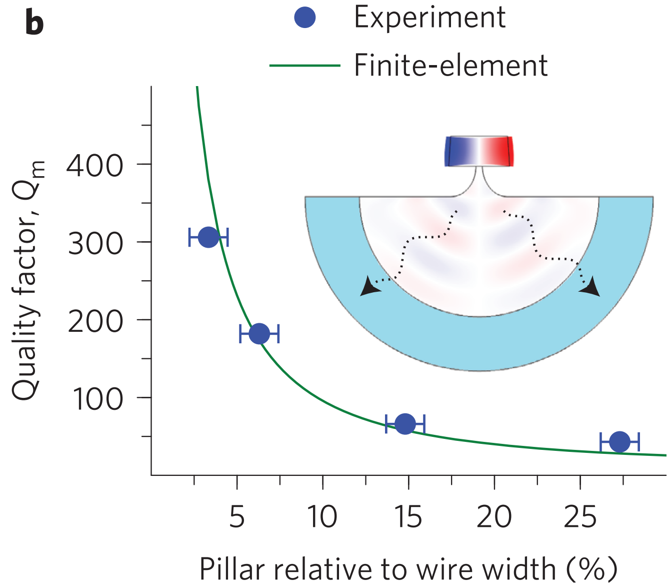
Interaction between light and highly confined hypersound in a silicon photonic nanowire

Raphaël Van Laer[1,2]*, Bart Kuyken[1,2], Dries Van Thourhout[1,2] and Roel Baets[1,2]



Brillouin amplification





Fundamental & Practical applications

nature COMMUNICATIONS

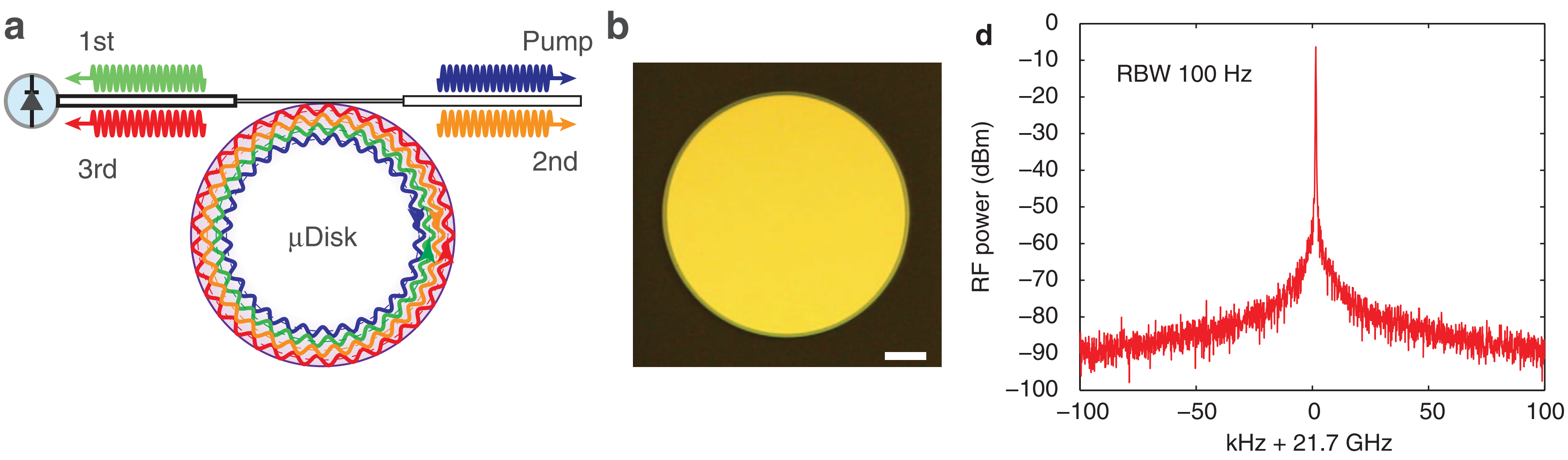
ARTICLE

Received 20 Mar 2013 | Accepted 4 Jun 2013 | Published 28 Jun 2013 DOI: 10.1038/ncomms3097

Microwave synthesizer using an on-chip Brillouin oscillator

Jiang Li[1], Hansuek Lee[1] & Kerry J. Vahala[1]

Low-phase noise microwave oscilator

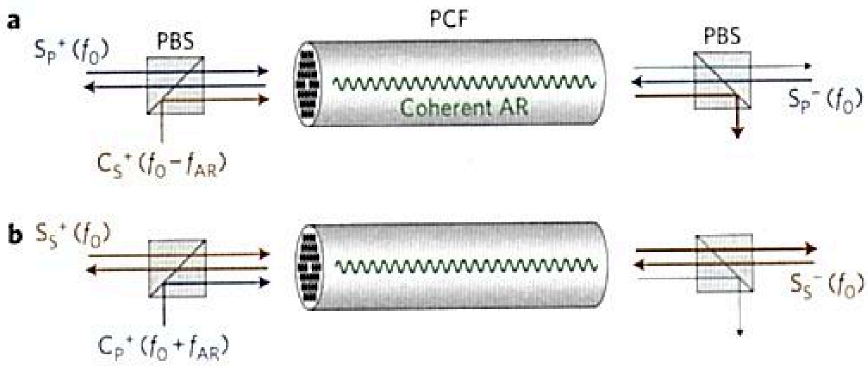


Fundamental & Practical applications

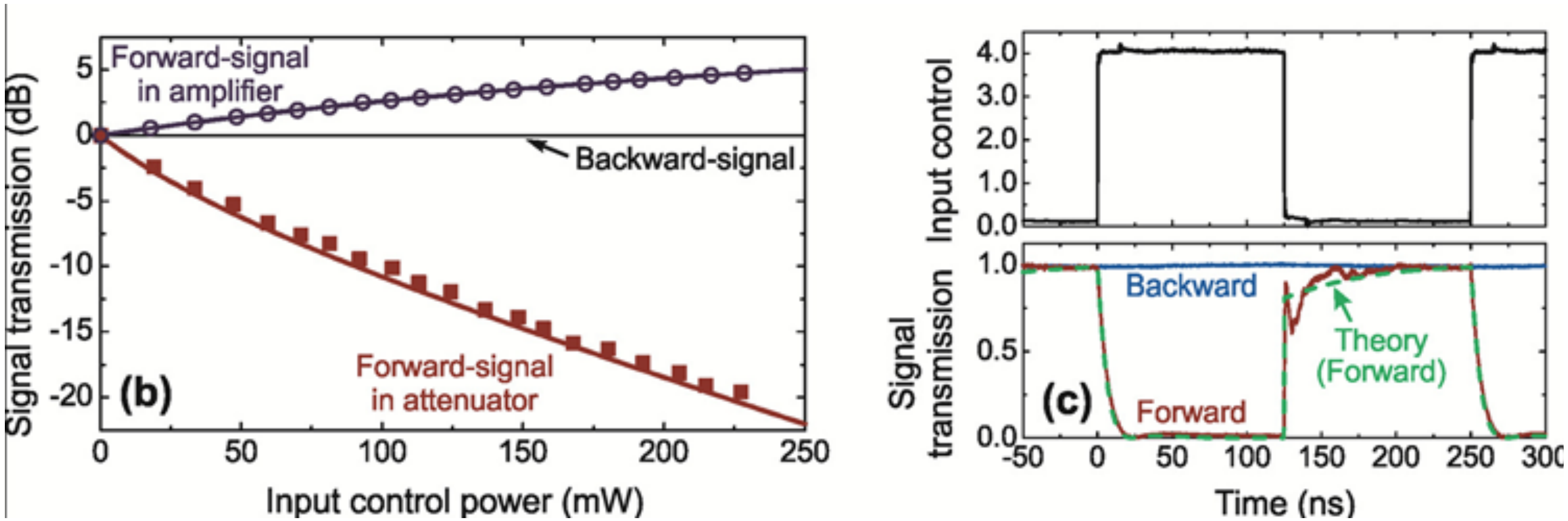
nature photonics
ARTICLES
PUBLISHED ONLINE: 14 AUGUST 2011 | DOI: 10.1038/NPHOTON.2011.180

Reconfigurable light-driven opto-acoustic isolators in photonic crystal fibre

M. S. Kang*, A. Butsch and P. St. J. Russell



Optical isolator and switching



Fundamental & Practical applications

Research Article Vol. 1, No. 3 / September 2014 / *Optica* 158

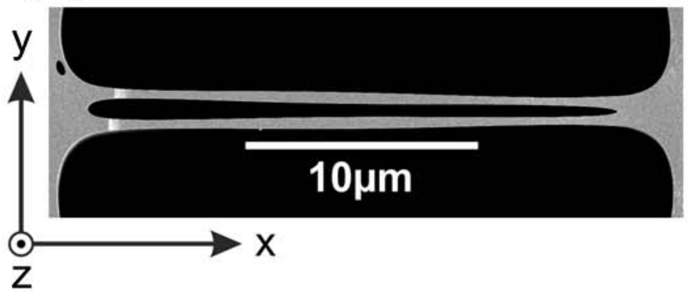
optica

CW-pumped single-pass frequency comb generation by resonant optomechanical nonlinearity in dual-nanoweb fiber

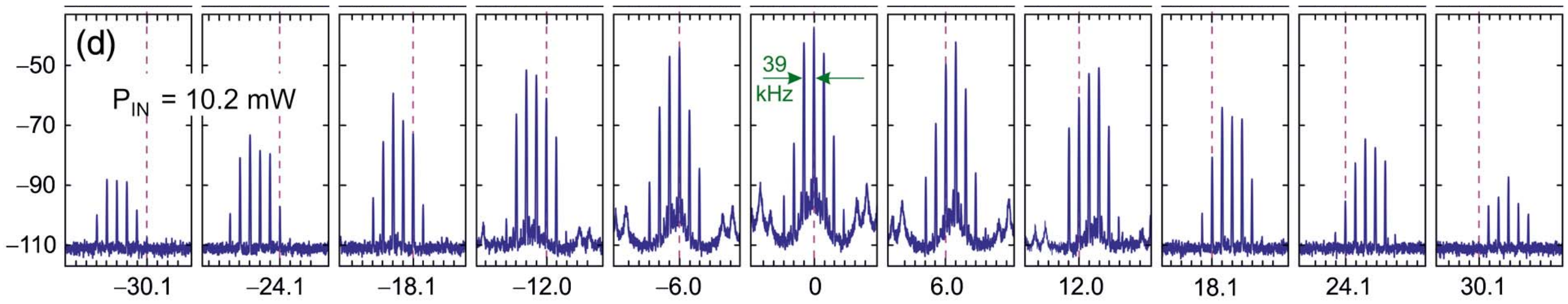
A. Butsch,* J. R. Koehler, R. E. Noskov, and P. St.J. Russell

Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1, 91058 Erlangen, Germany

**Corresponding author: anna.butsch@mpl.mpg.de*



Generation of Frequency Combs



A. Butsch et al. Optica **1**, 158-164 (2014)

Fundamental & Practical applications

LETTER

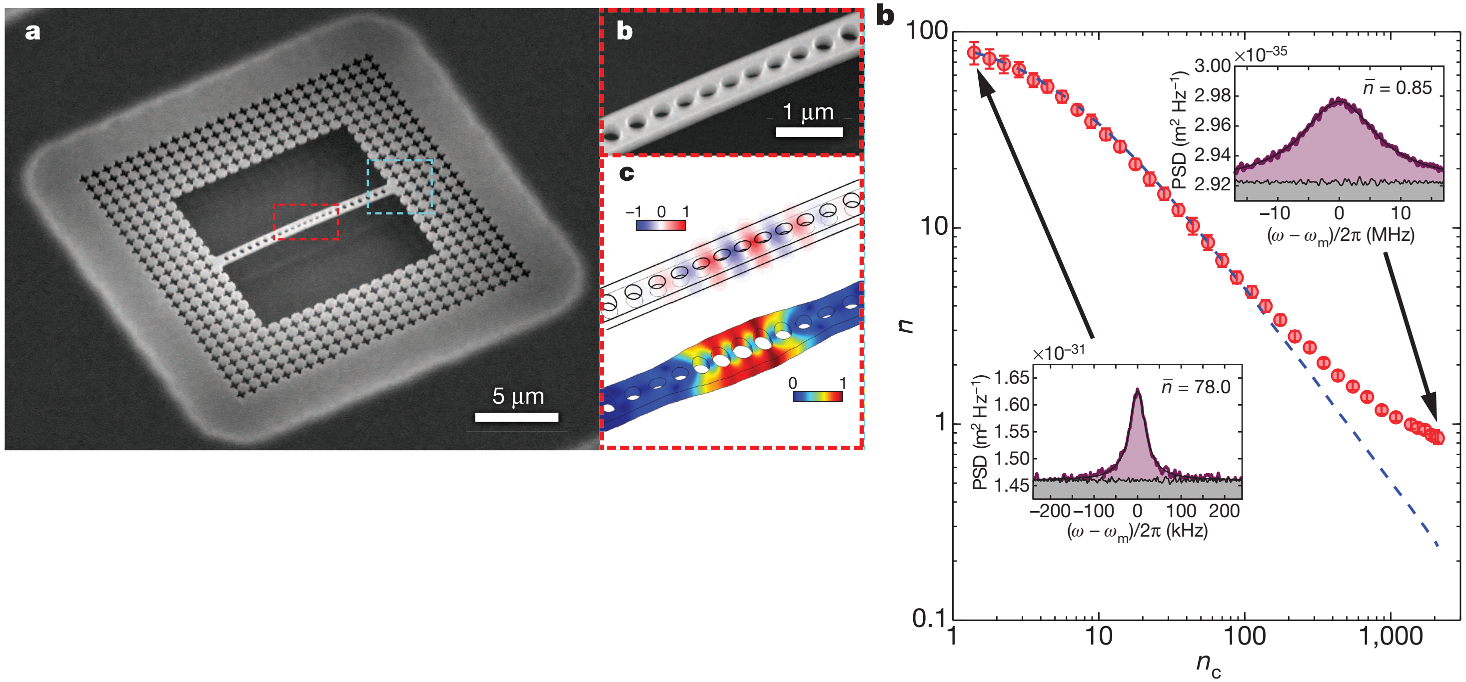
doi:10.1038/nature10461

Laser cooling of a nanomechanical oscillator into its quantum ground state

Jasper Chan[1], T. P. Mayer Alegre[1]†, Amir H. Safavi-Naeini[1], Jeff T. Hill[1], Alex Krause[1], Simon Gröblacher[1,2], Markus Aspelmeyer[2] & Oskar Painter[1]

6 OCTOBER 2011 | VOL 478 | NATURE | 89

Laser cooling of a nanomechanical oscillator



Outline

- Future of Optical Communications
- Why are we interested in photon-phonon interaction?
- **Our work: Brillouin scattering self-cancellation effect**

- what else is going on in our lab…
  - Free-carriers dispersion and thermal phase shift in silicon waveguides
  - High-order modes in photonics bandgap fibers and tapers
  - Broadband & small footprint dielectric antenna

our work

nature COMMUNICATIONS

ARTICLE

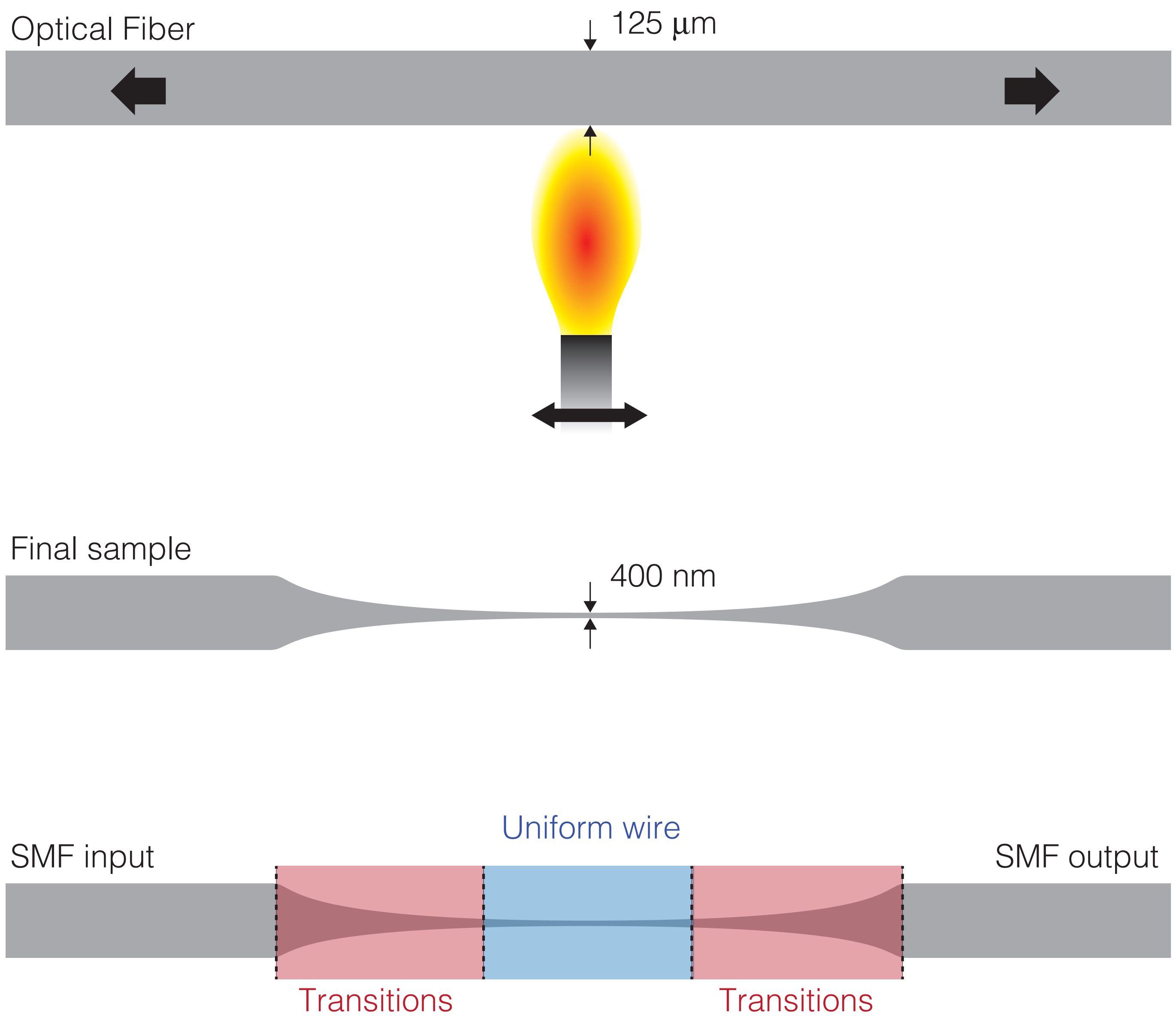
Received 23 Mar 2016 | Accepted 26 Apr 2016 | Published 10 Jun 2016 DOI: 10.1038/ncomms11759 OPEN

Brillouin scattering self-cancellation

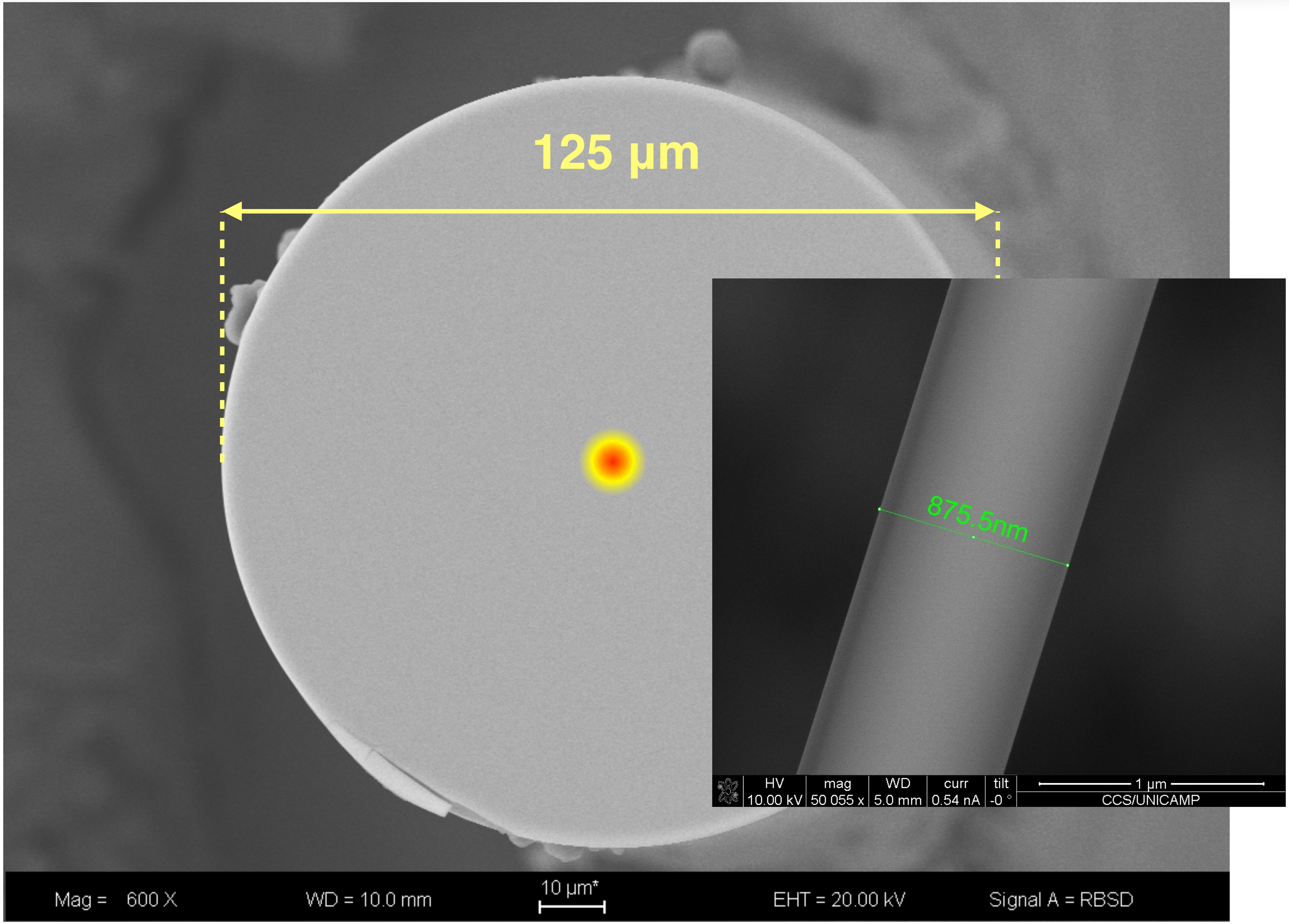
O. Florez[1], P.F. Jarschel[1], Y.A.V. Espinel[1], C.M.B. Cordeiro[1], T.P. Mayer Alegre[1], G.S. Wiederhecker[1] & P. Dainese[1]

- We **expect** strong photon-phonon interaction when:
  - both elastic and optical waves tightly confined and overlapping
  - energy and momentum conservation fully satisfied
  - coupling mechanisms individually strong
- and yet…despite all physical conditions favoring strong interaction, a self-cancellation effect can take place
- and light scattering is completed suppressed!

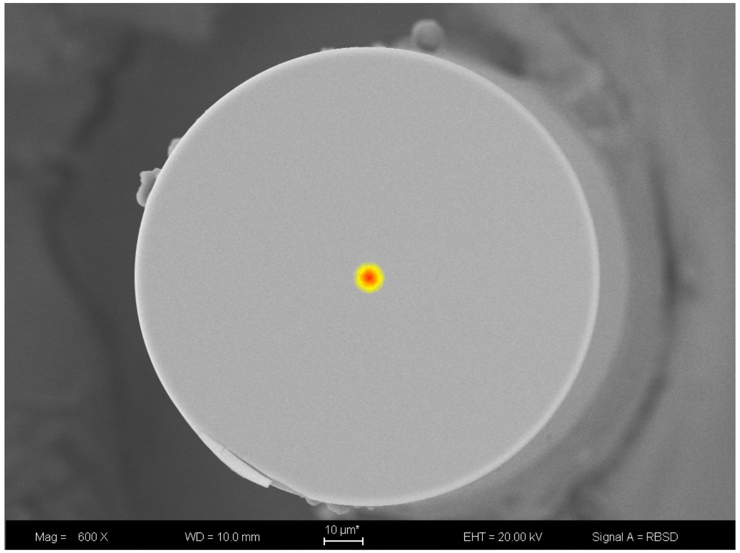
How are the samples manufactured?

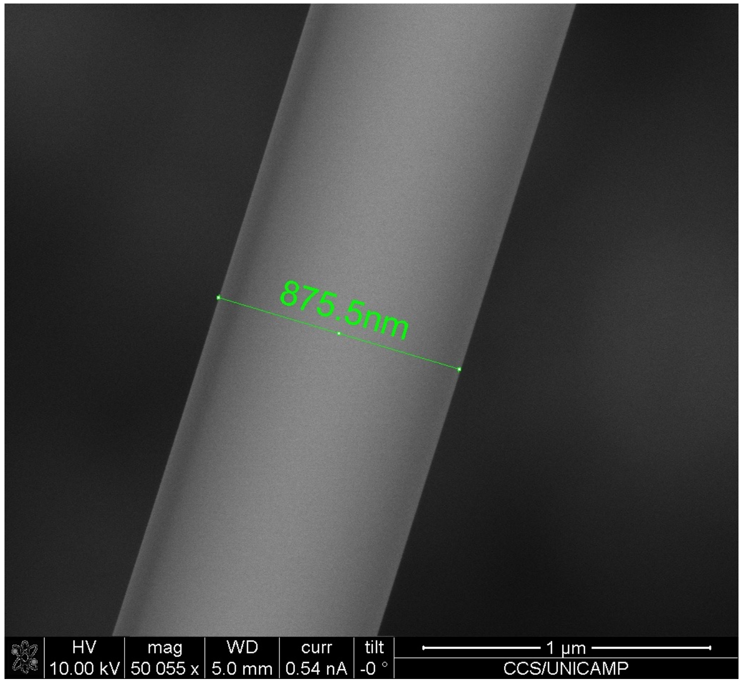


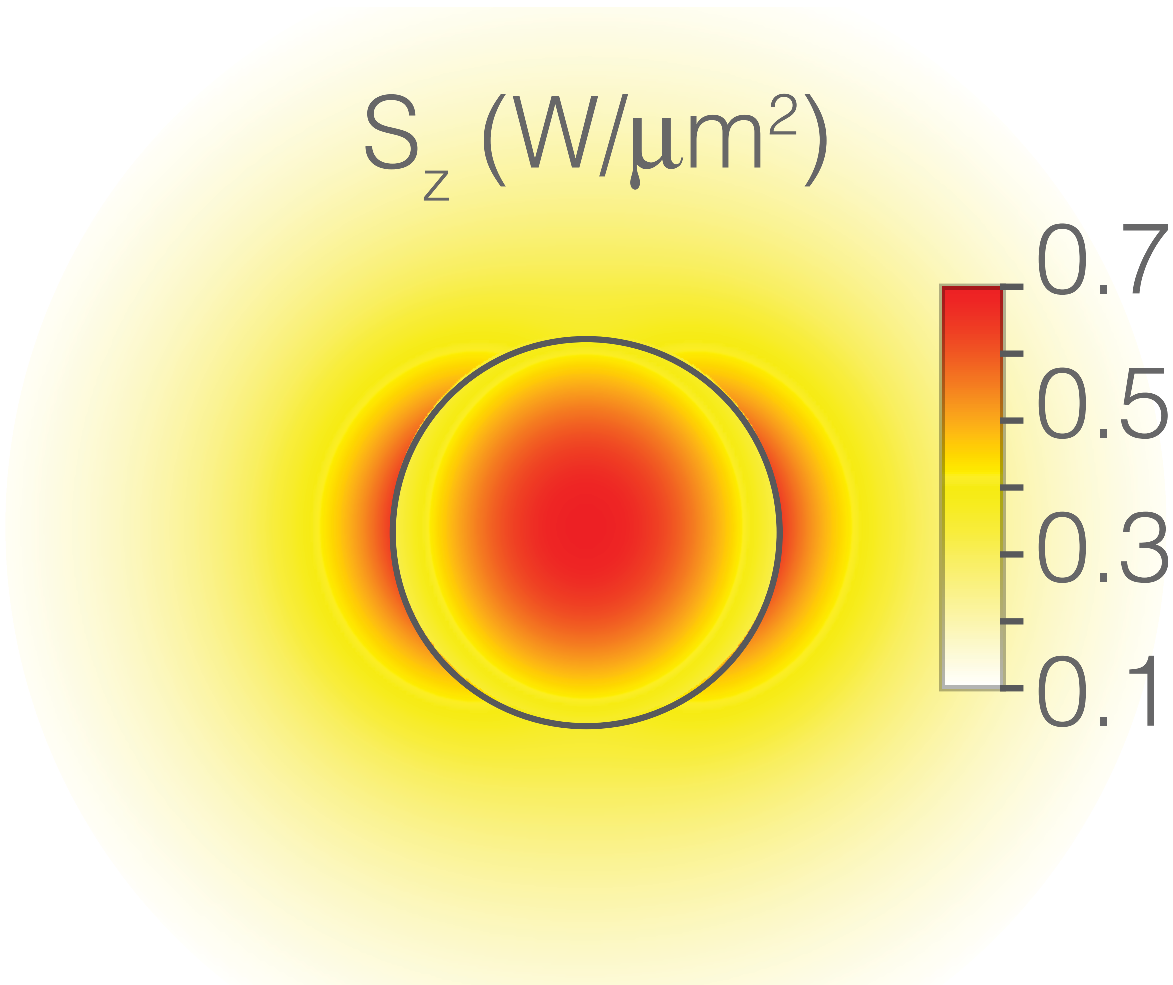
Sub-wavelength confinement of optical and elastic waves



Sub-wavelength confinement of optical and elastic waves

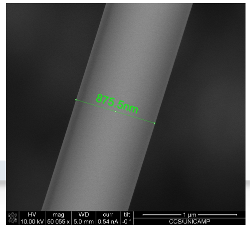




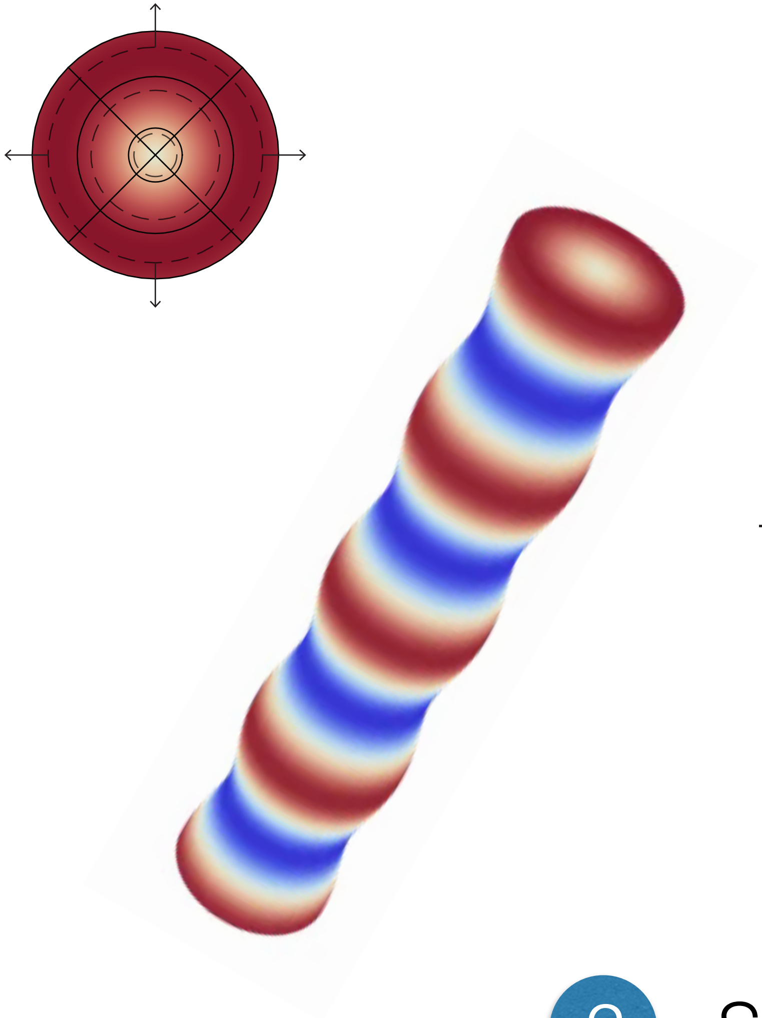


1 Light field "sees" the nanowire surface

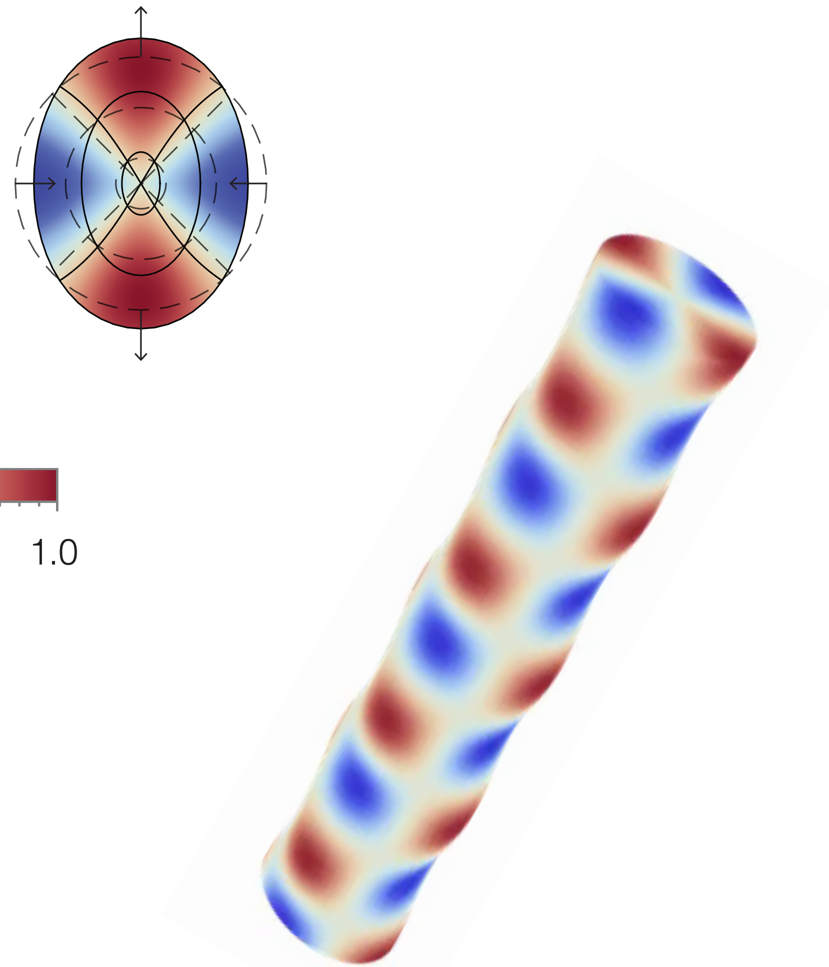
Nanowire elastic modes

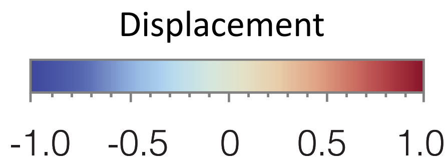


Radial (R_{01})



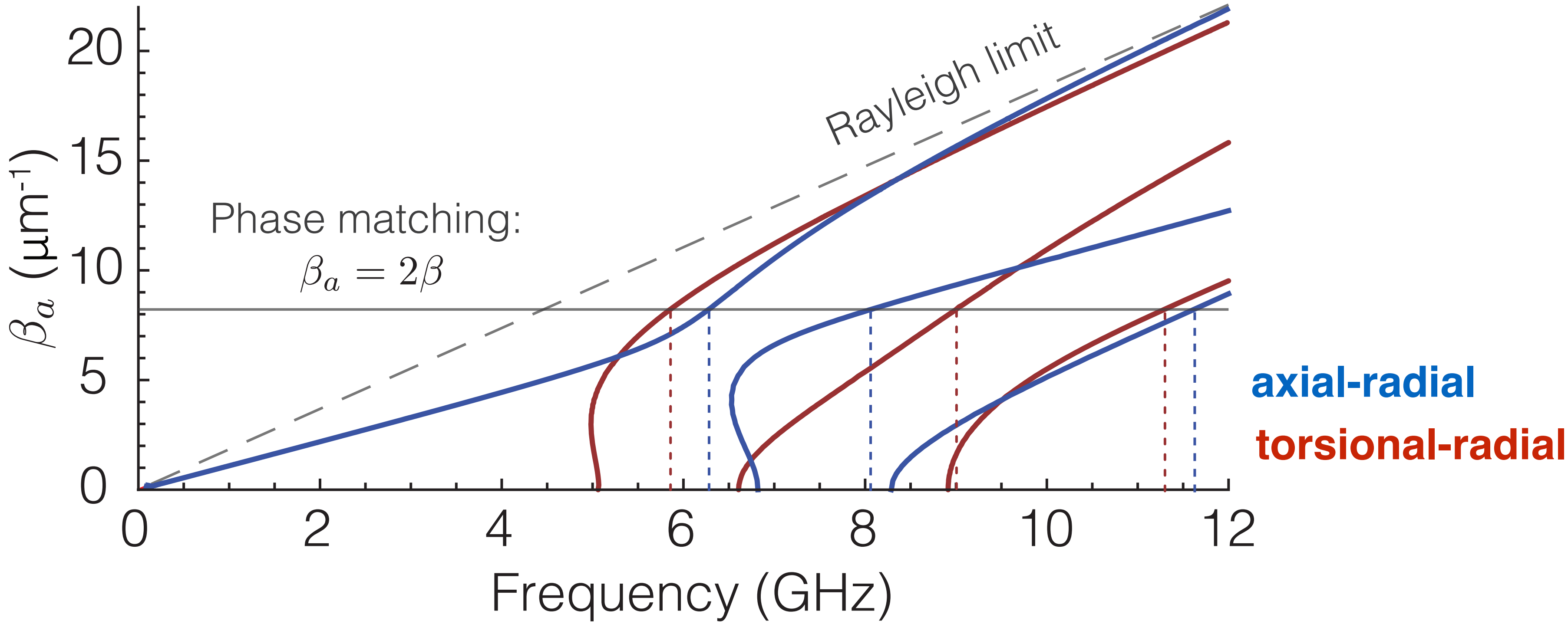
Torsional-Radial (TR_{21})

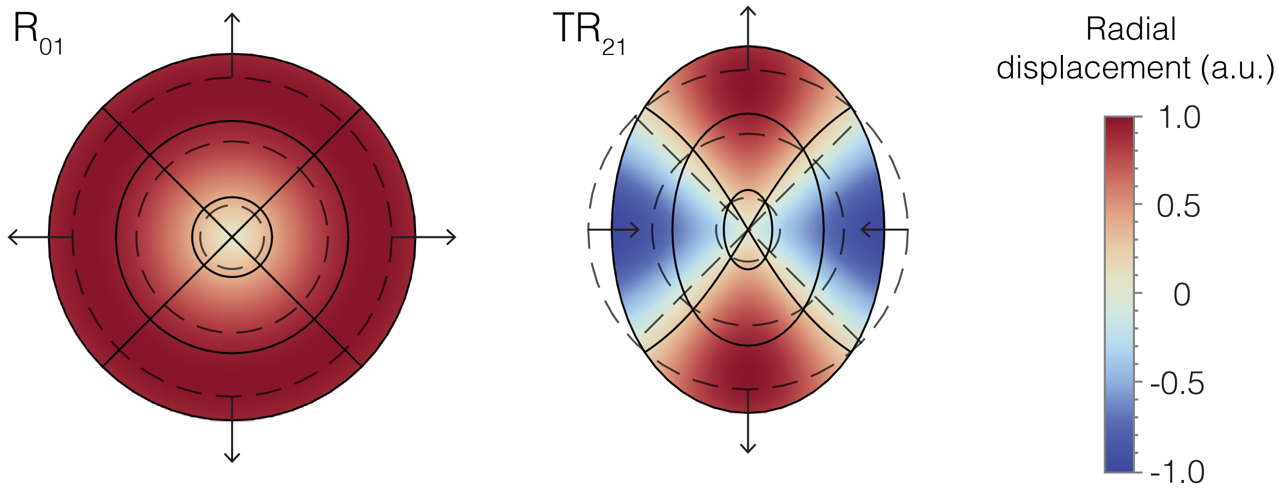




2 Strong surface vibrations

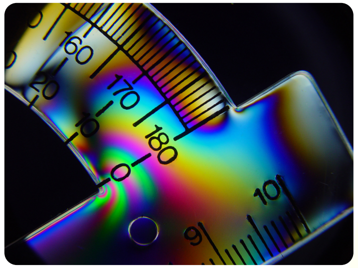
Acoustic dispersion relation





Perturbation mechanisms

Photo-elastic effect

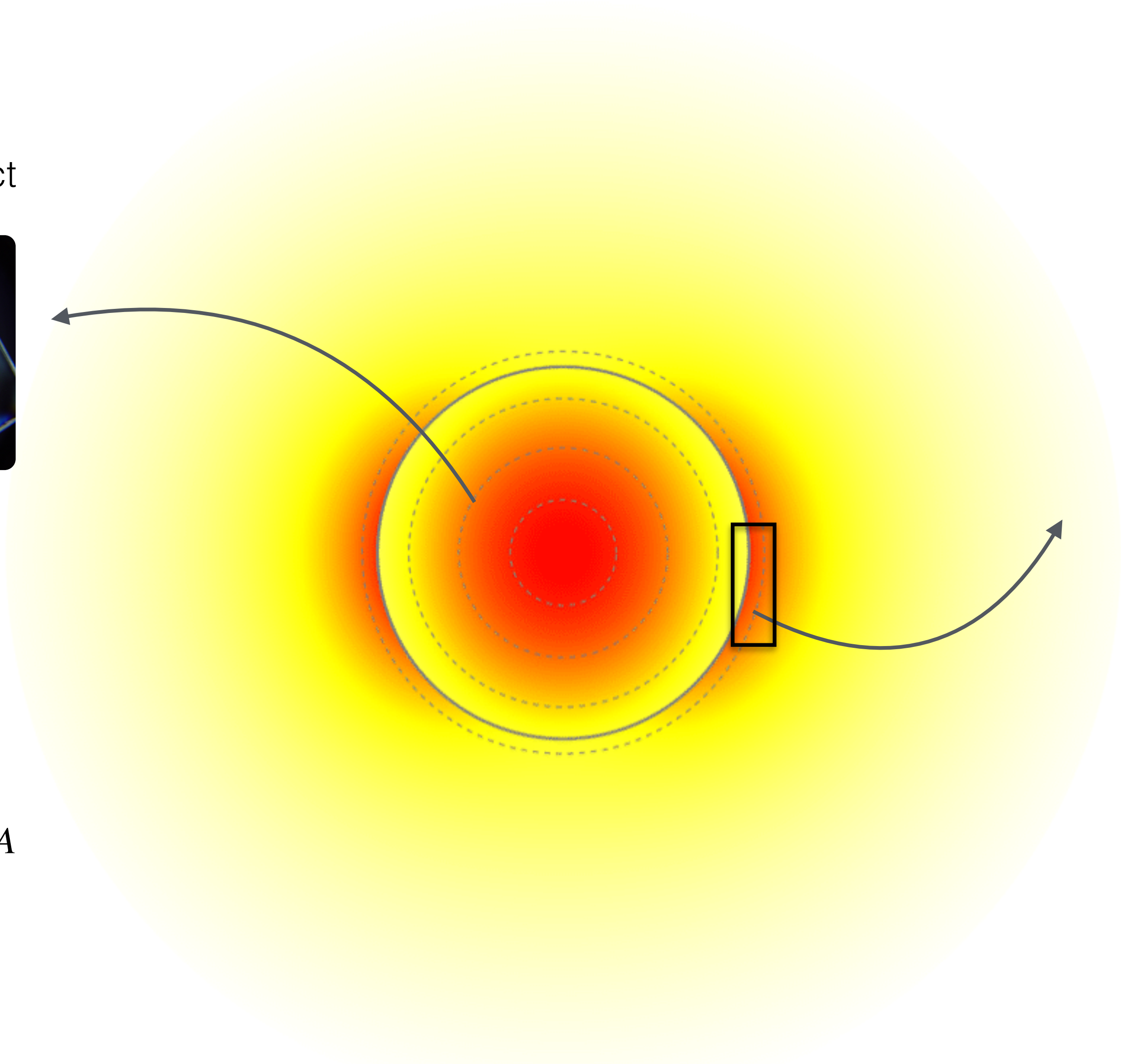


$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}_{NL}$$

$$\mathbf{P}_{NL} = \Delta\varepsilon \cdot \mathbf{E}$$

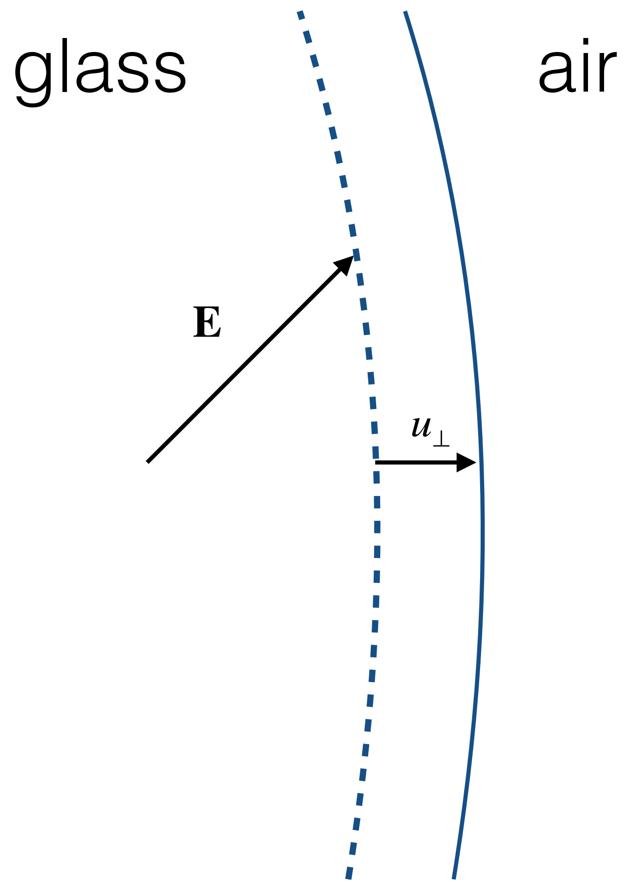
$$\Delta\varepsilon = -\varepsilon_0 n^4 \mathbf{p} \cdot \mathbf{S}$$

$$\kappa_{pe} \propto \int \mathbf{E}_s^* \cdot \Delta\epsilon_{pe}^* \cdot \mathbf{E}_p \, dA$$



S.G.Johnson et al, Physical Review E **65**, 066611 (2002)
C. Wolff et al, Physical Review A **92**, 013836 (2015)

Moving boundary perturbation



$$\mathbf{D}_{before} = \varepsilon_{air}\mathbf{E}_{||} + \mathbf{D}_{\perp}$$

$$\mathbf{D}_{after} = \varepsilon_{glass}\mathbf{E}_{||} + \mathbf{D}_{\perp}$$

$$\Delta\mathbf{D} = \left(\varepsilon_{glass} - \varepsilon_{air}\right)\mathbf{E}_{||} = \Delta\varepsilon_{mb}\mathbf{E}_{||}$$

$$\mathbf{E}_{before} = \mathbf{E}_{||} + \varepsilon_{air}^{-1}\mathbf{D}_{\perp}$$

$$\mathbf{E}_{after} = \mathbf{E}_{||} + \varepsilon_{glass}^{-1}\mathbf{D}_{\perp}$$

$$\Delta\mathbf{E} = \left(\varepsilon_{glass}^{-1} - \varepsilon_{air}^{-1}\right)\mathbf{D}_{\perp} = \Delta\varepsilon_{mb}^{-1}\mathbf{D}_{\perp}$$

perturbation area

$$u_{\perp}dl$$

$$\kappa_{mb} = \frac{\omega}{8}\oint u_{\perp}\left(\Delta\epsilon_{mb}\mathbf{E}_{s,||}^{*}\cdot\mathbf{E}_{p,||} - \Delta\epsilon_{mb}^{-1}\mathbf{D}_{s,\perp}^{*}\cdot\mathbf{D}_{p,\perp}\right)dl$$

Photo-elastic and Moving-Boundary Perturbations

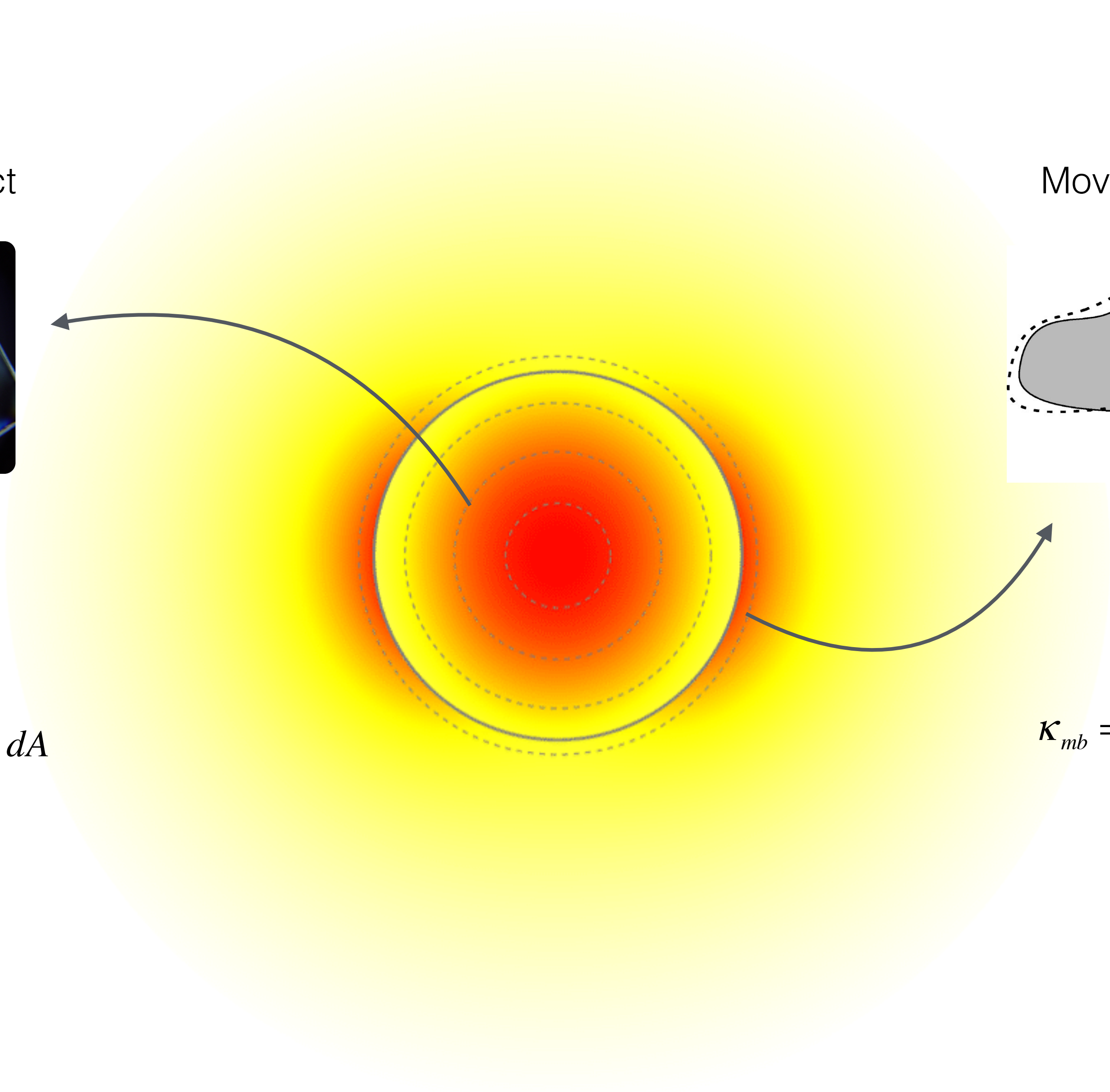
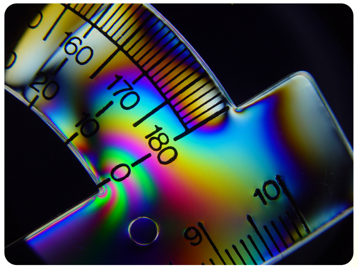
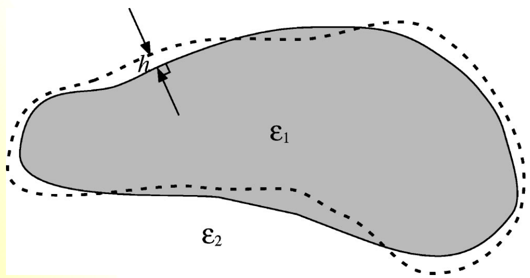


Photo-elastic effect



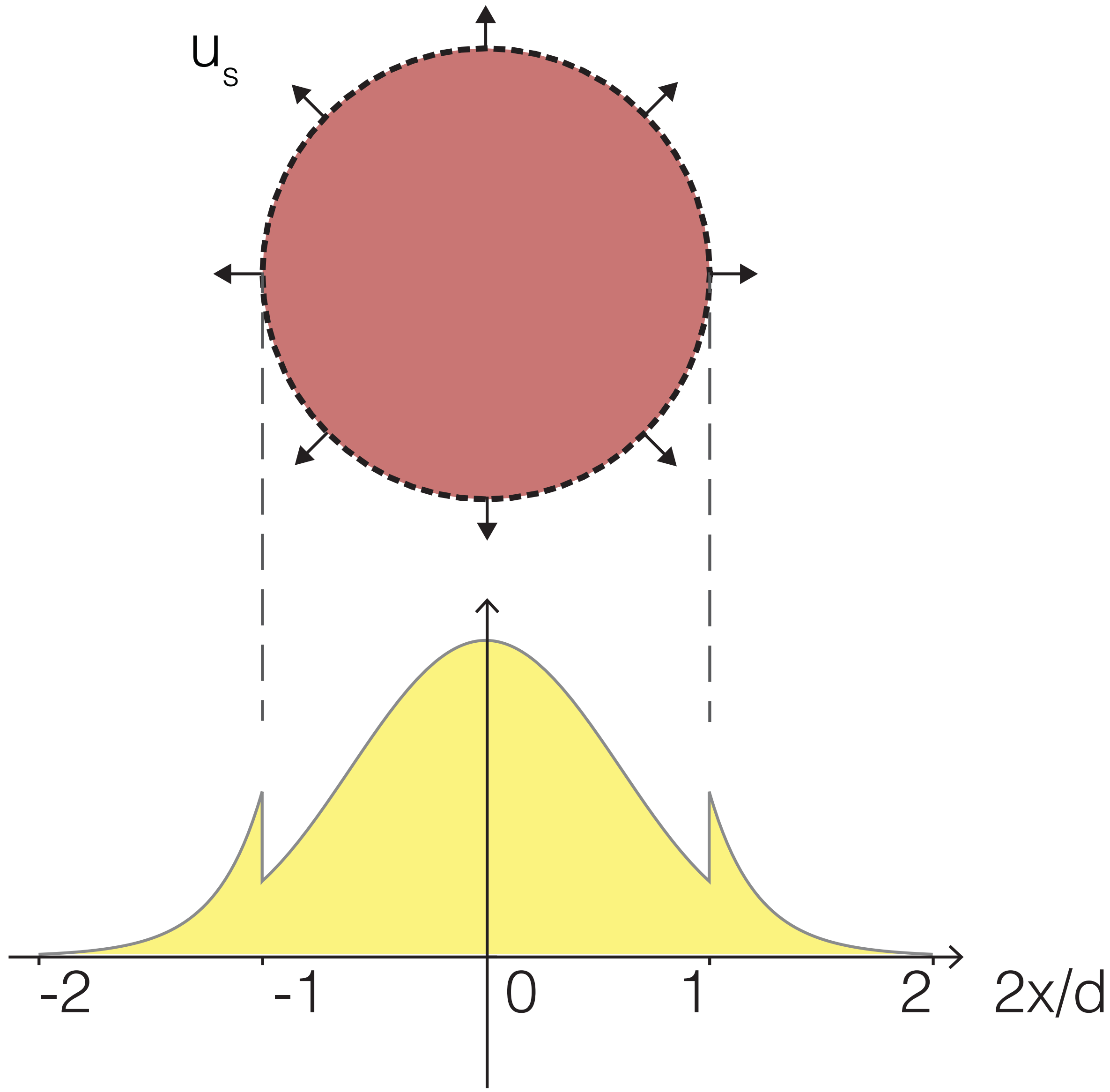
$$\kappa_{pe} = \frac{\omega}{8}\int \vec{E}_s^* \cdot \Delta\vec{\epsilon}_{pe}^{\,*} \cdot \vec{E}_p \, dA$$

Moving-boundary effect



$$\kappa_{mb} = \frac{\omega}{8}\oint u_\perp \left(\Delta\epsilon_{mb}\vec{E}_{s,\parallel}^* \cdot \vec{E}_{p,\parallel} - \Delta\epsilon_{mb}^{-1}\vec{D}_{s,\perp}^* \cdot \vec{D}_{p,\perp}\right) dl$$

Toy model



Toy model

Moving-boundary:

$$\eta_{mb} = \Delta n_{mb} A_{mb} = \left(n_{glass} - n_{air}\right)\pi d u_s$$

Large index perturbation

Small area

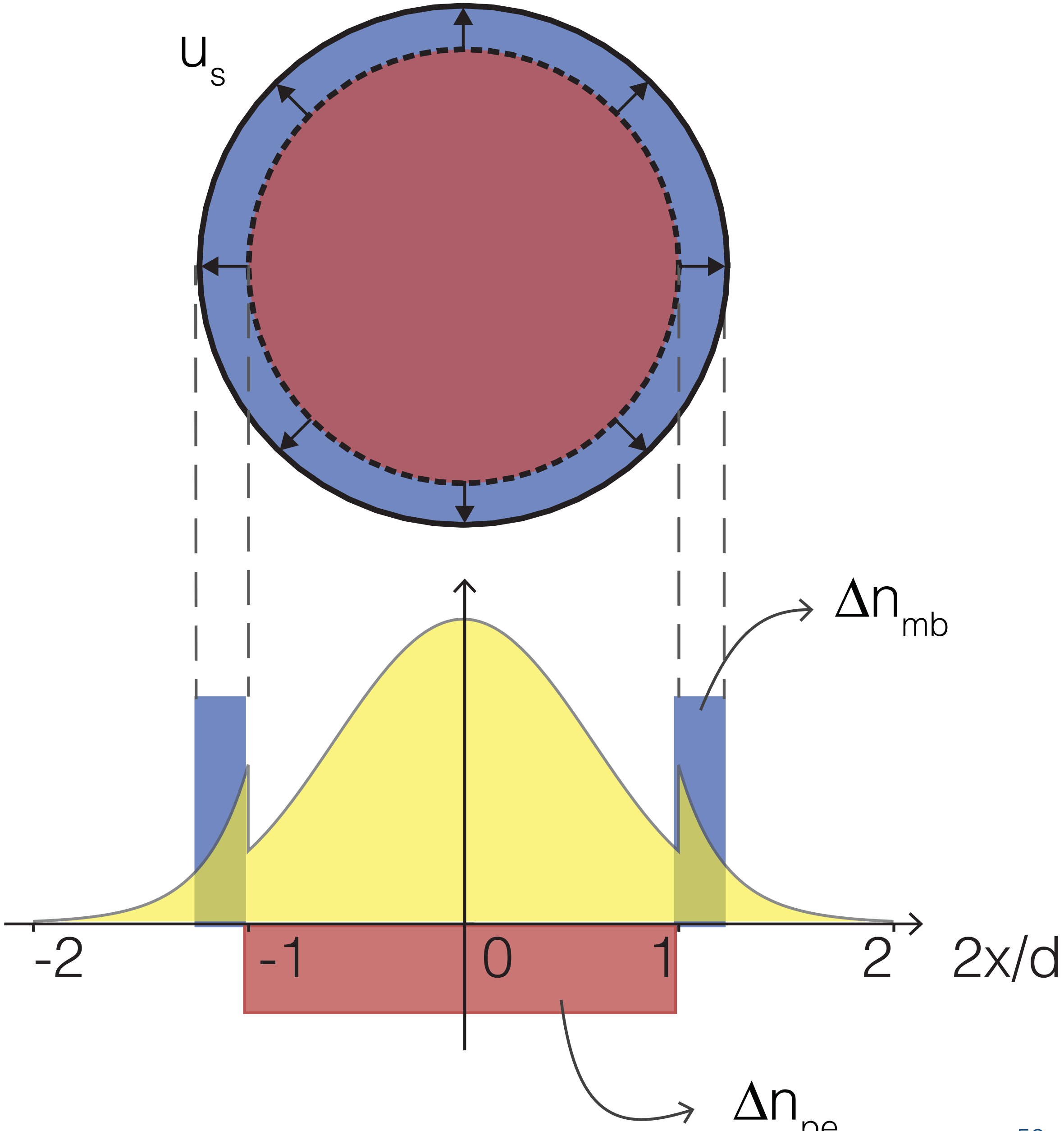
Photo-elastic:

$$\eta_{pe} = \Delta n_{pe} A_{pe} = -\left(n_{glass}^3 p_{11} \frac{2u_s}{d}\right)\pi d^2$$

Small index perturbation

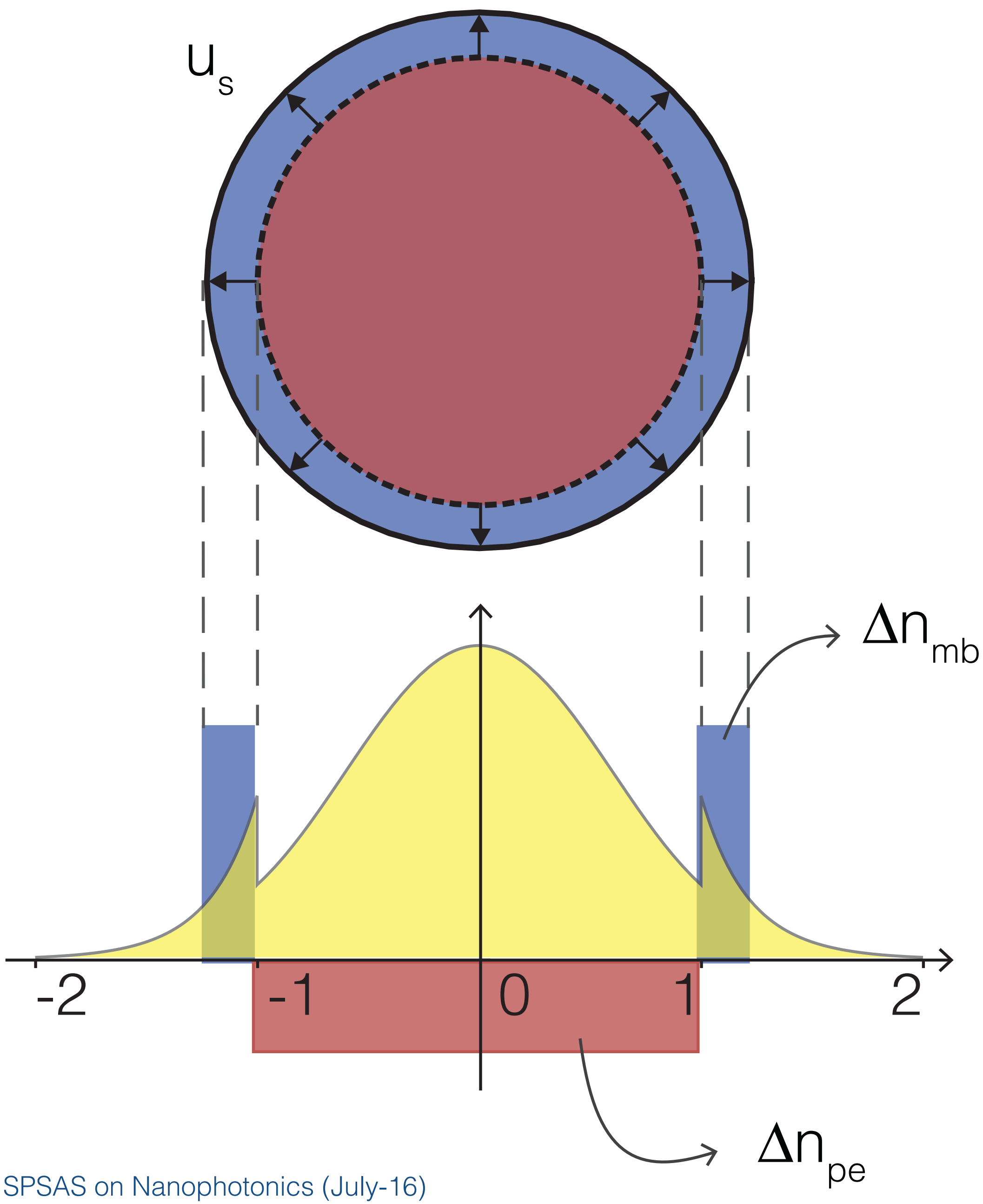
Large area

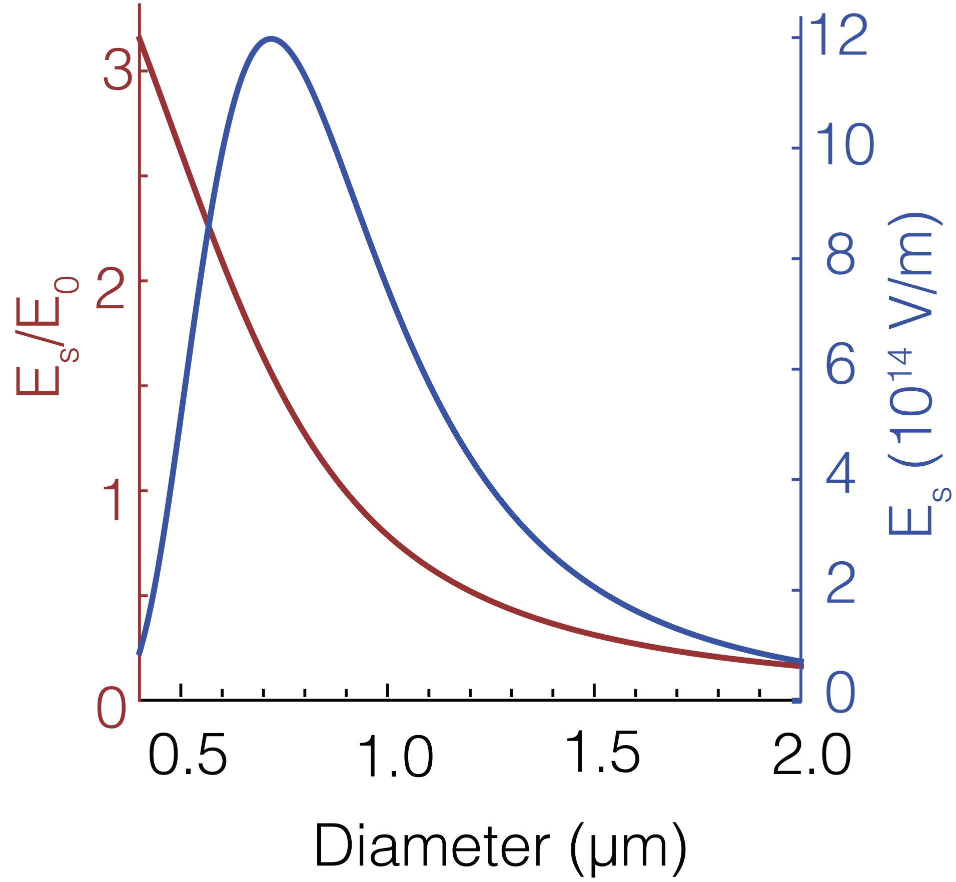
$$\frac{\eta_{pe}}{\eta_{mb}} = -\frac{n_{glass}^3 p_{11}}{4\left(n_{glass} - n_{air}\right)} \simeq -0.2$$



3 Two competing physical mechanisms

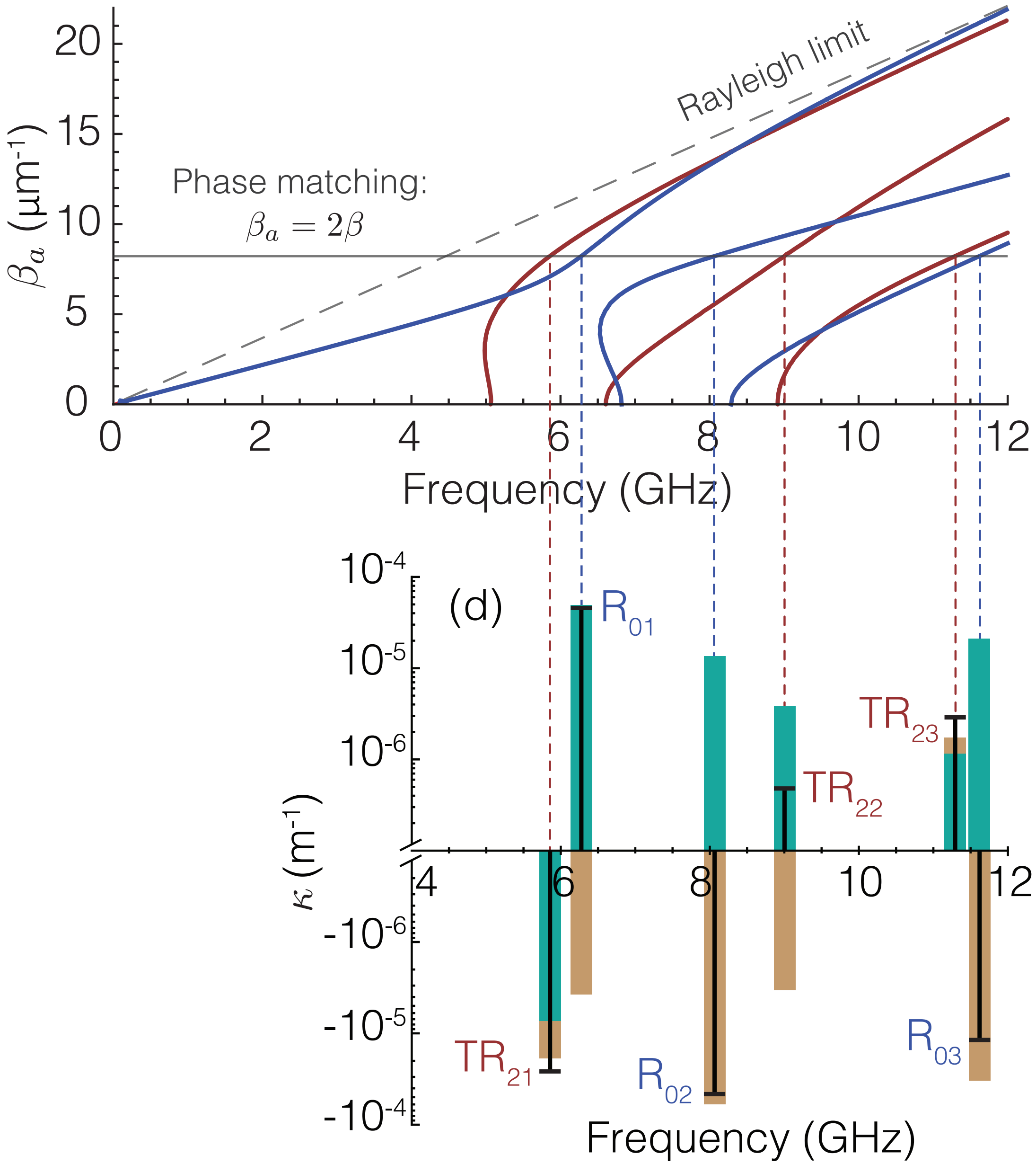
Brillouin Self-Cancellation effect (BSC)

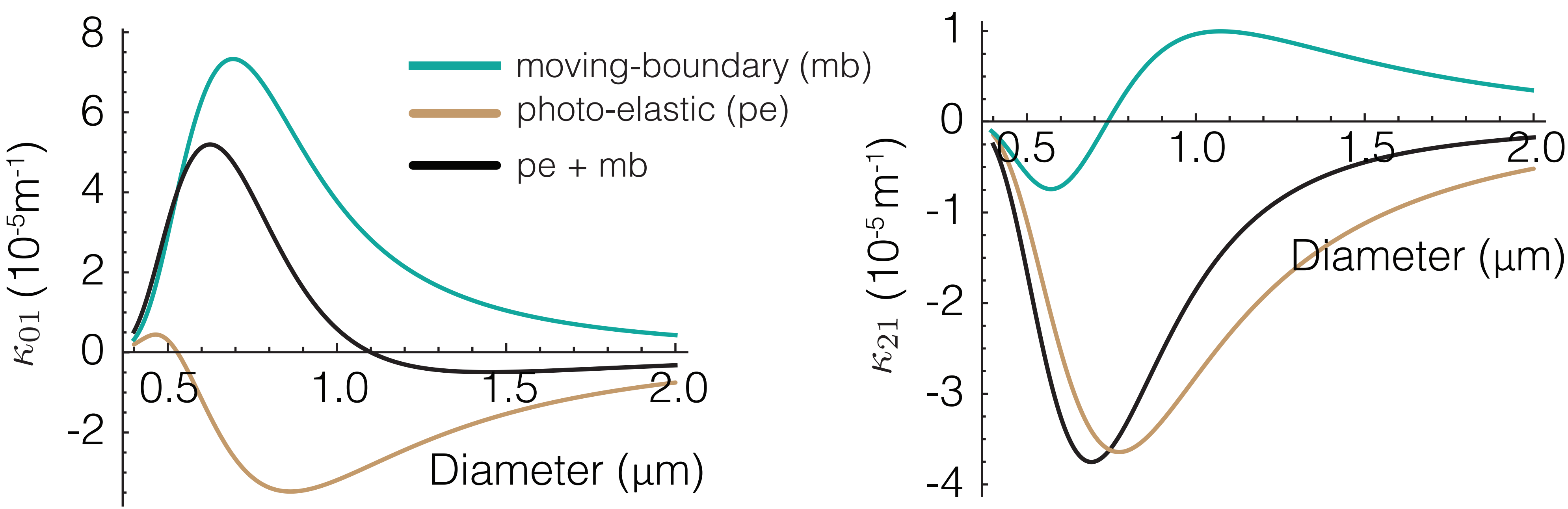


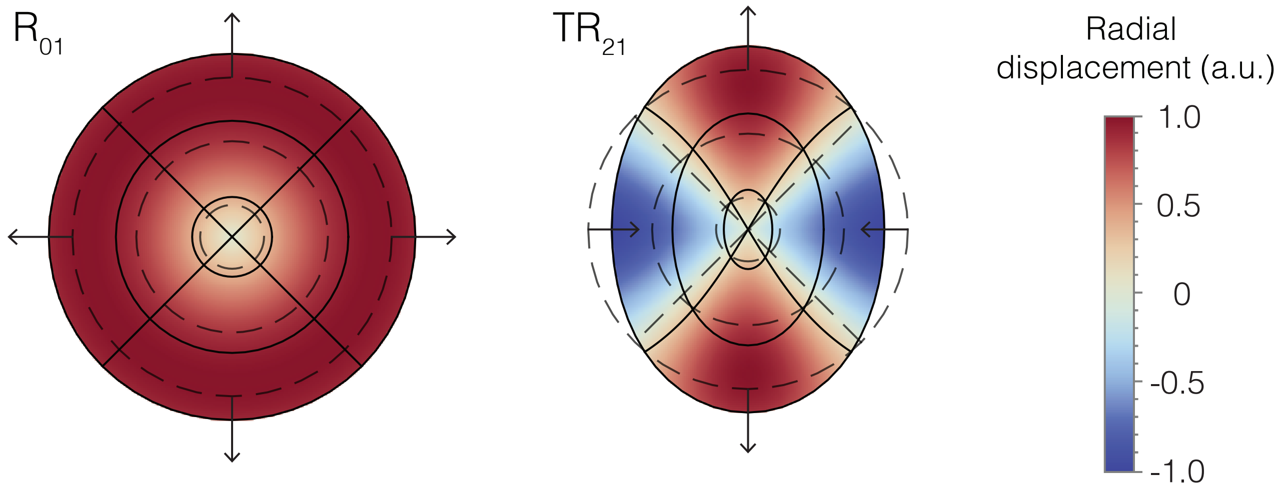


4 Optical fields tune m.b. and p.e. relative contributions

Exact computation of coupling coefficients

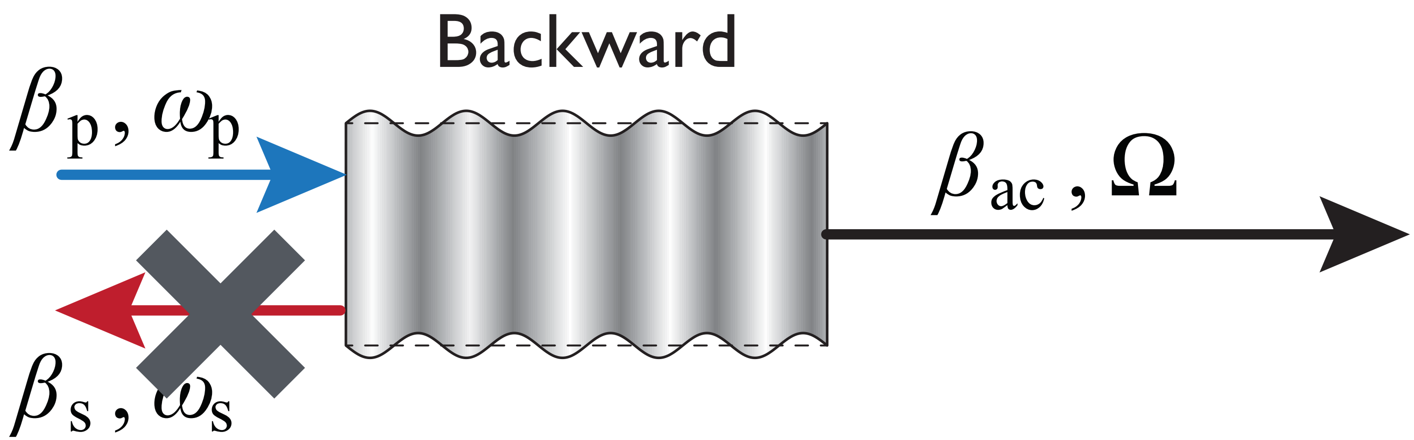



8
6
4
2
0
-2
0.5
1.0
1.5
2.0
κ_{01} ($10^{-5}m^{-1}$)
moving-boundary (mb)
photo-elastic (pe)
pe + mb
Diameter (μm)
1
0
-1
-2
-3
-4
κ_{21} ($10^{-5}m^{-1}$)
Diameter (μm)

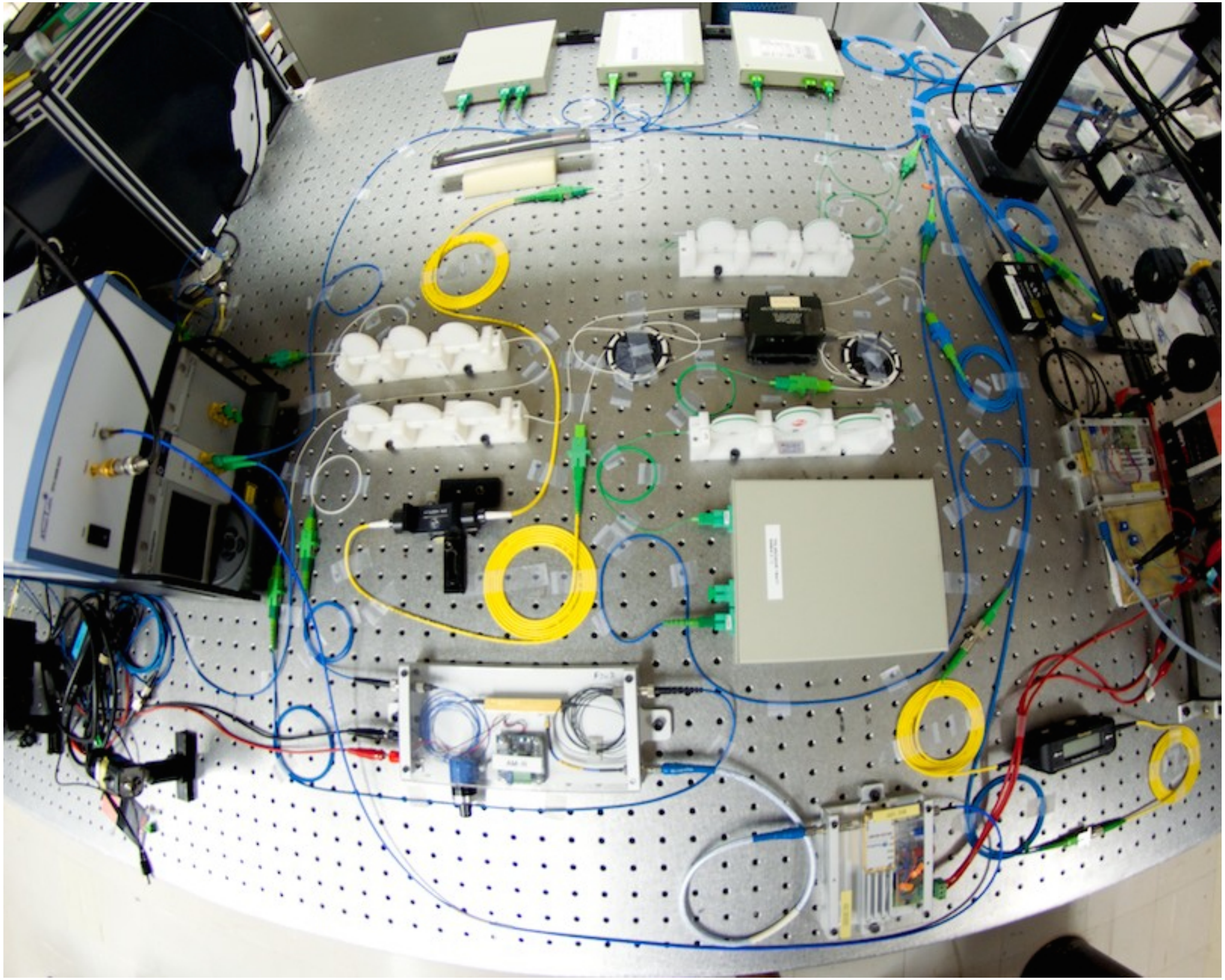

R_{01}
TR_{21}
Radial
displacement (a.u.)
1.0
0.5
0
-0.5
-1.0

Brillouin Self-Cancellation effect (BSC)

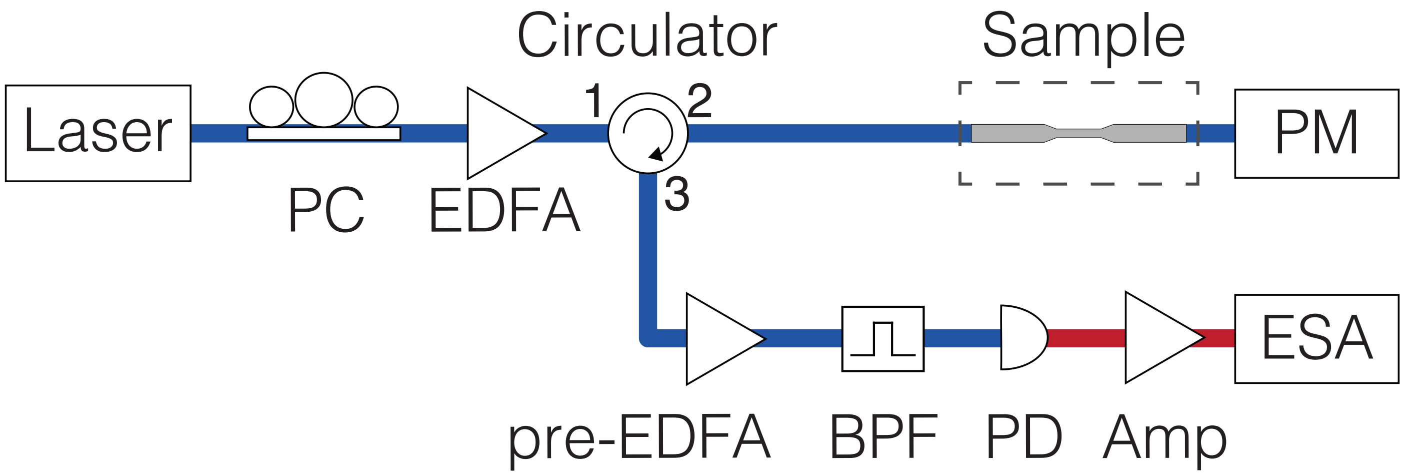
1. Light field "sees" the nanowire surface
2. Strong surface vibrations
3. Two competing physical mechanisms
4. Optical fields tune m.b. and p.e. relative contributions



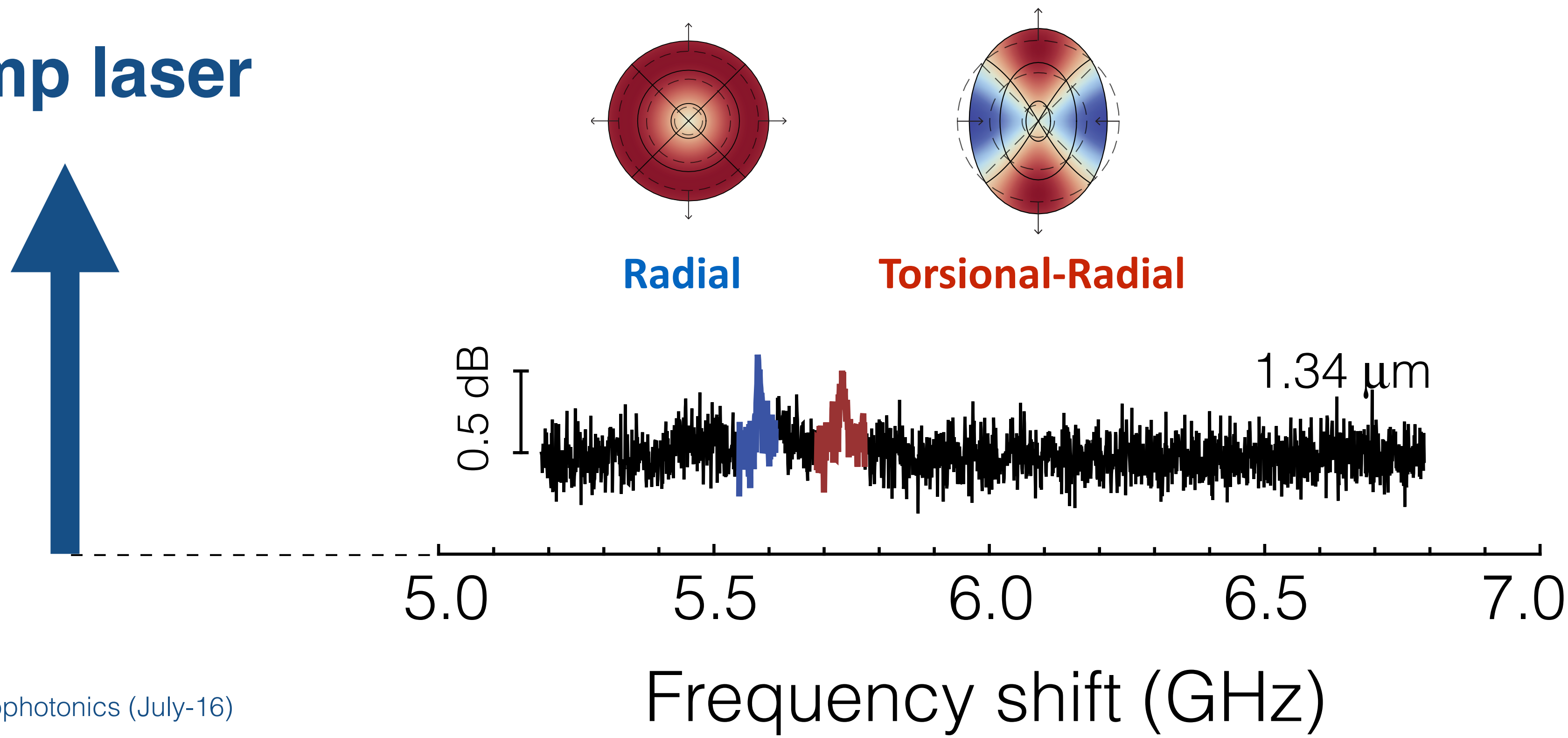
Experimental setup



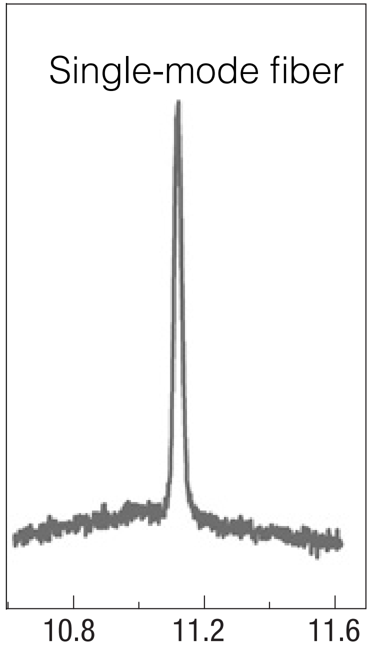
Experimental setup

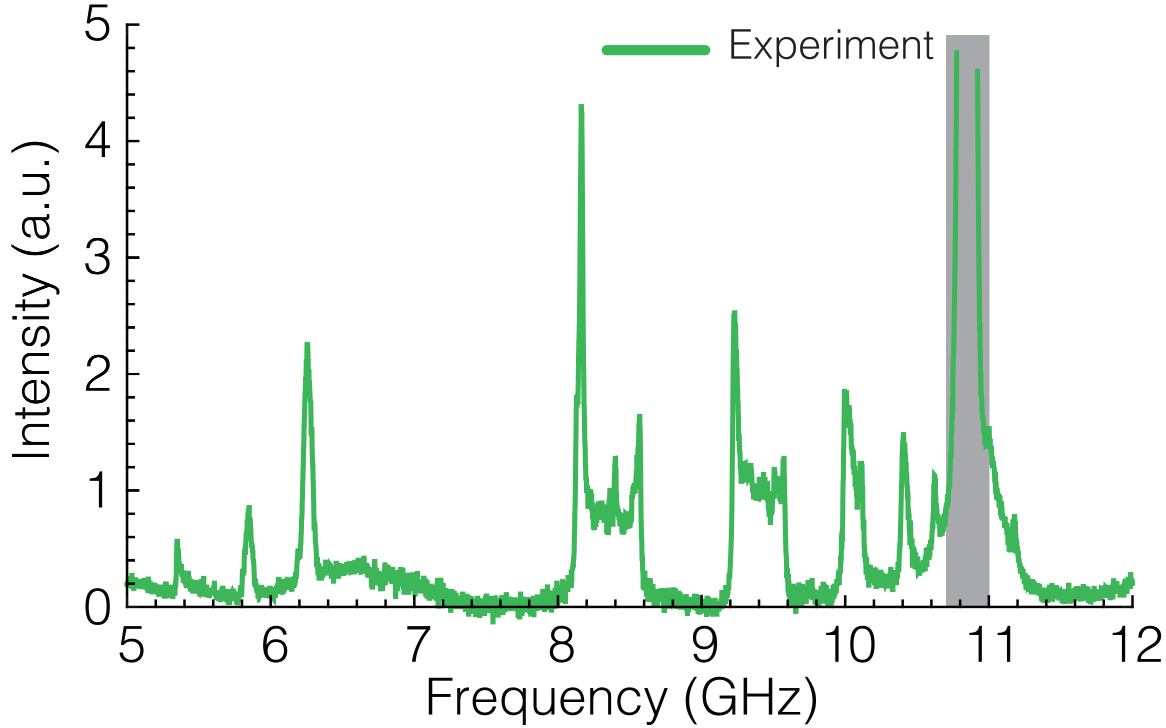


Pump laser

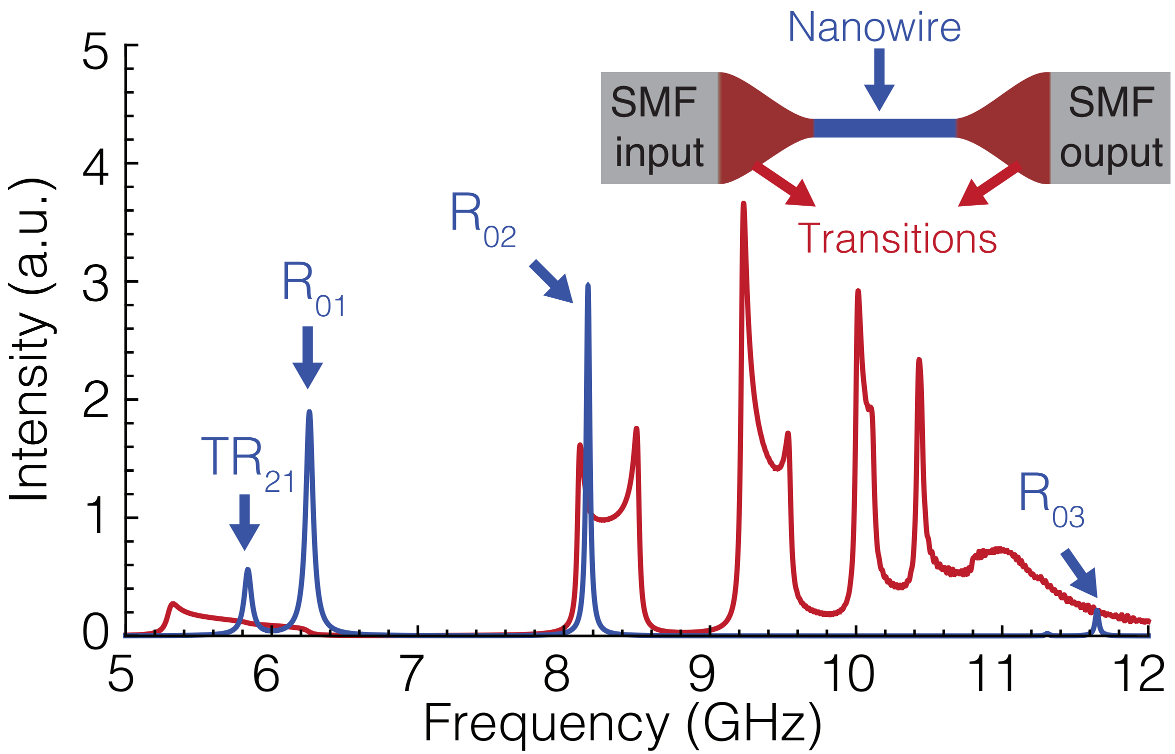


Experimental results: full spectrum

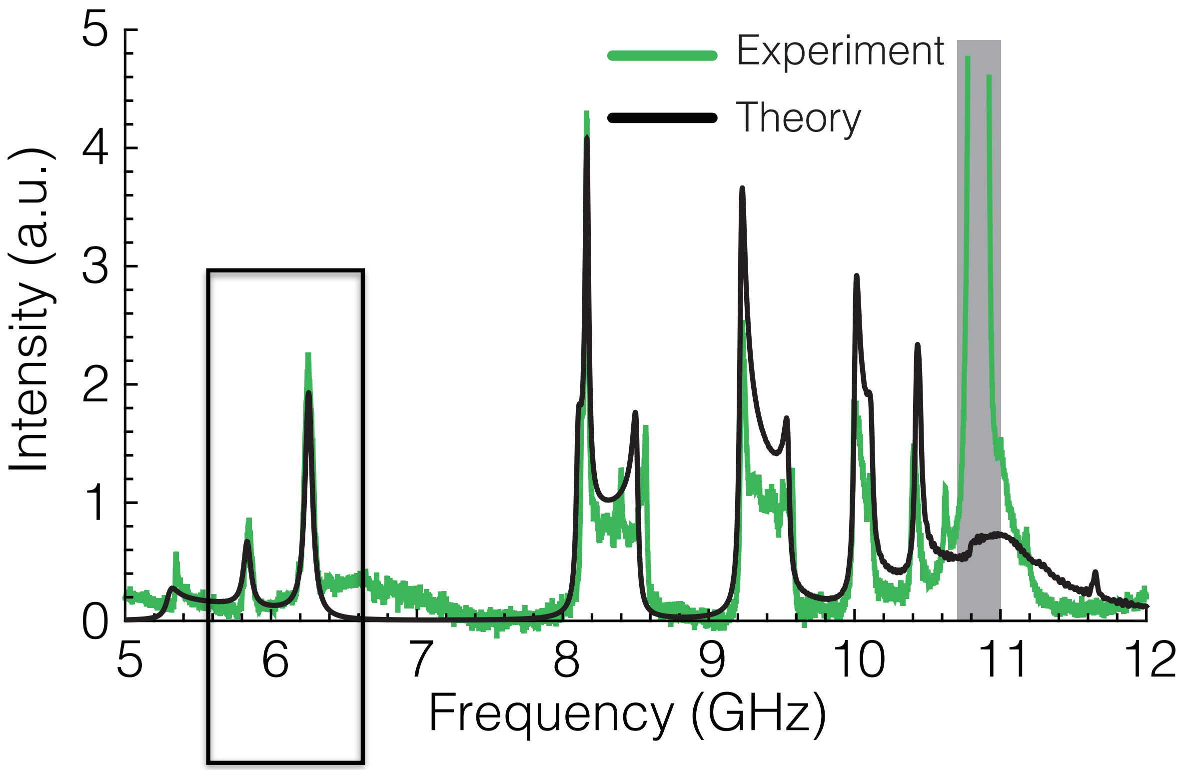


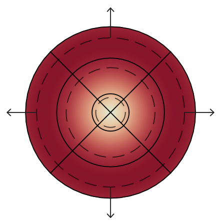


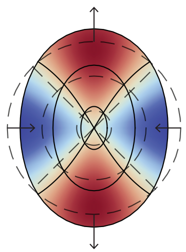
Theory


Nanowire
SMF input
SMF ouput
Transitions
R_{02}
R_{01}
TR_{21}
R_{03}
Intensity (a.u.)
Frequency (GHz)
0
1
2
3
4
5
5
6
7
8
9
10
11
12

Comparison

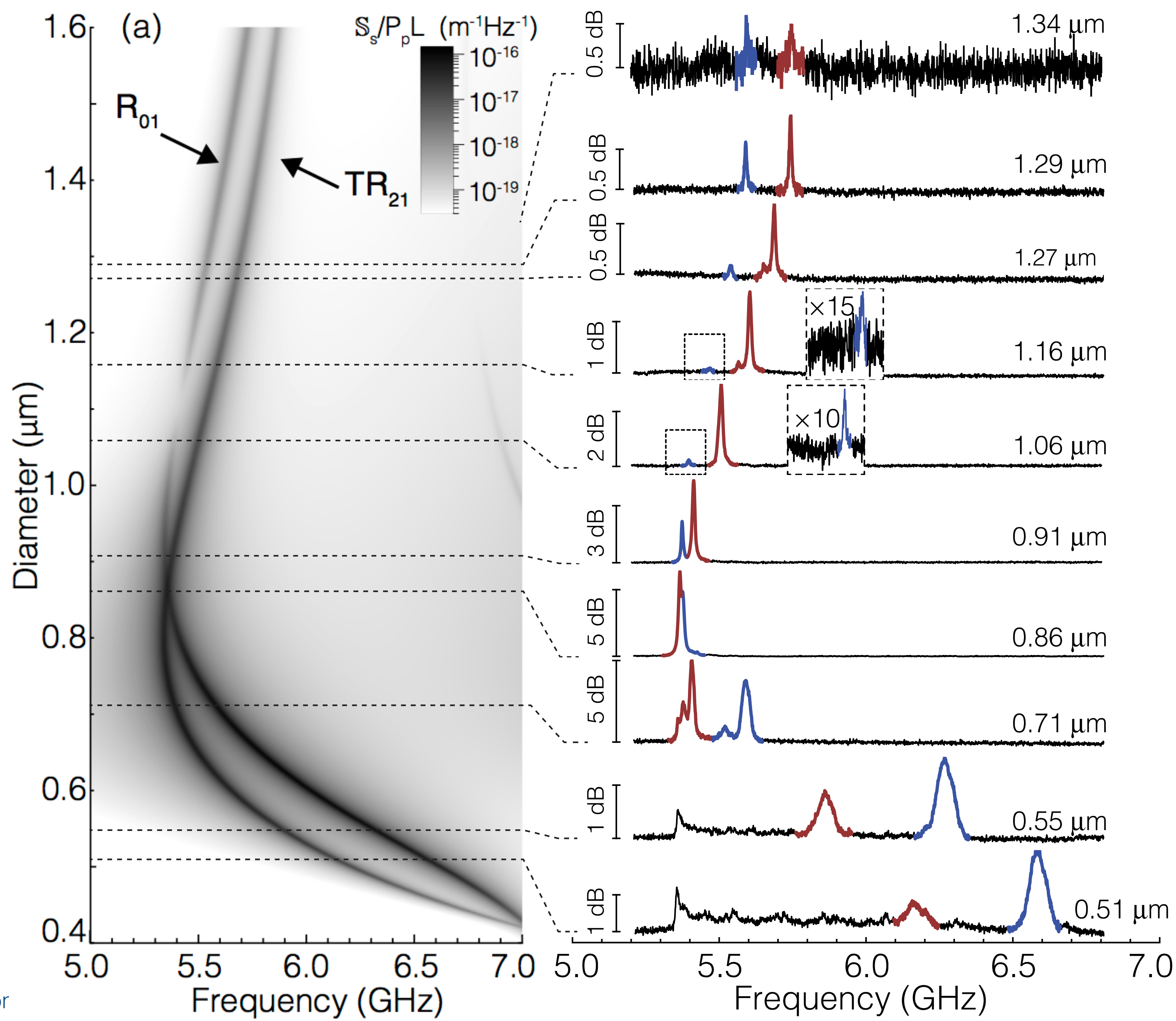




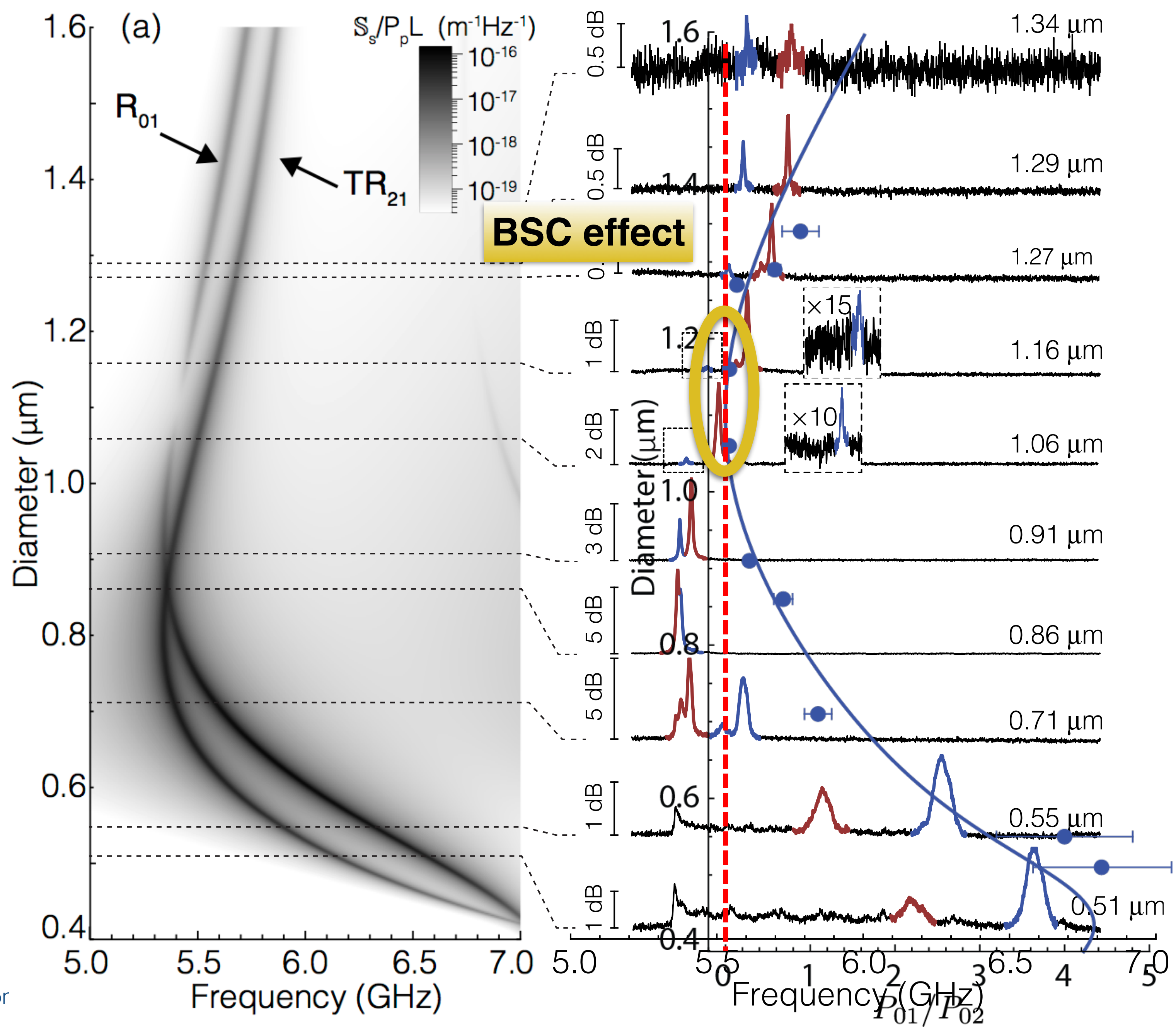


Radial **Torsional-Radial**

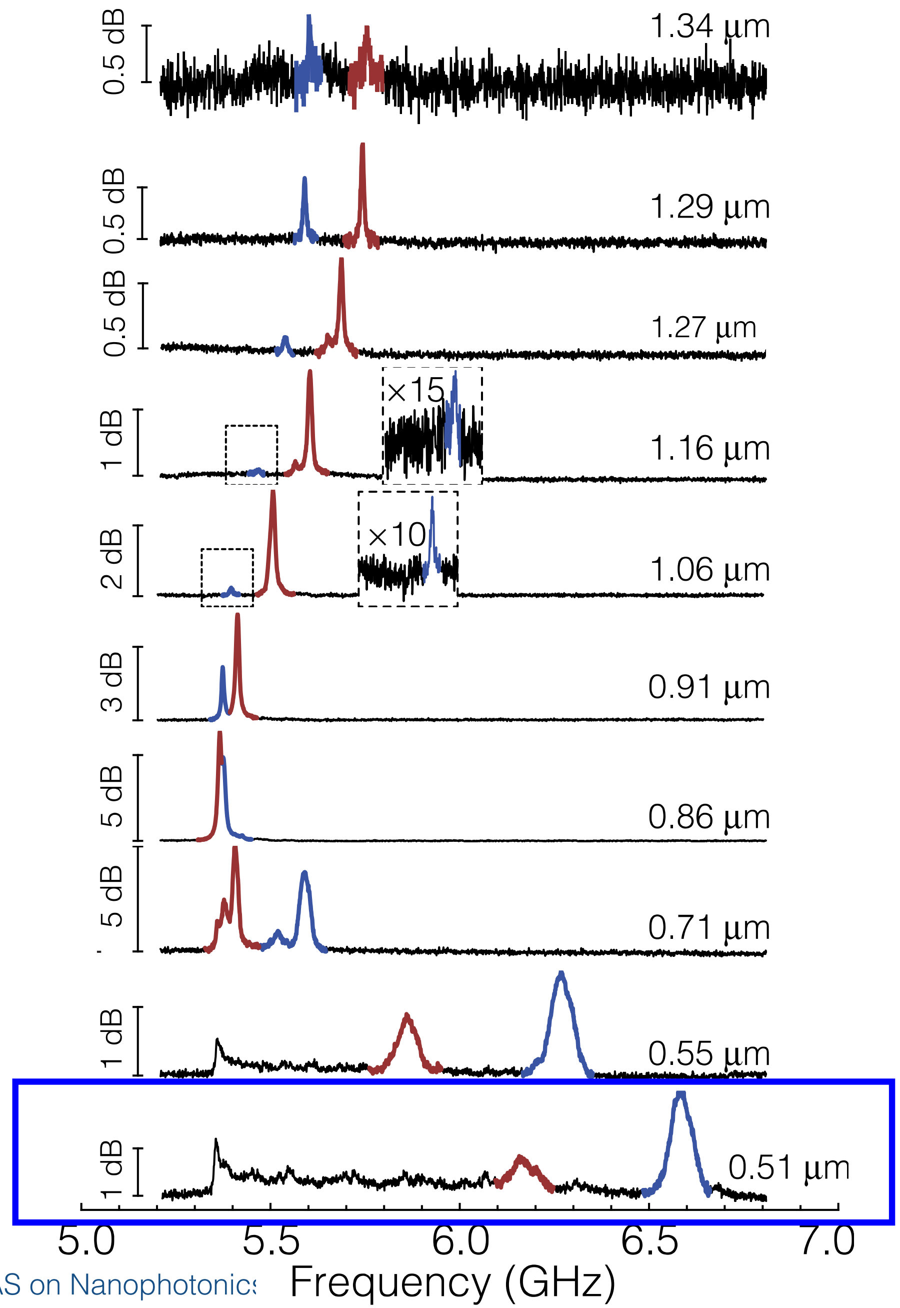
Theory Vs. Experimental results

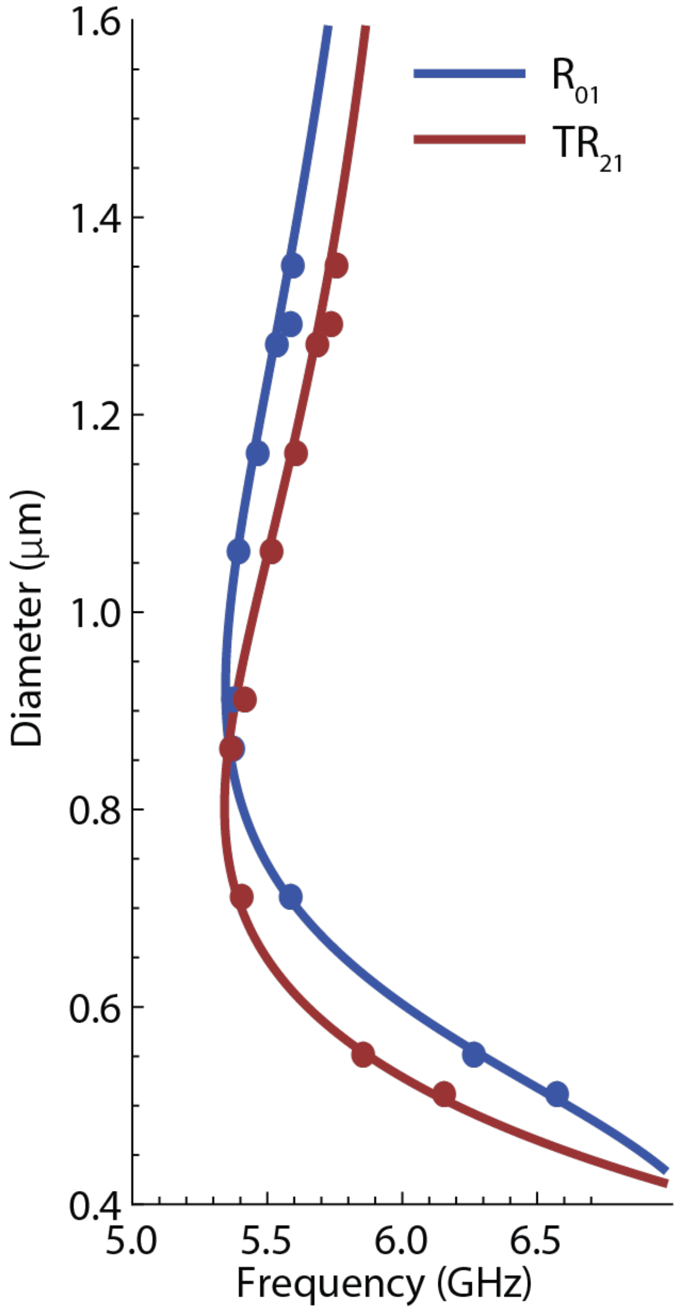


Theory Vs. Experimental results



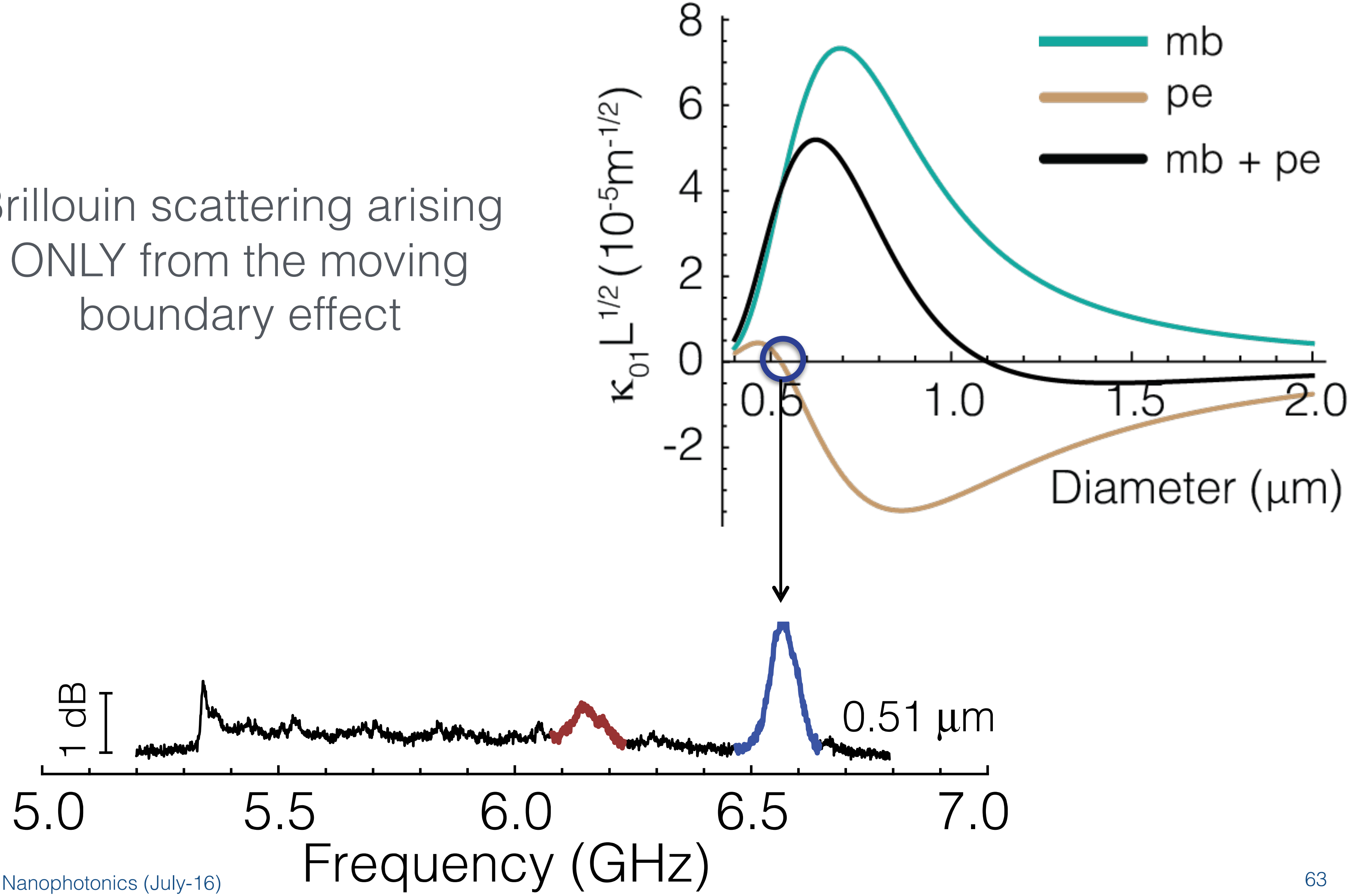
Theory Vs. Experimental results





Theory Vs. Experimental results

Brillouin scattering arising ONLY from the moving boundary effect

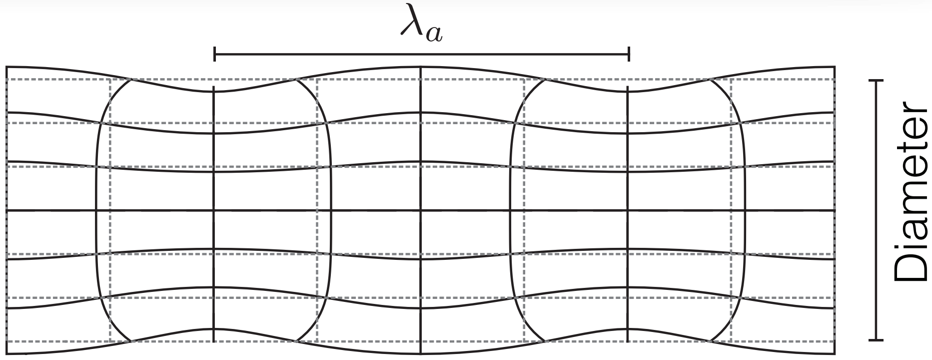


Understanding net-zero Photo-Elastic effect

$$\kappa_{pe} \propto \int \mathbf{E}_s^* \cdot \Delta\epsilon_{pe}^* \cdot \mathbf{E}_p \, dA$$

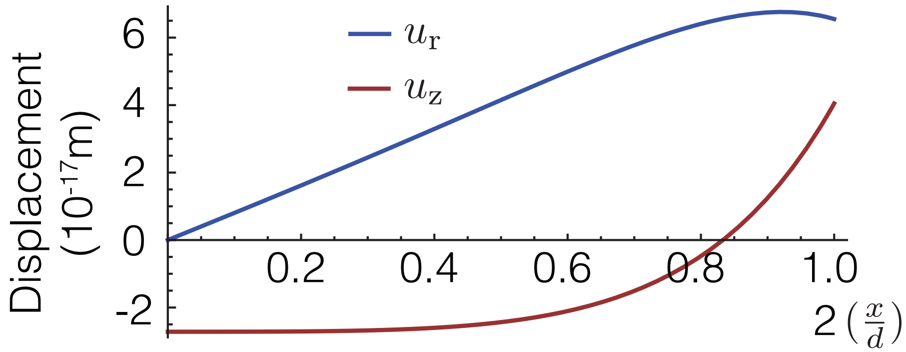
transverse — longitudinal — crossed

$$\mathbf{E}_s^* \cdot \Delta\epsilon_{pe}^* \cdot \mathbf{E}_p = \Delta\epsilon_{rr}|E_r|^2 + \Delta\epsilon_{\phi\phi}|E_\phi|^2 - \Delta\epsilon_{zz}|E_z|^2 - 2\Delta\epsilon_{rz}E_r E_z$$



$$\Delta\varepsilon = -\varepsilon_0 n^4 \mathbf{p} \cdot \mathbf{S}$$

$$\Delta\varepsilon_{rr} = -\varepsilon_0 n^4 \left(p_{11} S_{rr} + p_{12} S_{\phi\phi} + p_{12} S_{zz} \right)$$

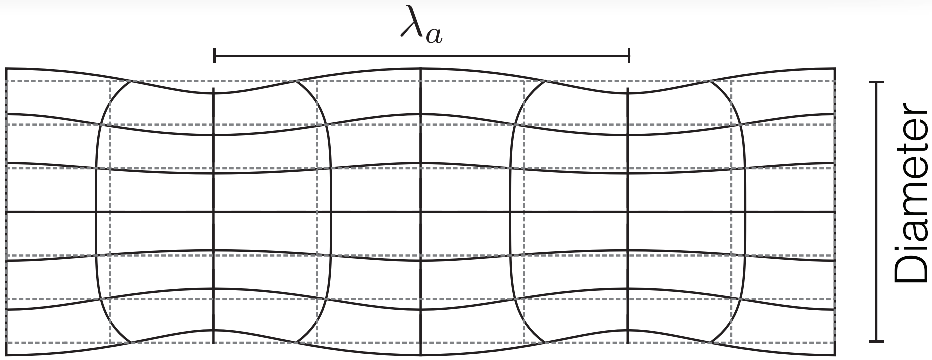


Understanding net-zero Photo-Elastic effect

$$\kappa_{pe} \propto \int \mathbf{E}_s^* \cdot \Delta\epsilon_{pe}^* \cdot \mathbf{E}_p \, dA$$

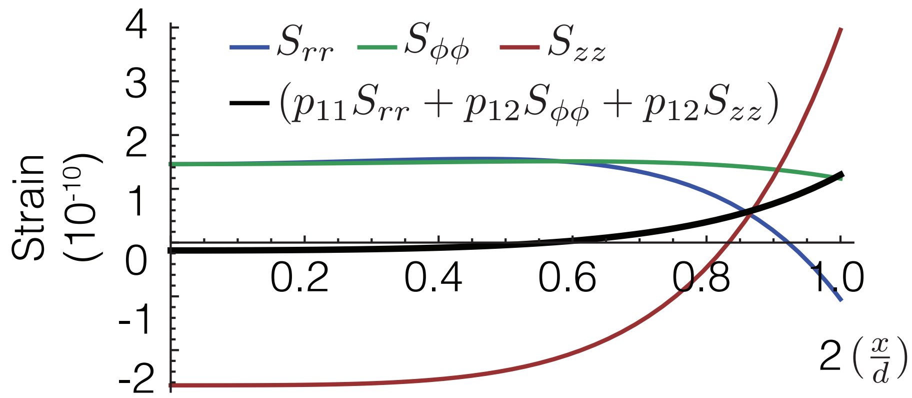
transverse | longitudinal | crossed

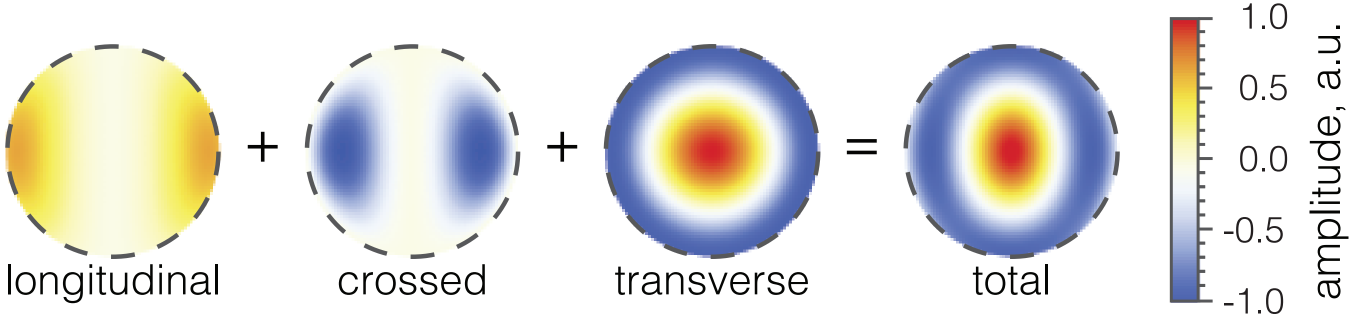
$$\mathbf{E}_s^* \cdot \Delta\epsilon_{pe}^* \cdot \mathbf{E}_p = \Delta\epsilon_{rr}\left|E_r\right|^2 + \Delta\epsilon_{\phi\phi}\left|E_\phi\right|^2 - \Delta\epsilon_{zz}\left|E_z\right|^2 - 2\Delta\epsilon_{rz}E_rE_z$$



$$\Delta\varepsilon = -\varepsilon_0 n^4 \mathbf{p}\cdot\mathbf{S}$$

$$\Delta\varepsilon_{rr} = -\varepsilon_0 n^4 \left(p_{11}S_{rr} + p_{12}S_{\phi\phi} + p_{12}S_{zz}\right)$$



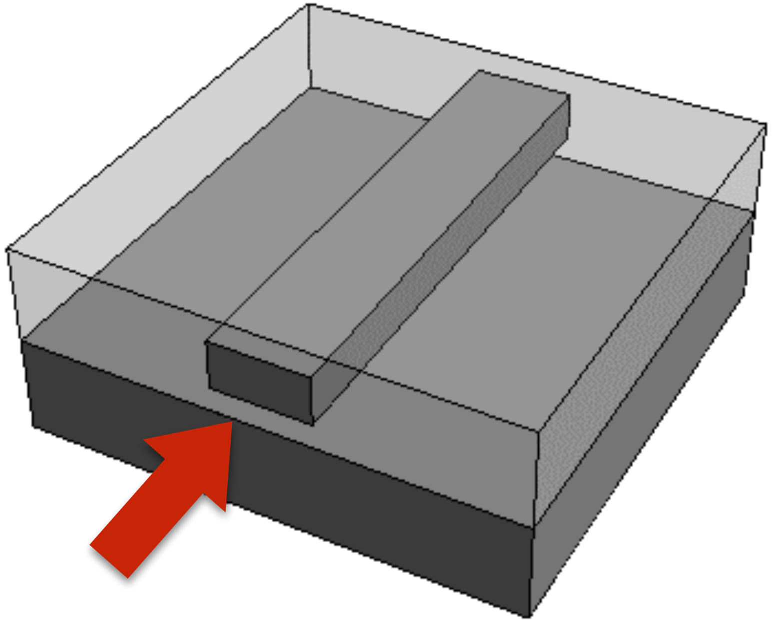


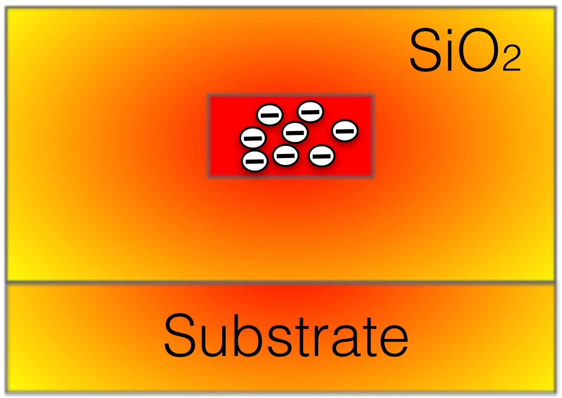
Outline

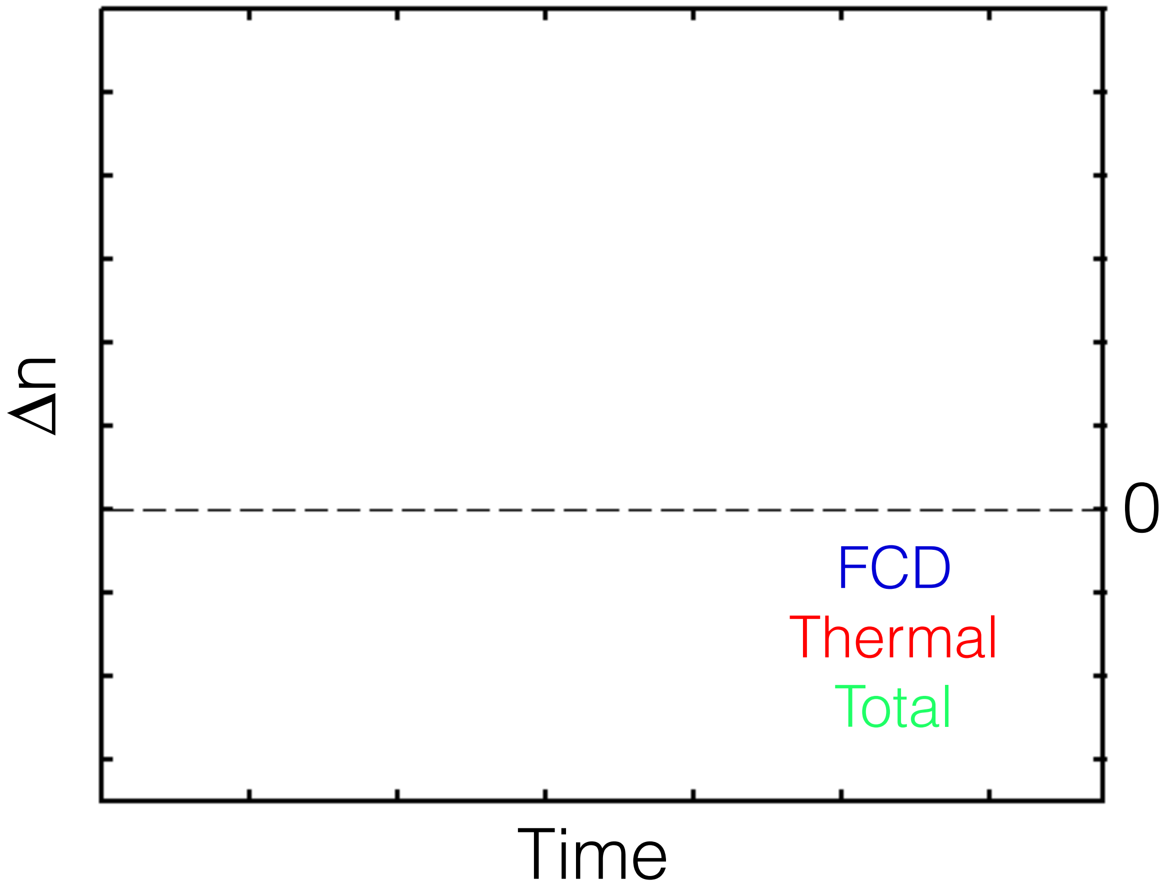
- Future of Optical Communications
- Why are we interested in photon-phonon interaction?
- **Our work: Brillouin scattering self-cancellation effect**

- what else is going on in our lab…
  - Free-carriers dispersion and thermal phase shift in silicon waveguides
  - High-order modes in photonics bandgap fibers and tapers
  - Broadband & small footprint dielectric antenna

Two-photon absorption, Free-carrier dispersion and Self-heating



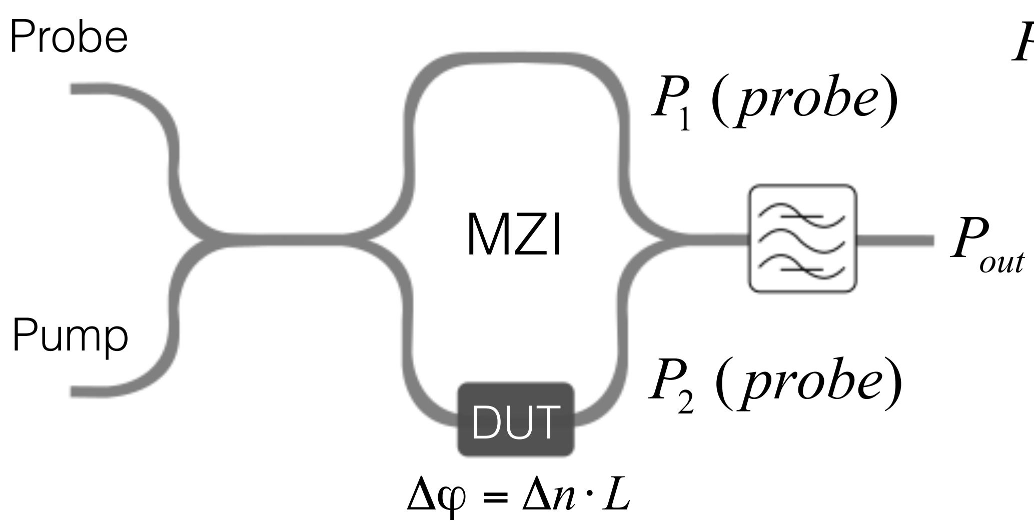


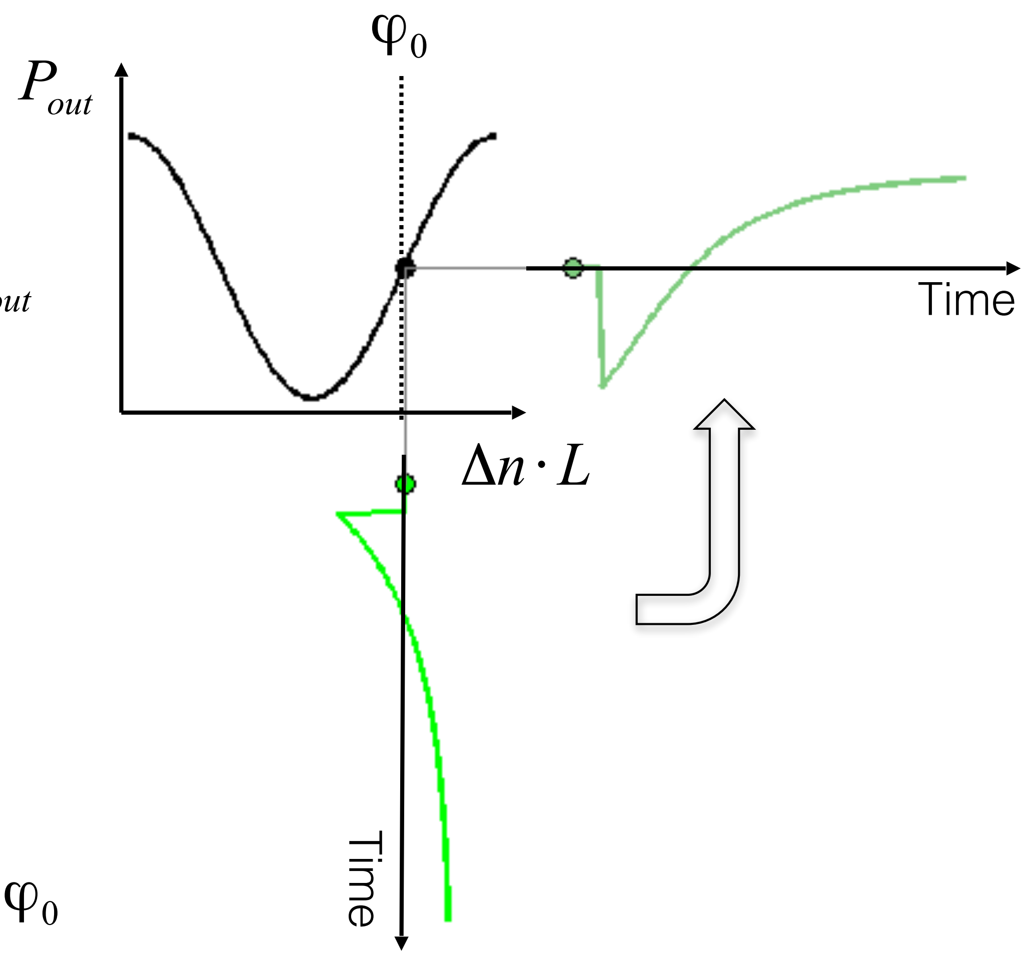


I. Aldaya, A. Gil-Molina, H.L. Fragnito, and P. Dainese, "Time-domain Interferometric Characterization of Nonlinear and Thermal-induced Phase-shift in Silicon Waveguides", Conference on Lasers and Electro-Optics, SM3R. 7 (2016);

Δn measurement in non-resonant structures

- A straightforward phase discrimination method is a pump-and-probe MZI

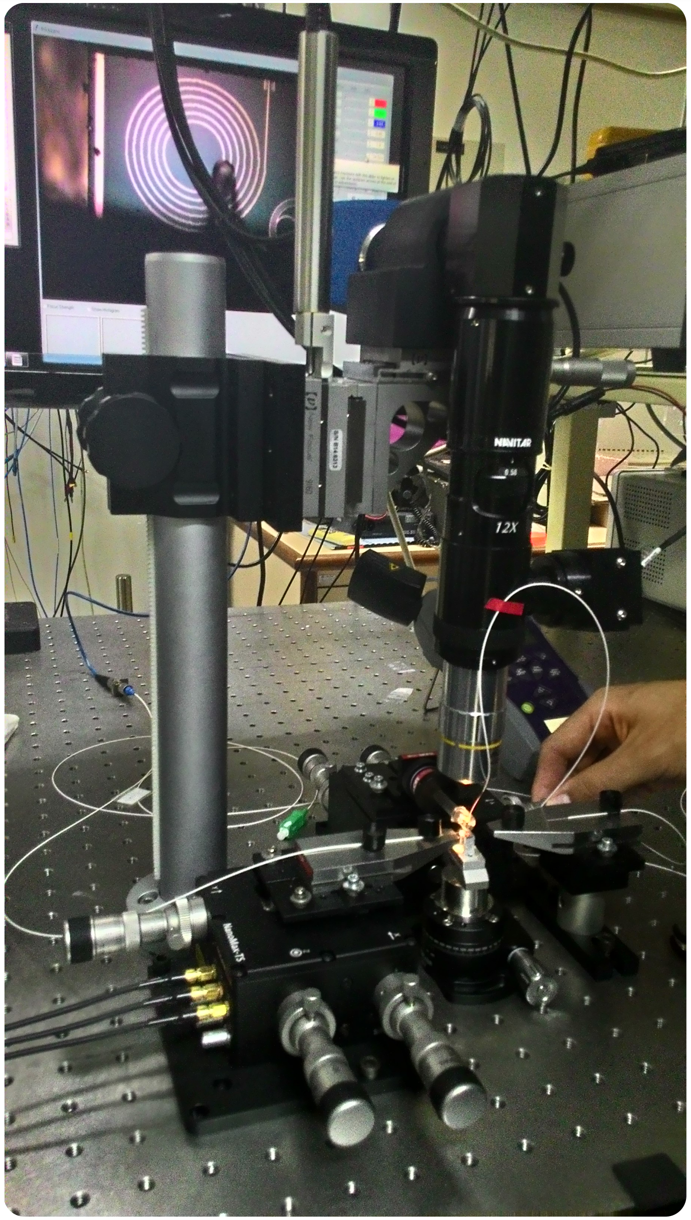


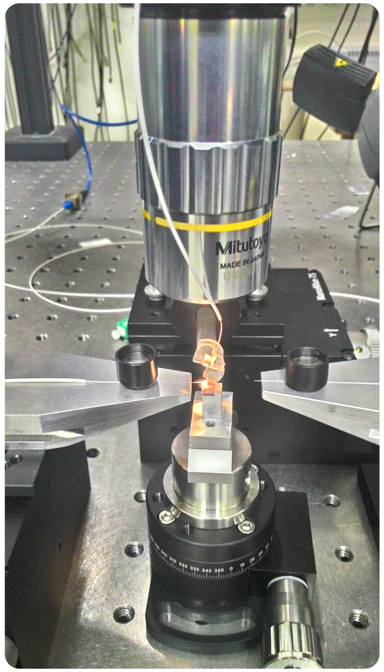


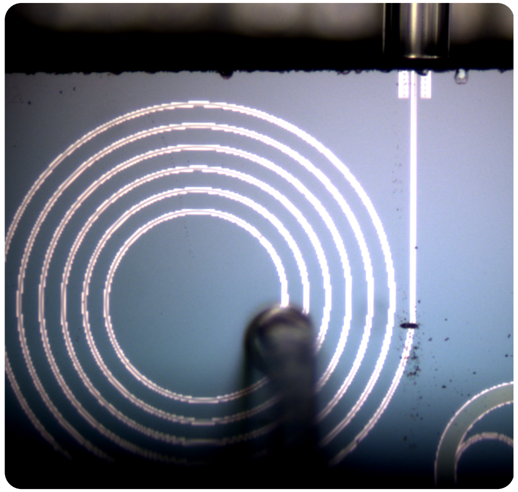
$$P_{out} = P_1 + P_2 + 2P_1 \cdot P_2 \cos(\Delta n \cdot L + \varphi_0)$$

$$\Rightarrow \Delta\varphi = \Delta n \cdot L = \arccos\left[\frac{P_{out} - P_1 - P_2}{2P_1 \cdot P_2}\right] - \varphi_0$$

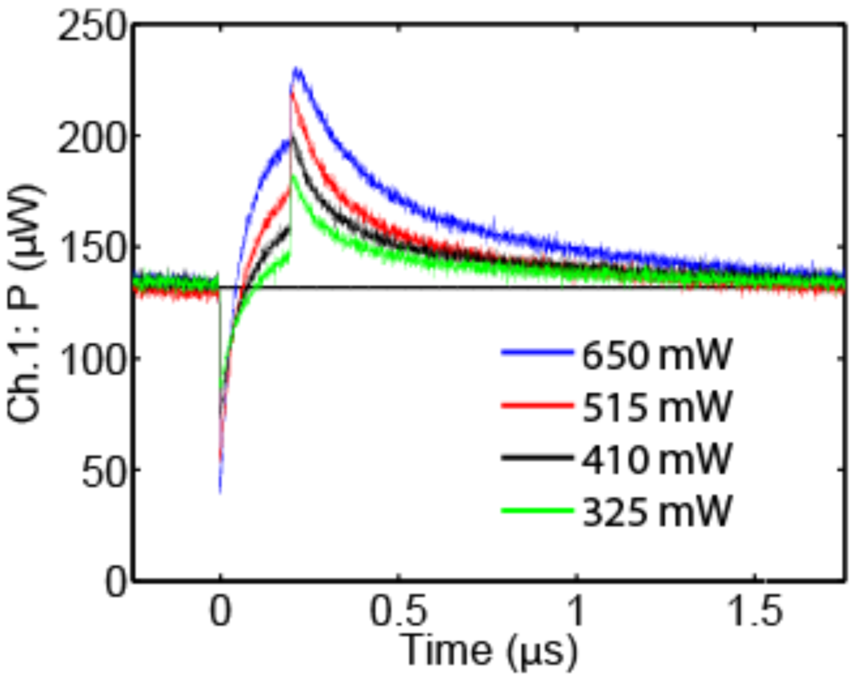
Characterization method

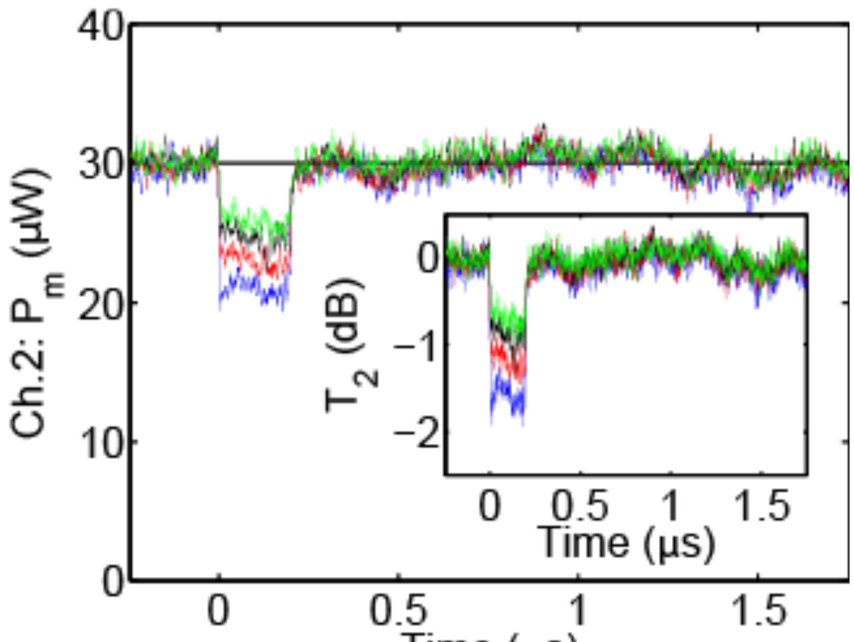




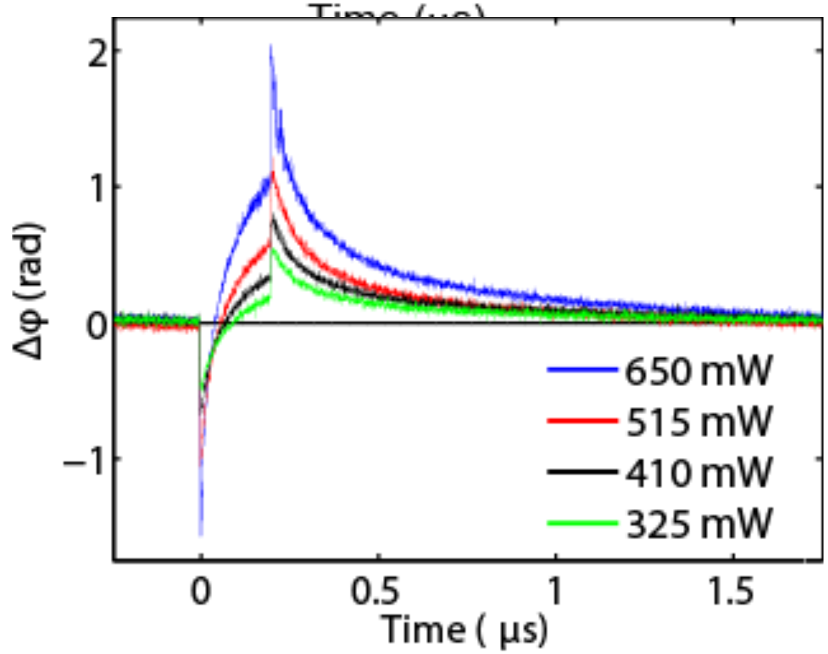


Characterization method



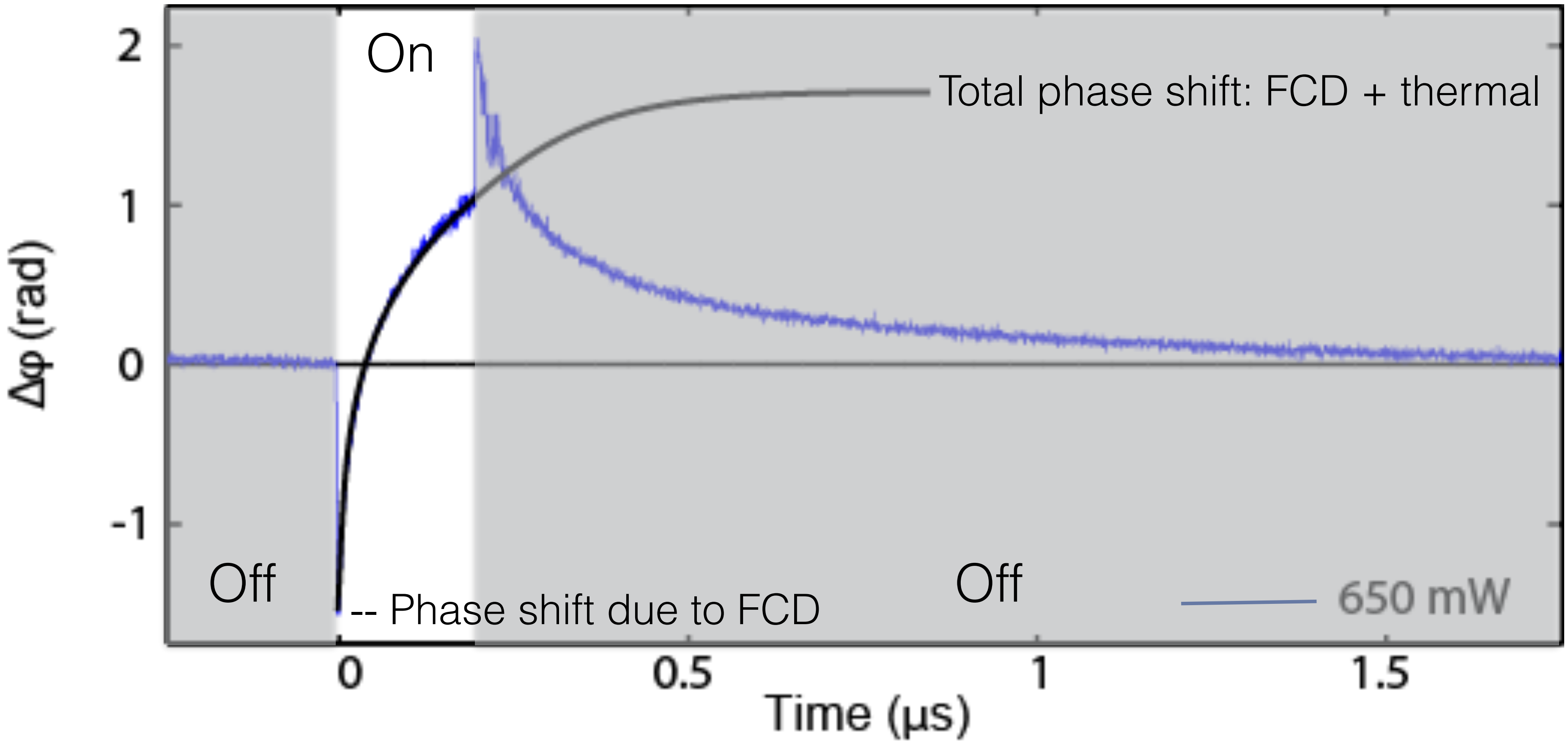


$$\Delta\varphi = \arccos\left[\frac{P_{out} - P_1 - P_2(t)}{2P_1 \cdot P_2(t)}\right] - \varphi_0$$

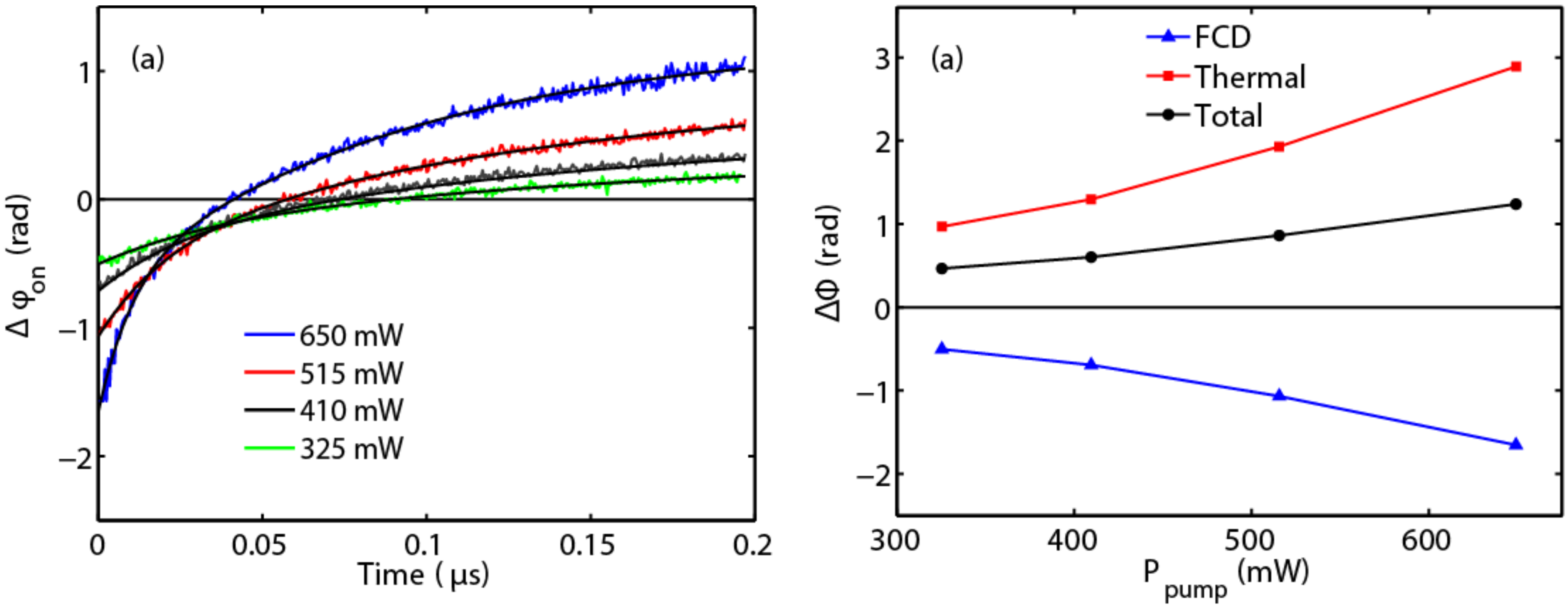


Results

- We applied the method to a 4-mm long fully-etched waveguide
- The cross-section was 220 nm x 450 nm
- The waveguide had silica cladding



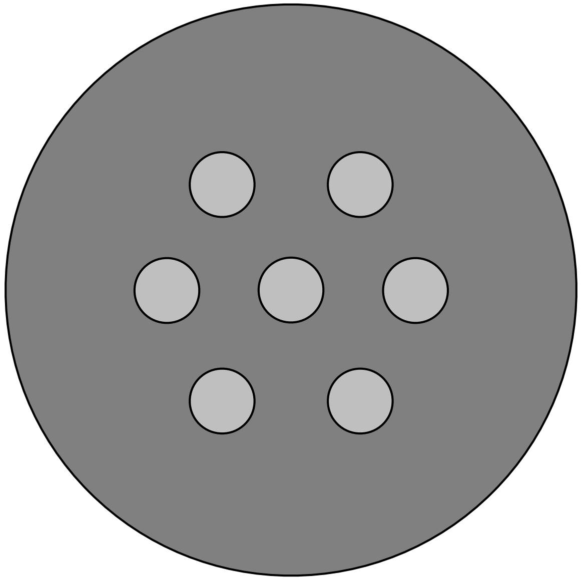
Results



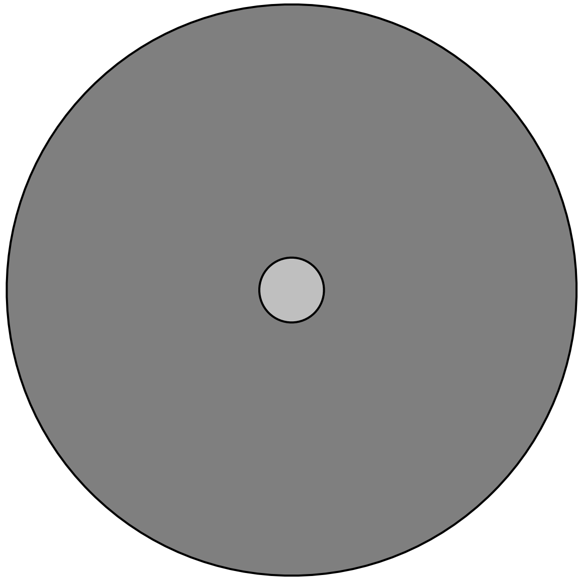
- We propose a simple interferometric characterization method.
- Given the different time scales, the method allows the simultaneous measurement of FCD and self heating phase-shift.
- For a 4-mm long fully-etched waveguide with silica cladding, we found that for 650 mW, the contribution of self-heating is %70 higher than the FCD, resulting in a net positive phase-shift of 1 rad.

Understanding modal content vs. offset launch in novel fiber designs

Multi-core

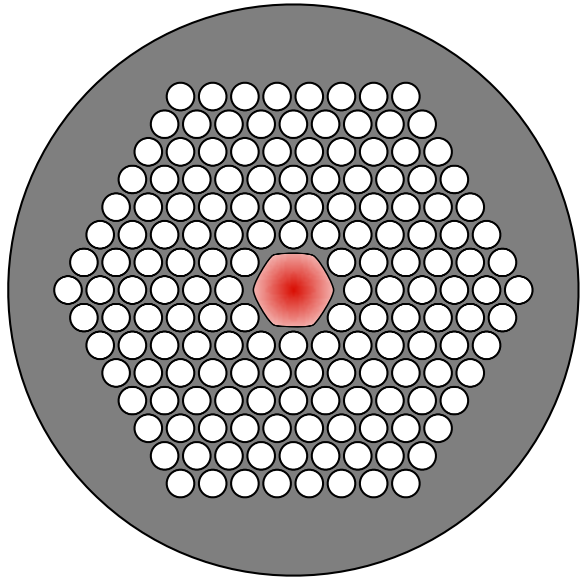


Few-moded

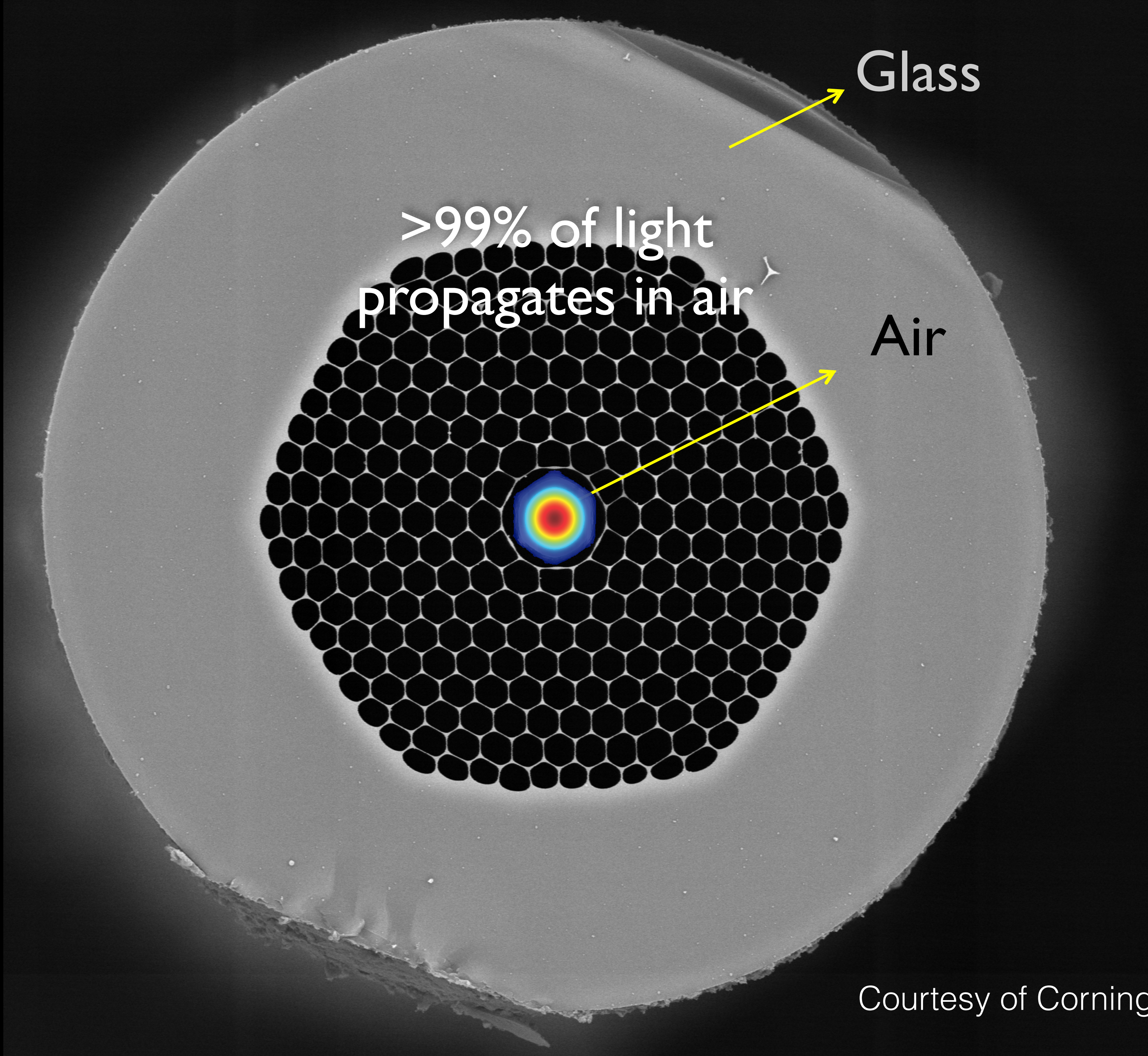


Parallel multiplexing

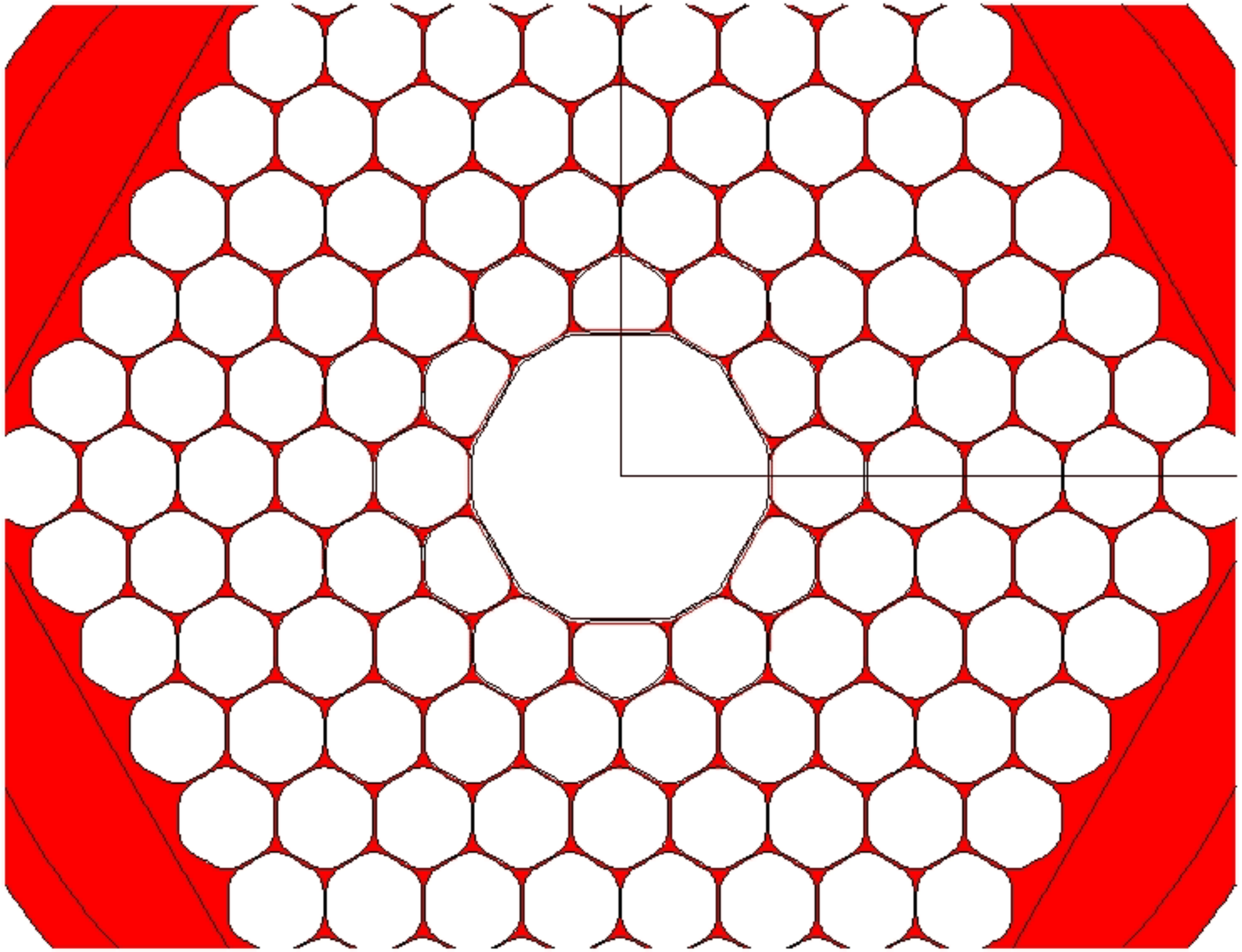
Hollow-Core Photonic Bandgap



Low-nonlinearity (~1000x)
Potentially low-loss (<0.1 dB/km?)

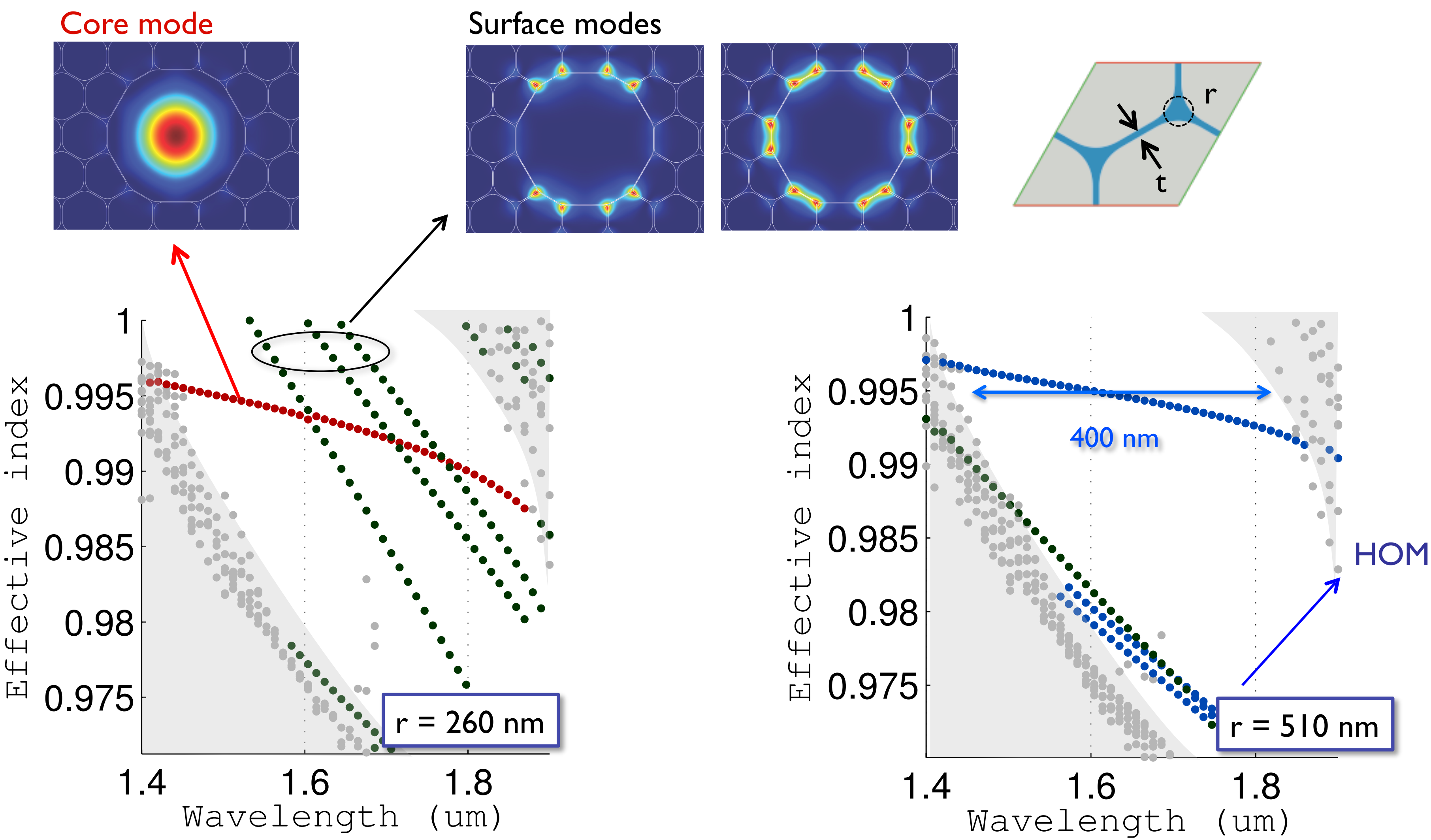

Glass
>99% of light
propagates in air
Air
Courtesy of Corning Inc.

Structural deformations: simulation

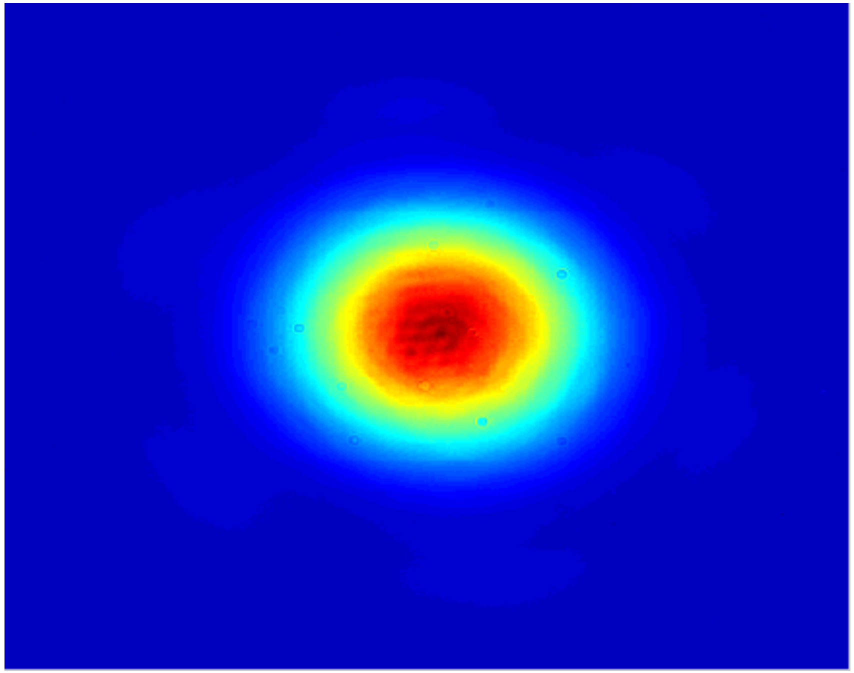


- Pressure applied inside the core inner boundary
- **Motion is constrained**
- Static solid mechanics model is solved.
- Material model is linear elastic, but can be changed

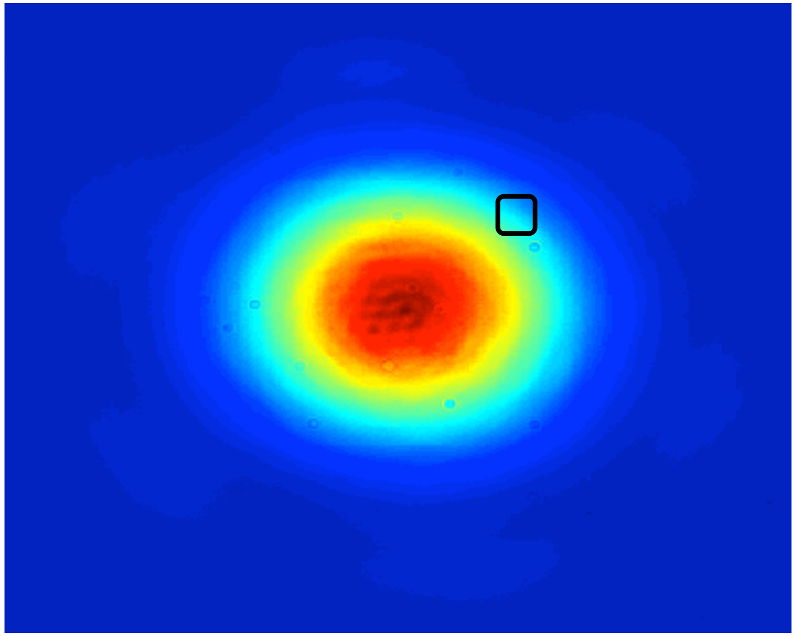
Surface modes: termination of the photonic crystal lattice becomes



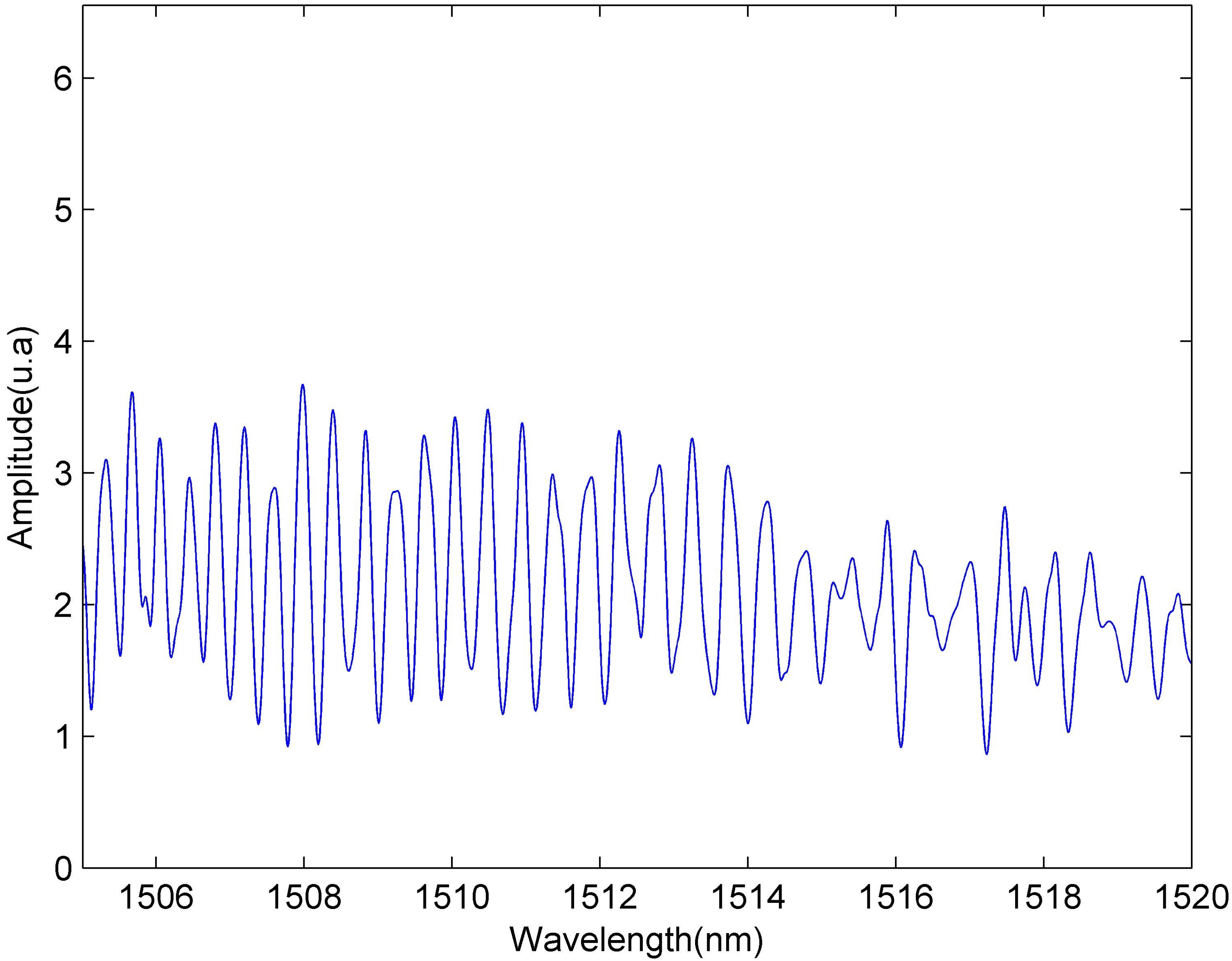
Output beam projected image



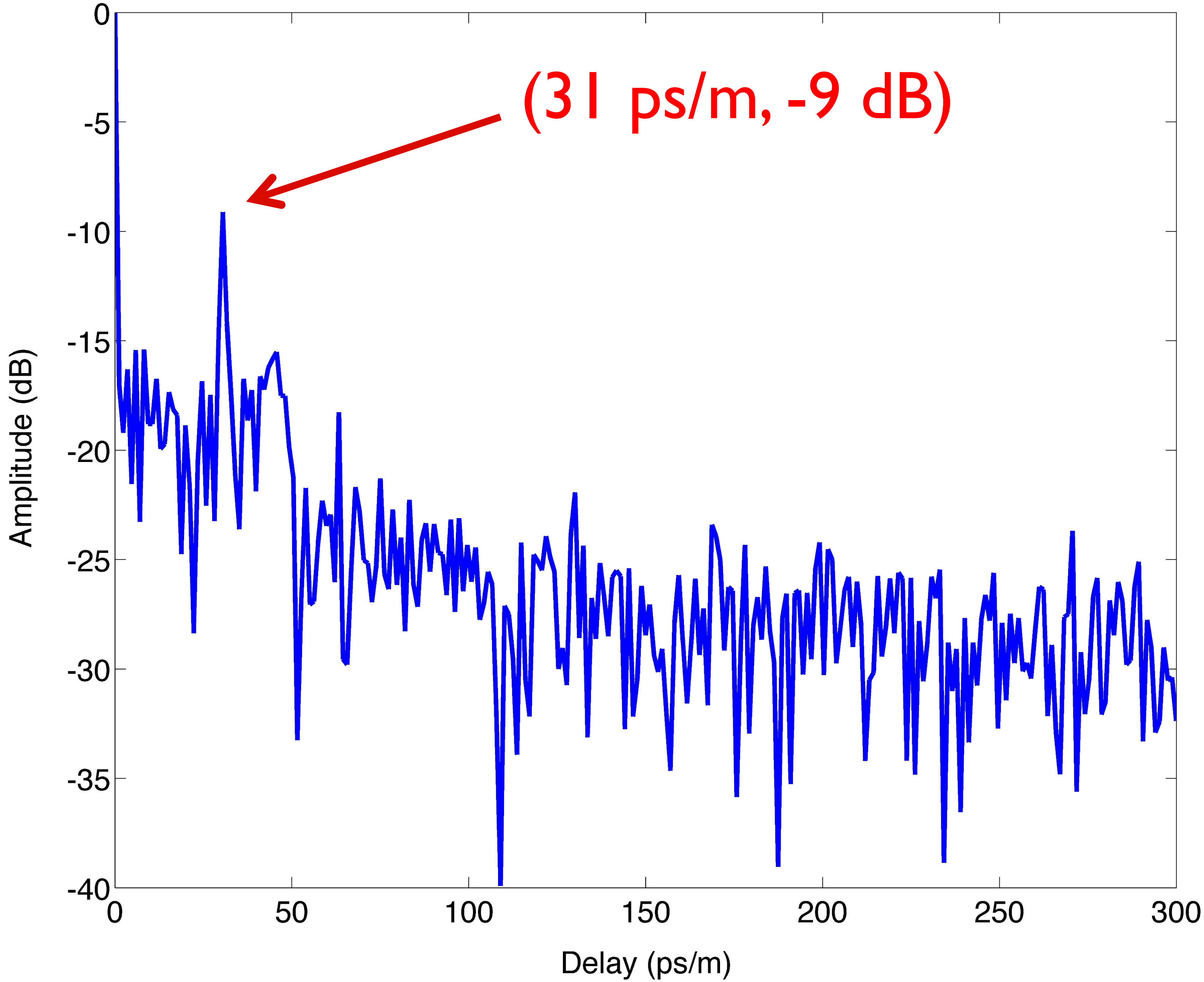
Output beam projected image



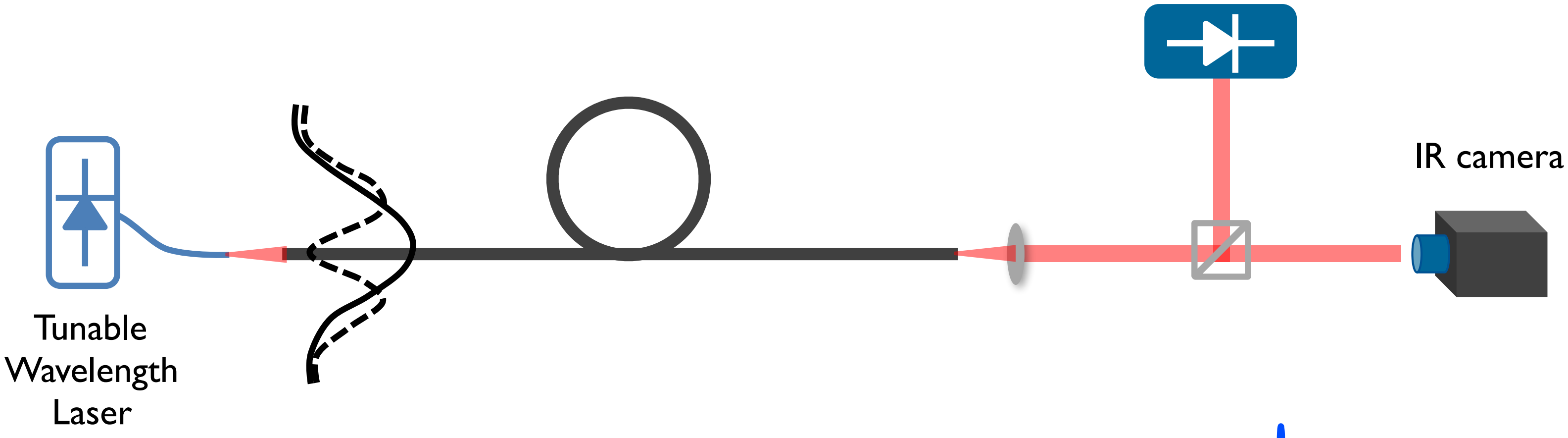
Spectral response at a fixed position (x,y)

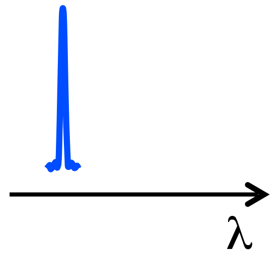


Fourier Transform at a fixed position (x,y)

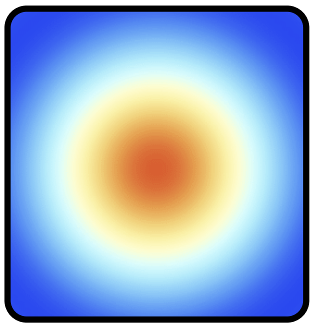


Direct measurement of guided modes (amplitude and phase)



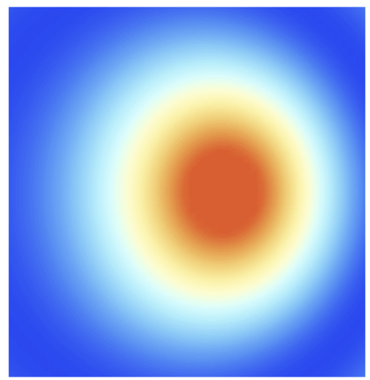


Fundamental mode



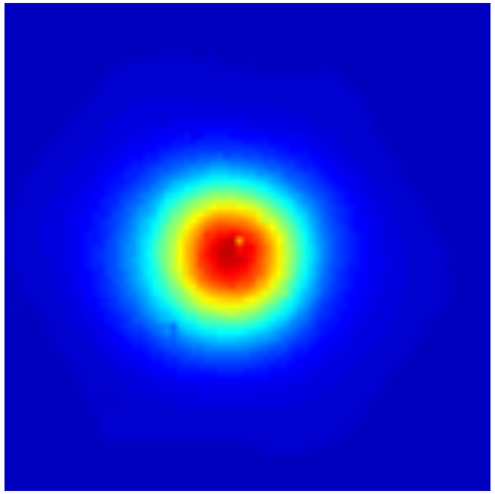
High order mode

Interference pattern

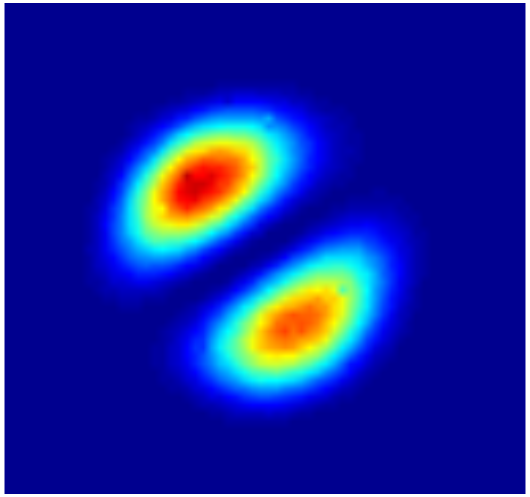


Experimentally recovered mode amplitude and phase

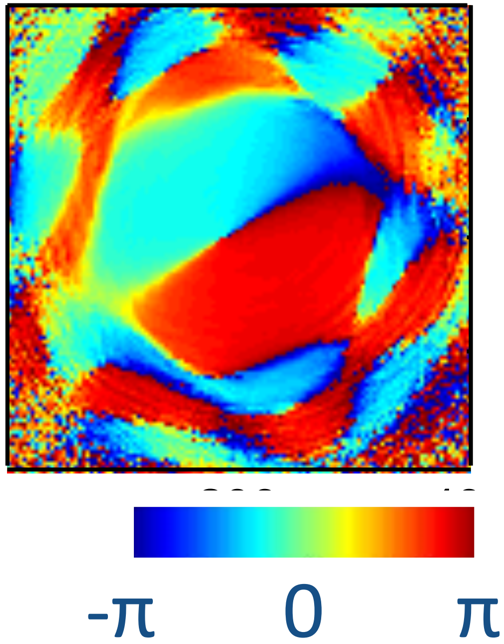
Fundamental mode profile



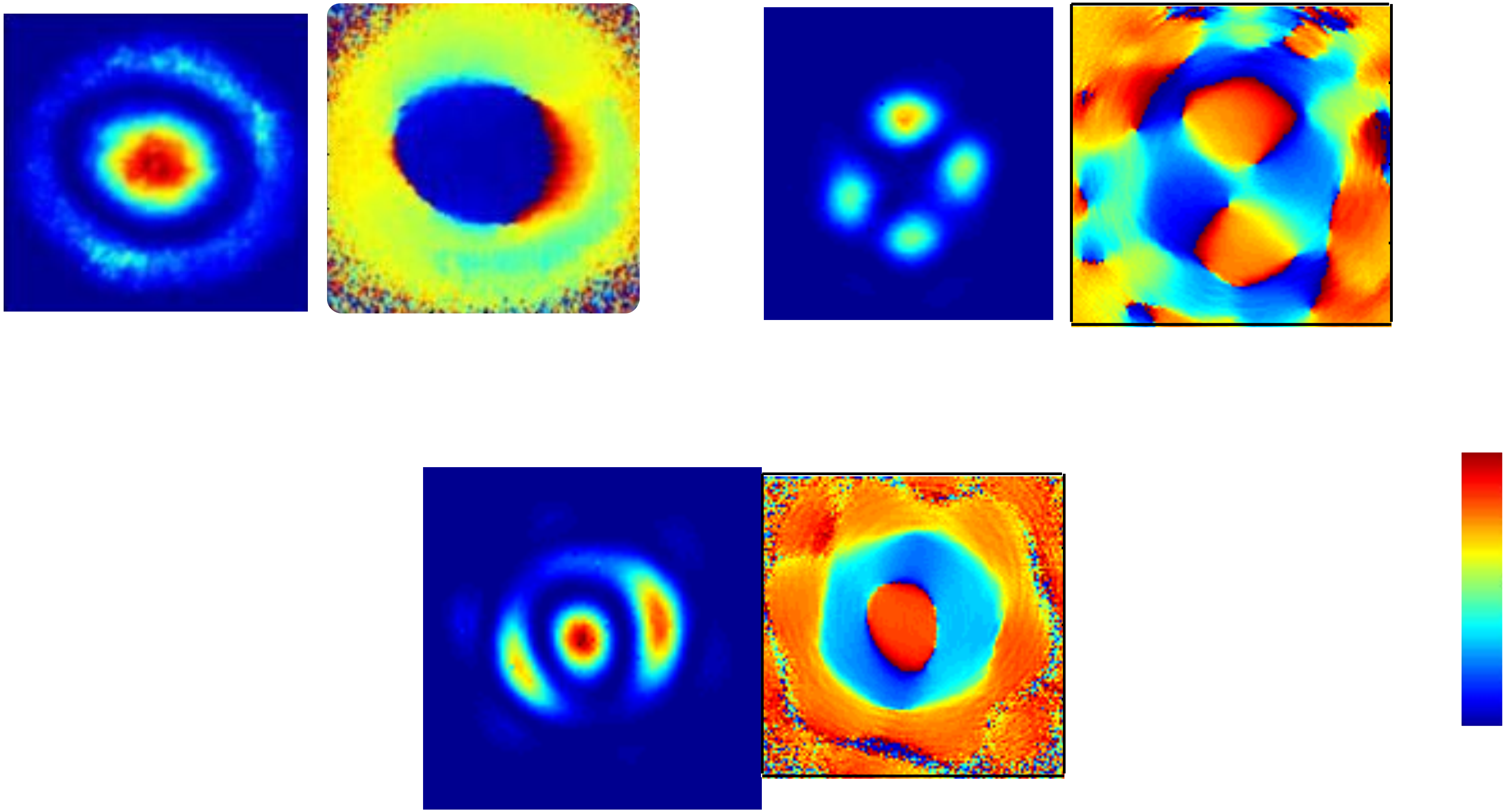
LP_{11}-like mode profile



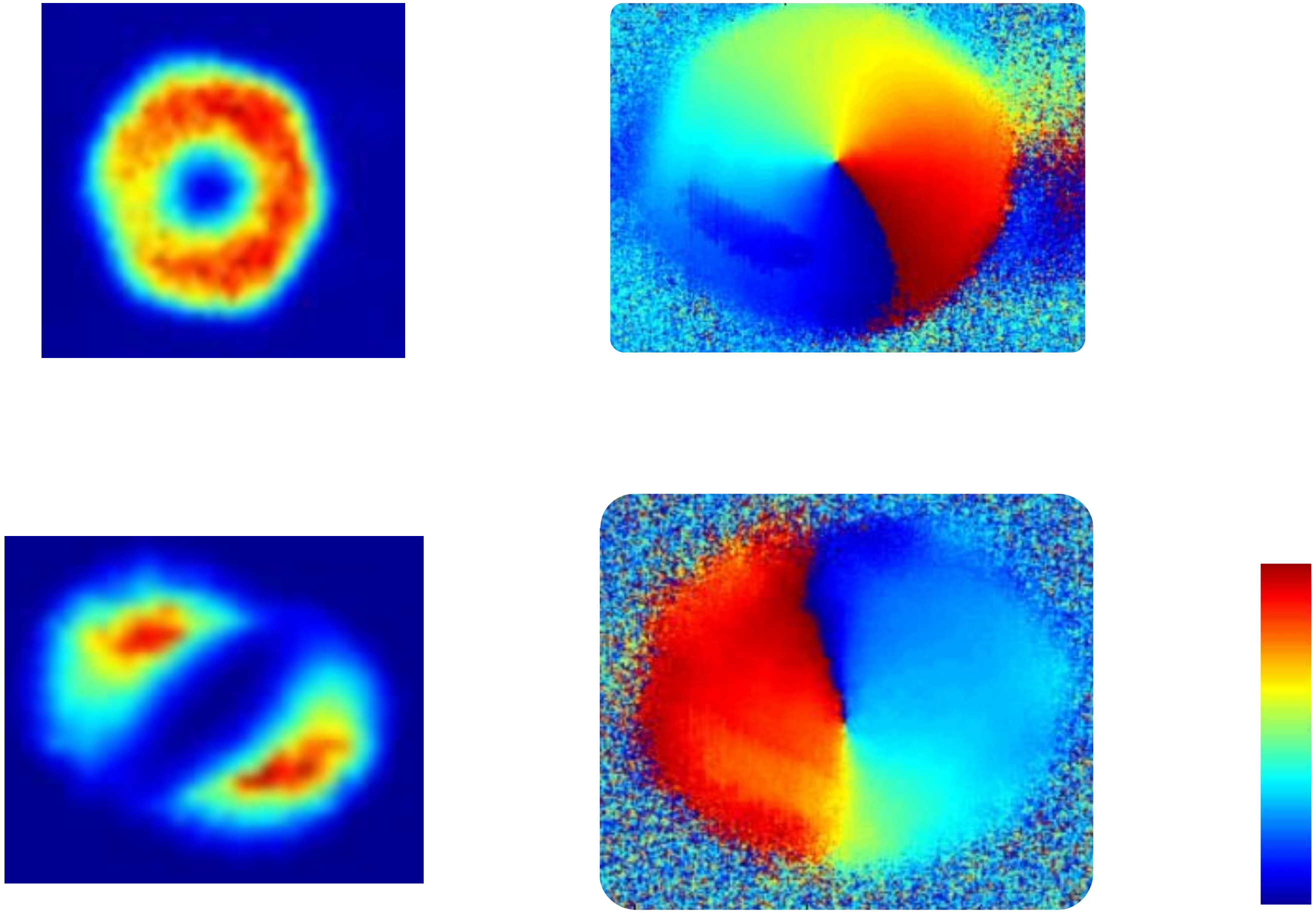
LP_{11}-like mode phase



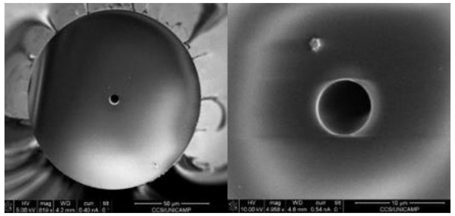
Lager core (22 micron core PBGF)

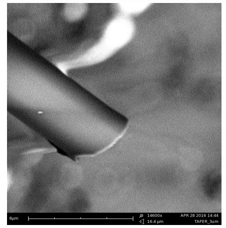


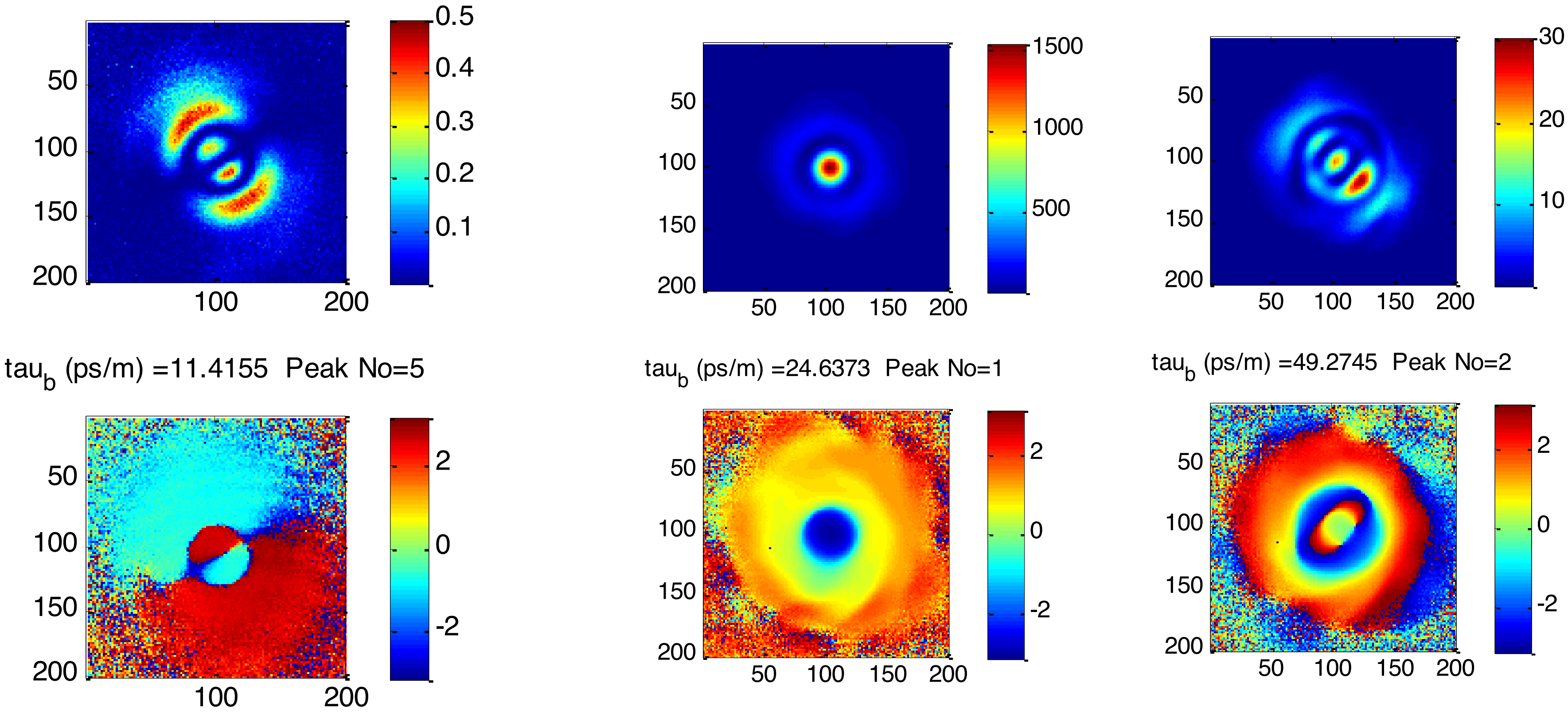
Lager core (22 micron core PBGF)



Fiber with center hole and cleaved taper

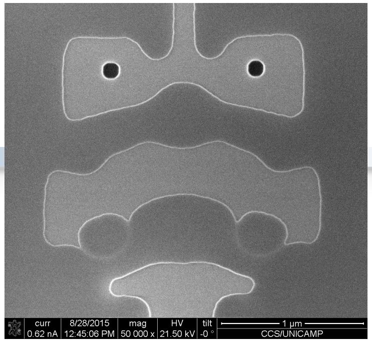






E. Lamilla, I. Aldaya, C. M. Serpa, P. Jarshel, and P. Dainese, "Modal Content in a 7-cell Hollow-Core Photonic Bandgap Fiber and its Dependence with Offset Launch Conditions", accepted Latin-America Optics and Photonics Conference, oral presentation (2016);

Motivation and state-of-art

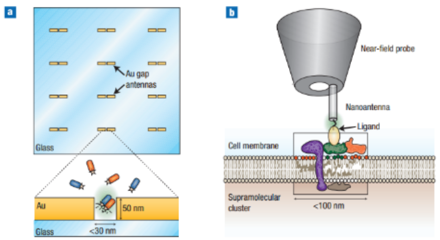


J. Pita, P. Dainese, H. Hernandez-Figueroa, and L.H. Gabrielli, "Ultra-Compact Broadband Dielectric Antenna" Conference on Lasers and Electro-Optics, SM3R. 7 (2016);

Sensors

Optical antennas focus in on biology

MARIA F. GARCIA-PARAJO

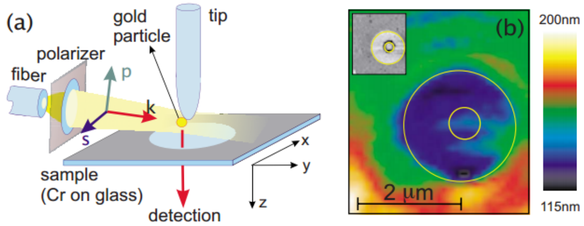


nature photonics | VOL 2 | APRIL 2008 | www.nature.com/naturephotonics

Microscopy

Optical Antennas

Palash Bharadwaj, Bradley Deutsch, and Lukas Novotny*



Advances in Optics and Photonics 1, 438–483 (2009) doi:10.1364/AOP.1.000438

Metallic antennas:

- Small footprint
- Incompatible with the CMOS technology

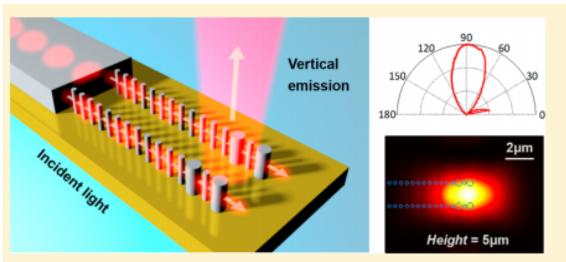
Dielectric antennas:

- Large footprint
- Wavelength-dependent

Optical communications

High-Efficiency Vertical Light Emission through a Compact Silicon Nanoantenna Array

Haiyang Huang,[†,§] Hao Li,[†,§] Wei Li,[*,†,‡] Aimin Wu,[*,†] Xin Chen,[†] Xuefeng Zhu,[‡] Zhen Sheng,[†] Shichang Zou,[†] Xi Wang,[†] and Fuwan Gan[*,†]

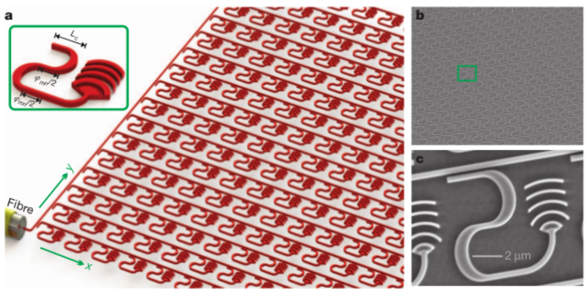


DOI: 10.1021/acsphotonics.5b00641
ACS Photonics 2016, 3, 324–328

Phased arrays

Large-scale nanophotonic phased array

Jie Sun[1], Erman Timurdogan[1], Ami Yaacobi[1], Ehsan Shah Hosseini[1] & Michael R. Watts[1]



196 | NATURE | VOL 493 | 10 JANUARY 2013

Optimized antenna design

1

Design goals:

- Small footprint (3.2 um^2)
- Broadside radiation
- Broadband (>150 nm)

2

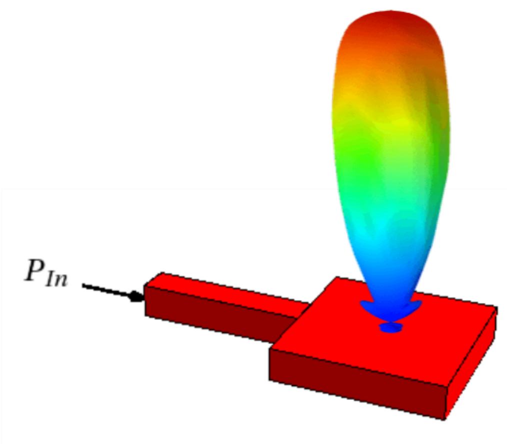
Topology optimization:

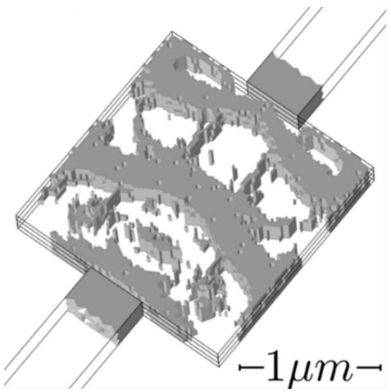
- SNOPT algorithm [1]
- Silicon/Silicon dioxide
- Maximize the far-field in the perpendicular direction

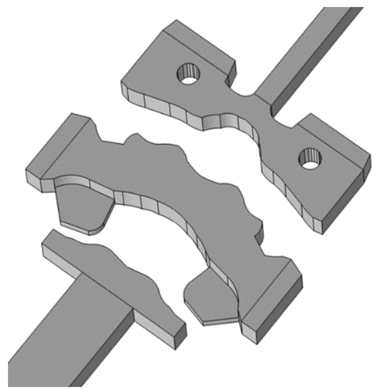
3

Foundry constrains:

- Minimum enclosure
- Minimum spacing
- Singular point







1. SNOPT (Sparce non-linear optimization)

Fabricated and characterized devices

1 Grating antenna

2 Optimized antenna

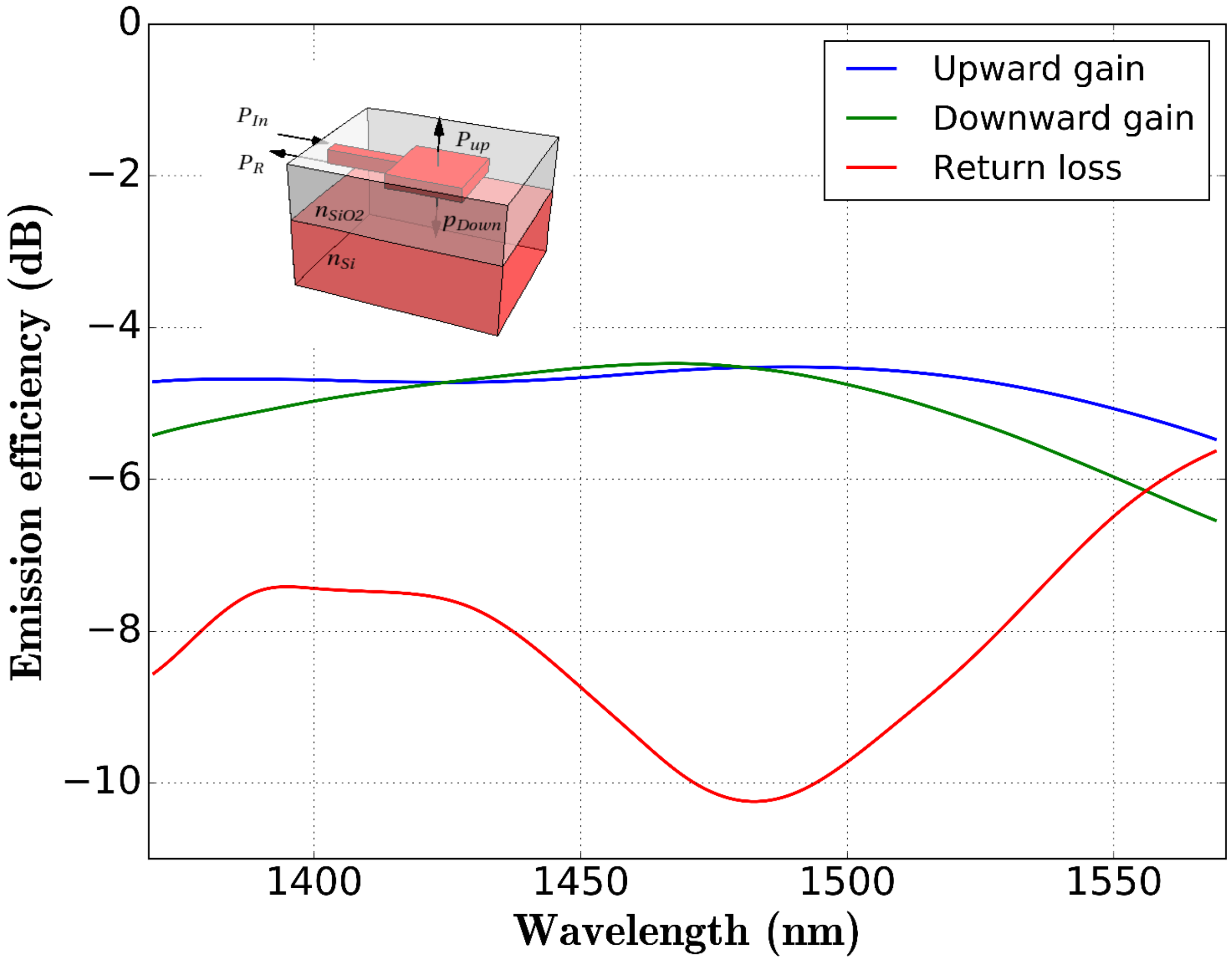
Grating antenna taken from: J. Sun, *et al*. "Large-scale nanophotonic phased array," Nature, vol. 493, no. 7431, pp. 195–199 (2013).

Laboratory of Electronics, MIT.

Silicon dioxide

Silicon

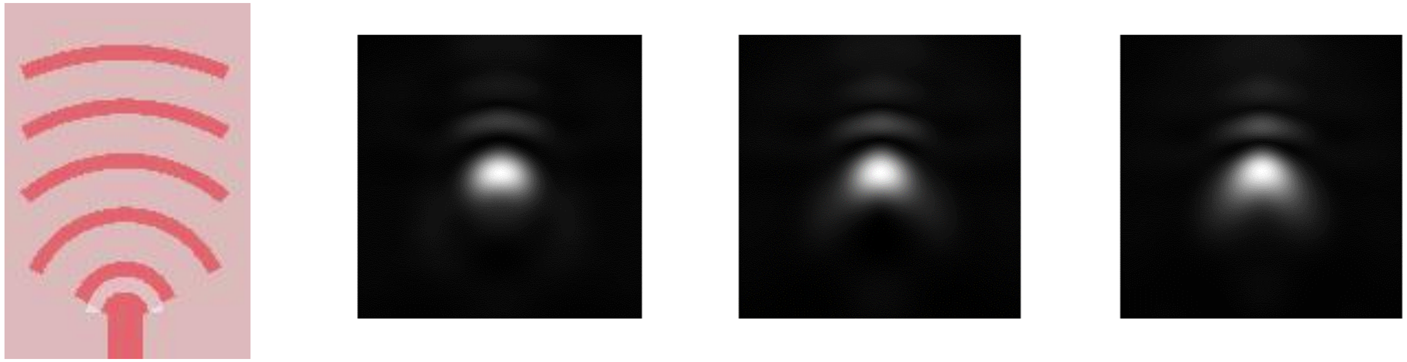
Broadband emission efficiency



- Peak at 1482 nm
- Bandwidth of 1 dB (>150nm)

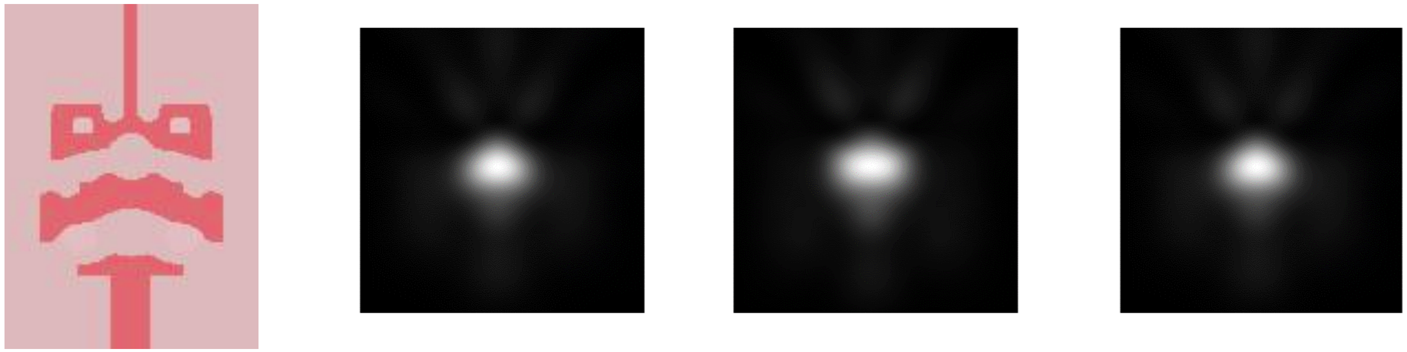
Simulated near-field pattern

Grating antenna

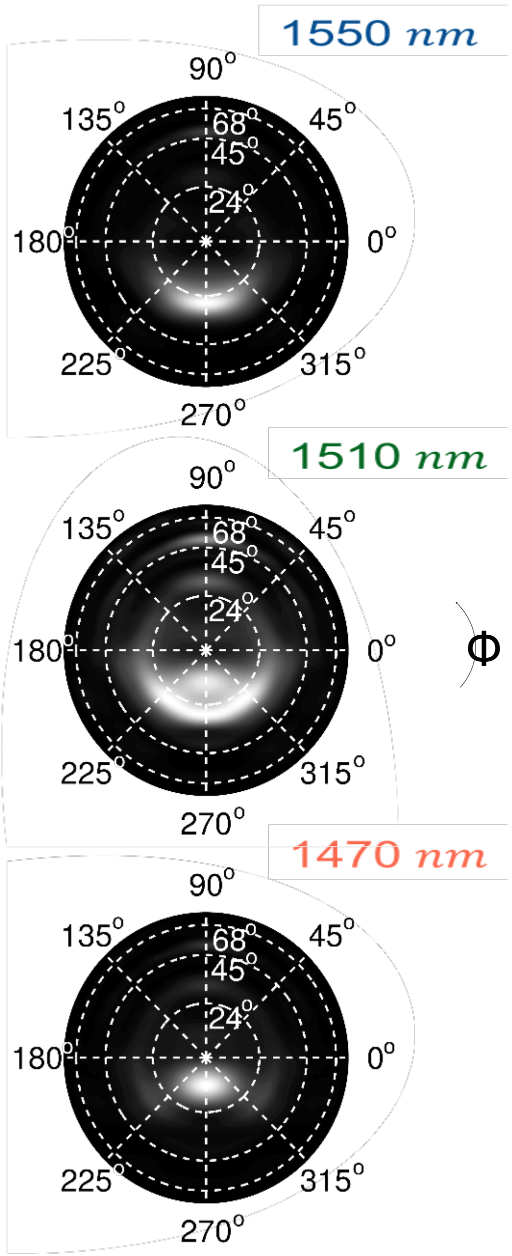


1550 nm 1510 nm 1470 nm

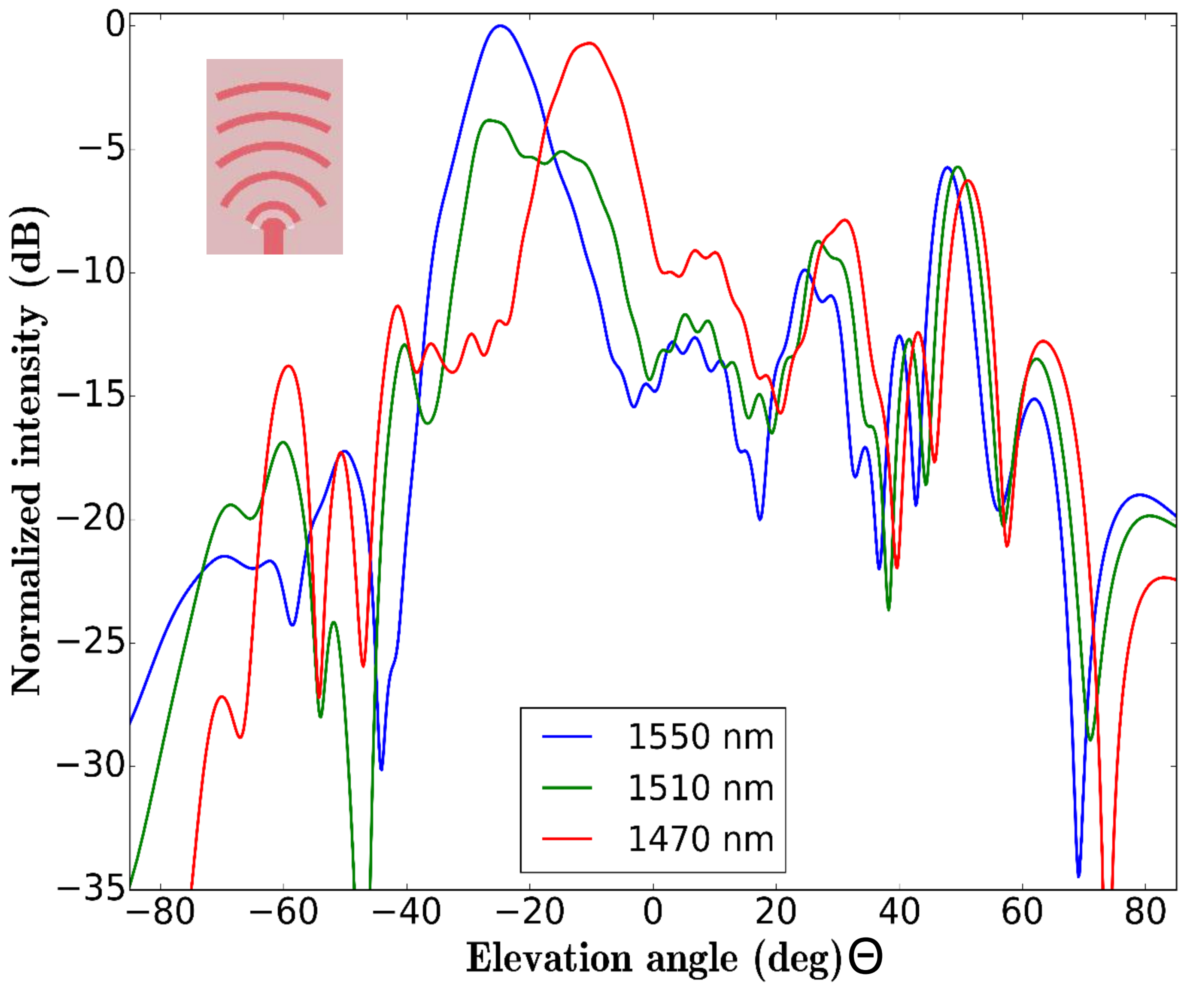
Optimized antenna



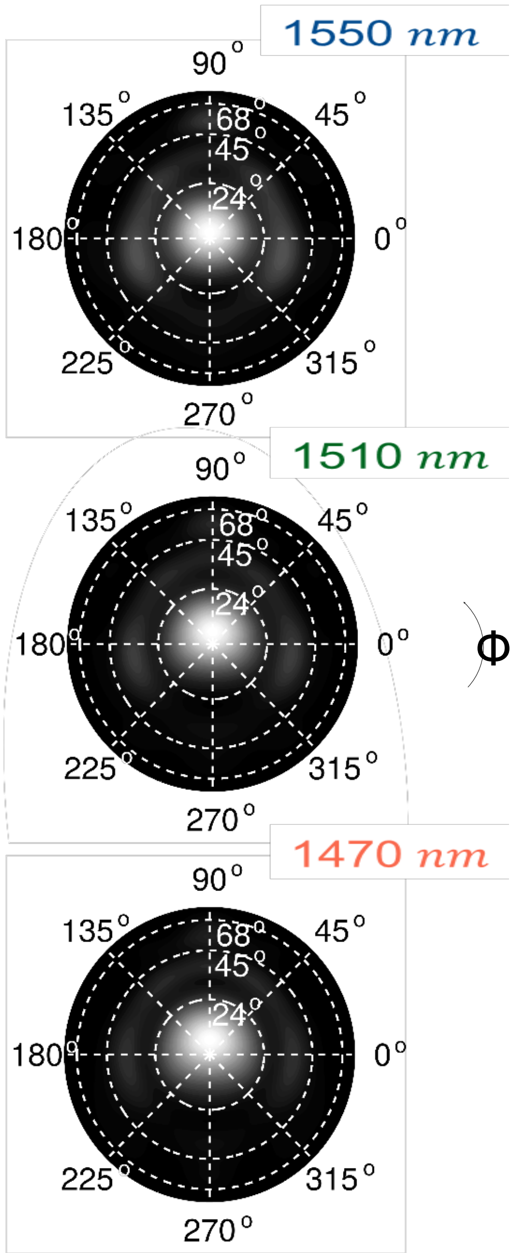
Grating antenna far-field pattern



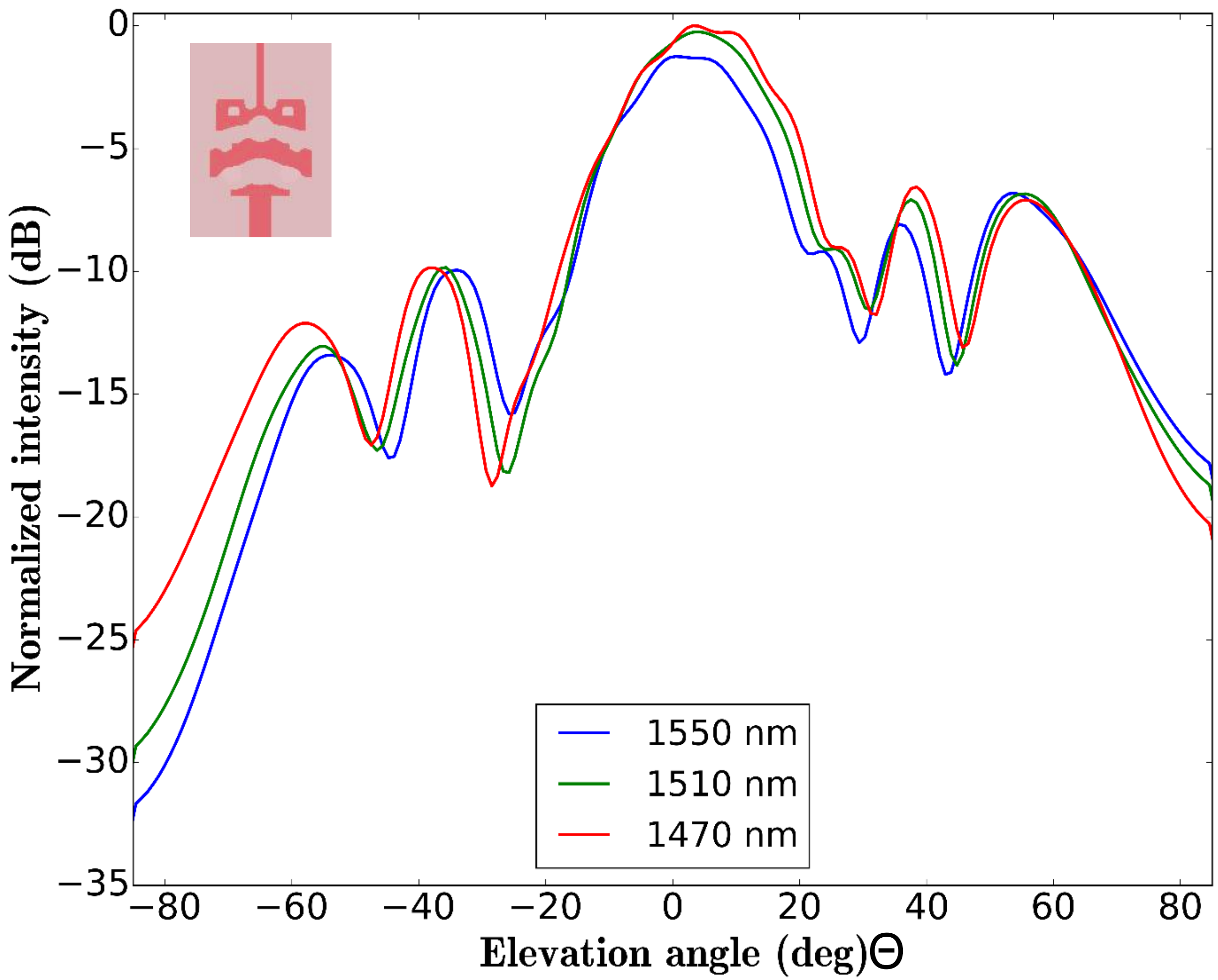
Θ-distribution pattern at Φ=90°



Antenna far-field pattern



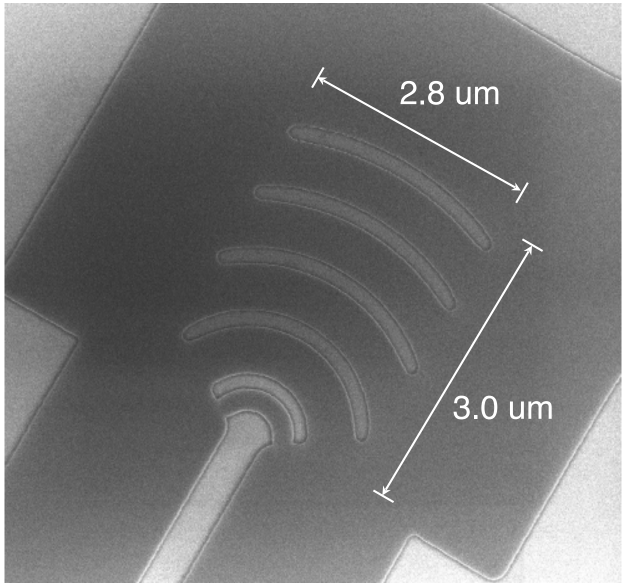
Θ-distribution pattern at Φ=90°

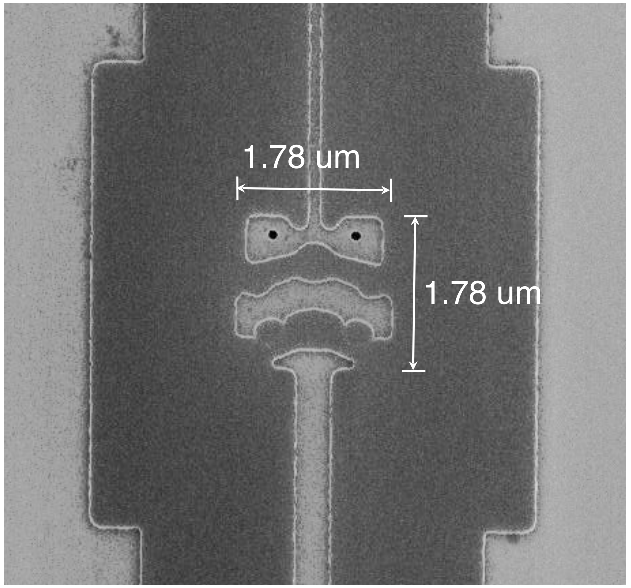


Fabricated devices

Grating antenna

Optimized antenna

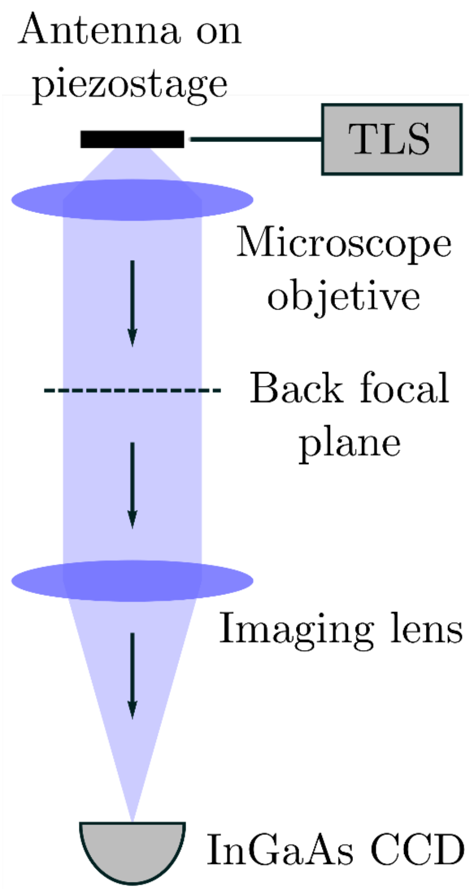




SEM images

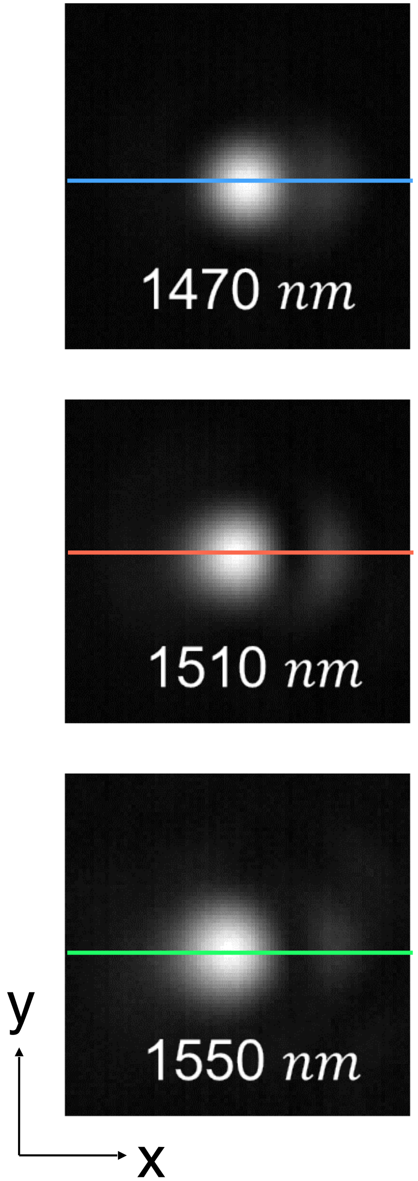
Grating antenna taken from: J. Sun, *et al.* "Large-scale nanophotonic phased array," Nature, vol. 493, no. 7431, pp. 195–199 (2013).

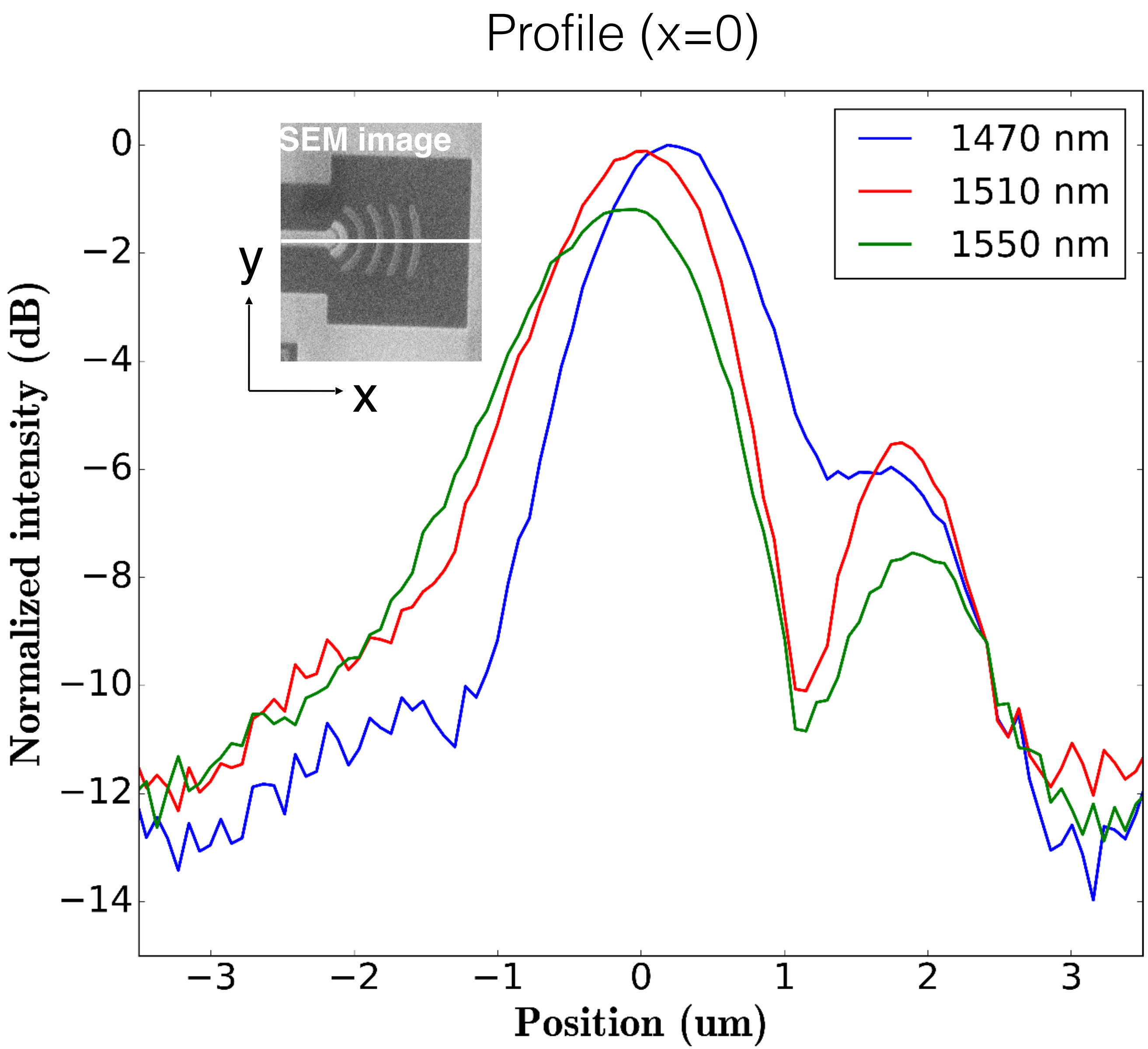
Experimental setup:
4-f system



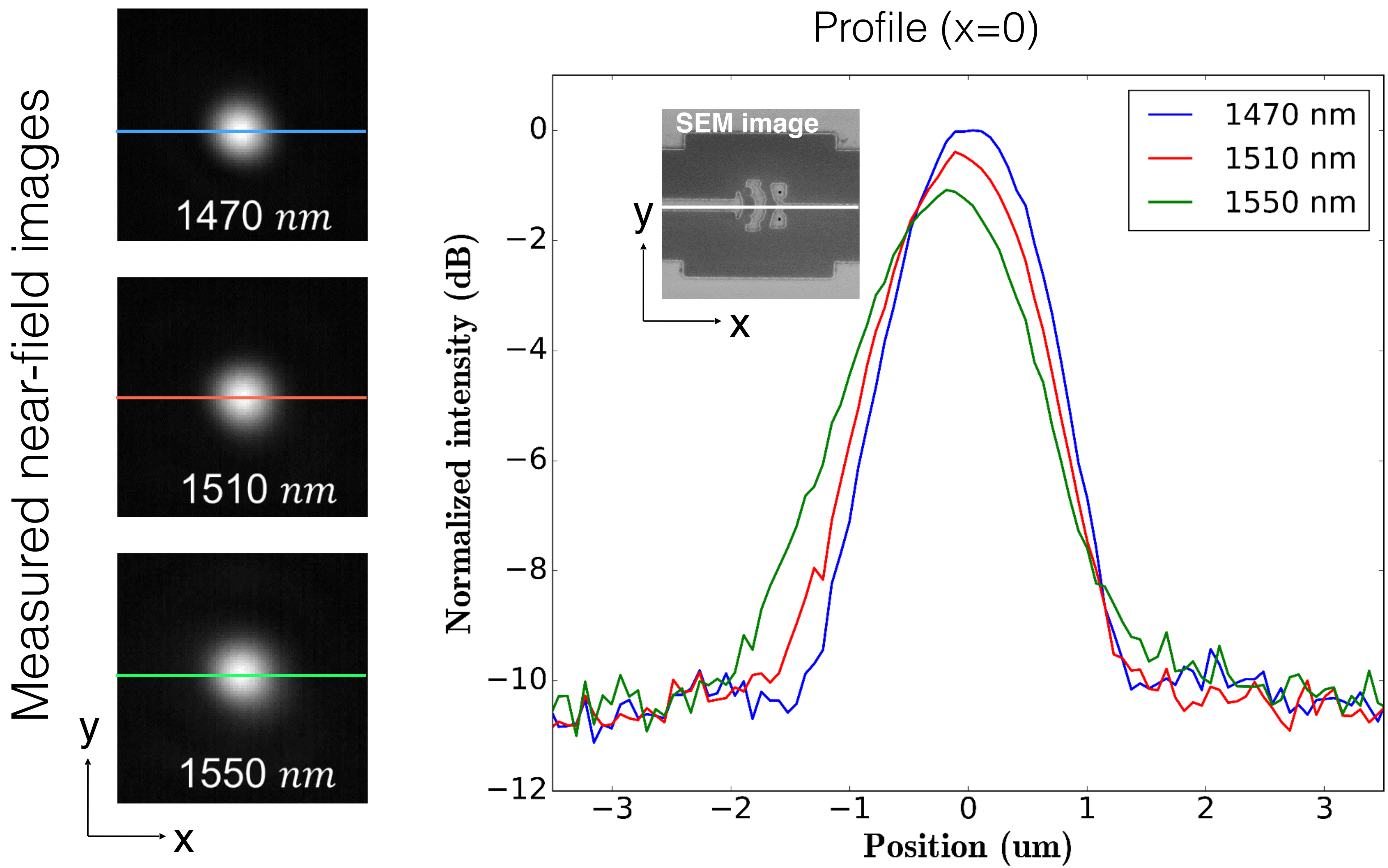
Grating antenna near-field

Measured near-field images

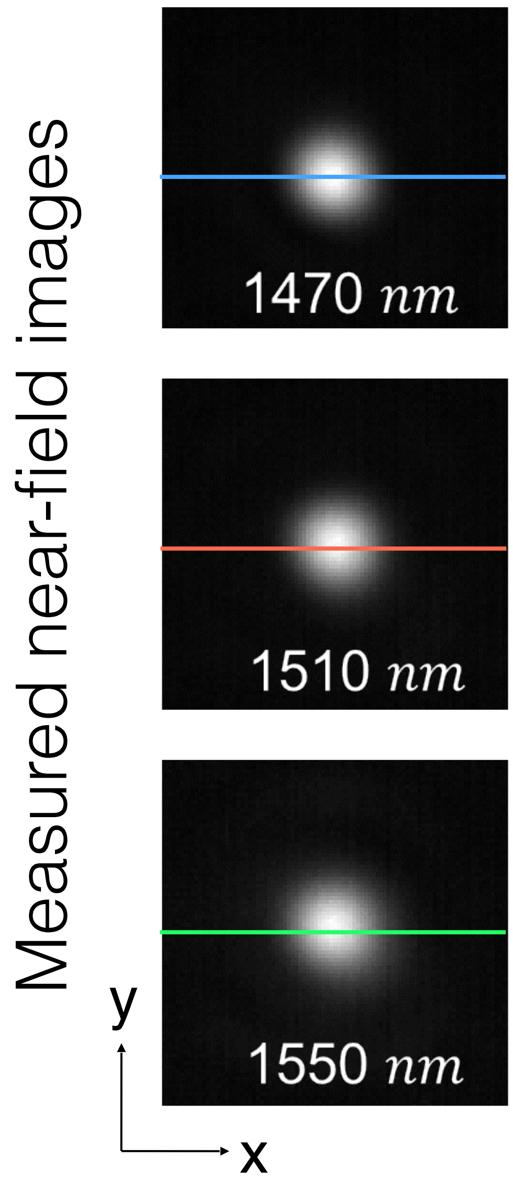


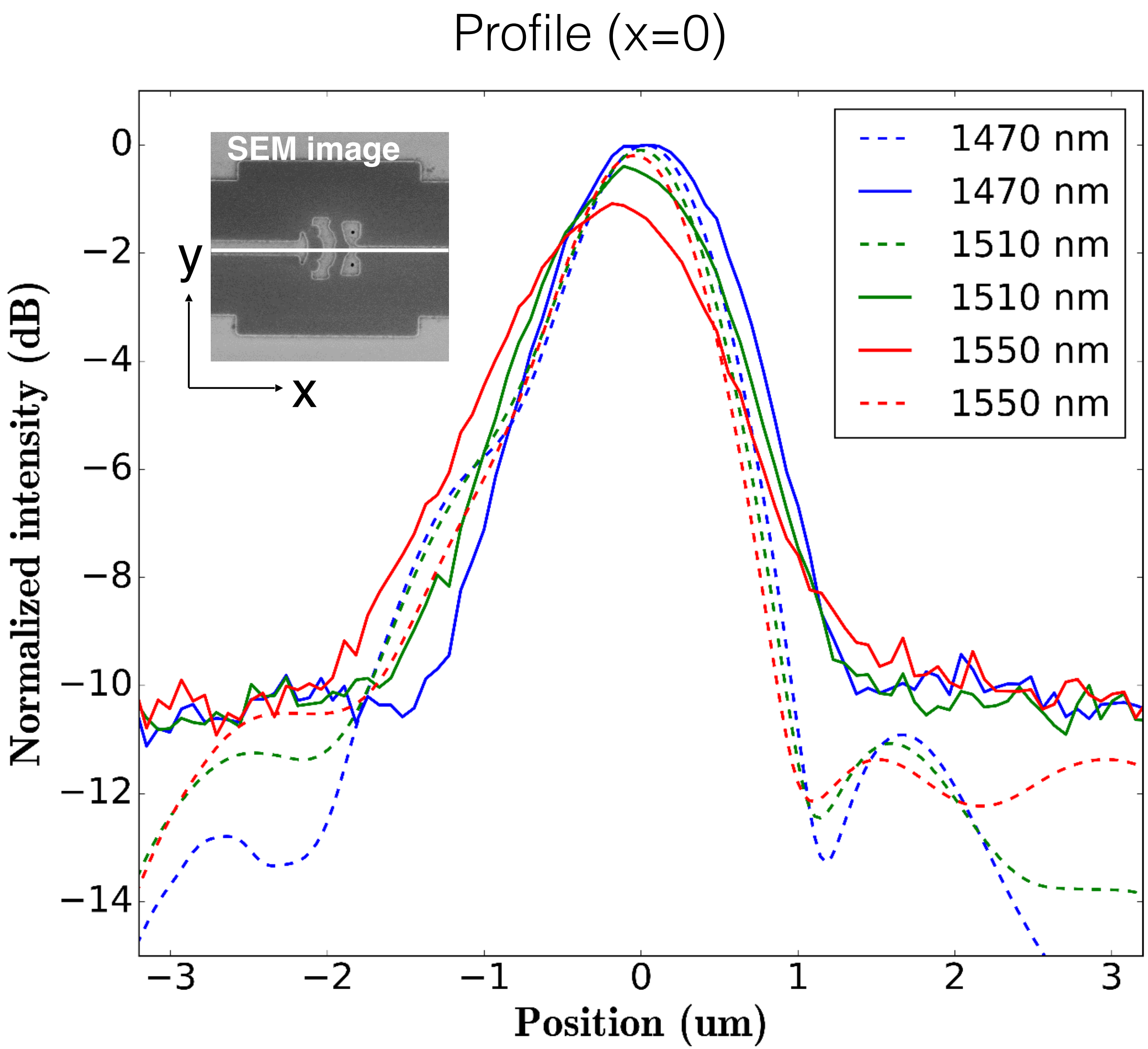


Optimized antenna near-field



Optimized antenna near-field





Thank you!

FAPESP
SÃO PAULO RESEARCH FOUNDATION

Prof. Cristiano Cordeiro

Prof. Thiago Alegre

Prof. Gustavo Wiederhecker

Prof. Lucas H. Gabrielli

Projeto Jovem Pesquisador FAPESP (2014-2018)

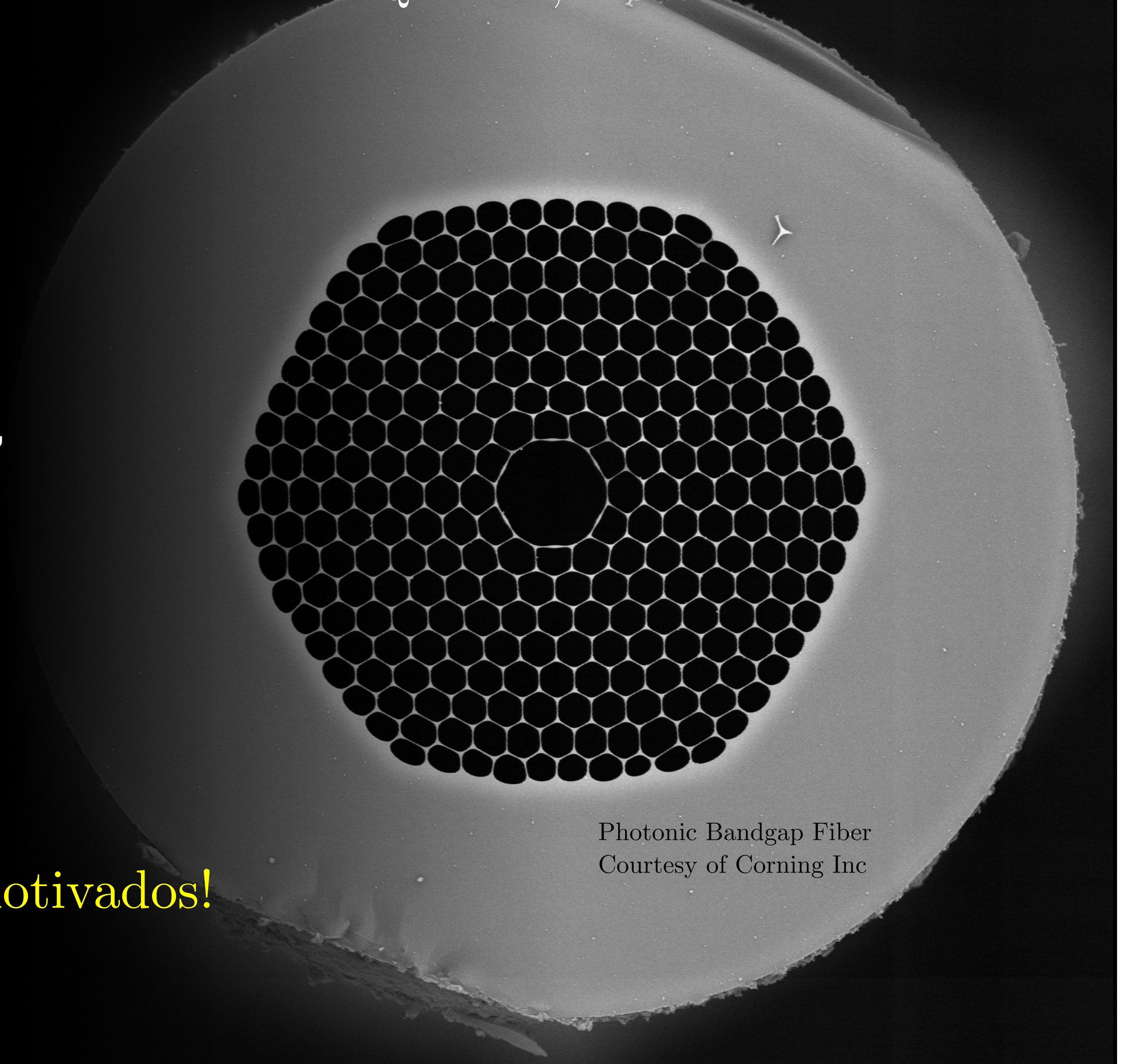
Light Scattering Processes in Photonic Microstructures

Prof. Dr. Paulo Dainese – Departamento de Eletrônica Quântica, IFGW

Bolsas:

Doutorado Direto

Iniciação Científica



Photonic Bandgap Fiber
Courtesy of Corning Inc

Oportunidade para alunos motivados!

dainese@ifi.unicamp.br
Sala 219 - DEQ