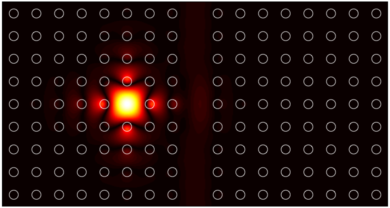
Modeling and Simulations of Light Emission and Propagation in Open Nanophotonic Systems



Jakob Rosenkrantz de Lasson

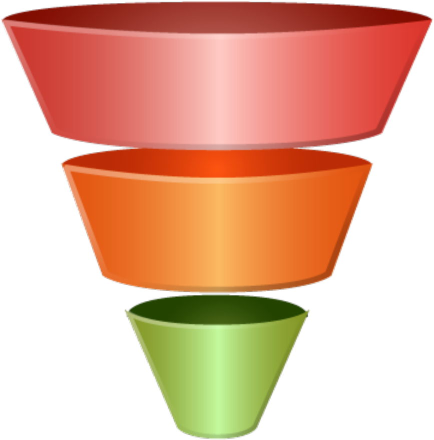
Nanophotonics Theory
& Signal Processing

www.nanophotonics.dk

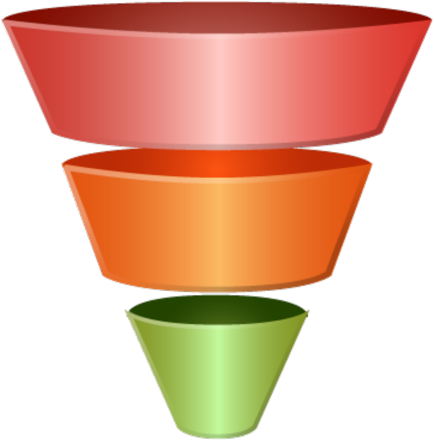
Ph.D. Lecture, December 16 2015

DTU Fotonik
Department of Photonics Engineering

DTU

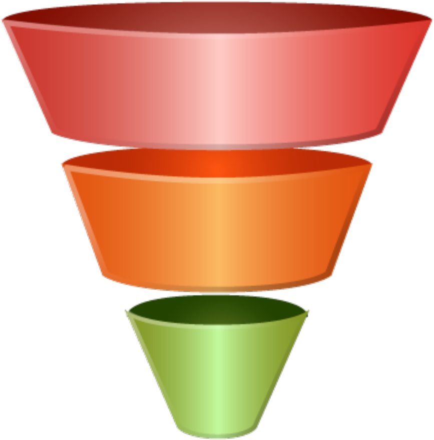


I. *Why*



I. *Why*

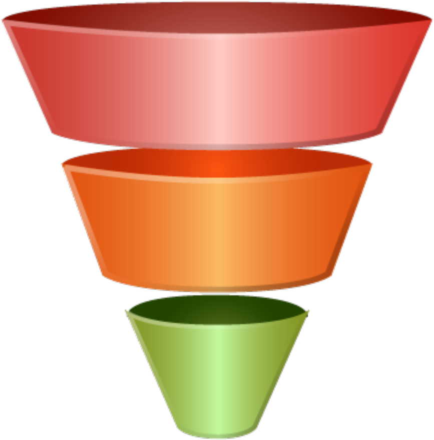
II. *How*



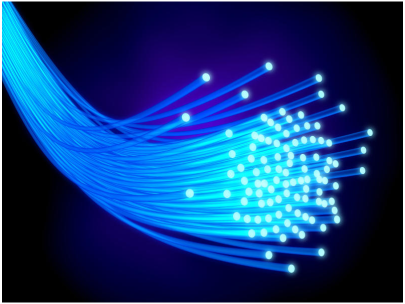
I. ***Why***

II. ***How***

III. ***What***

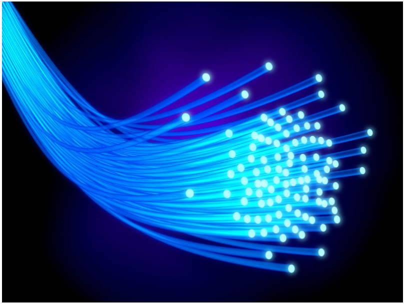


I. ***Why*** do we do our research?



Vidensklumme: Verdens største maskine kører på lys

Internettet vokser med 35-50 procent om året, og havde det ikke været for lyset, ville det være brudt sammen for længe siden.



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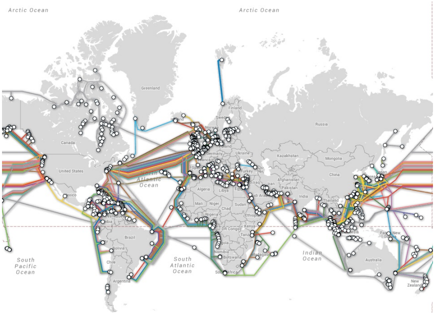

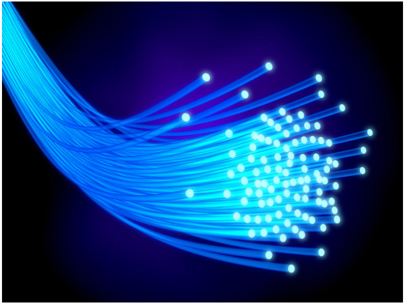

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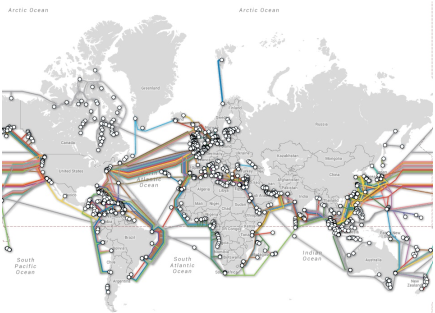
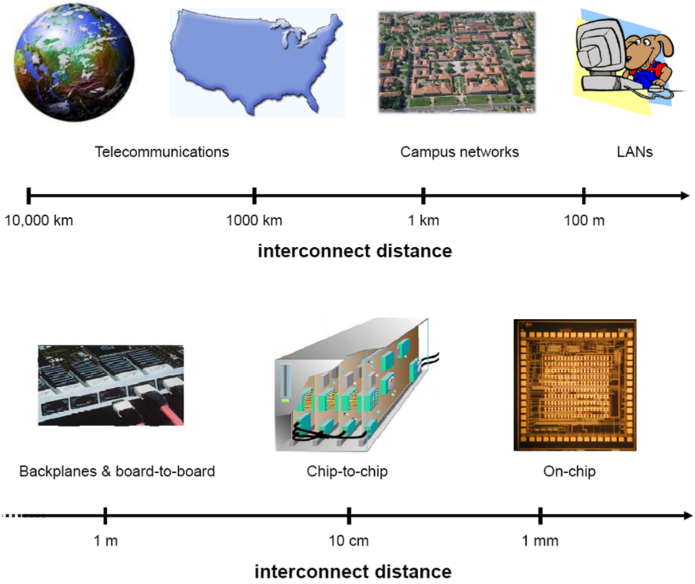
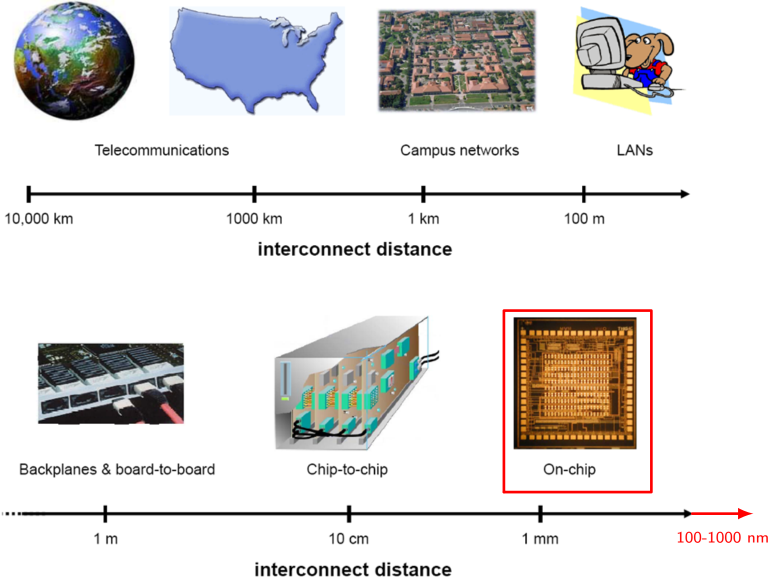




[D. A. B. Miller, ICTON 2009]



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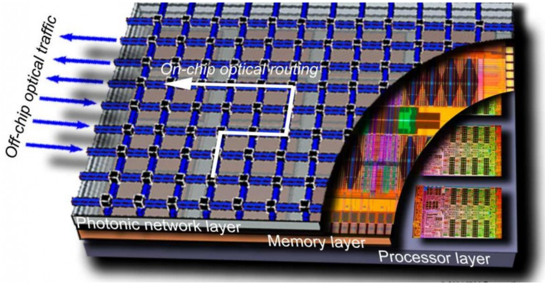
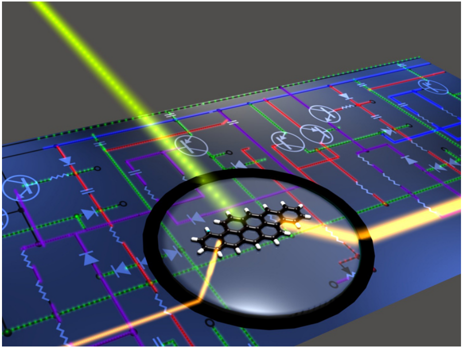
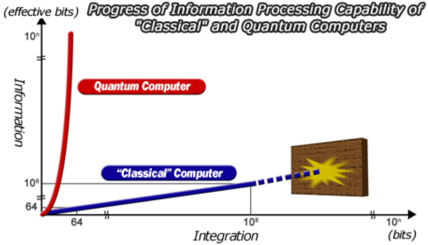


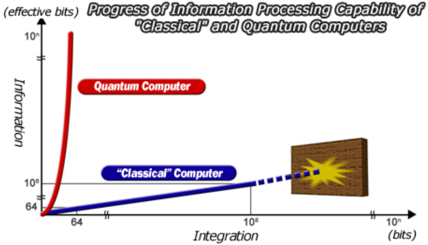
[IBM]



[ETH Zürich]


quantum computer


(effective bits)
Progress of Information Processing Capability of "Classical" and Quantum Computers
Information
Quantum Computer
"Classical" Computer
Integration
(bits)
64
64



NATURE|Vol 453|19 June 2008|doi:10.1038/nature07127 INSIGHT REVIEW

The quantum internet

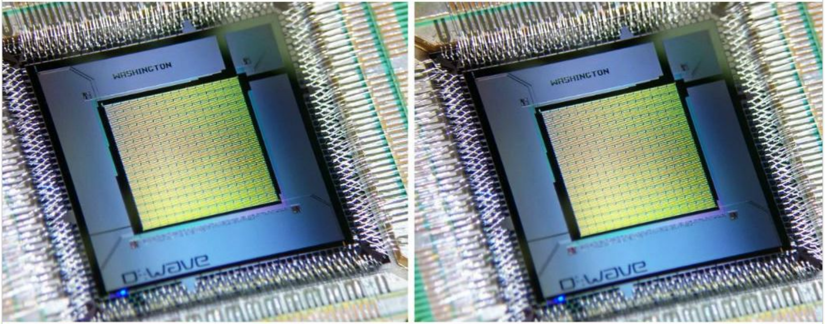
H. J. Kimble[1]

Quantum networks provide opportunities and challenges across a range of intellectual and technical frontiers, including quantum computation, communication and metrology. The realization of quantum networks composed of many nodes and channels requires new scientific capabilities for generating and characterizing quantum coherence and entanglement. Fundamental to this endeavour are quantum interconnects, which convert quantum states from one physical system to those of another in a reversible manner. Such quantum connectivity in networks can be achieved by the optical interactions of single photons and atoms, allowing the distribution of entanglement across the network and the teleportation of quantum states between nodes.

Forbes / Tech

DEC 13, 2012 @ 06:15 PM 8,905 VIEWS

Why IBM and Intel Are Chasing the $100B Opportunity in Nanophotonics



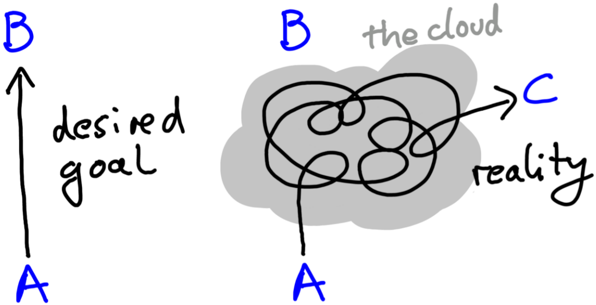
D-Wave

Google's quantum computer is 100 million times faster than your laptop

But is it a true quantum computer?

DAVID NIELD 10 DEC 2015

[C. Wilke, "The Serial Mentor"]



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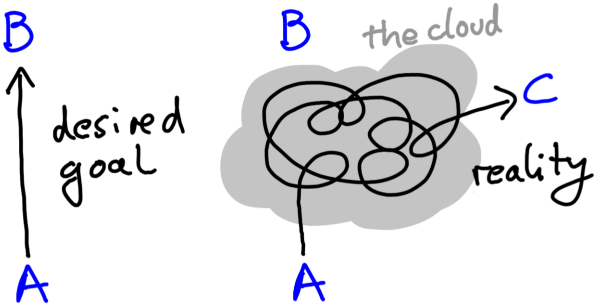

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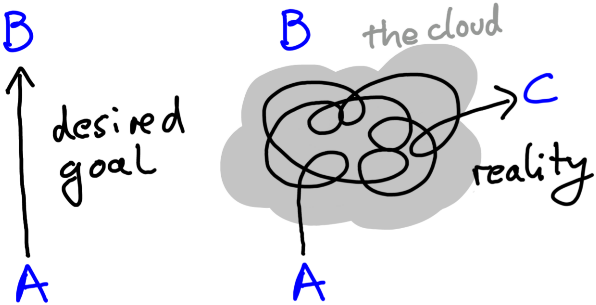

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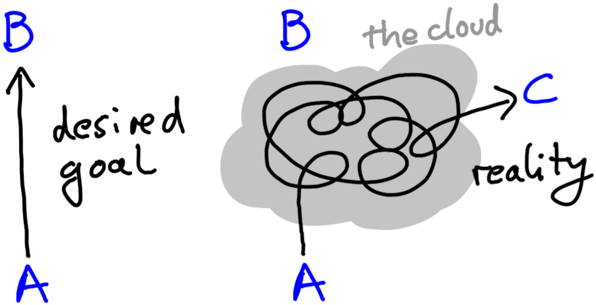

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II. *How* do we do our research?

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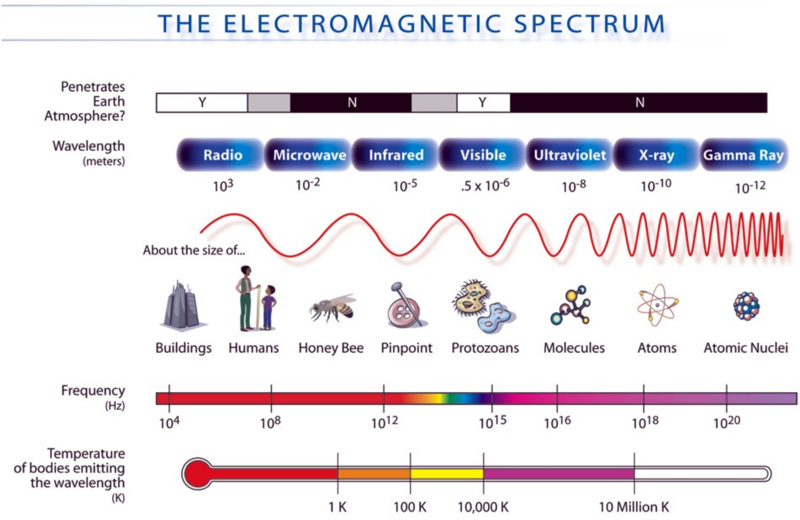
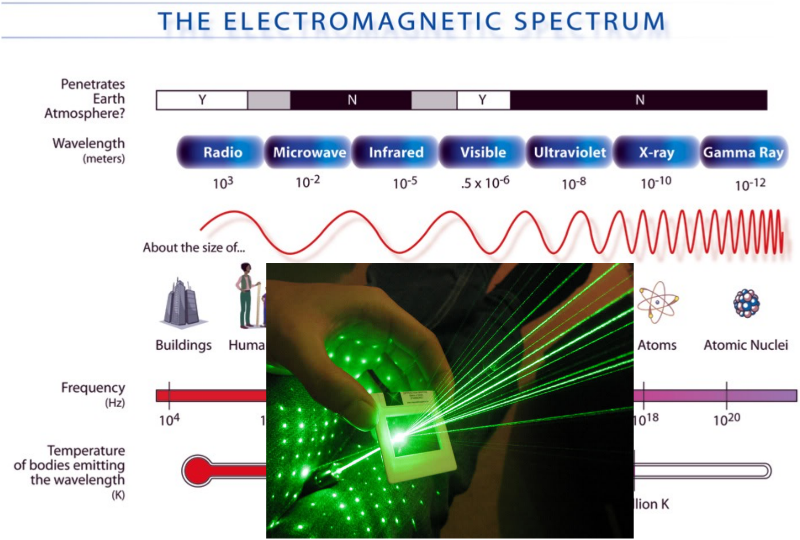
– First half: The structures


THE ELECTROMAGNETIC SPECTRUM
Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^{3}
10^{-2}
10^{-5}
$.5 \times 10^{-6}$
10^{-8}
10^{-10}
10^{-12}
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^{4}
10^{8}
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K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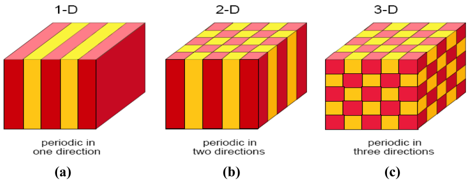
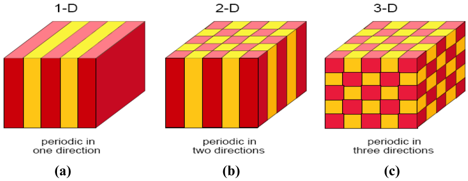
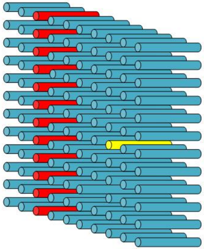


[J. D. Joannopoulos *et al.*, "Photonic Crystals – Molding the Flow of Light"]





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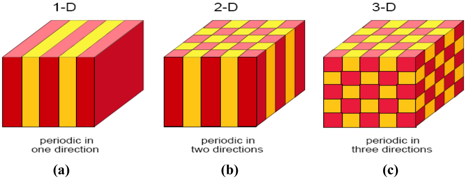

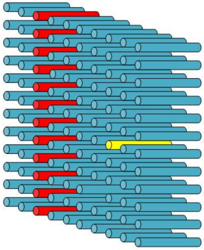

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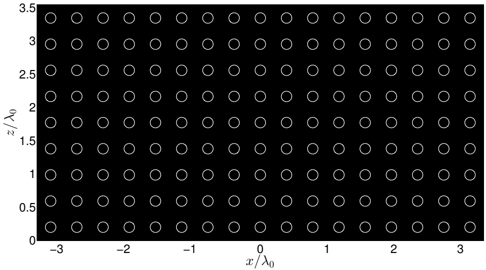

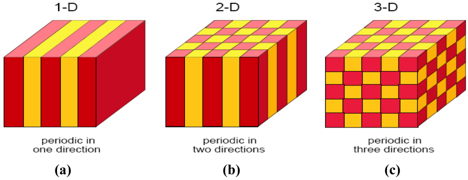

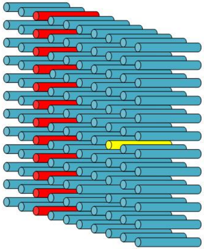

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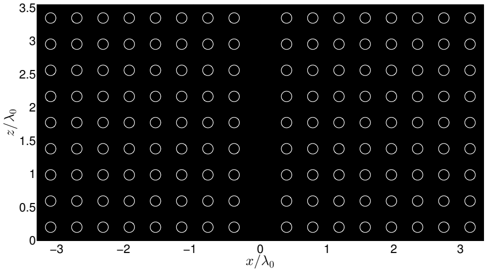

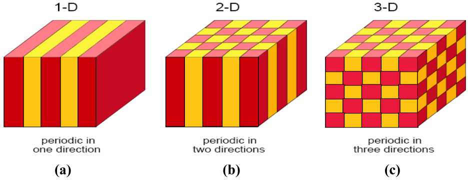

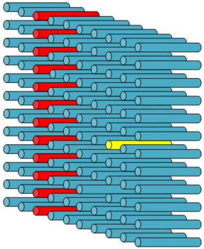

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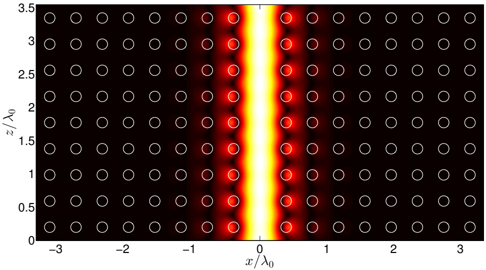

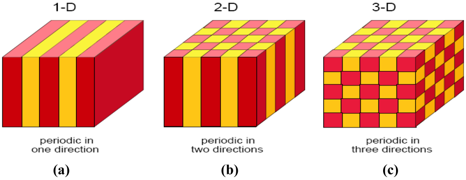

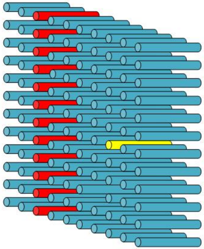

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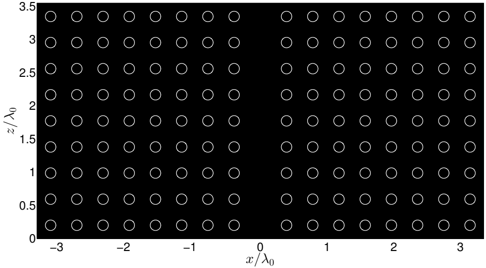
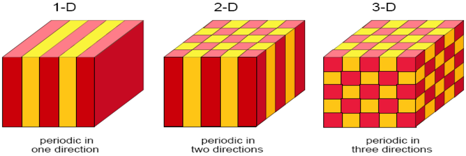
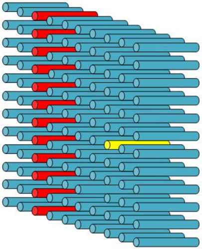




(a) (b) (c)



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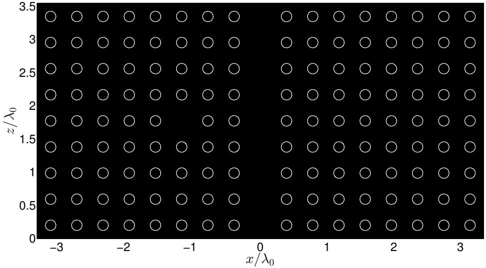

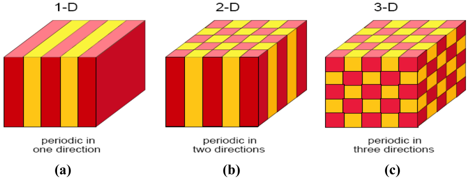

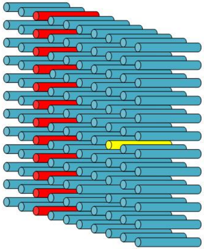

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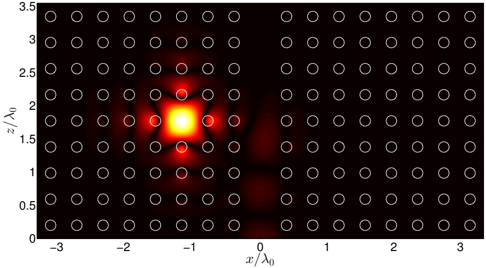

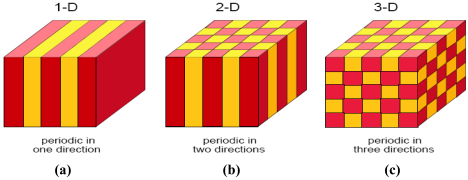

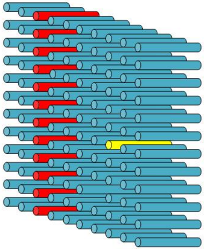

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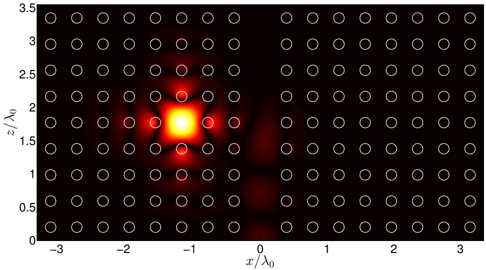

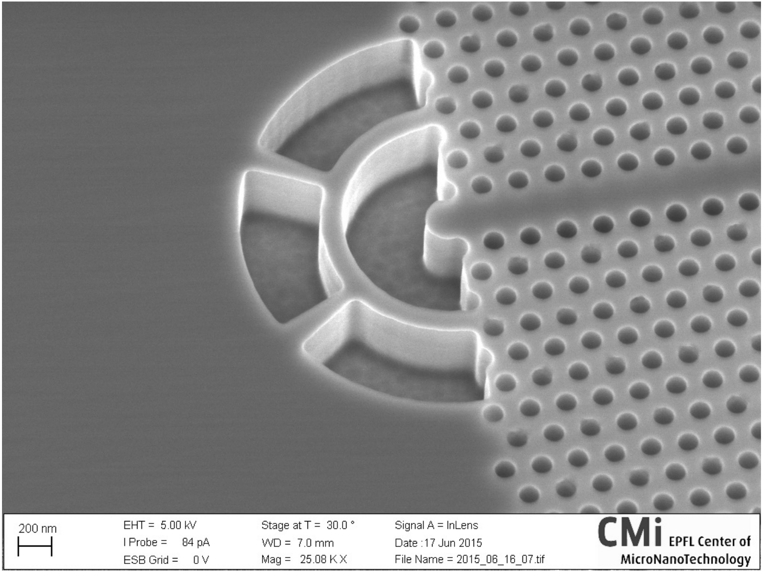

[Courtesy of Laboratory of Physics of Nanostructures, EPFL, Switzerland]

Light speed reduction to 17 metres per second in an ultracold atomic gas

Lene Vestergaard Hau[*†], S. E. Harris[‡], Zachary Dutton[*†] & Cyrus H. Behroozi[*§]

[L. V. Hau *et al.*, Nature **397**, 594 (1999)]

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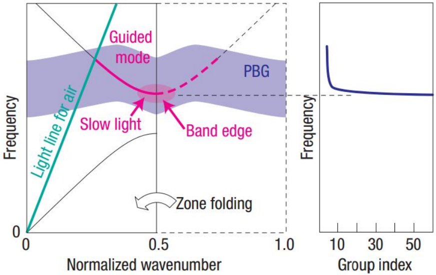

[T. Baba, Nat. Photonics **2**, 465 (2008)]

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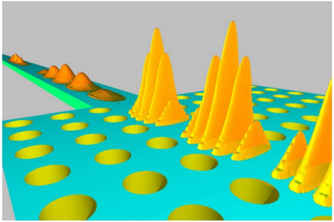
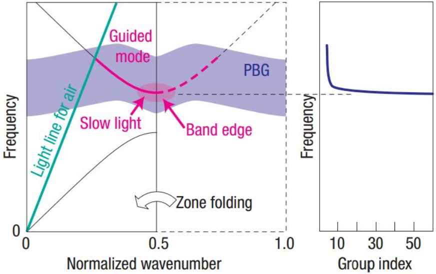


[T. F. Krauss, J. Phys. D **40**, 2666 (2007)]



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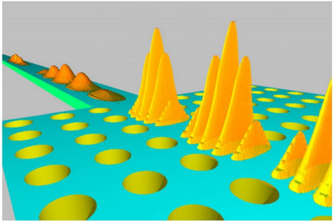

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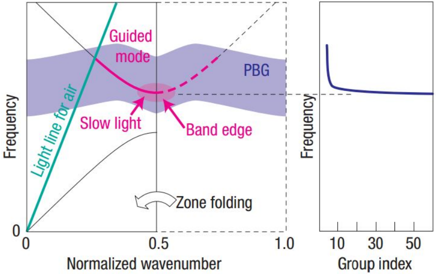

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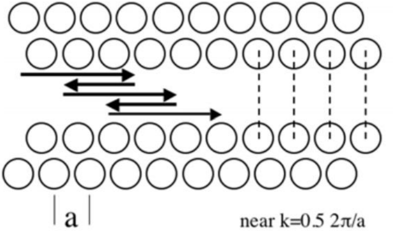

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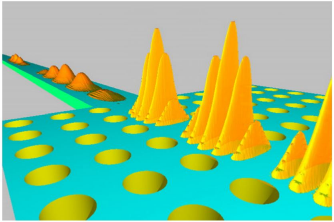

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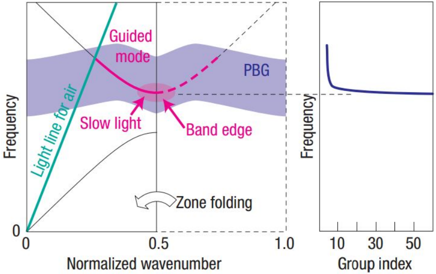

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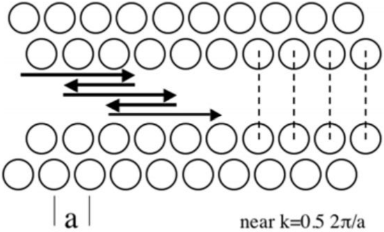

Why do we need slow light?

THOMAS F. KRAUSS

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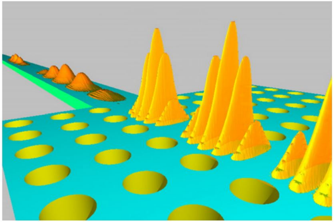

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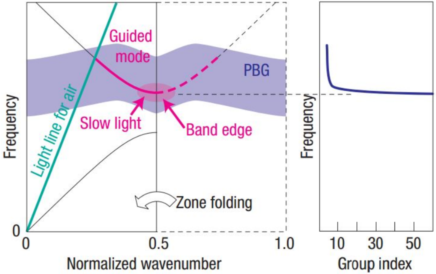
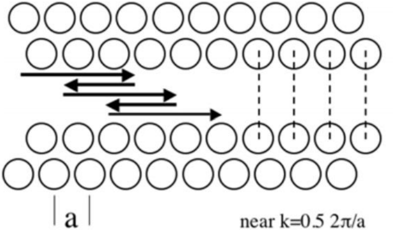


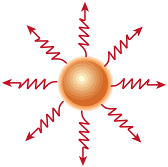
[T. Baba, Nat. Photonics **2**, 465 (2008)]



Why do we need slow light?

THOMAS F. KRAUSS

"Because we can" ☺



[K. J. Vahala, Nature **424**, 839 (2003)]

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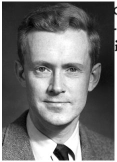

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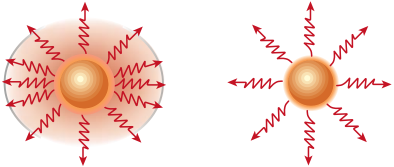

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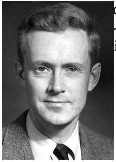

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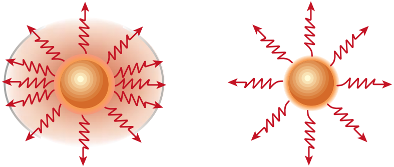

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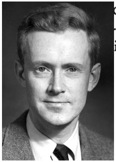

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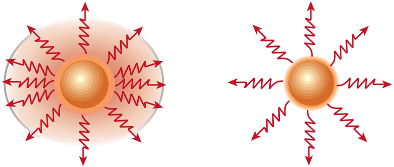

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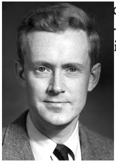

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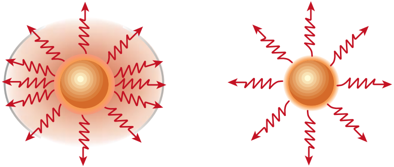

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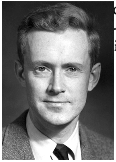

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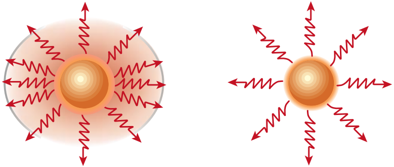

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$$\Gamma = \frac{2\pi}{\hbar^2}\sum_f \left|\left\langle f \,\middle|\, \hat{H}_\mathrm{I} \,\middle|\, i\right\rangle\right|^2 \delta(\omega_i - \omega_f)$$

$$\hat{H}_\mathrm{I} = -\hat{\mathbf{p}}\cdot\hat{\mathbf{E}}$$

[L. Novotny and B. Hecht, "Principles of Nano-Optics" (2012)]

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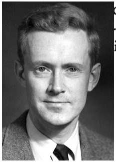

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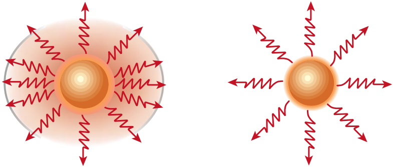

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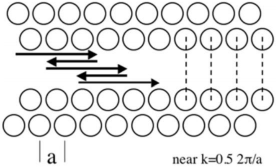

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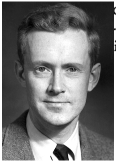

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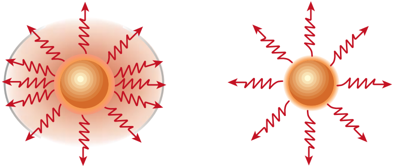

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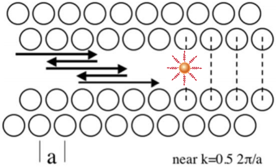

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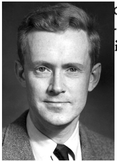

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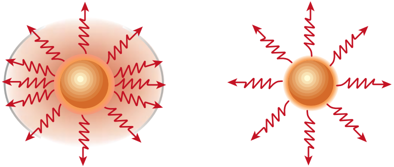

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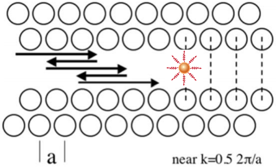

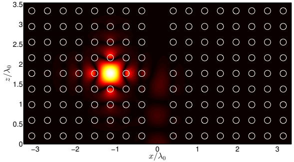

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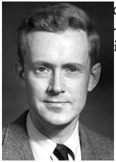

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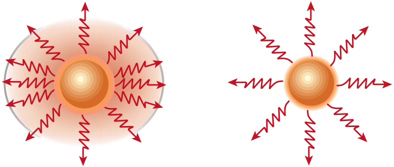

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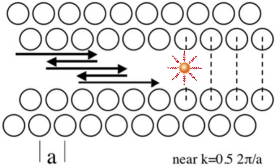

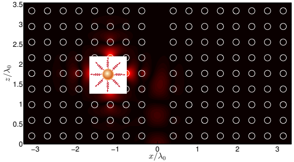

II. *How* do we do our research?

– First half: The structures

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– Second half: The methods

Modeling and Simulations of Light Emission and Propagation in Open Nanophotonic Systems

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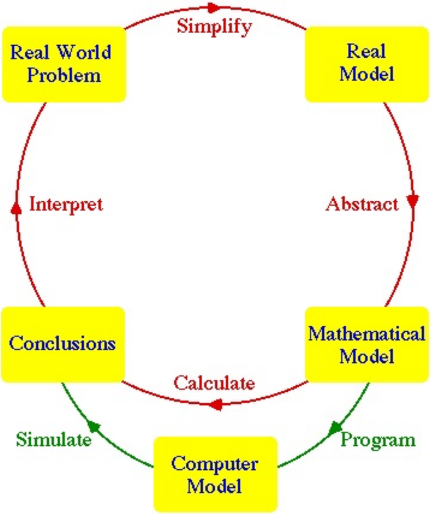
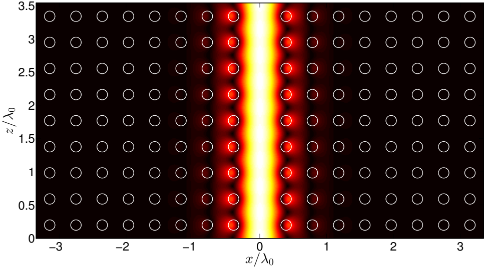
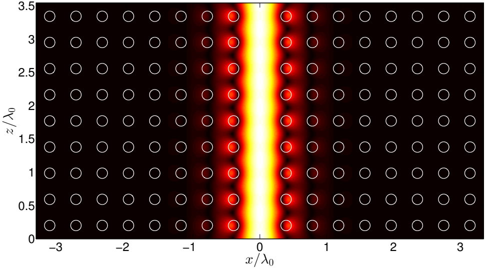


["Stepping Stones to Mathematical Modeling", Indiana University]


3.5
3
2.5
2
1.5
1
0.5
0
z/λ_0
–3
–2
–1
0
1
2
3
x/λ_0

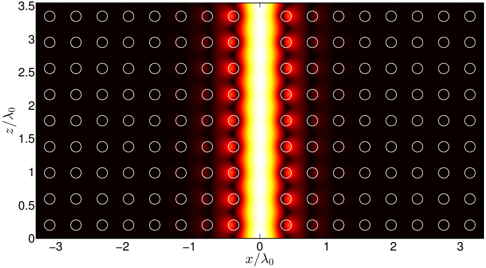


$$\nabla \cdot \mathbf{D} = \rho$$

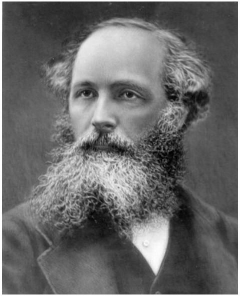
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

$$\nabla \times \mathbf{H} = \partial_t \mathbf{D} + \mathbf{J}$$



$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$
$$\nabla \times \mathbf{H} = \partial_t \mathbf{D} + \mathbf{J}$$

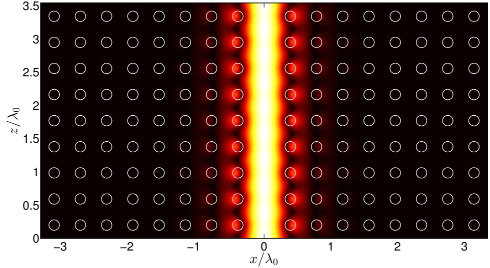


PHILOSOPHICAL
TRANSACTIONS:

VIII. *A Dynamical Theory of the Electromagnetic Field.*

By J. CLERK MAXWELL, *F.R.S.*

[Phil. Trans. R. Soc. Lond. **155**, 459-512 (1865)]



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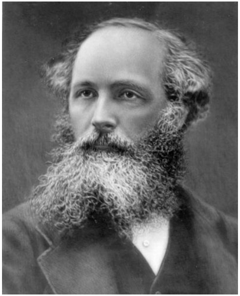

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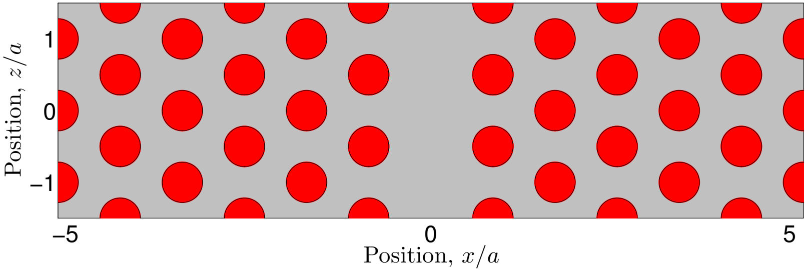
DTU Indefra

Maxwells ligninger - sværere end kvantemekanik!

Af Jakob Rosenkrantz de Lasson 4. jun 2014 kl. 07:30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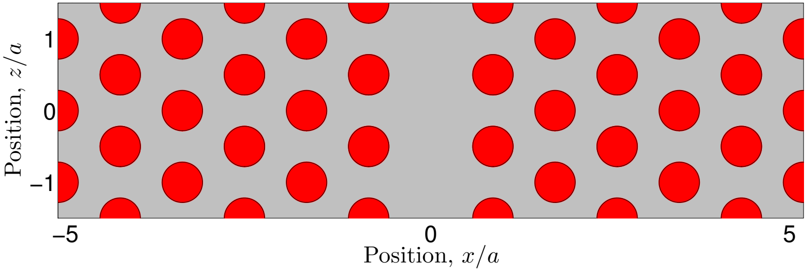
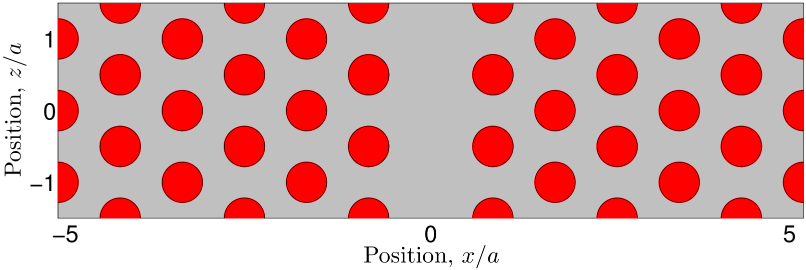
Position, x/a

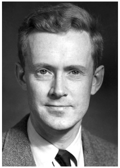


Über die Quantenmechanik der Elektronen in Kristallgittern.

Von **Felix Bloch** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 10. August 1928.)





1952 Nobel Prize

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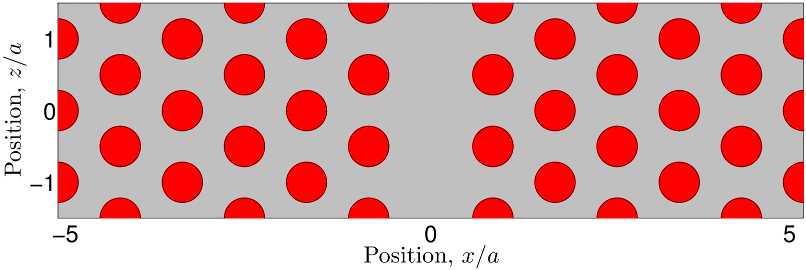

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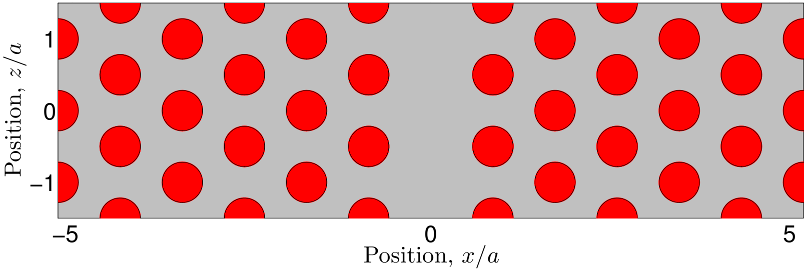
$$u(\mathbf{r}+\mathbf{T}) = u(\mathbf{r})$$



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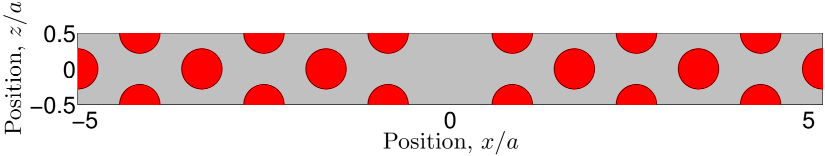
$$\psi(\mathbf{r} + a\hat{\mathbf{z}}) = \exp(\mathrm{i}k_z a)\psi(\mathbf{r})$$



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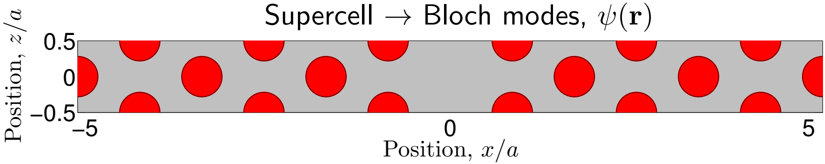
$$\psi(\mathbf{r}+a\hat{\mathbf{z}}) = \exp(\mathrm{i}k_z a)\psi(\mathbf{r})$$



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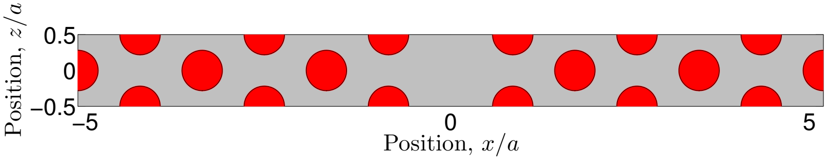
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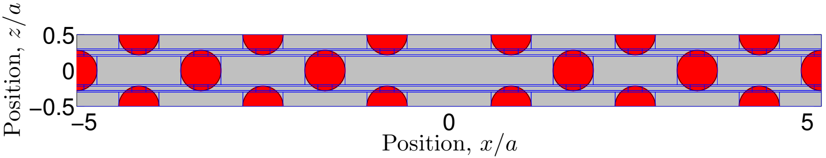
Position, x/a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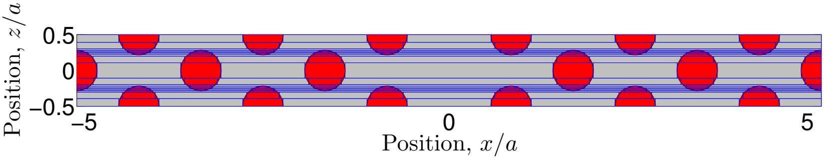
Position, x/a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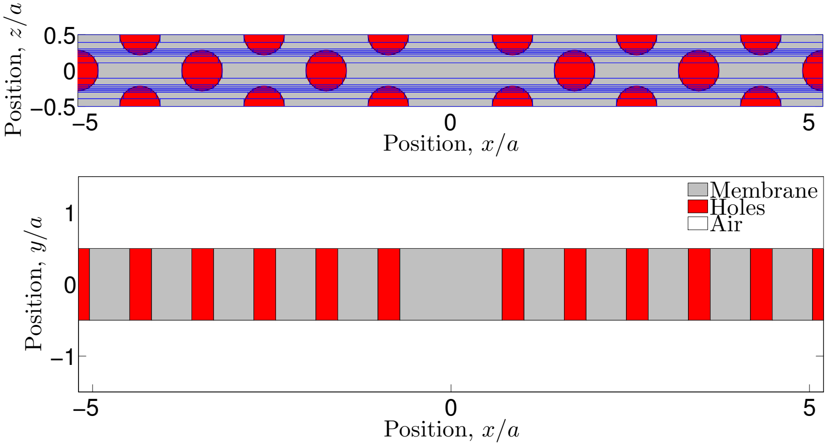
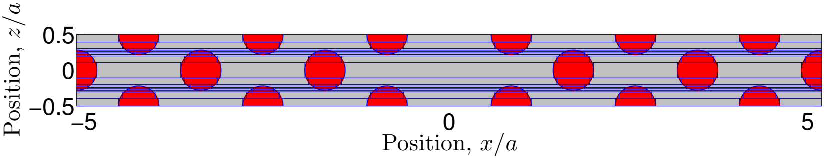
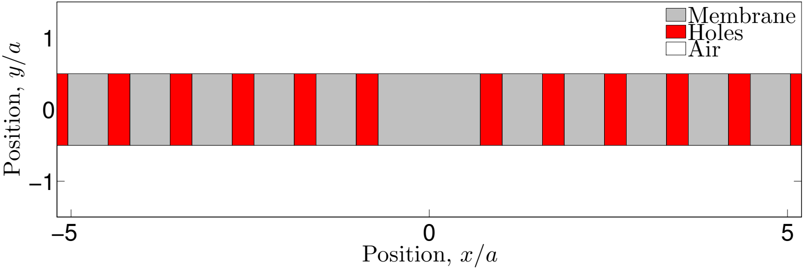
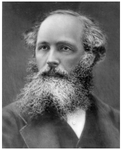
Position, x/a



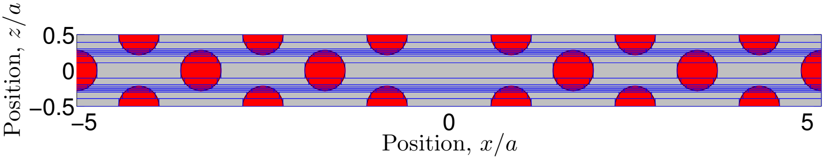
0.5
0
−0.5
Position, z/a
−5
0
5
Position, x/a
Membrane
Holes
Air
1
0
−1
Position, y/a
−5
0
5
Position, x/a

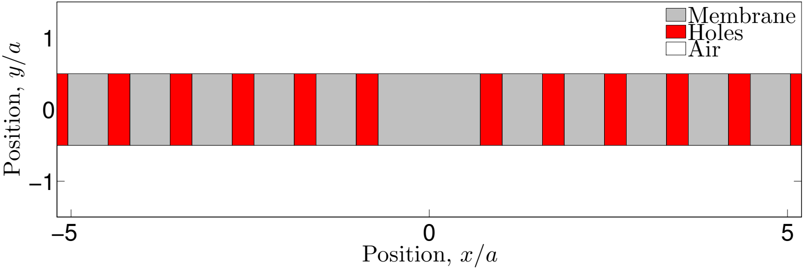


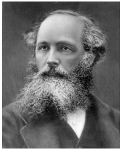




$$+ \quad \mathbf{E}(\mathbf{r}_\perp) \sim \sum_\nu c_\nu \exp(\mathrm{i}\mathbf{k}_\nu \cdot \mathbf{r}_\perp)$$



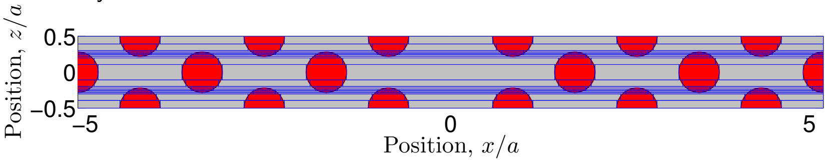


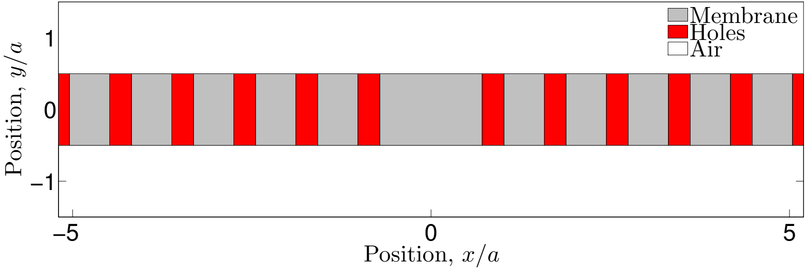


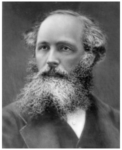
$$+ \quad \mathbf{E}(\mathbf{r}_\perp) \sim \sum_\nu c_\nu \exp(\mathrm{i}\mathbf{k}_\nu \cdot \mathbf{r}_\perp) \quad \Longrightarrow$$

$$\mathbf{Md} = \lambda \mathbf{Nd}$$
$$\lambda = \exp(\mathrm{i}k_z a)$$

Hybrid method:







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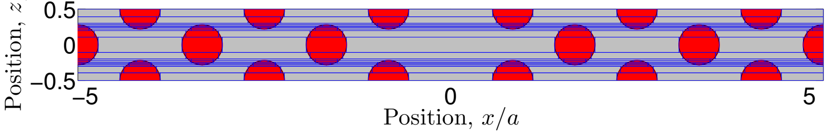
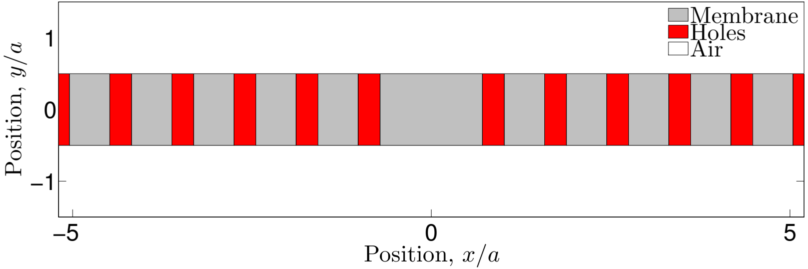
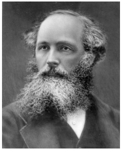
Hybrid method:
- Spatial discretization (z)
- Plane waves ($\mathbf{r}_\perp$)



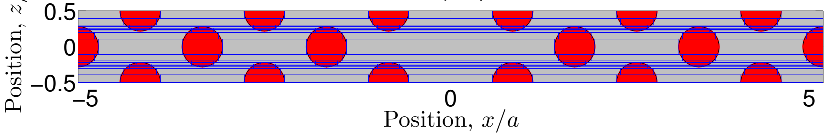


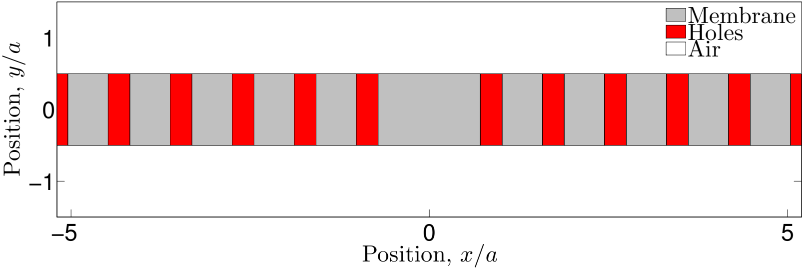


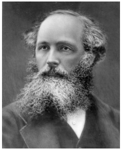
$$+ \quad \mathbf{E}(\mathbf{r}_\perp) \sim \sum_\nu c_\nu \exp(\mathrm{i}\mathbf{k}_\nu \cdot \mathbf{r}_\perp) \quad \Longrightarrow$$

$$\mathbf{Md} = \lambda \mathbf{Nd}$$
$$\lambda = \exp(\mathrm{i}k_z a)$$

Hybrid method: Spatial discretization (z) / Plane waves ($\mathbf{r}_\perp$) $\neq$ FDTD, FEM



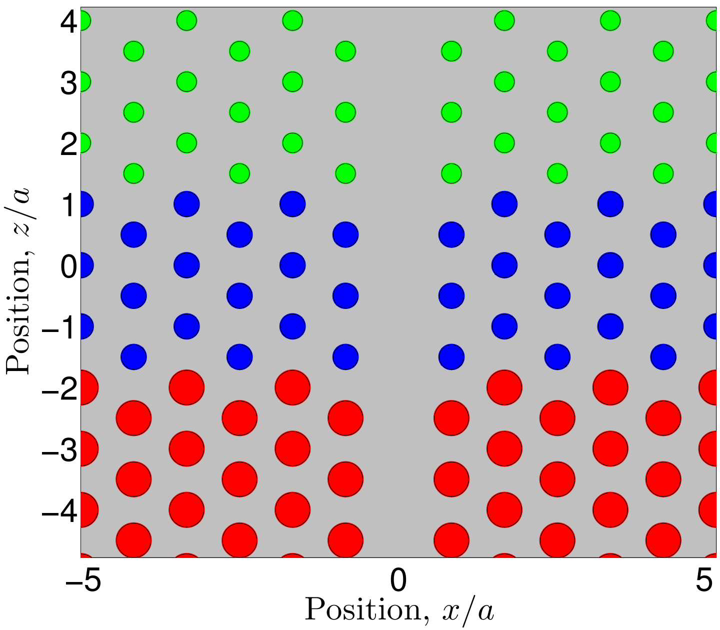




$+$ $\mathbf{E}(\mathbf{r}_\perp) \sim \sum_\nu c_\nu \exp(\mathrm{i}\mathbf{k}_\nu \cdot \mathbf{r}_\perp)$ $\implies$

$$\mathbf{Md} = \lambda \mathbf{Nd}$$

$$\lambda = \exp(\mathrm{i}k_z a)$$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2
1
0
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−2
−3
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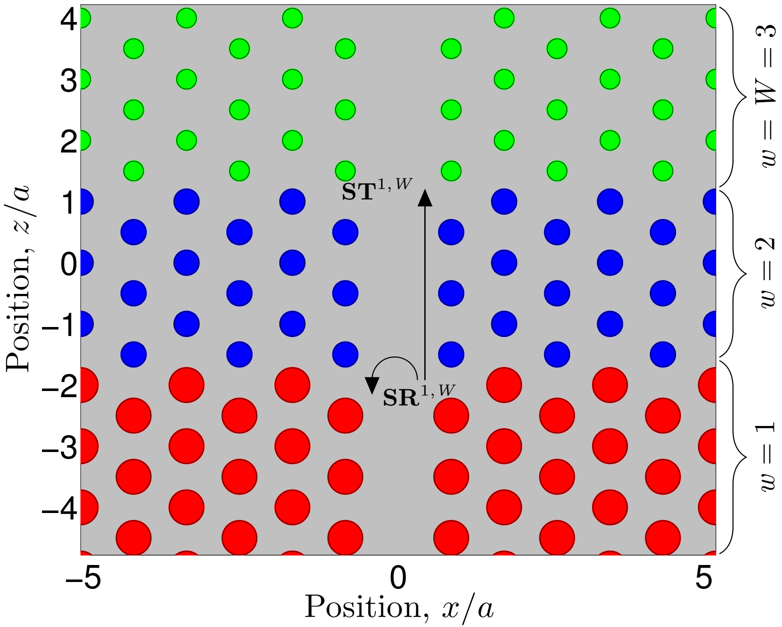
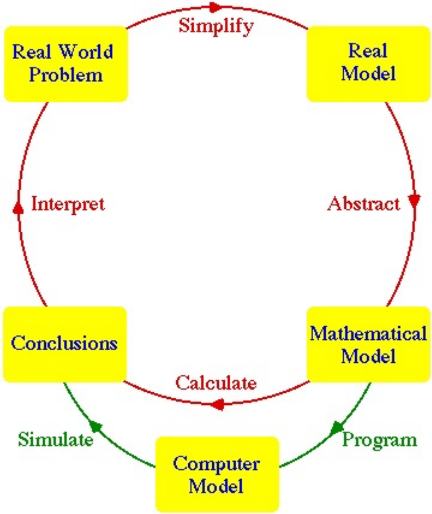
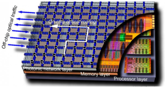
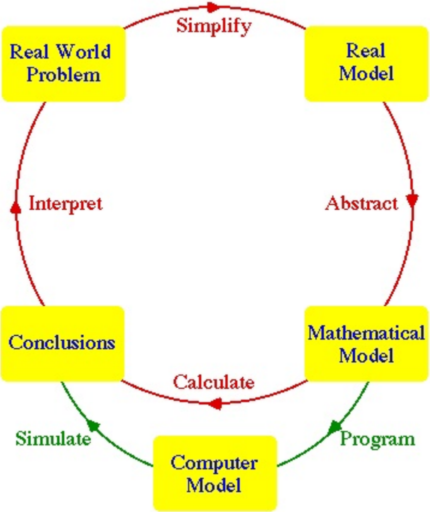
Position, z/a
−5
0
5
Position, x/a



4
3
2
1
0
–1
–2
–3
–4
Position, z/a
$\mathbf{ST}^{1,W}$
$\mathbf{SR}^{1,W}$
$w = W = 3$
$w = 2$
$w = 1$
–5
0
5
Position, x/a


Simplify
Real World Problem
Real Model
Interpret
Abstract
Conclusions
Mathematical Model
Calculate
Simulate
Program
Computer Model


Off-chip optical traffic
Memory layer
Processor layer


Real World Problem
Simplify
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Mathematical Model
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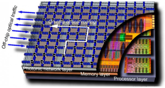

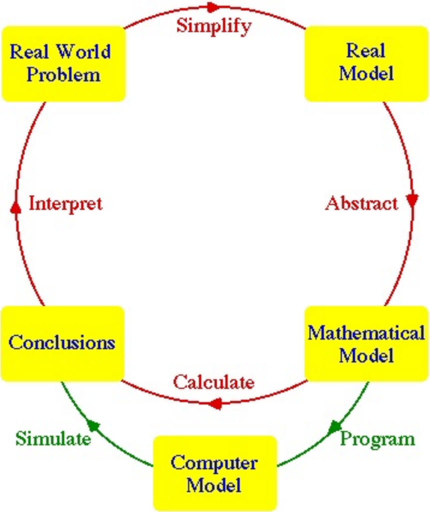
Real World Problem
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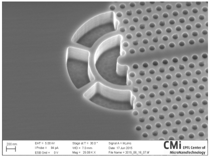
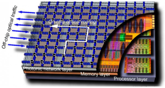
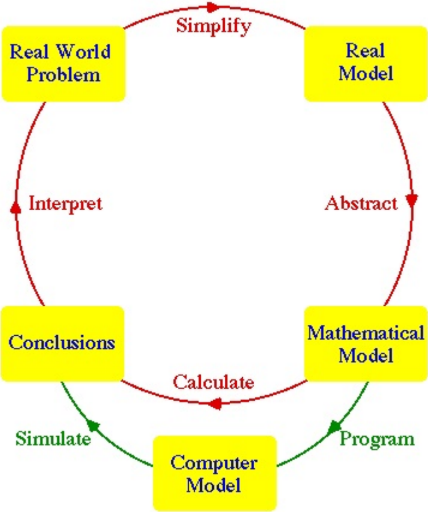



Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer


Real World Problem
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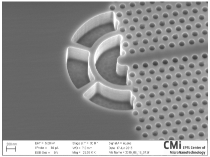
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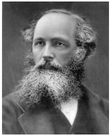

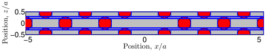
Position, z/a
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Position, x/a

III. *What* do we do in our research?

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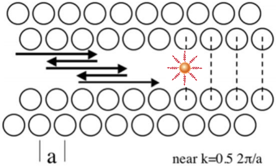
– First half: Light control

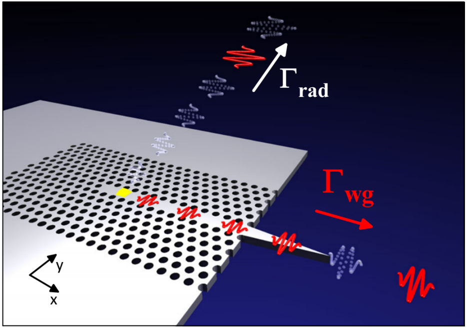
with slow light waveguides



III. *What* do we do in our research?

– First half: Light control with slow light waveguides


clic



[M. Arcari *et al.*, Phys. Rev. Lett. **113**, 093603 (2014)]

See also: [V. S. C. Manga Rao and S. Hughes, Phys. Rev. B **75**, 205437 (2007)]
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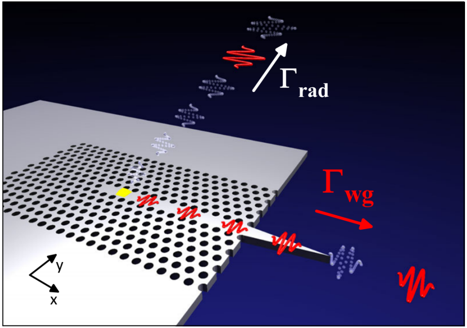
[S. J. Dewhurst *et al.*, Appl. Phys. Lett. **96**, 031109 (2010)]
[A. Schwagmann *et al.*, Appl. Phys. Lett. **99**, 261108 (2011)]
[A. Laucht *et al.*, Phys. Rev. X **2**, 011014 (2012)]
[T. Ba Hoang *et al.*, Appl. Phys. Lett. **100**, 061122 (2012)]



[M. Arcari *et al.*, Phys. Rev. Lett. **113**, 093603 (2014)]

$$\beta = \frac{\Gamma_{\mathrm{G}}}{\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{Rad}} + \Gamma_{\mathrm{NR}}}$$

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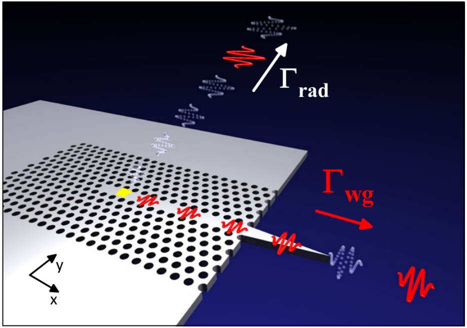

[M. Arcari *et al.*, Phys. Rev. Lett. **113**, 093603 (2014)]

$$\beta = \frac{\Gamma_{\mathrm{G}}}{\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{Rad}} + \Gamma_{\mathrm{NR}}}$$

$$\Gamma_{\mathrm{G}} \uparrow n_{\mathrm{G}}$$

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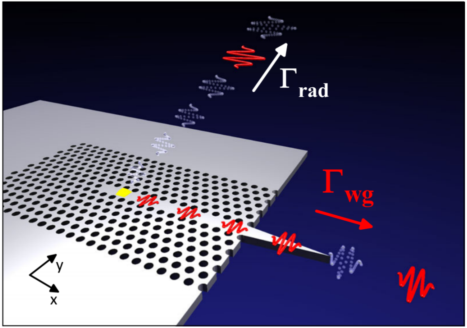

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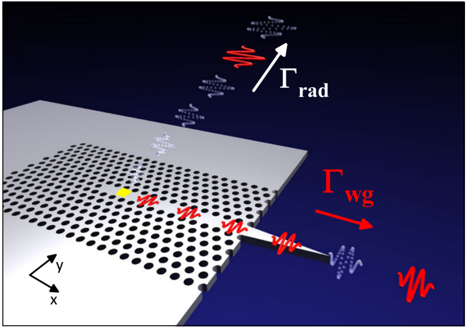
$$\beta = \frac{\Gamma_{\mathrm{G}}}{\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{Rad}} + \Gamma_{\mathrm{NR}}}$$

$$\Gamma_{\mathrm{G}} \uparrow n_{\mathrm{G}}$$

$$\Gamma_{\mathrm{Rad}} \downarrow \Delta n$$

See also: [V. S. C. Manga Rao and S. Hughes, Phys. Rev. B **75**, 205437 (2007)]
[G. Lecamp *et al.*, Phys. Rev. Lett. **99**, 023902 (2007)]
[S. J. Dewhurst *et al.*, Appl. Phys. Lett. **96**, 031109 (2010)]
[A. Schwagmann *et al.*, Appl. Phys. Lett. **99**, 261108 (2011)]
[A. Laucht *et al.*, Phys. Rev. X **2**, 011014 (2012)]
[T. Ba Hoang *et al.*, Appl. Phys. Lett. **100**, 061122 (2012)]



[M. Arcari *et al.*, Phys. Rev. Lett. **113**, 093603 (2014)]

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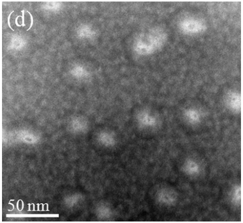

[E. Semenova *et al.*, Appl. Phys. Lett. **99**, 101106 (2011)]

See also: [V. S. C. Manga Rao and S. Hughes, Phys. Rev. B **75**, 205437 (2007)]
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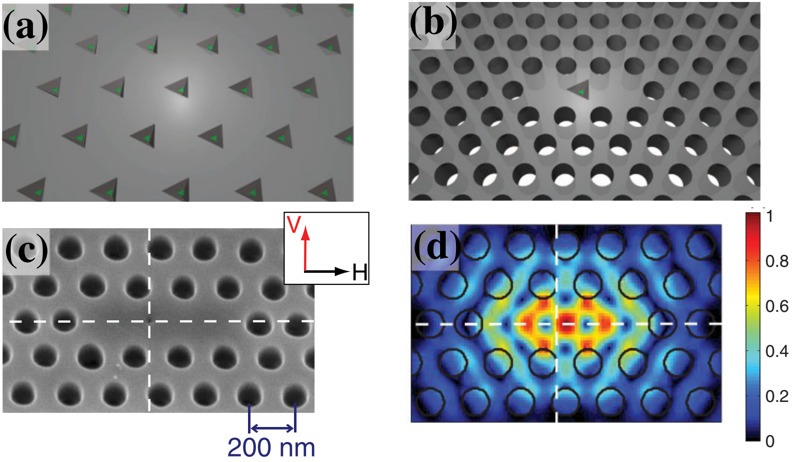

[M. Calic *et al.*, Phys. Rev. Lett. **106**, 227402 (2011)]

$$\frac{\rho_{\mathrm{G}}}{\rho_{\mathrm{Bulk}}} = \frac{3}{4\pi^2}\left(\frac{\lambda_0}{n}\right)^3 \frac{Q}{V_{\mathrm{eff}}}\eta \qquad Q = \frac{\omega a}{2\mathrm{c}} n_{\mathrm{G}} \qquad V_{\mathrm{eff}} = \frac{\int_{\mathrm{uc}} \epsilon(\mathbf{r})|\mathbf{E}(\mathbf{r})|^2 \,\mathrm{d}V}{\max\left[\epsilon(\mathbf{r})|\hat{\mathbf{n}}\cdot\mathbf{E}(\mathbf{r})|^2\right]}$$

[V. S. C. Manga Rao and S. Hughes, Phys. Rev. B **75**, 205437 (2007)]

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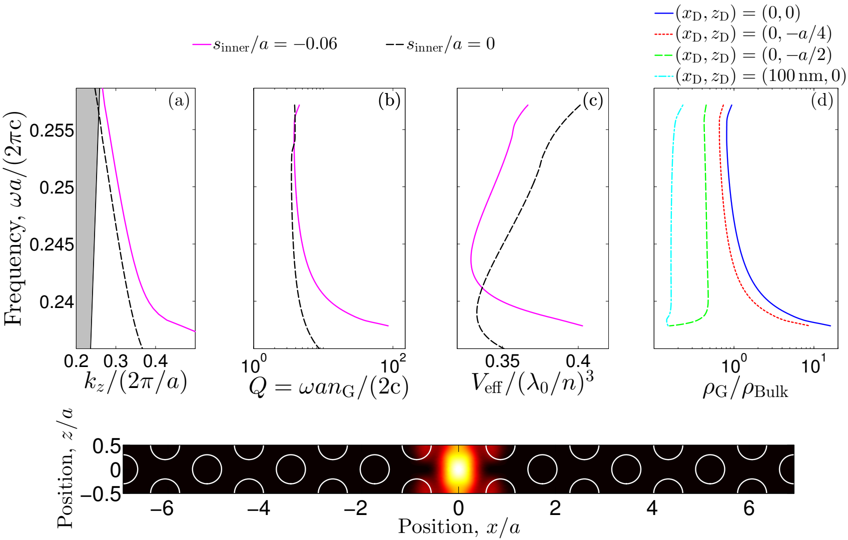
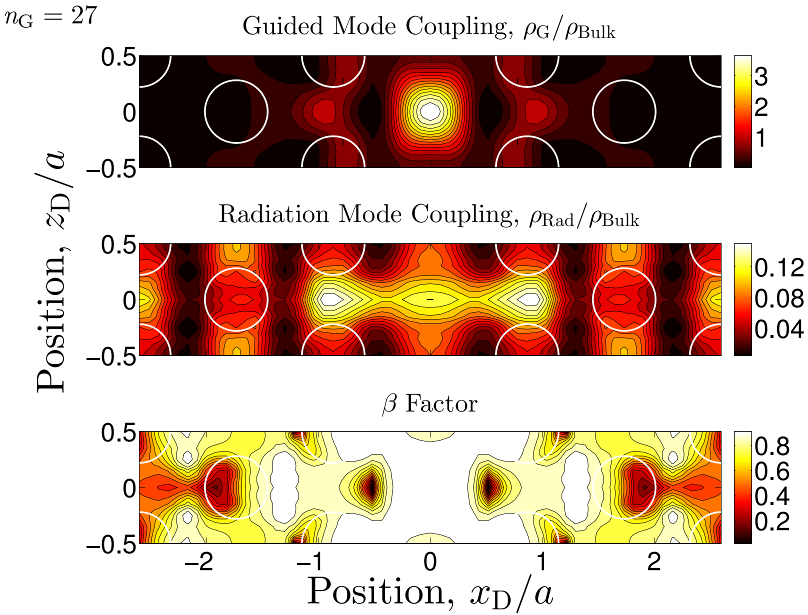
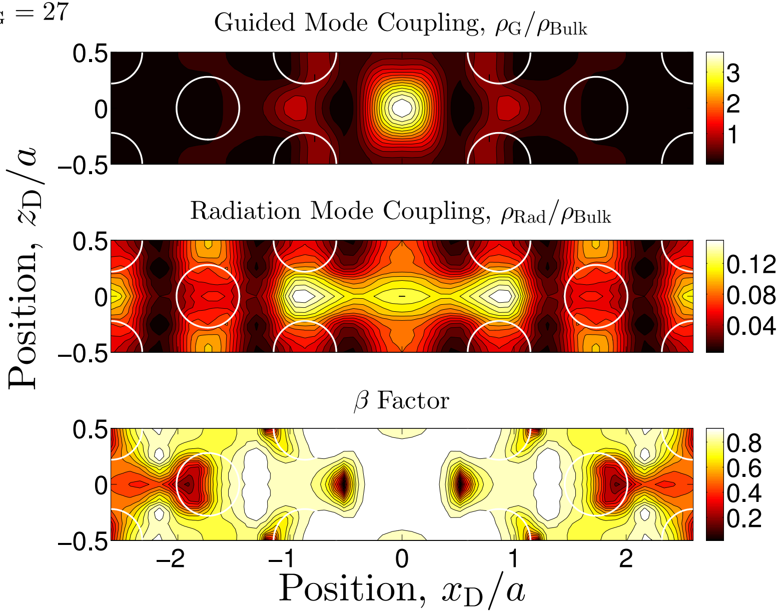


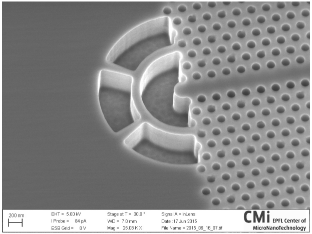


$n_G = 27$
Guided Mode Coupling, ρ_G/ρ_{Bulk}
Radiation Mode Coupling, ρ_{Rad}/ρ_{Bulk}
β Factor
Position, z_D/a
Position, x_D/a
0.5
0
−0.5
−2
−1
0
1
2
3
2
1
0.12
0.08
0.04
0.8
0.6
0.4
0.2

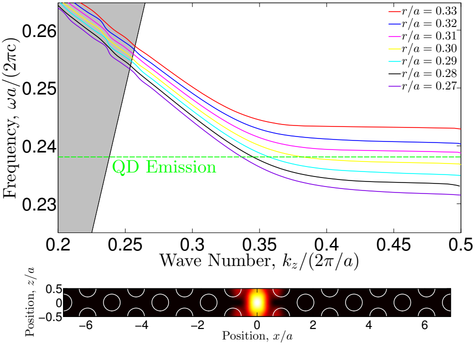
$n_G = 27$

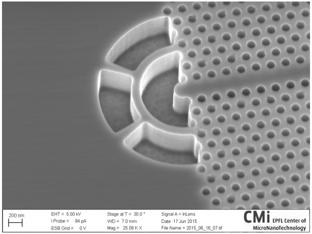


Position matters!



[Work in progress]





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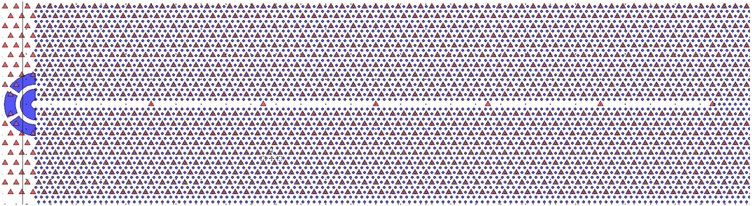

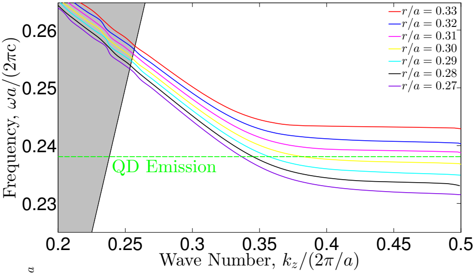

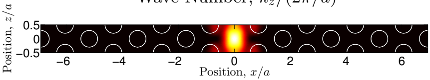

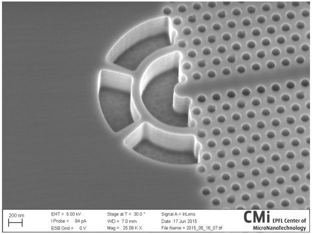

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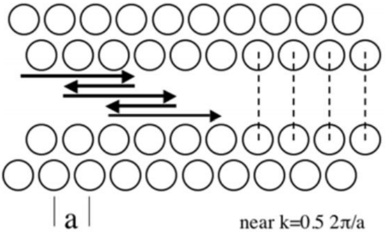
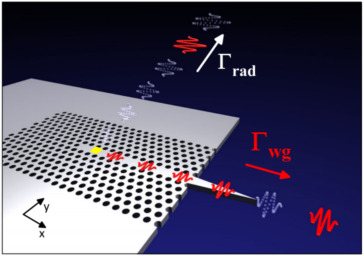
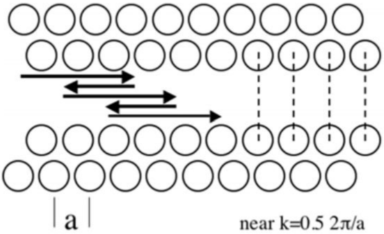

a
near k=0.5 2π/a


Γ rad
Γ wg
y
x

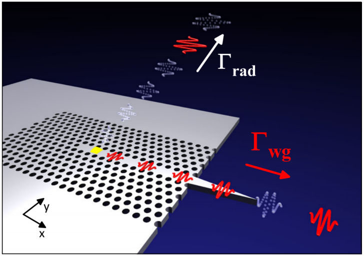


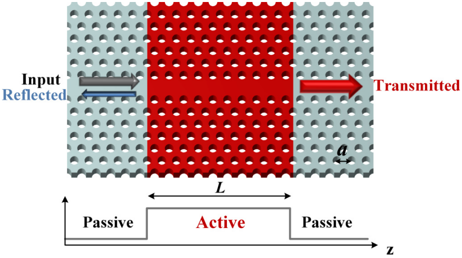
The photonic band edge laser: A new approach to gain enhancement

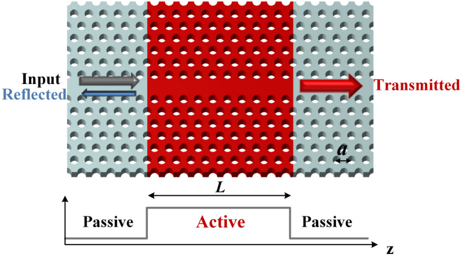
Jonathan P. Dowling, Michael Scalora, Mark J. Bloemer, and Charles M. Bowden
Weapons Sciences Directorate, AMSMI-RD-WS, Research, Development, and Engineering Center, U. S. Army Missile Command, Redstone Arsenal, Alabama 35898-5248

(Received 23 September 1993; accepted for publication 8 November 1993)

[J. P. Dowling *et al.*, J. Appl. Phys. **75**, 1896 (1994)]



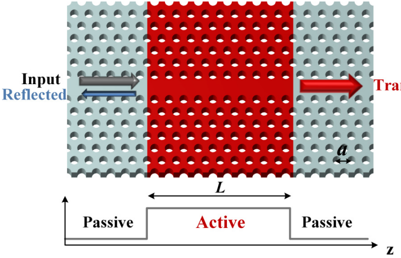




[Y. Chen *et al.*, Phys. Rev. A **92**, 053839 (2015)]

See also: [S. Ek *et al.*, Nat. Commun. **5**, 5039 (2014)]

[J. Grgić *et al.*, Phys. Rev. Lett. **108**, 183903 (2012)]



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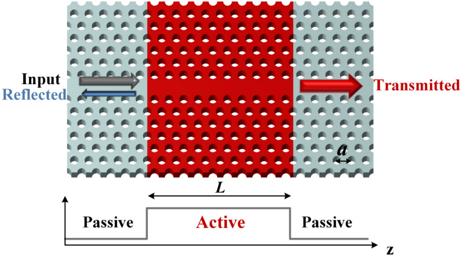

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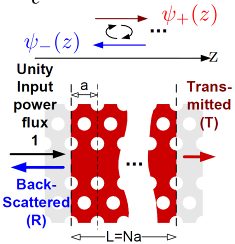

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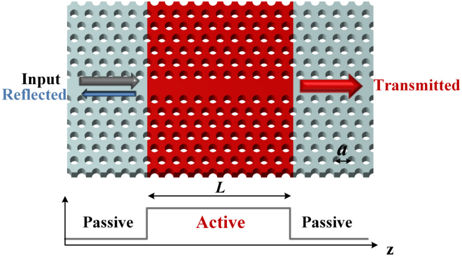

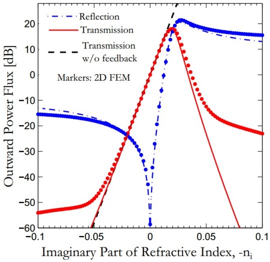

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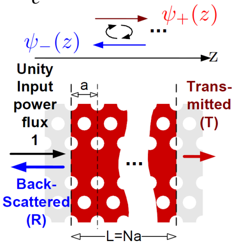

Active PhC Waveguide

[Y. Chen *et al.*, Phys. Rev. A **92**, 053839 (2015)]

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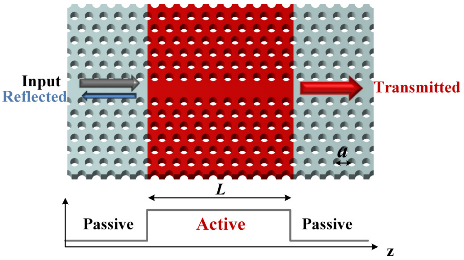

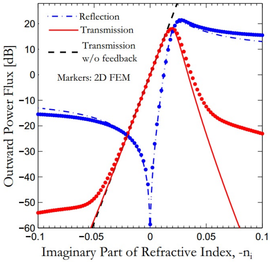

Fundamental Limitations to Gain Enhancement in Periodic Media and Waveguides

Jure Grgić,[1] Johan Raunkjær Ott,[1] Fengwen Wang,[2] Ole Sigmund,[2] Antti-Pekka Jauho,[3]
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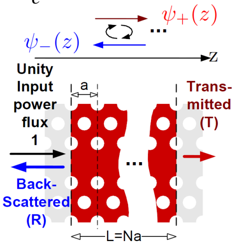

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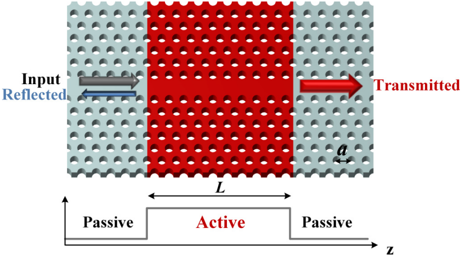

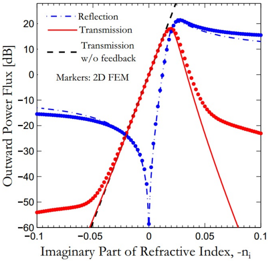

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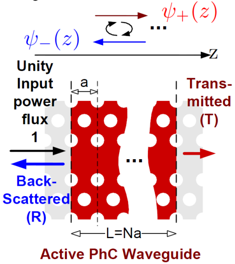

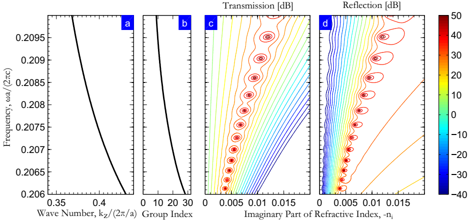

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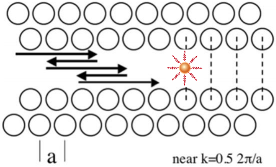

III. *What* do we do in our research?

– First half: Light control
with slow light waveguides

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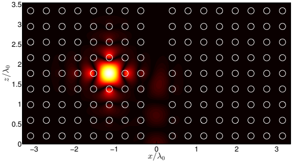
– Second half: Light control with cavities



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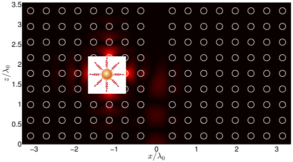

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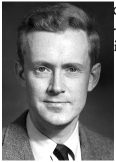
B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. Purcell, *Harvard University.*—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2)\ \text{sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2 V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V \sim a^3$, and if δ is the skin-depth at frequency ν, $f \sim \lambda^3/a^2\delta$. For a non-resonant circuit $f \sim \lambda^3/a^3$, and for $a < \delta$ it can be shown that $f \sim \lambda^3/a\delta^2$.



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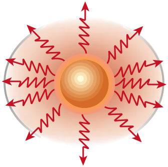
[E. Purcell, Phys. Rev. **69**, 681 (1946)]



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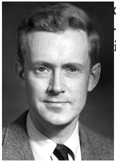

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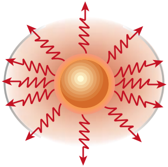

$$\frac{\Gamma(\mathbf{r};\omega)}{\Gamma_0} = \sum_\mu f_{\tilde{\omega}_\mu}(\mathbf{r};\omega)$$

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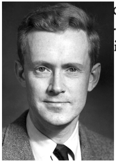
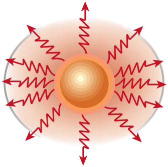


[E. Purcell, Phys. Rev. **69**, 681 (1946)]



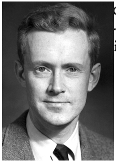
$$\frac{\Gamma(\mathbf{r};\omega)}{\Gamma_0} = \sum_\mu f_{\tilde{\omega}_\mu}(\mathbf{r};\omega)$$

$$\frac{\Gamma(\mathbf{r};\omega\simeq\tilde{\omega}_{\mu'})}{\Gamma_0} \simeq f_{\tilde{\omega}_{\mu'}}(\mathbf{r};\omega) \propto \frac{Q_{\mu'}}{V_{\mu'}}$$

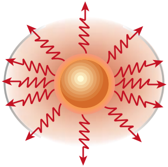
B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University*.—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2)\ \text{sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2 V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V \sim a^3$, and if δ is the skin-depth at frequency ν, $f \sim \lambda^3/a^2\delta$. For a non-resonant circuit $f \sim \lambda^3/a^3$, and for $a < \delta$ it can be shown that $f \sim \lambda^3/a\delta^2$.
c particles, of diameter 10^{-3} cm are mixed -magnetic medium at room temperature, ission should establish thermal equilibrium order of minutes, for $\nu = 10^7$ sec.$^{-1}$.



[E. Purcell, Phys. Rev. **69**, 681 (1946)]

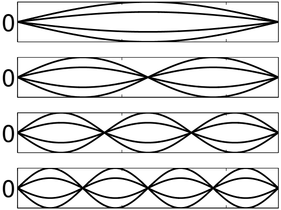


$$\frac{\Gamma(\mathbf{r};\omega)}{\Gamma_0} = \sum_\mu f_{\tilde{\omega}_\mu}(\mathbf{r};\omega)$$

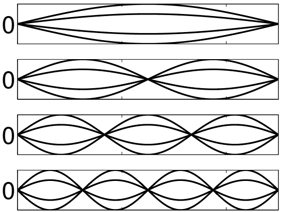
$$\frac{\Gamma(\mathbf{r};\omega \simeq \tilde{\omega}_{\mu'})}{\Gamma_0} \simeq f_{\tilde{\omega}_{\mu'}}(\mathbf{r};\omega) \propto \frac{Q_{\mu'}}{V_{\mu'}}$$

Quasi-normal modes

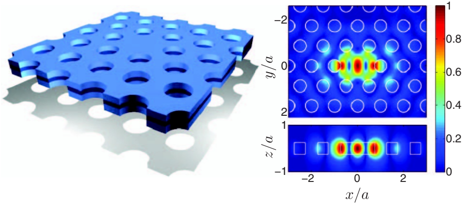
Closed cavity: Normal modes



Closed cavity: Normal modes

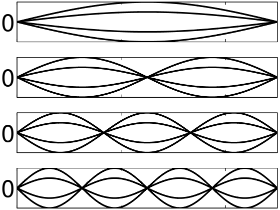


Open cavity: Quasi-normal modes

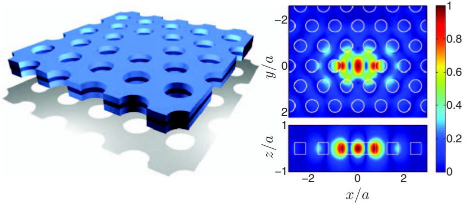


[P. T. Kristensen *et al.*, Opt. Lett. **37**, 1649 (2012)]

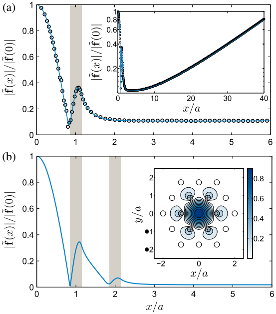
Closed cavity: Normal modes



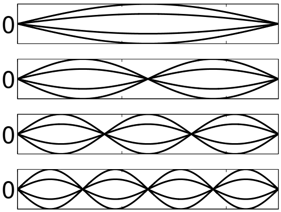
Open cavity: Quasi-normal modes



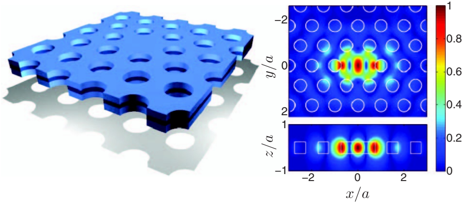
[P. T. Kristensen *et al.*, Opt. Lett. **37**, 1649 (2012)]



Closed cavity: Normal modes



Open cavity: Quasi-normal modes

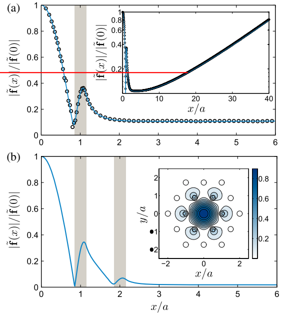


[P. T. Kristensen *et al.*, Opt. Lett. **37**, 1649 (2012)]

FDTD

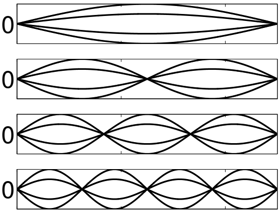
and

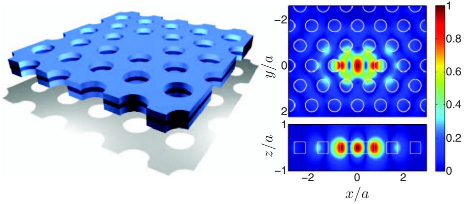
VIE



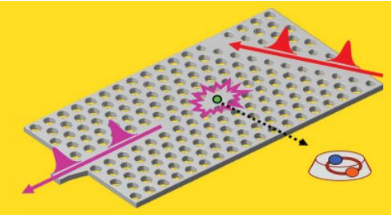
Closed cavity: Normal modes

Open cavity: Quasi-normal modes



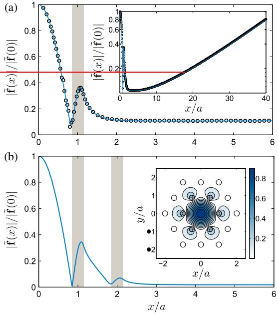


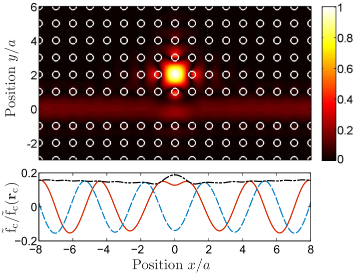
[P. T. Kristensen *et al.*, Opt. Lett. **37**, 1649 (2012)]



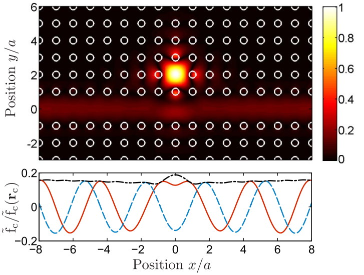
[O. Yao *et al.*, Laser Photonics Rev. **4**, 499 (2010)]

FDTD
and
VIE

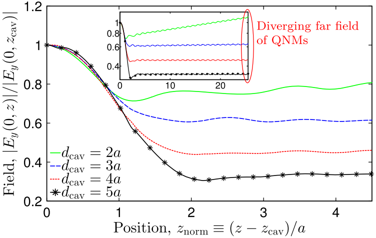




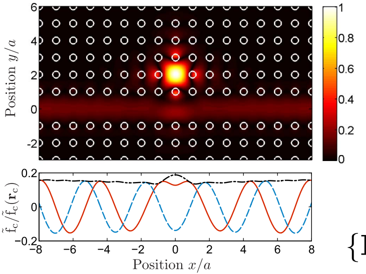
[P. T. Kristensen *et al.*, Opt. Lett. **39**, 6359 (2014)]



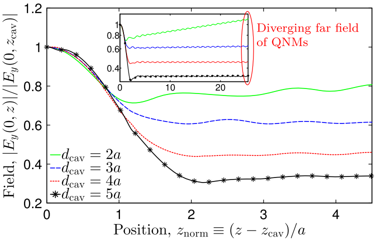
[P. T. Kristensen *et al.*, Opt. Lett. **39**, 6359 (2014)]



[J. R. de Lasson *et al.*, J. Opt. Soc. Am. A **31**, 2142 (2014)]



$$\{\mathbf{E}_\mu;\ \tilde{\omega}_\mu\}$$



[P. T. Kristensen *et al.*, Opt. Lett. **39**, 6359 (2014)]

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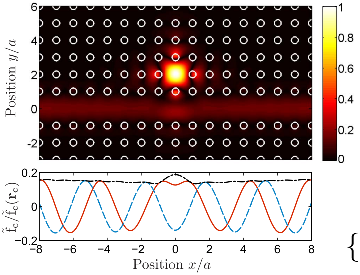

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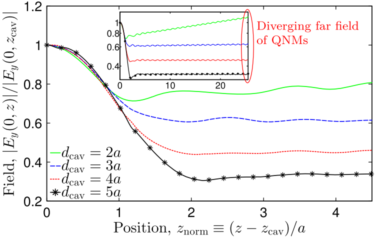


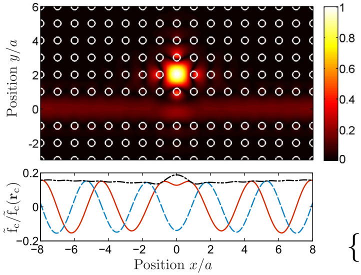
[P. T. Kristensen *et al.*, Opt. Lett. **39**, 6359 (2014)]

[J. R. de Lasson *et al.*, J. Opt. Soc. Am. A **31**, 2142 (2014)]

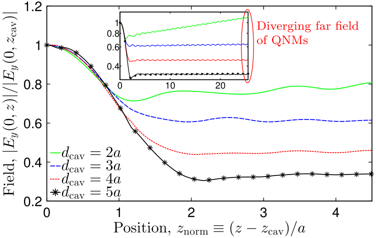
$$\Gamma(\mathbf{r};\omega) = \frac{\pi\omega}{\hbar\epsilon_0}|\mathbf{p}|^2 \rho(\mathbf{r};\omega)$$

LDOS

[L. Novotny and B. Hecht, "Principles of Nano-Optics" (2012)]



$$\{\mathbf{E}_\mu;\, \tilde{\omega}_\mu\}$$



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LDOS

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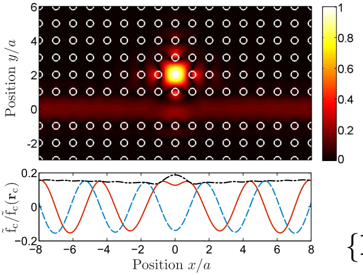
[L. Novotny and B. Hecht,
"Principles of Nano-Optics" (2012)]



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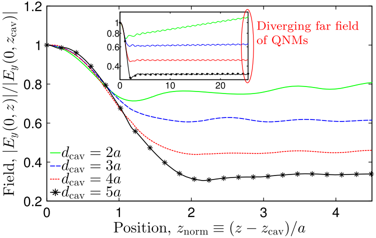

[P. T. Kristensen *et al.*, Opt. Lett. **39**, 6359 (2014)]

[J. R. de Lasson *et al.*, J. Opt. Soc. Am. A **31**, 2142 (2014)]

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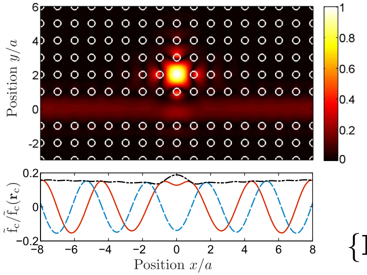
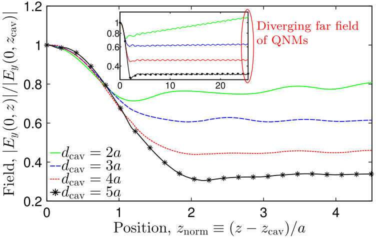
[L. Novotny and B. Hecht,
"Principles of Nano-Optics" (2012)]

See also: [C. Sauvan *et al.*, Phys. Rev. Lett. **110**, 237401 (2013)]
[R.-C. Ge *et al.*, New J. Phys. **16**, 113048 (2014)]



$$\{\mathbf{E}_\mu;\ \tilde{\omega}_\mu\}$$



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See also: [C. Sauvan *et al.*, Phys. Rev. Lett. **110**, 237401 (2013)]
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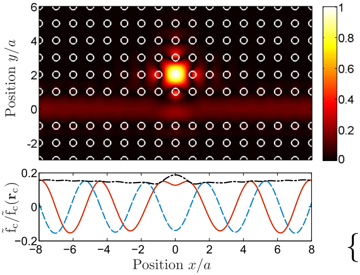

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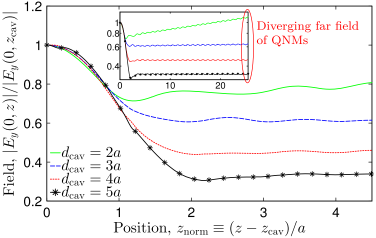

[P. T. Kristensen *et al.*, Opt. Lett. **39**, 6359 (2014)]

[J. R. de Lasson *et al.*, J. Opt. Soc. Am. A **31**, 2142 (2014)]

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See also: [C. Sauvan *et al.*, Phys. Rev. Lett. **110**, 237401 (2013)]
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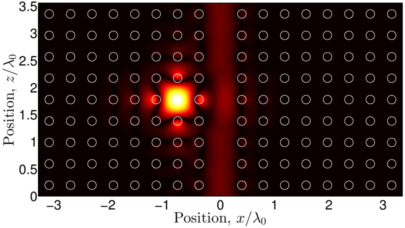
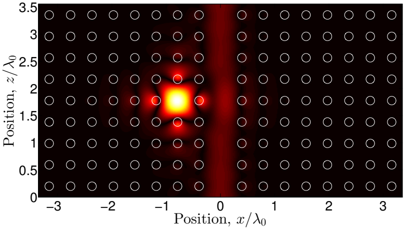


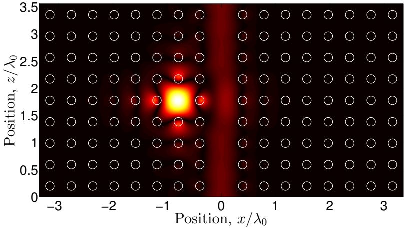
[J. R. de Lasson *et al.*, Opt. Lett. **40**, 5790 (2015)]



$$\rho^y(\mathbf{r}_\mathrm{D};\omega) = \frac{\omega}{\pi}\frac{1}{\epsilon(\mathbf{r}_\mathrm{D})}\mathrm{Im}\left[\frac{1}{\tilde{\omega}_\mu(\tilde{\omega}_\mu-\omega)}\frac{1}{a_\mu}\right]$$

$$a_\mu = \frac{1}{\epsilon(\mathbf{r}_\mathrm{D})\left[\mathbf{E}_\mu(\mathbf{r}_\mathrm{D})\cdot\hat{\mathbf{y}}\right]^2}$$

[J. R. de Lasson *et al.*, Opt. Lett. **40**, 5790 (2015)]



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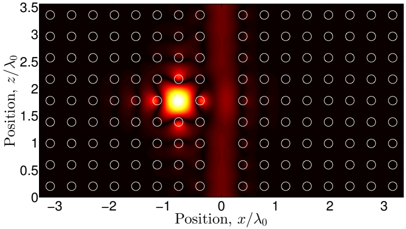
$$F_\mathrm{P} \equiv \frac{\rho^y(\mathbf{r}_\mathrm{D};\omega_\mu)}{\rho_\mathrm{Bulk}} \simeq \frac{1}{\pi^2}\left(\frac{\lambda_0}{n(\mathbf{r}_\mathrm{D})}\right)^2\frac{Q_\mu}{A_\mu}$$

[J. R. de Lasson *et al.*, Opt. Lett. **40**, 5790 (2015)]



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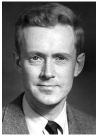
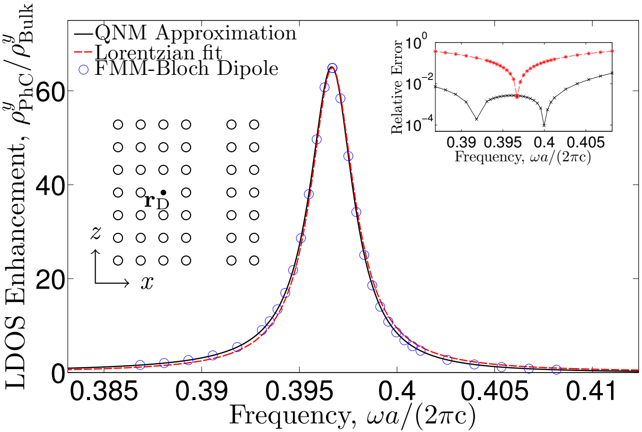


[J. R. de Lasson *et al.*, Opt. Lett. **40**, 5790 (2015)]



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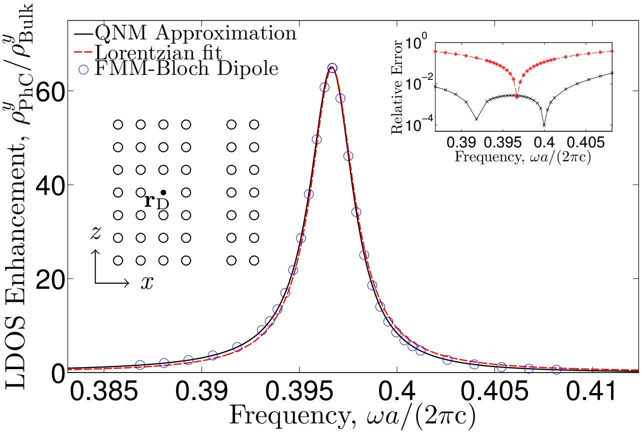
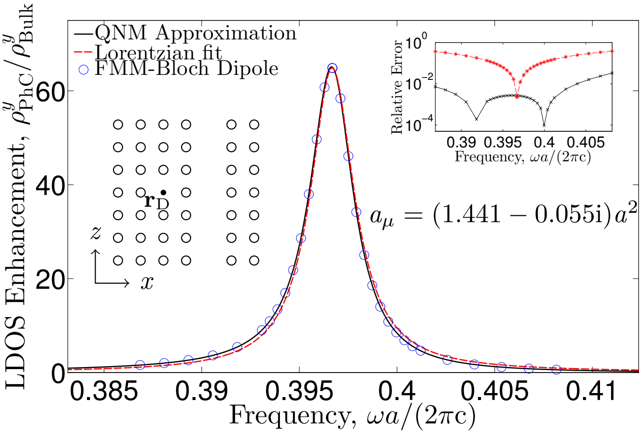


$$\rho^y_{\mathrm{PhC}}(\mathbf{r}_\mathrm{D};\omega) = \frac{\omega}{\pi}\frac{1}{\epsilon(\mathbf{r}_\mathrm{D})}\frac{1}{|\tilde{\omega}_\mu|^2}\frac{1}{|a_\mu|^2}\frac{1}{(\omega-\omega_\mu)^2+\gamma_\mu^2} \times\left\{\mathrm{Re}\left(a_\mu\right)\left[2\omega_\mu-\omega\right]\gamma_\mu + \mathrm{Im}\left(a_\mu\right)\left[\omega_\mu\left(\omega-\omega_\mu\right)+\gamma_\mu^2\right]\right\}$$

[J. R. de Lasson *et al.*, Opt. Lett. **40**, 5790 (2015)]



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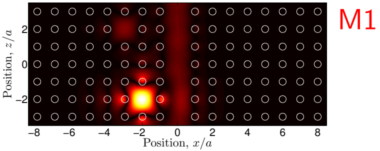
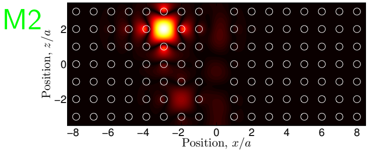
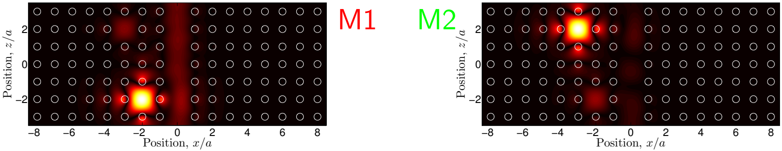
$$\times\left\{\mathrm{Re}\left(a_\mu\right)\left[2\omega_\mu-\omega\right]\gamma_\mu + \mathrm{Im}\left(a_\mu\right)\left[\omega_\mu\left(\omega-\omega_\mu\right)+\gamma_\mu^2\right]\right\}$$

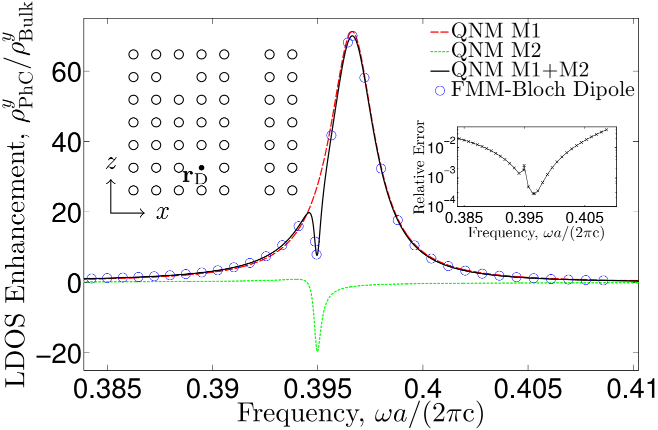
[J. R. de Lasson *et al.*, Opt. Lett. **40**, 5790 (2015)]



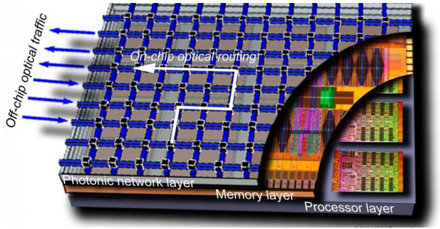


[J. R. de Lasson *et al.*, Opt. Lett. **40**, 5790 (2015)]

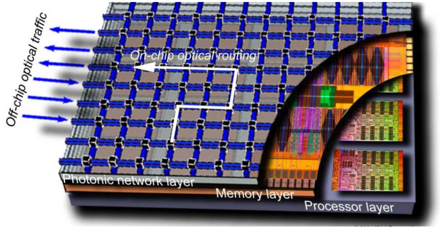


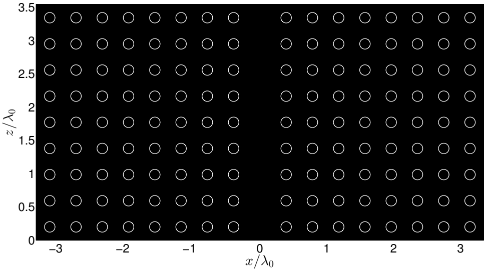


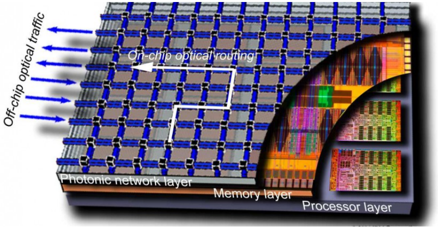
[J. R. de Lasson *et al.*, Opt. Lett. **40**, 5790 (2015)]

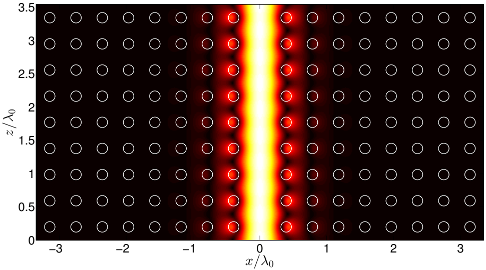


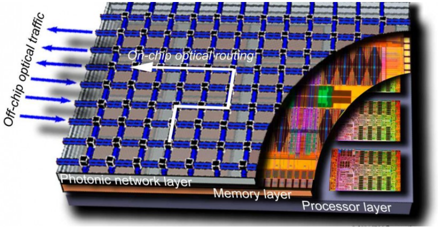
Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer

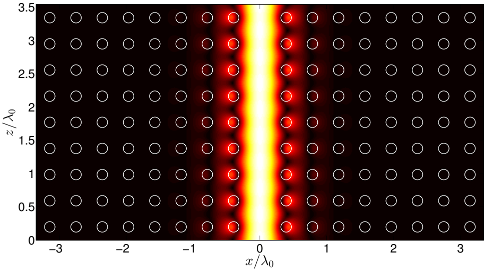

Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer


3.5
3
2.5
2
1.5
1
0.5
0
z/λ_0
–3
–2
–1
0
1
2
3
x/λ_0


Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer


3.5
3
2.5
2
1.5
1
0.5
0
z/λ_0
−3
−2
−1
0
1
2
3
x/λ_0


Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer


3.5
3
2.5
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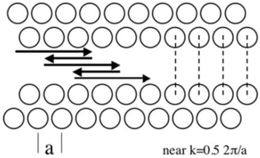
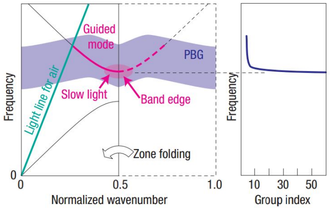
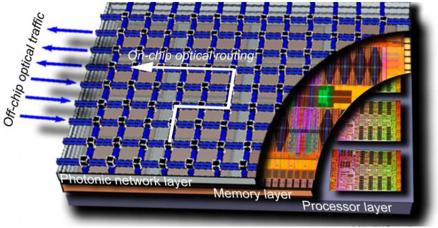
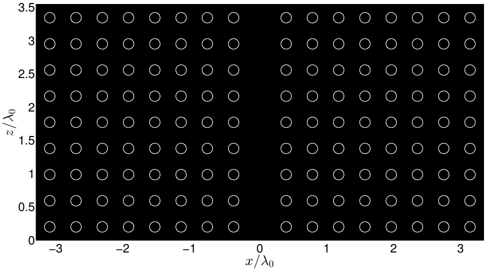
1.5
1
0.5
0
z/λ_0
−3
−2
−1
0
1
2
3
x/λ_0


a
near k=0.5 2π/a


Guided mode
PBG
Slow light
Band edge
Light line for air
Zone folding
Frequency
0
0
0.5
1.0
Normalized wavenumber
Frequency
10
30
50
Group index



Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer



3.5
3
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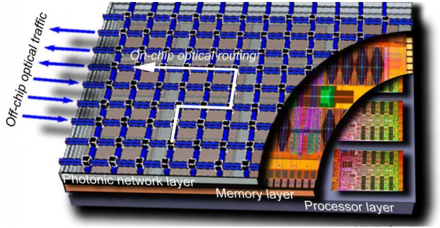
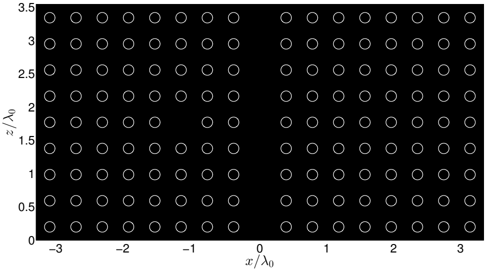
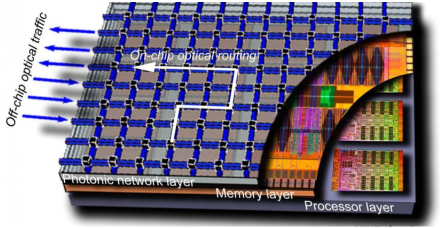
1.5
1
0.5
0
z/λ_0
–3
–2
–1
0
1
2
3
x/λ_0

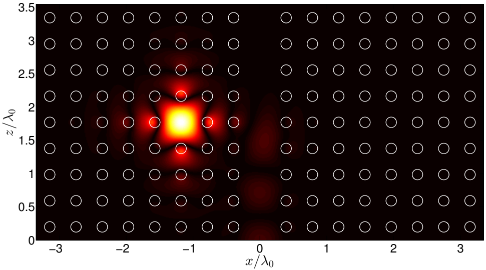


Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer



3.5
3
2.5
2
1.5
1
0.5
0
z/λ_0
−3
−2
−1
0
1
2
3
x/λ_0


Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer


3.5
3
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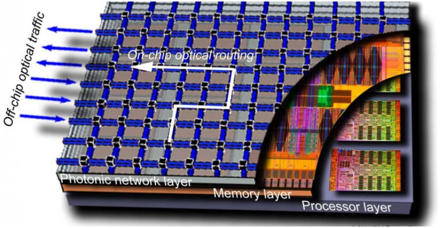
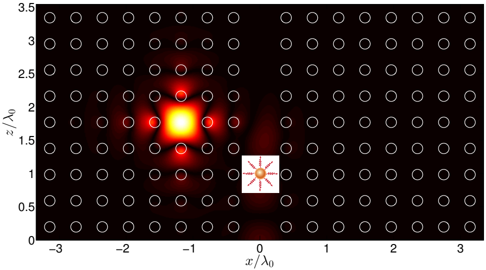
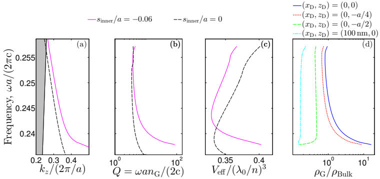
1.5
1
0.5
0
z/λ_0
–3
–2
–1
0
1
2
3
x/λ_0



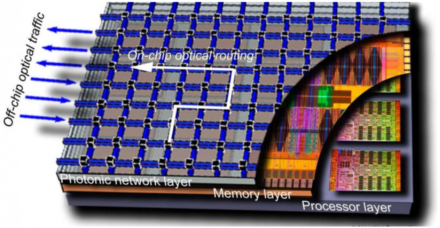
Off-chip optical traffic
On-chip optical routing
Photonic network layer
Memory layer
Processor layer



z/λ_0
x/λ_0



$s_{\mathrm{inner}}/a = -0.06$
$s_{\mathrm{inner}}/a = 0$
$(x_D, z_D) = (0, 0)$
$(x_D, z_D) = (0, -a/4)$
$(x_D, z_D) = (0, -a/2)$
$(x_D, z_D) = (100\,\mathrm{nm}, 0)$
(a)
(b)
(c)
(d)
Frequency, $\omega a/(2\pi c)$
$k_z/(2\pi/a)$
$Q = \omega a n_G/(2c)$
$V_{\mathrm{eff}}/(\lambda_0/n)^3$
$\rho_G/\rho_{\mathrm{Bulk}}$


Off-chip optical traffic
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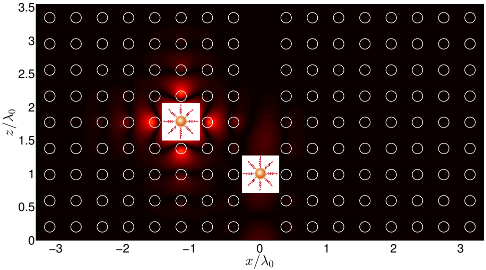
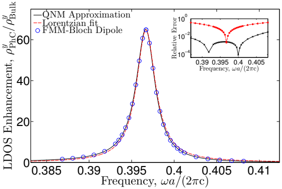
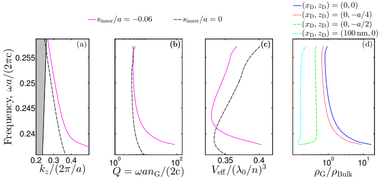

z/λ_0
x/λ_0


QNM Approximation
Lorentzian fit
FMM-Bloch Dipole
LDOS Enhancement, $\rho^y_{\rm PhC}/\rho^y_{\rm Bulk}$
Frequency, $\omega a/(2\pi c)$
Relative Error


$s_{\rm inner}/a = -0.06$
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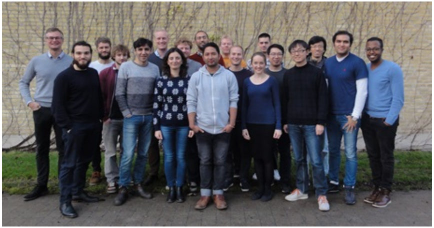
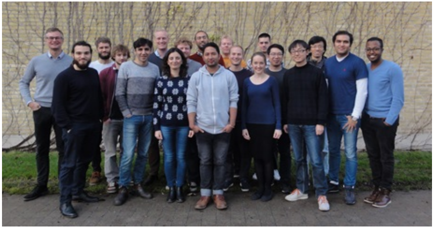
$(x_D, z_D) = (0, -a/2)$
$(x_D, z_D) = (100\,{\rm nm}, 0)$
Frequency, $\omega a/(2\pi c)$
$k_z/(2\pi/a)$
$Q = \omega a n_G/(2c)$
$V_{\rm eff}/(\lambda_0/n)^3$
$\rho_G/\rho_{\rm Bulk}$

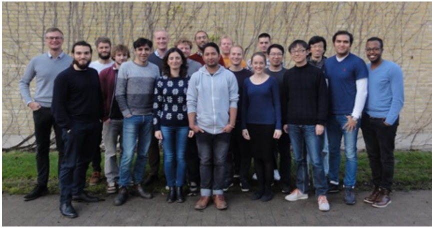


Nanophotonics Theory



Nanophotonics Theory

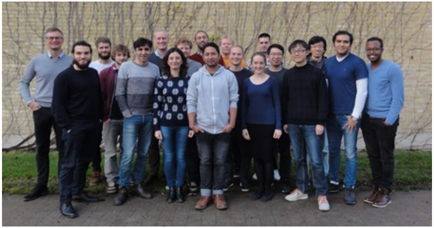
Nanophotonics



Nanophotonics Theory

Nanophotonics

EPFL-LPN



Nanophotonics Theory

Nanophotonics

EPFL-LPN

Niels

Jesper

Philip

September 3, 2007 → December 18, 2015

September 3, 2007 $\rightarrow$ December 18, 2015

...Thanks for your attention $\ddot{\smile}$