Photonic Crystals:
Properties, Modeling, and Applications

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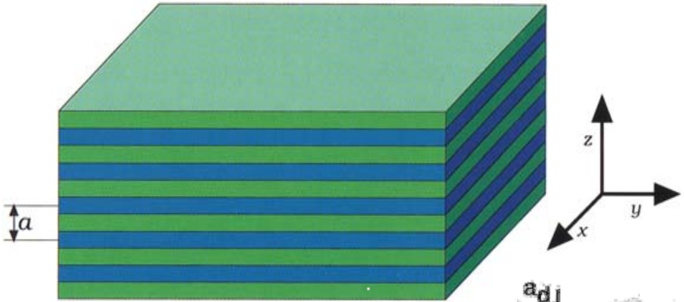
Schottky-Seminar, Walter-Schottky-Institut (WSI), Technische Universität
January 27, 2009, München

Shapes of Photonic Crystals — 1D Photonic Crystals

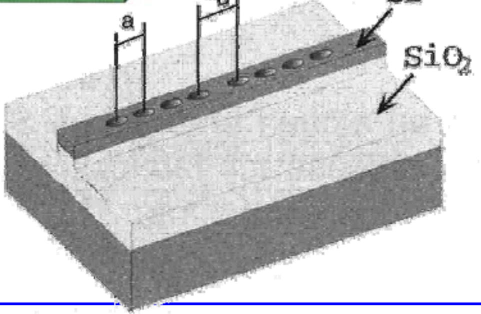
Regular arrays of regions $a \approx \lambda_e/2$ with different refractive indices resembling solid-state crystals, with 1D, 2D and 3D variants

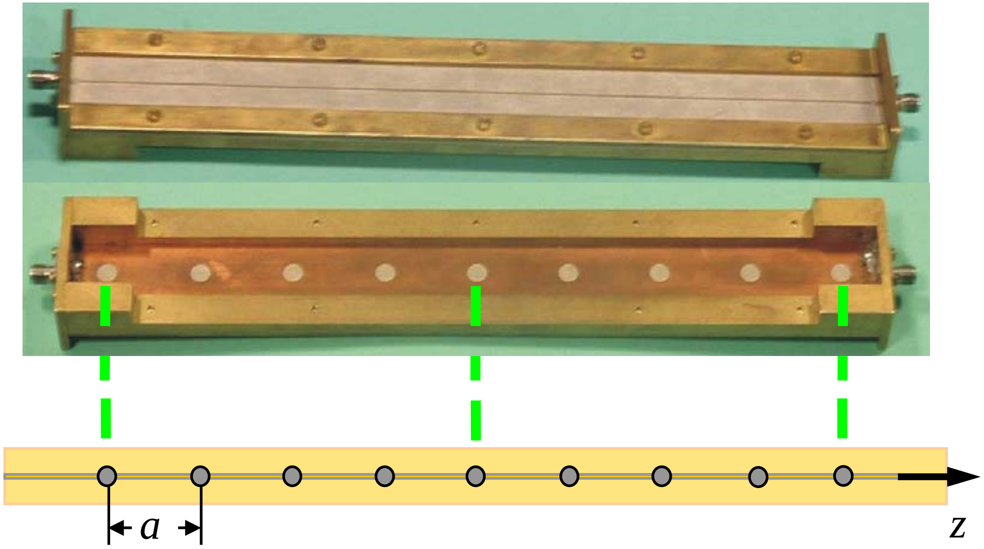
1D Periodic multilayer film with alternating high and low-index dielectric layers; also periodic perturbations along a transmission line. Spatial period $a \approx \lambda_e/2$ along propagation direction z (distributed Bragg reflector, DBR)

Joannopoulis, J. D.; Johnson, S. G.; Winn, J. W.; Meade, R. D.: Photonic crystals — Molding the flow of light, 2. Ed. Princeton: University Press 2008



J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, Henry I. Smith, E. P. Ippen: Photonic-bandgap microcavities in optical waveguides. Nature 390 (1997) 143–145



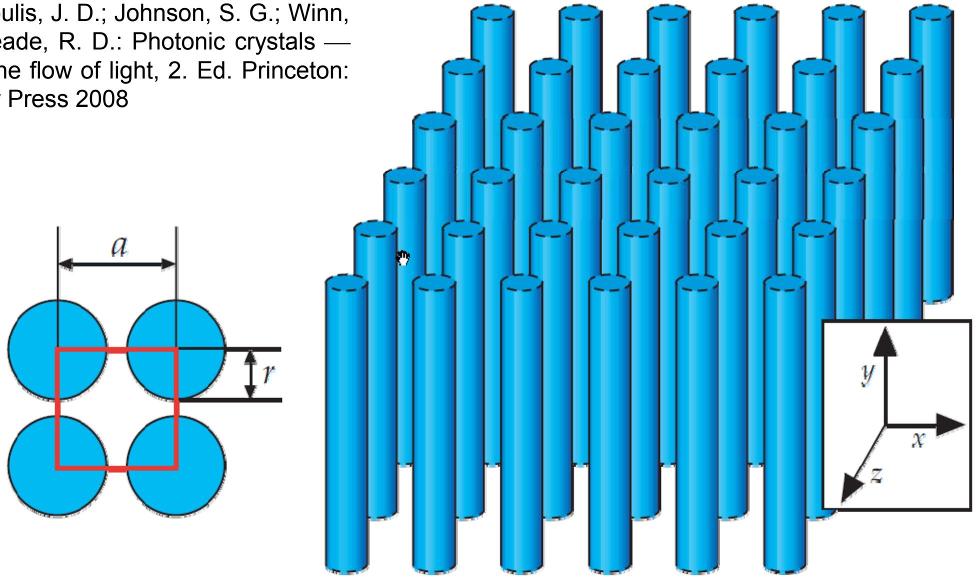


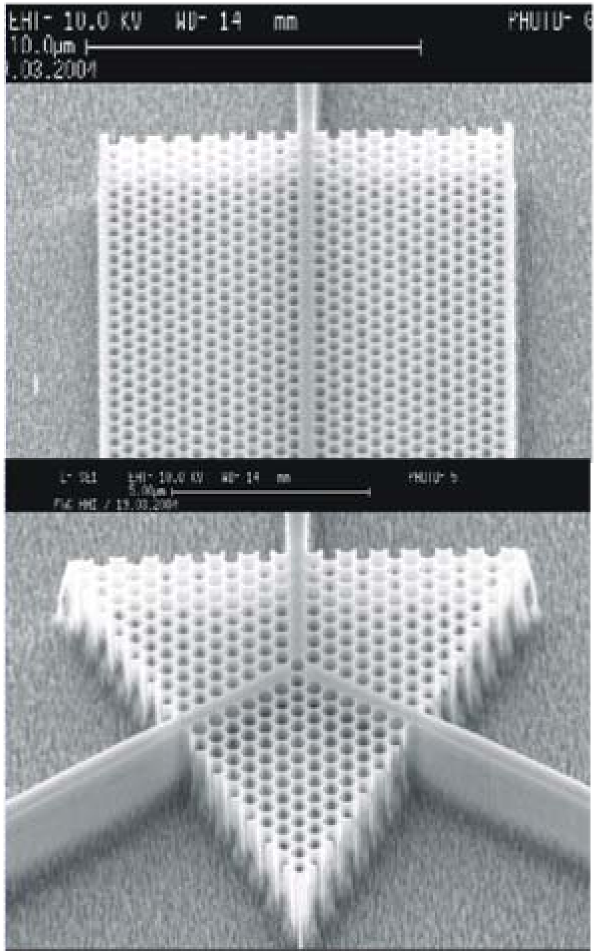
2D Photonic Crystals

Regular arrays of regions $a \approx \lambda_e/2$ with different refractive indices resembling solid-state crystals, with 1D, 2D and 3D variants

2D Periodic arrangement of (not necessarily circular) rods or holes in a medium with different refractive index. Usually in form of a slab structure with vertical index guiding.

Joannopoulis, J. D.; Johnson, S. G.; Winn, J. W.; Meade, R. D.: Photonic crystals — Molding the flow of light, 2. Ed. Princeton: University Press 2008

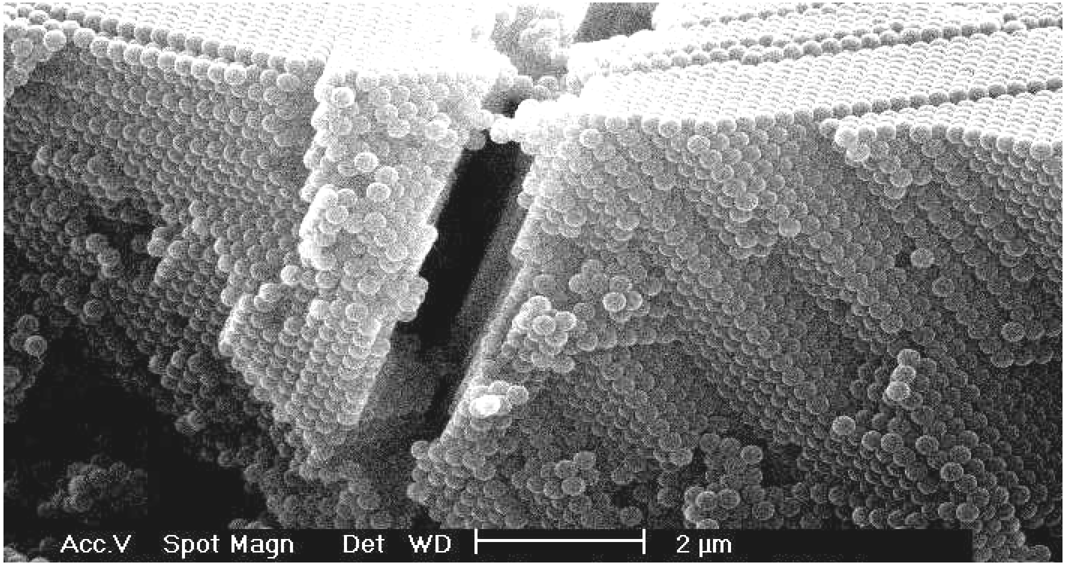




3D Photonic Crystals — Opals and Woodpile

Regular arrays of regions $a \approx \lambda_e/2$ with different refractive indices resembling solid-state crystals, with 1D, 2D and 3D variants

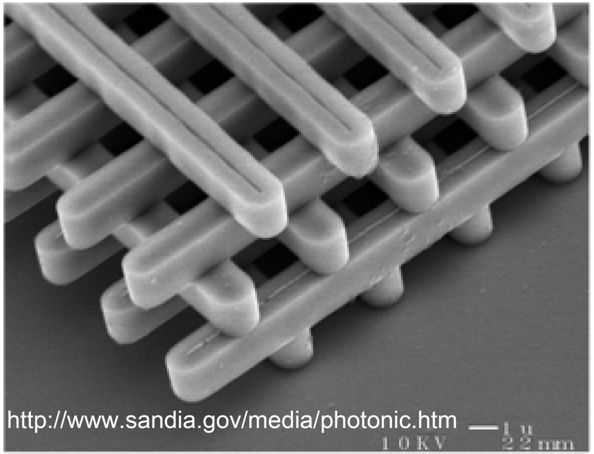
3D Periodic arrangement of balls, holes or bars in a medium with different refractive index.



Opaline fcc lattice latex spheres 250 nm$^{\varnothing}$

SotomayorTorres, C. M.; Romanov, S. G.: Opal- and polymer-based photonic crystals. Heraeus Summer School on Photonic Crystals, Wittenberg, July 14–25, 2002. http://www.photonische-kristalle.de/summerschool

Woodpile structure



http://www.sandia.gov/media/photonic.htm

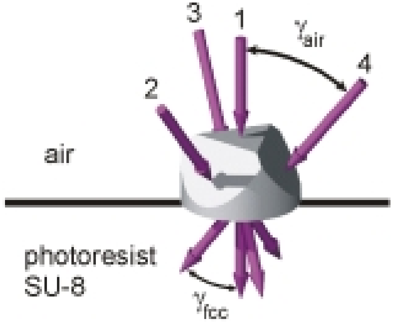
Lin, S. Y.; Fleming, J. G.; Hetherington, D. L.; Smith, B. K.; Biswas, R.; Ho, K. M.; Sigalas, M. M.;. Zubrzycki, W.; Kurtz, S. R.; Bur, J.: A three-dimensional photonic crystal operating at infrared wavelengths. Nature 394 (1998) 251–253
Lin, S. Y.; Fleming, J. G.: A three-dimensional optical photonic crystal. J. Lightw. Technol. 17 (1999) 1944–1947

Noda, S.; Tomoda, K.; Yamamoto, N.; Chutinan, A.: Full three-dimensional photonic bandgap crystals at near-infrared wavelengths. Science 289 (2000) 604 – 606

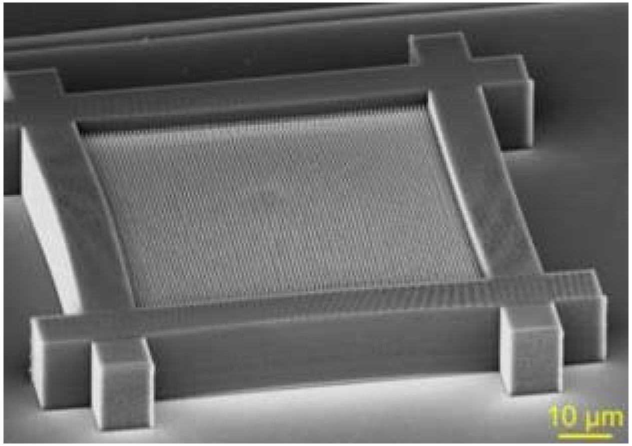
3D Photonic Crystals — Direct Laser Writing

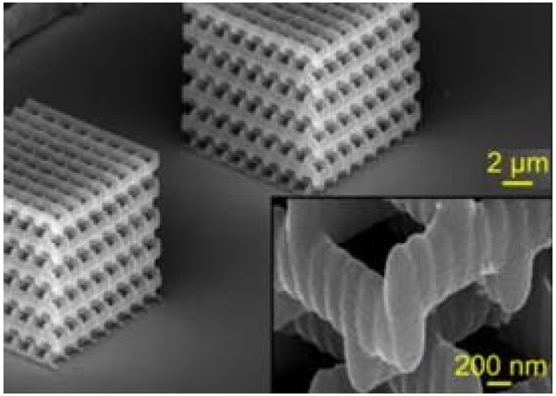
Regular arrays of regions $a \approx \lambda_e/2$ with different refractive indices resembling solid-state crystals, with 1D, 2D and 3D variants

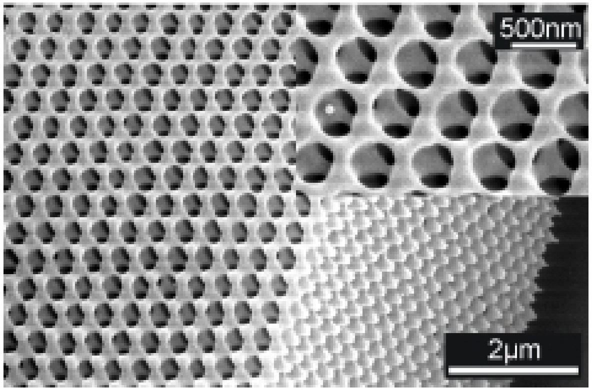
3D Periodic arrangement of balls, holes or bars in a medium with different refractive index. Done with direct laser writing in SU-8 and inversion

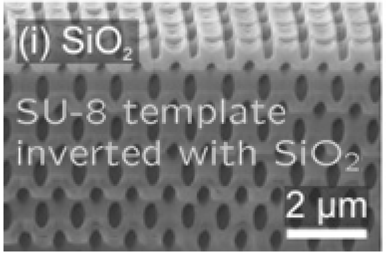


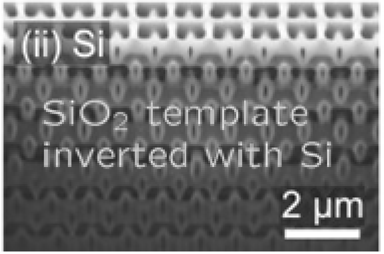
Prof. Dr. Martin Wegener´s group at the Institute of Applied Physics, University of Karlsruhe
http://www.aph.uni-karlsruhe.de/...
…wegener/en/research/photonic-crystals

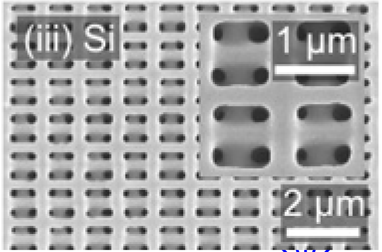










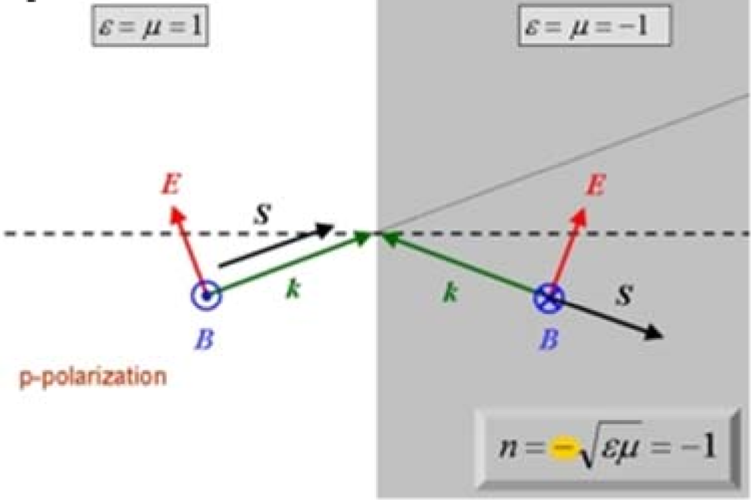


Metamaterials vs. Photonic Crystals

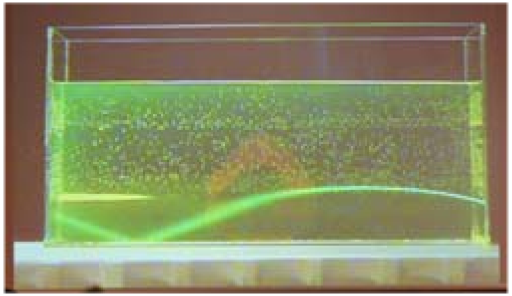
Metamaterials: Macroscopic composites having a manmade, mostly 3D and periodic ($a \ll \lambda_e$) cellular architecture designed to produce, e. g., a negative refractive index $n = \underset{[+]}{-}\sqrt{\epsilon_r \mu_r}$.

$n = +1.33$

$n = -1.33$



Martin Wegener´s group at the Institute of Applied Physics, University of Karlsruhe — http://www.aph.uni-karlsruhe.de/wegener/en/research/photonic-crystals

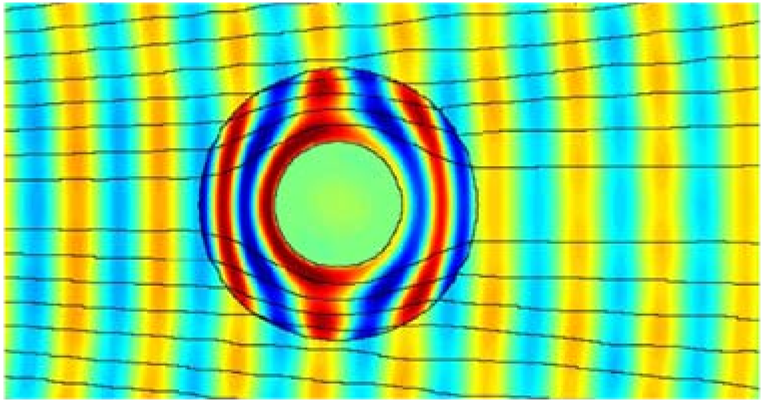


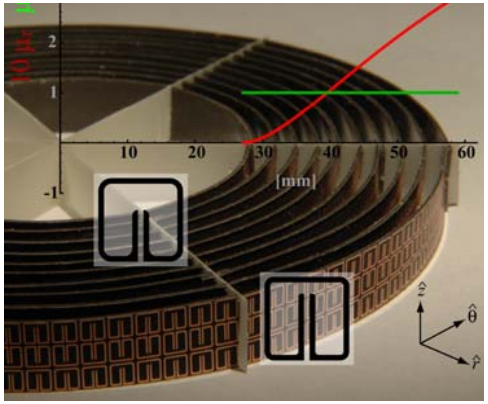
Equivalent of an optical cloaking experiment: Water with sugar solution acts as graded-index guide. Laser beam travels around an object.

Gießen, H.: Öffentliche Vorlesung über Tarnkappen im Mercedes Museum am 22.7.2008. http://www.pi4.uni-stuttgart.de/

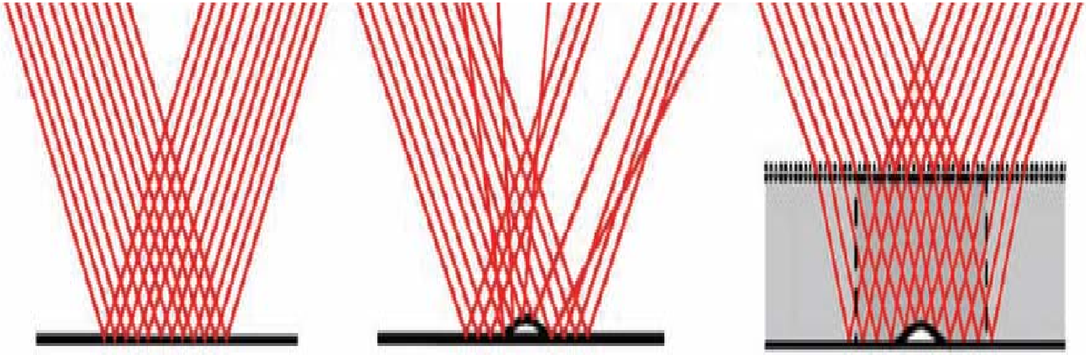
Metamaterials in the Microwave Range — Cloaking

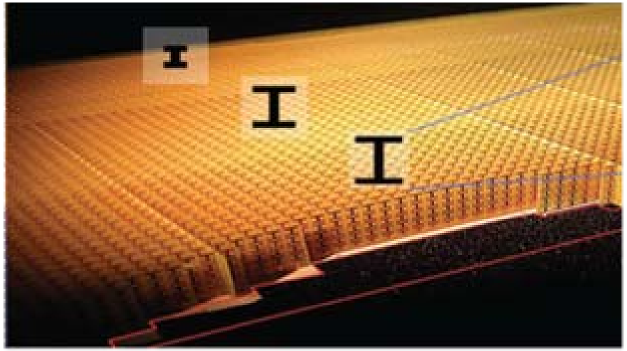
Metamaterials: Macroscopic composites having a manmade, mostly 3D and periodic ($a \ll \lambda_e$) cellular architecture designed to produce, e.g., a negative refractive index $n = \underset{[+]}{-}\sqrt{\epsilon_r \mu_r}$.





Schurig, D.; Mock, J. J.; Justice, B. J.; Cummer, S. A.; Pendry, J. B.; Starr, A. F.; Smith, D. R.: Metamaterial electromagnetic cloak at microwave frequencies. Science*express* http://www.sciencexpress.org 19 Oct 2006 10.1126/science.1133628

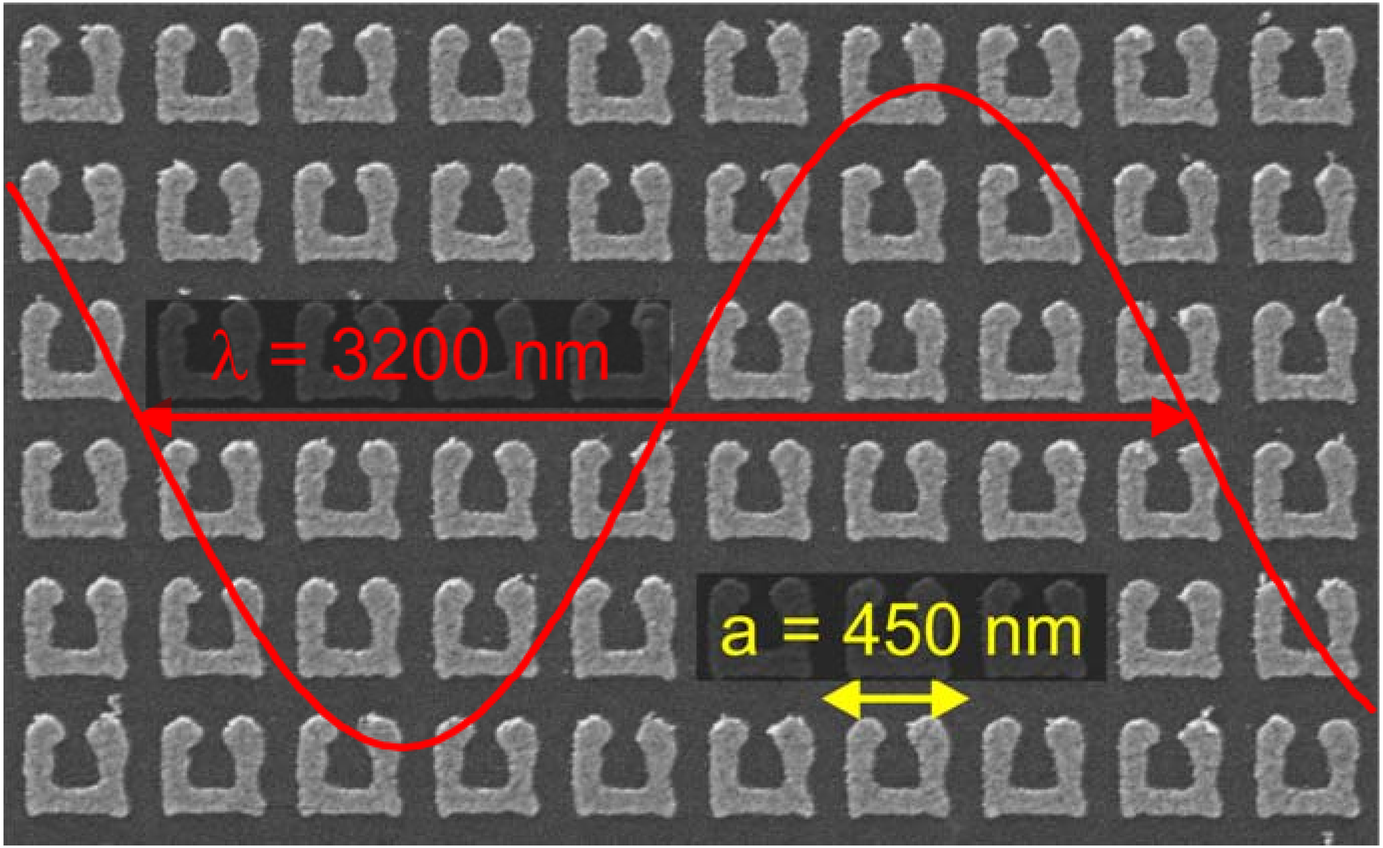




Liu, R.; Ji, C.; Mock, J. J.; chin, J. Y.; Cui, T. J.; Smith, D. R.: Broadband ground-plane cloak. Science 323 (2008) 366–369

Metamaterials in the Optical Range — Towards an Ideal Lens?

Metamaterials: Macroscopic composites having a manmade, mostly 3D and periodic ($a \ll \lambda_e$) cellular architecture designed to produce, e. g., a negative permeability $\mu_r < 0$.



Linden, S.; Enkrich, C.; Wegener, M.; Zhou, J.; Koschny, T.; Soukoulis, C. M.: Magnetic Response of Metamaterials at 100 Terahertz. Science 306 (2004) 1351–1353

Outline

- Fundamentals of photonic crystals
  - Maxwell’s equations and the scaling law
  - Bandstructure of photonic crystals
- Applications and technology
  - Optical communications and silicon photonics
  - Slowing down light
  - Designing chromatic dispersion
  - Coupling to photonic crystals
- Photonic crystal devices
  - Tunable dispersion compensator
  - Tunable delay line
  - Electro-optic modulator
  - Measurements
- Summary

Maxwell's Equations and the Scaling Law $n\,\omega L = \text{const}$

Decoupling Maxwell's equations ($\mathcal{L}_H$ Hermitian):

$$\mathcal{L}_H \vec{H} \equiv \left(\text{curl}\,\frac{1}{\epsilon_r}\,\text{curl}\right)\vec{H} = \left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{H},\quad \Big(\overbrace{\frac{1}{\epsilon_r}\,\text{curl}\,\text{curl}}^{\mathcal{L}_E\ \text{(non-Hermitian)}}\Big)\vec{E} = \Big(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Big)\vec{E}$$

Harmonic solutions with $\vec{H}(t,\vec{r}) = \vec{H}(\vec{r})\,\mathrm{e}^{\mathrm{j}\,\omega t}$, $\vec{E}(t,\vec{r}) = \vec{E}(\vec{r})\,\mathrm{e}^{\mathrm{j}\,\omega t}$

$$\mathcal{L}_H \vec{H}(\vec{r}) = \frac{\omega^2}{c^2}\,\vec{H}(\vec{r})\,,\quad \text{eigenfreq.}|\text{fct. } \omega|\vec{H}(\vec{r}),\ (\vec{F},\mathcal{L}_H\vec{G}) = (\mathcal{L}_H\vec{F},\vec{G})$$

Scaling (enlargening) dimensions by $\sigma \geq 1$:

$$\vec{r}\,' = \sigma\,\vec{r},\qquad \epsilon_r(\vec{r}) \to \epsilon_r'(\vec{r}) = \epsilon_r(\vec{r}/\sigma),\qquad \text{curl}' = \frac{1}{\sigma}\,\text{curl}$$

Eigenequation transformed ($\epsilon_r(\vec{r}\,'/\sigma) = \epsilon_r'(\vec{r}\,')$, $\vec{H}(\vec{r}\,'/\sigma) = \vec{H}'(\vec{r}\,')$):

$$\left(\text{curl}'\,\frac{1}{\epsilon_r'(\vec{r}\,')}\,\text{curl}'\right)\vec{H}'(\vec{r}\,') = \frac{\omega'^2}{c^2}\,\vec{H}'(\vec{r}\,')\,,\qquad \omega' = \omega/\sigma$$

Enlarged structure $\epsilon_r'(\vec{r}\,')$ with enlarged eigenfunction $\vec{H}'(\vec{r}\,')$ for scaled dimension $\vec{r}\,' = \sigma\,\vec{r}$ and frequency $\omega' = \omega/\sigma$.

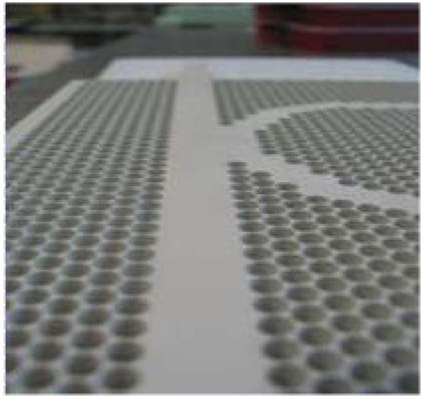
Microwave Experiments $n\,\omega L = \mathrm{const}$

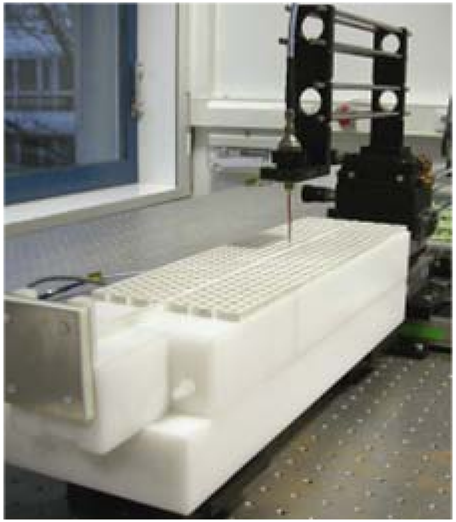
Enlargement of structure by σ = 20,000 (400 nm → 8 mm)

Decrease of frequency by 20,000 (200 THz → 10 GHz)

Advantages:

- Highly precise fabrication (CNC), equivalent accuracy 0.5 nm
- Highly accurate measurement equipment with large bandwidth
- Flexible and modular setup





Material:

Ceramic-reinforced PTFE (Teflon)
Refractive index at 10 GHz similar as for silicon at 200 THz

→ Accurate real-time check of numerical simulations (“analogue computer”)

→ Influence of fabrication imperfections may be investigated

Result:

→ Simulations with finite-integration technique (FIT) and guided-mode expansion (GME) method well suited for design

Brosi et. al., J. Lightw. Technol., vol. 25, no. 9, pp. 2502-2510, Sept. 2007

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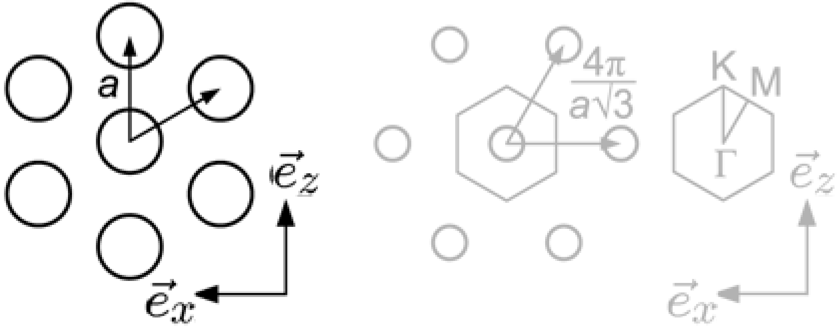
2D Photonic Crystal Bandstructure — Infinitely High Air Cylinders

Eigenvalue problem for isotropic non-magnetic material:

$$\mathcal{L}_H \vec{H}(\vec{r}) \equiv \left(\text{curl} \frac{1}{\epsilon_r(\vec{r})} \text{curl} \right) \vec{H}(\vec{r}) = \frac{\omega^2}{c^2} \vec{H}(\vec{r}) , \quad \text{div} \, \vec{H}(\vec{r}) = 0, \quad \mu_r = 1$$

Discrete translational symmetry in xz-plane. Lattice represented by 2 primitive lattice vectors $\vec{a}_{1,2}$, length a (lattice constant).



Lattice vector $\vec{R}$ fixes positions of cylinder centers:

$$\vec{R} = \mu_1 \, \vec{a}_1 + \mu_2 \, \vec{a}_2, \quad \mu_{1,2} \in \mathbb{Z}, \qquad \epsilon_r(\vec{r}\,) = \epsilon_r(\vec{r} + \vec{R})$$

Spatially periodic $\epsilon_r^{-1}(\vec{r})$ → Fourier series:

$$\frac{1}{\epsilon_r(\vec{r}\,)} = \sum\nolimits_{\vec{G}} \tilde{\kappa}_{\vec{G}} \, \mathrm{e}^{-\mathrm{j}\,\vec{G}\cdot\vec{r}} = \sum\nolimits_{\vec{G}} \tilde{\kappa}_{\vec{G}} \, \mathrm{e}^{-\mathrm{j}\,\vec{G}\cdot(\vec{r}+\vec{R})} = \frac{1}{\epsilon_r(\vec{r} + \vec{R}\,)}$$

Reciprocal lattice vector $\vec{G}$:

$$\vec{G} = \nu_1 \, \vec{b}_1 + \nu_2 \, \vec{b}_2, \;\; \nu_{1,2} \in \mathbb{Z}, \qquad \mathrm{e}^{-\mathrm{j}\,\vec{G}\cdot\vec{R}} = 1 \, , \qquad \vec{G} \cdot \vec{R} = n \cdot 2\pi \, , \;\; n \in \mathbb{Z}$$

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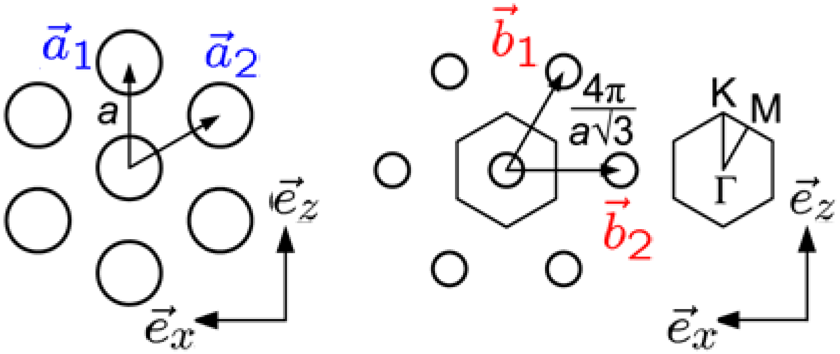
Eigenvalue problem for isotropic non-magnetic material:

$$\mathcal{L}_H \vec{H}(\vec{r}) \equiv \left(\text{curl}\,\frac{1}{\epsilon_r(\vec{r})}\,\text{curl}\right)\vec{H}(\vec{r}) = \frac{\omega^2}{c^2}\,\vec{H}(\vec{r})\,,\ \ \text{div}\,\vec{H}(\vec{r}) = 0,\ \ \mu_r = 1$$

Triangular lattice

Primitive lattice vectors $\vec{a}_{1,2}$:

$$\vec{a}_1 = a\,\vec{e}_z, \qquad \vec{a}_2 = -\frac{\sqrt{3}\,a}{2}\,\vec{e}_x + \frac{a}{2}\,\vec{e}_z$$



Reciprocal lattice vectors $\vec{b}_{1,2}$:

$$\vec{b}_1 = -\frac{4\pi}{\sqrt{3}\,a}\,\vec{e}_x,\ \ \vec{b}_2 = -\frac{2\pi}{\sqrt{3}\,a}\,\vec{e}_x + \frac{2\pi}{a}\,\vec{e}_z$$

Spatially periodic $\epsilon_r^{-1}(\vec{r})$ → Bloch's theorem (similar for $\vec{E}(\vec{r})$):

$$\vec{H}(\vec{r}) \equiv \vec{H}_{\vec{k}}(\vec{r}) = \vec{u}_{\vec{k}}(\vec{r})\,\mathrm{e}^{-\mathrm{j}\,\vec{k}\cdot\vec{r}}, \qquad \vec{u}_{\vec{k}}(\vec{r}) = \vec{u}_{\vec{k}}(\vec{r}+\vec{R})$$

Spatially periodic $\vec{H}(\vec{r})$ → $\vec{k}\cdot\vec{R} = n\cdot 2\pi$, $\vec{G}\cdot\vec{R} = n\cdot 2\pi\,,\ \ n\in\mathbb{Z}$:

$$\vec{H}_{\vec{k}}(\vec{r}) = \sum_{\vec{G}} \tilde{\vec{H}}_{\vec{k},\vec{G}}\,\mathrm{e}^{-\mathrm{j}(\vec{k}+\vec{G})\cdot\vec{r}} = \sum_{\vec{G}} \tilde{\vec{H}}_{\vec{k},\vec{G}}\,\mathrm{e}^{-\mathrm{j}(\vec{k}+\vec{G})\cdot(\vec{r}+\vec{R})} = \vec{H}_{\vec{k}}(\vec{r}+\vec{R})$$

2D Photonic Crystal Bandstructure — Eigenvalues

Eigenvalue problem for isotropic non-magnetic material:

$$\mathcal{L}_H \vec{H}(\vec{r}) \equiv \left(\operatorname{curl}\frac{1}{\epsilon_r(\vec{r})}\operatorname{curl}\right)\vec{H}(\vec{r}) = \frac{\omega^2}{c^2}\vec{H}(\vec{r}),\quad \operatorname{div}\vec{H}(\vec{r}) = 0,\quad \mu_r = 1$$

Triangular lattice

Primitive lattice vectors $\vec{a}_{1,2}$:

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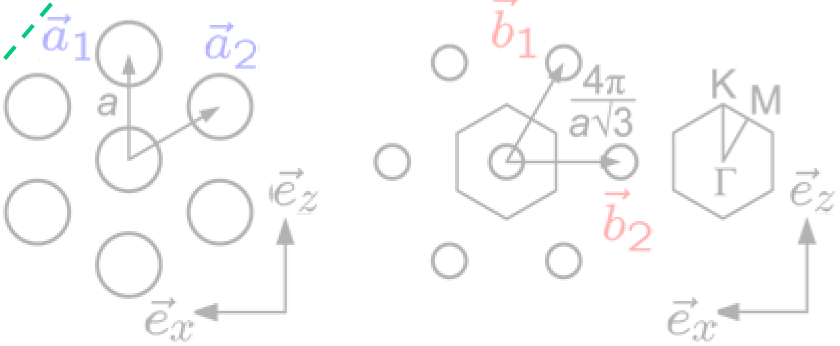


Reciprocal lattice vectors $\vec{b}_{1,2}$:

$$\vec{b}_1 = -\frac{4\pi}{\sqrt{3}\,a}\,\vec{e}_x,\quad \vec{b}_2 = -\frac{2\pi}{\sqrt{3}\,a}\,\vec{e}_x + \frac{2\pi}{a}\,\vec{e}_z$$

Eigenvalues $\omega_{\vec{k}}$ for fixed $\vec{k}$

Spatially periodic $\epsilon_r^{-1}(\vec{r})$ → Fourier series:

$$\frac{1}{\epsilon_r(\vec{r})} = \sum_{\vec{G}'}\tilde{\kappa}_{\vec{G}'}\,\mathrm{e}^{-\mathrm{j}\vec{G}'\cdot\vec{r}} = \sum_{\vec{G}'}\tilde{\kappa}_{\vec{G}'-\vec{G}}\,\mathrm{e}^{-\mathrm{j}(\vec{G}'-\vec{G})\cdot\vec{r}} = \frac{1}{\epsilon_r(\vec{r}+\vec{R})}$$

Spatially periodic $\vec{H}(\vec{r})$ → Fourier series as with $\epsilon_r(\vec{r})$:

$$\vec{H}(\vec{r}) \equiv \vec{H}_{\vec{k}}(\vec{r}) = \sum_{\vec{G}}\tilde{\vec{H}}_{\vec{k},\vec{G}}\,\mathrm{e}^{-\mathrm{j}(\vec{k}+\vec{G})\cdot\vec{r}} = \vec{H}_{\vec{k}}(\vec{r}+\vec{R})$$

1D Photonic Crystal Bandstructure — Computation Example (1)

$\epsilon_r(\vec{r}) = \epsilon_r(z) \rightarrow \vec{H}(\vec{r}) = H_x(z)\,\vec{e}_x + H_y(z)\,\vec{e}_y + H_z(z)\,\vec{e}_z,\ \partial_x = \partial_x = 0$:

$$\mathcal{L}_H \vec{H}(\vec{r}) \equiv \begin{pmatrix} -\partial_z \dfrac{1}{\epsilon_r(z)}\partial_z H_x(z) \\ -\partial_z \dfrac{1}{\epsilon_r(z)}\partial_z H_y(z) \\ 0 \end{pmatrix} = \frac{\omega^2}{c^2} \begin{pmatrix} H_x(z) \\ H_y(z) \\ H_z(z) \end{pmatrix} \begin{array}{l} \text{TM } (\vec{E} \text{ vertical}) \\ \text{TE } (\vec{E} \text{ horizontal}) \\ \text{no longitud. field} \end{array}$$

$$\partial_z \underbrace{\sum\nolimits_{G'} \tilde{\kappa}_{G'-G}\,\mathrm{e}^{-\mathrm{j}(G'-G)z}}_{\epsilon_r^{-1}(z)} \underbrace{\sum\nolimits_{G} \mathrm{j}(k+G)\tilde{H}_{k,G}\,\mathrm{e}^{-\mathrm{j}(k+G)z}}_{\partial_z H_y(z)} = \frac{\omega_k^2}{c^2} \overbrace{\sum\nolimits_{G} \tilde{H}_{k,G}\,\mathrm{e}^{-\mathrm{j}(k+G)z}}^{H_y(z)}$$

Periodic $\epsilon_r^{-1}(z)$ ($R = \mu a$, $G = \nu \frac{2\pi}{a}$):

$$\frac{1}{\epsilon_r(z)} = \sum\nolimits_{G'} \tilde{\kappa}_{G'}\,\mathrm{e}^{-\mathrm{j}G'z} = \sum\nolimits_{G'} \tilde{\kappa}_{G'-G}\,\mathrm{e}^{-\mathrm{j}(G'-G)z} = \frac{1}{\epsilon_r(z+R)}$$

Periodic $\vec{H}(z)$:

$$H_y(z) \equiv H_k(z) = \sum\nolimits_{G} \tilde{H}_{k,G}\,\mathrm{e}^{-\mathrm{j}(k+G)z} = H_k(z+R)$$

1D Photonic Crystal Bandstructure — Computation Example (3)

Infinite matrix eigenvalue problem for finding all ω_k belonging to k:

$$\sum_{G'}(k+G)(k+G')\tilde{\kappa}_{G-G'}\tilde{H}_{k,G'} = \frac{\omega_k^2}{c^2}\,\tilde{H}_{k,G} \qquad \left(GR = \nu\frac{2\pi}{a}\,\mu a = 2\pi\,\mu\nu\right)$$

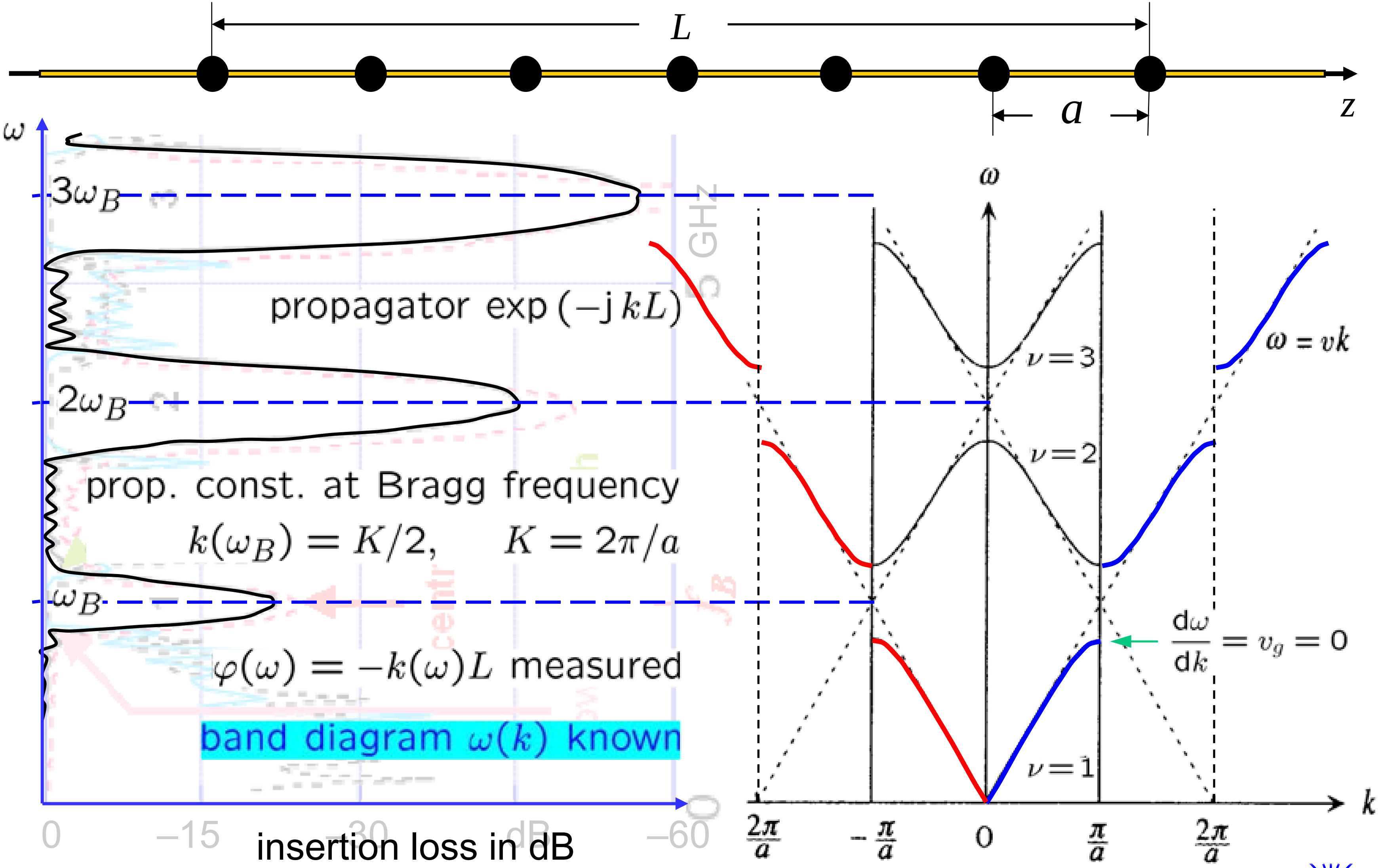
Spatially periodic $\epsilon_r^{-1}(z)$ → Fourier series ($G = \nu\frac{2\pi}{a}$):

$$\begin{aligned}
\frac{1}{\epsilon_r(z)} &= \sum_G \tilde{\kappa}_G\,\mathrm{e}^{-\mathrm{j}\,Gz} = \sum_{\nu=-N}^{+N} \tilde{\kappa}_\nu\,\mathrm{e}^{-\mathrm{j}\,\nu\frac{2\pi}{a}\,z} \\
&= \tilde{\kappa}_0\left[1+2\frac{|\tilde{\kappa}_1|}{\tilde{\kappa}_0}\cos\!\left(\frac{2\pi}{a}z-\arg(\tilde{\kappa}_1)\right)+2\frac{|\tilde{\kappa}_2|}{\tilde{\kappa}_0}\cos\!\left(2\frac{2\pi}{a}z-\arg(\tilde{\kappa}_2)\right)+\ldots\right] \\
&= \frac{1}{\frac{1}{\tilde{\kappa}_0}\left[1-2\frac{|\tilde{\kappa}_1|}{\tilde{\kappa}_0}\cos\!\left(\frac{2\pi}{a}z-\arg(\tilde{\kappa}_1)\right)-2\frac{|\tilde{\kappa}_2|}{\tilde{\kappa}_0}\cos\!\left(2\frac{2\pi}{a}z-\arg(\tilde{\kappa}_2)\right)-\ldots\right]}
\end{aligned}$$

Maximum number N ($=2$) of relevant spatial harmonics of $\epsilon_r(z)$.

$(2N+1)\times(2N+1)$ matrix with real eigenvalues $\omega_{k,\nu}$, which form $N+1$ “bands” (numbered by $\nu = 1\ldots N+1$) as a function of k.

1D Photonic Crystal Bandstructure — Insertion Loss



propagator $\exp(-\mathrm{j}\,kL)$

prop. const. at Bragg frequency

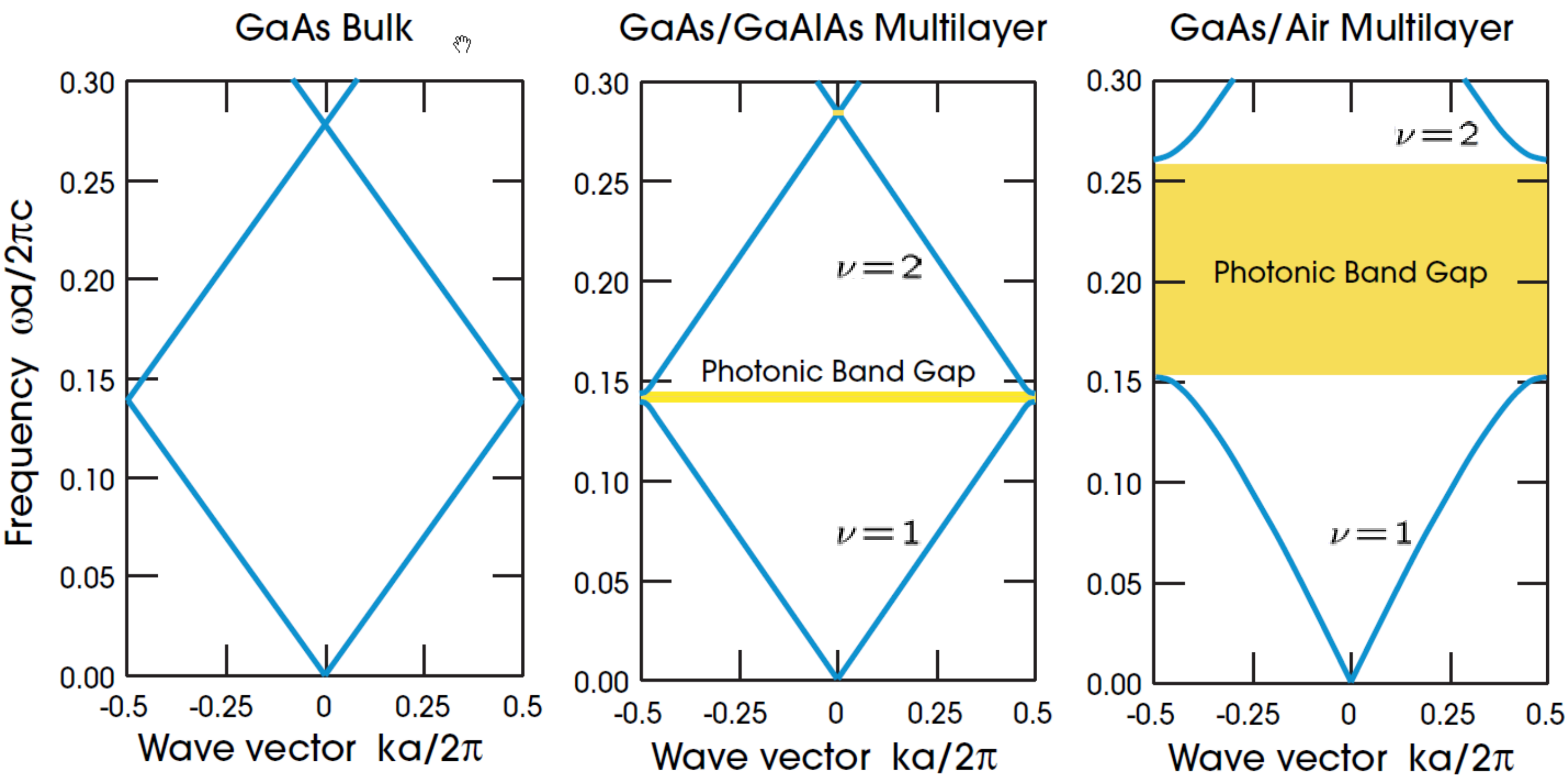
$$k(\omega_B) = K/2, \qquad K = 2\pi/a$$

$\varphi(\omega) = -k(\omega)L$ measured

band diagram $\omega(k)$ known

insertion loss in dB

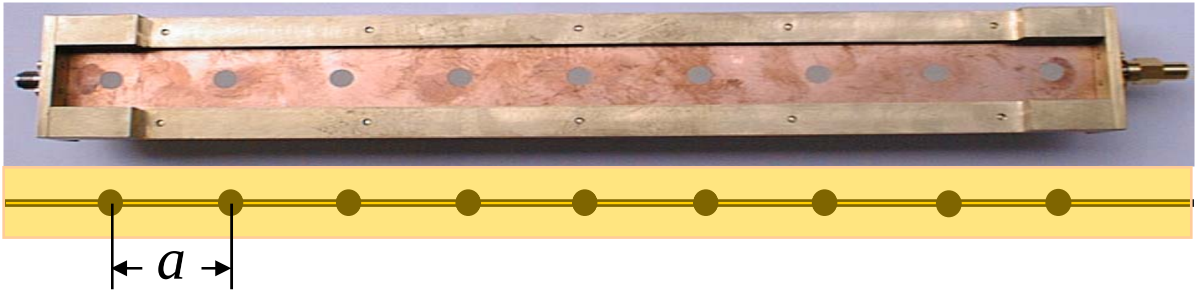
1D Photonic Crystal Bands — GaAs / GaAlAs Multilayer Film

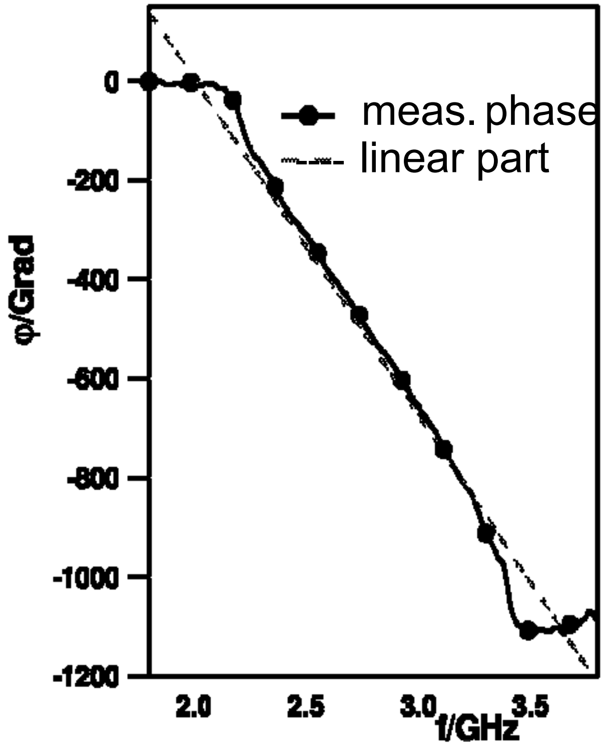


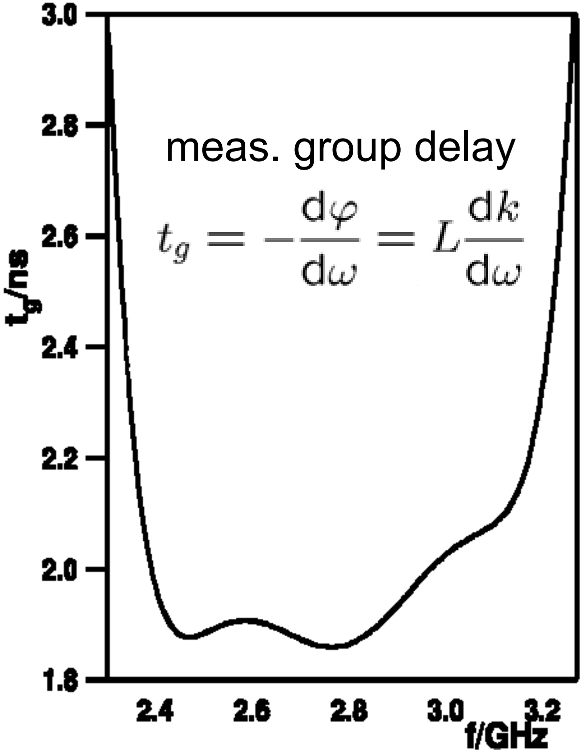
The photonic band structures for on-axis propagation, as computed for three different multilayer films. In all three cases, each layer has a width $0.5a$. *Left:* every layer has the same dielectric constant $\varepsilon = 13$. *Center:* layers alternate between ε of 13 and 12. *Right:* layers alternate between ε of 13 and 1.

Joannopoulis, J. D.; Johnson, S. G.; Winn, J. W.; Meade, R. D.: Photonic crystals — Molding the flow of light, 2. Ed. Princeton: University Press 2008 (Sect. 4 Fig. 2 p. 46)

1D Photonic Crystal Bands — Group Delay at Band Edges



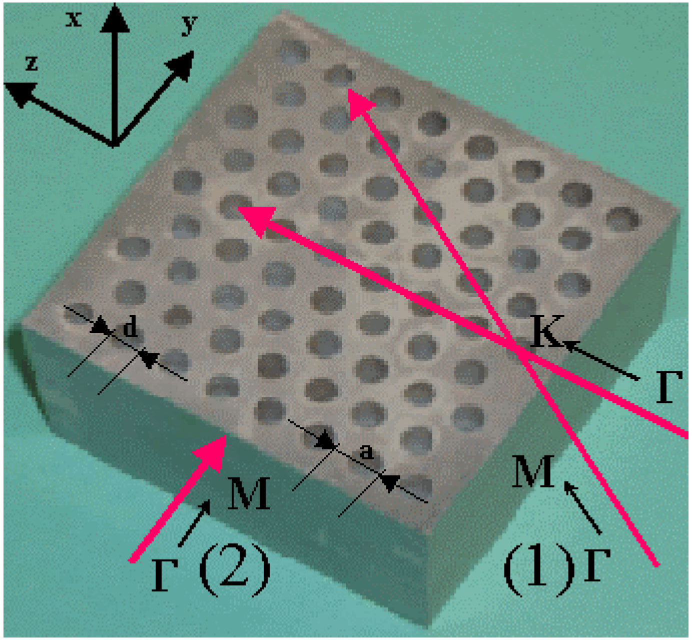


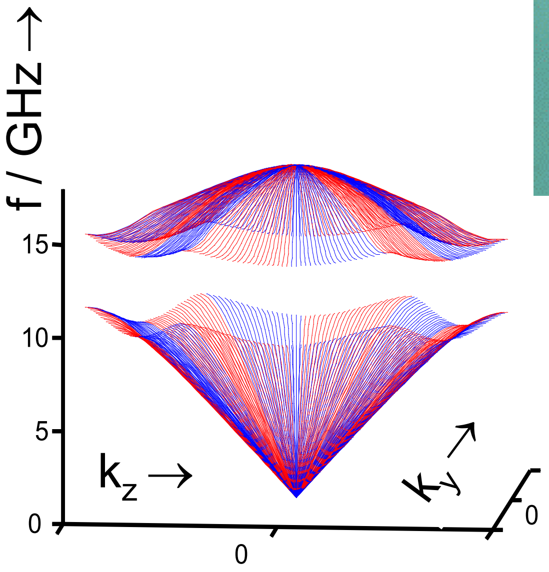


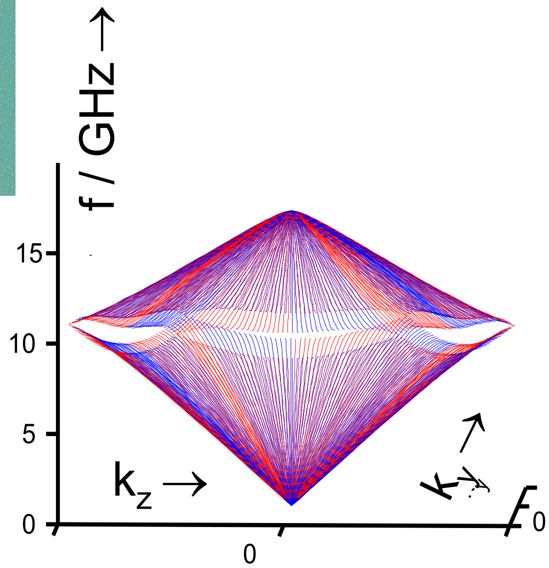
meas. group delay

$$t_g = -\frac{\mathrm{d}\varphi}{\mathrm{d}\omega} = L\frac{\mathrm{d}k}{\mathrm{d}\omega}$$

2D Photonic Crystal with Air Cylinders — Complete Bandstructure







TE

TM

Outline

- Fundamentals of photonic crystals
  Maxwell’s equations and the scaling law
  Bandstructure of photonic crystals
- Applications and technology
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  Slowing down light
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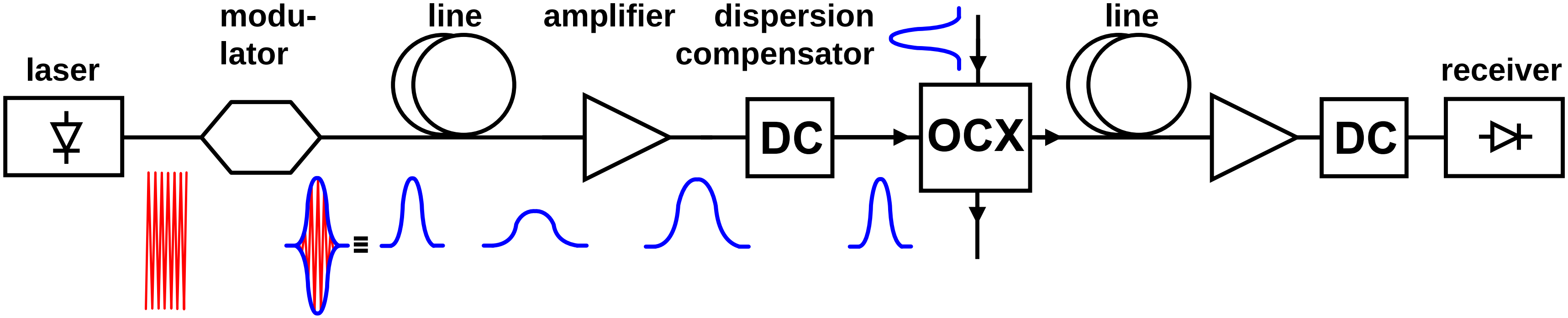
High-Bitrate Optical Transmission and Signal Processing



- *Laser:* Optical carrier at λ = 1.55 µm
- *Modulator:* Transfers signals on optical carrier (10 Gbit/s …100 Gbit/s)
- *Line:* Attenuation and positive dispersion
  dispersion (= frequency-dependent group velocity) → impulse broadening
- *Amplifier*
- *Dispersion compensator* (*DC*)*:* Negative dispersion → impulse shortening
- *Optical cross-connect* (*OCX*)*:* Aggregation & grooming (requires delay), switching

Goals:

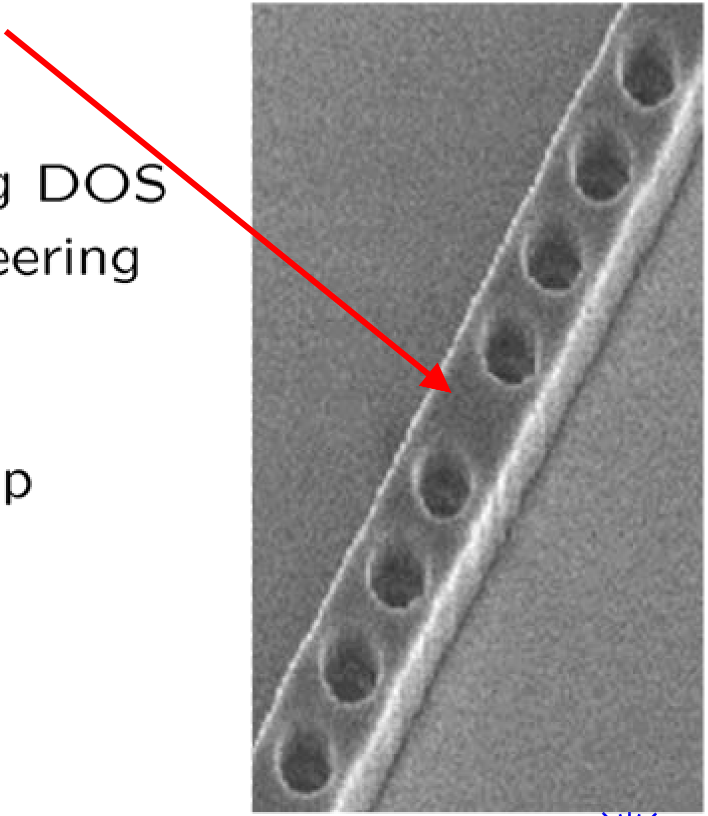
- ➢ *Modulator*, *DC*, *delay* with high functionality and low price
- ➢ Silicon chips fabricated with CMOS technology
- ➢ Possible combination of optics and electronics

In this Scenario: Applications for Photonic Crystals

PC without defects (“intrinsic crystal”):

- ○ Bandgap material with limited use (no “conductivity”):
- ○ Reflector, AR coating, filter
- ○ Dispersion, superprism

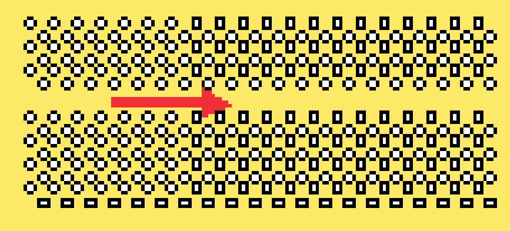
What are defects in photonic crystals?



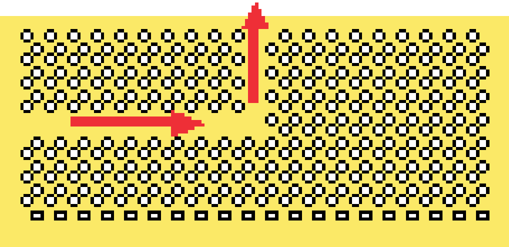
PC with defects (“impurities, doping”):

- ○ Waveguides, bends, cavities, shaping DOS
- ● Group velocity and dispersion engineering
- ● Slow and fast light
- ○ Nonlinear applications:
  - ○ Bistable resonator, optical flip-flop
  - ○ Optical isolator
  - ● Tunable dispersion compensator
  - ● Tunable delay line
  - ● Electro-optic modulator

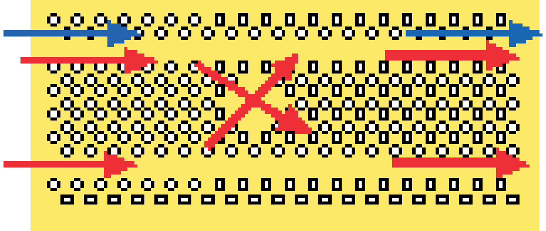
2D Photonic Crystals with Defects



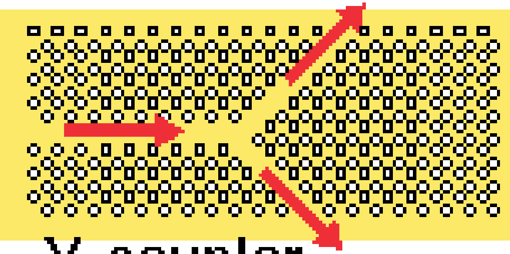
guide



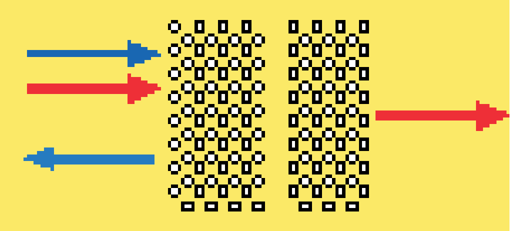
sharp bend



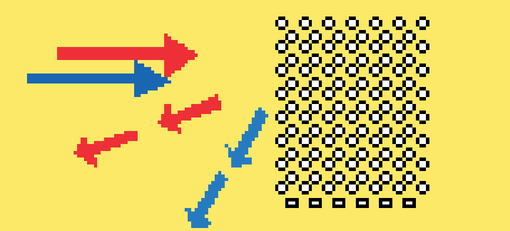
“add/drop”



Y-coupler

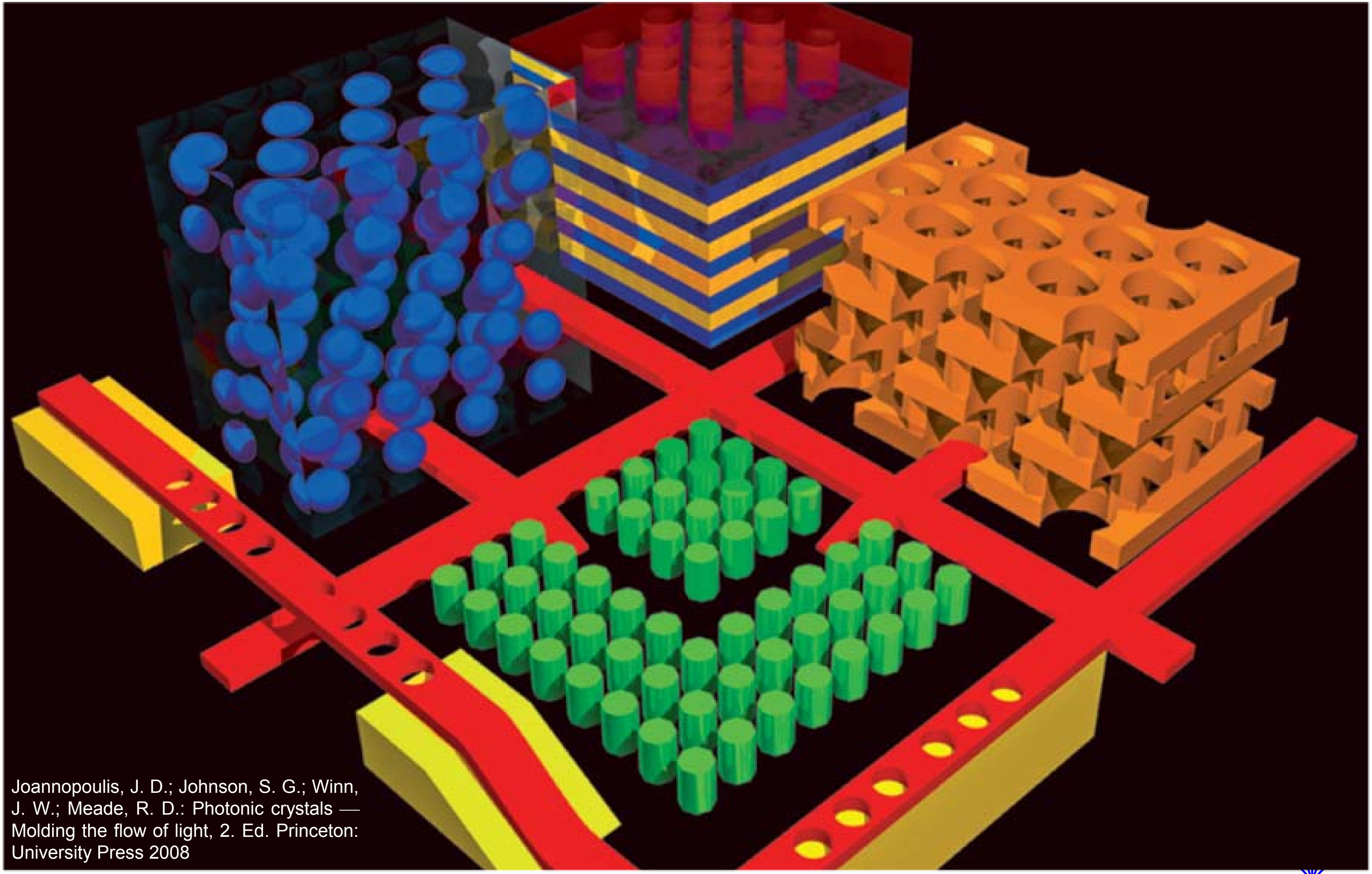


filter



dispersive element

Vision of Photonic Crystals: Guide, Filter, Delay, NL Processing

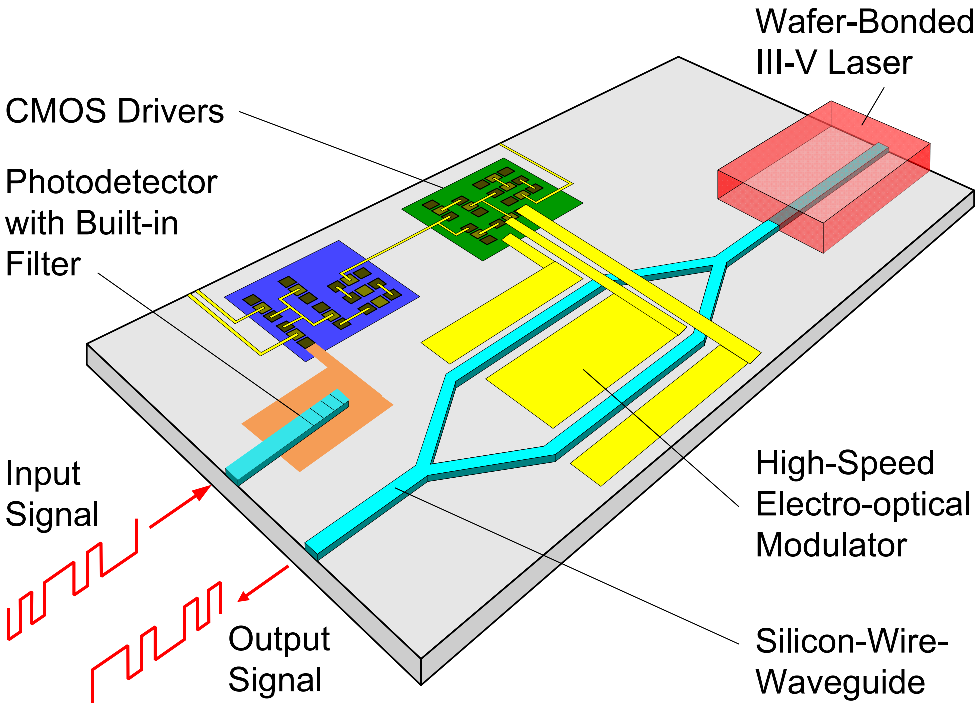


Joannopoulis, J. D.; Johnson, S. G.; Winn, J. W.; Meade, R. D.: Photonic crystals — Molding the flow of light, 2. Ed. Princeton: University Press 2008

Photonic Crystals and Silicon Photonics

Silicon-on-insulator (SOI) systems promise:

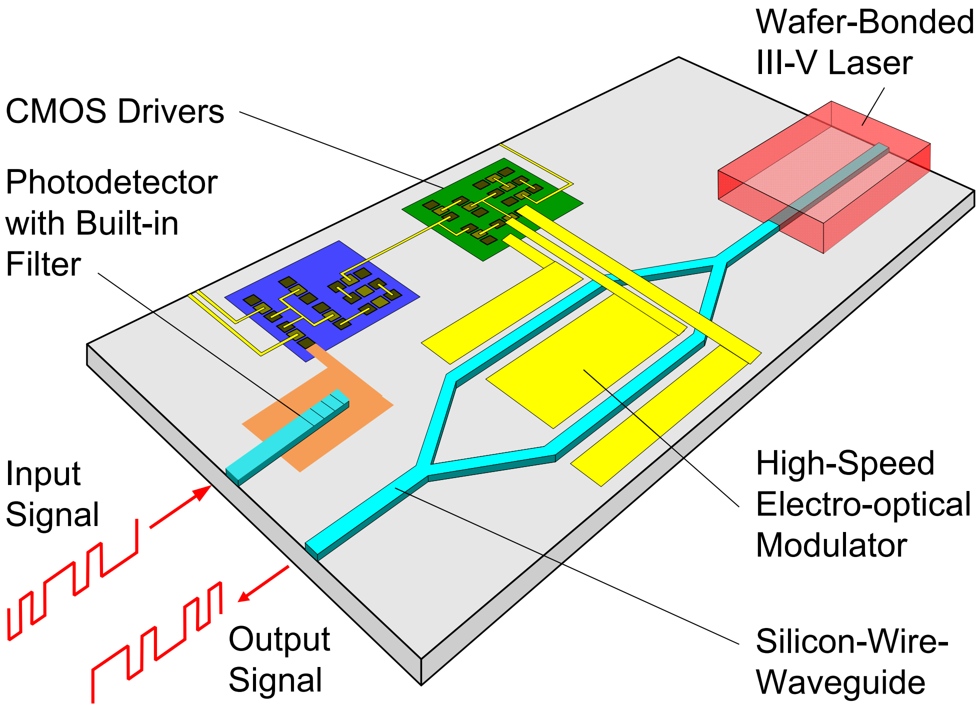
- Full integration of electronic and optical components
- Low-cost CMOS-based technology
- Fabrication of ultra-compact and ultra-fast optical devices
- Electronically powered light sources so far only in hybrid integration
- Fabrication of active and passive optical components.



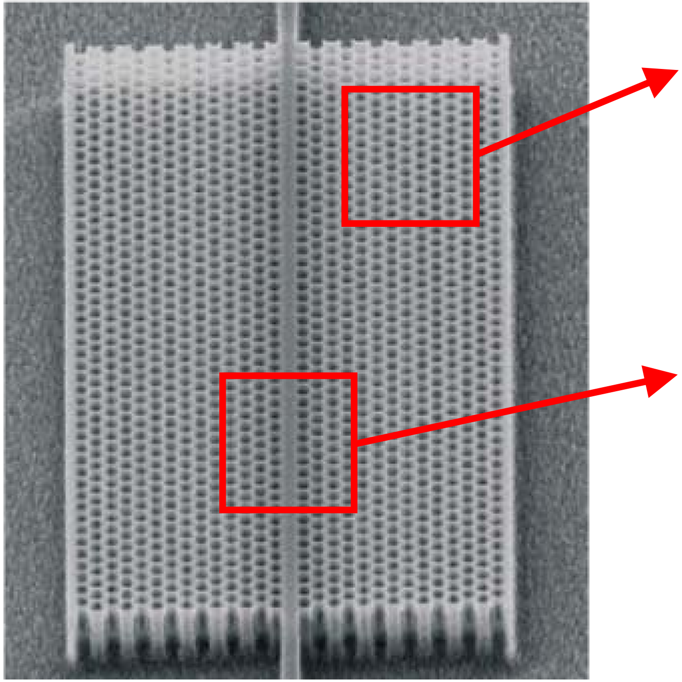
Silicon-Organic Hybrid Systems: Improvements over SOI

Silicon-organic hybrid (SOH) systems promise in addition:

- Wide choice of low-index materials (backend processing)
- Large $\chi^{(2)}$-nonlinearity (strained silicon not fit for standard CMOS)
- Large $\chi^{(3)}$-nonlinearity
- No impairment by TPA-induced FCA → large intensities
- Emphasis in this talk on tunable dispersion and SOH modulators



Photonic Crystals in SOI



Dielectric transparent material (silicon) with periodic structure

→ Bragg reflexion, if $\lambda_e / 2 \approx a$

→ No light propagation for certain frequencies
$\rightarrow$ photonic bandgap

Introducing defects (impurities, doping)

→ Light propagation along defects

→ Slow group velocity v_g
(slow light) and large dispersion $v_g(f)$

→ Designing $v_g(f)$ by structural changes

Applications for tailored dispersion:

- Large negative chromatic dispersion, e.g., for dispersion compensation
- Slow light for optical delay, e.g., for aggregation in OXC
- Slow light for increased light-matter interaction, e.g., for modulation

Fabrication Technologies

Structure roughness: Main source of losses

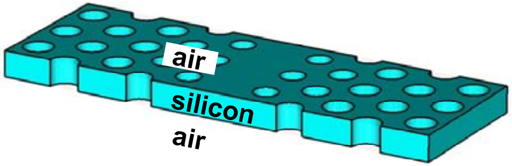
- Losses increase for small group velocities v_g
- Losses limit the lowest usable v_g

Numerical investigations of roughness loss

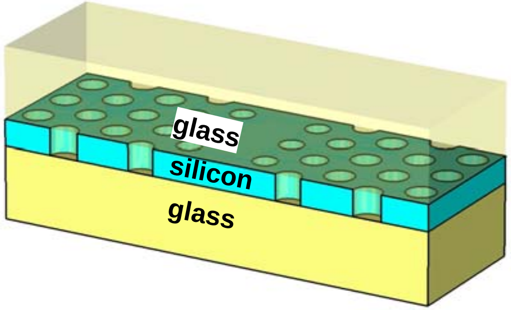
- Air hole positions regular
- Radii with normal distribution, $\sigma_r = 5$ nm

Design goal: Minimum loss

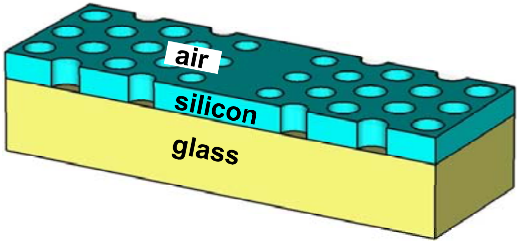
Comparison of different structures: Broadband slow light with $v_g / c = 4$ %



symmetric in air
membrane structure



symmetric in glass
buried structure



unsymmetric
silicon-on-insulator (**SOI**)

Variation of defect (WG) width, mode number and height of silicon layer (220 nm)

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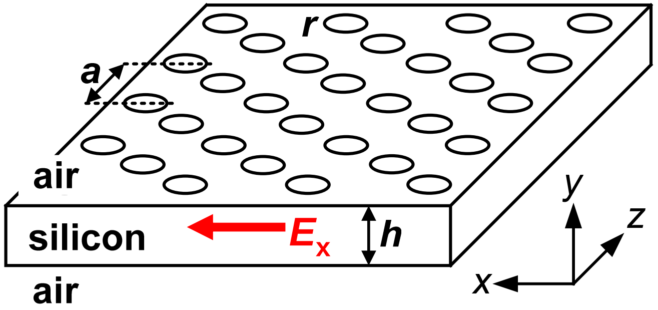
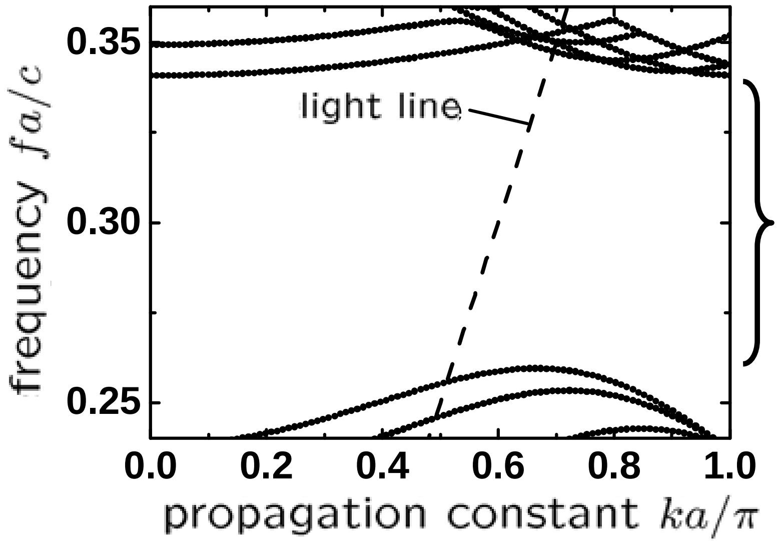
Slow Light in Photonic a Crystal (1)



TE polarisation: Dominant electric field E_x

Parameter

h	Waveguide height	~ 220 nm
r	Radii of air holes	~ 120 nm
a	Lattice constant of PC	~ 400 nm

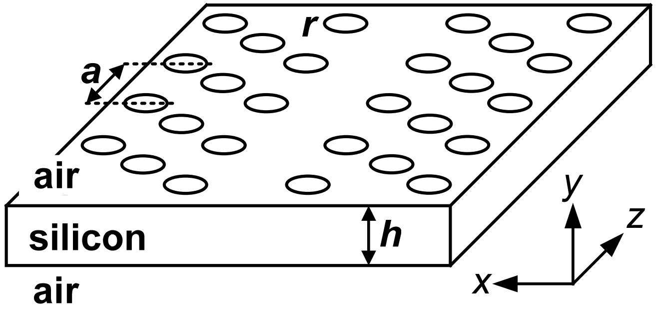


Without crystal defects:
Photonic bandgap

c Vacuum speed of light

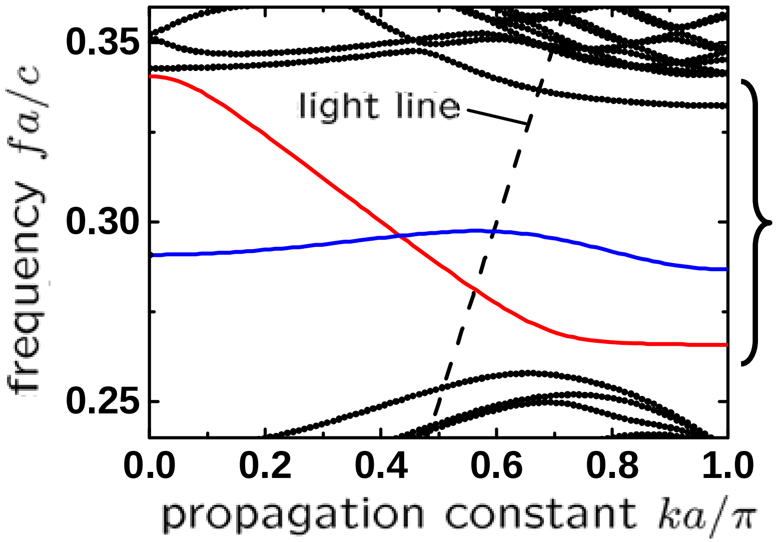
k Propagation constant in *z*-direction

Slow Light in Photonic a Crystal (2)



Parameter

h	Waveguide height	~ 220 nm
r	Radii of air holes	~ 120 nm
a	Lattice constant of PC	~ 400 nm



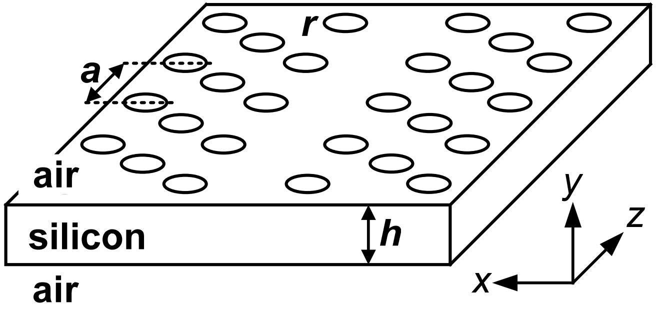
With crystal defects: Waveguiding in photonic bandgap

Light propagation $\exp(\mathrm{j}\omega t - \mathrm{j}kz)$

c Vacuum speed of light

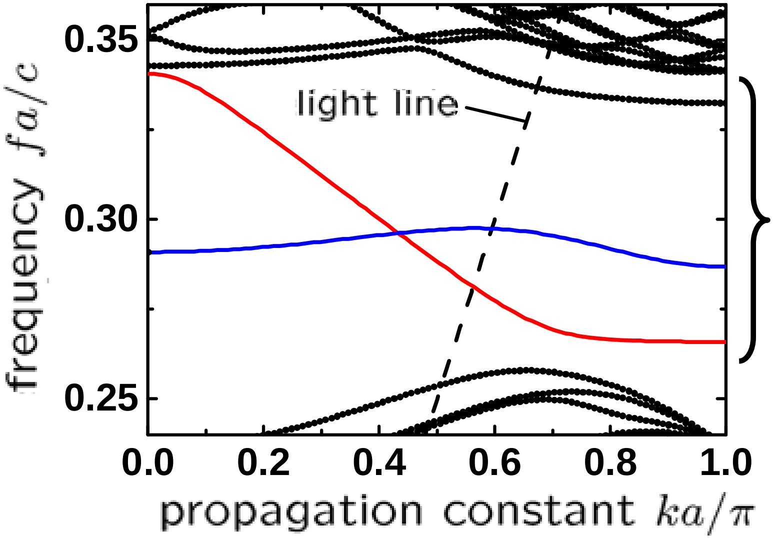
k Propagation constant in *z*-direction

Slow Light in Photonic a Crystal (3)



Parameter

h	Waveguide height	~ 220 nm
r	Radii of air holes	~ 120 nm
a	Lattice constant of PC	~ 400 nm

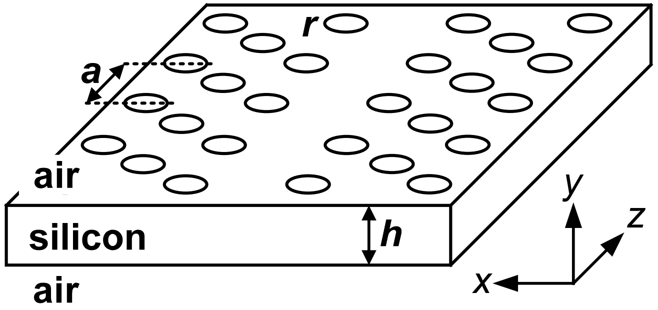


With crystal defects: Waveguiding in photonic bandgap

Light line: Describes propagation in homogeneous cladding (here: air)

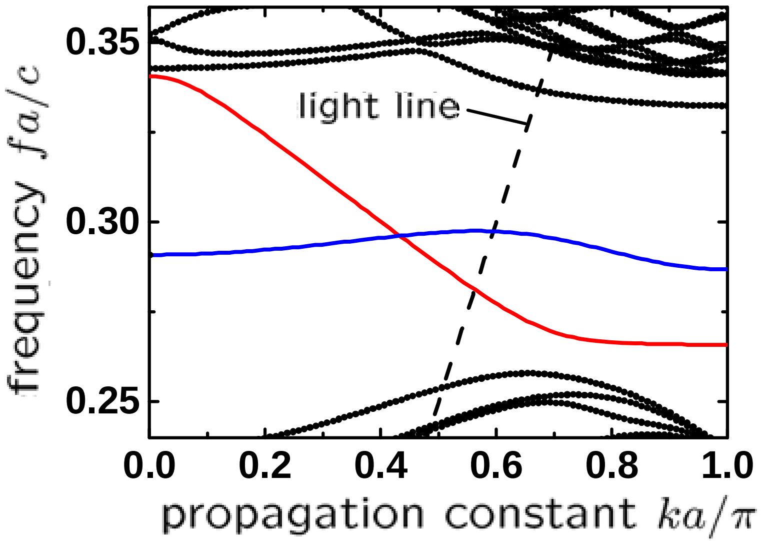
- Below LL: Guiding of modes in silicon layer
- Above LL: Radiation (leaky waves)

Slow Light in Photonic a Crystal (4)



Parameter

h	Waveguide height	~ 220 nm
r	Radii of air holes	~ 120 nm
a	Lattice constant of PC	~ 400 nm



$$\boxed{v_{\mathrm{g}} = 2\pi \frac{\mathrm{d}\, f}{\mathrm{d}\, k}}$$

***v*_g** Group velocity

$$\boxed{t_{\mathrm{g}} = L / v_{\mathrm{g}}}$$

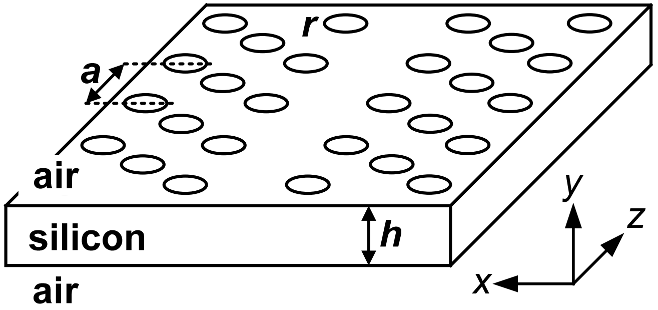
***t*_g** Group delay

$$\boxed{\begin{aligned} C &= -\frac{f^2}{2\pi c} \frac{\mathrm{d}^2 k}{\mathrm{d}\, f^2} \\ &= -\frac{f^2}{Lc} \frac{\mathrm{d}\, t_{\mathrm{g}}}{\mathrm{d}\, f} \end{aligned}}$$

C Chromatic dispersion

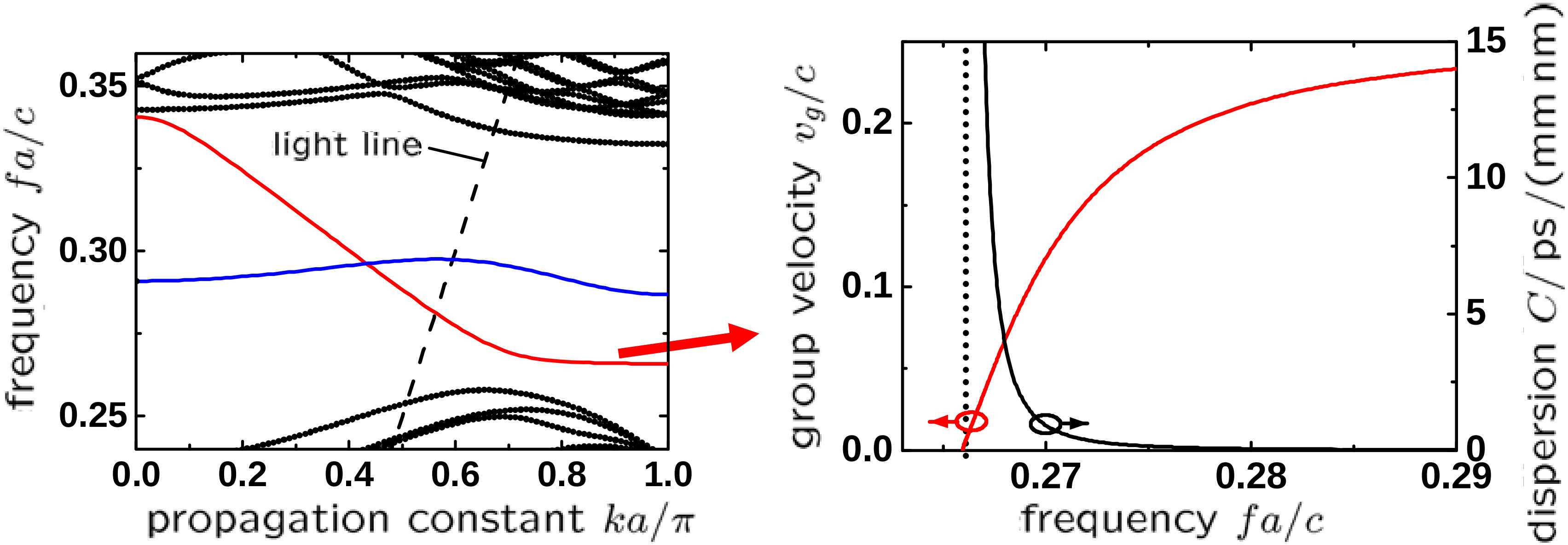
***C* = 1 ps / (mm nm):** Impulse with bandwidth 1 nm (125 GHz) widens during propagation over a distance of 1 mm by 1 ps.

Slow Light in Photonic a Crystal (5)



Parameter

h	Waveguide height	~ 220 nm
r	Radii of air holes	~ 120 nm
a	Lattice constant of PC	~ 400 nm

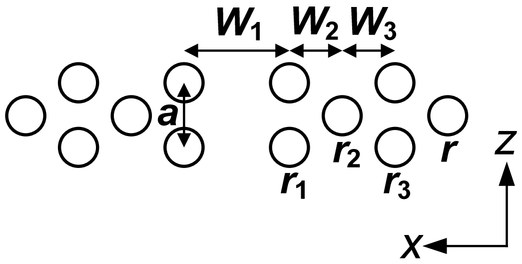


→ v_g approaches zero at Brillouin zone boundary at $k = \pi / a$

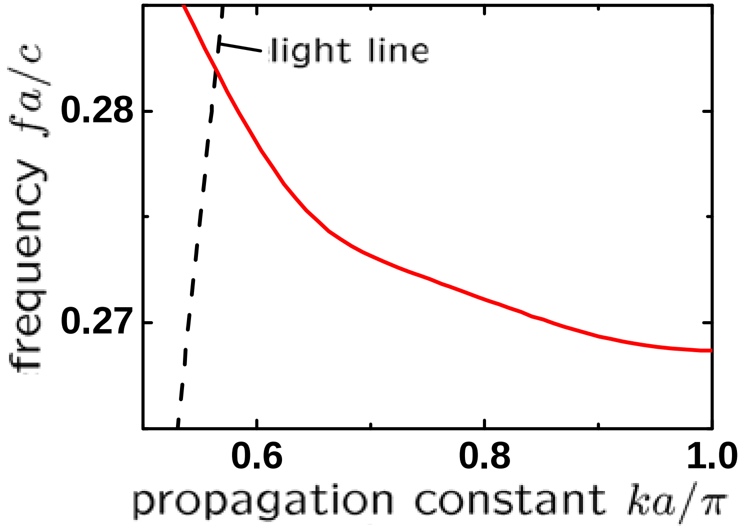
→ C very large because v_g changes strongly with f

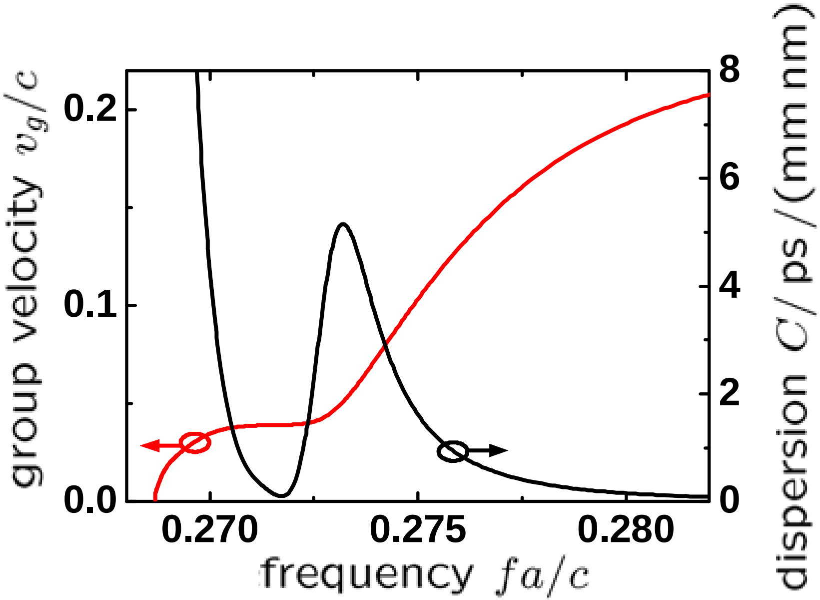
Broadband Slow Light in a Photonic Crystal

Optimizing dispersion properties:
Systematic variation of structural parameters



- Hole radii not too small ($r > 100$ nm)
- Wall thickness between holes not too small (> 100 nm)





→ Group velocity only 3.9 % of vacuum speed of light in a bandwidth of 1.9 THz

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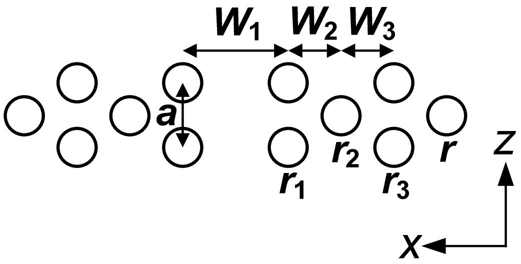
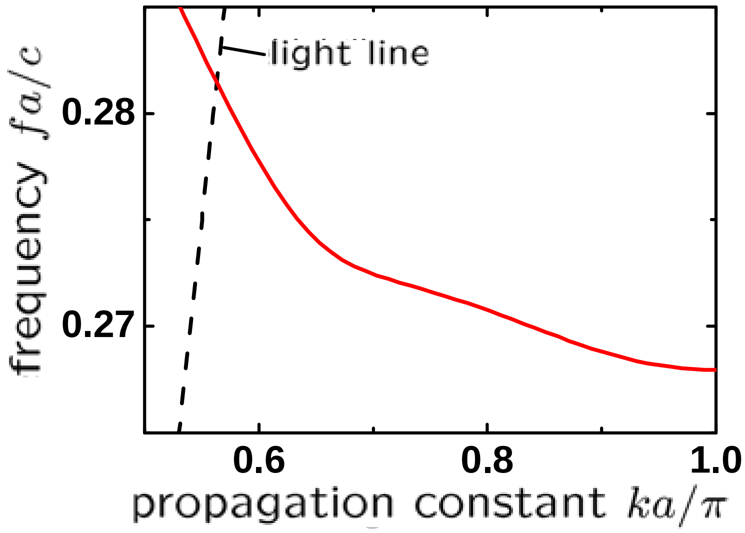
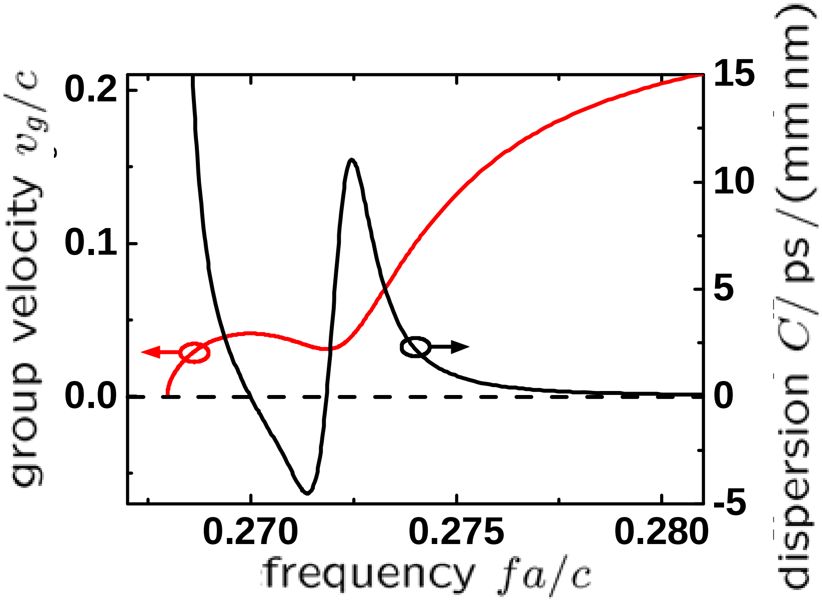
Negative Chromatic Dispersion

Optimizing dispersion properties:
Systematic variation of structural parameters



- Hole radii not too small (r > 100 nm)
- Wall thickness between holes not too small (> 100 nm)





→ Negative chromatic dispersion of –4.5 ps / (mm nm) and regions with linear dispersion

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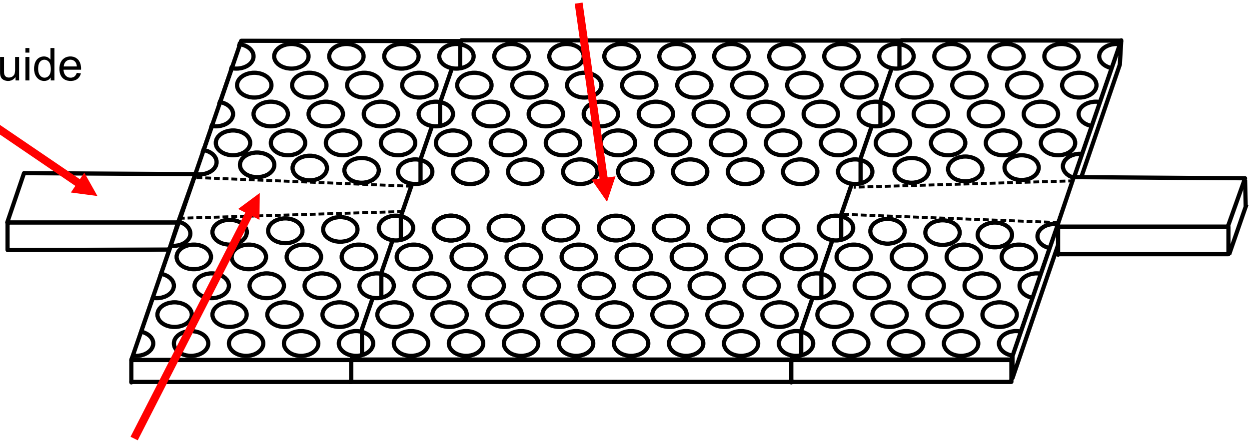
Improved Coupling with Taper (1)

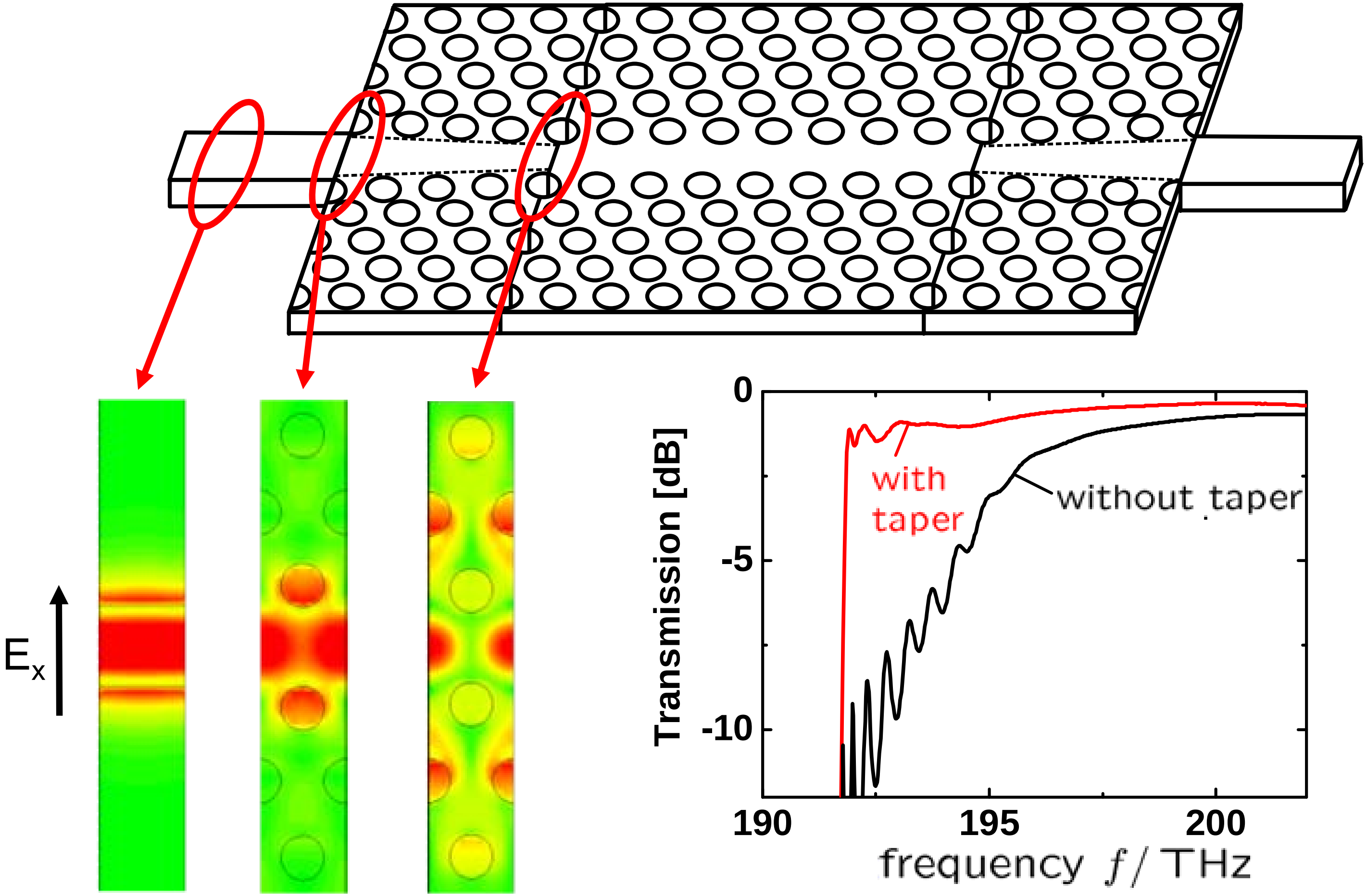


slow-light waveguide

strip waveguide

Taper: Slight continuous structural change

Improved Coupling with Taper (2)



→ Loss < 0.5 dB / transition

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Tunable Dispersion Compensator (1)

Idea: Linear falling and linear rising dispersion $C(f)$ in series

$$C_{ges} \times L_{ges} = C_1(f) \times L_1 + C_2(f) \times L_2$$

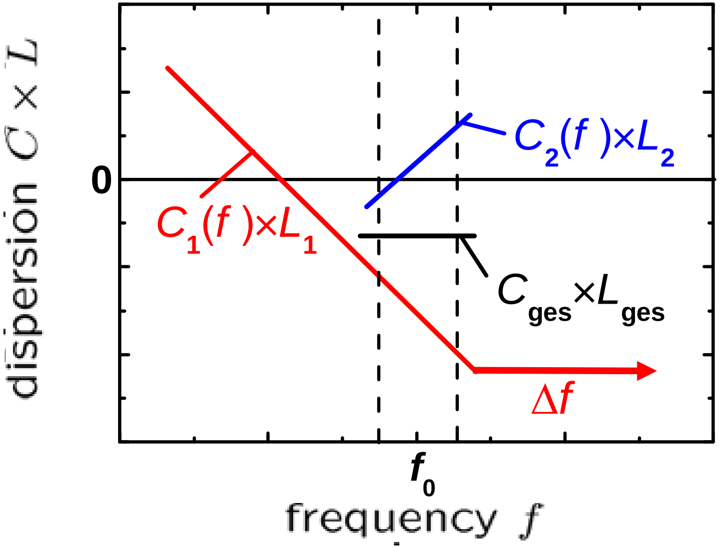
→ Flattened total dispersion $C_{ges} \times L_{ges}$

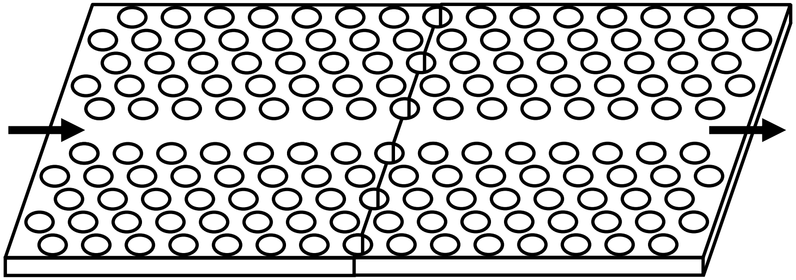
Tuning of section 1 (e. g., by cooling or carrier injection):

→ Refractive index change Δn

→ Shift by Δf

→ Total dispersion $C_{ges} \times L_{ges}$ changes





Section 1: C_1, L_1 Section 2: C_2, L_2

Tunable Dispersion Compensator (2)

Idea: Linear falling and linear rising dispersion $C(f)$ in series

$$C_{ges} \times L_{ges} = C_1(f) \times L_1 + C_2(f) \times L_2$$

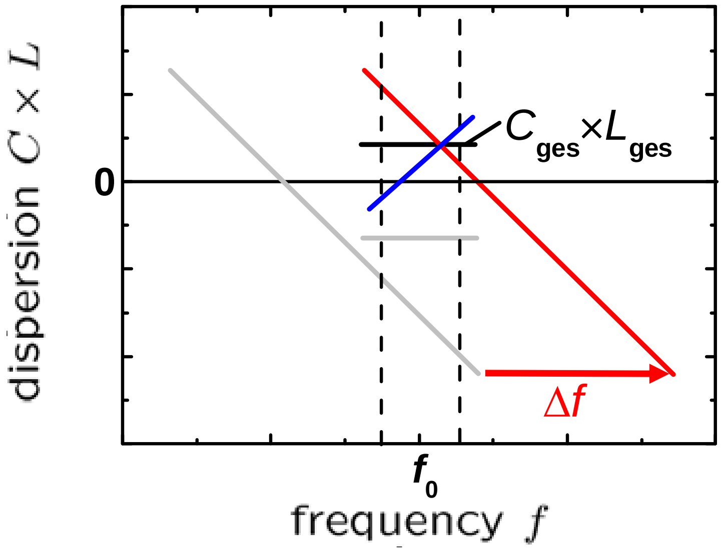
→ Flattened total dispersion $C_{ges} \times L_{ges}$

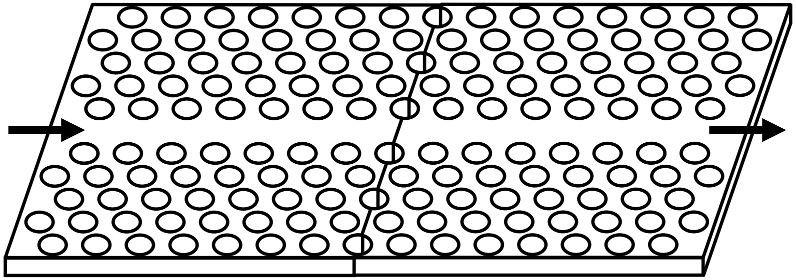
Tuning of section 1 (e. g., by cooling or carrier injection):

→ Refractive index change Δn

→ Shift by Δf

→ Total dispersion $C_{ges} \times L_{ges}$ changes





Section 1: C_1, L_1 Section 2: C_2, L_2

Tunable Dispersion Compensator (3)

Idea: Linear falling and linear rising dispersion $C(f)$ in series

$$C_{\text{ges}} \times L_{\text{ges}} = C_1(f) \times L_1 + C_2(f) \times L_2$$

→ Flattened total dispersion $C_{\text{ges}} \times L_{\text{ges}}$

Tuning of section 1 (e. g., by cooling or carrier injection):

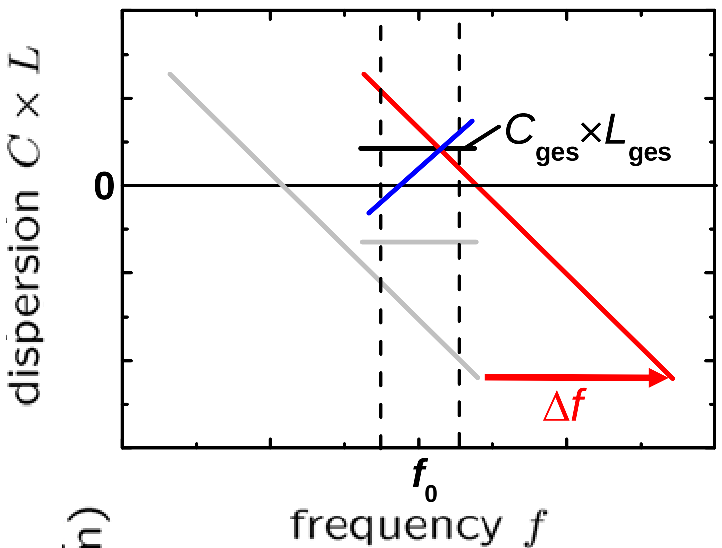
→ Refractive index change Δn

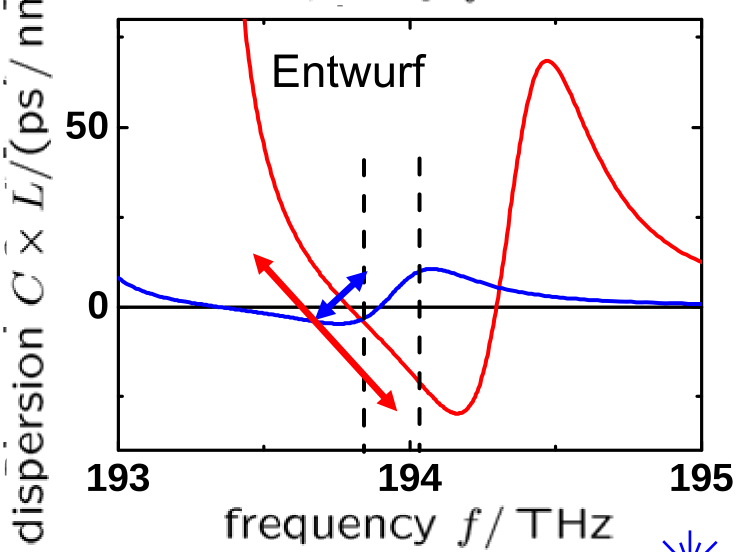
→ Shift by Δf

→ Total dispersion $C_{\text{ges}} \times L_{\text{ges}}$ changes

Design: Based on waveguide with negative dispersion minimum

→ Tuning range (–19 … +7) ps / (mm nm) in an optical bandwidth of 125 GHz.





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Tunable Delay Line (1)

Idea: Linear falling and linear rising group delay $t_g(f)$ in series

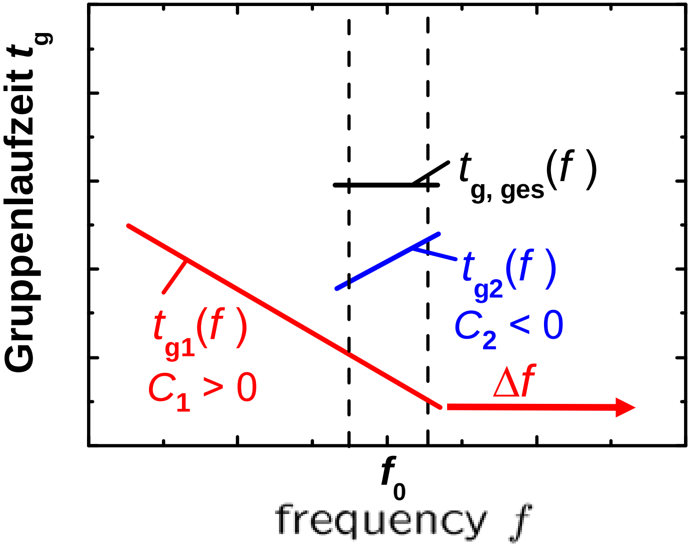
$$t_{g,\,ges} = t_{g1}(f) + t_{g2}(f)$$

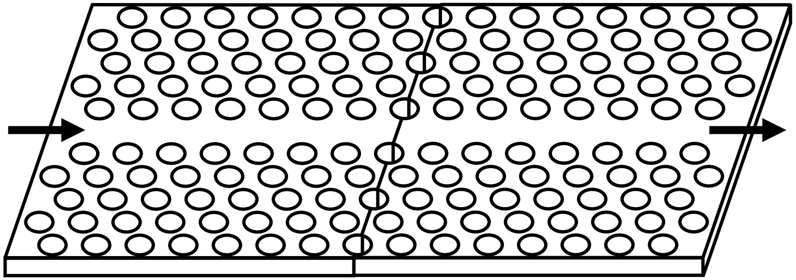
→ Constant total group delay $t_{g,\,ges}$

Linear t_g-depencence by constant positive or negative dispersion C:

$$C \propto -\mathrm{d}t_g / \mathrm{d}f$$

Tuning of section 1





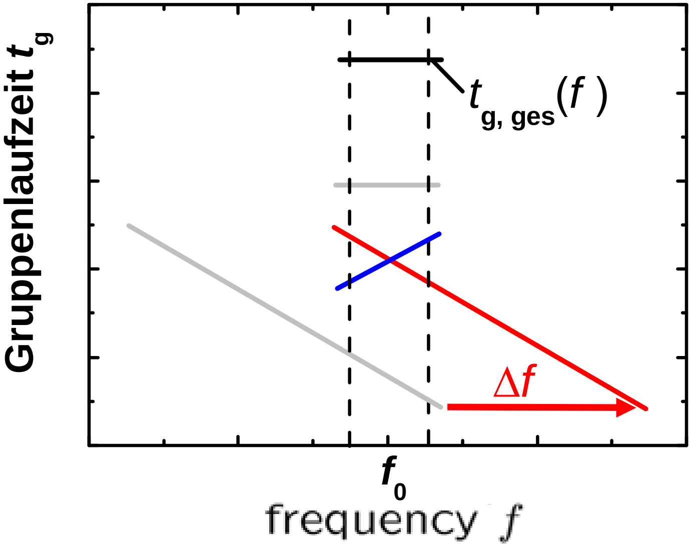
Section 1: t_{g1} Section 2: t_{g2}

Tunable Delay Line (2)

Idea: Linear falling and linear rising group delay $t_g(f)$ in series

$$t_{g,\,ges} = t_{g1}(f) + t_{g2}(f)$$

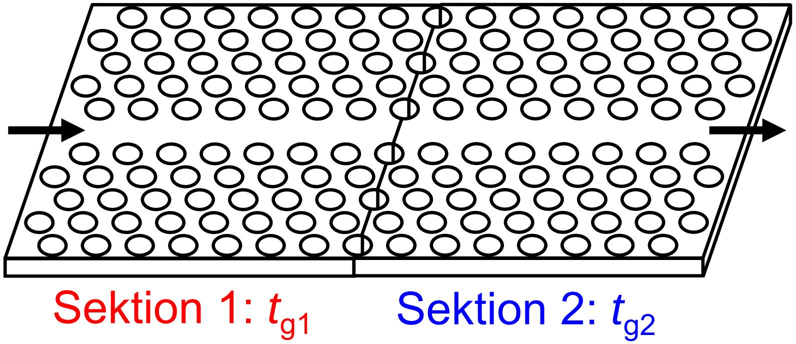
→ Constant total group delay $t_{g,\,ges}$



Linear t_g-depencence by constant positive or negative dispersion C:

$$C \propto -\mathrm{d}t_g / \mathrm{d}f$$

Tuning of section 1



Tunable Delay Line (3)

Idea: Linear falling and linear rising group delay $t_g(f)$ in series

$$t_{g,\,ges} = t_{g1}(f) + t_{g2}(f)$$

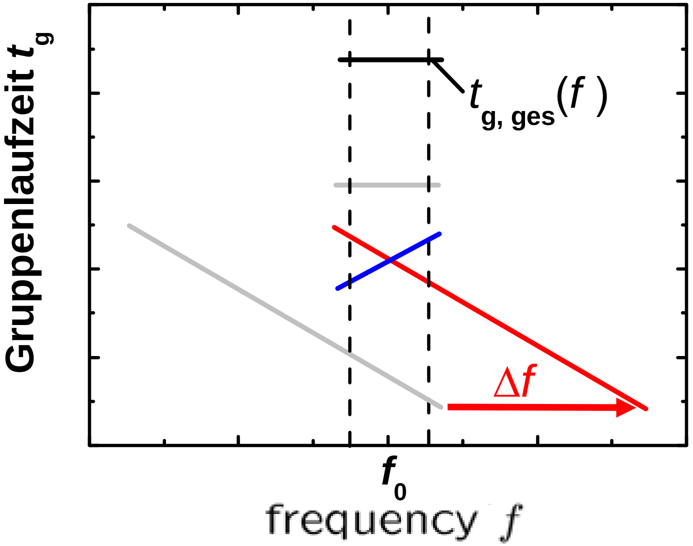
→ Constant total group delay $t_{g,\,ges}$

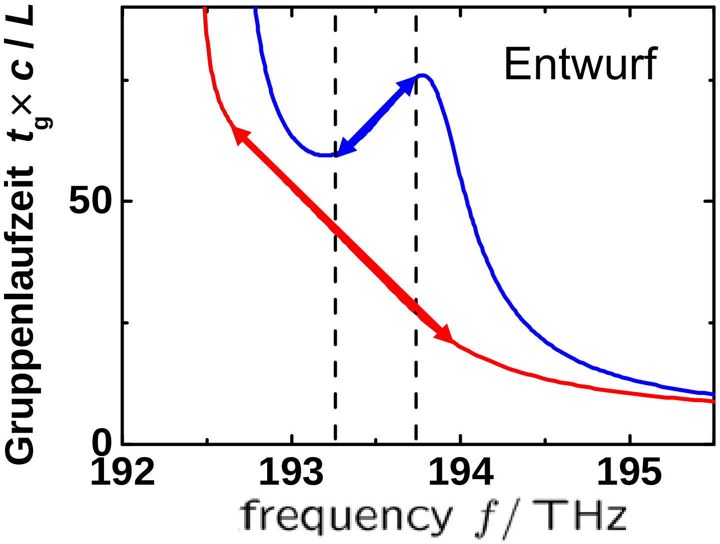
Linear t_g-depencence by constant positive or negative dispersion C:

$$C \propto -\mathrm{d}t_g/\mathrm{d}f$$

Tuning of section 1
→ Total group delay $t_{g,\,tot}$ changes.

Design:
→ Tuning range 42 ps (1.7 bit at 40 Gbit/s)
in an optical bandwidth of 125 GHz
for a length of 1 mm.





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Silicon-on-Insulator and Silicon-Organic Hybrid Systems

Silicon-on-insulator (SOI) offers:

- Mature silicon technology, with 35 nm and higher-resolution lithography
- Compatibility with CMOS electronics
- Foundry service → low cost
- Ultra-compactness due to high confinement of optical modes

Silicon-organic hybrid systems (SOH) combine the best of two worlds:

Strong electro-optic effect

Material	**λ [nm]**	**EO coefficient**
DAST	1535	r_{11} = 50 pm/V
EO polymers	1300	r_{33} = 90 – 133 pm/V
$LiNbO_3$	1500	$r_{33} \approx r_{42}$ = 30 pm/V

Mutter *et al.*, Cleo Europe 2007, paper CE-1449

Chen *et al.*, Appl. Phys. Lett. 70, 1997, 3335-3337

Kerr-effect without TPA

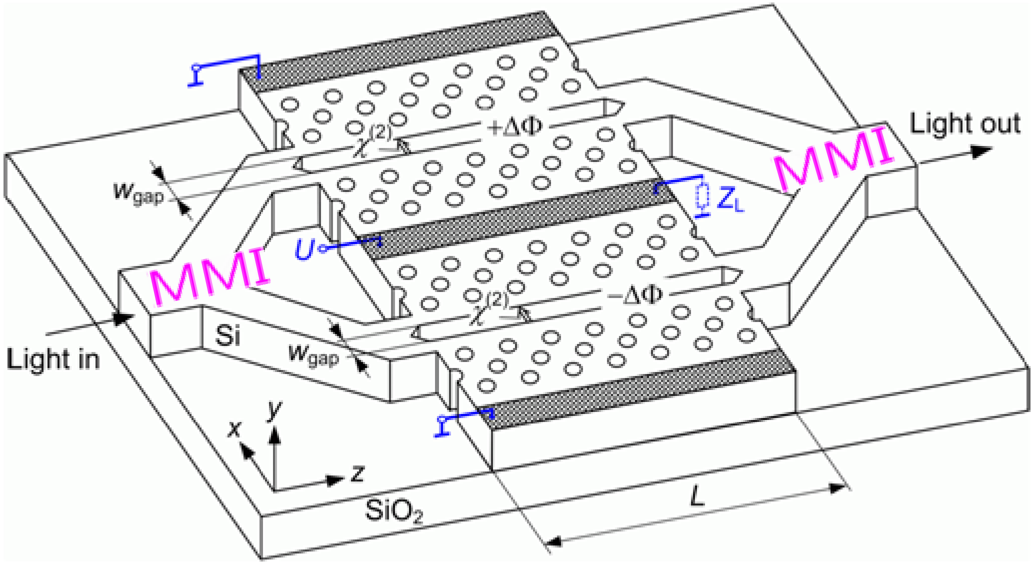
Material	**λ [nm]**	**n_2 [m^2/W]**	**FOM_{TPA}**
DDMEBT	1500	2×10^{-17}	est. > 5
PTS (PDA)	1600	2.2×10^{-16}	> 27
Si	1500	4.5×10^{-18}	0.3

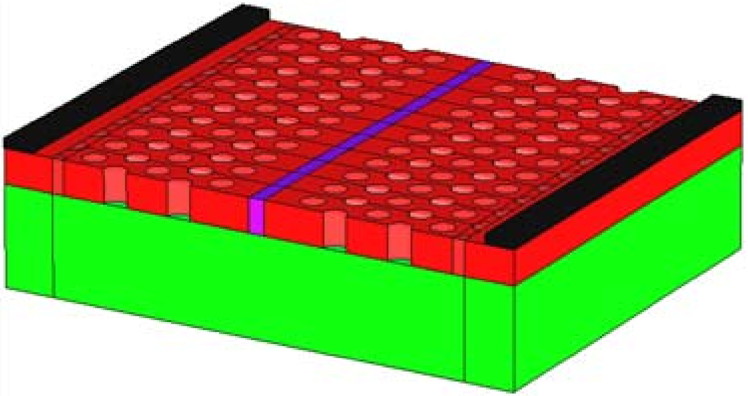
Koos, C.; Jacome, L.; Poulton, C.; Leuthold, J.; Freude, W.: Nonlinear silicon-on-insulator waveguides for all-optical signal processing. Opt. Express 15 (2007) 5976–5990, May 2007

FOM relates nonlinear phase shift to associated intensity change:

$$\mathrm{FOM}_{\mathrm{TPA}} = \frac{1}{2\pi}\,\frac{\Re\{\gamma\}}{2\,\mathrm{Im}\{\gamma\}} = \frac{n_2}{\alpha_2 \lambda}$$

SOH MZ-Modulator with Slow-Light Photonic Crystal Slot WG





Phase modulator (PM)

$r_{33} \approx 80\,\text{pm/V}$

U_π voltage:

$$U_\pi \propto \frac{W_\text{gap}}{r_{33}} \frac{1}{\Gamma L} \propto \frac{W_\text{gap}}{r_{33}} \frac{v_\text{g, opt}}{L}, \quad \Gamma = \frac{\int_\text{gap} \frac{n}{Z_0} |\hat{E}_x|^2 \,\mathrm{d}V}{\int a\, \Re(\hat{\mathbf{E}} \times \hat{\mathbf{H}}^*) \cdot \mathbf{e}_z \,\mathrm{d}A} \propto \frac{1}{v_\text{g, opt}}$$

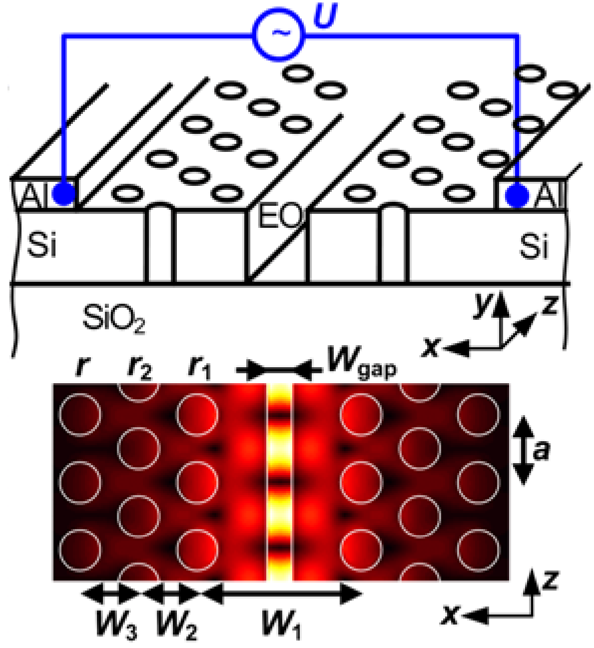
Modulation BW: $f_\text{3 dB}^{-1} = f_\text{walk-off}^{-1} + \cancel{f_{RC}^{-1}} + \cancel{f_\text{material}^{-1}}, \quad v_\text{g, opt} \ll v_\text{g, el}$

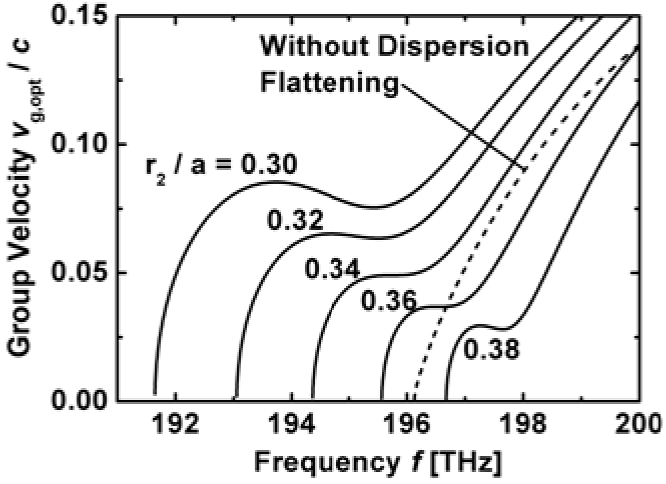
$$f_\text{3 dB} \approx \frac{0.5}{t_\text{g, opt}} = 0.5 \frac{v_\text{g, opt}}{L} \qquad \left(\frac{0.5}{f} \geq t_\text{g, opt} \right)$$

J.-M. Brosi, C. Koos, L. C. Andreani, M. Waldow, J. Leuthold, W. Freude: High-speed low-voltage electro-optic modulator with a polymer-infiltrated silicon photonic crystal waveguide, Opt. Express, vol. 16, pp. 4177–4191, March 2008

Half mod. period ≥ opt. transit

SOH PM with Slow-Light Slotted Photonic Crystal WG





Structure of SOH phase modulator:

- Photonic crystal line-defect WG $\{W1.4, W1.25\} \widehat{=} W_1$ with slot W_{gap}
- Slot filled with poled electro-optic (EO) organic mat. ($\chi^{(2)}$-nonlinearity)
- E_x strongly confined to slot
- U drops essentially across slot

Two types of photonic crystals:

- Standard $W1.4$, large disp. (– – –)
- Optimized $W1.25$, flattened disp.

Tailoring a photonic crystal for

- slow-wave propagation (4 % of c) by
- adjusting defect width W_1, and for
- zero dispersion (BW 1 . . . 2 THz) by
- adjusting hole radii, e. g., r_2

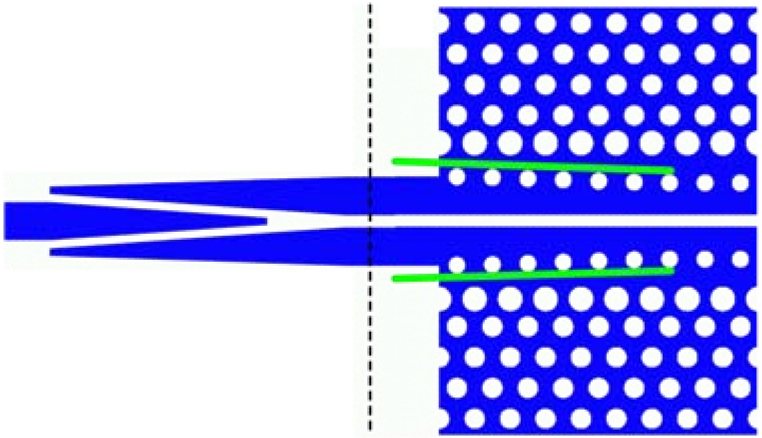
SOH MZ-Modulator: Expected Data

Characteristic data for SOH slow-wave slot PC WG modulator:

- Fixed modulation amplitude $\hat{U} = U_\pi/4 = 1\,\mathrm{V}$, $U_\pi \propto \frac{W_\mathrm{gap}}{r_{33}} \frac{v_\mathrm{g,\,opt}}{L}$
- $v_\mathrm{g,\,opt}$ chosen, modulator length L adapted $U_\pi L < 0.04\,\mathrm{Vcm}$
- Modulation BW $f_{3\,\mathrm{dB}} \approx 0.5 \frac{v_\mathrm{g,\,opt}}{L}$ depends weakly on $v_\mathrm{g,\,opt}$

Structure	r_2 / a	f_o (THz)	$v_{g,opt}/c$	Γ	L (µm)	f_{3dB} (GHz)
W1.4 dispersion large	0.3	196.4	2.4%	4.8	36	103
		196.6	3.4%	3.2	54	97
		196.9	4.8%	2.2	80	90
		196.2	6.4%	1.5	113	83
		197.7	8.2%	1.1	155	76
W1.25 dispersion flattened	0.38	197.5	3.2%	3.1	57	87
	0.36	**196.5**	**4.0%**	**2.2**	**80**	**78**
	0.34	195.8	5.2%	1.6	111	71
	0.32	195.2	6.6%	1.1	158	61
	0.30	194.6	7.9%	0.8	215	53

Taper for Broadband Low Dispersion Slow Light PC Slot-WG



PC taper in transition from strip-WG → slot-WG → PC WG improves transmission significantly.

Expected data:

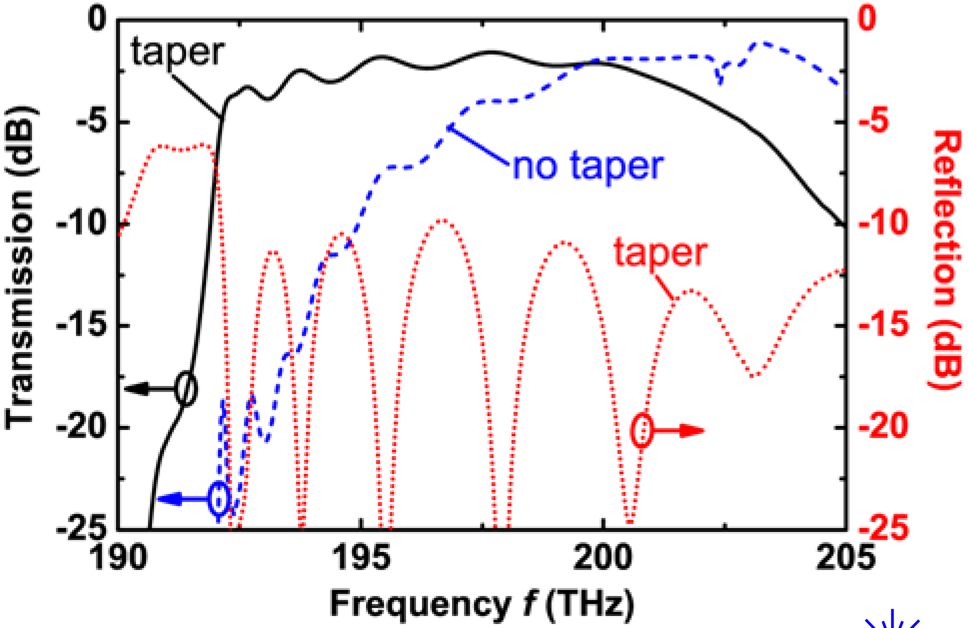
Transmission / reflection for transitions slot-WG → PC-WG → slot-WG, with / without PC taper. **With taper:**

$$\text{transmission} > -\ 4\,\text{dB}$$

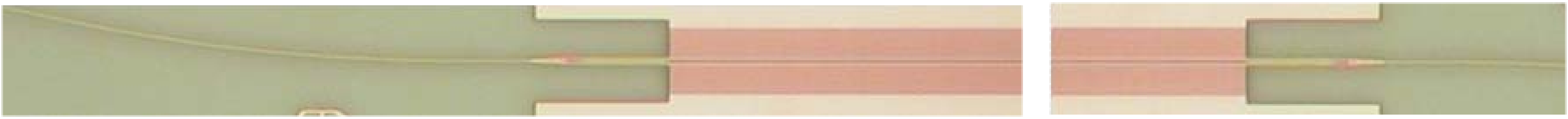
$$\text{reflection} < -10\,\text{dB}$$

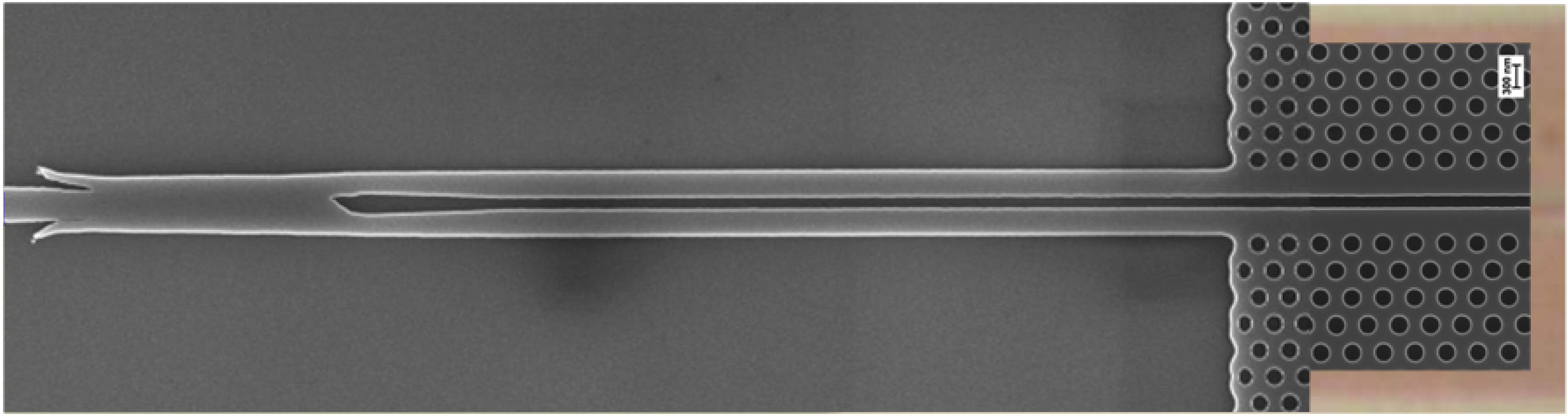
$$W_{\text{strip}} = 440\,\text{nm}$$

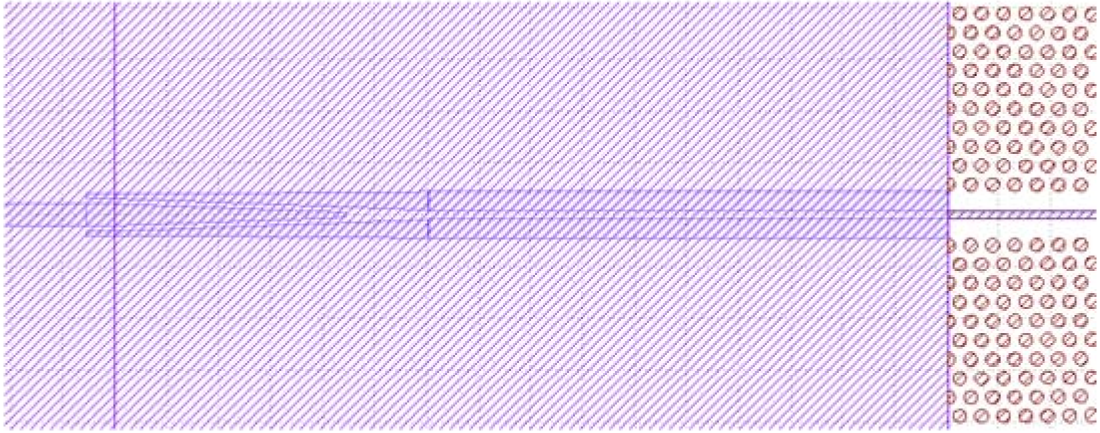
$$W_{\text{gap}} = 150\,\text{nm}$$



Fabrication of SOH Phase (and MZ) Modulator with PC Taper

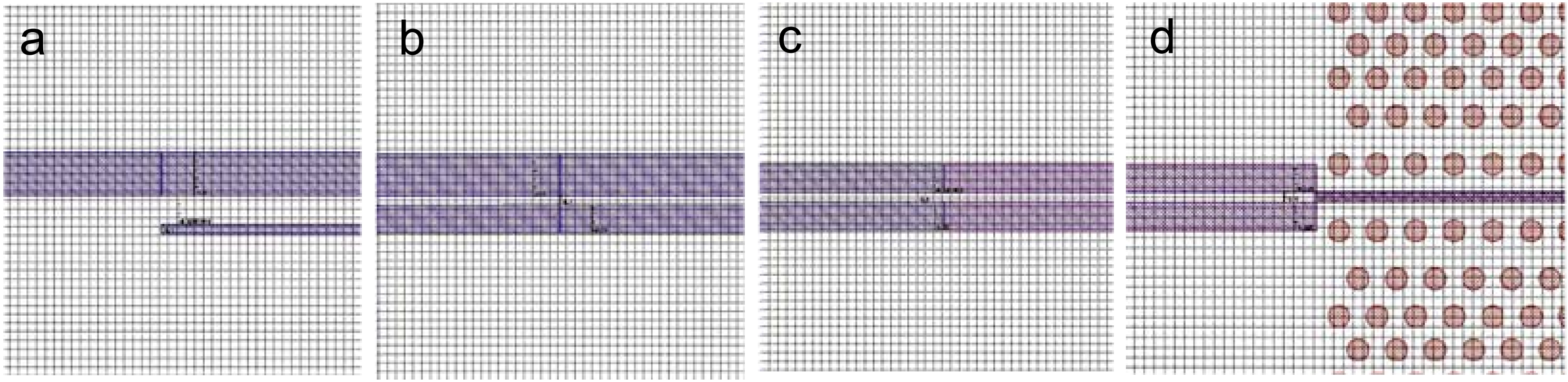






← Mask layout

Rib-to-Slot Transition



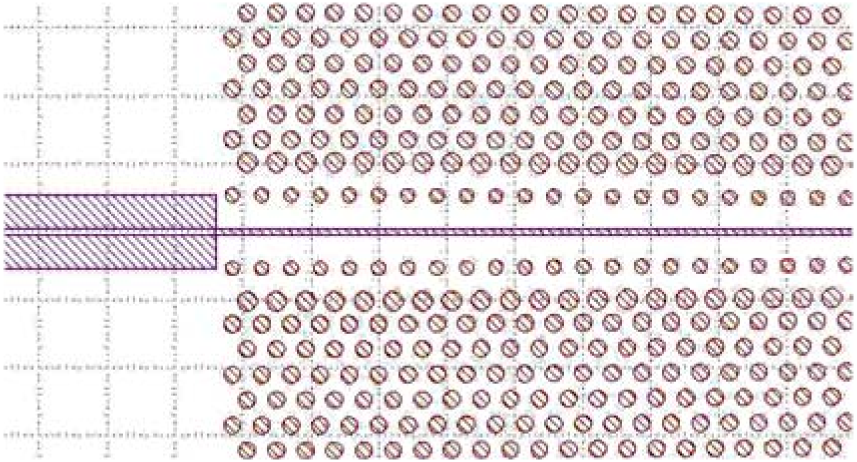
Details of rib-to-slot transition:

- a Very thin (100 nm) second rib begins, light totally confined to thicker rib (500 nm).
- b Thin rib has widened to final thickness 330 nm.
- c Thicker rib is thinned. Double ribs are now symmetric for exciting the first-order PC mode.
- d Double rib couples to PC

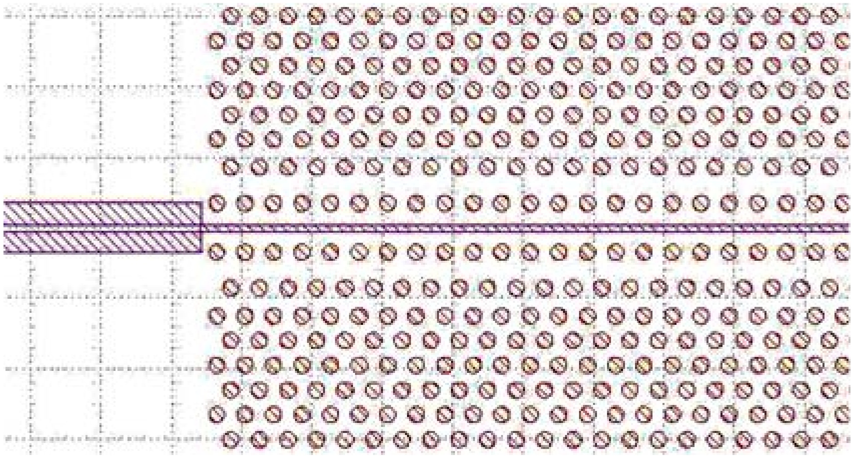
Pre-emphasized WG dimensions compensate fabrication errors. Slot mask for 100 nm has expected outcome 150 nm.

Two Slow-Light Photonic Crystal Families

varying radii



identical radii, shifted position



Designing a slow-light photonic crystal

- Varying radii:
  - Good coupling
  - Difficult fabrication (varying pre-emphasis)
- Identical radii:
  - Poor coupling
  - Simple fabrication (same pre-emphasis)

J.-M. Brosi, C. Koos, L. C. Andreani, M. Waldow, J. Leuthold, W. Freude: High-speed low-voltage electro-optic modulator with a polymer-infiltrated silicon photonic crystal waveguide, Opt. Express, vol. 16, pp. 4177–4191, March 2008

J. Li, T. P. White, L. O`Faolain, A. Gomez-Iglesias, T. F. Krauss: Systematic design of flat and slow light in photonic crystal waveguide. Opt. Express, vol. 16, pp. 6227–6232, April 2008

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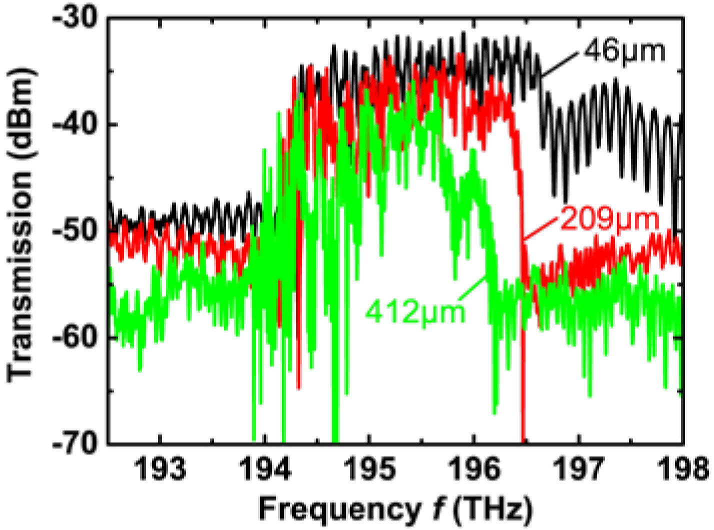
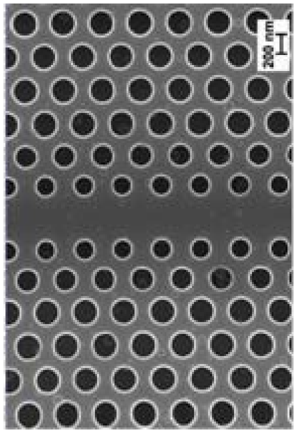
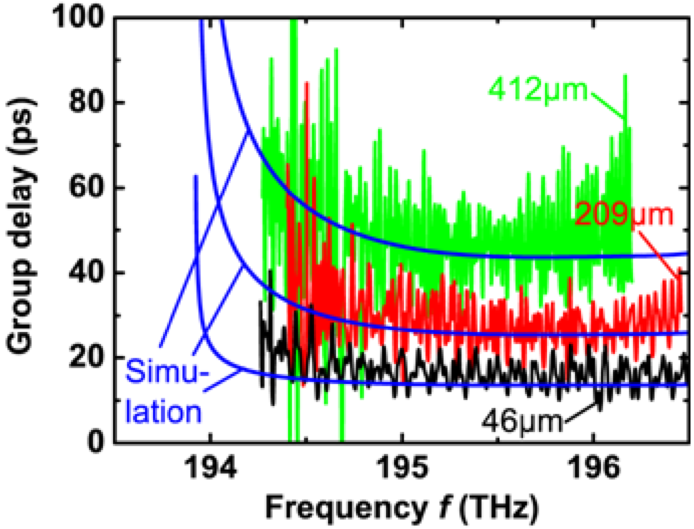
Broadband Slow Light PC WG with Low Dispersion

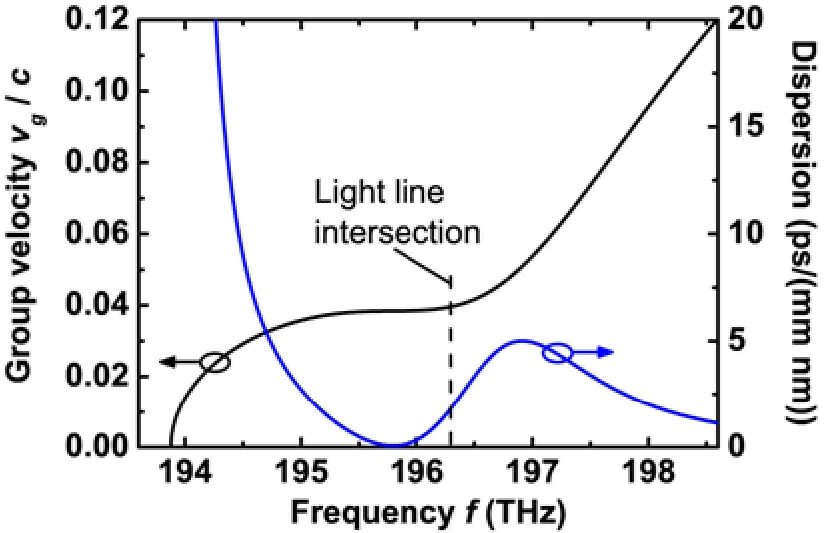


Preliminary measurement without slot. Attached strip-WG, three lengths. Minimum loss 14 dB/mm at $\lambda = 195.35$ THz.

Group delay meas. & simulated → v_g & dispersion







Brosi, J.-M.; Koos, C.; Andreani, L. C.: Dumon, P.; Baets, R.; Leuthold, J.; Freude, W.: '100 Gbit/s / 1 V optical modulator with slotted slow-light polymer-infiltrated silicon photonic crystal', OSA Topical Meeting on Slow and Fast Light (SL'08), Boston (MA), USA, 13–16 July 2008. Paper SWC3

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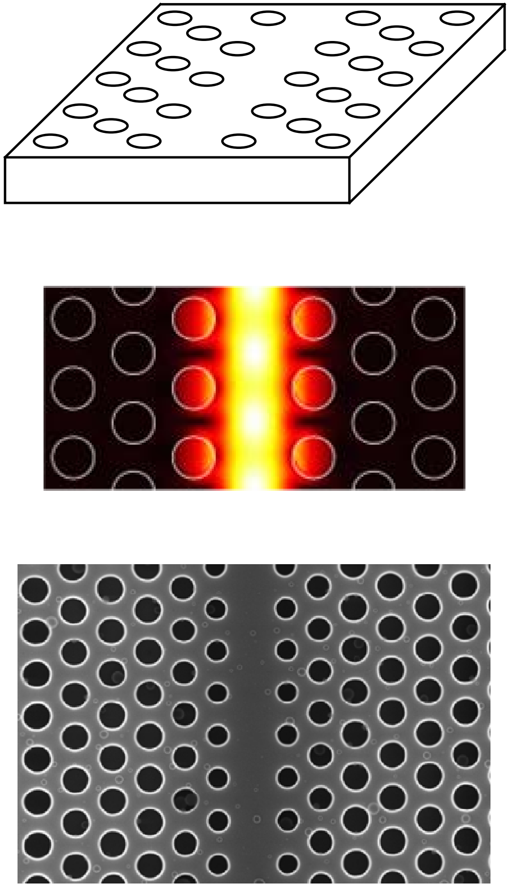
Photonic Crystals: Properties, Modeling, and Applications



- PC could find applications whenever dispersion properties need tailoring
- Slow-light devices have increased losses, but may be designed for wide bandwidth
- PC especially useful in hybrid combination with nonlinear organic materials
  - for tunable dispersion (–19…+7) ps / (mm nm)
  - for tunable delay 0…1.7 bit / mm @ 40 Gbit/s
  - for electro-optic modulation 100 Gbit/s / 1 V
- A few experiments demonstrated
  - the use of microwave models
  - the present status of our EO modulator

Further Reading (1/2)

Textbooks, software and reviews in photonic crystals

[1] Sakoda, K.: Optical properties of photonic crystals. Berlin: Springer-Verlag 2001

[2] Freude, W.; Chakam, G.-A.; Brosi, J.-M.; Koos, C.: Microwave Modelling of Photonic Crystals. In: Busch, K.; Lölkes, S.; Wehrspohn, R.; Föll, H. (Eds.): Photonic Crystals — Advances in Design, Fabrication, and Characterization. Wiley VCH, Berlin 2004, pp. 198–214

[3] Joannopoulis, J. D.; Johnson, S. G.; Winn, J. W.; Meade, R. D.: Photonic Crystals — Molding the Flow of Light, 2. Ed. Princeton: Princeton University Press 2008.
Free book download: `http://ab-initio.mit.edu/book/`

[4] Johnson, S. G.; Joannopoulos, J. D.: The MIT photonics-bands package home page.
Free Linux software download: `http://ab-initio.mit.edu/mpb`

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[6] Chakam G.-A.: Periodische Strukturen im Mikrowellenbereich für planare Antennen und zur Modellierung integriert-optischer Komponenten (Periodic Structures in the Microwave Region for Planar Antennas, and for Modelling Integrated-Optical Components). Göttingen: Cuvillier-Verlag 2003

[7] Maitra, A.: Nonlinear Resonant Devices for All-Optical Signal Processing. In: Leuthold, J.; Freude, W.: Karlsruhe Series in Photonics & Communications, Vol. 2. Karlsruhe: Universitätsverlag 2007 — `http://www.uvka.de`

[8] Brosi, J.-M.: Slow-Light Photonic Crystal Devices for High-Speed Optical Signal Processing. In: Leuthold, J.; Freude, W.: Karlsruhe Series in Photonics & Communications, Vol. 4. Karlsruhe: Universitätsverlag 2008 — `http://www.uvka.de`

Further Reading (2/2)

Recent publications

[9] Scarmozzino, R.; Gopinath, A.; Pregla, R.; Helfert, S.: Numerical techniques for modeling guided-wave photonic devices. IEEE J. Sel. Topics Quantum Electron. 6 (2000) 150–162

[10] Brosi, J.-M.; Leuthold, J.; Freude, W.: Microwave-frequency experiments validate optical simulation tools and demonstrate novel dispersion-tailored photonic crystal waveguides. J. Lightw. Technol. 25 (2007) 2502–2510

[11] Koos, C.; Jacome, L.; Poulton, C.; Leuthold, J.; Freude, W.: Nonlinear silicon-on-insulator waveguides for all-optical signal processing. Opt. Expr. 15 (2007) 5976–5990

[12] Brosi, J.-M.; Koos, C.; Andreani, L. C.; Waldow, M.; Leuthold, J.; Freude, W.: High-speed low-voltage electro-optic modulator with a polymer-infiltrated silicon photonic crystal waveguide. Opt. Expr. 16 (2008) 4177–4191