Novel electromagnetic structures for high frequency acceleration
(Part 1-3)

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Cockcroft Institute, Spring term, 6/03/17

Lectures outline

Lecture 1 – Introduction to high frequency dielectric acceleration

- Novel accelerating structures
- Dielectric laser acceleration
- Important parameters

Lecture 2 – Photonic crystal technology

- What is a photonic crystal
- Bandgap property
- Intentional defects in Photonic Crystals
- Photonic crystal cavities and waveguides

Lecture 3 – Properties of photonic structures for acceleration

- Photonic crystal structures
- Wakefields in dielectrics
- Requirements and challenges
- THz laser acceleration

Lectures outline

Lecture 4 – Introduction to Metamaterials

- Novel electromagnetic properties
- Dispersion engineering
- Metamaterials loaded waveguides
- Potential application in accelerators

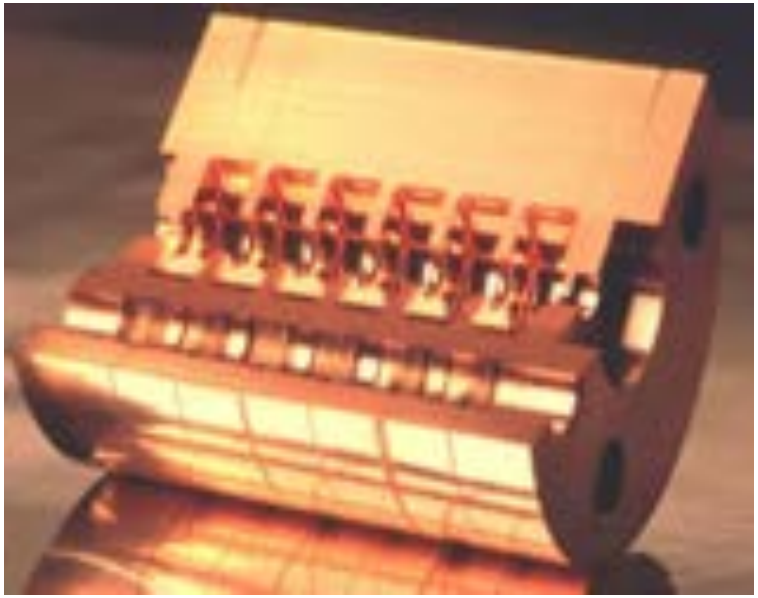
Lecture 5 – Introduction to Plasmonic waveguiding

- Surface plasmon polariton
- Dispersion
- Plasmonic waveguide
- Accelerators applications

Lecture 6 – Introduction to Finite Difference Time Domain

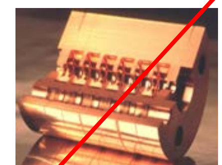
- Time domain computational modelling
- Finite Difference Time Domain
- Examples

Scaling the accelerator size



Iris-loaded structure

Conventional RF technology scaled down?



$\lambda \cong 1 \mu m$

- Metal absorbs at optical frequency
- Difficult to fabricate

→ Lasers produce high power (~J, >TW)

- Scale in size by orders of magnitude
- λ < 1um gives challenges in beam dynamics
- Reinvent resonant structures using dielectric
- Potentially low cost

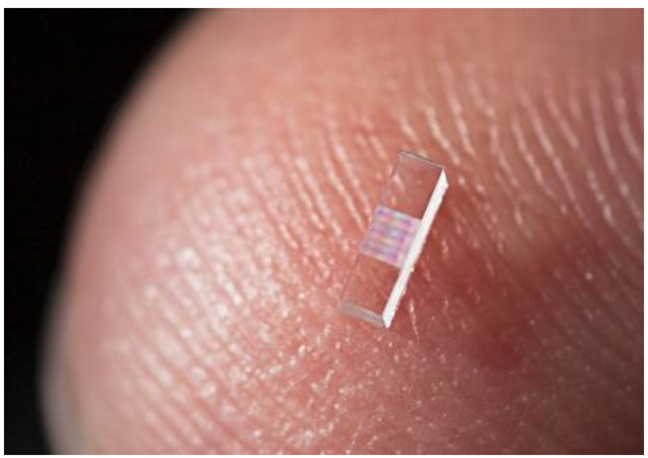
Recent demonstrations

LETTER

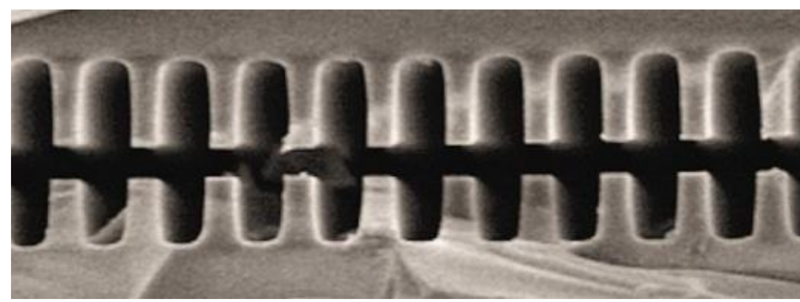
doi:10.1038/nature12664

Demonstration of electron acceleration in a laser-driven dielectric microstructure

E. A. Peralta[1], K. Soong[1], R. J. England[2], E. R. Colby[2], Z. Wu[2], B. Montazeri[3], C. McGuinness[1], J. McNeur[4], K. J. Leedle[3], D. Walz[2], E. B. Sozer[4], B. Cowan[5], B. Schwartz[5], G. Travish[4] & R. L. Byer[1]



800 nm period
550 µm structures



Energy ≈ 190-250 MeV per meter

Recent demonstrations

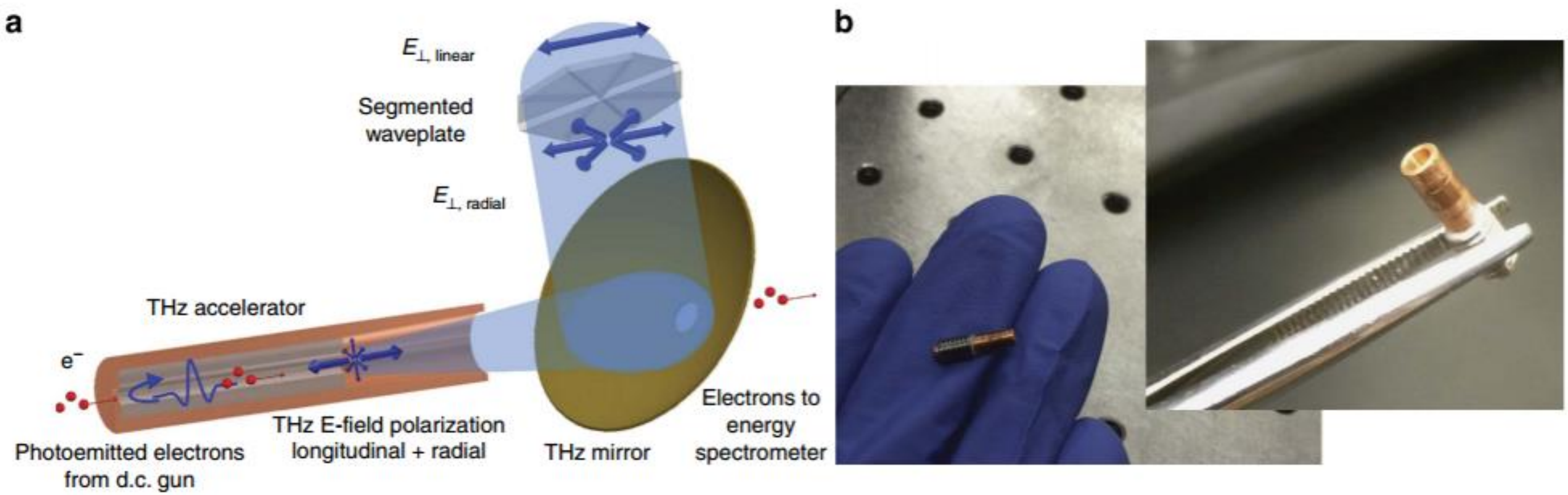
nature
COMMUNICATIONS

ARTICLE

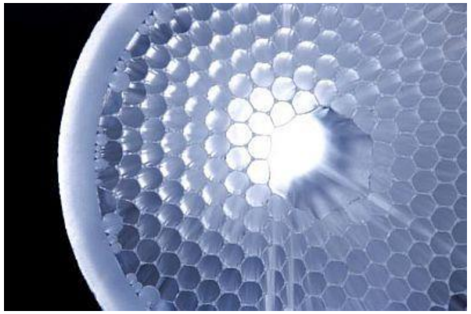
Received 20 Apr 2015 | Accepted 27 Aug 2015 | Published 6 Oct 2015 DOI: 10.1038/ncomms9486 OPEN

Terahertz-driven linear electron acceleration

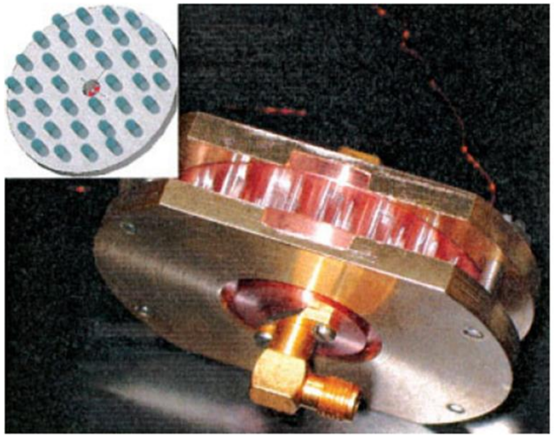
Emilio A. Nanni[1], Wenqian R. Huang[1], Kyung-Han Hong[1], Koustuban Ravi[1], Arya Fallahi[2,3], Gustavo Moriena[4], R.J. Dwayne Miller[3,4,5] & Franz X. Kärtner[1,2,3,6]



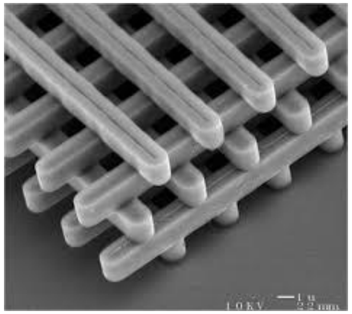
New structures – dielectrics



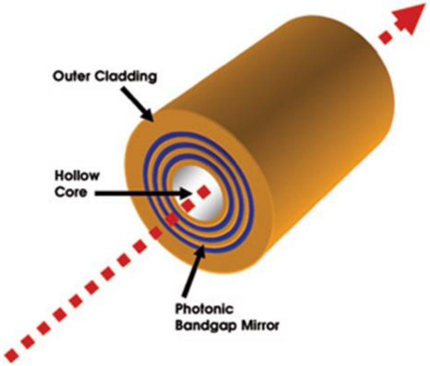
http://www.laserfocusworld.com/articles/oiq/2011/12/nkt-photonics-licenses-pcf-technology-portions.html

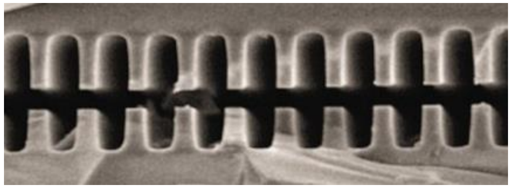


[Masullo et al., 2006]



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

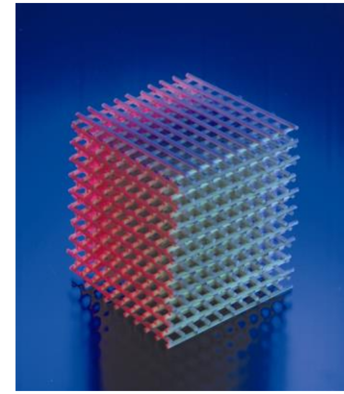




[T. Plettner 2009]

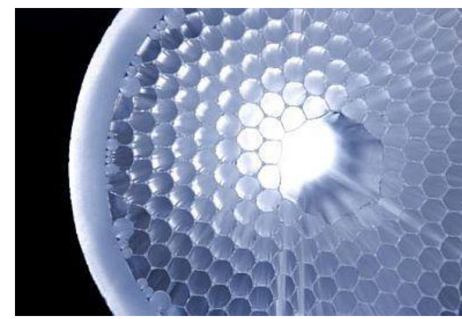
Emerging electromagnetic concepts

- Overcoming the limitations of natural materials by means of “**function through structure**” concept
  - Photonic Crystal (PhC) technology
  - Metamaterials



http://arstechnica.com/science/2011/10/making-a-photonic-crystal-with-a-couple-of-light-beams/

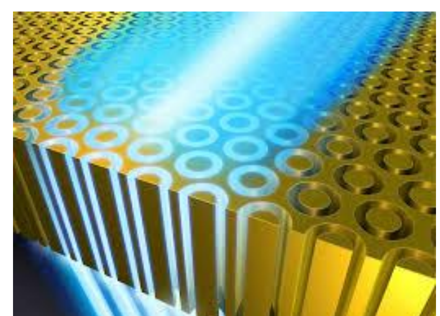
- Engineering of the geometry of the structure allows for creation of “artificial materials” for unusual EM responses



http://www.laserfocusworld.com/articles/oiq/2011/12/nkt-photonics-licenses-pcf-technology-portions.html

- Scalability

- Interference lithography (IL) holds the promise of fabricating large-area, defect-free 3D structures on the sub-micrometer scale both rapidly and cheaply



[http://wiesner.mse.cornell.edu/res_optics.htm]

Dielectric accelerators

Types:

- Dielectric wall acceleration
- Dielectric wakefield acceleration
- Dielectric laser acceleration
- Dielectric assisted waveguide
- Dielectric loaded waveguides

Advantages:

- High breakdown threshold (1-5 GV/m)
- High frequency operation
- Can reduce wakefields (photonic crystals)
- Mature fabrication technologies available

Dielectric laser accelerators

- Typically refers to accelerators concepts operating at optical frequencies, driven by lasers in all- dielectric structures

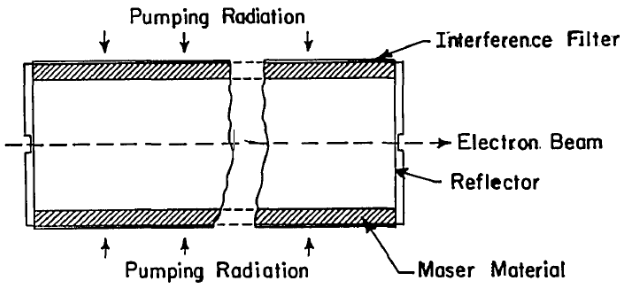
- Acceleration of any particle by fields requires equal amount of energy taken out of em fields

- Requirements for the accelerating mode:
  - Speed-of-light TM mode

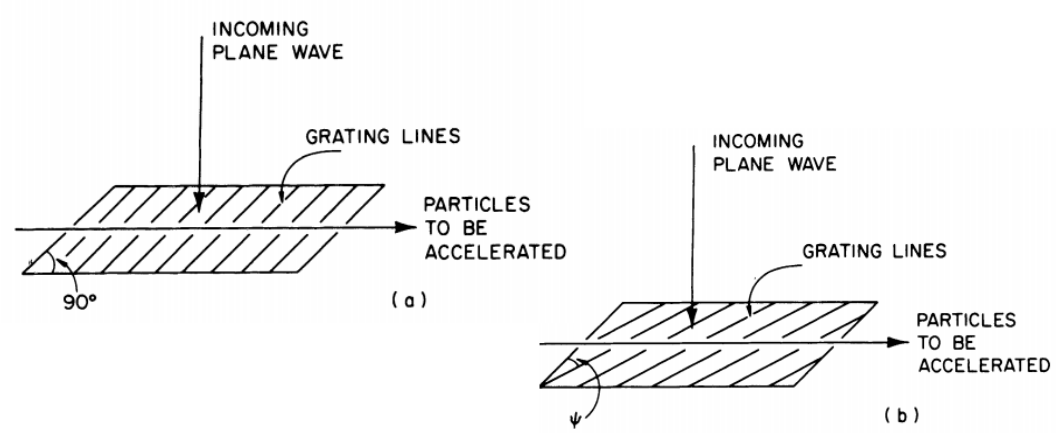
- The non existence of metal boundaries allows structures to damp high order modes

Early concepts

- First proposals to use lasers to accelerate particles by operating known radiative processes in reverse:
- Inverse Cherenkov effect in a gas (Shimoda, 1962)



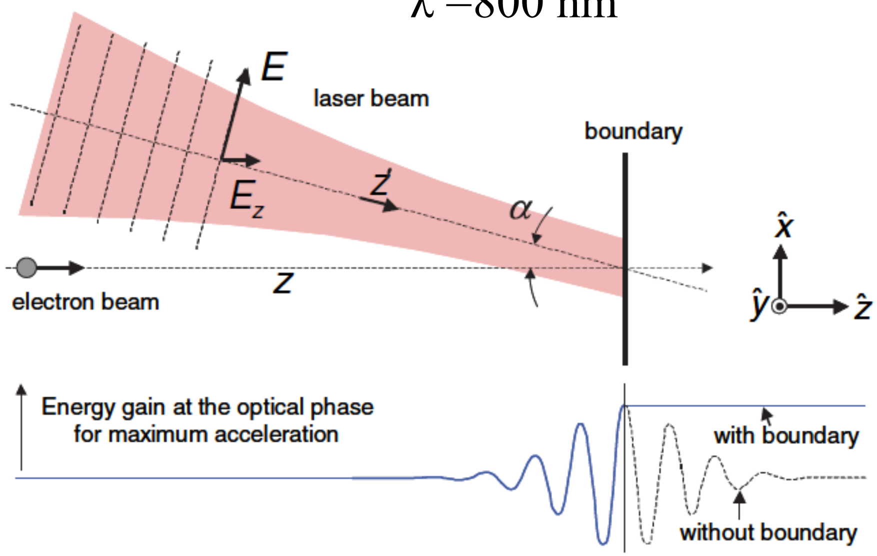
- Close to a periodic structure, Inverse Smith-Purcell acceleration (Takeda and Matsui, 1968; Palmer, 1980)



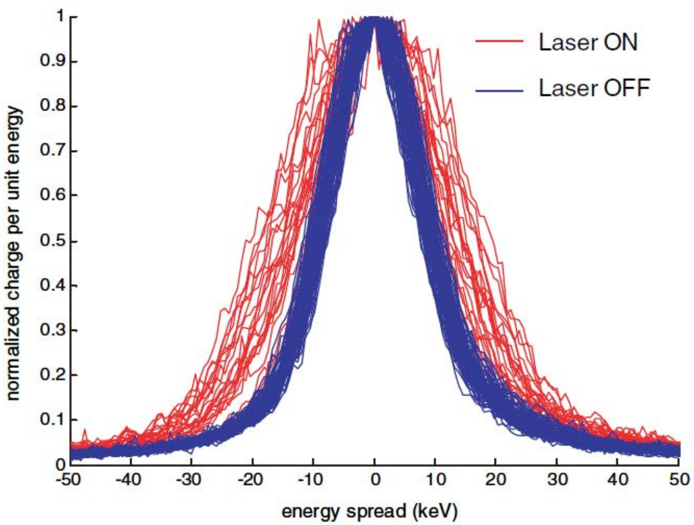
Laser/electron energy exchange

- Laser-driven particle accelerator in structure loaded vacuum (waveguides, semi-open free-space structures, ect)
- **2005** – first experiment to demonstrate laser acceleration mechanism could be achieved in semi-infinite vacuum

λ =800 nm



Up to 30KeV modulation over 1000 μm (40 MeV/m)

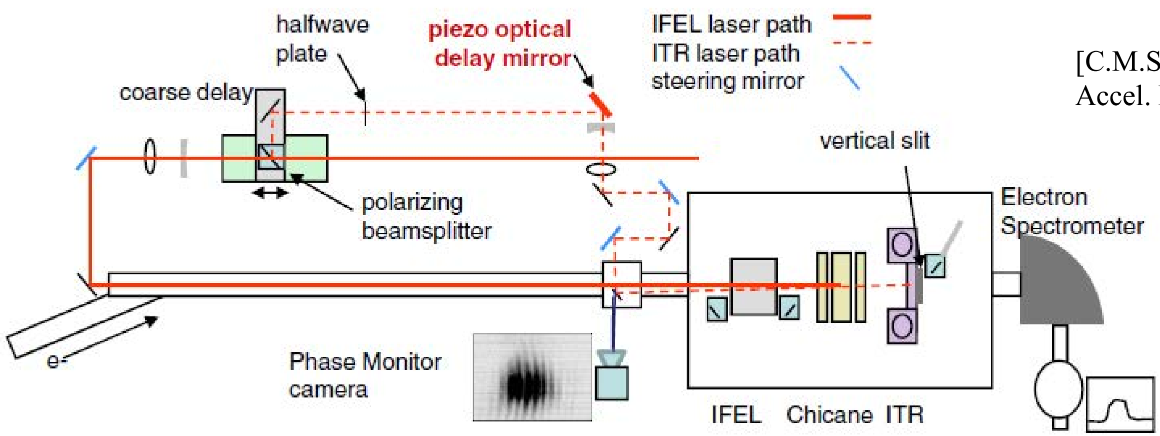


[T. Plettner et al., PRL, 95, 134801, 2005]

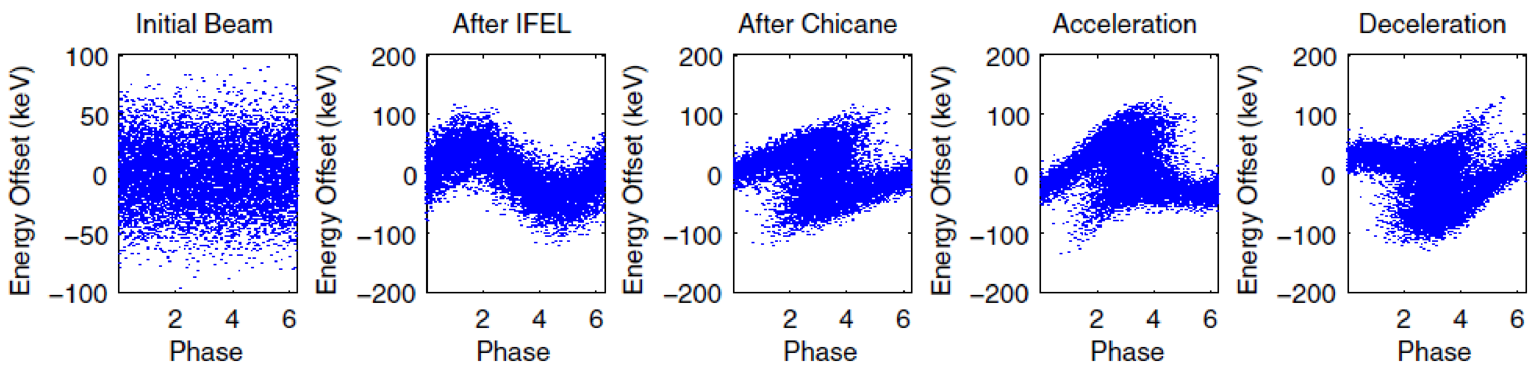
Optical micro-bunching

2008 - Demonstration optical bunching and acceleration (acceleration in 2 stages):

1. Slice the electron beam in microbunches spaced by the optical period
2. Optical acceleration by inverse transition radiation (ITR) mechanism



[C.M.S. Sears et al., Phys Rev. ST Accel. Beams 11, 101301, 2008]



Photonic acceleration concepts

- The laser field co-propagates with the particle beam with a phase velocity equal to speed of light in vacuum

- Particle beam must form short optical bunches which have only small phase extent within a laser oscillation

- Photonic Band Gap (PBG) waveguides are transmission-mode structures, frequency selectivity can be used to damp HOMs.

- Ultrafast pulses (~ 1 ps) so material can sustain larger fields

- Accelerating segments in waveguide (**individual segment** length ~ 100μm – 1mm)

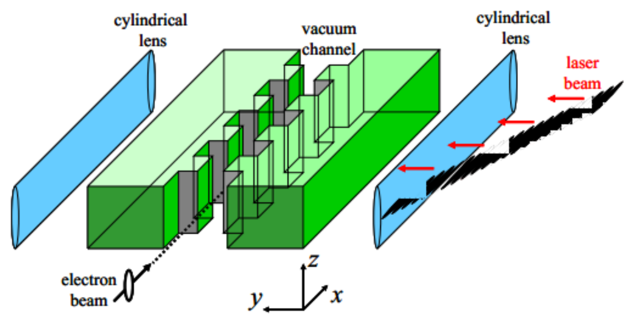
- Deflecting mode-driven instabilities limit the amount of charge we can accelerate

All-dielectric accelerating structures

- A range of proposals:
- Lin (2001)
- Mizrahi and Schachter (2004)
- Plettner, Lu, Byer (2006)
- Cowan (2008)
- Naranjo et al. (2012)
- First demonstration - Peralta et al. (2013)

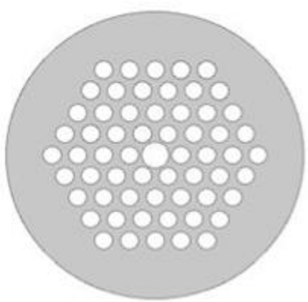
Structures proposed

Planar grating structures (“Phase mask”)

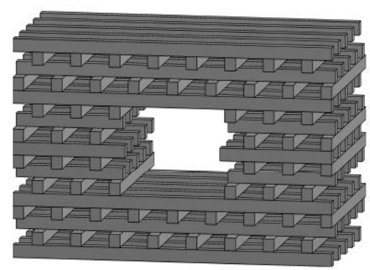


[T. Plettner 2009]

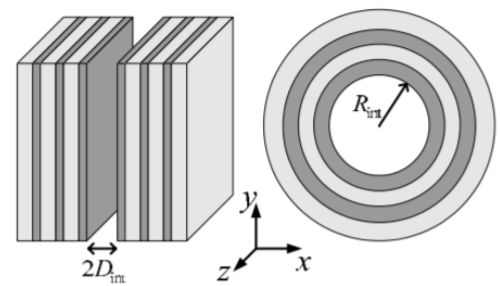
PhC confinement



[Lin, 2001, R. Noble, 2007]

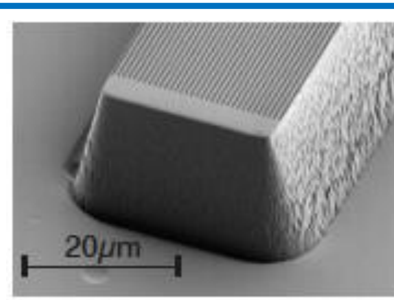


[B. Cowan, 2006]



[Mizrahi and Schachter, 2004]

Open gratings (Low-β acceleration)



[J. Breuer, P. Hommelhoff, 2013]

[K. J. Leedle et al, 2015]

How to choose the material?

- Material choice:
  - High thermal conductivity
  - Low loss tangent
  - **High damage threshold**
  - High dielectric breakdown
  - No charging from beam

- Maximum gradient is proportional to ***laser damage threshold fluence*** (energy/unit area) of the material as $\sqrt{F_{th}}$

- F_{th} depends also on the laser parameters (pulse length/ wavelength)

- Common choices:
  - Si, Quartz, CVD diamond, and SiO_2

Laser-induced breakdown

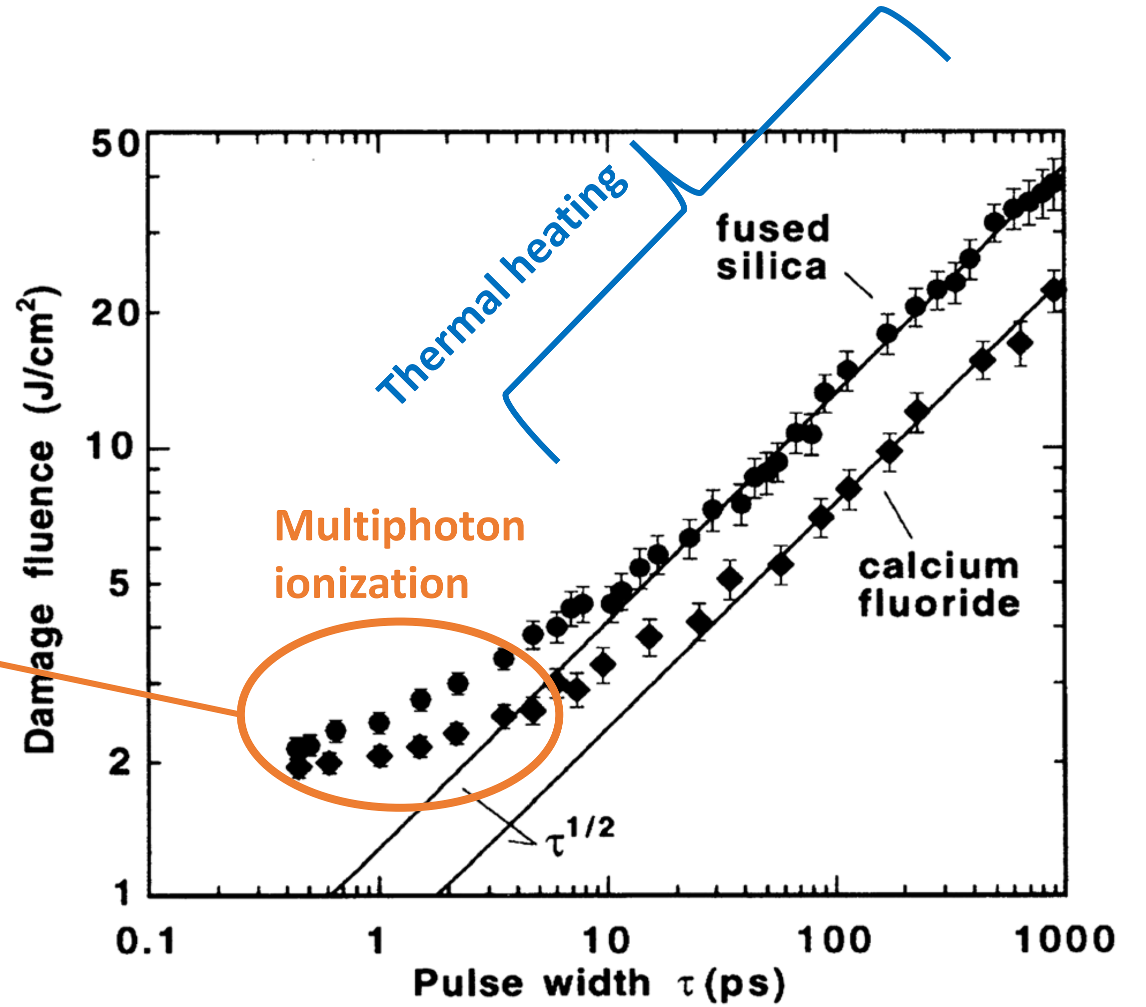
- Well characterised for long pulse lasers (1 ns-10 ps)

Plasma density

$$\omega_{laser} = \omega_p = \sqrt{\frac{4\pi n_e e^2}{m^*}}$$

Electron Plasma frequency

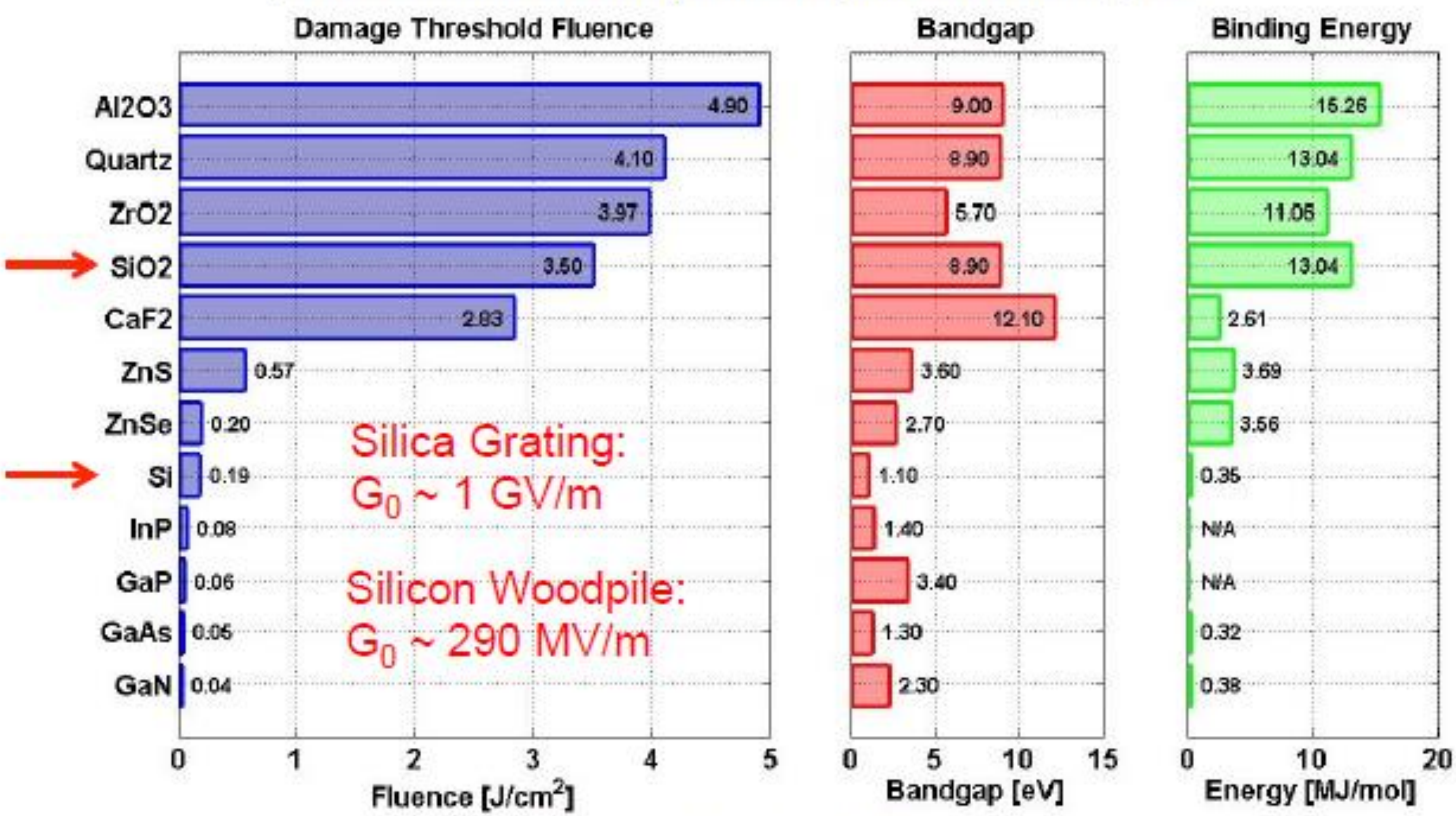
[Soong et al., 2011]



[Stuart et al., PRL, 74, 2248, 1995]

Laser-induced breakdown

- Short pulse (1 ps), 800 nm, 600 Hz laser:



[Soong et al., 2012]

Laser damage threshold fluence is defined as the laser fluence where damage to the sample has a 50% probability of occurrence

Important parameters

- Gradient (> 1 GeV/m)
- Efficiency (diode lasers systems approach 50% efficiency)
  - Efficiency of the laser (wall-plug power to light)
  - Efficiency of acceleration process (how many electrons we can accelerate in a bunch)
- Luminosity (important for colliders)
- Single-mode operation (apertures are typically 0.3 to 0.8 λ)

From metal to all-dielectric structures

- Useful general scaling laws exists linking group velocity, surface field, accelerating field.

Accelerating field

$$\frac{E_z}{|\mathbf{E}_\perp|} = \frac{1+\alpha_e}{\pi D/\lambda}$$

Constant (→1 for circular cross section, → 0 for a slab cross section with gap D)

Diameter/gap

Transverse electric components

- Smaller apertures D and cylindrical geometry are preferred
- Planar structures however may be preferred because of simple planar fabrication and simpler heat removal

From metal to all-dielectric structures

- Useful general scaling laws exist linking group velocity, surface field, accelerating field.

$$v_g \le \frac{c}{1 + 2\left(E_z / |\mathbf{E}_\perp|\right)^2}$$

Group velocity of accelerating field

Valid only for the fundamental space harmonic

- Example: planar geometry with $D = \lambda \Rightarrow E_z / |\mathbf{E}_\perp| = 0.32$
  - If max surface field allowed = 2GV/m → max gradient = 600 MV/m
  - Pulse length typically limited to 1 ps. Since max group velocity is 0.83*c*, the structure length is limited at 1.5 mm.

Note: To avoid pulse shape slippage, $\tau > \left(1 - v_g / c\right) L / c$
where L is the structure length.
(Not valid for some of the structures proposed, e.g. phase mask structure)

From metal to all-dielectric structures

- There exist useful general scaling laws linking group velocity, surface field, accelerating field.

$$Z_c = \frac{(E_{acc}\lambda)^2}{P}$$

Mode's power flow

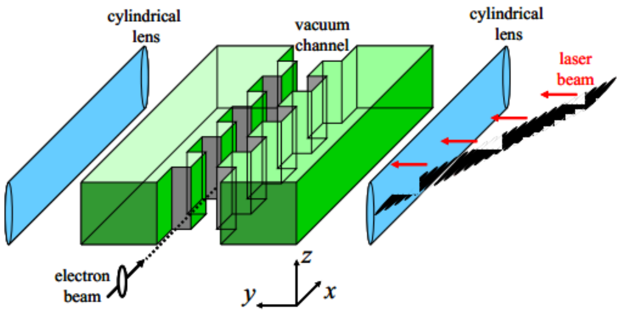
Characteristic interaction impedance

- Different from shunt impedance: $$R_{sh} = \frac{(E_{acc}\lambda)^2}{P_{loss}}$$

- Zc is a function of the waveguide geometry, independent on the length and losses

Structures proposed

Planar grating structures ("Phase mask")



[T. Plettner 2009]

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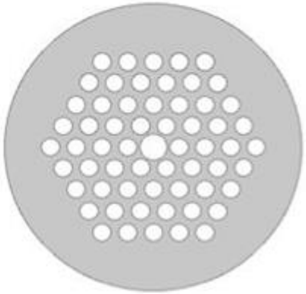
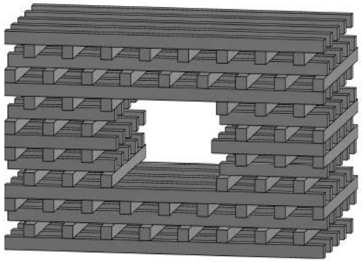
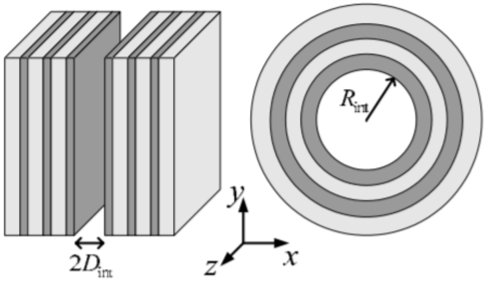


[Lin, 2001, R. Noble, 2007]

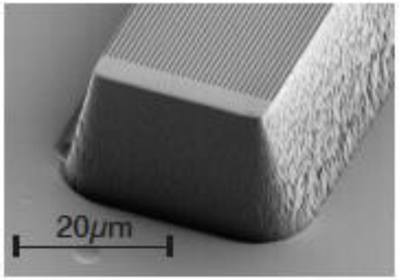


[B. Cowan, 2006]



[Mizrahi and Schachter, 2004]

Open gratings (Low-β acceleration)

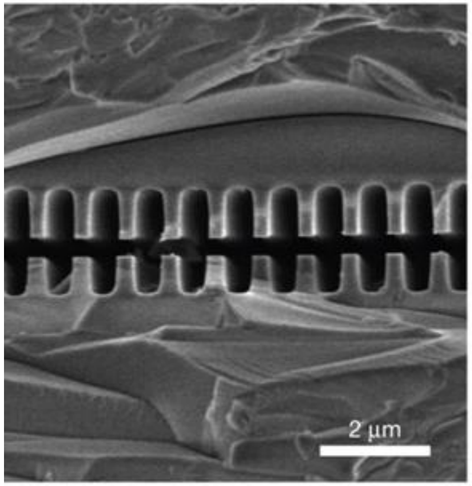


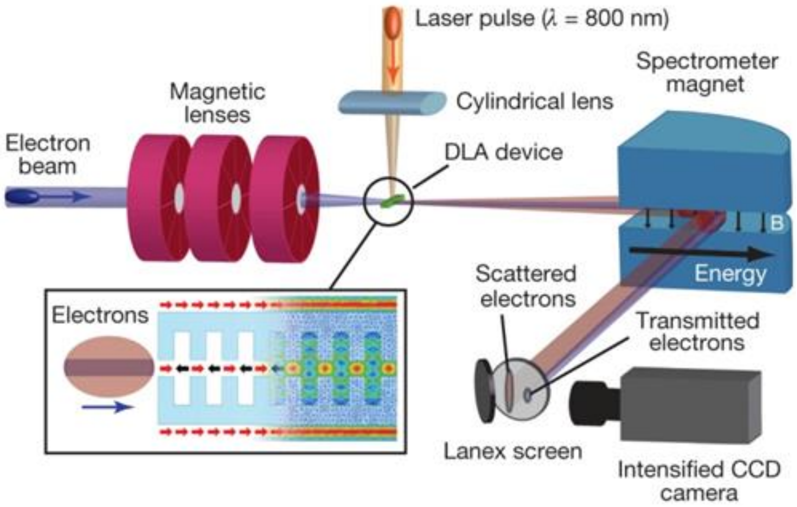
[J. Breuer, P. Hommelhoff, 2013]

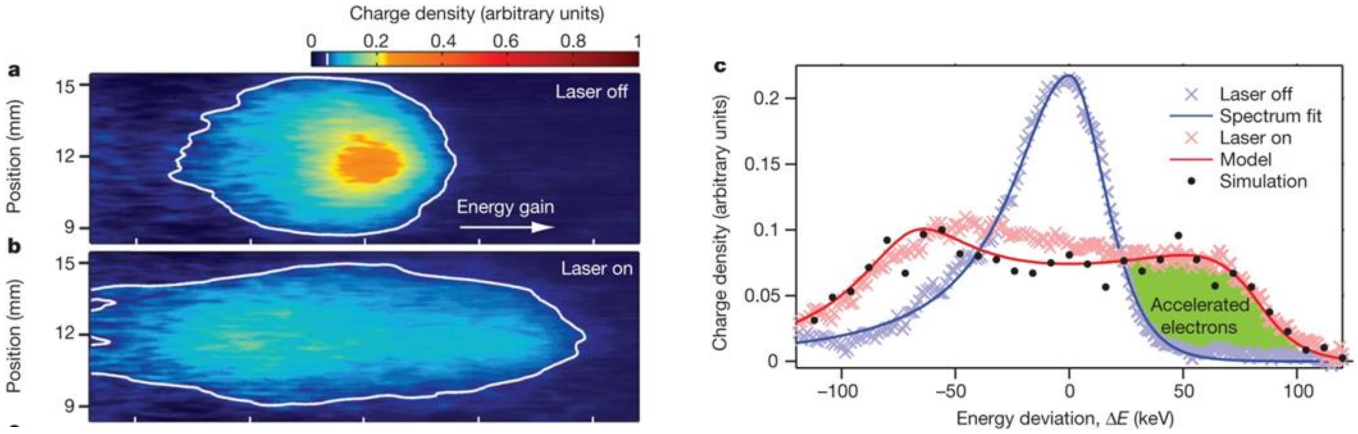
[K. J. Leedle et al, 2015]

Double grating – relativistic acceleration

- Demonstrated acceleration up to **300 MV/m** in fused silica double grating (800 nm, …laser, interaction length: 0.36 mm, 400 nm gap)





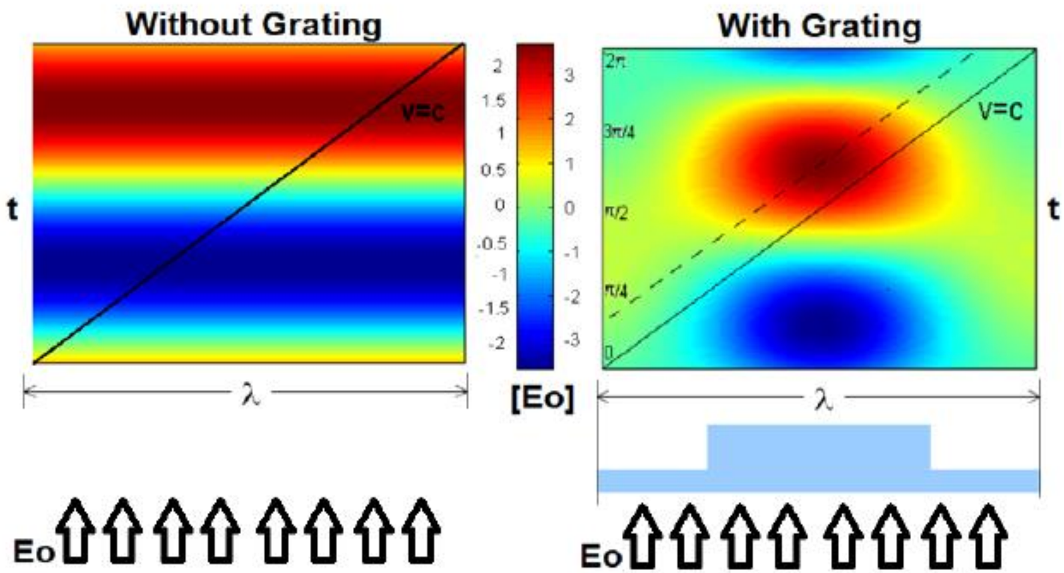


2% of electrons in test beam accelerated.

[E. A Peralta et al, Nature, 2013]

Double grating – relativistic acceleration

- Not a PBG structure, not a resonant structure.
- Behaves as phase mask which realises a speed-of-light TM mode within the channel.
- Phase-reset, correct acceleration phase in ensured on axis → no pulse-slippage problem.
- CMOS technology to realise it.



Minimized exposure to decelerating phase, net acceleration in each period

[E. A Peralta et al, 2012]

Novel electromagnetic structures for high frequency acceleration
(Part 2)

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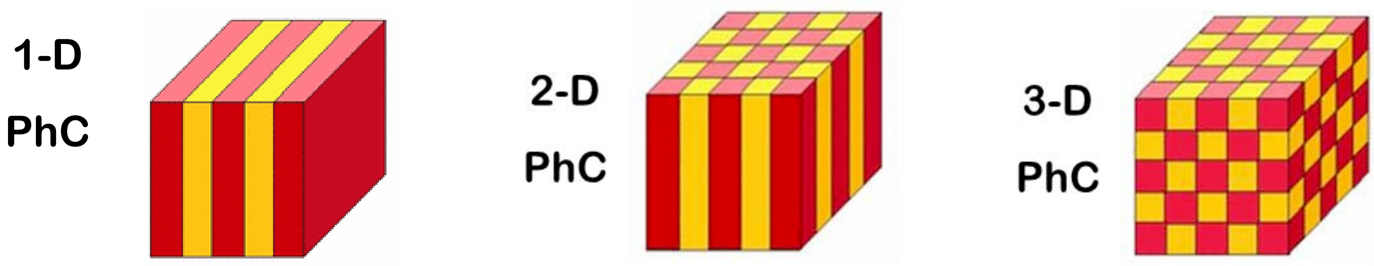
Cockcroft Institute, Spring term, 6/03/17

What are photonic crystals (PhCs)?

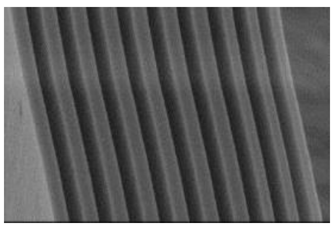


Periodic arrangement of materials (typically dielectrics) with high contrast of refractive index

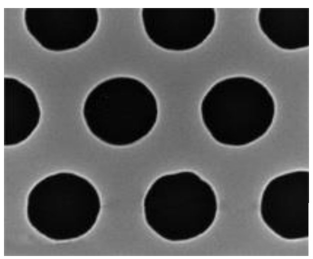
Period ≈ λ

Photonic crystals: semiconductors of light

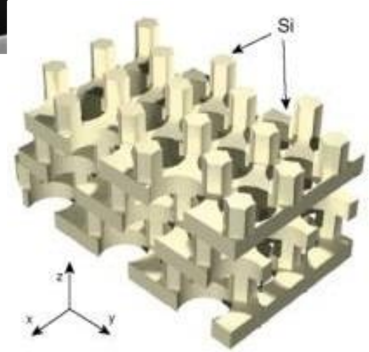
"Artificial crystal structure that could manipulate beams of light in the same way that silicon and other semiconductors control electric currents"



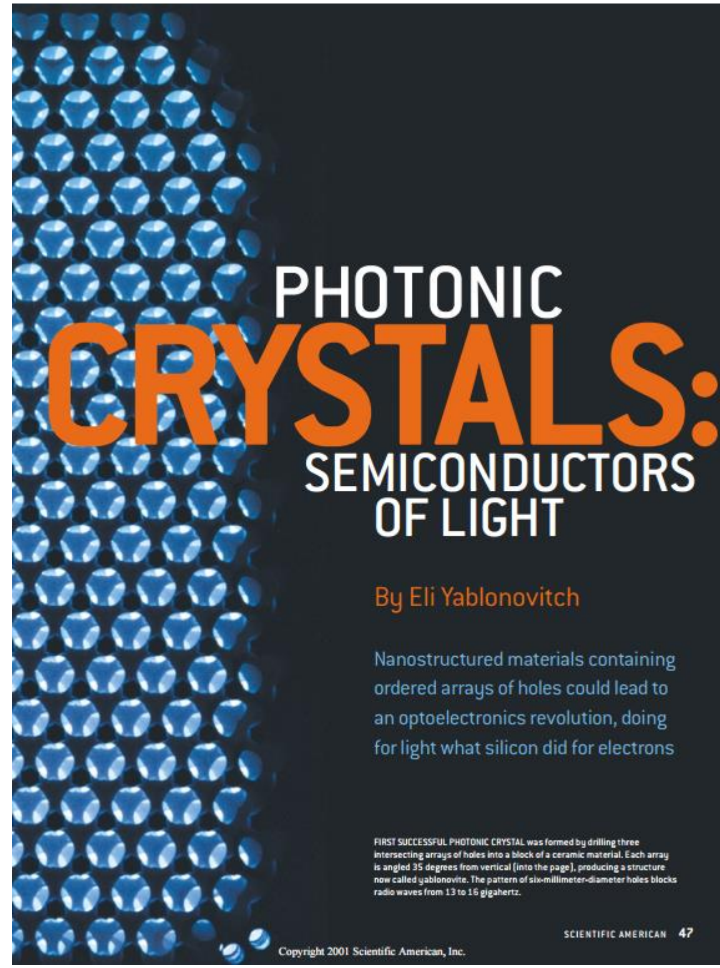
1D



2D



3D



PHOTONIC
CRYSTALS:
SEMICONDUCTORS
OF LIGHT

By Eli Yablonovitch

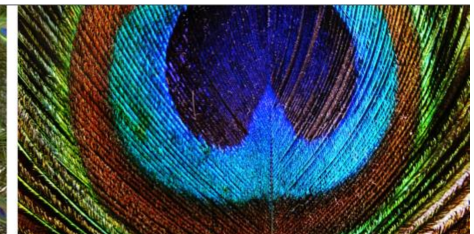
Nanostructured materials containing ordered arrays of holes could lead to an optoelectronics revolution, doing for light what silicon did for electrons

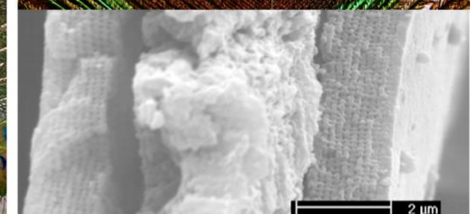
FIRST SUCCESSFUL PHOTONIC CRYSTAL was formed by drilling three intersecting arrays of holes into a block of a ceramic material. Each array is angled 35 degrees from vertical (into the page), producing a structure now called yablonovite. The pattern of six-millimeter-diameter holes blocks radio waves from 13 to 16 gigahertz.

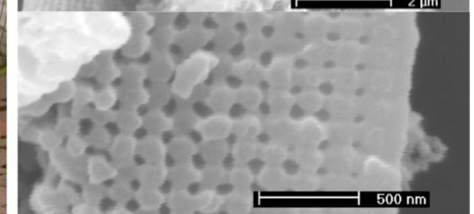
SCIENTIFIC AMERICAN 47

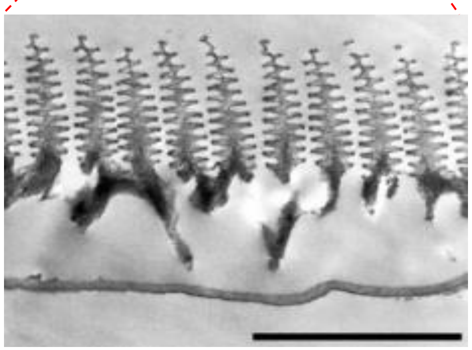
Photonic Crystals in nature – ‘Structural’ colours

The mixing of photonic structures and organic pigments will vary the shades we see









3µm

[P. Vukosic *et al.*, *Proc. Roy. Soc: Bio. Sci.* **266**, 1403 (1999)]

[also: B. Gralak *et al.*, *Opt. Express* **9**, 567 (2001)]

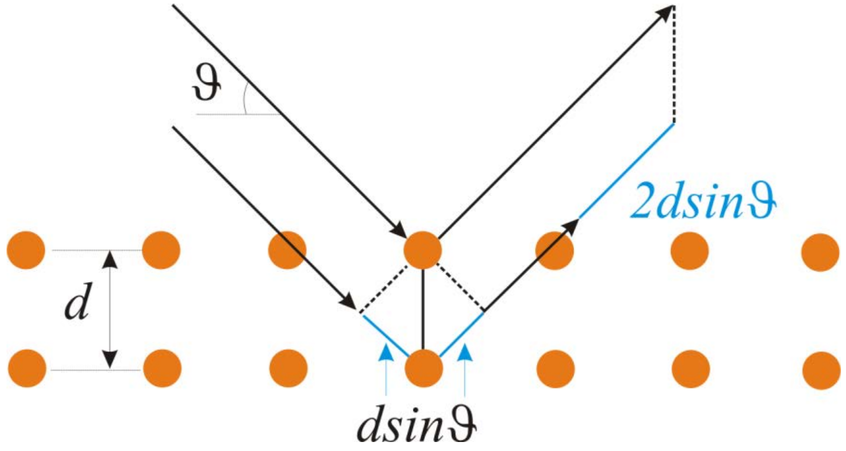
Bragg's diffraction law

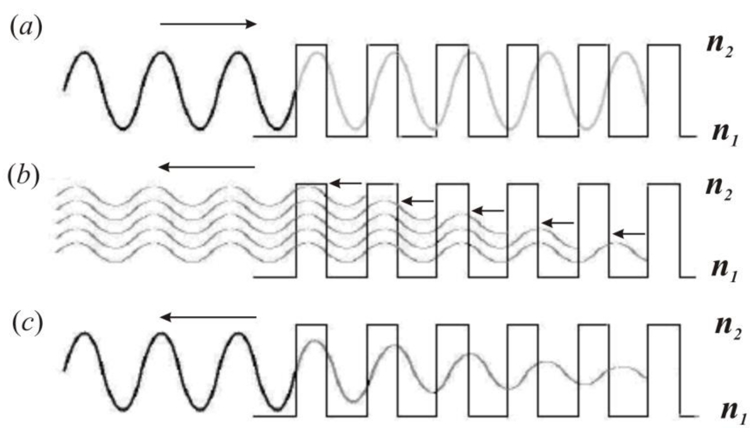
The condition that defines constructive interference.

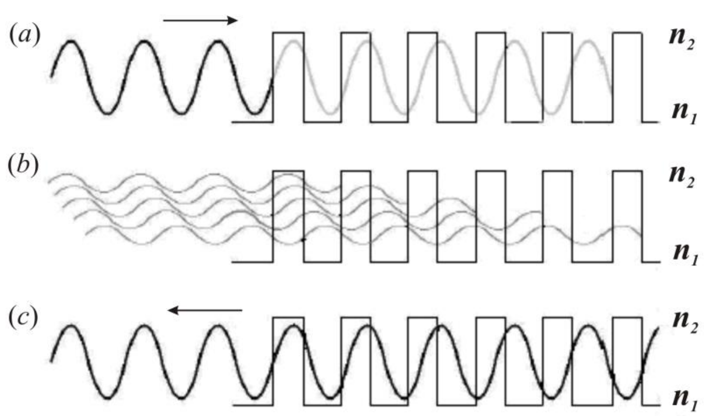
Interference between two diffracted waves from a series of atomic planes separated by d:

$$m\lambda = 2 \cdot d \cdot \sin\theta$$

$$m = 1,2,3..$$







Maxwell's equations in periodic media

First studied in 1982 by Bloch who extended a theorem developed by Floquet in 1883 for the 1D case.

BLOCH-FLOQUET THEOREM: ***waves in a periodic material can propagate with no scattering and their behaviour is ruled by a periodic envelop function which is multiplied by a plane wave.***
(for most λ, scattering cancels coherently)

$$\varepsilon(r) = \varepsilon(r + a)$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{D} = 0$$

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

$$\vec{D} = \varepsilon_0 \varepsilon(r) \vec{E}$$

$$\vec{B} = \mu_0 \vec{H}$$

$$\vec{\nabla} \times \frac{1}{\varepsilon} \vec{\nabla} \times \vec{H} = \left(\frac{\omega}{c}\right)^2 \cdot \vec{H}$$

HERMITIAN eigen-operator for real ε

EIGEN-VALUE (real)

EIGEN-STATE (are orthogonal and complete)

Maxwell's equations in periodic media

First studied in 1982 by Bloch who extended a theorem developed by Floquet in 1883 for the 1D case.

BLOCH-FLOQUET THEOREM: ***waves in a periodic material can propagate with no scattering and their behaviour is ruled by a periodic envelop function which is multiplied by a plane wave. (for most λ, scattering cancels coherently)***

Plane wave

The eigen-modes can be expressed as:

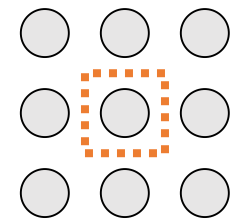
$$\vec{H}_{n,k}(r) = e^{jk\cdot r} u_{n,k}(r)$$

Has the periodicity of the crystal lattice

BLOCH MODES

All the modes are univocally defined by the Bloch wave vector k in the first Brillouin zone and by the integer index n

Maxwell's equations in periodic media



- $u_{n,k}(r)$ is given by a finite unit cell so $\boldsymbol{\omega_n(k)}$ is discrete (the dispersion relation is organised in bands defined by the index *n*)

- The solutions of the wave equation:
  - The inverse of the dielectric constant and the Bloch modes are expanded in Fourier series upon the reciprocal vector of the lattice, G

$$\eta(r) = \frac{1}{\varepsilon(r)} = \sum_G \eta_G e^{jk\cdot r}$$

$$\vec{H}_{n,k}(r) = \sum_G u_G^{n,k} e^{j(k+G)\cdot r}$$

$$\sum_G \eta_{G-G'}(k+G')\times\left[(k+G)\times u_G^{n,k}\right] = \frac{\omega_n(k)^2}{c^2} u_{G'}^{n,k},$$

$$-\frac{\pi}{a} < k \le \frac{\pi}{a}$$

First Brillouin zone

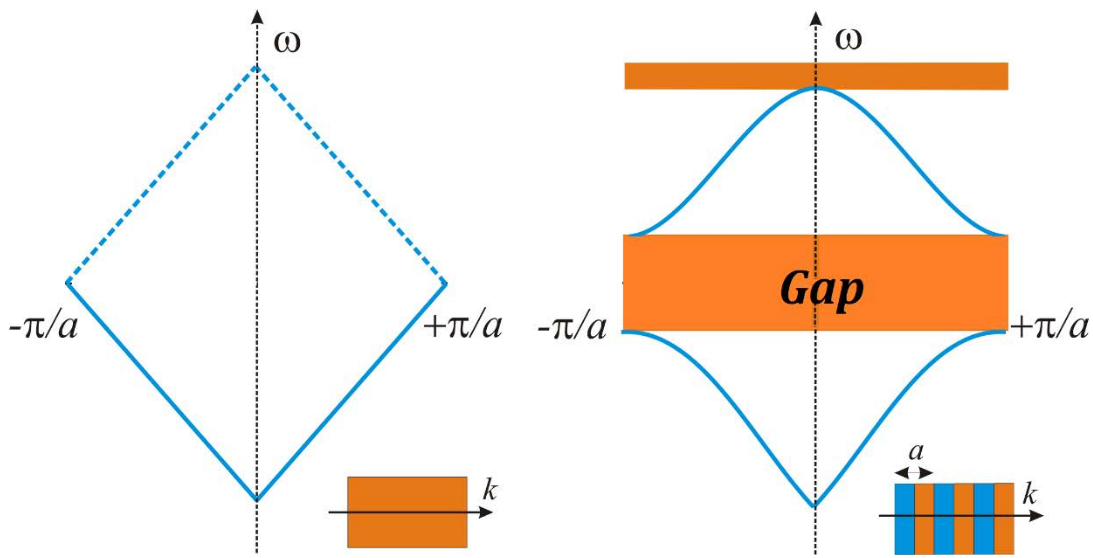
Eigen-solutions are also periodic functions of k, solutions at k = solutions at k+G (where G·*a* = 2 πδ)

Origin of the bandgap

A complete photonic bandgap is a range of frequencies ω in which there are no propagation solutions (**real *k***) of Maxwell's equations for any vector k and it is surrounded by propagation states above and below the forbidden gap.

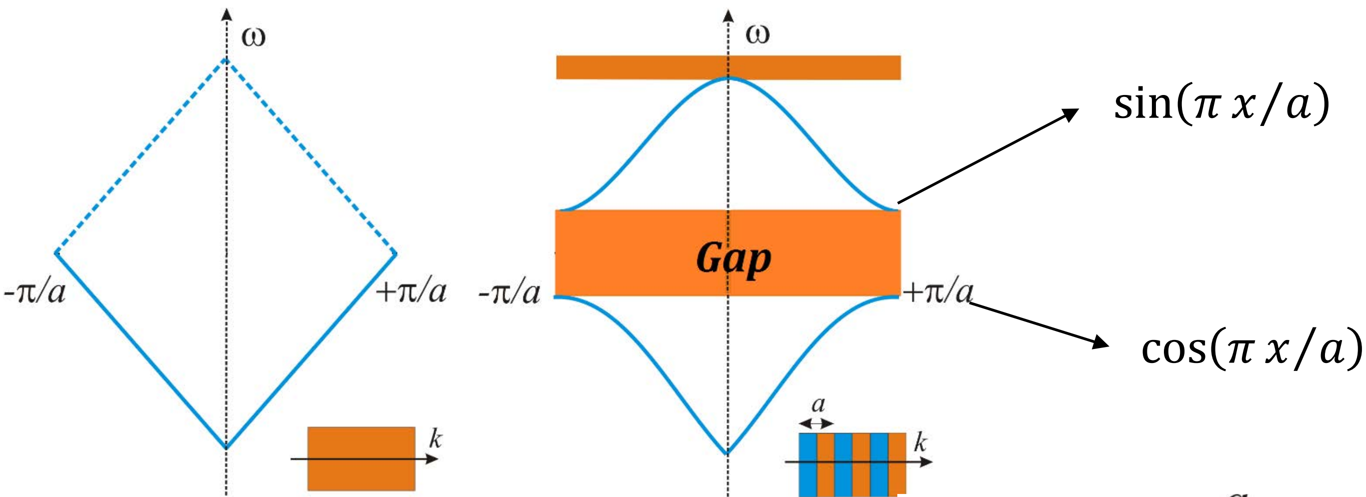
$$\varepsilon(x) = \varepsilon(x + a)$$

$$\omega(k) = ck$$

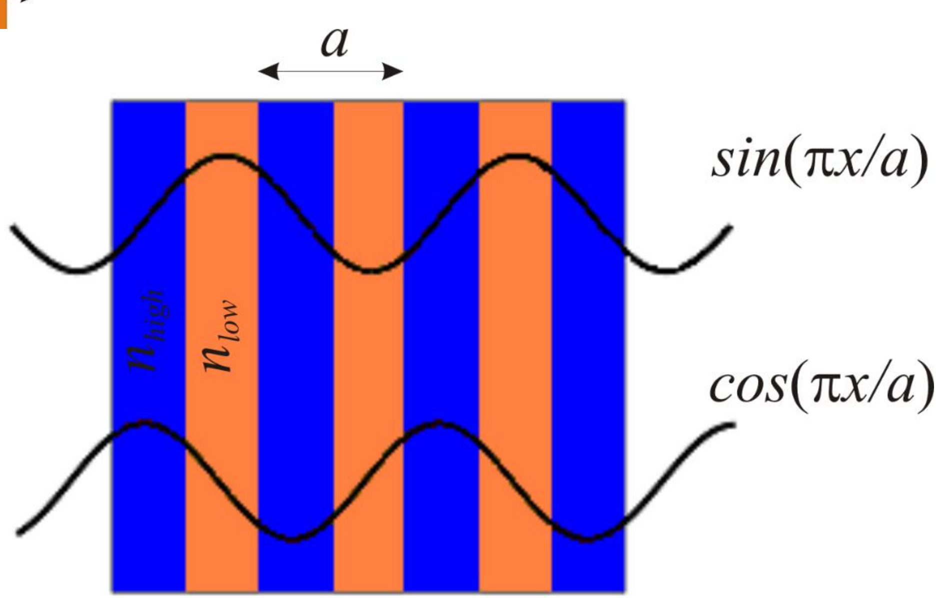


a*=0** → usual dispersion relation. States can be defined as Bloch functions and wavevectors → the bands for ***k>π/a are translated 'folded' into the first Brillouin zone

Origin of the bandgap



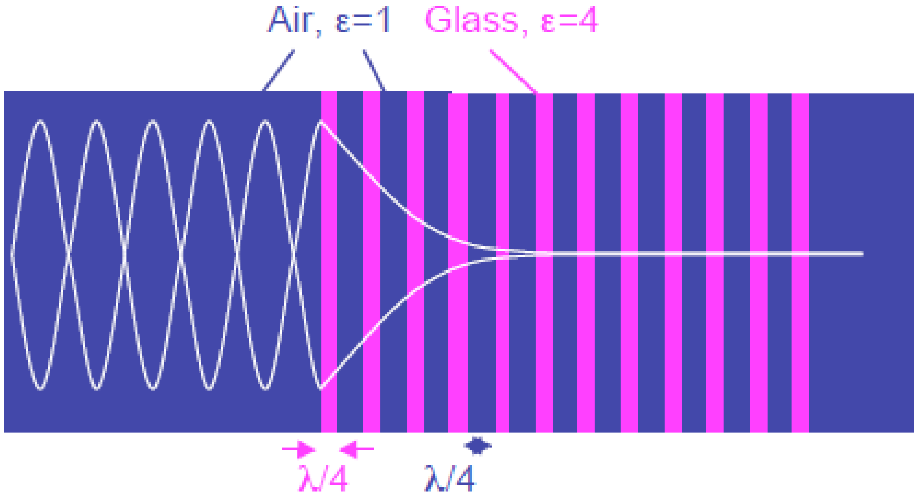
The degeneracy is broken, the **shift of the bands** leads to the formation of **bandgap**



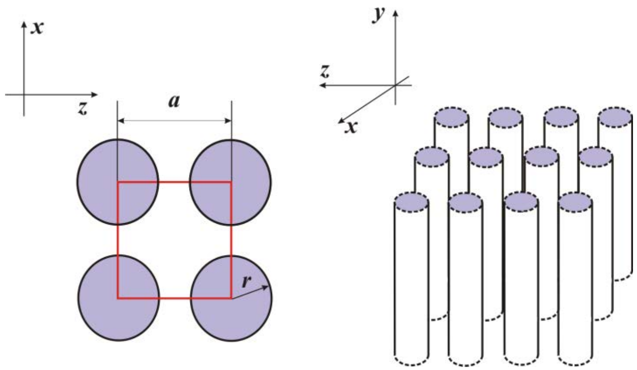
A 1D PhC – Quarter wave stack

- All 1D periodicity in space give rise to a bandgap for any contrast of the refractive index.
- Smaller the contrast and smaller is the size of the badgap
- **A peculiar case**: quarter-wave stack can maximise the size of its photonic bandgap by making the all reflected waves from the layers exactly in phase one with each others at the midgap frequency

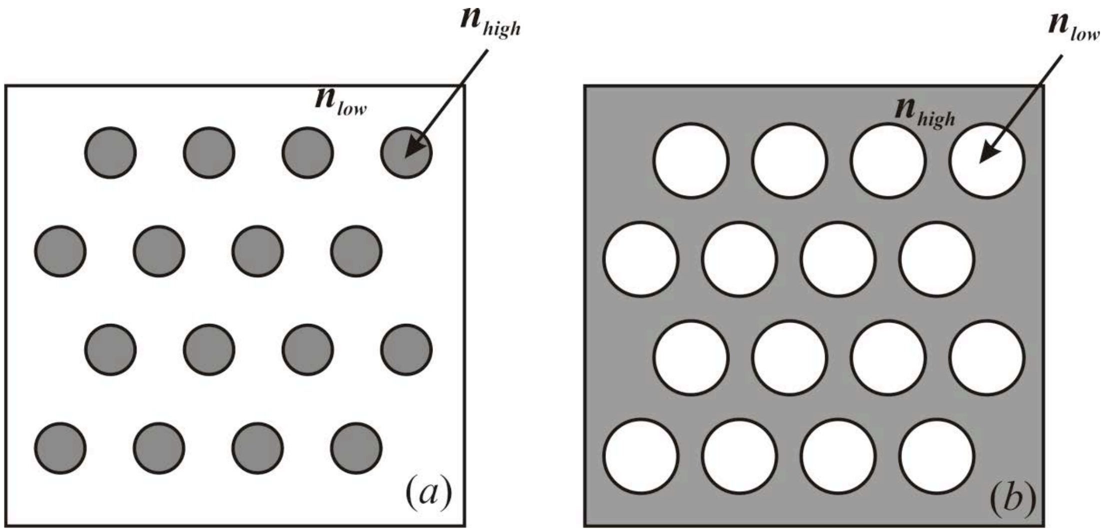
A 1D PhC
(a dielectric mirror)



2D photonic crystals

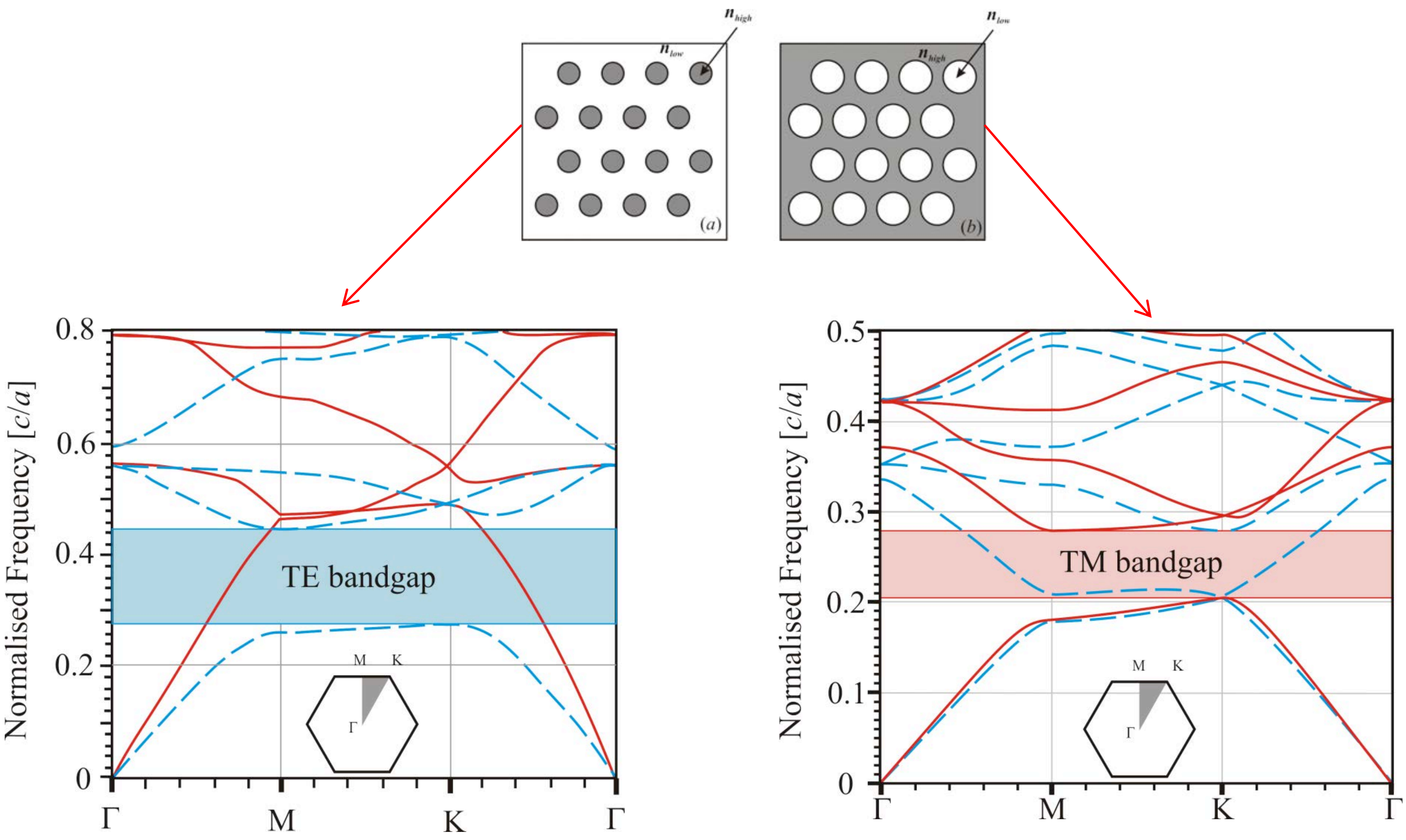


Rectangular lattice



Hexagonal lattice

2D photonic crystals

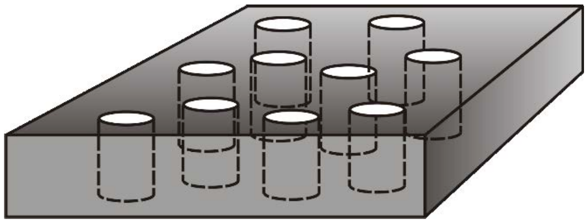


TE: E-field parallel to rods

TM: E-field localised around the holes

Photonic crystal slab

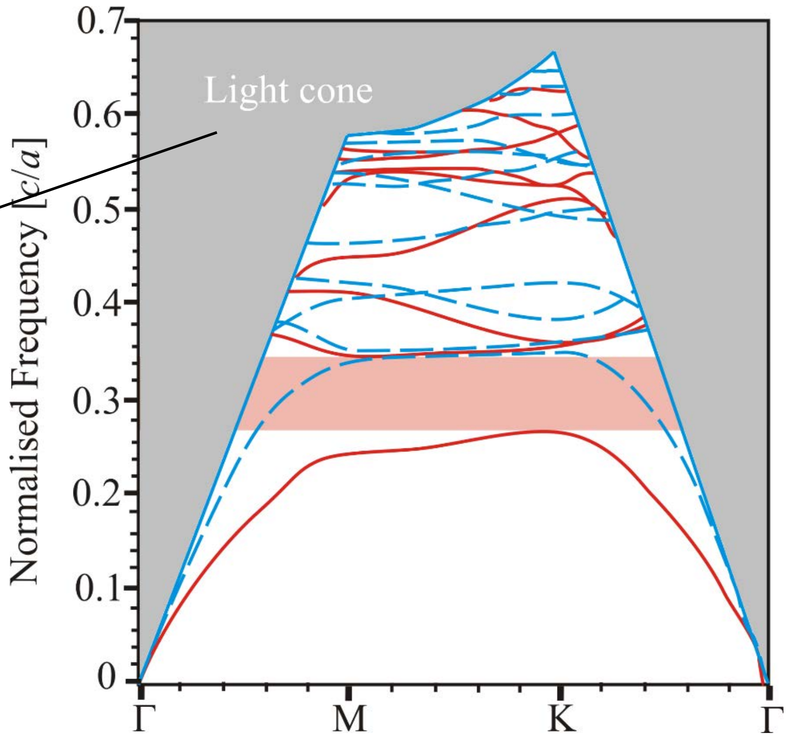
Uses *index guiding effect* (total internal reflection) to confine waves in the third dimension.



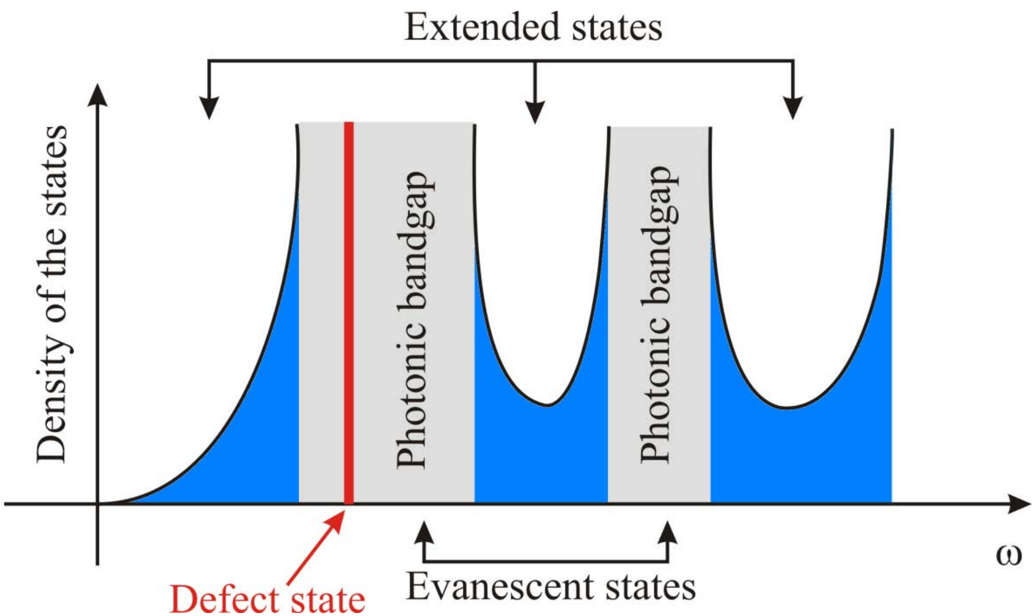
All states in the substrate/superstrate versus in plane k (radiate in the vertical direction)

$$\omega \geq c \cdot |k_{\parallel}|$$

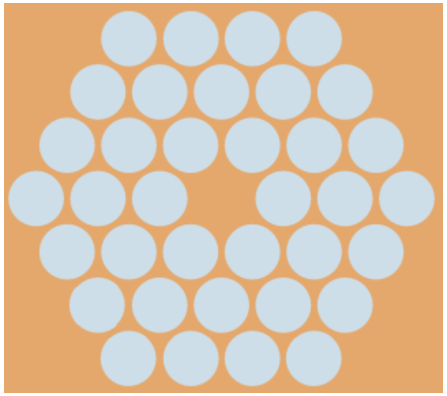
Generally optimum value of thickness around 0.5*a*.



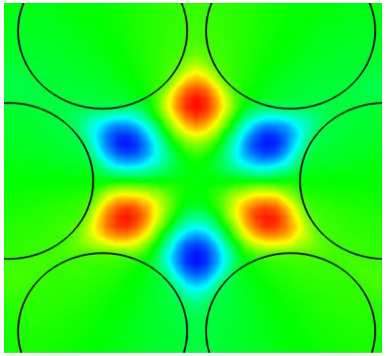
Point defect – PhC cavity



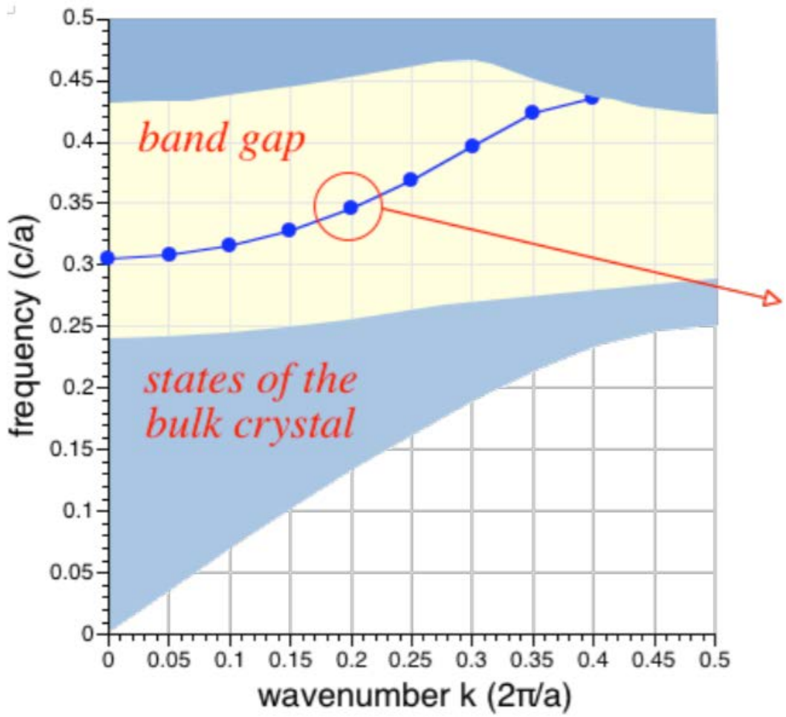
[Joannopoupos, *Photonic Crystals Molding the flow of light*: jdj.mit.edu/book]

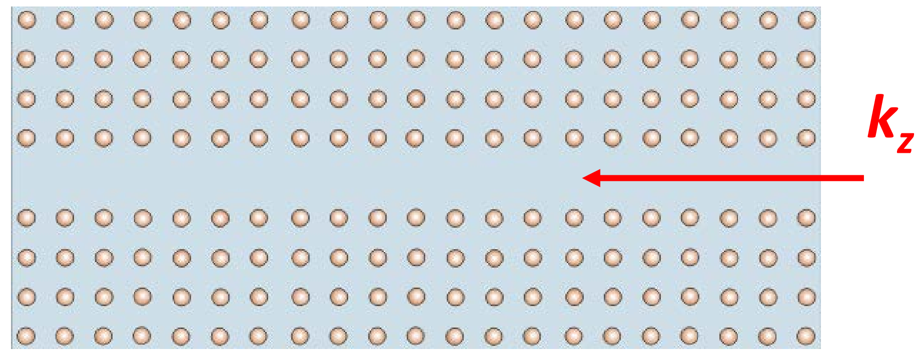


Cavity



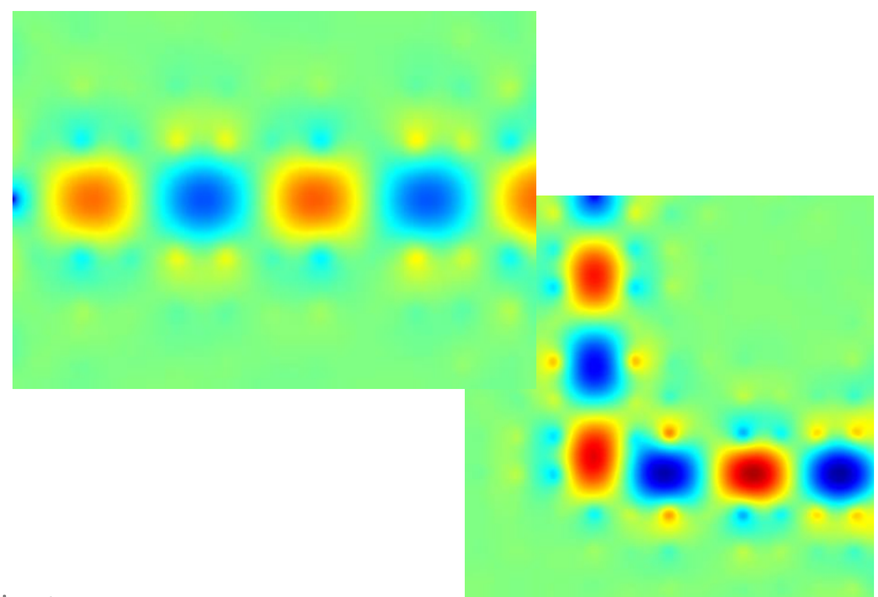
Photonic crystals waveguide





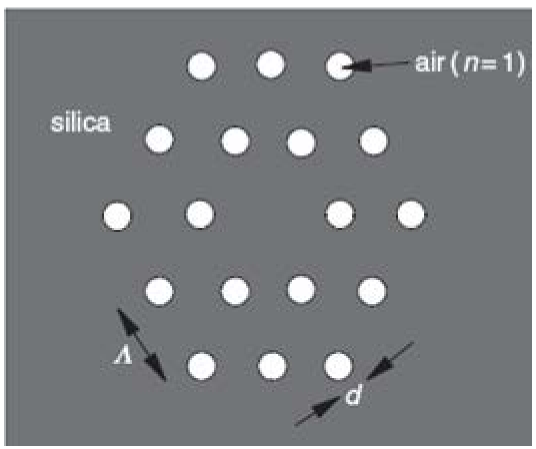
Waveguide

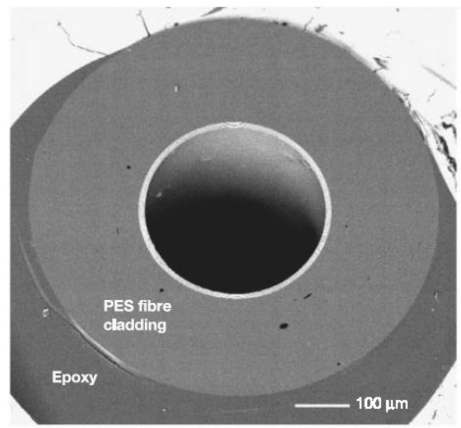
Plot only the ω - k_z diagram where the periodicity is conserved.

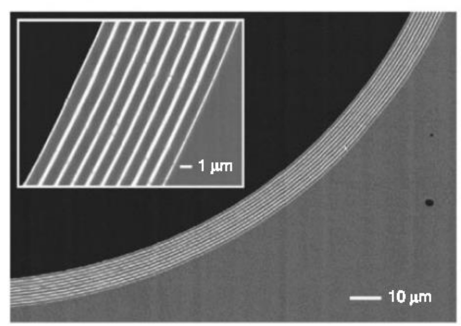


Photonic crystal fibres

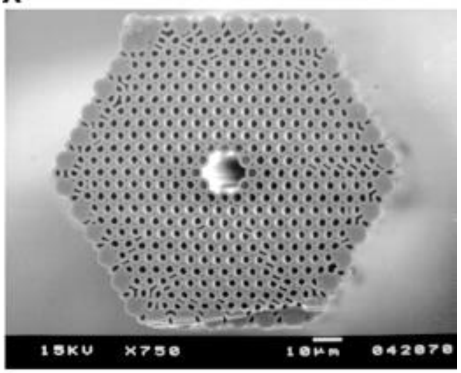
- Wide single mode wavelength range
- large effective mode area
- anomalous dispersion at visible and near IR wavelengths
- Hollow core is allowed (no limited by material absorption)



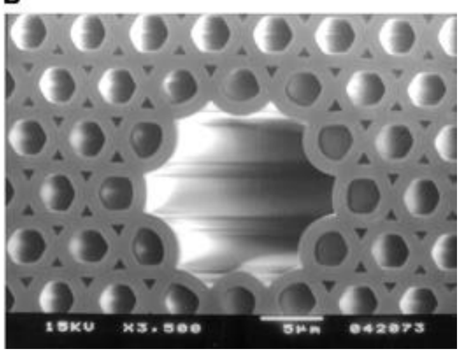




A



B



[R. F. Cregan *et al.*, *Science* **285**, 1537 (1999)]
[B. Temelkuran *et al.*, *Nature* **420**, 650 (2002)]

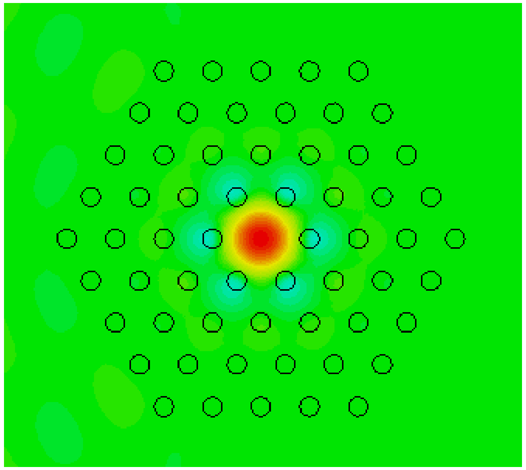
Photonic crystal confinement

- Good confinement depends on the ***contrast of dielectric constant*** within the PhC and thickness of the PhC surrounding the defect.

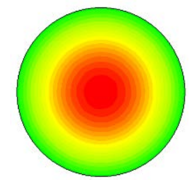
- PhC waveguides and cavities have much larger transverse size than metallic structures (typically order of a single wavelength).

- In PhC stuctures the defect “modes” do not behave exactly as TM modes, however in the centre of the vacuum channel the em properties of these “modes” are very similar to those of accelerating modes in metal cavities.

Photonic crystals cavity



PBG cavity, TM_{01} - like mode



Pillbox cavity, TM_{01} mode

Size/geometry of the defect and filling factor (*f* = pillar radius/period) of the PhC can control the existence of higher order modes.

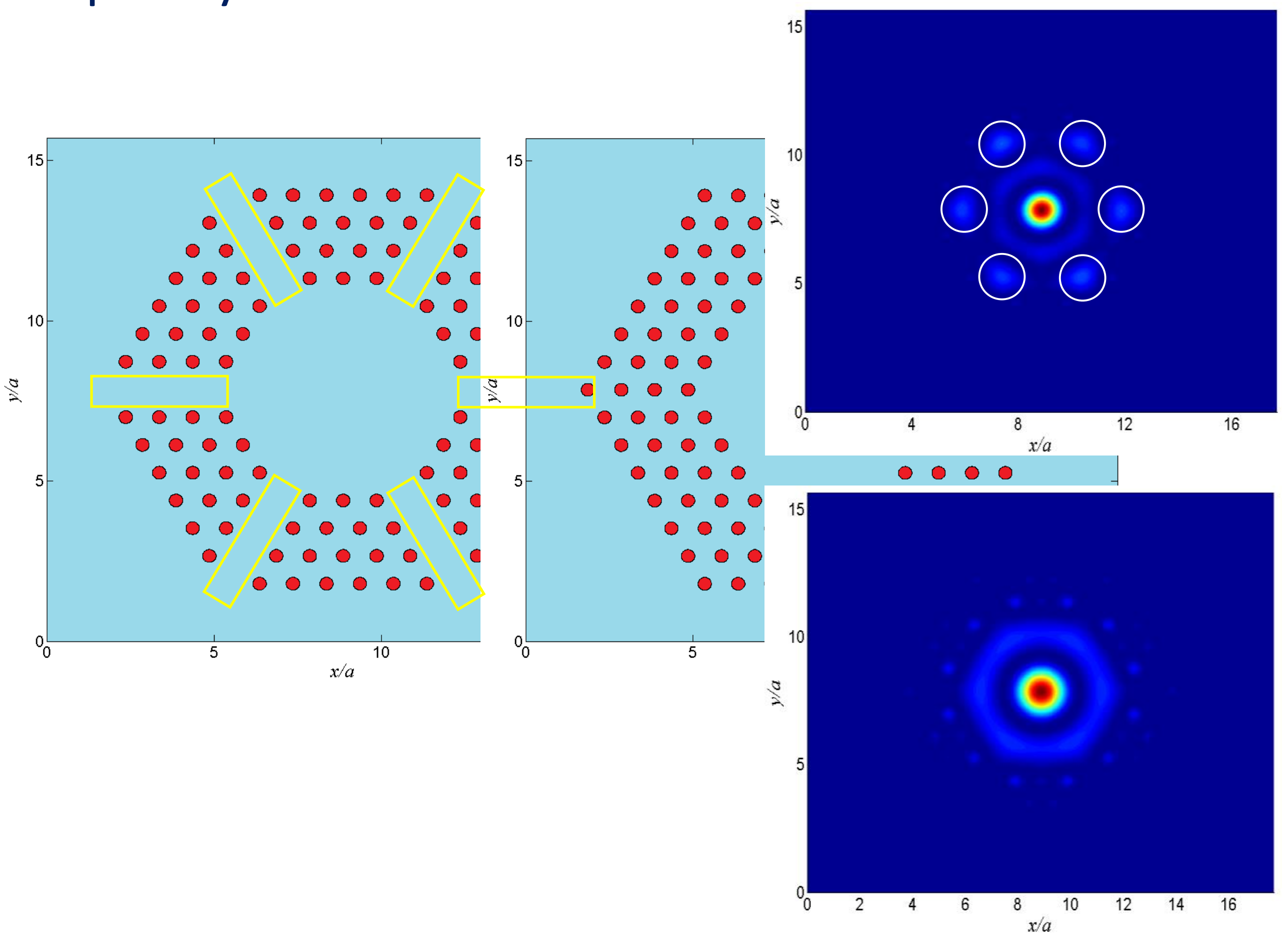
Quality factor: behaviour of the resonant “mode” → $\omega_c = \omega_0 - i\,\gamma/2$

the imaginary part is an exponential decay.

Loss rate is characterised by Υ → $Q = \dfrac{\omega_0}{\gamma}$

Suppression of HOMs

However, PhC cavities can be highly overmoded thus strategies are needed to completely remove (or at least to highly suppress) higher frequency resonant modes



$f_n = 0.38$

~~$Q \cong 1200$~~

$Q \cong 70$

$f_n = 0.27$

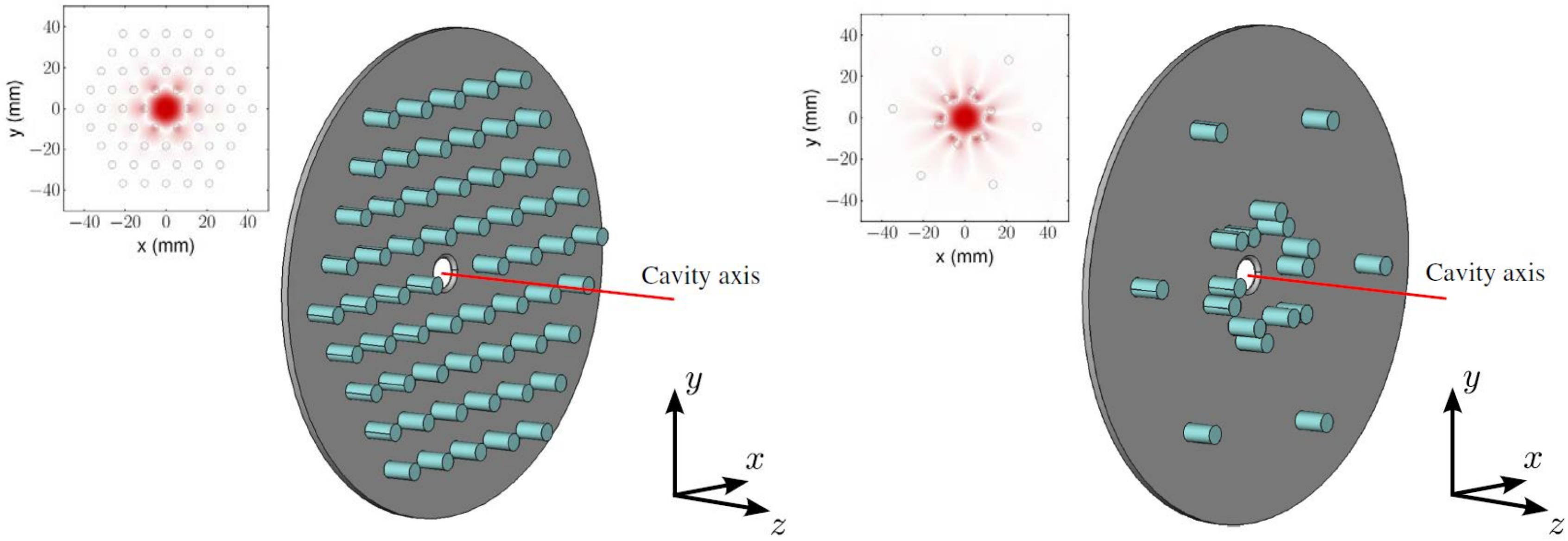
~~$Q \cong 500$~~

$Q \cong 400$

Improving the Q-factor

- Q – factor (radiative) depends on the number of layers surrounding the defect
- Desire to improve confinement while using less layers of surrounding PhC
- Suggested solutions where the principle of PBG does not apply anymore:
    - Photonic quasi-crystals (PhQCs)
    - Irregular structures from numerical techniques for optimisation

Improving the Q-factor

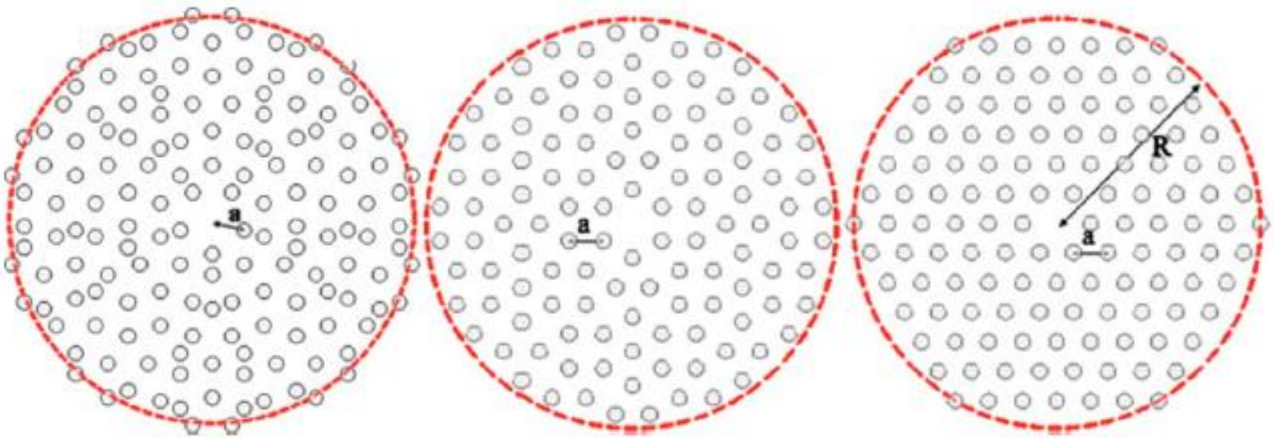


- 18 sapphire rods in optimised position increased Q (radiative) from 130 to 10^4
- No self-consistent theory to calculate the optimum arrangement, result of numerical techniques for optimisation
- More sensitive to rod positions (tighter tolerances)

[Bauer, Werner and Cary, 2008 and 2016]

Photonic quasi-crystals

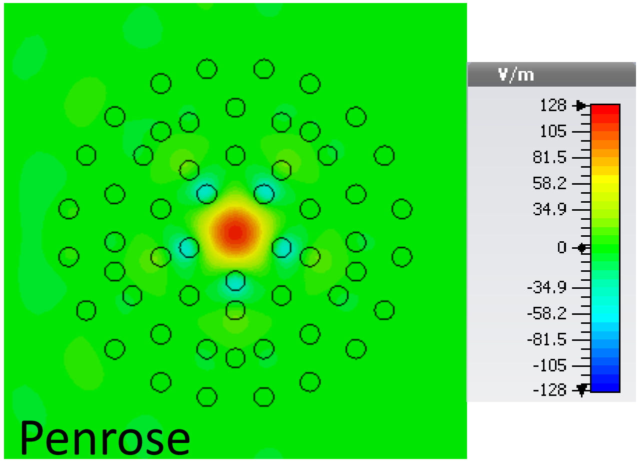
- "Photonic quasicrystals" (PQCs) are based on the so-called aperiodic-tiling geometries characterised by weak rotational symmetry of "non-crystallographic" type.
- In PQCs, the EM response can be strongly dependent on the lattice short-range configuration and an additional degree of freedom for design can come from aperiodicity.

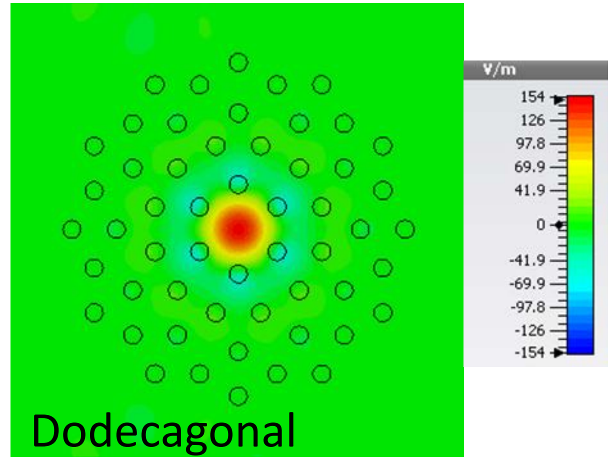


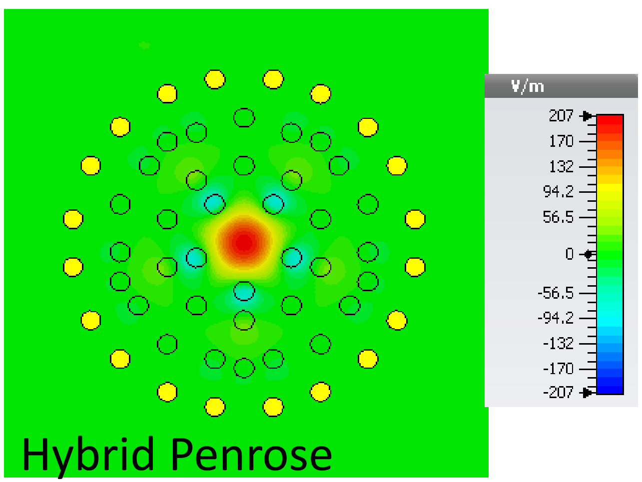
- In terms of quality factor, the quasycristal PhC cavity outperform the counterpart hexagonal lattice PhC
- A prototype of a PQC has been fabricated and tested and it has been shown that hybrid-dielectric structures can be successfully exploited for the design of high-gradient accelerators*

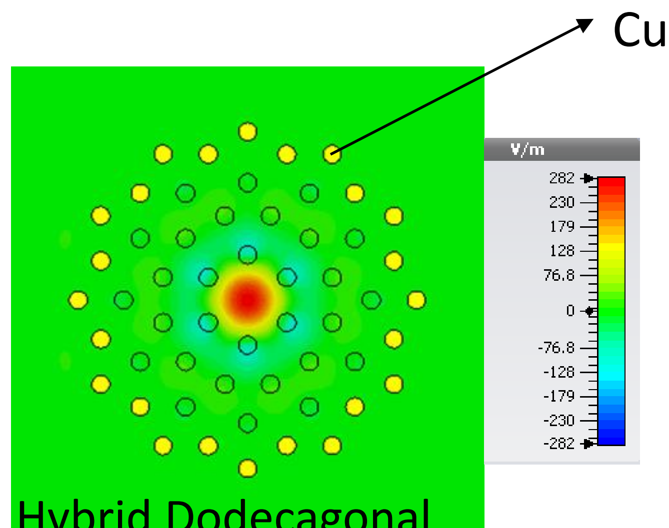
* E. Di Gennaro, *et al.*, Appl. Phys. Lett., **93**, 164102 (2009)

Photonic quasi-crystals cavity









PBG dielectric structures for DLA

- PBG fibre – 2D PBG transverse confinement (Lin 2001)
- Omniguide/ planar Bragg waveguide - 1D PBG confinement, (Mizrahi and Schachter, 2004)
- 2D PBG waveguide – longitudinal confinement (Cowan, 2003)
- Woodpile - 3D PBG confinement, (Cowan 2004)

Novel electromagnetic structures for high frequency acceleration
(Part 3)

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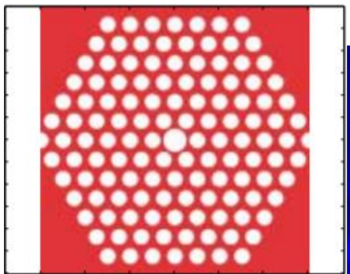
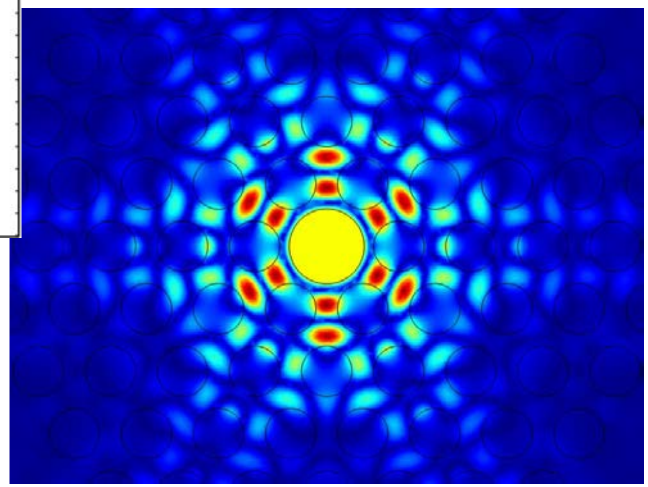
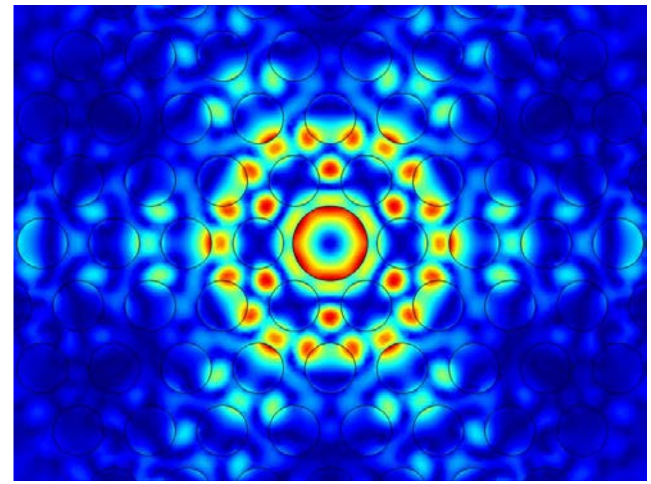
Cockcroft Institute, Spring term, 6/03/17

PBG fibre (Lin 2001)

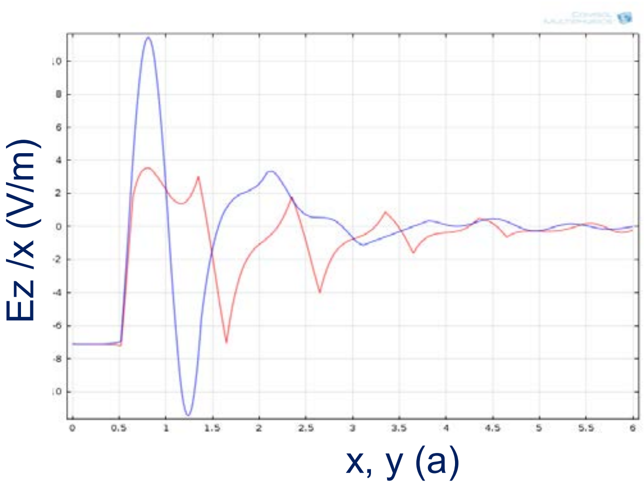
- TM-like defect mode needs to intersect the light line near the centre of the bandgap for good confinement of the mode.





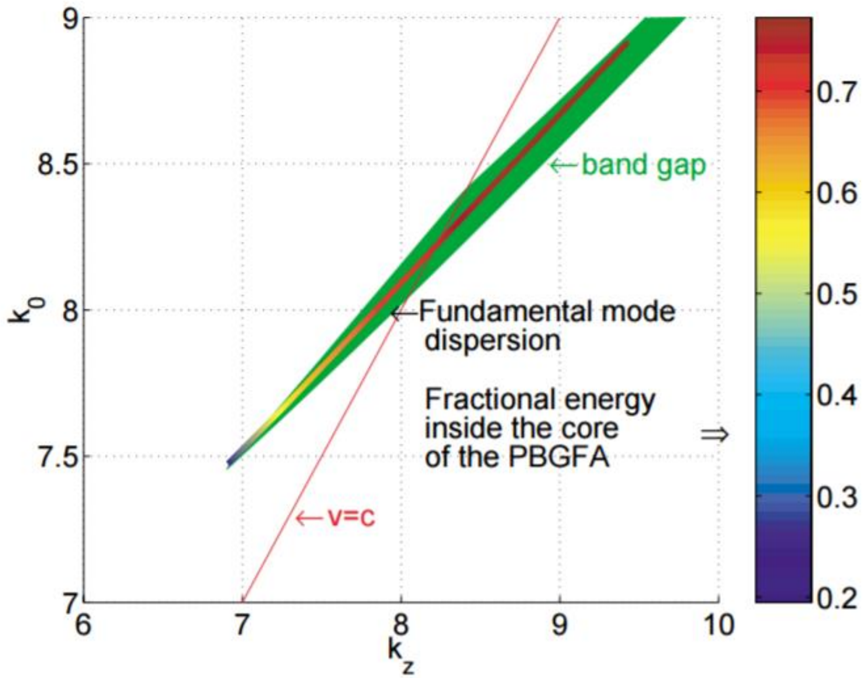


Silica and air. Defect region = R < 0.52 a



- Size of defect determines characteristic impedance and gradient

PBG fibre (Lin 2001)



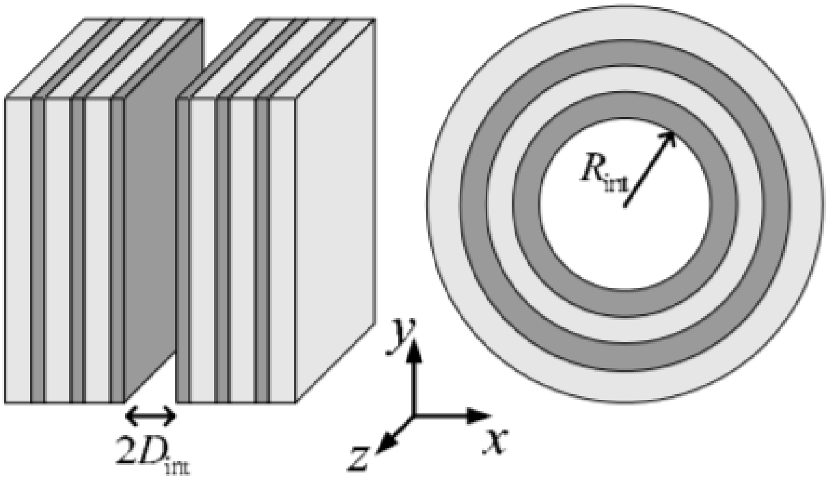
$$R_{int} = 0.68\lambda$$
$$\lambda = 1\mu m$$
$$\varepsilon = 2.1$$

$$Z_c \approx 19.5\Omega$$
$$\beta_g \approx 0.58$$
$$\frac{E_{acc}}{E_{max}} \approx 0.5$$

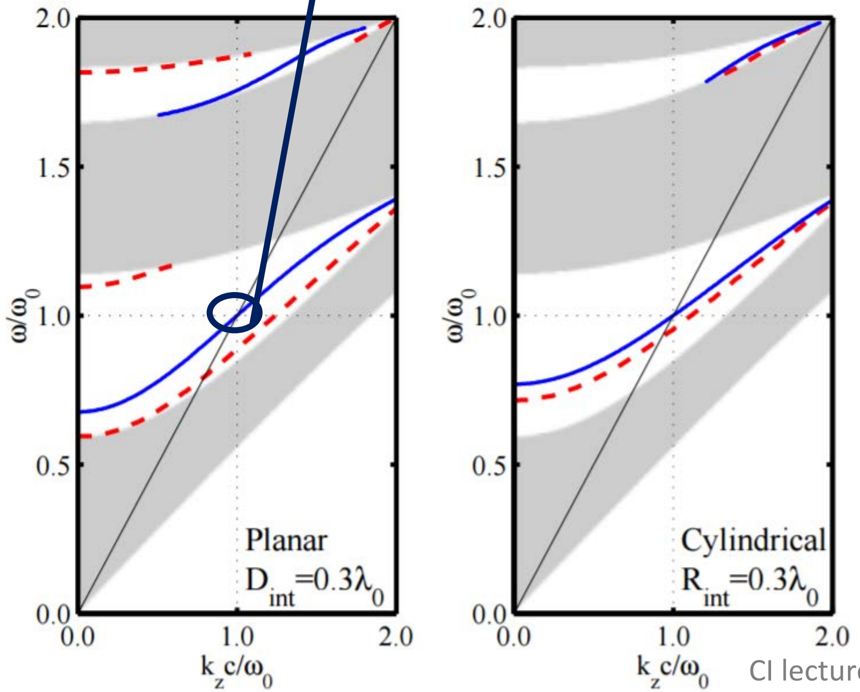
- Modification of the lattice can make just one bandgap
- The impedance increases with smaller defects as $(\lambda/R)^4$

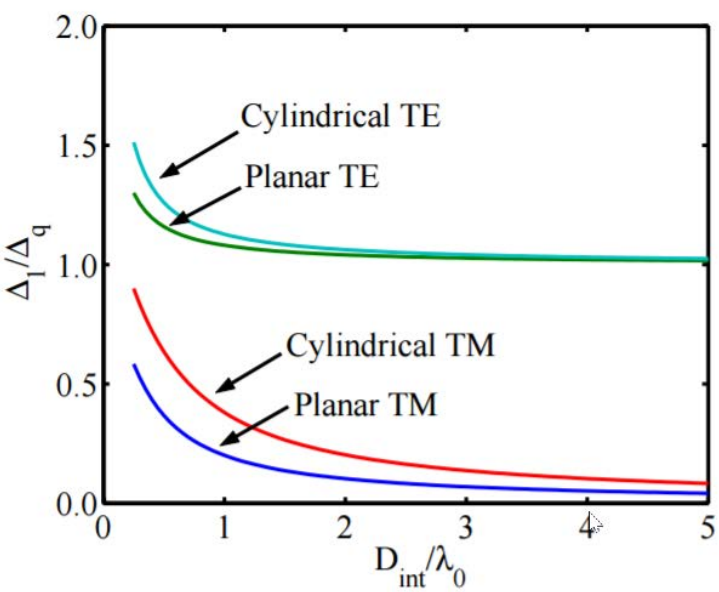
[X. Lin., PR-STAB, **4**, 051301 (2001)]

Bragg waveguide/omniguide (Mizrahi/Schachter 2004)



Inner layer acts as matching layer





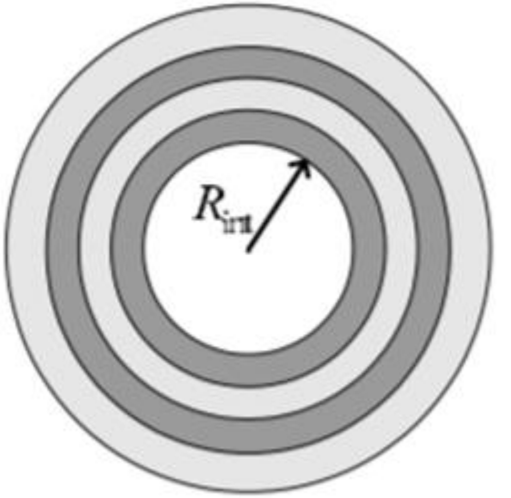
[Mizrahi and Schachter, Opt Express, 12, 3156 (2004)]

Bragg waveguide/omniguide (Mizrahi/Schachter 2004)

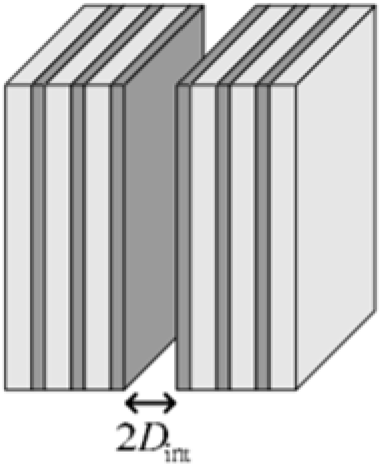
$$R_{\text{int}} = 0.3 - 0.8\lambda$$
$$\lambda = 1\mu m$$
$$\varepsilon_1 = 2.1, \varepsilon_2 = 4$$

$$Z_c \approx 37 - 268\Omega$$
$$\beta_g \approx 0.41 - 0.48$$
$$\frac{E_{acc}}{E_{\max}} \approx 0.37 - 0.73$$

Cylindrical



Planar



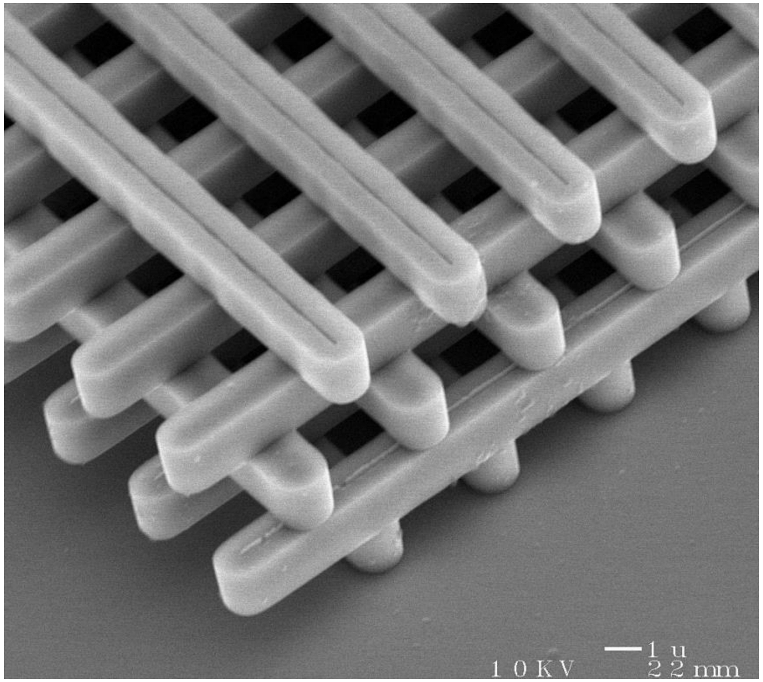
$$D_{\text{int}} = 0.3 - 0.8\lambda$$
$$\lambda = 1\mu m$$
$$\varepsilon_1 = 2.1, \varepsilon_2 = 4$$

$$Z_c \frac{\Delta y}{\lambda} \approx 25.7 - 147\Omega$$
$$\beta_g \approx 0.42 - 0.53$$
$$\frac{E_{acc}}{E_{\max}} \approx 0.20 - 0.47$$

[Mizrahi and Schachter, Opt Express, 12, 3156 (2004)]

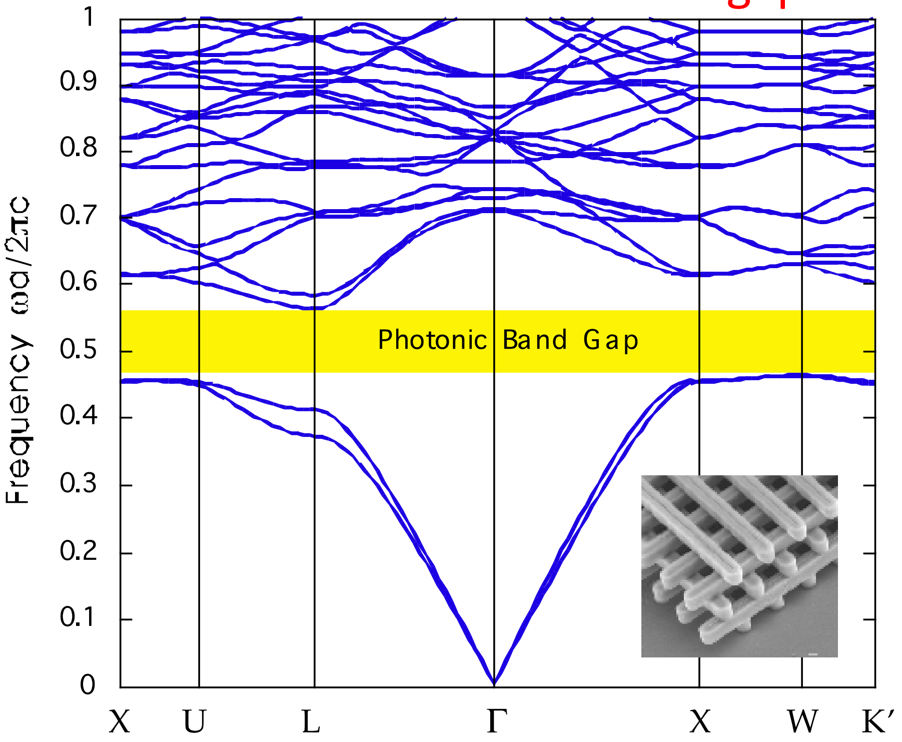
3D PhC - Woodpile structure

Unit cell: 4 layers



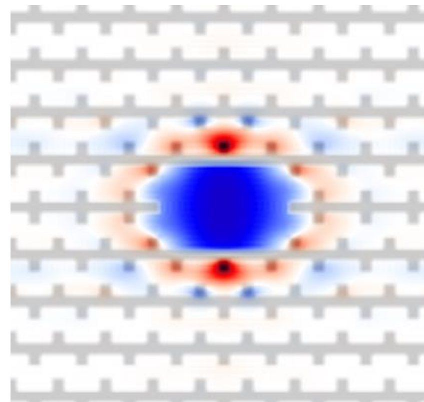
http://www.sandia.gov/media/photonic.htm

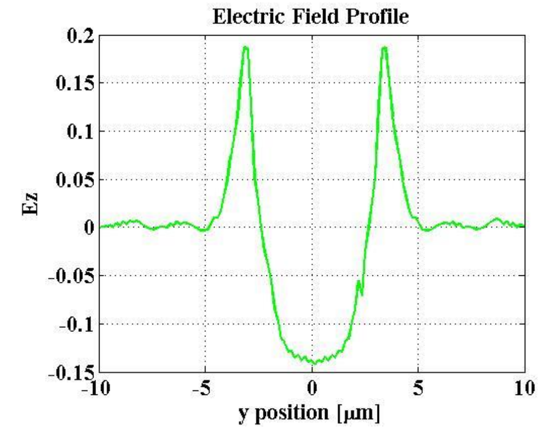
Omnidirectional bandgap



Woodpile structure

Si E_{acc}=337 MV/m
@1550nm

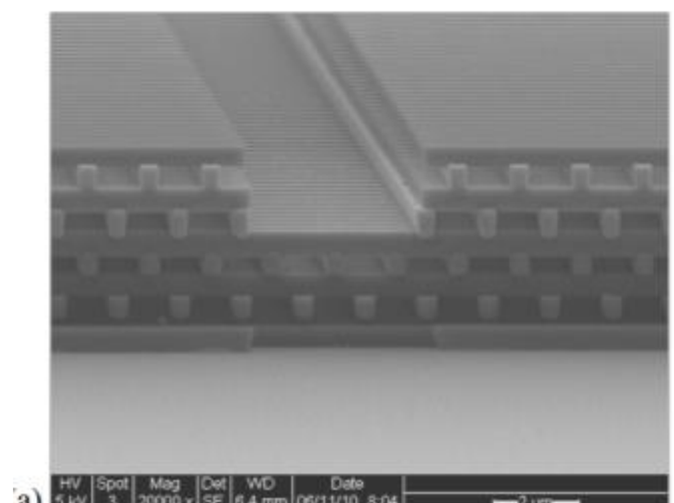




[B. Cowan., Phys Rev. ST Accel. Beams 11, 011301, 2008]

$$a = 565nm$$
$$\lambda = 1.55\mu m$$
$$Si$$

$$Z_c \approx 484\Omega$$
$$E_{acc} \approx 300MV/m$$



[C. McGuinness, 2012]

Summary on PBG waveguides

- Interaction impedance can be enhanced by reducing the defect transverse size and through optimum contrast of refractive index.

- In the Bragg structures the group velocity of the mode does not change significantly while changing defect size.

- 3D PhC structures have the potential to show very high interaction impedance but fabrication is more challenging and material choice might be limited.

Wakefields with dielectric boundaries

- A charged particle bunch passing in proximity of a material boundary will generate em fields at the head of the bunch.
- These can affect the rest of particles within the bunch and following bunches.
- They are both longitudinal and transverse.

- ***Longitudinal wakes:*** reduce the accelerating voltage on the bunch and distort the voltage gain along the bunch from the ideal harmonic form of the externally applied RF (beam loading)
- ***Transverse wakes:*** major source of beam instability (e.g. head-tail instability, emittance growth)

Wakefields with dielectric boundaries

- For a ***metal*** boundary:
  - Resistive metal wall contribution
  - Geometric variation of the boundary contribution (larger)
- For a ***dielectric*** boundary:
  - ***Cherenkov radiation*** condition: if $\beta = v/c > 1/n_r$
  - → the beam will generate wakefields
  - Stronger than wakes from resistive metal walls.
  - In general the RF accelerators theories on beam loading and efficiency can also be applied here.

An estimate of efficiency

- Considering a point charge through a cylindrical or planar dielectric structure, the wake coefficient:

Cylindrical: $$k_l = \frac{1}{\left(2\pi\varepsilon_0 R_{\text{int}}^2\right)}$$

Planar: $$k_l = \frac{1}{\left(4\varepsilon_0 D_{\text{int}}\right)}$$

- Projection of the total deceleration on the fundamental mode λ0, (Bane and Stupakov, 2003):

$$k_{l1} = \frac{\beta_g}{1-\beta_g}\frac{Z_c}{4\varepsilon_0\lambda_0^2 Z_0}$$

- Max efficiency:

$$\eta_{\max} = k_{l1}/k_l$$ → **Optimal charge**

An estimate of efficiency

- For a ***train of microbunches:***
  - Only some excited modes are coherent, the others will detune.
  - Max efficiency of train of bunches acceleration was given by Schachter (2004) at $q_{opt} \cong G_0 \xi / k_l$

$$\eta_{t-\max} \cong 12(1-\beta_g)\beta_g^2 \xi \frac{(1-\xi)}{(\xi^2 + 3\beta_g^2)}$$

$$\xi = 3\beta_g^2 \left(\sqrt{1+\beta_g^{-2}} - 1\right)$$ and $$k_l = 1/2\pi\varepsilon_0 R_{eff}^2$$

- ***Depends strongly on group velocity***
- Note: G_0 = initial gradient set by the input laser

Wake impedance in dielectric structures

- In terms of wake impedance, the wakefield can be expressed as

$$Z_w = \frac{\left|E_{dec}\lambda\right|^2}{P_w} = \frac{Z_0\lambda^2}{2\pi R_{eff}}$$

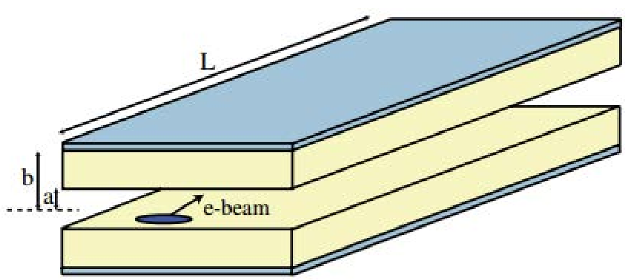
Self decelerating field of the particles

Effective radius of the waveguide beam channel

Structures with one wide transverse dimension

- ***Wide aspect ratio structures*** (one wide transverse dimension) permits the acceleration of relatively large fluxes of charge despite the short wavelength.

- Beam can take asymmetric shape, e.g. rms beam size $\sigma x >> \sigma y$.
  - Limitation of beam loading effect
  - Limitation of space charges by the geometric spreading of beam in x
  - Transverse wakefields are greatly reduced
  - An example: Andonian et al. (2012)



Requirements on the electron beam

- Optical structures naturally have ***sub-fs*** time scales and favour high repetition rate operation

- Typical e- beam required: bunch charge 10-20 fC, bunch length < 1ps, bunch radius has to match the transverse size of the optical accelerating structure, energy of 1 MeV, repetition rate > 10 MHz.

- The bunch length is much longer than accelerating wavelength → the optical accelerator produces bunches with a ***very large energy spread***.

- To improve the quality of the e^- beam and make a more efficient use of the initial charge the beam should be ***"micro-bunched"*** (particles need to fit individual acceleration buckets).

Injection: low-beta DLA structures

- Low-beta DLA structures are relevant as ***pre-acceleration stage*** (from tens of keV to 1 MeV) to solve the low-energy injection problem
- Also applications for proton, ion acceleration
- Structure geometry needs to change as particle velocity increases (synchronous approach)
- Asynchronous approach also possible
- Mm-wave Mizuno et al (1987)
- Mc Neur et al (2012)
- NIR, Breuer and Hommelhoff (2014)

Sub-relativistic acceleration

The Cockcroft Institute of Accelerator Science and Technology

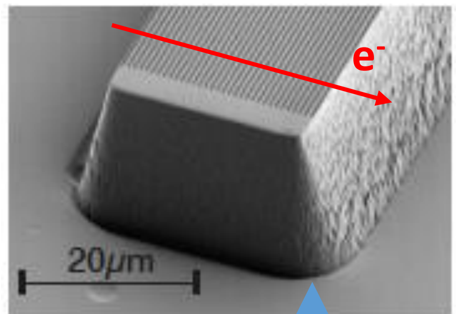
Lancaster University

- Demonstrated acceleration of 28 keV electrons in open grating of fused silica (110 fs, 800 nm laser) → gradient up to 25 MV/m

Synchronism:

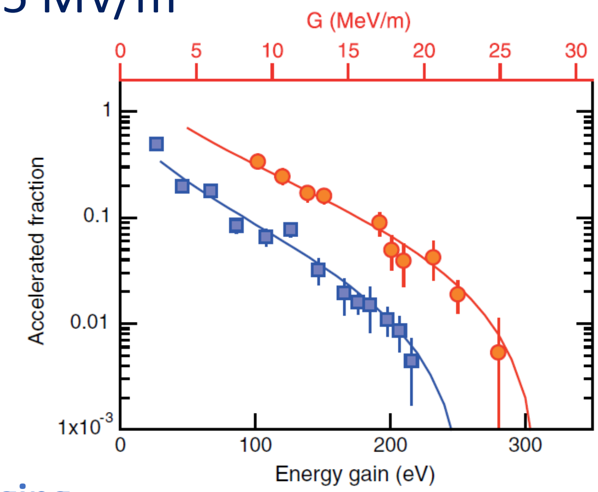
$$\beta c = v_{ph} = \frac{ca}{n\lambda}$$

$$\beta = \frac{a}{n\lambda}$$



Laser

Thin metal coating to prevent charging

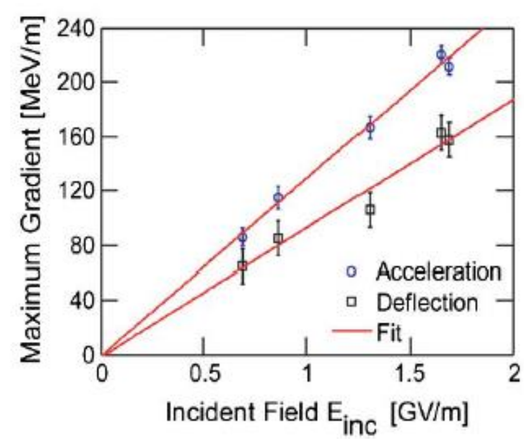


[J. Breuer, P. Hommelhoff, 2013]

***a*: grating period**

***n*: order of the spatial harmonic**

- Demonstrated acceleration of 96 keV electrons in silicon open grating (130 fs, 907 nm laser) → up to 200 MeV/m



[K. J. Leedle et al, 2015]

Limitations on structures and materials

- Structures:
  - Dephasing
  - Damage threshold
  - Heat dissipation at the outer boundaries (planar structures may be preferred at optical frequency)

- Materials:
  - Degradation with high field and radiation exposure
  - Charging and multipactoring
  - Thermal conductivity of the material
  - Nonlinear polarizability and Raman scattering

Terahertz acceleration

- To achieve GV/m, only need THz frequency acceleration

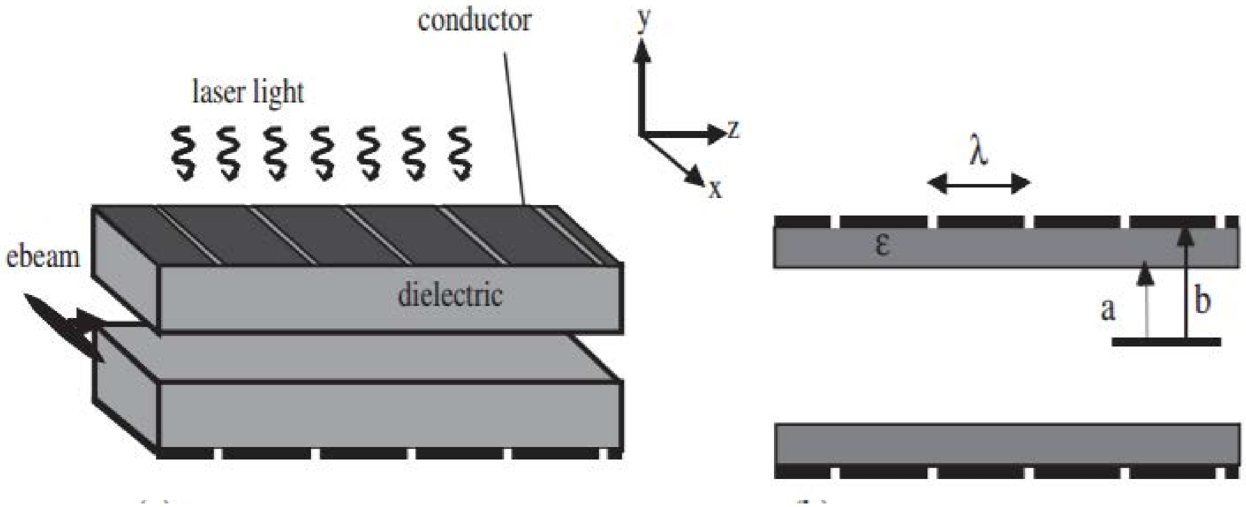
- Significant increase of beam quality

- Main challenges in this range:
  - Metal displays high losses → the design of high-Q cavities is precluded and dissipated energy at the metal walls is much higher than at RF regime

  - Limited THz high power sources

- The advent of efficient coherent THz pulse generation techniques has made acceleration in waveguides possible

Terahertz acceleration – simulation results



- 100 MeV/m computed for 100 MW laser pulse at 340 μm.
- Proposal for side coupling method
  - geometry of the slots is critical for frequency detuning and field distortion
  - Study of wakefields/Smith Purcell effect from slots

[R. B. Yoder and J. B. Rosenzweig, PR-STAB, 8, 2005]

Terahertz acceleration – simulation results

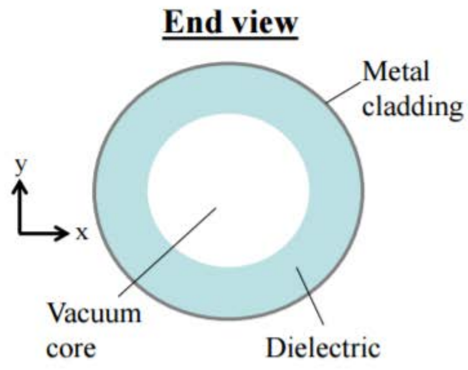
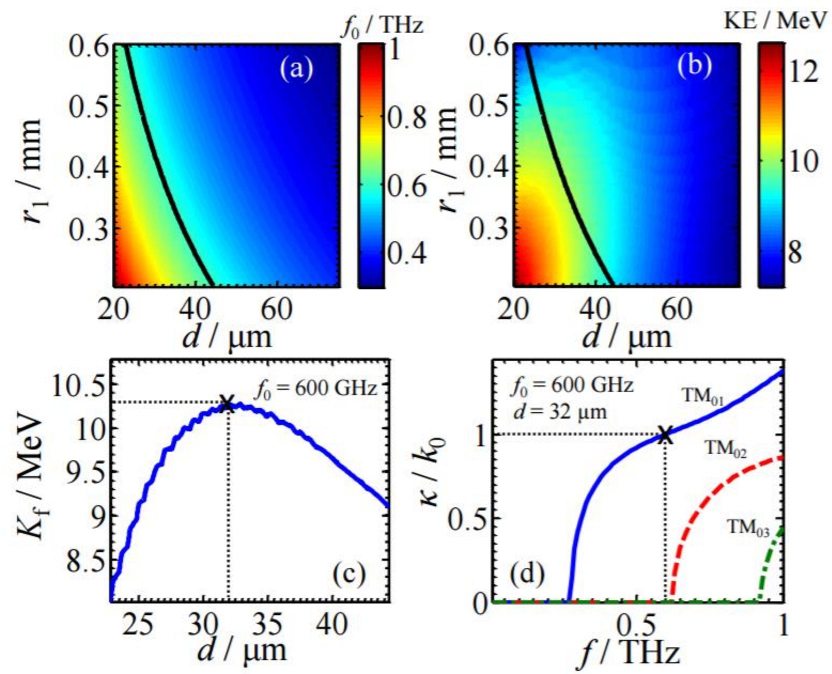


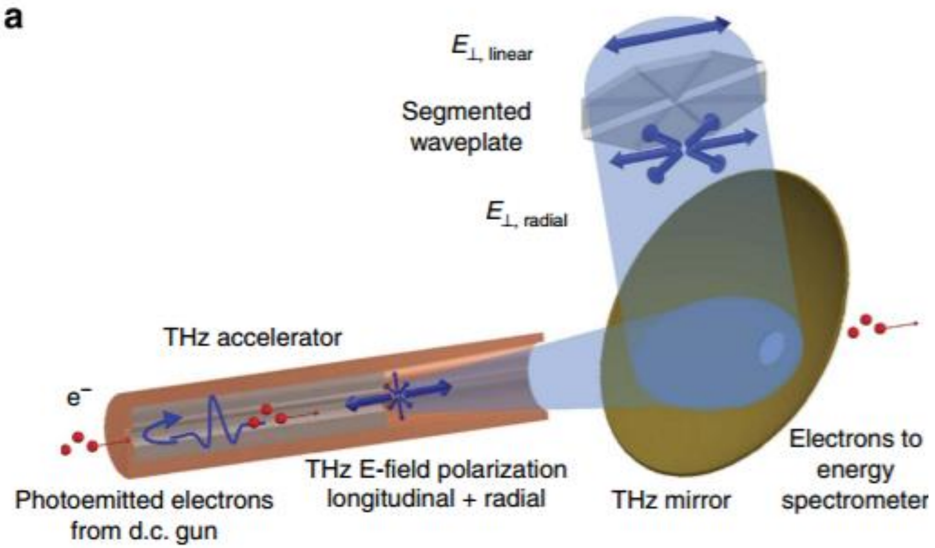
Fig. 2. Schematic of proposed waveguide and simulation setup. In this study, the dielectric is diamond ($\varepsilon_r = 5.5$). The initial relativistic electron bunch is shot through the THz pulse, which propagates at a non-relativistic group velocity.



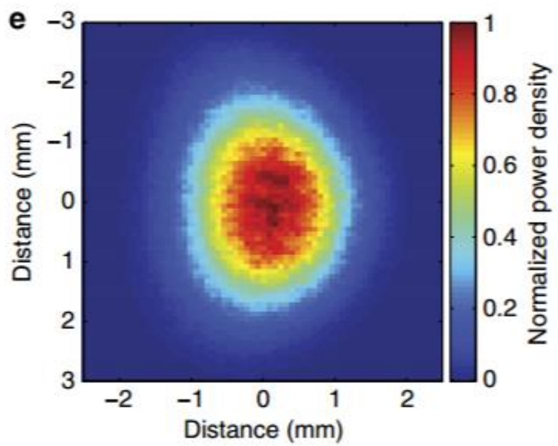
- 1.6 pC electron bunch, 1 MeV → 10 MeV using 20 mJ 10-cycle 0.6 THz pulse
- Optimisation of the dielectric lined waveguide

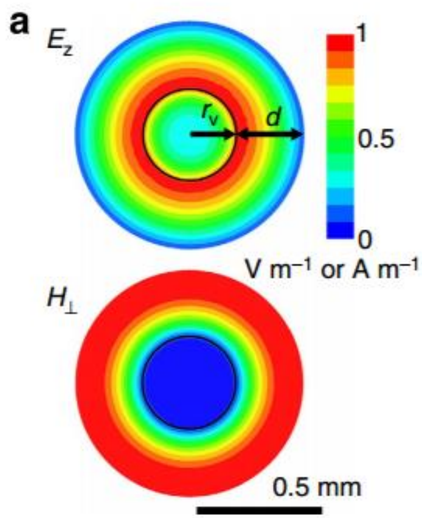
[Wong et al, Optics express, 21, 8, 2013]

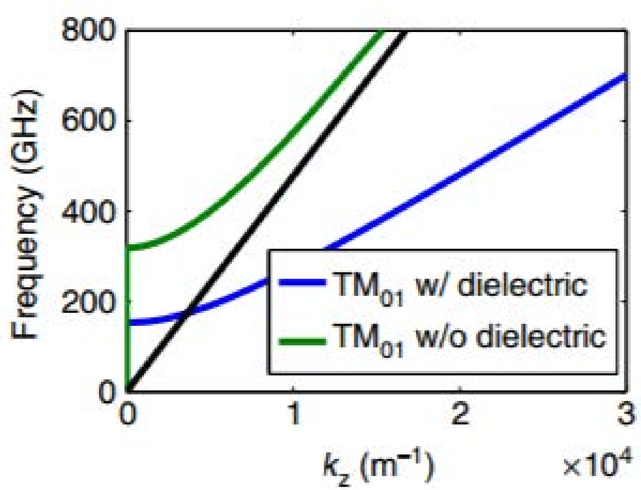
Terahertz acceleration – demonstration



- 2.5 MeV/m acceleration demonstrated for bunch in phase with THz pulse







[E. A. Nanni et al., THz driven linear acceleration, Nat. Commun. 6, 8486 (2015)]

Terahertz acceleration – demonstration

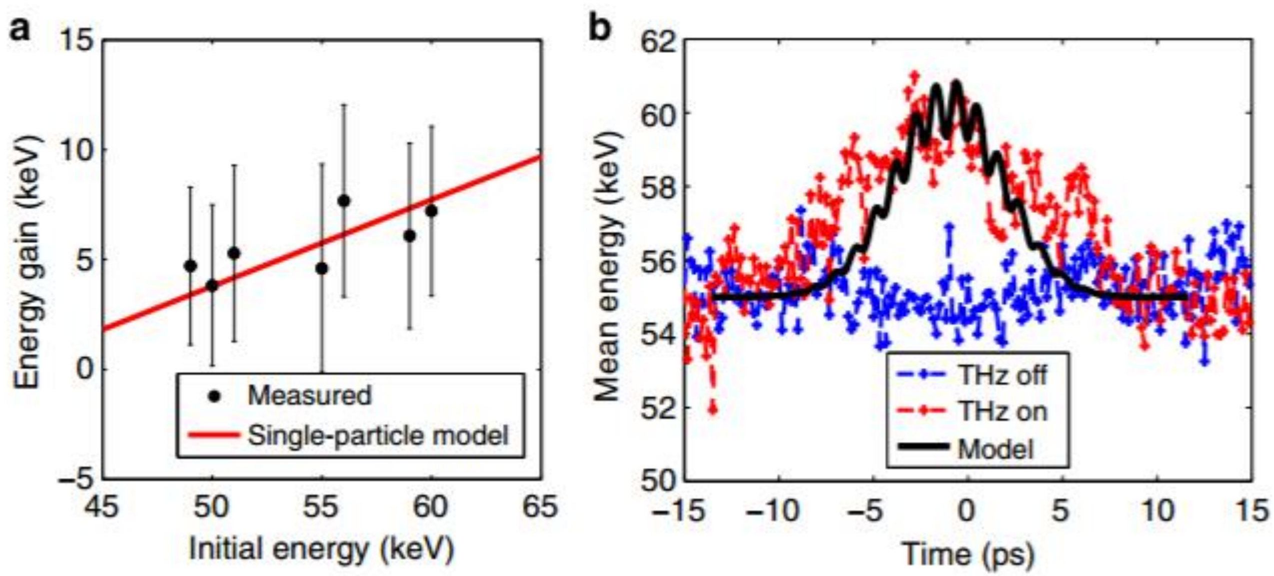


Figure 3 | Acceleration gradient and terahertz phasing. (**a**) Scaling of energy gain for accelerated electrons as a function of the initial electron energy at the entrance of the THz LINAC. Black dots with one s.d. error bars are measured values and the red line is a single-particle model. (**b**) The temporal profile for the mean energy gain of accelerated electrons comparing the THz on and THz off signal against the simulated electron bunch. The initial electron energy was set at 55 keV to ensure stable performance of the d.c. electron gun over the acquisition time of the data set.

[E. A. Nanni et al., THz driven linear acceleration, Nat. Commun. 6, 8486 (2015)]

Conclusions

- High frequency acceleration can provide high gradient, extremely compact and low cost particle accelerators.
- Concepts exist from the THz to the optical frequency range.
- Structures are mainly all-dielectric and travelling wave based on PhC waveguides.
- Proof-of-concept experiments are taking place.
- Challenges: low-beta acceleration, power coupling, beam transport, material?, longer wavelength high power laser?, …