Photonic crystals, PHYS-605

Ecole doctorale photonique

Romuald Houdré

Summer semester 2017

I History

History of photonic crystals

- ✳ Prehistory and pioneers
- ✳ Official birth 1987
- ✳ Setting up of the main concepts 1987 - 2000
- ✳ Current trends

Prehistory

Lord Rayleigh (1842-1919), Philos. Mag. 24, 145-159 (1887)

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

AUGUST 1887.

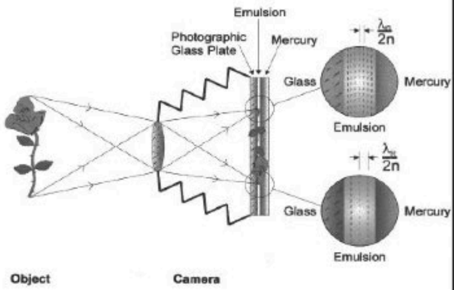
XVII. *On the Maintenance of Vibrations by Forces of Double Frequency, and on the Propagation of Waves through a Medium endowed with a Periodic Structure. By* Lord RAYLEIGH, *Sec. R. S., Professor of Natural Philosophy in the Royal Institution*.*

Philos. Mag. 34, 481-502 (1892) and many other papers

LVI. *On the Influence of Obstacles arranged in Rectangular Order upon the Properties of a Medium. By* Lord RAYLEIGH, *Sec. R.S.**

Prehistory

G.Lippmann (1845-1921), color photography



Probably the first to fabricate "photonic crystal" structures

ca. 1891-1899

Prehistory

G. Floquet (1847-1920), Annales Scientiques de l'Ecole Normale Supérieure, 12, 48-88 (1883)

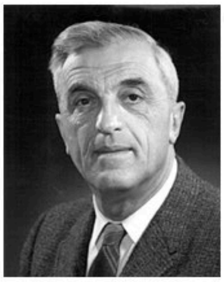
SUR LES

ÉQUATIONS DIFFÉRENTIELLES LINÉAIRES

A COEFFICIENTS PÉRIODIQUES,

PAR M. G. FLOQUET,

F. Bloch (1905-1983), Zeitschrift für Physik, 52, 555-600 (1928)



Über die Quantenmechanik der Elektronen in Kristallgittern.

Von **Felix Bloch** in Leipzig.

$$\psi_{klm}(x\,y\,z) = e^{2\pi i\left(\frac{kx}{a\,G_1} + \frac{ly}{b\,G_2} + \frac{mz}{c\,G_3}\right)} \cdot u_{klm}(x\,y\,z),$$

Pioneers

Control of spontaneous emission, **E.M. Purcell** (1912-1997), 1946

PHYSICAL REVIEW VOLUME 69, NUMBERS 11 AND 12 JUNE 1 AND 15, 1946 pp. 681

B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University.*

The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2 V$, Purcell factor

Propagation in periodic medium, **F. Abelès** (1922-2005),1946 and latter

SUR LA PROPAGATION DES ONDES ÉLECTROMAGNÉTIQUES DANS LES MILIEUX STRATIFIÉS

Considers the case of a periodic stack

Par FLORIN ABELÈS

Ann. de Phys., 12e Série, t. 3 (Juillet-Août 1948). pp. 504-520

Control of spontaneous emission, V.P. Bykov, 1972

SOVIET PHYSICS JETP VOLUME 35, NUMBER 2 AUGUST, 1972 pp. 269-273

Spontaneous Emission in a Periodic Structure

V. P. BYKOV

Submitted May 31, 1971
Zh. Eksp. Teor. Fiz. **62**, 505–513 (February, 1972)

opacity band.
Forbidden electromagnetic bandgap
transparency band,

electromagnetic field which cannot propagate in a periodic structure.

Propagation in a stratified medium, P. Yeh, **A. Yariv**, 1976

Electromagnetic propagation in periodic stratified media. I. General theory*

Pochi Yeh, Amnon Yariv, and Chi-Shain Hong
California Institute of Technology, Pasadena, California 91125
(Received 8 November 1976)

Bloch waves, the dispersion relations, and the band structure

423 J. Opt. Soc. Am., Vol. 67, No. 4, April 1977

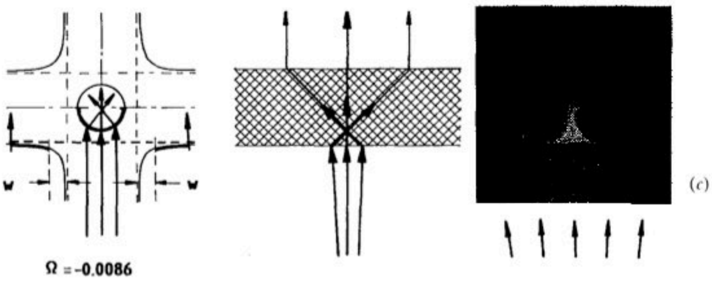
Propagation in a stratified medium, **R. Zengerle**, 1970-1987

JOURNAL OF MODERN OPTICS, 1987, VOL. 34, NO. 12, 1589–1617

Light propagation in singly and doubly periodic planar waveguides

R. ZENGERLE
Forschungsinstitut der Deutschen Bundespost,
P.O. Box 5000, D-6100 Darmstadt, F.R. Germany

(*Received 7 September 1987*)



Abstract. Light propagation in singly and doubly periodic planar waveguides is investigated with respect to future applications in integrated optics. The

Use of equi-frequency surfaces and reciprocal space.
Theory *and* experiment

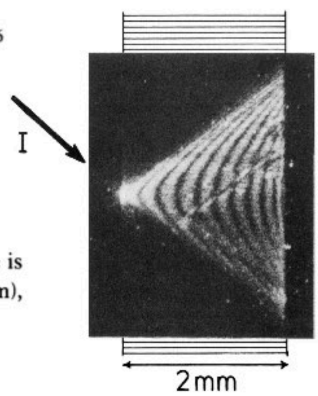
Propagation in a stratified medium, **P.St. Russell**, 1986

PHYSICAL REVIEW A VOLUME 33, NUMBER 5 pp. 3232-3242 MAY 1986

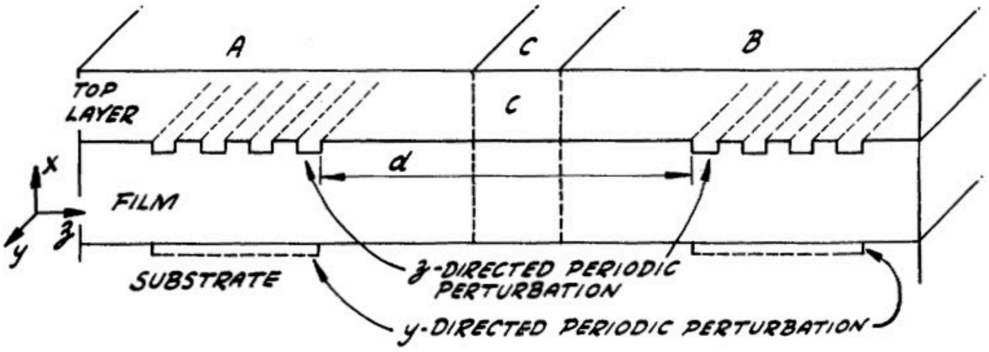
Interference of integrated Floquet-Bloch waves

P. St. J. Russell
IBM Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598
(Received 16 September 1985)

terference, producing, respectively, real and virtual spatial fringes. In the paper considerable use is made of a reciprocal-space representation of the Floquet-Bloch waves (the wave-vector diagram),



S. Wang and S. K. Sheem, Two dimensional distributed feedback devices and lasers
US patent publication US-3,884,549 A, 1975



Optical devices and waveguides using a thin film optical waveguide having a two dimensional array of perturbations associated therewith or with adjacent optically coupled layers. The array is regular and forms

Laser and Bragg waveguide, V.A. Sychugov, 1980

Thin-film laser based on a Bragg waveguide

V. A. Sychugov, A. V. Tishchenko, and A. A. Khakimov

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow
(Submitted April 3, 1980)
Kvantovaya Elektron. (Moscow) 7, 2254–2256 (October 1980)

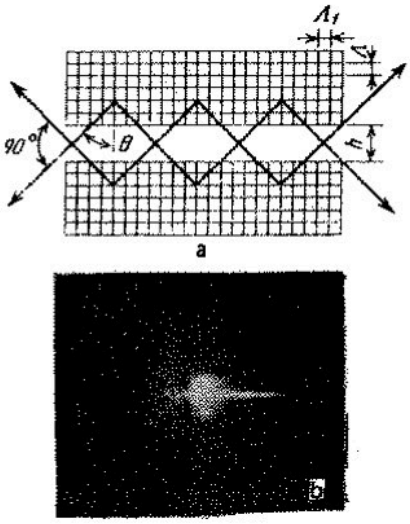


FIG. 2. Bragg-waveguide laser (a) and a photograph of track of laser beams (b).

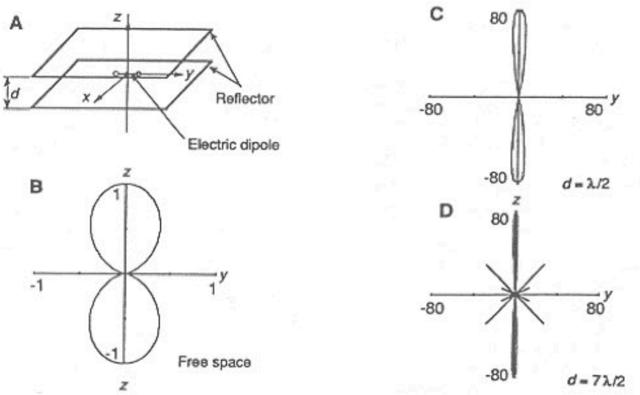
1314 Sov. J. Quantum Electron. 10(10), Oct. 1980 0049-1748/80/101314-02$02.40

Some scientific interests in semiconductor optics by the late 1980 and early 1990

H. Yokoyama, "Physics and Device Applications of Optical Microcavities", *Science* **256**, 66 (1992)

Physics and Device Applications of Optical Microcavities

H. Yokoyama



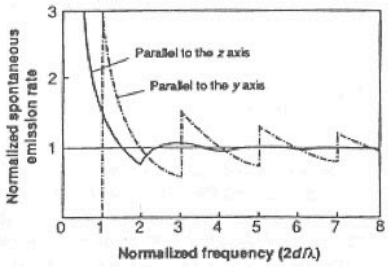


Fig. 2. Change in the spontaneous emission rate of an electric dipole in a planar microcavity as a function of the dipole oscillation frequency for two different dipole orientations. The spontaneous emission rate is normalized by the free space value, and the normalized frequency is given by the ratio $2d/\lambda$.

Control of spontaneous mission, emission pattern and radiative lifetime

Some scientific interests in semiconductor optics by the late 1980 and early 1990 :

VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992 pp. 3314-3317

Observation of the Coupled Exciton-Photon Mode Splitting in a Semiconductor Quantum Microcavity

C. Weisbuch,[a] M. Nishioka,[b] A. Ishikawa, and Y. Arakawa
Research Center for Advanced Science and Technology, University of Tokyo, 4-6-1 Meguro-ku, Tokyo 153, Japan
(Received 12 May 1992)

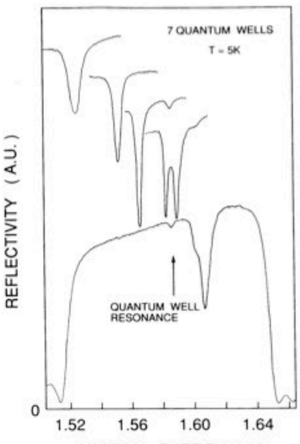


FIG. 2. 5-K reflectivity curves on a seven-QW microcavity structure. Various detuning conditions between cavity and QW exciton frequencies are obtained by choosing various points on the wafer, typically 0.5 mm apart. Note the line narrowing approaching and at resonance, the resonance mode splitting, and the indication of a light-hole exciton mode splitting around 1.605 eV for the lowest trace.

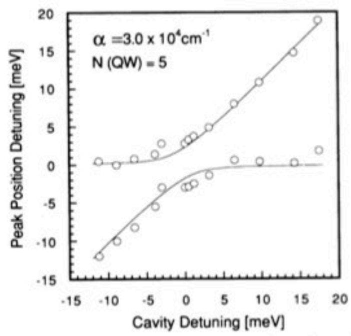


FIG. 3. Reflectivity peak positions as a function of cavity detuning for a five-quantum-well sample at $T = 5$ K. The theoretical fit is obtained through a standard multiple-interference analysis of the DBR–Fabry-Pérot–quantum-well structure.

Trends : Implement in solid state physics the concepts developed in atomic physics

The official birth ...

Control of spontaneous emission, **E.Yablonovitch**, 1987

VOLUME 58, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1987

pp. 2059-2061

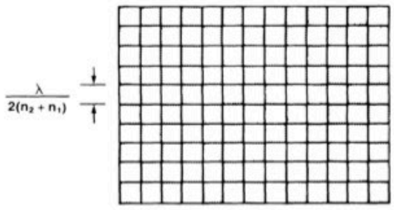
Inhibited Spontaneous Emission in Solid-State Physics and Electronics

Eli Yablonovitch

Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701

(Received 23 December 1986)

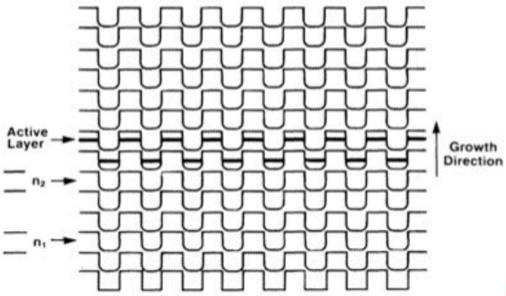
junction bipolar transistors, and solar cells. If a three-dimensionally periodic dielectric structure has an electromagnetic *band gap* which overlaps the electronic *band edge,* then spontaneous emission can be rigorously forbidden.



(a)

dex can result in a forbidden gap in the electromagnetic spectrum near the wavelength λ *irrespective of propagation direction,* just as the electronic spectrum has a band

Omnidirectionality



(b)

With a sufficiently large difference in refractive index between n_1 and n_2, a gap will open up in the electromagnetic density of states. The idea here is for the gap or

Minimum
index contrast

The official birth ...

Control of spontaneous emission, **E.Yablonovitch**, 1987

VOLUME 58, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1987

pp. 2059-2061

Inhibited Spontaneous Emission in Solid-State Physics and Electronics

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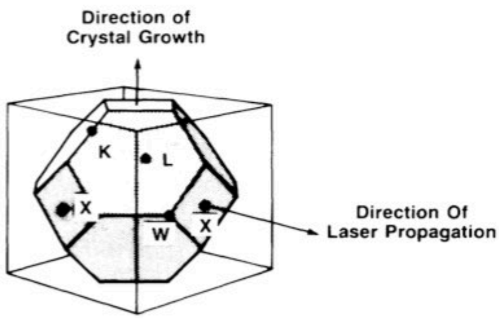


(c)

of the electromagnetic band gap can be explored in such experimental systems as hexagonal-close-packed glass or polystyrene spheres.

Opals

Proposal of 3D structure
fabricated by epitaxy

The official birth ...

Light Anderson localization, **S. John**, 1987

VOLUME 58, NUMBER 23 PHYSICAL REVIEW LETTERS 8 JUNE 1987

Strong Localization of Photons in Certain Disordered Dielectric Superlattices

Sajeev John
Department of Physics, Princeton University, Princeton, New Jersey 08544
(Received 5 March 1987)

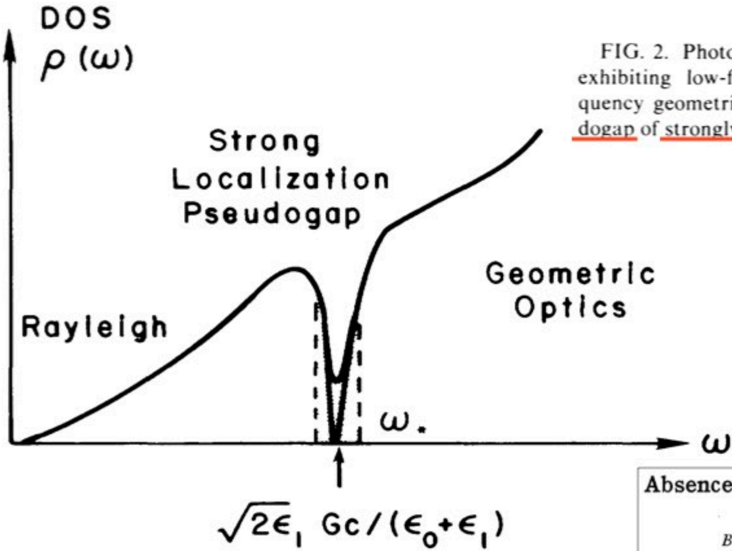


FIG. 2. Photon density of states in a disordered superlattice exhibiting low-frequency Rayleigh scattering and high-frequency geometric-optics extended states separated by a pseudogap of strongly localized photons.

Absence of Diffusion in Certain Random Lattices

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 10, 1957)

The official birth ... a chaotic birth

First attempt in the microwave domain

VOLUME 63, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1989

pp. 1950-1953

Photonic Band Structure: The Face-Centered-Cubic Case

E. Yablonovitch and T. J. Gmitter
Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701-7040
(Received 25 July 1989)

mensionally periodic face-centered-cubic (fcc) dielectric structures. This can produce a "photonic band gap" in which optical modes, spontaneous emission, and zero-point fluctuations are all absent. In the

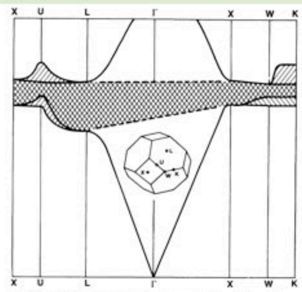


FIG. 2. The experimentally observed photonic band structure in reciprocal space of the 86% spherical-air-atom crystal. The right-sloping lines represent polarization parallel to the X plane, while the left-sloping lines represent the orthogonal polarization which has a partial component out of the X plane. The cross-hatched region where both polarizations are forbidden in all directions in k space is the "photonic band gap."

Theory

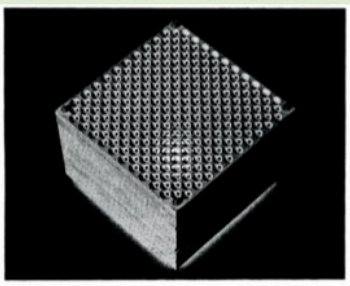


Fig.3 A photograph of the 3-dimensional periodic structure which had a "photonic band gap". This face-centered-cubic crystal consisted of spherical air-atoms which were *larger* than close-packed. The resulting overlap of the air-atoms allows us to see visible light transmitted all the way through along the <111> direction. The spherical air-atoms occupy 86% of the volume. The interstices between the atoms are filled with dielectric material of refractive index 3.5. The overall structure is 86% air and only 14% solid material.

J. Opt. Soc. Am. A, vol. 7, 1792-1800, 1990

Fabrication

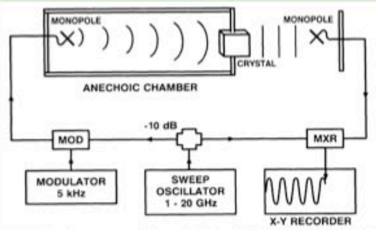
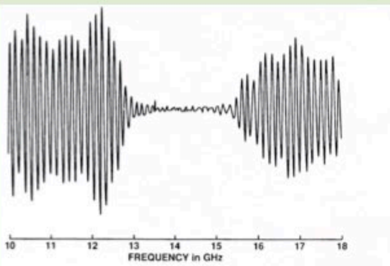


FIG. 1. A sweep oscillator feeds a 10-dB splitter. Part of the signal is modulated (MOD) and then propagated as a plane wave through a face-centered-cubic dielectric crystal. The other part of the signal is used as a local oscillator for the mixer (MXR) to measure the amplitude change and phase shift in the crystal. Between the mixer and the X-Y recorder is a lock-in amplifier (not shown).



The forbidden gap observed on the crystal displayed in Fig.3 measured along the L–U line of the L-plane. The electromagnetic wave is polarized parallel to the X-plane (s-polarization).

The interference pattern produced when a microwave signal being transmitted between antennas interferes with a local oscillator wave.

J. Opt. Soc. Am. A, vol. 7, 1792-1800, 1990

Measurements

First troubles : computation performed with a vectorial model of the electromagnetic field do not predict a bandgap

VOLUME 65, NUMBER 21 PHYSICAL REVIEW LETTERS 19 NOVEMBER 1990

Full Vector Wave Calculation of Photonic Band Structures in Face-Centered-Cubic Dielectric Media

pp. 2646-2649

K. M. Leung and Y. F. Liu
Department of Physics, Polytechnic University, Brooklyn, New York 11201
(Received 17 April 1990)

except that we do not find a true gap for this configuration.

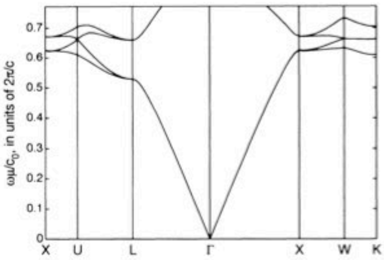


FIG. 3. The computed photonic band structure for an 86% volume filling fraction of air atoms embedded in a dielectric material with a refractive index of 3.5. The spherical voids are actually closer than close packed, and are overlapping.

VOLUME 65, NUMBER 21 PHYSICAL REVIEW LETTERS 19 NOVEMBER 1990

Electromagnetic Wave Propagation in Periodic Structures: Bloch Wave Solution of Maxwell's Equations

pp. 2650-2653

Ze Zhang and Sashi Satpathy
Department of Physics and Astronomy, University of Missouri–Columbia, Columbia, Missouri 65211
(Received 4 June 1990)

at best, a dip in the density of states

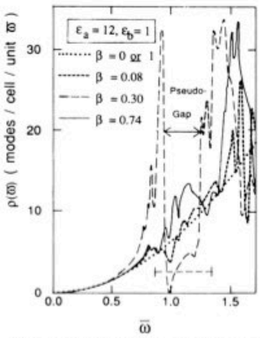


FIG. 4. The calculated DOS of the photon modes, $\rho(\bar{\omega})$, for $\epsilon_a = 12$, $\epsilon_b = 1$, and several values of packing fraction β. The dotted line corresponds to a uniform medium with the DOS varying as $\bar{\omega}^2$. A well-developed pseudogap, seemingly a remnant of the single-sphere Mie resonance, is seen for the sphere packing fraction $\beta = 0.3$. The dashed horizontal line indicates the region of strong Mie scattering for this case.

The end ? December 1990 in Nature

NEWS AND VIEWS

Photonic band-gaps bite the dust

Hopes that dielectric materials in which the transmission of certain frequencies would be forbidden seem to have been disappointed by the difficulty of realizing expectation and, now, by calculation.

New structures, new calculations

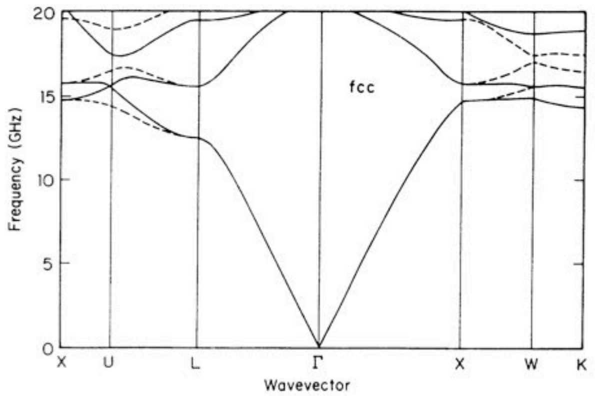
VOLUME 65, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1990

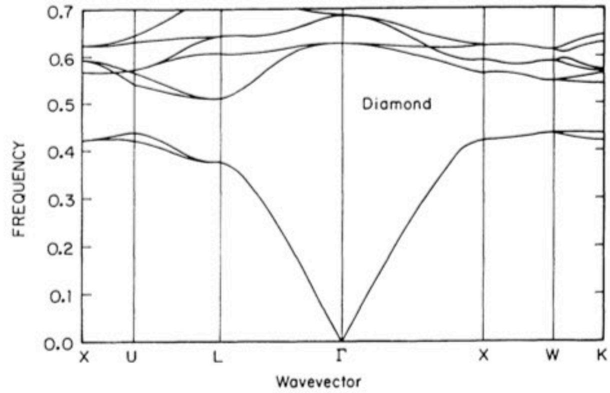
pp. 3152-3155

Existence of a Photonic Gap in Periodic Dielectric Structures

K. M. Ho, C. T. Chan, and C. M. Soukoulis
Ames Laboratory and Department of Physics, Iowa State University, Ames, Iowa 50011
(Received 4 September 1990)

Stack of dielectric spheres in vacuum or spherical holes in a dielectric medium





fcc structure cfc previously investigated, no bandgap

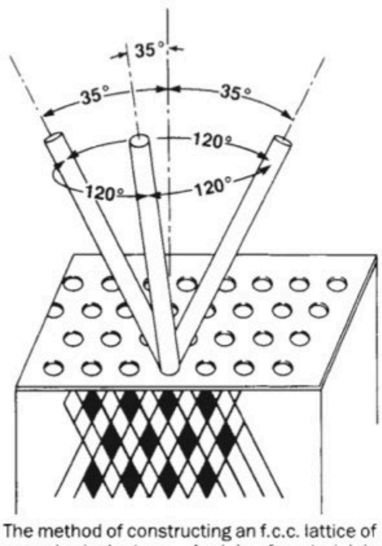
Diamond structure, bandgap

Yes, but fabrication ????

May 1991 in Nature

Hope for photonic bandgaps

SIR — The search for photonic bandgaps has not bitten the dust, John Maddox suggests[1].



The method of constructing an f.c.c. lattice of nonspherical atoms. A slab of material is covered by a mask consisting of a triangular array of holes. Each hole is drilled through three times, at an angle 35.26° away from normal, and spread out 120° on the azimuth. The resulting criss-cross of holes below the surface of the slab, suggested by the cross-hatching shown here, produces a fully three-dimensionally periodic f.c.c. structure. The drilling can be done by a real drill bit for microwave work, or by reactive ion-etching to create an f.c.c. structure at optical wavelengths.

additional drilling directions in addition to those shown in the figure, all in the plane of the slab.

E. YABLONOVITCH

First modelling of bi-dimensional structures, 1991

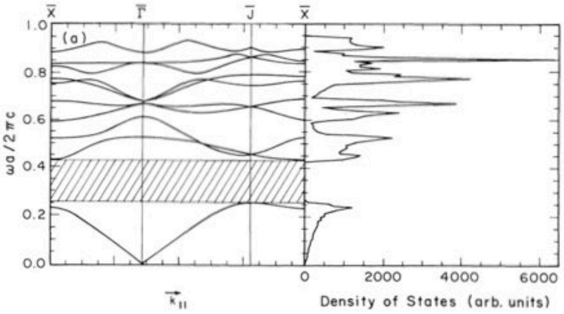
Volume 80, number 3,4 OPTICS COMMUNICATIONS 1 January 1991
pp. 199-204

Two-dimensional photonic band structures

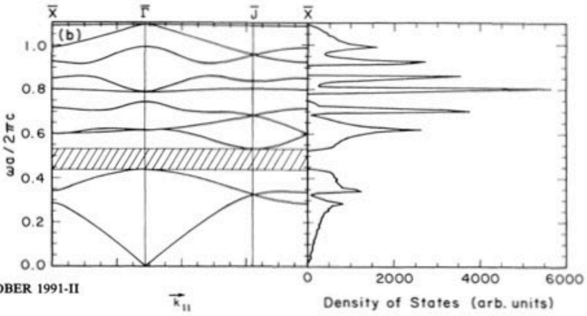
M. Plihal, A. Shambrook, A.A. Maradudin
Department of Physics, University of California, Irvine, CA 92717, USA

and

Ping Sheng
Exxon Research and Engineering Co., Route 22 East Clinton Township, Annandale, NJ 08801, USA



square, triangular, honeycomb lattices of holes or pillars etc...



PHYSICAL REVIEW B VOLUME 44, NUMBER 16 15 OCTOBER 1991-II

Photonic band structure of two-dimensional systems: The triangular lattice

pp. 8565-8571

M. Plihal and A. A. Maradudin
Department of Physics, University of California, Irvine, California 92717
(Received 8 February 1991)

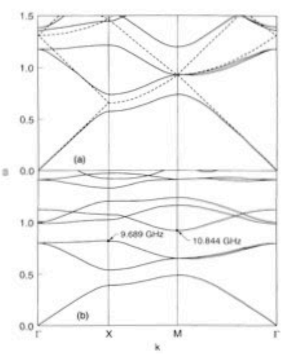
First measurements of 2D structures (microwaves), 1991-1992

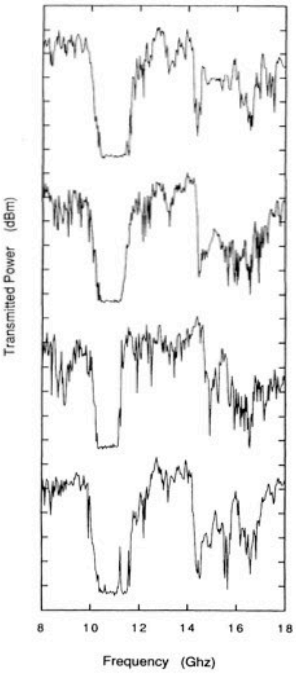
VOLUME 67, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1991

Microwave Propagation in Two-Dimensional Dielectric Lattices

pp. 2017-2020

S. L. McCall and P. M. Platzman
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974
R. Dalichaouch, David Smith, and S. Schultz
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0319
(Received 15 February 1991)



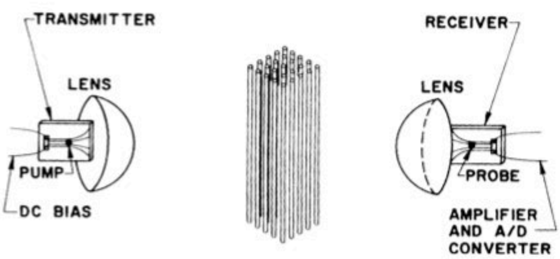


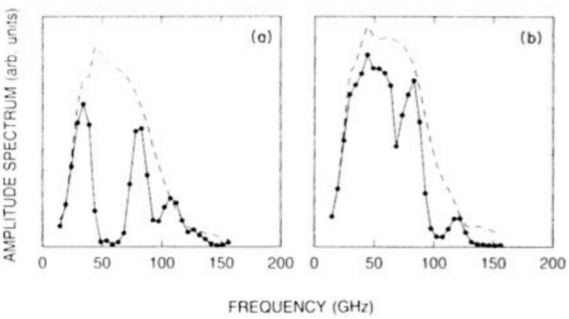
VOLUME 68, NUMBER 13 PHYSICAL REVIEW LETTERS 30 MARCH 1992

Measurement of Photonic Band Structure in a Two-Dimensional Periodic Dielectric Array

pp. 2023-2026

W. M. Robertson and G. Arjavalingam
IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598
R. D. Meade, K. D. Brommer, A. M. Rappe, and J. D. Joannopoulos
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 10 January 1992)





Yablonovite, 1991

VOLUME 67, NUMBER 17 PHYSICAL REVIEW LETTERS pp. 2295-2298 21 OCTOBER 1991

Photonic Band Structure: The Face-Centered-Cubic Case Employing Nonspherical Atoms

E. Yablonovitch and T. J. Gmitter
Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701-7040

K. M. Leung
Department of Physics, Polytechnic University, Brooklyn, New York 11201
(Received 26 December 1990)

We introduce a practical, new, face-centered-cubic dielectric structure which simultaneously solves two of the outstanding problems in photonic band structure. In this new "photonic crystal" the atoms are nonspherical, lifting the degeneracy at the W point of the Brillouin zone, and permitting a full photonic band gap rather than a pseudogap. Furthermore, this fully three-dimensional fcc structure lends itself readily to microfabrication on the scale of optical wavelengths. It is created by simply drilling three sets of holes 35.26° off vertical into the top surface of a solid slab or wafer, as can be done, for example, by chemical-beam-assisted ion etching.

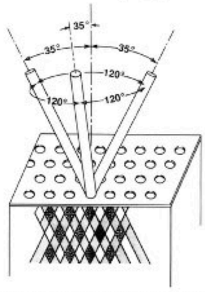
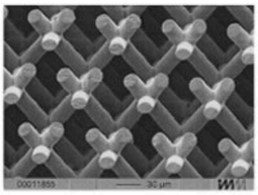
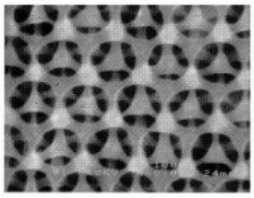


FIG. 2. The method of constructing an fcc lattice of the Wigner-Seitz cells as shown in Fig. 1(b). A slab of material is covered by a mask consisting of a triangular array of holes. Each hole is drilled through 3 times, at an angle 35.26° away from normal, and spread out 120° on the azimuth. The resulting crisscross of holes below the surface of the slab, suggested by the cross hatching shown here, produces a fully three-dimensionally periodic fcc structure, with unit cells as given by Fig. 1(b). The drilling can be done by a real drill bit for microwave work, or by reactive ion etching to create an fcc structure at optical wavelengths.



3-cylinder structure

G. Feiertag et al.
Appl. Phys. Lett. 71, 1441 (1997)



Inverse 3-cylinder structure
or Yablonovite

C. C. Cheng et al.
Physica Scripta. T68, 17 (1996)

Microwaves Near IR

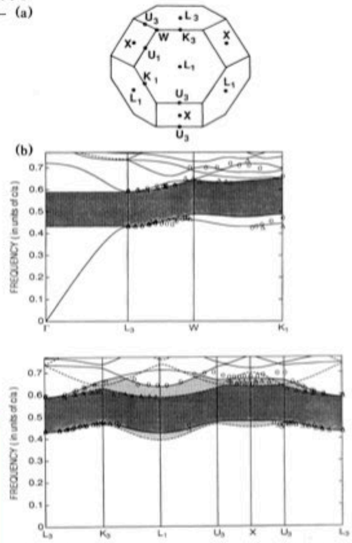


FIG. 3. (a) The Brillouin zone of an fcc structure incorporating nonspherical atoms, as in Fig. 1(b). Since the space lattice is not distorted, this is simply the standard fcc Brillouin zone lying on a hexagonal face rather than the usual cubic face. Only the L points on the top and bottom hexagons are threefold symmetry axes. Therefore they are labeled L_3. The L points on the other six hexagons are labeled L_1. The U_3-K_3 points are equivalent since they are a reciprocal-lattice vector apart. Likewise, the U_1-K_1 points are equivalent. (b) Frequency vs wave vector, ω vs k, dispersion along the surface of the Brillouin zone shown in (a), where c/a is the speed of light divided by the fcc cube length. The ovals and triangles are the experimental points for s and p polarizations, respectively. The solid and dashed lines are the calculations for s and p polarizations, respectively. The dark shaded band is the totally forbidden band gap. The lighter shaded stripes above and below the dark band are forbidden only for s and p polarizations, respectively.

First mention of impurity modes in a photonic crystal, 1991

VOLUME 67, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1991
pp. 3380-3383

Donor and Acceptor Modes in Photonic Band Structure

E. Yablonovitch and T. J. Gmitter
Navesink Research Center, Bell Communications Research, Red Bank, New Jersey 07701-7040

R. D. Meade, A. M. Rappe, K. D. Brommer, and J. D. Joannopoulos
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 11 March 1991)

Three-dimensionally periodic dielectric structures, photonic crystals, possessing a forbidden gap for electromagnetic wave propagation, a photonic band gap, are now known. If the perfect 3D periodicity is broken by a local defect, local electromagnetic modes can occur within the forbidden band gap. Addition of extra dielectric material locally, inside the photonic crystal, produces "donor" modes. Conversely, removal of dielectric material from the crystal produces "acceptor" modes. It is now possible to make high-Q electromagnetic cavities of ~1 cubic wavelength, for short wavelengths at which metallic cavities are useless. These new dielectric cavities can cover the range from mm waves to uv wavelengths.

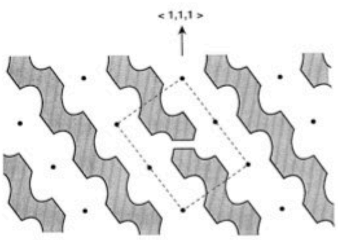


FIG. 1. A ⟨1$\bar{1}$0⟩ cross-sectional view of our face-centered-cubic photonic crystal [2] consisting of nonspherical "air atoms" centered on the large dots. Dielectric material is represented by the shaded area. The rectangular dashed line is a face-diagonal cross section of the unit cube. Donor defects consisted of a dielectric sphere centered in an atom. We selected an acceptor defect as shown, centered in the unit cube. It consists of a missing horizontal slice in a single vertical rib.

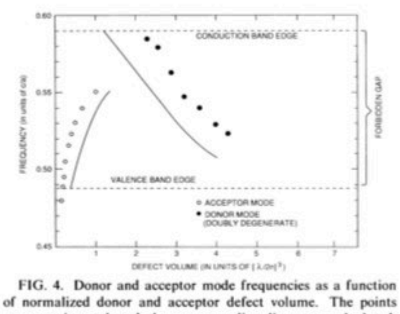


FIG. 4. Donor and acceptor mode frequencies as a function of normalized donor and acceptor defect volume. The points are experimental and the corresponding lines are calculated. Defect volume is normalized to $(\lambda/2n)^3$, where λ is the midgap vacuum wavelength and n is the refractive index. A finite defect volume is required to bind a mode in the forbidden gap.

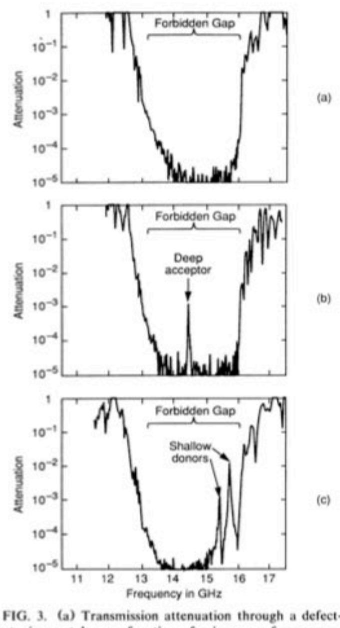


FIG. 3. (a) Transmission attenuation through a defect-free photonic crystal, as a function of microwave frequency. The forbidden gap falls between 13 and 16 GHz. (b) Attenuation through a photonic crystal with a single acceptor in the center. The large acceptor volume moved its frequency near midgap. The electromagnetic resonator Q was ~1000, limited only by the loss tangent of the dielectric material. (c) Attenuation through a photonic crystal with a single donor defect, an uncentered dielectric sphere, leading to two shallow donor modes.

First conference dedicated to photonic crystals,1992

NATO ARW, "Localization and Propagation of Classical Waves in Random and Periodic Structures," Crete, Greece, May 26-30, 1992, organisée par **C. M. Soukoulis**.

Followed by:

NATO ASI entitled "Photonic Band Gap Materials," Elounda, Crete, Greece, 1995.
www.public.iastate.edu/~cmpthy/ASI/photonics
NATO ASI, "Photonic Crystals and Light Localization," Limin Hersonissou, Crete, Greece, 2000.

Proceedings:
— Photonic Band Gaps and Localization, Plenum Publishers (1993).
— Photonic Band Gap Materials, Kluwer Publishers (1996).
— Photonic Crystals and Light Localization in the 21st Century, Kluwer Publishers (2001)

PECS: Photonic and Electromagnetic Crystal Structures www.pecsconference.org
— PECS-I (Laguna Beach, USA, 1999) www.mtci.com.au/WECSr2/index.html
— PECS-II (Sendai, Japan, 2000) www.mtci.com.au/RIEC-WWW/index.html
— PECS-III (St. Andrews, UK, 2001) www.pecsconference.org/PECSIII/
— PECS-IV (Los Angeles, USA,2002) www.ipam.ucla.edu/programs/pecs-iv/
— PECS-V (Kyoto, Japon,2003) www.pecsconference.org/PECSV/
— PECS-VI (Aghia Pelaghia, Crète, Grèce, 2005) www.pecsconference.org/PECSVI/
— PECS-VII (Monterey, USA, 2007) www.pecsconference.org/PECSVII/
— PECS-VIII (Sydney, Australie, 2009) pecs8.mtci.com.au
— PECS-IX (Granada, Spain, 2010) www.pecs-ix.org
— PECS-X (Santa Fe, USA, 2012) pecs-x.pecsconference.org
— PECS-XI (Shanghai, China, 2014) www.pecs-xi.fudan.edu.cn
— PECS-XII (York, UK, 2016) www.york.ac.uk/physics/pecs-xii/
— PECS-XIII (USA, 2018)

1987 - 2000

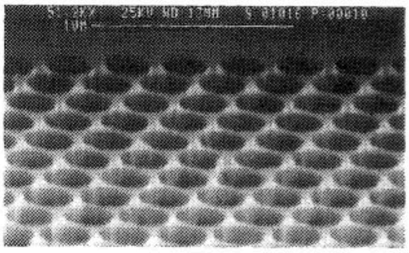
Setting up of new concepts

Blooming of numerous technological approaches

First fabrication of a 2D photonic crystal operating in the near infra-red, 1992-1993

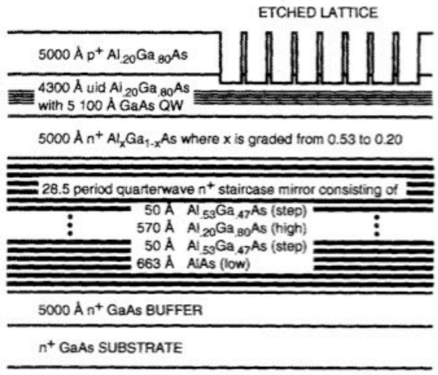
Nanofabrication of photonic lattice structures in GaAs/AlGaAs

J. R. Wendt, G. A. Vawter, P. L. Gourley, T. M. Brennan, and B. E. Hammons
Sandia National Laboratories, Albuquerque, New Mexico 87185



J. Vac. Sci. Technol. B 11(6), Nov/Dec 1993
pp. 2637-2640

Basic optical measurements
Note the choice of vertical surface emitting laser structure



Fabrication of 2-D photonic bandgap structures in GaAs/AlGaAs

T. Krauss, Y.P. Song, S. Thoms, C.D.W. Wilkinson and R.M. DelaRue

No optical measurement

ELECTRONICS LETTERS 18th August 1994 Vol. 30 No. 17
pp. 1444-1445

PHOTONIC BANDGAP OF TWO-DIMENSIONAL DIELECTRIC CRYSTALS

J. M. Gerard[1], A. Izraël[1], J. Y. Marzin[1], R. Padjen[1] and F. R. Ladan[2]
[1]France Telecom/CNET/PAB, 196 av Henri Ravera, F-92220 Bagneux and [2]Laboratoire de Microstructures et Microélectronique, CNRS, 196 av Henri Ravera, F-92220 Bagneux, France

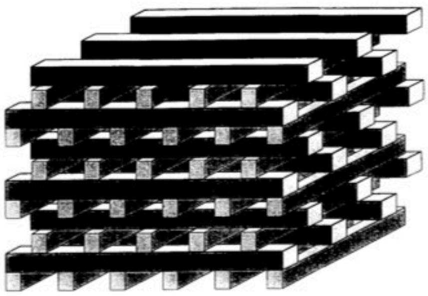
Etching in bulk GaAs, no waveguide
No optical measurement

Woodpile structure, 1994

PHOTONIC BAND GAPS IN THREE DIMENSIONS: NEW LAYER-BY-LAYER PERIODIC STRUCTURES

K. M. Ho, C. T. Chan, C. M. Soukoulis, R. Biswas* and M. Sigalas

Solid State Communications, Vol. 89, No. 5, pp. 413-416, 1994



Metallic structures, 1993-1994

Photonic band structures of two- and three-dimensional periodic metal or semiconductor arrays

Arthur R. McGurn
Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008

Alexei A. Maradudin
Department of Physics, University of California, Irvine, California 92717

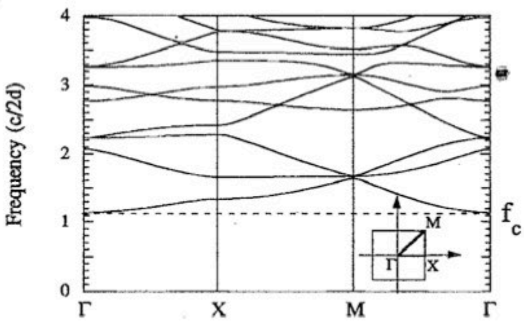
Phys. Rev. B 48, 15 576-16 579, 1993

Experimental and theoretical results for a two-dimensional metal photoni band-gap cavity

D. R. Smith, S. Schultz, and N. Kroll
Department of Physics, University of California, San Diego, 9500 Gilman Drive, LaJolla, California 92093-0319

M. Sigalas, K. M. Ho, and C. M. Soukoulis
Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011

Appl. Phys. Lett. 65 (5), 1 August 1994 pp. 645-647



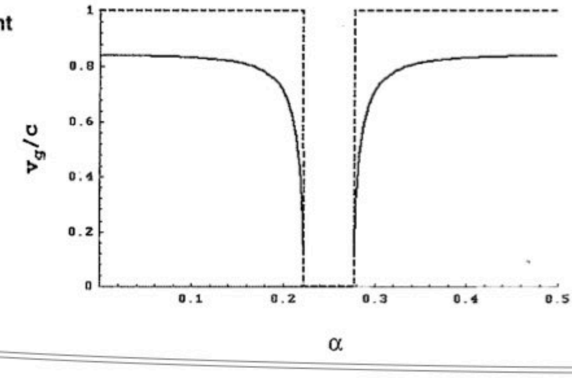
Forbidden gap between 0 and fc

Slow light, 1994

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

Jonathan P. Dowling, Michael Scalora, Mark J. Bloemer, and Charles M. Bowden

1896 J. Appl. Phys. 75 (4), 15 February 1994



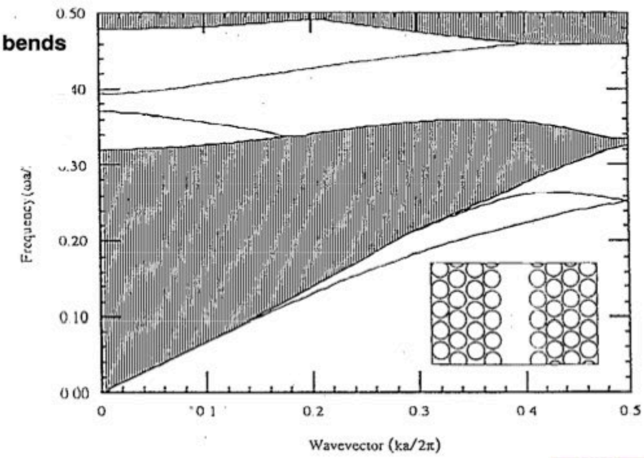
Bends and cavities, 1994

Novel applications of photonic band gap materials: Low-loss bends and high *Q* cavities

Robert D. Meade, A. Devenyi, and J. D. Joannopoulos
Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02143
O. L. Alerhand, D. A. Smith, and K. Kash
Bell Communications Research, 331 Newman Springs Road, Red Bank, New Jersey 07701-7040

J. Appl. Phys. 75 (9), 1 May 1994 pp. 4753-4755

First mention in a rather obscur paper



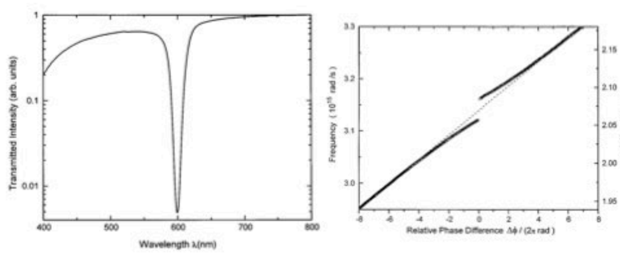
Fabrication, 1995

First opals

Interferometric technique for the measurement of photonic band structure in colloidal crystals

İ. İnanç Tarhan, Martin P. Zinkin, and George H. Watson

July 15, 1995 / Vol. 20, No. 14 / OPTICS LETTERS 1571



and first not very successful attempts of modification of the spontaneous emission lifetime

Optical Spectroscopy of Opal Matrices with CdS Embedded in its Pores: Quantum Confinement and Photonic Band Gap Effects (*).

V. N. Astratov (1), V. N. Bogomolov (1), A. A. Kaplyanskii (1), A. V. Prokofiev (1)
L. A. Samoilovich (2), S. M. Samoilovich (3) and Yu. A. Vlasov (1)

Il Nuovo Cimento, 17, 1349-1354, 1995

First anodization of micro-porous Si

Possibility of InP-Based 2-Dimensional Photonic Crystal: An Approach by the Anodization Method

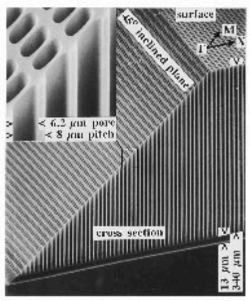
Toshihiko Baba and Miyuki Koma

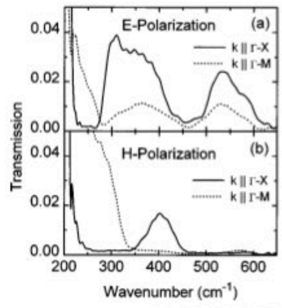
Jpn. J. Appl. Phys. Vol. 34 (1995) pp. 1405-1408

Two-dimensional infrared photonic band gap structure based on porous silicon

U. Grüning and V. Lehmann
Siemens AG, Dept. ZFE T HE, Otto-Hahn-Ring 6, 81730 München, Germany
C. M. Engelhardt
Walter-Schottky-Institut, Am Coulombwall, 85748 Garching, Germany

3254 Appl. Phys. Lett. 66 (24), 12 June 1995



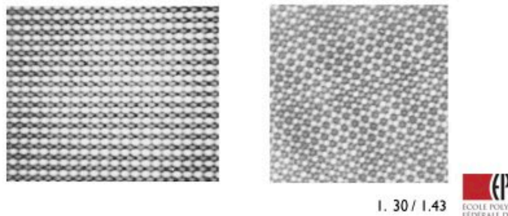


First holographic fabrication

Three-dimensional ordered patterns by light interference

Dongbin Mei, Bingying Cheng, Wei Hu, Zhaolin Li, and Daozhong Zhang

March 1, 1995 / Vol. 20, No. 5 / OPTICS LETTERS 429

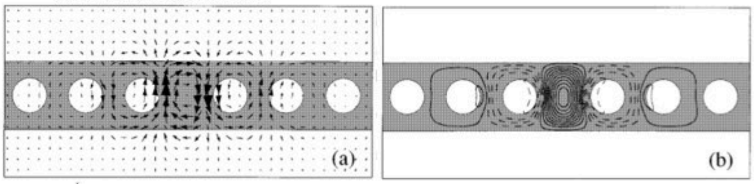


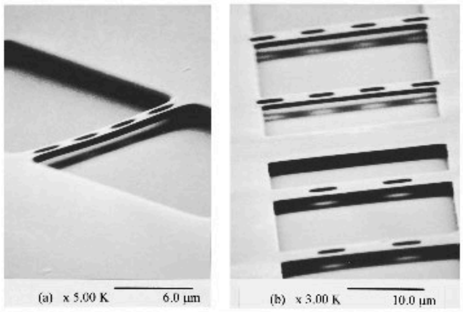
First membrane structures, 1995

Air-bridge microcavities

Pierre R. Villeneuve, Shanhui Fan, and J. D. Joannopoulos
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Kuo-Yi Lim, G. S. Petrich, L. A. Kolodziejski, and Rafael Reif
Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139





Appl. Phys. Lett. **67** (2), 10 July 1995 pp. 167-169

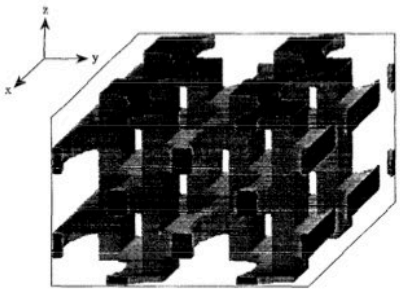
First investigation on the impact of fabrication defects, 1995

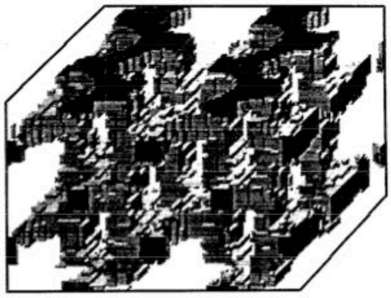
Theoretical investigation of fabrication-related disorder on the properties of photonic crystals

Conclusion very/too naïve/optimistic
Will be revisited later

Shanhui Fan, Pierre R. Villeneuve, and J. D. Joannopoulos

J. Appl. Phys. **78** (3), 1 August 1995 pp. 1415-1418





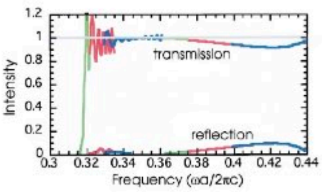
First proposal for integrated optics devices, 1996

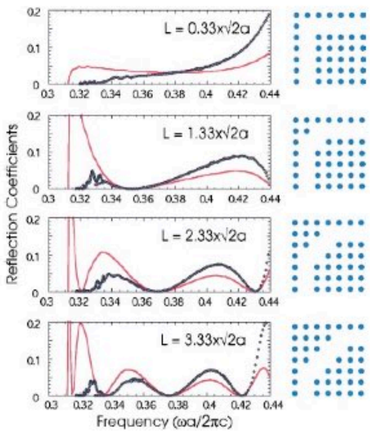
VOLUME 77, NUMBER 18 PHYSICAL REVIEW LETTERS 28 OCTOBER 1996 pp. 3787-3790

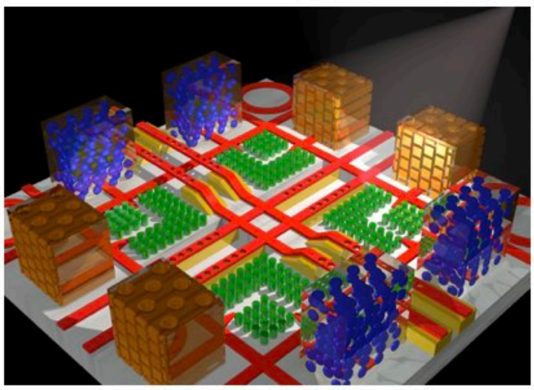
High Transmission through Sharp Bends in Photonic Crystal Waveguides

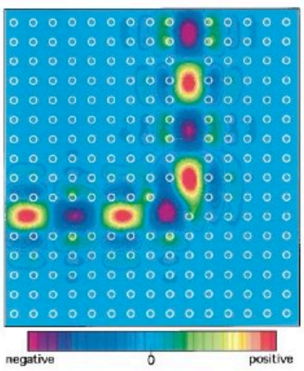
Attila Mekis, J. C. Chen, I. Kurland, Shanhui Fan, Pierre R. Villeneuve, and J. D. Joannopoulos
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 3 June 1996)

very high transmission (>95%) over wide frequency ranges. High transmission is observed even for 90° bends with zero radius of curvature, with a maximum transmission of 98% as opposed to 30% for analogous conventional dielectric waveguides. We propose a simple one-dimensional









Will be followed by a very long literature on hopeless devices due to a too large sensitivity to fabrication imperfections
- bends
- splitters / couplers
- add-drop filters
- polarisers

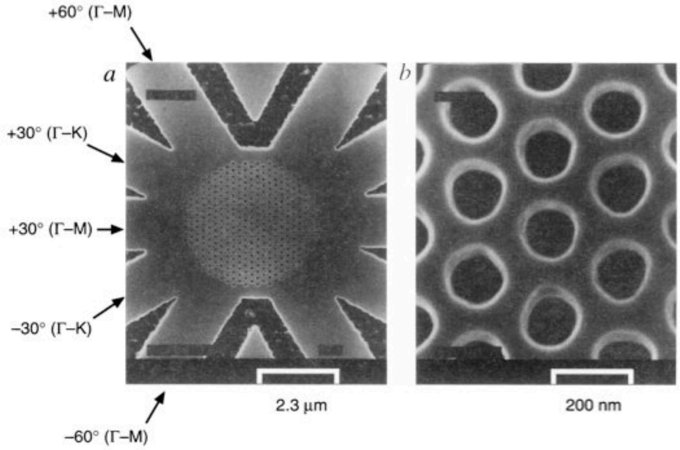
First fabrication with optical measurements of a 2D photonic crystal inoperating in the near infra-red, 1996

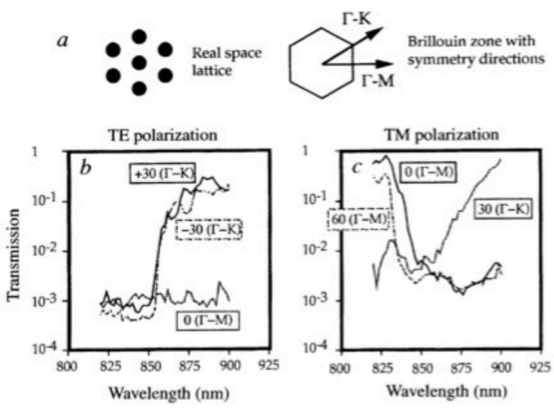
Two-dimensional photonic-bandgap structures operating at near-infrared wavelengths

Thomas F. Krauss*, Richard M. De La Rue*
& Stuart Brand†

* Optoelectronics Research Group, Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8LT, UK
† Department of Physics, University of Durham, Durham DH1 3LE, UK

NATURE · VOL 383 · 24 OCTOBER 1996 pp. 699-702





From the forbidden bandgap to Bloch modes, 1996 - 2000
(or 25 years after R. Zengerle)

- Equi-frequency surfaces
- Superprism
- Negative fraction
- Super lens
- Selfcollimation

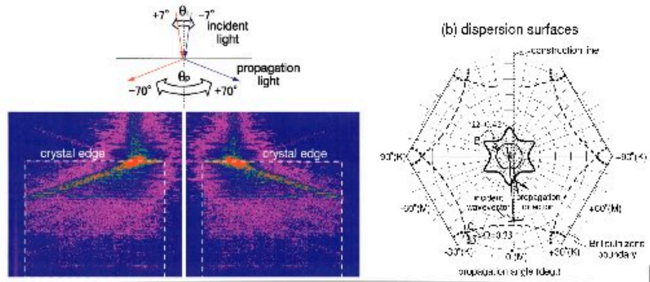
Highly dispersive photonic band-gap prism

1996

Shawn-Yu Lin, V. M. Hietala, Li Wang, and E. D. Jones

November 1, 1996 / Vol. 21, No. 21 / OPTICS LETTERS 1771

H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, and S. Kawakami, **Superprism phenomena in photonic crystals,** Physical Review B 58, 10096-10099 (1998)

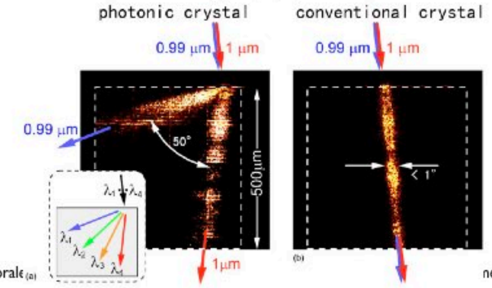


1998

Photonic crystals for micro lightwave circuits using wavelength-dependent angular beam steering

Hideo Kosaka,[a] Takayuki Kawashima,[b] Akihisa Tomita, Masaya Notomi,[c] Toshiaki Tamamura,[c] Takashi Sato,[b] and Shojiro Kawakami[b]

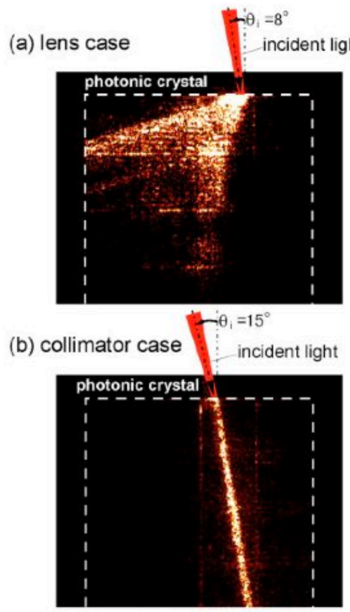
Appl. Phys. Lett., Vol. 74, No. 10, 8 March 1999 pp. 1370-1372



Self-collimating phenomena in photonic crystals

Hideo Kosaka,[a] Takayuki Kawashima,[b] Akihisa Tomita, Masaya Notomi,[c] Toshiaki Tamamura,[c] Takashi Sato,[b] and Shojiro Kawakami[b]

Appl. Phys. Lett., Vol. 74, No. 9, 1 March 1999 pp. 1212-1214



First photonic crystal laser, 1996

Lasers incorporating 2D photonic bandgap mirrors

J. O'Brien, O. Painter, R. Lee, C.C. Cheng, A. Yariv and A. Scherer

ELECTRONICS LETTERS 21st November 1996 Vol. 32 No. 24 pp. 2243-2244

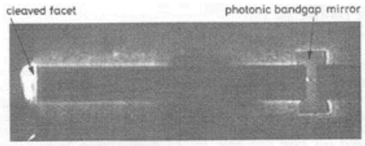


Fig. 2 *CCD camera image, taken from above, of laser above threshold*

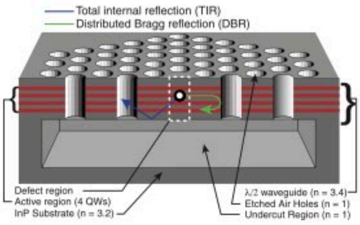
but especially, 1999

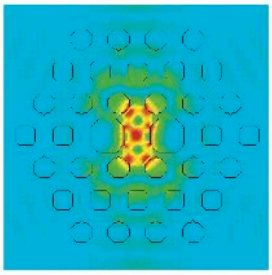
Two-Dimensional Photonic Band-Gap Defect Mode Laser

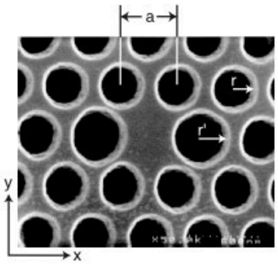
O. Painter,[1] R. K. Lee,[1] A. Scherer,[1*] A. Yariv,[1] J. D. O'Brien,[2] P. D. Dapkus,[2] I. Kim[2]

SCIENCE VOL 284 11 JUNE 1999 pp. 1819-1821

- Laser
- Design
  - \+ high-Q cavities
  - \+ small modal volume
- Membrane structure







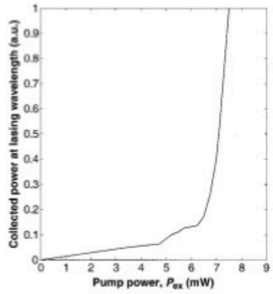


Fig. 5. L-L curve showing the power at the laser wavelength versus the incident pump power. The sample was cooled to 143 K and pumped with 10-ns pulses (4% duty cycle). The actual absorbed pump power is difficult to estimate for a structure with this geometry.

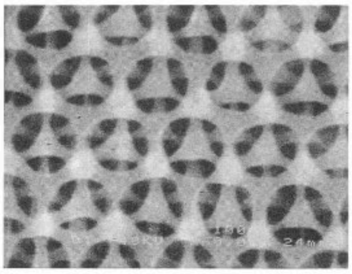
Fabrication of 3D structures in the near infra-red, 1996 - 2005

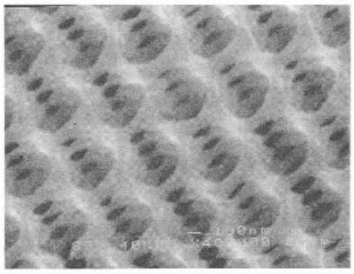
Physica Scripta. Vol. T68, 17–20, 1996

Nanofabricated Three Dimensional Photonic Crystals Operating at Optical Wavelengths

C. C. Cheng,[1] V. Arbet-Engels,[2] A. Scherer[1] and E. Yablonovitch[2]

1996



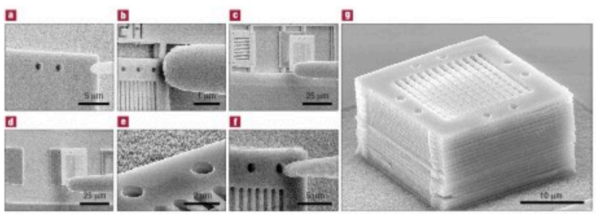


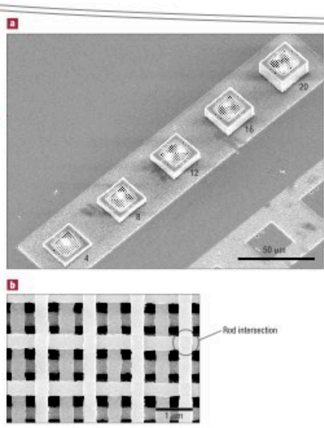
2003

Microassembly of semiconductor three-dimensional photonic crystals

KANNA AOKI*[†1], HIDEKI T. MIYAZAKI[2], HIDEKI HIRAYAMA[1], KYOJI INOSHITA[3], TOSHIHIKO BABA[3], KAZUAKI SAKODA[4], NORIO SHINYA[2] AND YOSHINOBU AOYAGI[1]

nature materials | VOL 2 | FEBRUARY 2003 | pp. 117-121





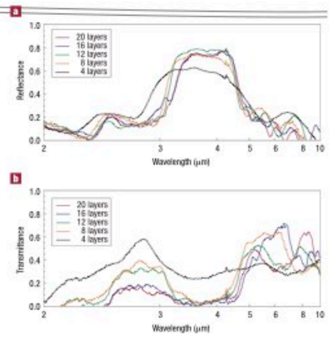


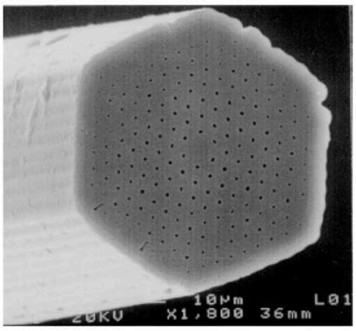
Figure 3 Optical properties of the fabricated 3D photonic crystals. a, Reflection spectra. **b,** Transmission spectra. The peaks appearing at 4.2 μm in all spectra are derived from absorption of carbon dioxide in air.

Photonic crystal fiber, 1997 - present

Endlessly single-mode photonic crystal fiber

T. A. Birks, J. C. Knight, and P. St. J. Russell

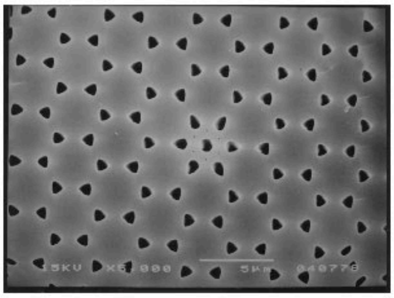
July 1, 1997 / Vol. 22, No. 13 / OPTICS LETTERS 961

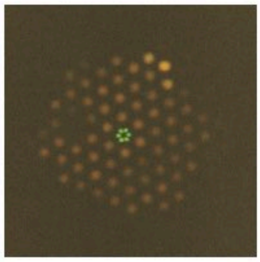


Photonic Band Gap Guidance in Optical Fibers

J. C. Knight, J. Broeng,* T. A. Birks, P. St. J. Russell

Science, 282, pp. 1476-1478, 1998

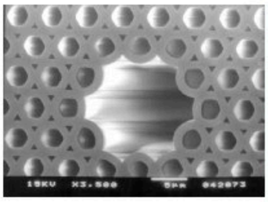


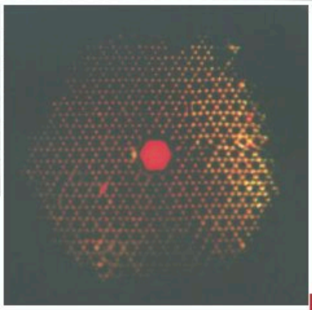


Single-Mode Photonic Band Gap Guidance of Light in Air

R. F. Cregan,[1] B. J. Mangan,[1] J. C. Knight,[1] T. A. Birks,[1] P. St. J. Russell,[1*] P. J. Roberts,[2] D. C. Allan[3]

3 SEPTEMBER 1999 VOL 285 SCIENCE pp. 1537-1539





hollow-core fiber

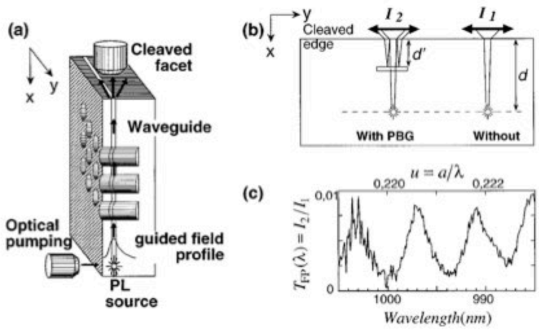
First true quantitative measurements, 1997

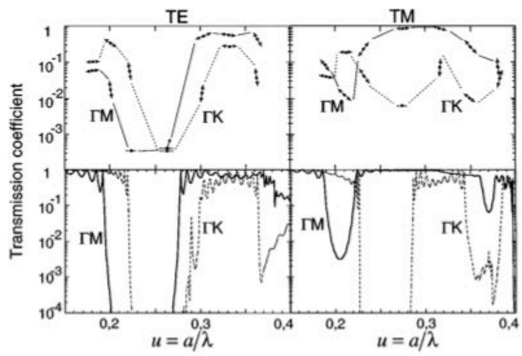
VOLUME 79, NUMBER 21 PHYSICAL REVIEW LETTERS 24 NOVEMBER 1997

Quantitative Measurement of Transmission, Reflection, and Diffraction of Two-Dimensional Photonic Band Gap Structures at Near-Infrared Wavelengths

D. Labilloy,[1] H. Benisty,[1] C. Weisbuch,[1] T. F. Krauss,[2,*] R. M. De La Rue,[2] V. Bardinal,[3,†] R. Houdré,[3] U. Oesterle,[3] D. Cassagne,[4] and C. Jouanin[4]

pp. 4147-4150



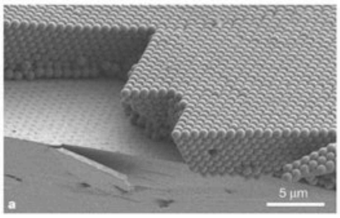


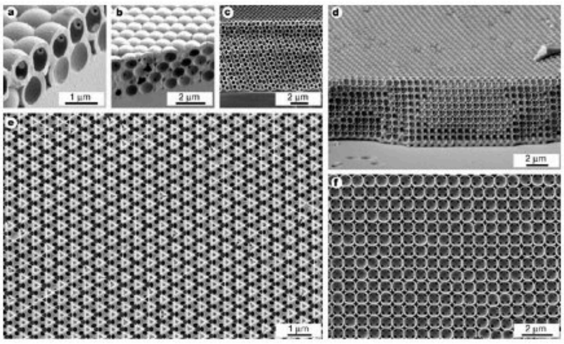
Fast development of opals fabrication, 1997 - 2001

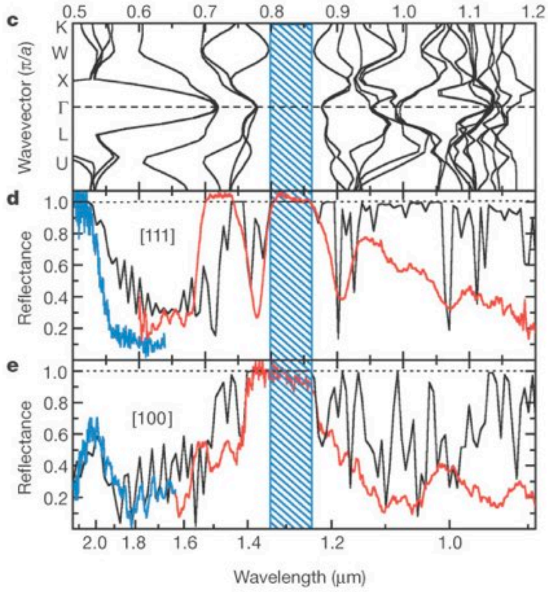
On-chip natural assembly of silicon photonic bandgap crystals

Yurii A. Vlasov*†, Xiang-Zheng Bo‡, James C. Sturm‡ & David J. Norris*

NATURE | VOL 414 | 15 NOVEMBER 2001 | pp. 289-293







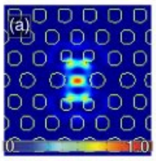
inverted structure

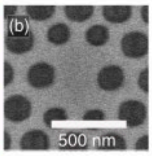
Finally, "true" quantum effects

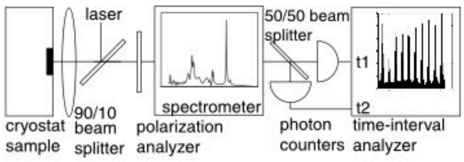
PRL 95, 013904 (2005) PHYSICAL REVIEW LETTERS week ending 1 JULY 2005

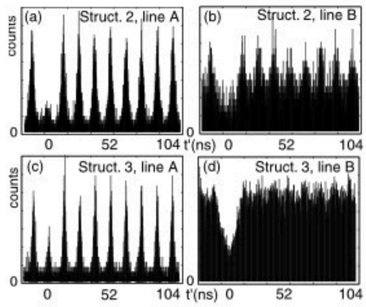
Controlling the Spontaneous Emission Rate of Single Quantum Dots in a Two-Dimensional Photonic Crystal

Dirk Englund,[1] David Fattal,[1] Edo Waks,[1] Glenn Solomon,[1,2] Bingyang Zhang,[1] Toshihiro Nakaoka,[3] Yasuhiko Arakawa,[3] Yoshihisa Yamamoto,[1] and Jelena Vučković[1]





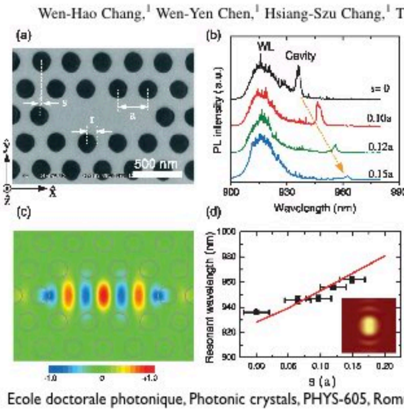


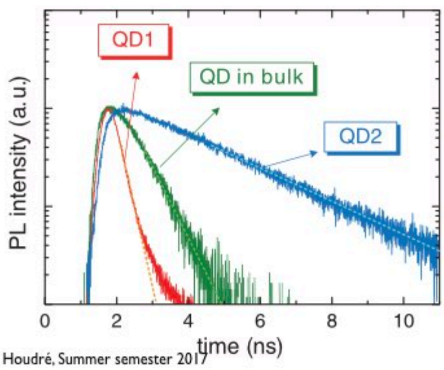


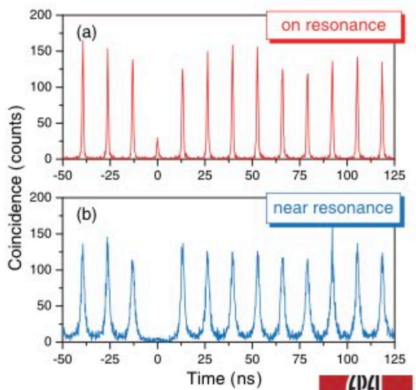
PRL 96, 117401 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

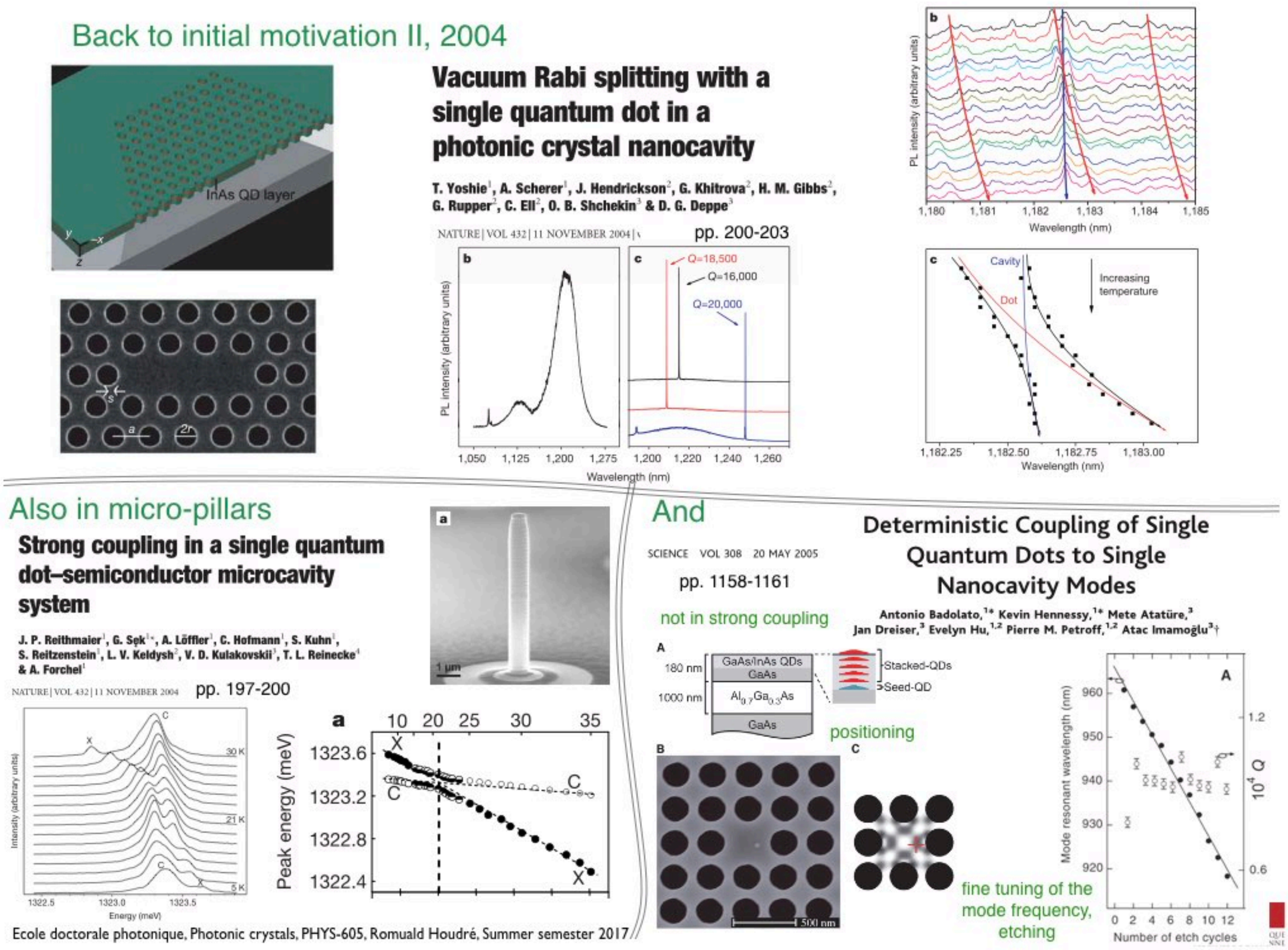
Efficient Single-Photon Sources Based on Low-Density Quantum Dots in Photonic-Crystal Nanocavities

Wen-Hao Chang,[1] Wen-Yen Chen,[1] Hsiang-Szu Chang,[1] Tung-Po Hsieh,[2] Jen-Inn Chyi,[2] and Tzu-Min Hsu[1,*]








Back to initial motivation II, 2004
InAs QD layer
Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity
T. Yoshie, A. Scherer, J. Hendrickson, G. Khitrova, H. M. Gibbs, G. Rupper, C. Ell, O. B. Shchekin & D. G. Deppe
NATURE | VOL 432 | 11 NOVEMBER 2004
pp. 200-203
PL intensity (arbitrary units)
Q=18,500
Q=16,000
Q=20,000
Wavelength (nm)
Cavity
Dot
Increasing temperature
Also in micro-pillars
Strong coupling in a single quantum dot–semiconductor microcavity system
J. P. Reithmaier, G. Sęk, A. Löffler, C. Hofmann, S. Kuhn, S. Reitzenstein, L. V. Keldysh, V. D. Kulakovskii, T. L. Reinecke & A. Forchel
NATURE | VOL 432 | 11 NOVEMBER 2004
pp. 197-200
Peak energy (meV)
Energy (meV)
Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017
And
Deterministic Coupling of Single Quantum Dots to Single Nanocavity Modes
SCIENCE VOL 308 20 MAY 2005
pp. 1158-1161
not in strong coupling
Antonio Badolato, Kevin Hennessy, Mete Atatüre, Jan Dreiser, Evelyn Hu, Pierre M. Petroff, Atac Imamoğlu
GaAs/InAs QDs
GaAs
Stacked-QDs
Seed-QD
GaAs
positioning
fine tuning of the mode frequency, etching
Mode resonant wavelength (nm)
Number of etch cycles
500 nm

Present

PhC nowadays

→Last lectures

- Integration with microfluidics systems
- Biology
- Slow light
- Nano-beam
- Subwavelength structures
- Slotted waveguides
- Sensors
- Optical trapping
- Optomechanic systems
- Dynamic control
- Non-reciprocal structures
- Topological photonic structures
- Novel materials (chalcogenide, diamond, GaN,…)
- Thermal photovoltaic
- …