Does disorder hurt in photonic crystals?

Ad Lagendijk[1,2], A. Femius Koenderink[2,*], and Willem L. Vos[1,2]

1. FOM Institute for Atomic and Molecular Physics,
Kruislaan 407, 1098 SJ,
Amsterdam,
The Netherlands

2. Complex Photonic Systems,
Dept. Science and Technology
University of Twente, PO Box 217,
7500 AE Enschede,
The Netherlands.

Disorder can play an important role in photonic crystals. Disorder effects range from anisotropic diffusion, and non-Lambertian light sources to light localization. Unavoidable variations in size and position of the building blocks of photonic crystals cause light scattering and extinction of coherent beams. We present a new model for both 2 and 3-dimensional photonic crystals that relates the extinction length to the magnitude of the variations. The predicted lengths agree well with our new experiments on high-quality opals and inverse opals, and with literature data analyzed by us. As a result, control over photons is limited to distances up to 50 lattice parameters in state-of-the-art structures, thereby seeming to impede at present large-scale applications such as integrated circuits. Conversely, scattering in photonic crystals may lead to novel physics such as Anderson localization and non-classical diffusion.

*Present address: Nano-Optics Group, Laboratory for Physical Chemistry, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland

Near-field Imaging and Manipulation of Light in Photonic Crystals

A.F. Koenderink, B.C. Buchler, M. Kafesaki, and V. Sandoghdar
Laboratory of Physical Chemistry, Swiss Federal Institute of Technology (ETH),
CH-8093 Zurich, Switzerland

We use Scanning Near-field Optical Microscopy to image directly the spatial extent of light in photonic crystal microcavities and waveguides. We show that the analysis of such field maps reveals important information about the deviations of the crystal structure from its nominal fabrication design [1, 2]. Our findings emphasize that the performance of photonic crystal structures is very sensitive to various design parameters and that a very high degree of control is necessary in the fabrication.

In addition to imaging, we discuss how a near-field probe can be used to manipulate the resonance of a photonic crystal microcavity. By performing Finite Difference Time Domain (FDTD) as well as perturbative analytic calculations, we demonstrate that it is possible to shift the resonance of a microcavity while maintaining a high quality factor [3]. We discuss prospects of this technique for opto-mechanical switching of photonic crystals. Furthermore, we will present results on the modification of spontaneous emission of a nanoscopic emitter placed in the near field of a two-dimensional photonic crystal slab [4].

[1] P. Kramper, et al., *Opt. Lett.* **29**, 174 (2004).
[2] B. C. Buchler, et al., *IEICE Trans.Electron.* **E87-C**, 371 (2004).
[3] A. F. Koenderink, M. Kafesaki, B. C. Buchler, V. Sandoghdar, *submitted*.
[4] A. F. Koenderink, et al., *in preparation*.

Controlling photonic materials by liquid crystal infiltration

D.S. Wiersma[1], S. Gottardo[1], M. Burresi[1], L. Pallavidino[2], F. Geobaldo[2] and F. Giorgis[3],
[1]European Laboratory for Non-linear Spectroscopy and INFM, Via Nello Carrara 1, I-50019 Sesto-Fiorentino (Florence), Italy
[2]Dept. of Material Science and Chemical Engineering, Polytechnical University of Torino, C.so Duca degli Abruzzi 24, I-10129 Turin, Italy.
[3]Dept. of Physics, Polytechnical University of Torino, C.so Duca degli Abruzzi 24, I-10129 Turin, Italy.

Triggered by a proposal of Busch and John [1], there has been an enormous interest in recent years in infiltrating photonic crystal with liquid crystals, in order to obtain electric and magnetic field control over the photonic crystal bandgap. This would allow for instance to create waveguide structures, filters, and resonators that can be tuned and switched externally. Whereas temperature tuning was demonstrated [2], so far most attempts of electric field switching were hampered by surface anchoring of the liquid crystal [3]. Liquid crystal infiltration was successfully applied in disordered structures in which case it was used to obtain temperature tuning [4] and electric field switching of random lasers [5]. Very recently we found a way to overcome the surface anchoring problems in photonic crystals and have observed huge electric field switching effects and controllable optical birefringence in liquid crystal infiltrated opals [6].

In this contribution we will give an overview of the possibilities offered by photonic materials infiltrated by liquid crystals. We will focus on ordered systems (3D photonic crystals) and report our recent results on electric field switching and controlled birefringence but will also briefly touch the possibilities in disordered systems and the role of multiple scattering in photonic crystals.

[1] K. Busch and S. John, *Phys. Rev. Lett.* **83**, 967 (1999).
[2] K. Yoshino, Y. Shimoda, Y. Kawagishi, K. Nakayama, and M. Ozaki, *Appl. Phys. Lett.* **75**, 932 (1999).
[3] D. Kang, J.E. Maclennan, N.A. Clark, A.A. Zakhidov, and R.H. Baughman, *Phys. Rev. Lett.* **86**, 4055 (2001).
[4] D.S. Wiersma and S. Cavalieri, *Nature* **414**, 708 (2001).
[5] S. Gottardo, S. Cavalieri, O. Yaroshchuk, and D.S. Wiersma, *Phys. Rev. Lett.* **93**, 263901 (2004).
[6] S. Gottardo, M. Burresi, F. Giorgis, L. Pallavidino, and D.S. Wiersma, *Controllable birefringence in liquid crystal infiltrated opals*, to be published.

Anderson Localization of Classical Waves In Disordered Photonic Crystals with Absorption or Gain

A. Lerch, A. Lubatsch, and J. Kroha
Physikalisches Institut, Universität Bonn, Nussallee 12, 53115 Bonn, Germany

Anderson localization of classical or electromagnetic waves In disordered media, although not unambiguously realized to date In 3D random media due to the ubiquitous presence of absorption, has recently regained Interest In becausee of Its possible relevance for random lasers [1]. We present a diagrammatic theory of Anderson localization of classical waves In 3D, disordered photonic crystals with absorption or gain. Since the standard mechanisms of Anderson localization, diffusion ("diffusons") and coherent backscattering ("Cooperons"), rely fundamentally on particle number conservation, which Is broken here, we reformulate the transort theory for absorbing/emitting media, employing an exact, generalized Ward Identity [2], and resum the modified diffuson and Cooperon contributions. We find that In absorbing media true Anderson localization Is Impossible. Stimulated emission, In turn, enhances the localization effect by Increasing the weight of long, constructively Interfering wave paths In the random system. The latter leads to a modification of the Ioffe-Regel criterion. We discuss, If this can explain the experimentally observed [1] localized modes In systems with gain whose mean free path by far exceeds the wave length of light.

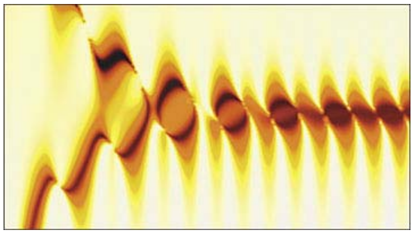
[1] H. Cao et al., *Phys. Rev. Lett.* **82**, 2278 (1999); **84**, 5584 (2000).
[2] A. Lubatsch, J. Kroha, and K. Busch, *cond-mat/0412083* (2004).

Unusually strong optical interactions between particles in a waveguide

J.J. Sáenz(1) and R. Gómez-Medina(2)
(1) "Moving Light and Electrons" Group, Dept. Física de la Materia Condensada,
Universidad Autónoma de Madrid, 28049-Madrid, Spain.
(2) Donostia Internacional Physics Center (DIPC), 20018 San Sebastián, Spain

Intense optical fields can induce significant forces "*between*" particles [1,2]. In absence of absorbing or "Mie"-like resonances, light forces on atoms, molecules, and nanometer-sized particles are, in general, very small. However, when the fields are confined in quasi-one-dimensional (Q1D) waveguide structures, geometric resonant modes can lead to unusual strong optical interactions "*between*" particles [3].

In the presence of two particles, there is a non-trivial splitting of the geometric resonance which does not always correspond to the expected familiar bonding-antibonding picture of atomic physics [2]. We show that, under the presence of two counter-propagating (non-correlated) modes, the effective interaction potential can be tuned to induce a stable optically bound dimer [3].



Contour plot, in frequency-distance space, of the calculated optical force on a two-particle system inside a waveguide. [Cover page, Phys. Rev. Lett. **93** No 24 (2004)]

[1] M. M. Burns, J.-M. Fournier and J. A. Golovchenko, Science **249**, 749 (1990).
[2] M. I. Antonoyiannakis and J. B. Pendry, Phys. Rev. B. **60**, 2363 (1999).
[3] R. Gómez-Medina *et al.*, Phys. Rev. Lett. **86**, 4275 (2001); **93,** 243602 (2004).

Dynamic photonic crystals

Shanhui Fan
Department of Electrical Engineering, Stanford University, Stanford, CA 94305

The use of dynamic photonic structures open fascinating new possibilities for controlling the properties of light. The general idea is to create a photoinc crystal system such that a light pulse can be held in the structure for a sufficiently long time, and to modulate the refractive index of the system while the pulse is in the system. Doing so allows the spectrum of the pulse to be molded almost arbitrarily with small refractive index modulations, leading to highly non-trivial information processing capabilities on chip. As examples of such capabilities, here we show that light pulses can be stopped, stored, and time-reversed with these dynamic systems. [1-4]

[1] M. F. Yanik and S. Fan, “Stopping light all-optically”, Physical Review Letters, vol. 92, art. No. 083901 (2004).
[2] M. F. Yanik and S. Fan, “Time reversal of light with linear optics and modulators ”, Physical Review Letters, vol. 93, art. No. 173903 (2004).
[3] M. F. Yanik, W. Suh, Z. Wang and S. Fan, “Stopping light in a waveguide with an all-optical analogue of electromagnetic induced transparency”, Physical Review Letters, vol. 92, art. No. 233903 (2004).
[4] M. F. Yanik, and S. Fan, “Stopping and storing light coherently”, Physical Review A, vol. 71, art. No. 013803 (2005).

Wave-front in photonic crystals: Influence of the form-anisotropy

D. N. Chigrin
Institute of Physics, University of Bonn, Nussallee 12, D-53115 Bonn, Germany

Photonic crystals possess strong dispersion and anisotropy. Anisotropy of a photonic crystal leads to the beam steering effect: the group-velocity direction does not necessarily coincide with the wave-vector direction. As a consequence the wave-front due to a point isotropic light source can be strongly non-spherical inside a photonic crystal (Fig. 1). In this contribution, a theoretical study of wave-front images in a photonic crystal is presented based on numerical finite-difference time-domain (FDTD) calculations and asymptotic analysis of the Maxwell's equations. Numerical examples are given for 2D and 3D periodic dielectric structures.

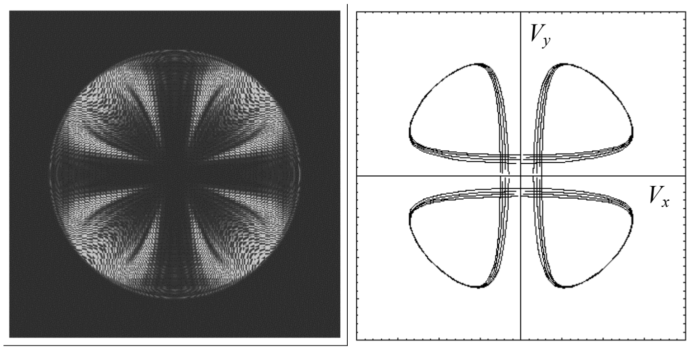
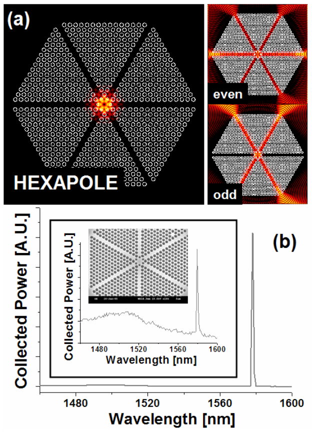


Figure 1. FDTD wave-front image (left) and group velocity contours (right) of the light pulse propagating inside 2D polymer photonic crystal.

How to get decimated spectrum from a photonic crystal single-cell cavity with Γ-k directional waveguides

Sun-Kyung Kim, Guk-Hyun Kim, Se-Heon Kim and Yong-Hee Lee
Department of Physics, Korea Advanced Institute of Science and Technology,
Taejon 305-701, Korea

In order to excite a sole photonic crystal single-cell cavity mode from many available resonant modes, we placed six Γ-k directional waveguides in the proximity of the single-cell cavity. In such a structure, we sought conditions that only one hexapole mode survives maintaining its high-Q while all the other modes are fully depressed. The mechanism to encourage the hexapole mode selectively relies on the symmetry matching of the cavity- and the waveguide- mode profile [1]. Based on this modeling, we fabricated hexapole-mode resonators in InP-InGaAsP slab structures. In the experiment, we found out that the hexapole mode solely made a laser and the other modes were buried in photoluminescence spectrum.



(a) Calculated electric-field intensity of hexapole mode and two degenerate-quadrupole modes
(b) Typical spectrum above- and below- threshold

[1] G. H. Kim, Y.H. Lee, A. Shinya, M. Notomi, *Optics Express 12,* **26** 6624 (2004)

Theory of unconventional Smith-Purcell radiation involving photonic crystal

Tetsuyuki Ochiai[1] and Kazuo Ohtaka[2],
[1]Nanomaterials Laboratory, National Institute for Materials Science,
Tsukuba 305-0044, Japan,
[2]Center for Frontier Science, Chiba University, Chiba 263-8522, Japan.

A running charged particle induces a coherent radiation when it passes above a periodic dielectric structure such as photonic crystal (PhC). Conventionally, this radiation, so-called Smith-Purcell radiation (SPR), can be understood as a consequence of the Umklapp scattering of the evanescent wave accompanied by the charged particle. However, when an ultra-relativistic electron beam is used in the experiments of the SPR in PhC, unexpected phenomena contrary to the conventional understanding of the SPR are observed [1]. This unconventional SPR has several remarkable properties such as a peculiar angular distribution of the induced radiation.

Here, we present a theoretical analysis of the unconventional SPR in a PhC composed of cylinders by using the multiple-scattering formalism [2]. The analysis shows that the above properties are reasonably understood by taking account of the boundary of the PhC. It also predicts various finite size effects, an additional selection rule, and the interplay between the conventional and unconventional SPRs.

[1] N. Horiuchi et al., in preparation.
[2] T. Ochiai and K. Ohtaka, *Phys. Rev.* B 69, 125106, 125107 (2004).

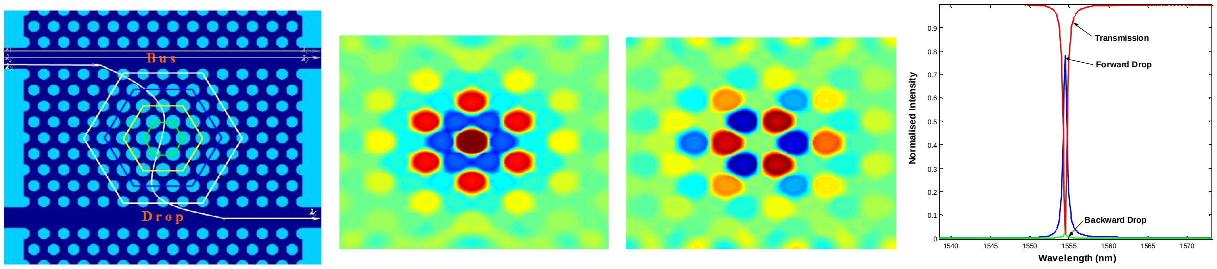
A compact design of in-plane channel drop filter using degenerate modes in 2D photonic crystal slabs

Ziyang Zhang and Min Qiu,
Laboratory of Optics, Photonics and Quantum Electronics,
Department of Microelectronics and Information Technology,
Royal Institute of Technology (KTH),
Electrum 229, 164 40 Kista, Sweden,
min@imit.kth.se

We have recently designed an in-plane channel drop in triangular-lattice 2D photonic crystal slabs. The system consists of two conventional waveguides and a cavity system. Three-dimensional finite difference time domain simulations have shown that the power transferred to the drop waveguide is 78% and only 1.6% is left in the bus waveguide. The quality factor is around 3,000. By tuning surrounding air holes, the light remaining in the bus waveguide can be further reduced to 0.3% at resonance.

The cavity is constructed by carefully arranging the radii of some periods of air holes into a graded pattern and involves no missing air holes [1]. This cavity supports two modes of opposite symmetry, one even with respect to the central plane perpendicular to the waveguides and the other odd. Since both modes remain even with respect to the central plane parallel to the waveguides, the transfer occurs along the forward direction of the drop waveguide [2]. The presence of Bus and Drop waveguides does not affect the vertical light confinement of the cavity and both modes keep high vertical Q values (>35,000). By tuning the radii properly, the two modes can achieve degeneracy with the same resonant wavelength. Moreover, both modes prove to couple equally into the waveguides and have similar coupling Q values (~3,000). Since the vertical Q is much larger than the coupling Q, the vertical loss of the system is kept low.

We believe this novel and compact design is adequate for dense wavelength division multiplexing applications in modern optical networks.



(a) (b) (c) (d)

Figure (a) top view of the system. (b) $\mathbf{H_z}$ field of the even mode at central slab plane. (c) $\mathbf{H_z}$ field of the odd mode at central slab plane. (d) intensity spectra.

[1] K. Srinivasan and O. Painter, *Optics Express*, **11**, 579 (2003).
[2] S. Fan, P. R. Villeneuve and J. D. Joannopoulos, *Optics Express*, **3**, 4 (1998).

Semiconductor photonic crystal and microdisk quantum dot devices for chip-based cavity QED

K. Srinivasan, P.E. Barclay, and O. Painter
Department of Applied Physics, MS 128-95, California Institute of Technology,
Pasadena, CA 91125, USA

For semiconductor microcavity-quantum dot systems to realize their potential in cavity QED (cQED)-based implementations of quantum information processing, the cavities must exhibit a sufficiently high quality factor (Q) and small mode volume (V_{eff}) for coherent interaction to take place before dissipation sets in, as well as an efficient input and output channel for transferring light to and from the microcavity-quantum dot interaction region. We have developed optical fiber-pigtailed microcavities in which all of these properties are exhibited. Recent demonstrations include silicon photonic crystal defect cavities with Q~40,000 and V_{eff}~$0.9(\lambda/n)^3$, and AlGaAs microdisk cavities with an embedded layer of quantum dots and Q~360,000 and V_{eff}~$6(\lambda/n)^3$ [1,2]. The latter devices also exhibited lasing with thresholds approaching the transparency values for the quantum dot epitaxy.

We will discuss a number of applications of these systems, including fiber-pigtailed microlasers, high-efficiency single photon sources, and fiber-based optical spectroscopy. In addition, we will compare the relative merits of the different microcavity geometries as they pertain to these applications.

[1] K. Srinivasan et al., *Physical Review B,* **70**, 081306(R), 2004
[2] K. Srinivasan et al., submitted, http://www.arxiv.org/abs/quant-ph/0412085

Corpuscular description of chirped photonic crystal modes

Virginie Lousse[a,b] and Jean Pol Vigneron[b]
[a]Dept. of Electrical Engineering, Stanford University, Stanford, CA 94305, USA
[b]Lab. Phys. du Solide, Fac. Univ. Notre-Dame de la Paix, Namur, Belgium

Chirped photonic crystals are non-periodic optical structures which can be viewed as ordinary photonic crystals perturbed by a slowly-varying spatial modulation of the refractive index distribution. Such structures can be prepared with a gradual modification of the crystal periodic geometry or a gradual change of the refractive indexes. It is shown that, in such a perturbed system, the modes fields can be described as Bloch waves modified by a scalar envelope which adapts to the long-range dielectric function perturbation.

This envelope function obeys a simple linear Schrödinger equation of classical (non-quantum) origin. Close to a band extremum, at a gap edge, the envelope functions can be interpreted as wave functions of particles possessing a finite, spatially-variable, mass. These effective energy carriers come as two species, referred to as “effective photons” (for positive band curvatures) or “photonic holes” (for negative band curvatures). The energy transfer through the chirped structure can be viewed as resulting from the migration of these particles under forces controlled by the long-range dielectric function modulation. Due to the long-range, slowly-varying character of these forces, these particles are stable and are not destroyed by interband transitions.

All-optical effects in one-dimensional chirped photonic structures are investigated using the concept of photonic energy carriers: we reformulate optical shallow donor and acceptor bound states formation, optical Bloch oscillations, optical Zener and optical Frank-Keldysh effects in the framework of this corpuscular picture.