Nanostructures and Computation

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Introduction

Photonic crystals and nanophotonics employ nanoscale optical structures, on the scale of the wavelength of light, in order to produce optical phenomena far different from those in more homogeneous media. Our work has centered on three general categories of problems in nanophotonics: what new effects and devices can one achieve in such structures, how does one design devices given so many degrees of freedom, and what higher-level understanding can one develop for such complex systems. We have attacked these problems, in part, by developing new semi-analytical methods that allow us to treat difficult computational problems such as disorder and aperiodic taper transitions via small simulations combined with pertubative analyses. Electromagnetism also permits large-scale brute-force simulations that are essentially exact, and we have used this approach to demonstrate our ability to design optical cavities with a remarkable immunity to disorder. And using the efficient methods we have developed, we are able to bring powerful optimization approaches to bear on design problems such as input coupling for slow-light devices.

Disorder in photonic devices

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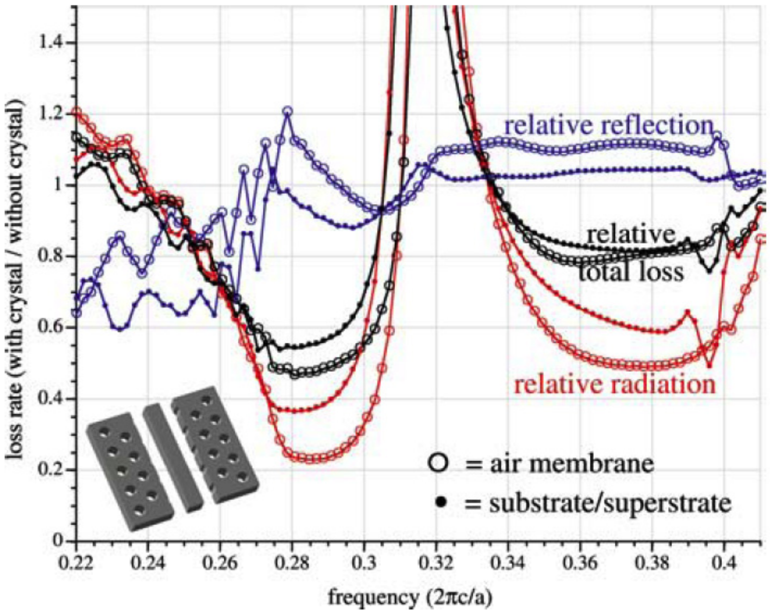
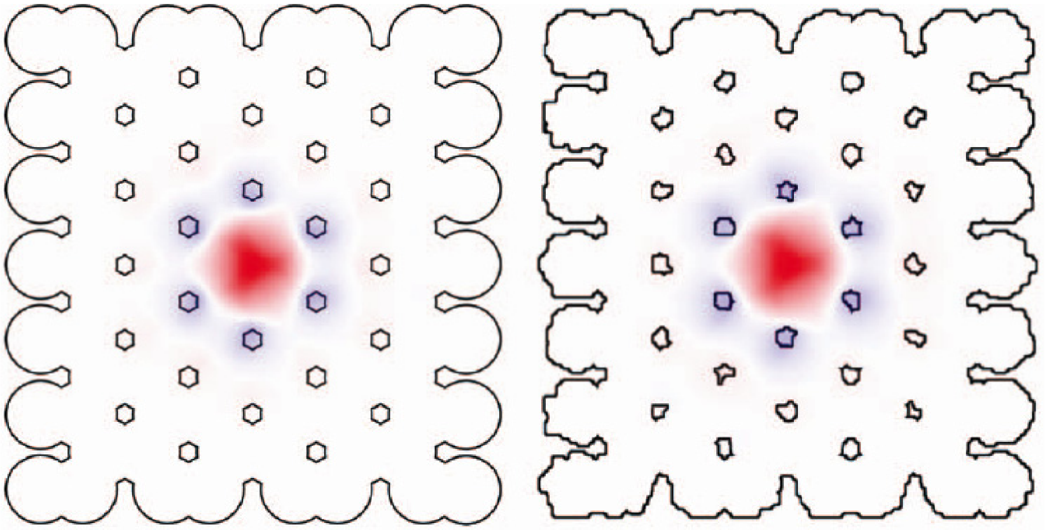
Project staff:
A. Farjadpour, Prof. J. D. Joannopoulos, Prof. S. G. Johnson, M. Ibanescu, and A. Rodriguez.

An ultimate limiting factor in the efficiency of photonic devices is fabrication disorder, which leads to unwanted scattering of light. This arises in everything from optical fibers (where density fluctuations in the glass set a lower bound on attainable losses in conventional fibers) to optical microcavities (where losses due to surface roughness limit the narrowness of the bandwidth). Our work in this area has focused both on developing new methods to analyse disorder effects and also new ways to compensate for it.



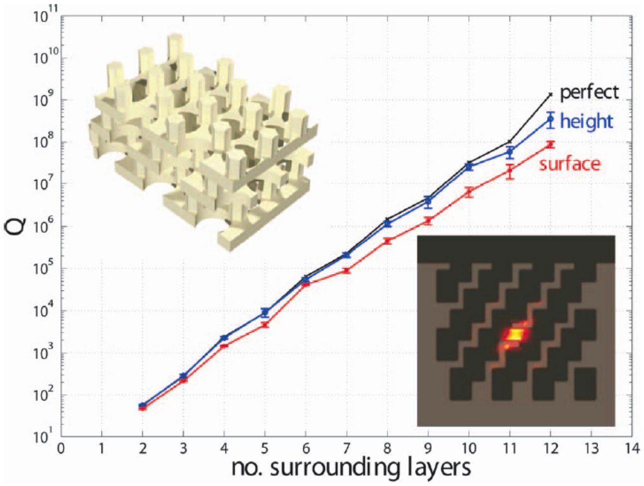
Relative surface-roughness losses (reflection, radiation, and total) of strip waveguide surrounded by photonic-crystal slab (inset) compared to isolated strip, versus frequency. There is a broad bandwidth (around a frequency of 0.29) where the photonic crystal is predicted to reduce total loss by a factor of two. (The spike in the center is caused by a Fabry-Perot resonance, which can be removed by changing the design.)

The most common form of disorder is nanometer-scale surface roughness, which poses special challenges for theoretical analysis. The spatial resolution needed to accurately model realistic surface roughness makes direct computational methods nearly prohibitive. Instead, we seek to treat the roughness as an *analytical* perturbation applied to the disorder-free system—such perturbative approaches are not only much more efficient, but they also can provide more insight than brute-force computation. For example, in previous work (Povinelli *et al.*, 2004), we used perturbative methods to rigorously prove that a photonic band-gap reduces disorder-induced radiative loss while backscattering (reflection) is unaffected, all other things equal. However, sbecause of the discontinuities in the electric field at an interface between two dielectric materials, the correct application of perturbative methods to surface roughness leads to unsolved problems. In Johnson *et al.* (2005), we have shown how to solve the elementary problem of the scattering from a single small surface bump, by reducing it to a simple electrostatics problem. Unlike previous work, ours is the first valid perturbative solution in the case of large material contrasts common in photonics. Furthermore, this immediately leads to the solution for the scattering loss from uncorrelated (or short-range correlated) surface roughness, since in that case one can simply multiply the power scattered by a single bump by the mean bump density. In this way, we were able to directly predict the effect of realistic surface roughness loss on strip waveguides, and show that a simple two-dimensionally periodic photonic-crystal structure surrounding the waveguide should reduce radiation loss by a factor of two as shown in the figure above.



Cross-section of a microcavity mode in a three-dimensional photonic crystal (red/blue/white = positive/negative/zero electric field out of the plane). *Left*: perfect crystal. *Right:* mode is barely affected by large surface roughness.

For a microcavity, disorder-induced radiation loss limits the ability to make narrow-band filters, to enhance nonlinear effects, and other goals associated with long photon lifetimes. However, we have shown (Rodriguez *et al*., 2005) that a microcavity whose losses are *immune* to bounded disorder can be constructed using a *three-dimensional* photonic crystal. In a three-dimensional crystal such as the one fabricated in Qi *et al.* (2004), the confinement mechanism is an omnidirectional photonic bandgap, analogous to the electronic bandgap that distinguishes insulators from conductors. It is known from solid-state physics that this bandgap is preserved in a disordered system, if the disorder is not too great. We have now demonstrated, by direct three-dimensional simulation (see above figure), the consequences of this for an optical microcavity: the modal volume and lifetime are nearly independent of the disorder, and only depend on the overall size of the crystal. As shown in the figure below, the lifetime increases exponentially with crystal size, with disorder only slightly impacting the exponential *rate*.



Lifetime (*Q*) for confined mode (inset, bottom-right) vs. number of layers of three-dimensional photonic crystal (inset, top-left). *Q* increases exponentially for both the perfect crystal and for large disorder in the layer heights or surfaces.

Slow-light design and devices

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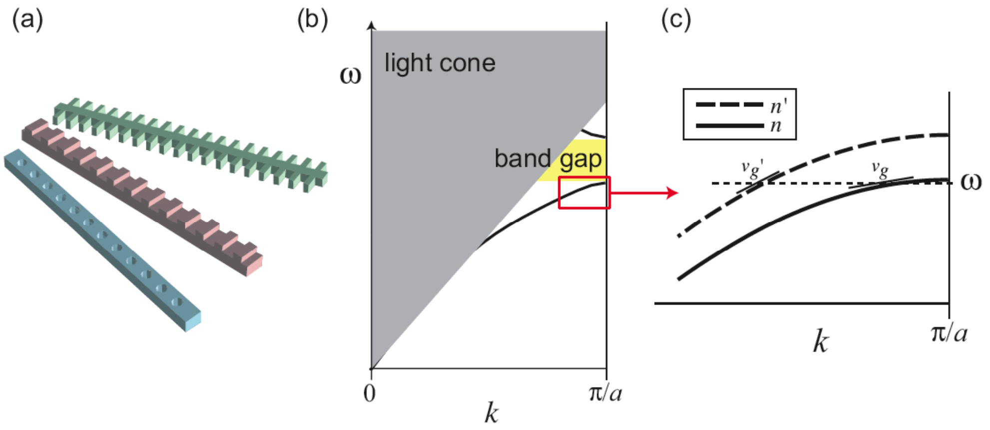
Prof. Y. Fink, M. Ibanescu, D. Roundy, Prof. J. D. Joannopoulos, Prof. S. G. Johnson, and M. L. Povinelli

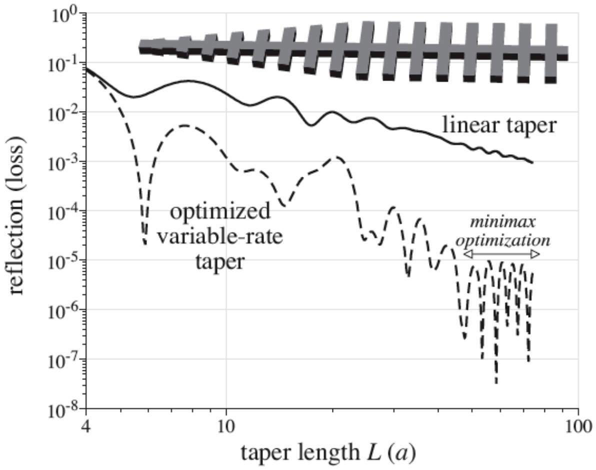
One of the most intriguing properties of periodic dielectric waveguide structures (such as in photonic crystals, but also in ordinary strip waveguides with a periodic grating) is their ability to produce *slow light*. As the frequency approaches the edge of the photonic band, the group velocity slows down, and its minimum is limited only by the size and perfection of the fabricated structure.

We have explored various ways to exploit this effect. Previously, we investigated slow-light applications for Mach-Zehnder interferometers (Soljacic *et al.*, 2002) and radiation pressure (Povinelli *et al.*, 2004). Our previous work on radiation pressure has carried over to new (Povinelli, 2005) papers on similar interactions in ring resonators and dielectric waveguides. This year, we have used slow light to design unusual high-*Q* microcavity structures (Ibanescu *et al.*, 2005), and also to design tunable optical delay lines (Povinelli, Johnson, and Joannopoulos, 2005). For an optical delay line, it is not the slowness per se of the light that we exploit, but rather the divergent group-velocity dispersion near the band edge—this dispersion allows a small change in the structure to produce a large change in the optical delay, allowing continuous tunability in a small device. This is schematically illustrated below.



(a) Types of periodic dielectric waveguides. (b) Schematic band structure, with slow-light band edge (red box). (c) Magnified band edge: the large dispersion means a slight shift of the band edge will cause a large change in group velocity (slope).

The desire to exploit slow light gives rise to several difficult design and fabrication problems. One difficulty is simply how to get light into the structure. A slow-light waveguide has a large "impedance mismatch" with an ordinary waveguide, making simple butt- or taper-coupler structures problematic. Our previous work (Johnson *et al.*, 2002) showed that there is an adiabatic theorem—a slow taper transition, properly designed, can have arbitrarily low loss, regardless of the impedance mismatch—but the required taper length may be very long. Fortunately, the same work gave us an efficient coupled-mode theory that we can use to predict the taper losses quickly, and using this method we are able to design an *optimized* structure with a variable taper rate that performs much better: 0.001% reflections with a taper only 20 periods long, shown at right.



Slow-light taper design performance, for three-dimensional periodic silicon waveguide (top inset) on silica substrate (not shown). As the taper length is increased, the transition losses decrease, but only very slowly for a linear taper because of the large impedance mismatch. A minimax-optimized variable-rate taper is found that yields much-improved performance for the same length.

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