Nanostructures and Computation

Academic and Research Staff
Professor Steven G. Johnson

Graduate Students
Ardavan Farjadpour, Ka-Yan Karen Lee, Alejandro Rodriguez, Hila Hashemi,
Alexander McCauley, Andre Kurs, Homer Reid, and Xiangdong Liang

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. Electromagnetism also permits large-scale brute-force simulations that are essentially exact, and this has led us to a second topic of research, that of efficient numerical methods for large-scale computation.

1. Robust Optimization of Nanophotonic Devices

Sponsors:
DARPA (award no. N00014-05-1-0700, Office of Naval Research)
National Science Foundation (grant no. 0423905)
Air Force Office of Scientific Research (grant no. F49620-01-1-0365)
MARCO Focus Center for Circuit & System Solutions (contract no. 2003-CT-888)

Project staff:
A. Mutapcic, A. Farjadpour, Y. Avniel, Prof. S. Boyd (Stanford), Prof. S. G. Johnson

The nanophotonics field is increasingly turning to large-scale optimization techniques to aid in designing complicated high-performance devices, in order to make sensible use of the huge number of degrees of freedom afforded by modern lithography techniques. Virtually any two-dimensional pattern can now be fabricated, but which pattern should be used for a given device? Employing optimization to automatically explore these degrees of freedom invites a new danger, however—the *nominal* optimum solution may be so sensitive to changes in the parameters than even tiny manufacturing deviations debilitate performance, making the design unmanufacturable in practice. This risk is especially pertinent in photonics, where the wave nature of the physics means that one can easily design devices whose performance relies on delicate interference phenomena that can be destroyed by tiny deviations from the nominal design. To combat this tendency, we have explored the use of *robust* optimization, in which manufacturing uncertainty is taken into account during the optimization process by optimizing the *worst*-case performance under uncertainty. Robust-optimization methods have been developed and applied in several other optimization problems such as linear programming, and in many cases produce solutions that perform nearly as well as the nominal optimum in the absence of uncertainty, but whose performance degrades much more gracefully when the design parameters are not fabricated exactly.

In Mutapcic et al. (2009), we applied these ideas to the problem of designing a taper coupler between a uniform waveguide and a periodic “slow-light” waveguide. Slow-light waveguides reduce the group velocity of light by a periodic structure, and are desirable to greatly enhance light-matter interactions for nonlinear and active devices, but are difficult to couple to because of their large “impedance mismatch” with an ordinary waveguide. As seen in figure 1, we showed that robustness made an enormous difference in the performance of the device in the presence of uncertainty (an order of magnitude or more, depending on the amount of manufacturing disorder assumed). Moreover, most previous robust-optimization techniques were developed for problems such as linear programming that are *convex*, having a unique optimum (no local minima) and efficient algorithms to find this optimum. Nanophotonics problems, on the other hand, are generally highly nonlinear and nonconvex with respect to the design parameters (the geometric shape), and we had to develop new methods to efficiently find good solutions for this problem. For example, many local optima are present, but we developed a "successive refinement" heuristic that finds a "more global" solution, insensitive to the starting guess and favoring solutions robust to manufacturing disorder.

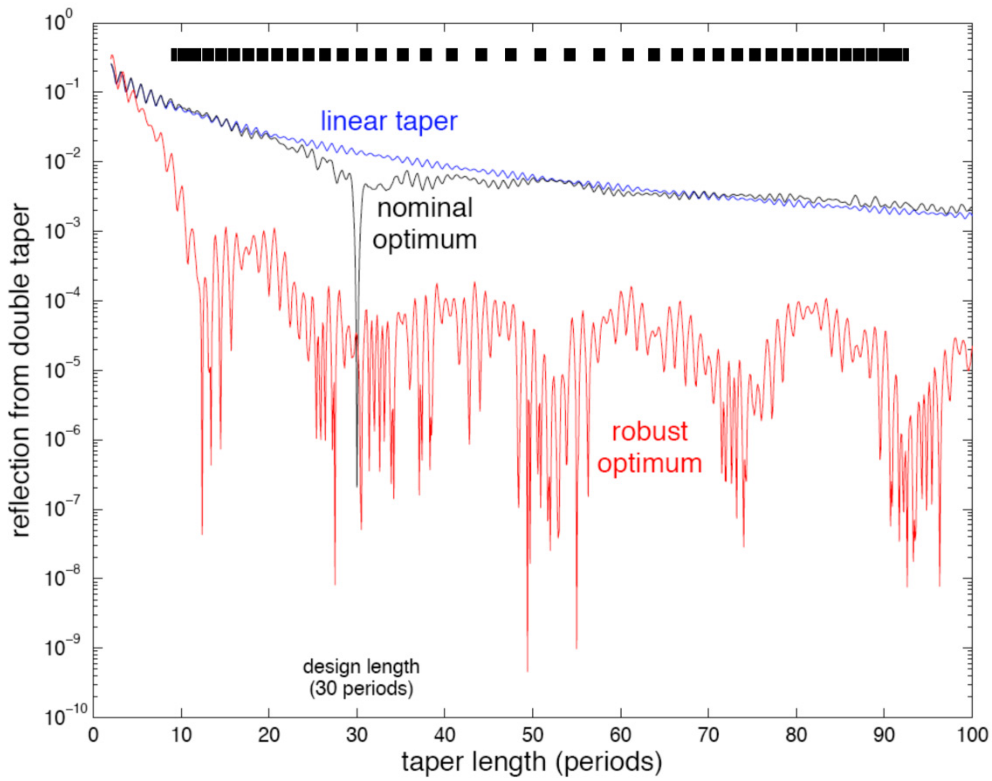


figure 1. Reflection vs. taper length for a taper between a uniform waveguide and a periodic slow-light waveguide (a periodic sequence of dielectric blocks, inset, in this 2d model system); a taper transition is formed by changing the spacing between the blocks. The taper rate is optimized to minimize reflections at the indicated design length. The three curves are the results for a simple linear (constant rate) taper, the nominal optimum structure (without uncertainty) and the robust optimum (designed for the worst case under uncertainty in taper length, taper shape, and operating frequency). The nominal optimum relies on a delicate interference effect manifesting as a sharp dip in reflection—any deviation from the design parameters will destroy this dip, whereas the robust optimum produces low reflection for a much broader range of parameters.

2. New Regimes for Casimir Forces in Nanostructured Mechanical Systems

Sponsors:
Department of Energy (grant no. DE-FG02-97ER25308)
National Science Foundation (grant no. DMR-0213282)
MIT Ferry Fund

Project staff:
Prof. S. G. Johnson, Prof. J. D. Joannopoulos, Prof. J. White, A. W. Rodriguez, A. P. McCauley, H. Reid

Casimir forces are an interaction between uncharged objects that arise at micrometer-scale separations due to quantum vacuum-photon fluctuations. Besides their importance in basic physics research as a direct manifestation of the quantum vacuum as a measurable force, Casimir forces have important influences on cold atom trapping, superfluid films, and potentially for future nanomechanical devices. Although they were first predicted in 1948 for parallel metallic plates, Casimir forces have proven surprisingly difficult to predict for non-planar geometries; the state of the art in 2006 was the first theoretical prediction of the force between an infinite perfect-metal cylinder and an infinite perfect-metal plane. In our previous work, we demonstrated new numerical techniques to accurately predict Casimir forces for arbitrary geometries, including arbitrary dispersive materials, which has enabled us to study a range of problems that had never previously been accurately modeled. We have continued to develop these methods, and have applied them to investigate new qualitative regimes for the behavior of Casimir forces. Perhaps most interesting is the possibility of *repulsive* Casimir forces—Casimir forces between nearby surfaces are almost always attractive, but a repulsive force could be used in passive suspension/separation of surfaces and would have many potential applications.

We have demonstrated precise calculations of a "repulsive" force that arises entirely from geometry, between metallic surfaces, for the interleaved "zipper" geometry shown in figure 2. In this case, we constructed a "repulsive" force out of conceptually attractive interactions by allowing the two structures to interleave (and yet still allowing them to separate by a rigid rotation). This geometry is unstable with respect to lateral translations, however. A "true" repulsive Casimir force (not requiring interleaved structures) is known to be possible for *fluid*-separated objects of disparate materials, such as silica and gold separated by ethanol fluid. These repulsive forces had been calculated for parallel plates (and recently demonstrated experimentally at Harvard), but our new methods now allow the same force to be calculated in non-planar geometries. In particular, we were able to directly compute the forces for a silica particle/cylinder suspended in a metallic cavity, and show that *stable suspension* results for a variety of particle shapes, as seen in figure 3. For asymmetric particle shapes (such as the square cylinder in figure 3), a stable *orientation* also results (with some surprising transitions in the stable orientation for different cavity sizes, which we explained as an effect of material dispersion).

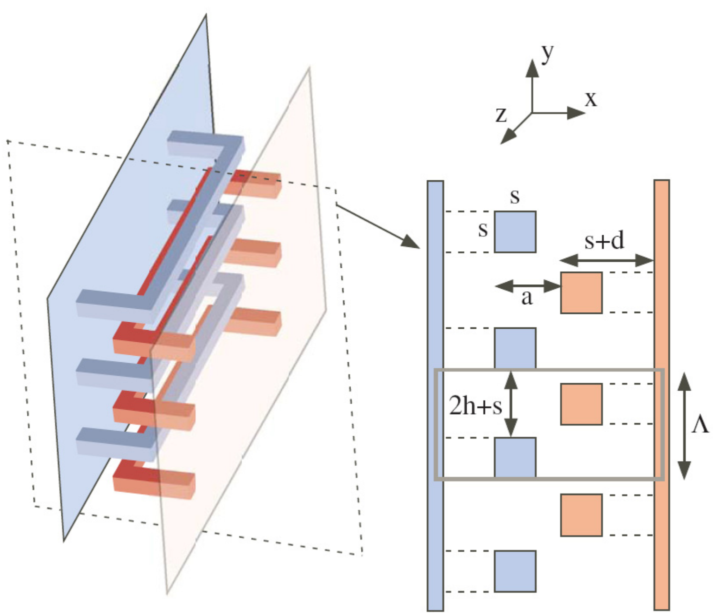


figure 2. Three-dimensional schematic of the Casimir "zipper" geometry of interlocking metal brackets (shown in different colors for illustration only), along with a two-dimensional *xy* cross section. The dashed lines extending from the plates to the squares indicate their out-of-plane connectivity. When the brackets interleave as shown at left, the Casimir force pushes the plates apart in a "repulsive" fashion.

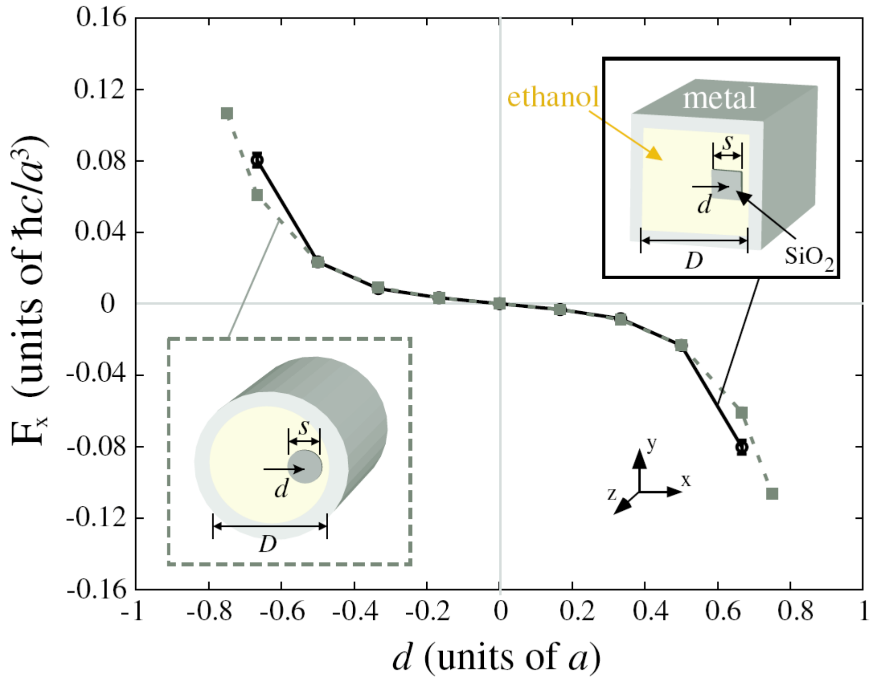
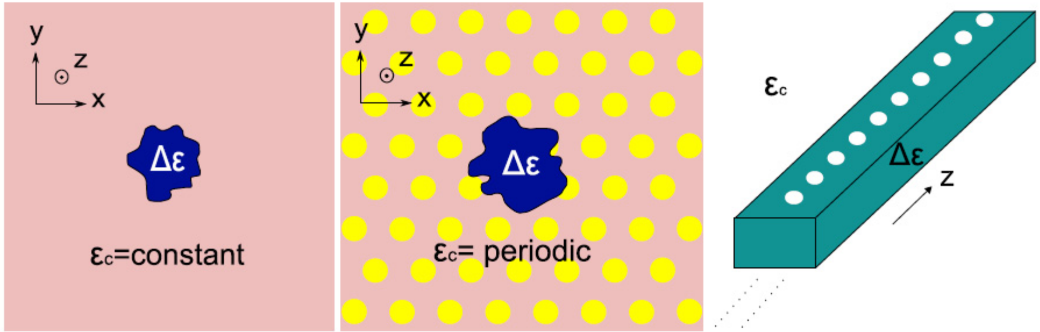


figure 3. Casimir force in the *x* direction, per unit *z* length, on a silica cylinder suspended within a metallic cylinder, separated by fluid, as a function of the displacement *d* from equlibrium, for both circular (dashed) and square (solid) cylinders. In both cases, the repulsive, rapidly decaying nature of the Casimir force leads to a restoring force (stable equilibrium).

3. Understanding Localization in Holey Fibers

Project Staff:
K. K.-Y. Lee, Dr. Y. Avniel, and Prof. S. G. Johnson

For several years now, it has been demonstrated both experimentally and numerically that microstructured "holey" optical fibers could guide light. These fibers are formed of a single solid material, typically silica glass, which is perforated by periodic holes in some regions to form an "average low-index" *cladding* that confines light within a solid *core* by a generalization of total-internal reflection. Although the existence of these guided modes is well-established by numerical and physical experiments, a deeper analytical understanding of the nature of this light-localization mechanism was lacking. Several open questions, such as the existence or lack of a long-wavelength cutoff for guiding, or exactly what is meant by "on average" lower index, remained. In recent work (Lee *et al.*, 2008), we have successfully tackled several of these questions by rigorous analytical methods, proving a very general theorem establishing sufficient conditions for localization in a wide variety of dielectric-waveguide geometries shown schematically in figure 4. The class of waveguides encompassed by our analysis includes holey fibers, but also general periodic structures such as traditional optical fibers, waveguides that are periodically modulated in the direction of propagation, anisotropic materials, and other structures. Moreover, the proof employs an elementary variational technique that (once presented) can be followed at an advanced undergraduate level. As a result, we believe that our theorem sheds new light on a broad class of dielectric waveguides in a manner accessible to a general audience interested in electromagnetic waves.



(a) Cross section of a waveguide (e.g. a conventional fiber) with a homogeneous cladding and an arbitrary-shape core.

(b) Cross section of a photonic-crystal fiber with periodic cladding and arbitrary-shape core.

(c) A waveguide periodic in the propagation (z) direction surrounded by a homogenous cladding.

figure 4. Schematic of various types of dielectric waveguides in which our theorem (proving conditions for localization) is applicable. Light propagates in the *z* direction (along which the structure is either uniform or periodic) and is confined in the *xy* directions by a higher-index core compared to the surrounding (homogeneous or periodic) cladding.

Publications

Journal Articles, Published

A. F. Oskooi, J. D. Joannopoulos, and S. G. Johnson, "Zero–group-velocity modes in chalcogenide holey photonic-crystal fibers," Optics Express, vol. 17, pp. 10082–10090, June 2009.

P.-R. Loh, A. F. Oskooi, M. Ibanescu, M. Skorobogatiy, and S. G. Johnson, "Fundamental relation between phase and group velocity, and application to the failure of perfectly matched layers in backward-wave structures," Physical Review E, vol. 79, p. 065601(R), June 2009.

I. B. Burgess, A. W. Rodriguez, M. W. McCutcheon, J. Bravo-Abad, Y. Zhang, S. G. Johnson, and M. Loncar, "Difference-frequency generation with quantum-limited efficiency in triply-resonant nonlinear cavities," Optics Express, vol. 17, pp. 9241–9251, May 2009.

A. Mutapcic, S. Boyd, A. Farjadpour, S. G. Johnson, and Y. Avniel, "Robust design of slow-light tapers in periodic waveguides," Engineering Optimization, vol. 41, pp. 365–384, April 2009.

R. E. Hamam M. Ibanescu, S. G. Johnson, J. D. Joannopoulos, and M. Soljacic, "Broadband5 super-collimation in a hybrid photonic crystal structure," Optics Express, vol. 17, pp. 8109–8118,5 5April 2009.

H. Hashemi, A. W. Rodriguez, J. D. Joannopoulos, M. Soljacic, and S. G. Johnson, "Nonlinear harmonic generation and devices in doubly-resonant Kerr cavities," Physical Review A, vol. 79, p. 013812, January 2009.

A. W. Rodriguez, J. N. Munday, J. D. Joannopoulos, F. Capasso, D. A. R. Dalvit, and S. G. Johnson, "Stable suspension and dispersion-induced transitions from repulsive Casimir forces between fluid-separated eccentric cylinders," Physical Review Letters, vol. 101, p. 190404, November 2008.

K. K. Lee, Y. Avniel, and S. G. Johnson, "Design strategies and rigorous conditions for single-polarization single-mode waveguides," Optics Express, vol. 16, pp. 15170–15184, September 2008.

R. E. Hamam, M. Ibanescu, E.J. Reed, P. Bermel, S. G. Johnson, E. Ippen, J.D. Joannopoulos, and M. Soljacic, "Purcell effect in nonlinear photonic structures: a coupled mode theory6 analysis," Optics Express, vol. 16, pp. 12523–12537, August 2008

A. F. Oskooi, L. Zhang, Y. Avniel, and S. G. Johnson, "The failure of perfectly matched layers, and towards their redemption by adiabatic absorbers," Optics Express, vol. 16, pp. 11376–11392, July 2008.

K. K. Y. Lee, Y. Avniel, and S. G. Johnson, "Rigorous sufficient conditions for index-guided modes in microstructured dielectric waveguides," Optics Express, vol. 16, pp. 9261–9275, June 2008.

A. W. Rodriguez, J. D. Joannopoulos, and S. G. Johnson, "Repulsive and attractive Casimir forces in a glide-symmetric geometry," Physical Review A, vol. 77, p. 062107, June 2008.