Characterization of a 3D Photonic Crystal Structure Using Port and S-Parameter Analysis

M. Dong[1], M. Tomes[1], M. Eichenfield[2], M. Jarrahi[1], T. Carmon[1]

[1]University of Michigan, Ann Arbor, MI, USA

[2]Sandia National Laboratories, Albuquerque, NM, USA

Abstract

Numerical simulations[1] are common in describing optical experiments in microdevices. Among them, light tunneling[2], optical level crossing[3], and generation of 3rd [4] and 4th [5] harmonics. In the mechanical domain, simulations of vibrational modes in microresonators [6,7] provide details on recently observed mechanical whispering-gallery modes [8,9] that are electrostictivly excited by light as well as on the traditional breath modes [10] that are excited by the centrifugal radiation pressure that the circulating light applies on the device walls. Numerical simulations also describe opto-mechanical crystals [11] and optomechanics in microfluidic devices [12,13]. In COMSOL Multiphysics®, the use of its eigenfrequency solver has been predominant in these characterizations, giving us the resonance frequency, field profile, and quality factor of the eigenmode. However, in order to model our real experiments more accurately, knowing the input and output coupling to these resonators is useful.

We present a 3D port sweep method in a lossy silicon photonic crystal resonator to demonstrate frequency domain analysis with input and output ports in COMSOL Multiphysics. This method benefits from the advantages of the S-parameter analysis to characterize the input and output coupling into the resonator. The model geometry is shown in Figure 1 and follows the design as described by Song[14], with a representing the lattice constant of the central cavity, a_r representing the lattice constant of the reflector region which is related to the cavity constant by the relation a_r=a_frac*a, and a_m representing the lattice constant of a "matching" region and is equal to the average of a and a_r. The photonic crystal is first characterized by an eigenfrequency analysis in order to find the cavity resonance. We then run a port simulation in which we send a correctly polarized plane wave from one end of the photonic crystal and monitor the power coming out of the other end. The frequency of the input wave is swept and we verify our eigenfrequency by identifying a resonance peak in the transmission and reflection coefficients in Figure 2. We proceed to varying the parameter a_frac in order to change the lattice constant of the reflector region, which then changes the bandgap of this region and ultimately changes the coupling into and out of the resonator. The transmission coefficient through the photonic crystal as a_frac is being swept is shown in Figure 3. Notice that as a_frac becomes closer to 1, meaning as the reflector region's lattice constant is approaching that of the cavity region, the mode is becoming less and less confined, eventually disappearing altogether when a_frac=1. Also as expected, because of material losses, the quality factor is decreasing while total transmission is increasing when the mode becomes less confined.

Although we only show the results of sweeping a single parameter, many other parameters in this photonic crystal cavity can be changed to see how they affect the overall transmission through the cavity. We hope that this method will be useful in the characterizations of other resonator systems, particularly if finding the coupling rate is of interest.

Reference

[1] M. Oxborrow, Traceable 2-D finite-element simulation of the whispering-gallery modes of axisymmetric electromagnetic resonators, IEEE Transactions on Microwave Theory and Techniques, Vol 55(6), 1209-1218 (2007)

[2] M. Tomes et al., Direct imaging of tunneling from a potential well, Optics Express, Vol 17, 19160 (2009)

[3] T. Carmon et al., Static envelope patterns in composite resonances generated by level crossing in optical toroidal microcavities, Phys. Rev. Let., Vol 100, 103905 (2008)

[4] T. Carmon, K. J. Vahala, Visible continuous emission from a silica microphotonic device by third-harmonic generation, Nature Physics, Vol 3(6), 430-435 (2007)

[5] J. Moore et al., Continuous-wave ultraviolet emission through fourth-harmonic generation in a whispering-gallery resonator, Optics Express, Vol 19(24), 24139-24146 (2011)

[6] J. Zehnpfennig et al., Surface optomechanics: Calculating optically excited acoustical whispering gallery modes in microspheres, Optics Express, Vol 19, 14240-8 (2011)

[7] G. Bahl et al., Acoustical whispering-gallery modes in optomechanical shells, New Jour. of Phys., Vol 14, 115026 (2012)

[8] G. Bahl et al., Stimulated optomechanical excitation of surface acoustic waves in a microdevice, Nat. Comm., Vol 2, 403 (2011)

[9] M. Tomes, T. Carmon, Photonic micro-electromechanical systems vibrating at X-band (11GHz) rates, Phys. Rev. Let., Vol 102(11), 113601 (2009)

[10] T. Carmon et al., Temporal behavior of radiation-pressure-induced vibrations of an optical microcavity phonon mode, Phys. Rev. Let., Vol 94, 223902 (2005)

[11] M. Eichenfield et al., Optomechanical Crystals, Nature, Vol 462(7269), 78-82 (2009)

[12] G. Bahl et al., Brillouin cavity optomechanics with microfluidic devices, Nat. Comm., Vol 4, 1994 (2013)

[13] K. H. Kim et al., Cavity optomechanics on a microfluidic resonator with water and viscous liquids, arXiv, 1205.5477 (2012)

[14] B. Song et al., Ultra-high-Q photonic double-heterostructure nanocavity, Nature Materials, Vol 4(3), 207-210 (2005)

Figures used in the abstract

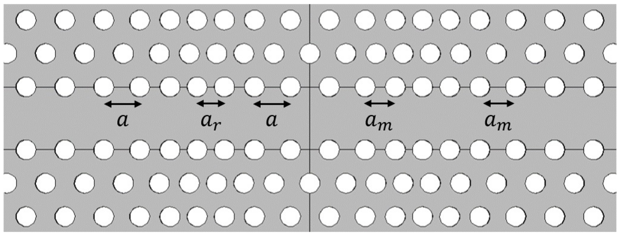

Figure 1: Exaggerated geometry of our system, a symmetric silicon photonic crystal cavity. a represents the lattice constant of the central cavity, a_r represents the lattice constant of the reflector region, with a_r=a_frac*a, and a_m represents the lattice constant of a “matching” region with a_m=(a_m+a)/2. Silicon’s material loss at 100GHz is included in the simulation.

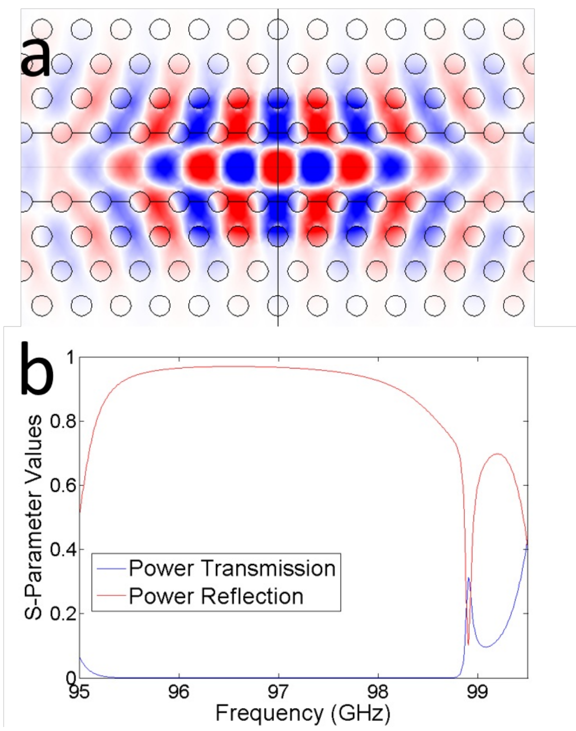

Figure 2: a) Field profile of the cavity mode from eigenfrequency analysis b) Power reflection and transmission (|S_21|^2 and |S_11|^2) at different frequencies obtained from the port sweep simulation.

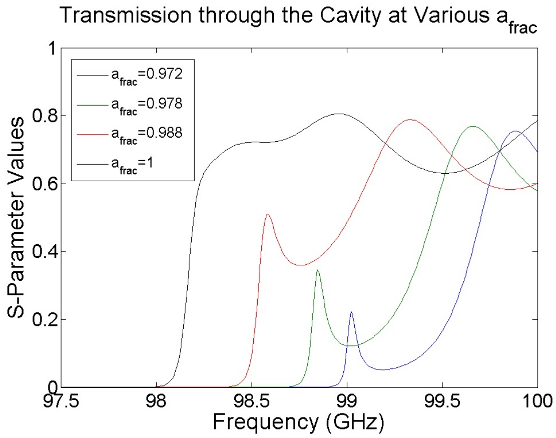

Figure 3: The power transmission (|S_21|^2) through the cavity as the parameter a_frac is swept, which changes the reflector region's lattice constant as defined a_r=a_frac*a which then changes the matching region's lattice constant as defined a_m=(a_m+a)/2.