

EE340: Advanced topics in optics and quantum optics

Optical microcavities

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Syllabus (tentative)

Part 1

Introduction to optical resonators

- Lossless hollow rectangular resonator
- Losses in a resonator. Quality (Q) factor of a resonator
- Finesse, free-spectral range, and mode volume of a resonator

References:

1. Ramo, Whinnery and Van Duzer, *Fields and waves in communication electronics*, 3rd edition, chapter 10
2. Jackson, *Classical electrodynamics*, 2nd edition, sections 8.7 and 8.8

Part 2 (1 hw)

Mechanisms for confinement of light

- Total internal reflection (TIR)
- Electromagnetic propagation in periodic media
 - Periodic media: Floquet (Bloch) theorem, Bloch waves, and band structure
 - Distributed Bragg reflection (DBR)
 - Photonic crystals, photonic band gap

References:

1. Born and Wolf, *Principles of optics*, 7th edition, section 1.5
2. Yariv and Yeh, *Optical waves in crystals*, chapter 6
3. Joannopoulos et. al, *Photonic crystals*

Part 3 (1 hw)

Electromagnetic field quantization in resonators

- Introduction: a brief review of classical mechanics, rules for quantization, quantum harmonic oscillator, and Maxwell's equations.
- Normal mode expansion of the electromagnetic field in:
 - Lossless medium with a uniform dielectric constant
 - Lossless medium with a non-uniform dielectric constant
 - Resonator (cavity)
- Electromagnetic field quantization in:
 - Lossless 1D resonator with a uniform dielectric constant
 - Free space
 - Lossless medium with a non-uniform dielectric constant
 - Resonator (cavity)
 - Very large Q-factor case: treating resonator as lossless
 - Lossy resonator: quantum Langevin equation

Useful references:

1. M. O. Scully and M. S. Zubairy, *Quantum optics*, Cambridge University Press 1997 (chapter 1)
2. R. Loudon, *The quantum theory of light*, Oxford Science Publications, 3rd edition (chapter 4)
3. R. J. Glauber and M. Lewenstein, "Quantum optics of dielectric media", *Physical Review A*, vol. 43, pp. 467-491 (1991)
4. Y. Yamamoto and A. Imamoglu, *Mesoscopic quantum optics*, Wiley and sons, 1999 (chapter 7)

Part 4 (1 hw)

Introduction to cavity quantum electrodynamics (cavity QED)

- Semi-classical treatment of the atom - electromagnetic field interaction: the interaction Hamiltonian in the dipole approximation
- Quantum-mechanical treatment of the atom - electromagnetic field interaction: Jaynes-Cummings Hamiltonian
- Strong and weak coupling regimes of the cavity QED
 - Strong coupling regime
 - Rabi oscillation
 - Normal mode splitting; dressed and bare states.
 - Weak coupling regime
 - Spontaneous emission rate in free space: Einstein's A coefficient
 - Spontaneous emission rate in a medium with a uniform dielectric constant
 - Modification of the density of photon states in a cavity
 - Spontaneous emission rate in a cavity; Purcell effect
 - Spontaneous emission coupling factor and relation to laser threshold

Useful references:

1. S. Haroche and D. Kleppner, "Cavity quantum electrodynamics", *Physics Today*, January 1989, pp. 24-30
2. K. Vahala, "Optical microcavities", *Nature*, vol. 424, pp. 839-846 (Aug. 14 2003)
3. H. J. Kimble, "Structure and dynamics in cavity quantum electrodynamics", in *Cavity Quantum Electrodynamics*, edited by P. Berman, pp. 203-267 (Academic Press 1994)
4. Y. Yamamoto and A. Imamoglu, *Mesoscopic quantum optics*, Wiley and sons, 1999 (chapter 6)
5. M. O. Scully and M. S. Zubairy, *Quantum optics*, Cambridge University Press 1997 (chapters 6, 9)
6. H. Mabuchi and A. C. Doherty, "Cavity quantum electrodynamics: coherence in context," *Science*, vol. 298, pp. 1372-1377 (2002).

Part 5 (~2 hws)

Types of optical microcavities

- Fabry-Perot resonators
- Microcavities employing only TIR (whispering gallery resonators)
 - Microdisk
 - Microring
 - Microsphere

- Microtorus
- Microcavities employing DBR combined with TIR
 - DBR micropost (micro-pillar)
 - Planar photonic crystal microcavities (cavities in two-dimensional photonic crystals of finite depth)
- Microcavities employing only DBR
 - Three-dimensional photonic crystal resonators

References (incomplete)

1. K. Vahala, "Optical microcavities", *Nature*, vol. 424, pp. 839-846 (Aug. 14 2003)
2. Y. Yamamoto and R. Slusher, "Optical processes in microcavities," *Physics Today*, June 1993, pp. 66-73.
3. C.J. Hood, T.W. Lynn, A.C. Doherty, A.S. parkins, and H. J. Kimble, "The atom-cavity microscope: single atoms bound in orbit by single photons," *Science*, vol. 287, No. 25, pp. 1447-1453 (2000).
4. Lord Rayleigh, "The Problem of the Whispering gallery", in *Scientific papers*, vol. 5, pp. 617-620, Cambridge University, Cambridge, England 1912. Also published in the *Philosophical magazine*, vol. XX, pp. 1001-10004 (1910).
5. Larry Coldren and Scott Corzine, *Diode lasers and photonic integrated circuits*, Wiley 1995.
6. S. L. McCall, A.F.J. Levi, R.E. Slusher, S.J. Pearton, and R.A. Logan, "Whispering-gallery mode microdisk lasers," *Applied Physics Letters*, vol. 60, pp. 289-291 (January 1992).
7. N.C. Frateschi and A.F.J. Levi, "The spectrum of microdisk lasers," *Journal of Applied Physics*, vol. 80, no. 2, pp. 644-653 (1996)
8. B. Gayral, J. M. Gérard, A. Lemaître, C. Dupuis, L. Manin, and J. L. Pelouard, "High- Q wet-etched GaAs microdisks containing InAs quantum boxes," *Applied Physics Letters*, Vol. 75, pp. 1908-1910 (1999)
9. P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, Lidong Zhang, E. Hu, and A. Imamoglu "A Quantum Dot Single-Photon Turnstile Device", *Science* vol.22, No. 290, pp. 2282-2285 (2000)
10. K. Djordjev, S.J. Choi, and P.D. Dapkus, "Microdisk tunable resonant filters and switches," *IEEE Photonics Technology Letters*, vol. 14, pp. 828-830 (2002).
11. P. Rabiei, W.H. Steier, Z. Chang, and L.R. Dalton "Polymer micro-ring filters and modulators," *J. of Lightwave Technology*, vol. 20, pp. 1968-1975 (2002).
12. B.E. Little et al, "Vertically coupled glass microring resonator channel dropping filtes," *IEEE Photonic Technology Letters*, vol. 11, pp. 215-217 (1999).
13. V.B. Braginsky, M. L. Gorodetsky, and V.S. Ilchenko, "Quality factor and nonlinear optical properties of whispering gallery modes," *Phys. Lett. A*, vol. 137, pp. 393-397 (1989).
14. M. L. Gorodetsky, A.A. Savchenkov, and V.S. Ilchenko, "Ultimate Q of optical microsphere resonators," *Optics Letters*, vol. 21, No. 7., pp. 453-455 (1996).
15. L. Lefevre-Seguin and S. Haroche, "Towards cavity-QED experiments with silica microspheres," *Mat. Sci. Eng. B*, vol. 48, pp. 53-58 (1997).
16. J. R. Buck and H. J Kimble, "Optimal sizes of dielectric microspheres for cavity QED with strong coupling", *Physical Review A*, vol. 67, article 033806 (2003)
17. S.M. Spillane, T.J. Kippenberg, and K. J. Vahala, "Ultralow-threshold Raman laser using a spherical dielectric microcavity," *Nature*, vol. 415, pp. 621-623 (2002).
18. D.K. Armani, T.J. Kippenberg, S.M. Spillane and K.J. Vahala, "Ultra-high-Q toroid microcavity on a chip," *Nature*, vol. 421, pp. 925-928 (2003).
19. J. Vuckovic, C. Santori, D. Fattal, M. Pelton, G.S. Solomon, and Y. Yamamoto "Cavity-enhanced single photons from a quantum dot" (*review article*), to appear in *Optical Microcavities*, edited by Kerry Vahala, World Scientific (2004). [Vuckovic1]
20. M.Pelton, J. Vuckovic, G.S. Solomon, A. Scherer and Y. Yamamoto, "Three dimensionally confined modes in micropost microcavities: quality factors and Purcell factors", *IEEE Journal of Quantum Electronics*, vol. 38, pp. 170-177 (2002). [Pelton1]

21. M. Pelton, C. Santori, J. Vuckovic, B. Zhang, G. S. Solomon, J. Plant, and Y. Yamamoto, "An efficient source of single photons: a single quantum dot in a micropost microcavity", *Physical Review Letters*, vol. 89, article 233602 (November 2002). [Pelton2]
22. J. Vuckovic, M. Pelton, Y. Yamamoto and A. Scherer, "Optimization of three-dimensional micropost microcavities for cavity quantum electrodynamics", *Physical Review A*, vol. 66, article 023808 (August 2002). (also available at www.arxiv.org, quant-ph/0208134). [Vuckovic2]
23. J. Vuckovic, M. Loncar, H. Mabuchi and A. Scherer "Design of photonic crystal microcavities for cavity QED", *Physical Review E*, vol. 65, article 016608 (2002) (also available at www.arxiv.org, quant-ph/0208101). [Vuckovic3]
24. E. Yablonovitch, T. J. Gmitter, R. D. Meade, A. M. Rappe, K. D. Brommer, and J. D. Joannopoulos, "Donor and acceptor modes in photonic band structure," *Physical Review Letters*, vol. 67 (24): 3380-3383 (1991).
25. O. Painter, R. K. Lee, A. Scherer, A. Yariv, J. D. O'Brien, P. D. Dapkus, and I. Kim, "Two-Dimensional Photonic Band-Gap Defect Mode Laser", *Science*, vol. 284, 1819-1821 (1999).

Part 6 (1-2 hws)

Applications of optical microcavities

- Use of quantum dots as artificial atoms for cavity QED
- Thresholdless laser
- Channel add/drop filter
- Sensing
- Optical delay lines
- Coupled microcavity arrays
- Nonlinear optics (e.g., Raman lasers)
- Quantum information processing
 - Single and entangled photon sources
 - Single atom laser