Design of High Q-Factor Defect Modes in 2D Photonic Crystals

Aydin Akyurtlu
Department of Electrical Engineering, Virginia Tech, Blacksburg VA, USA
Advisor: Dr. Yasuhiko Arakawa
Institute for Industrial Science, University of Tokyo, Tokyo, Japan

Photonic crystals have been the topic of extensive study for their potential applications in fiber optic networks, photonic IC design, study of cavity quantum electrodynamics, and a variety of others. By creating structures of periodic dielectrics, photonic bandgaps can be created similar to electronic bandgaps in semiconductors. Defects are introduced into the crystal structures to create highly localized modes lying in the photonic bandgap. Such modes are valued for their strong spatial confinement, uniformity, and high quality factors. The current research was done to design 2D photonic crystals of air columns in a GaAs slab with non-degenerate dipole modes at optical communications wavelengths (~ 1um) with high Q-factors. Non-degenerate dipole modes in H1 type structures (defects based on a single removed air column) are studied due to their high Q-factor to mode volume ratio. Increases to mode Q-factor were studied by varying cavity asymmetry. Crystals were designed and tested using plane-wave expansion and FDTD computer simulations. Fabricated crystals were tested using photoluminescence tests.

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Aydin Akyurtlu, Department of Electrical Engineering, Virginia Tech, Blacksburg, VA
Dr. Yasuhiko Arakawa, Institute for Industrial Sciences, University of Tokyo, Tokyo, Japan
Dr. Satoshi Iwamoto, Institute for Industrial Sciences, University of Tokyo, Tokyo, Japan

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Background and Motivation

Abstract

Photonic crystal cavities are widely studied as methods for enhancement of output and efficiency for optoelectronic devices. The presented research dealt with the optimization of photonic crystal structures for enhancement of spontaneous emissions in quantum dot lasers. The current research was aimed at desigining 2D photonic crystals of air columns in a GaAs slab with non-degenerate dipole cavity modes, highly localized modes in the photonic bandgap due to lattice defects, with high Q-factors and low mode volumes. Non-degenerate dipole modes in H1 type structures (defects based on a single removed air column) were studied due to their high Q-factor to mode volume ratio. Research focused on increasing Q-factor by optimizing the defect structure, and then by optimizing the fabrication process.

What are Photonic Crystals?

- *Photonic Crystals* are structures with periodic differences in refractive index
- Periodic structure creates *bandgaps*, frequencies ranges for which no light will propogate
  - Similar to electronic bandgaps in semiconductors
- Defects in crystal lattice support modes at frequencies inside the bandgap known as *cavity modes*
  - Highly localized, low radiative losses
- Photonic Crystal *slabs* are 2D PC structures clad on both sides by material with large index difference
  - Large index difference confines out-of-plane light via total internal reflection

Applications

- Studying cavity QED
- Waveguiding
- Laser Sources
- Photonic IC

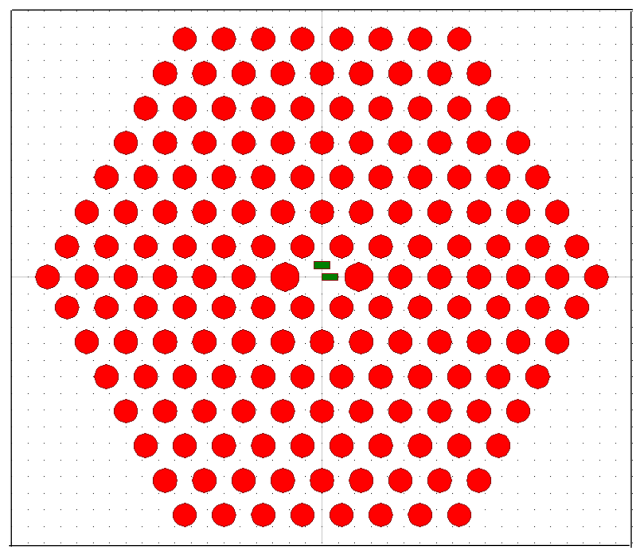


Fig. 1: Design with d = 1.2 and p = -0.05 (see Figs. 3 and 5 for variables)

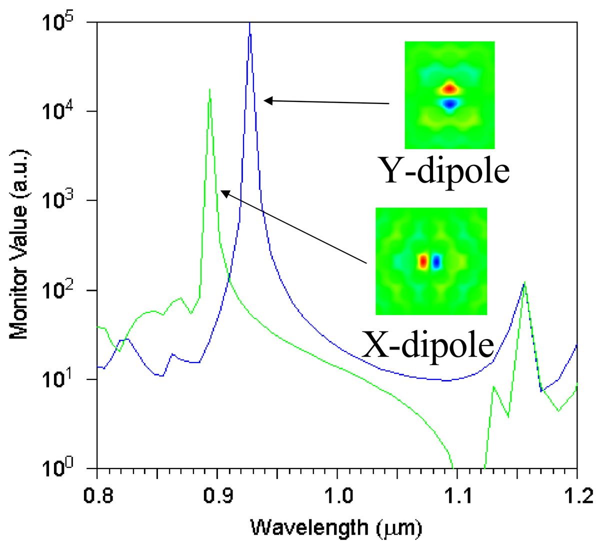


Fig. 2: Wavelength spectrum and dipole mode out-of-plane magnetic field profiles for d = 1.2 and p = -0.05

Design Optimization

Research Goals

- Design defect cavities that produce non-degenerate dipole modes
  - Degeneracy leads to lower mode Q-factor
- Design defect structure to optimize mode Q-factor
  - Increased Q-factor --> less radiation loss

Design Approach

- Use triangular lattice of air holes in GaAs with H1 (single hole) defect at center air hole for lowest mode volume
- Combinations of three structure types[1,2] studied:

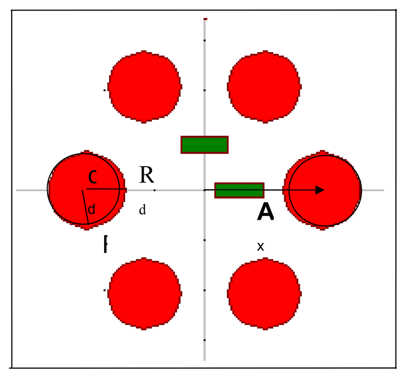


Fig. 3: *Y-split cavity* shown defect radius attenuated by d and moved along x-axis

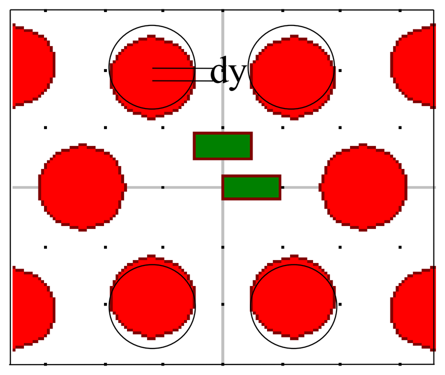


Fig. 4: *X-split cavity* shown defects moved along y-axis by dy

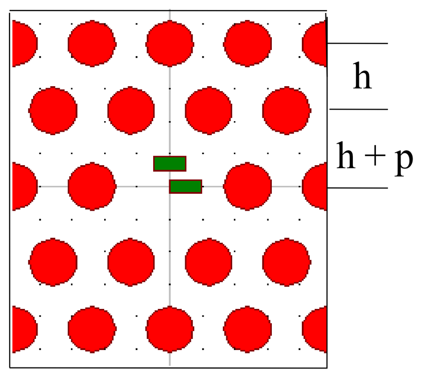
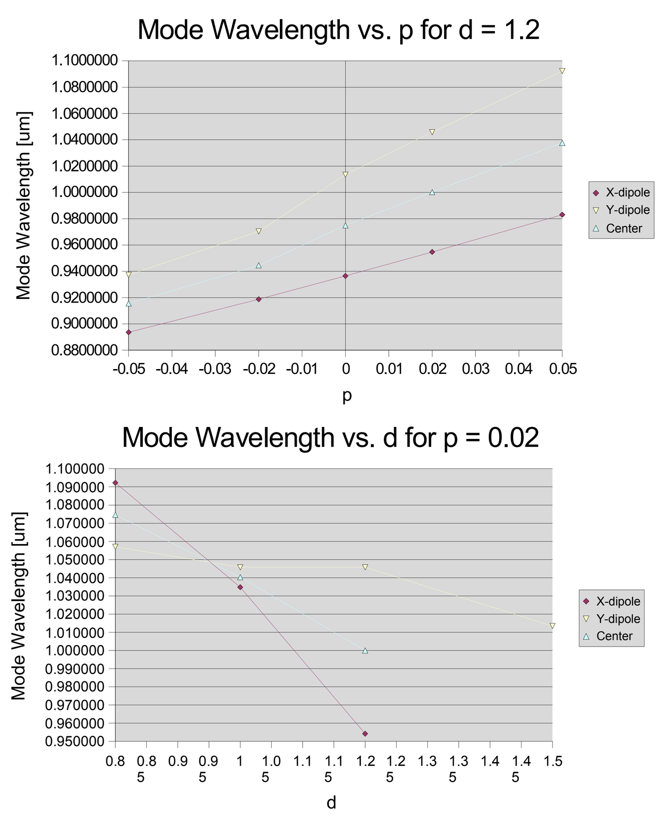


Fig. 5: *Fractional edge dislocation* all rows moved along y-axis by p

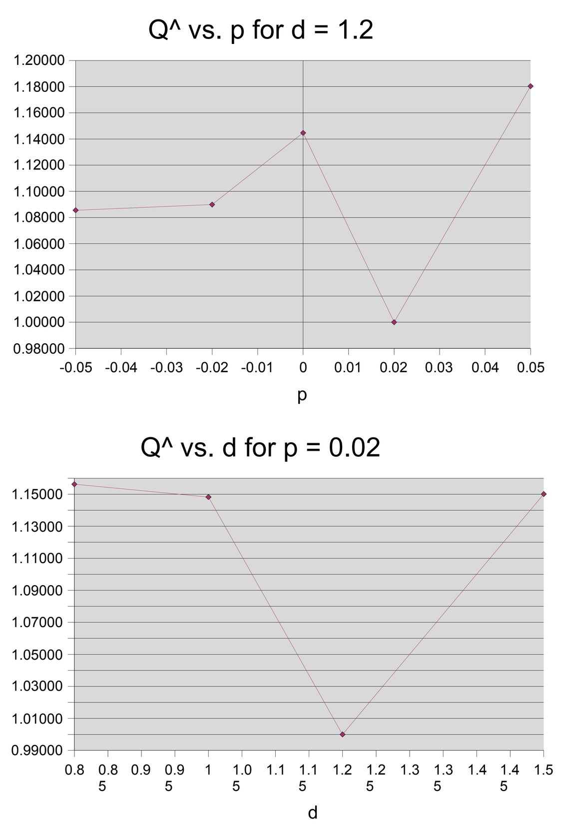
- Simulations run assuming infinite 2D crystal using FDTD
  - Simulations used 20 grid points per period
  - Because crystal was assumed to be infinite, only relative Q-factor values could be estimated by comparing 2D Fourier transforms of mode field profiles

Results and Analysis

- Most optimal structure found using combination of y-split cavity and fractional edge dislocation with d = 1.2 and p = 0.05 (see Figs. 3 and 5 above for description)
- Y-split structure breaks cavity symmetry, thereby removing the dipole degeneracy
- Fractional edge dislocation reduces Fourier components of the mode within light cone, indicating lower out-of-plane radiation



Figs. 6-7: Mode wavelength dependence on p and d



Figs. 8-9: Out-of-plane Q factor (normalized) dependence on p and d for y-dipole modes

Fabrication Optimization

Research Goals

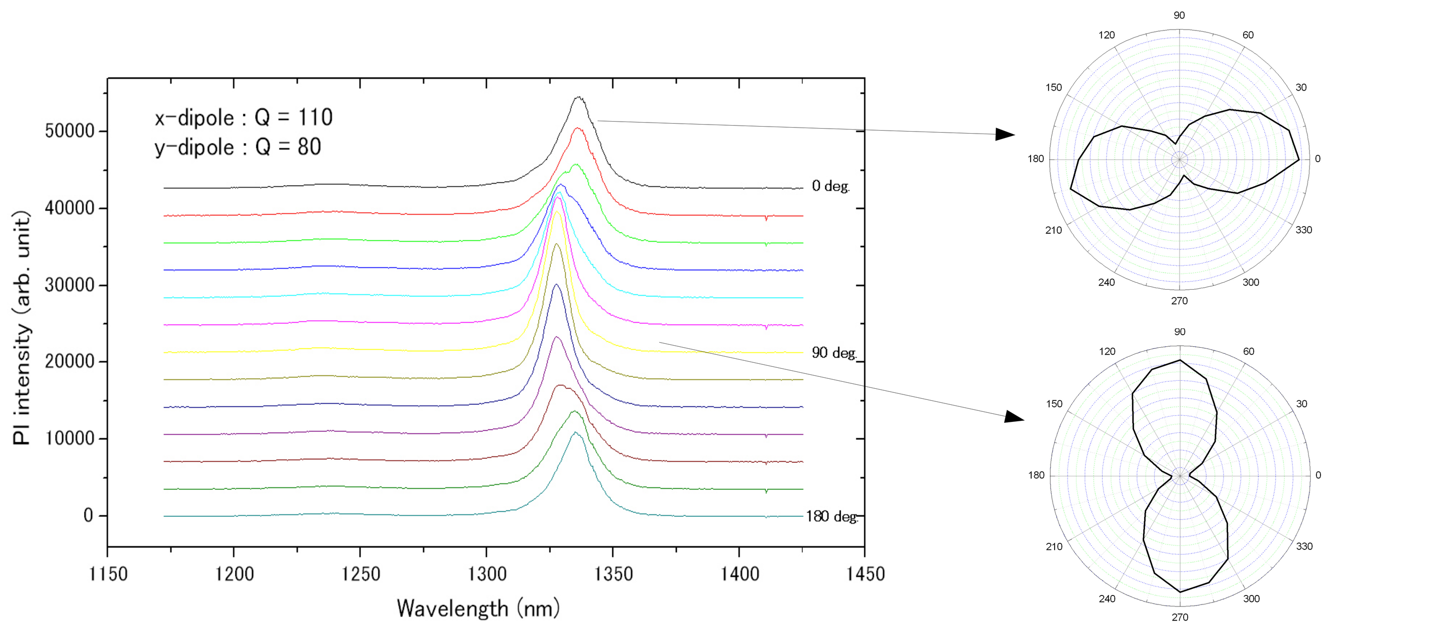
- Experimentally test fabricated crystal slabs
  - Determine mode excitations
  - Determine agreement with FDTD simulations
- Identify factors leading to errors in crystal during fabrication
  - Defects during fabrication limit variables such as air hole radius and cause lower Q-values

Approach

- GaAs layer clad by SiO_2 and resist above and an AlGaAs sacrificial layer below fabricated by MOCVD
  - Crystal structure patterned using electron beam lithography
  - SiO_2 layer etched using CF_4 and GaAs etched using Cl_2
  - Sacrificial layer and remaining SiO_2 removed using HF
- Samples tested using photoluminescence measurements
  - Modes excited by InAs quantum dot at ~1.25 um
    - Quantum dot pumped by Ti:Sapphire laser at 780 nm
  - Measurements taken at room temperature

Results

- Damage during resist development for structures with r/a > 0.36
- Doubly-degenerate dipole mode excited
  - Constituent dipoles filtered using polarizer
- PL results extremely consistent with FDTD simulations
  - Degenerate dipole mode Q-value ~80 compared to simulated Q-value of 120
  - Strong agreement suggests successful fabrication process



Figs. 9-11: Polarity dependence of degenerate mode wavelength and of constituent dipole mode magnitude

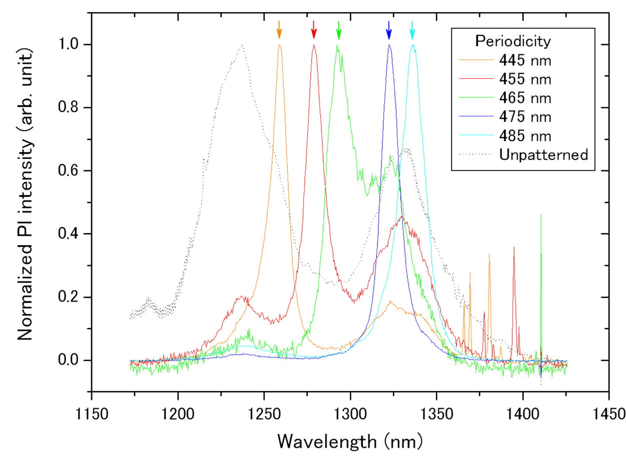


Fig. 12: Red shift of wavelength with increasing lattice period

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