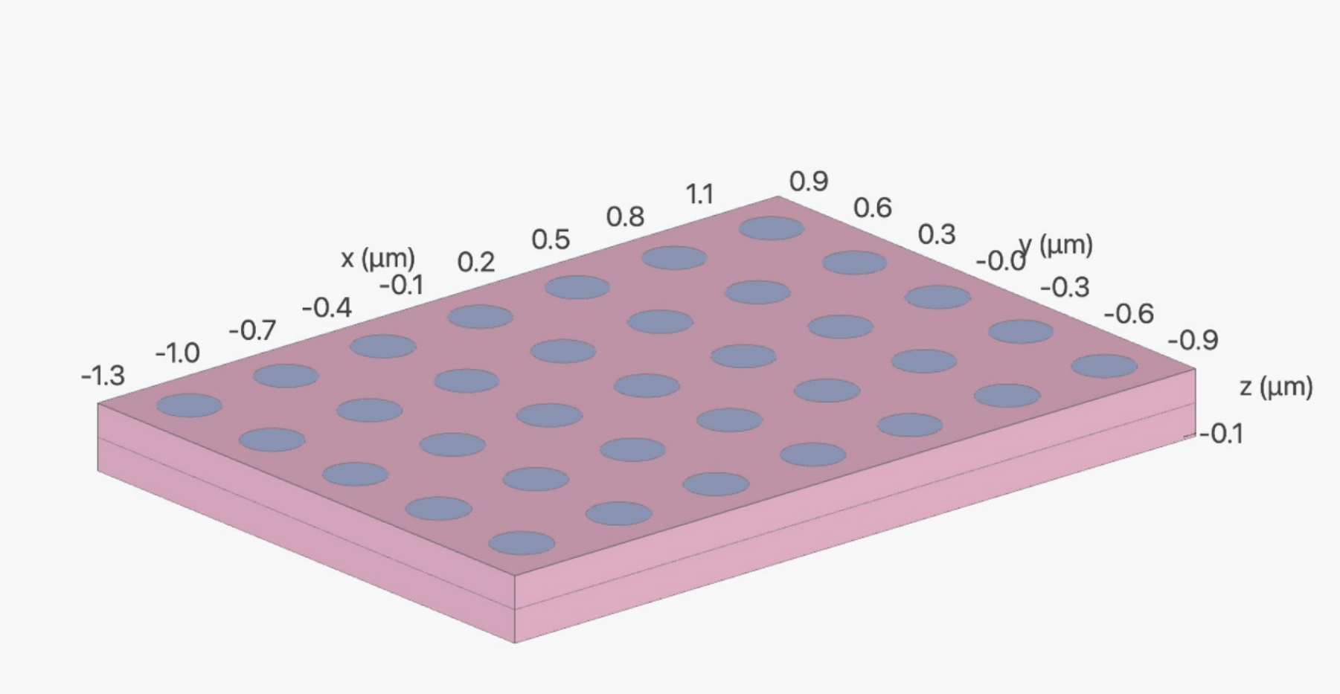
Particle Swarm Optimization for Robust Nanobeam Photonic Crystal Cavities

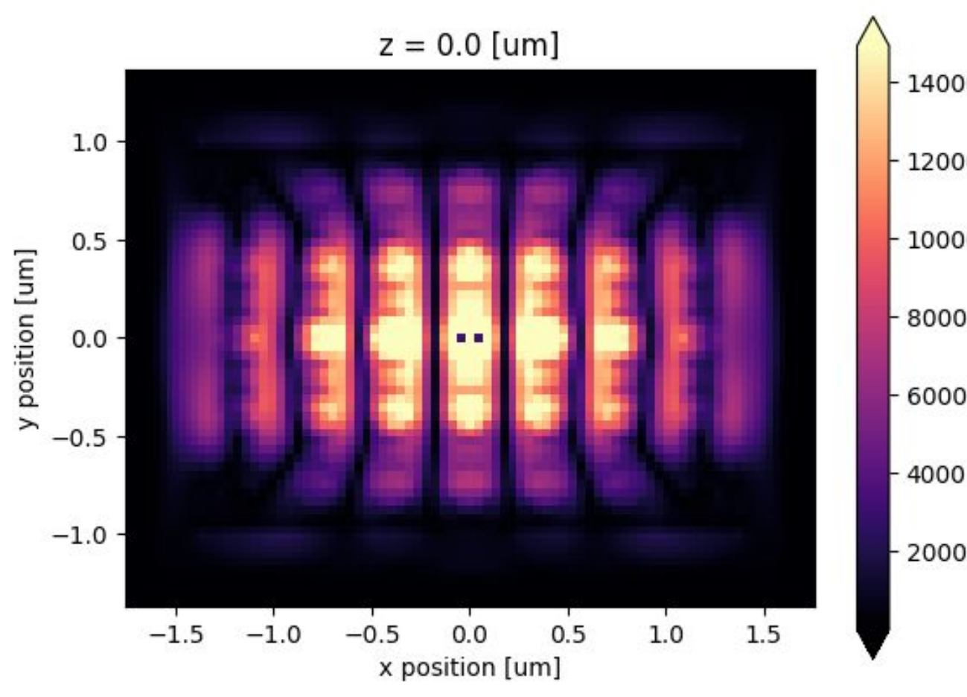
Jaden Hou[1,2], Neelesh Kumar Vij[1], Abhijit Biswas[1], Jasvith Raj Basani[1], Edo Waks[1]
[1]Quantum Photonics Group, University of Maryland, College Park, Maryland 20742, USA
[2]Poolesville High School, Maryland 20837, USA

Background

Photonic crystals are nanostructures that involve periodic changes of refractive index which leads to light constructively and destructively interfering.

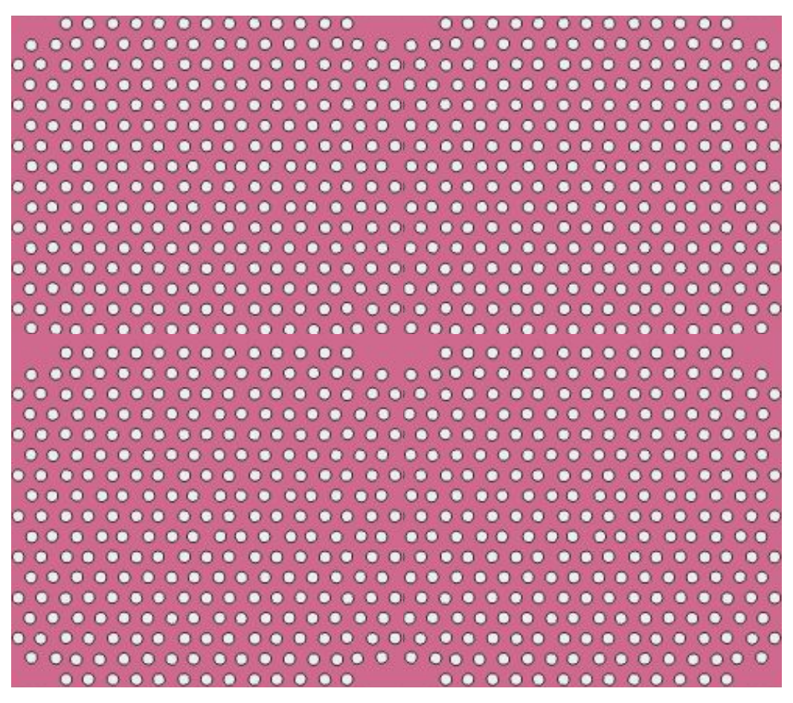


A semiconductor slab with air holes can be a photonic crystal.

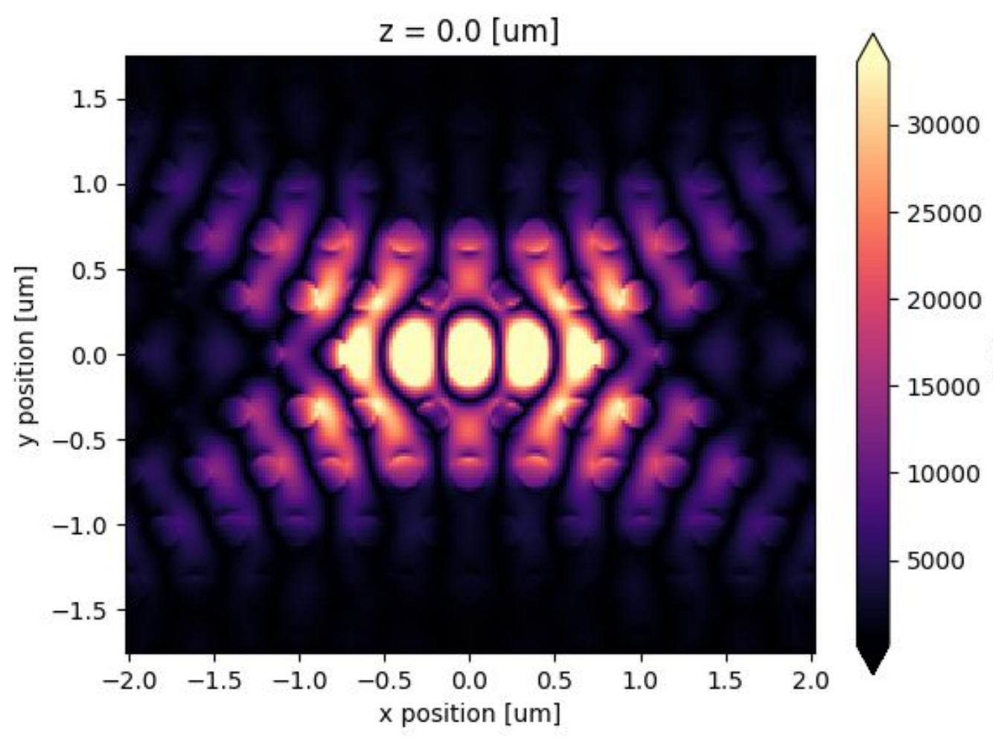


The electromagnetic mode (field pattern) of the light can tell us the spatial distribution of energy within the photonic crystal.

A photonic crystal cavity that is able to confine light can be created by introducing defects into the design such as removing holes or changing the lattice parameter. A common two-dimensional photonic crystal cavity is the L3 cavity.



L3 Cavity (Panuski et al., 2022)

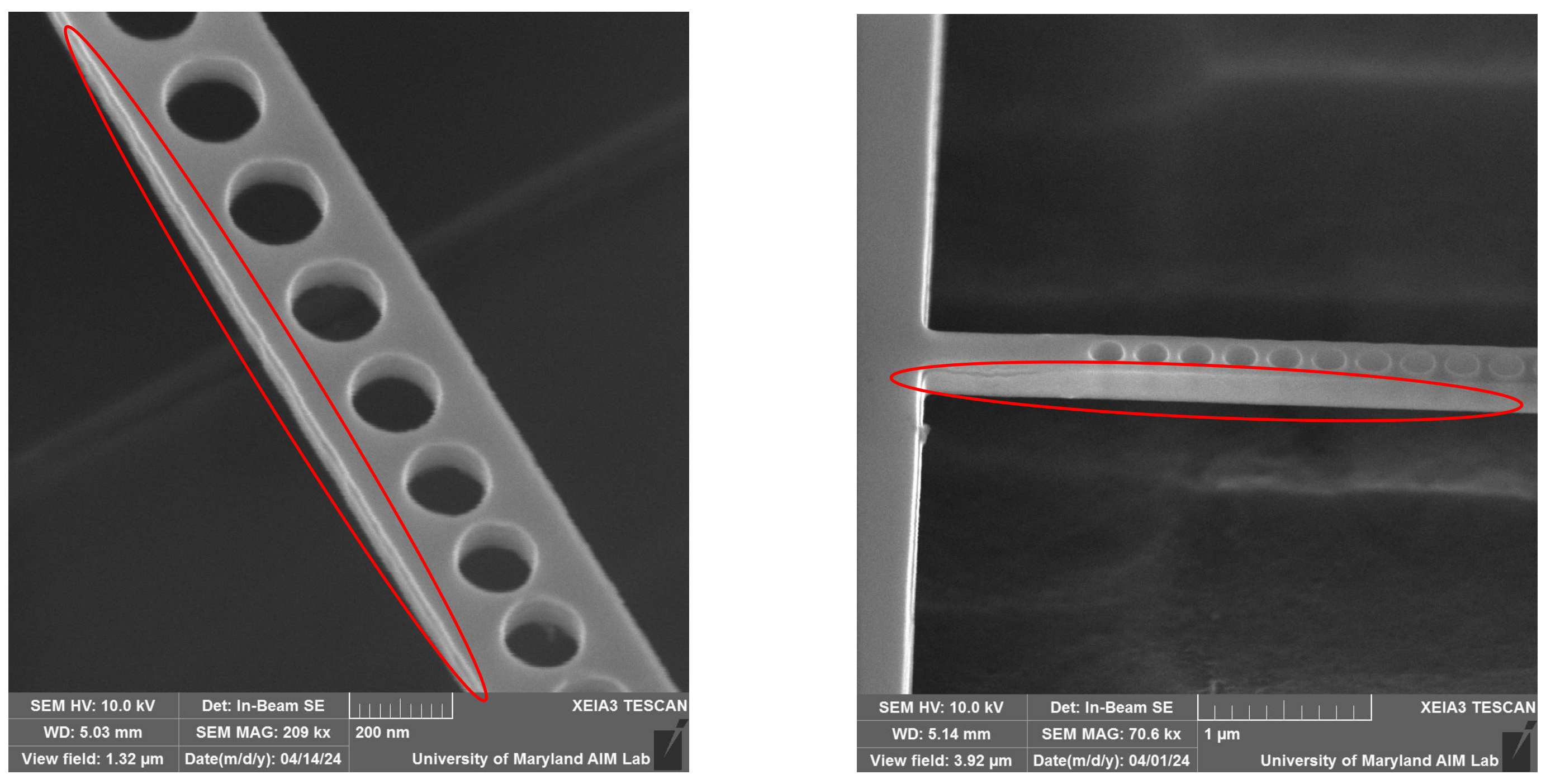


The electromagnetic mode of the light is more tightly confined. (Tidy3D, n.d.)

The amount of light/energy being confined depends on the geometry of the cavity.

In the photonics community, strong light-matter interactions are difficult to achieve (Vahala, 2003). These interactions are important for applications in quantum computing, communication, and sensing. However, when working with singular photons, these interactions are extremely difficult to achieve.

High-quality nanobeam cavities allow us to maximize these light-matter interactions (Deotare & Loncar, 2012). Yet, due to a common issue with fabricating nanobeam cavities, sidewall roughness, high-quality nanobeam cavities are difficult to achieve experimentally. In our case, from simulation to experiment, our nanobeam's quality factor, a measure of how well the cavity confines light (Englund et al., 2005), decreased by 3 orders of magnitude.



SEM image of fabricated nanobeam cavity with sidewall roughness (Biswas et al., 2024)

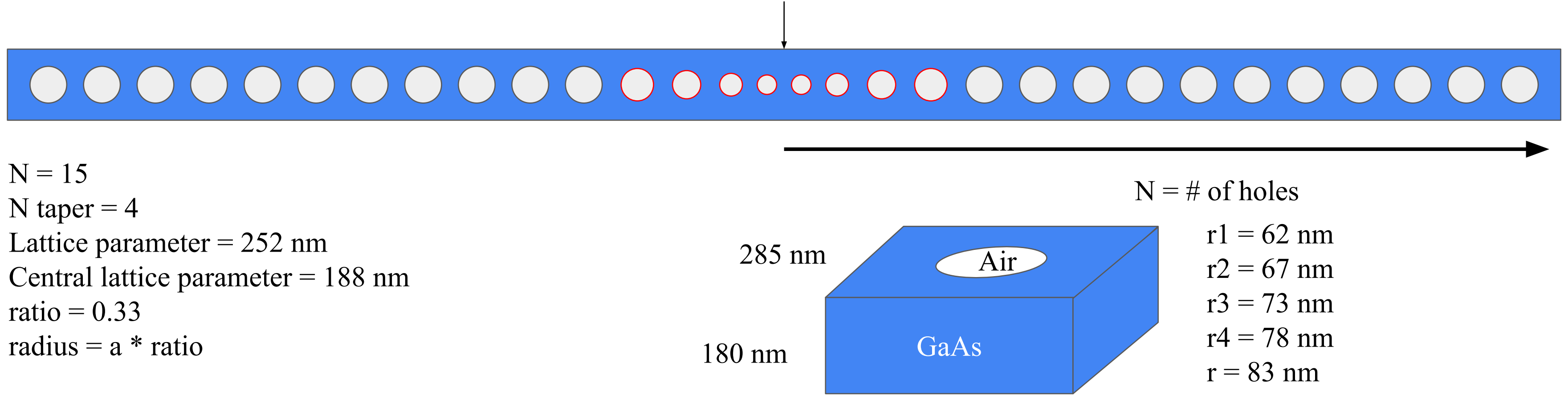
We attempt to alter the geometry of the nanobeam using particle swarm optimization to create a robust design that strongly confines the light, reducing interference and scattering from sidewalls.

Methodology

We approached this issues by:

1. Simulating sidewall roughness using an absorbing slab with an imaginary refractive index.
2. Optimizing the nanobeam cavity with absorbing slab design using particle swarm optimization, a non-gradient based optimization algorithm.

Ultimately, we wanted to replicate the experimental quality factor losses from sidewall roughness and alter the geometry of the nanobeam to maximize experimental quality factor. Our initial design was from Biswas et al.



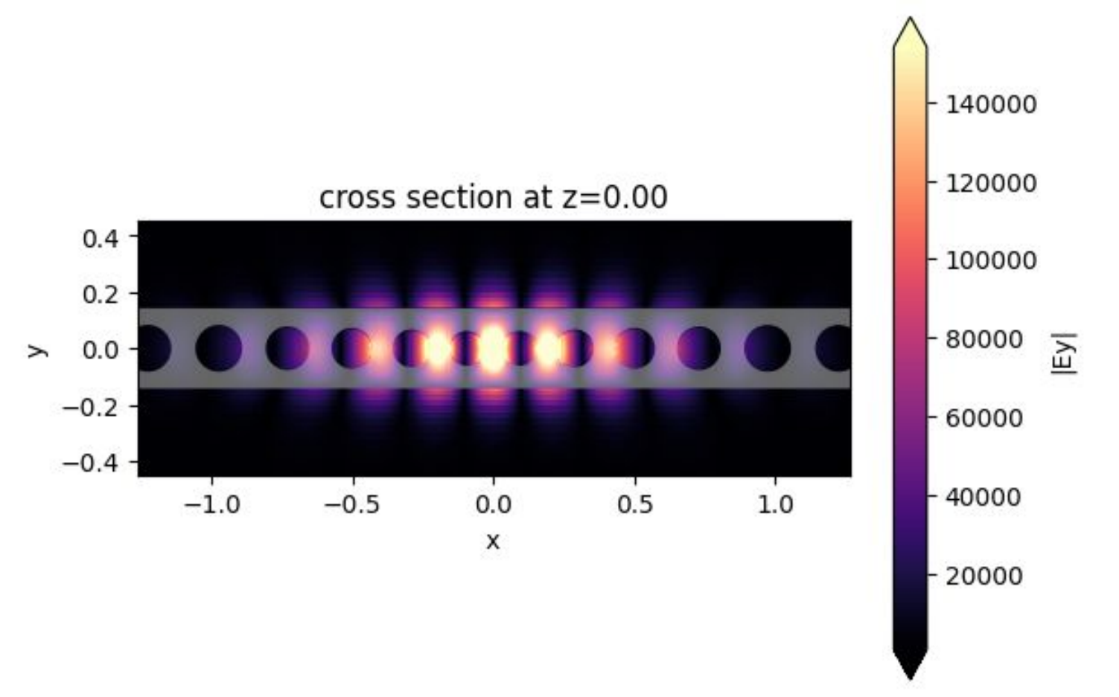
N = 15
N taper = 4
Lattice parameter = 252 nm
Central lattice parameter = 188 nm
ratio = 0.33
radius = a * ratio

r1 = 62 nm
r2 = 67 nm
r3 = 73 nm
r4 = 78 nm
r = 83 nm

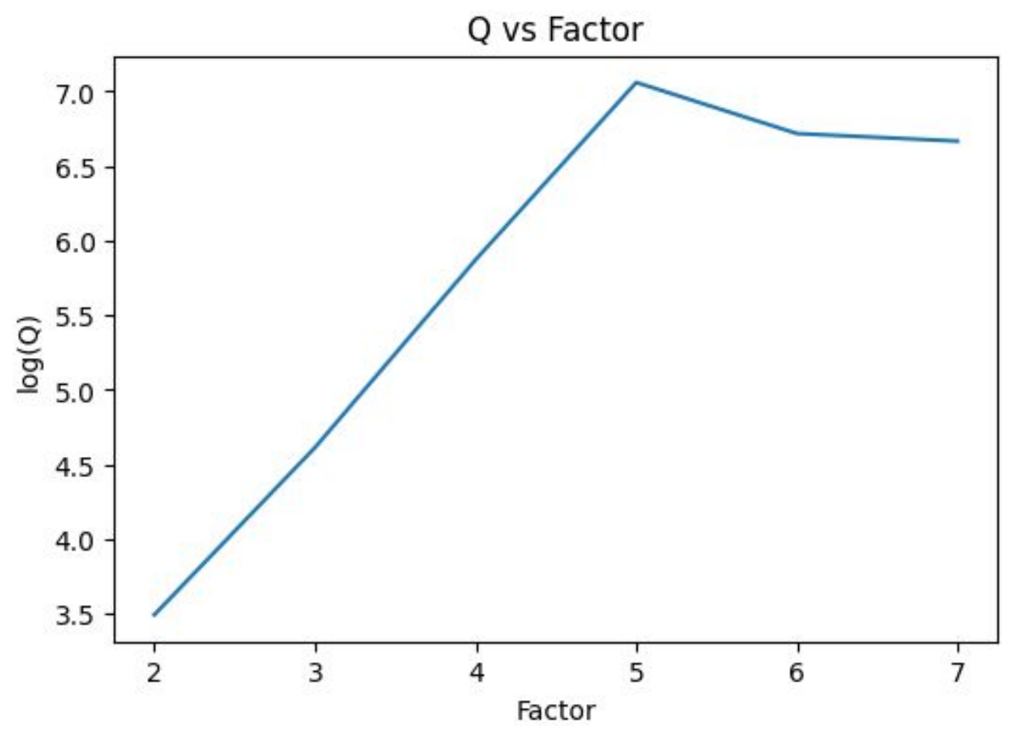
Initial design of nanobeam cavity

Numerical Simulations

To simulate this design, we used the finite difference time domain method, a common method for simulating nanoscale optical devices. We then varied the size of the simulation domain in a process called parameter sweeping to increase the accuracy of our experiment.

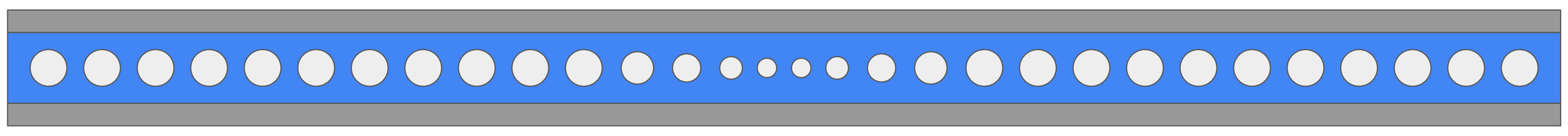


The electromagnetic mode of the light interacts with the sides of the nanobeam cavity, leading to interference and scattering.

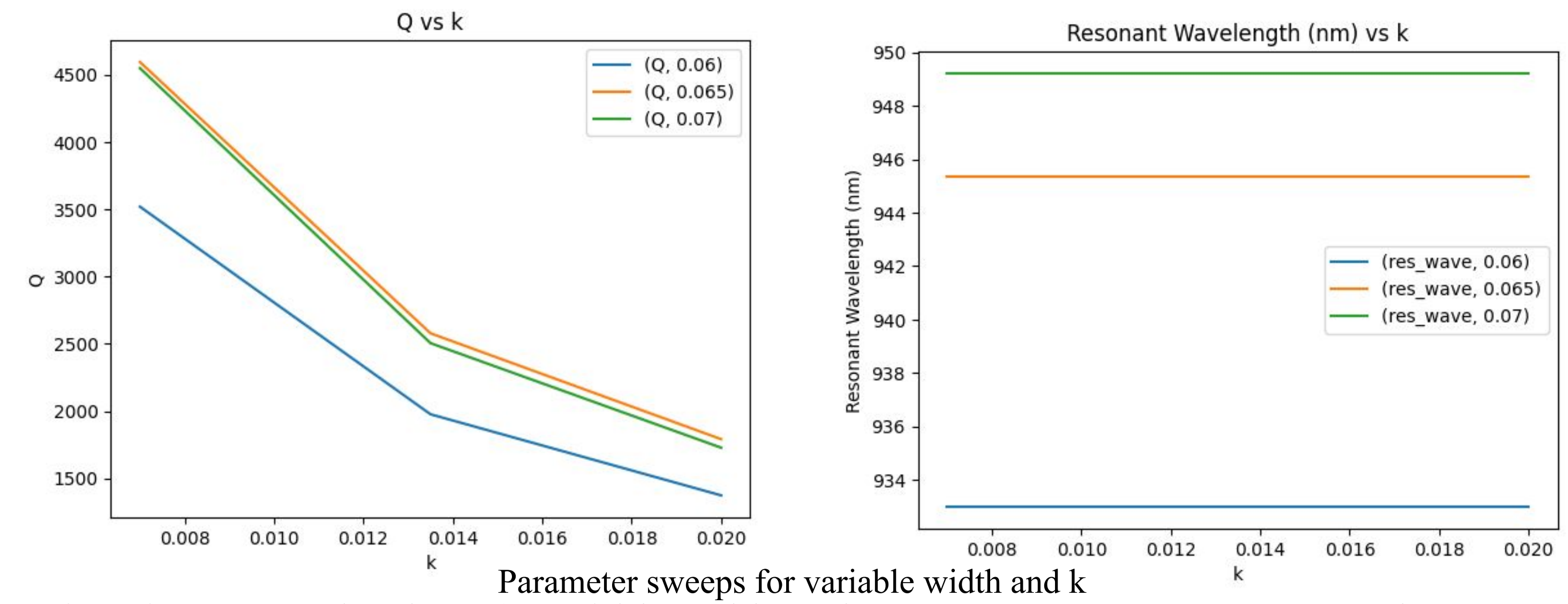


The quality factor reaches a maximum when the light does not interact with the simulation boundaries.

To simulate sidewall roughness, we added an absorbing slab to both sides of the nanobeam cavity. The slab was created using a medium that allows us to change the real and imaginary refractive indexes. We swept the width and imaginary refractive index (k) of the slab to replicate the effects of sidewall roughness, so we targeted a quality factor on the order of 10^3 and a resonant wavelength around 940 nm. We observed that width of the slab changes the resonant wavelength of the nanobeam cavity and the imaginary refractive index changes the quality factor of the nanobeam cavity.



Nanobeam cavity with absorbing slabs

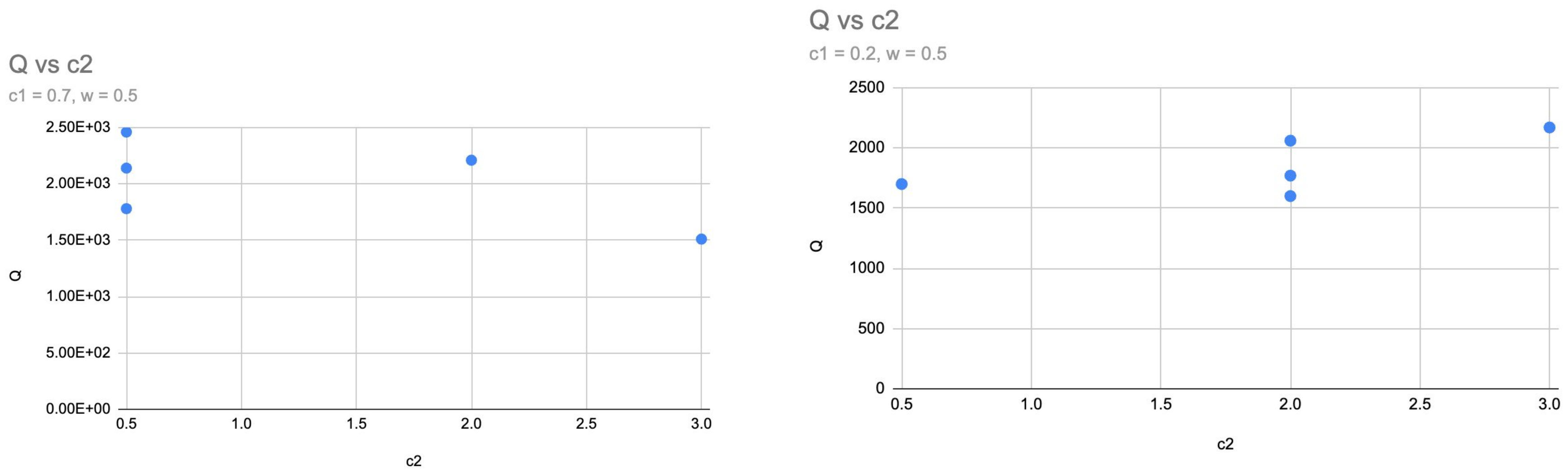


Parameter sweeps for variable width and k

Through estimating general values for width and k and more parameter sweeps not shown, we were able to create a design with a quality factor of 1668 and a resonant wavelength of 947.43 nm at k = 0.01675 and width = 63 nm. The initial design had a quality factor of 11471504 and a resonant wavelength of 940.58 nm

Particle Swarm Optimization

We then used the particle swarm optimization to alter the number of holes in the taper, lattice parameter, central lattice parameter, and ratio between lattice parameter and radius. We ran the algorithm multiple times, changing the social (c_2) and cognitive weight (c_1) and keeping the inertia (w) constant. The maximum quality factor found was 2460. This indicates that the scattering of the optical mode from the sidewalls may cause a fundamental limitation on the quality factor.



Results of runs with 5 particles and between 7 and 20 iterations

Conclusion

Preliminary results indicate that particle swarm optimization of robust nanobeam photonic crystal cavities is fundamentally limited by the scattering of the optical mode from sidewall roughness. As a result, altering the geometry of a nanobeam cavity with cylindrical holes may not result in a higher quality factor

Limitations:
- Particle Swarm Optimization-specific parameters
- Compute resources and time

Future Research:
- Elliptical Holes
- Bowtie Holes
- Including width into optimization

Key References

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