Department of Electrical Engineering and Computer Science

Howard University

Washington, DC 20059

EECE 404 Senior Design II

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High Q Resonances in Photonic Non-Hermitian Microcavities

By

Brandon Sierra

Reanna Jones

Dequane Nealy

Johan Milele

Instructor: Dr. Charles Kim

Project Advisor: Dr. Eric Seabron

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Abstract

This research explores the intricate interplay between the internal lattice structure and edge topology in Non-Hermitian Microcavities (NMCs), leading to the emergence of resonant cavity modes with strong Fano resonances and topological quantum bound in continuum (qBIC) behavior. By leveraging the internal lattice, formed by photonic crystals or metasurfaces, and manipulating edge topology through particle size and shape, NMCs exhibit remarkable resonant characteristics. Utilizing COMSOL simulations, we investigate various NMC configurations, focusing on optimizing key figures of merit such as Q-value and transmission/reflection coefficients.

In our research project, we introduce geometric defects, including dielectric point defects and asymmetry, to demonstrate functionality and topological robustness. Photonic NMCs offer several advantages for qBICs, including the potential for high-Q resonances, compact size suitable for inline photonic integrated circuit (PIC) integration, and interesting mode behavior arising from collective interactions. We observe transitions from Fano resonance to qBIC behavior in transmission spectra, with near-unity operations apparent. The internal topology allows for the tuning and preservation of resonances, while edge topology can significantly alter mode coupling. This research highlights the promise of NMCs for achieving robust and efficient photonic devices with enhanced functionalities.

Problem Statement

Inside photonic integrated circuits, microcavities, also known as waveguides, have a very simple design but constitute one of the largest components. Our approach involves developing several unique microcavity PIC device designs and cataloging strong modes to optimize. The benefit that we are looking to create in this design is an increase in figures of merit. The figures of merit we are looking to improve are an enhancement of light propagation and a clearer signal (1 or 0) for computing. An increase in these figures of merit for our design would make PICs more useful in devices that are sensitive to signals like sensors.

Design Requirements

Date:	9/25/23 Updated: 11/28/23	Project Updated:2/15/24
Project Name/Title:	Photonic MicroCavities with High-Q Resonances in PIC waveguides	
Team Advisor	Dr. Seabron	
Project's Goal/Scope	Develop several unique microcavity Photonic Integrated Circuit (PIC) devices, catalog strong modes to optimize performance, generate NMC waveguide designs, document designs featuring intriguing modes, export Electromagnetic (Em) and Magnetic (Hm) field images, and capture videos or GIFs of Electric field components (Ex, Ey, Ez).	
Team Members	Reanna Jones, Brandon Sierra, Dequane Nealy, Johan Milele	
4-sentence problem statement	In the realm of photonic integrated circuits, microcavities, also referred to as waveguides, present a seemingly straightforward design yet hold significant importance as a core component. Our proposed approach entails the development of multiple distinctive microcavity PIC device designs while meticulously cataloging potent modes for optimization. This endeavor aims to elevate key performance metrics, such as the enhancement of light propagation and the refinement of signal clarity (distinguishing between 1s and 0s) crucial for computing tasks. Improving these metrics in our designs has the potential to amplify the utility of PICs in signal-sensitive devices like sensors. Additionally, employing parameter sweeps to optimize specific modes' Figures of Merit, including light enhancement, Q-value sharpness, and transmission/reflection characteristics, will be pivotal in achieving desired performance levels. Furthermore, the introduction of defects, both geometric and dielectric point defects, will serve to demonstrate functionality and bolster topological robustness in our designs.	
Requirements	**Items**	**Quantity**
1. Product Specification	Designed & simulated through COMSOL	
	Power consumption:	1V or 10mA

	Transmit signals	1550nm
	Operations durations	24+ hrs
	Size	2.5 x 2.5 mm
	Standard & Regulation Requirements	Posted on IEEE website(we do not have access yet)
2. Constraints	**Environmental Constraints**	Limited environmental availability
	Socio-Cultural Constraints:	unknown fabrication effect
	Compliance (Rules, Regulations, and Standards):	Avoid unethical methods & behaviors according to IEEE Standards

Initial Solution Design

Our initial approach for our design was to create a multiport substrate integrated waveguide that used via holes as well as resonators to control the signal in the waveguide. The main idea of this design is that it would allow for signals to be controlled through phase change resonators which acted like a switch. The main problem with this design is that it implemented a phase change aspect to control how the light propagates. Additionally, this design was much larger than the standard substrate integrated waveguide that has only an in and an out port.

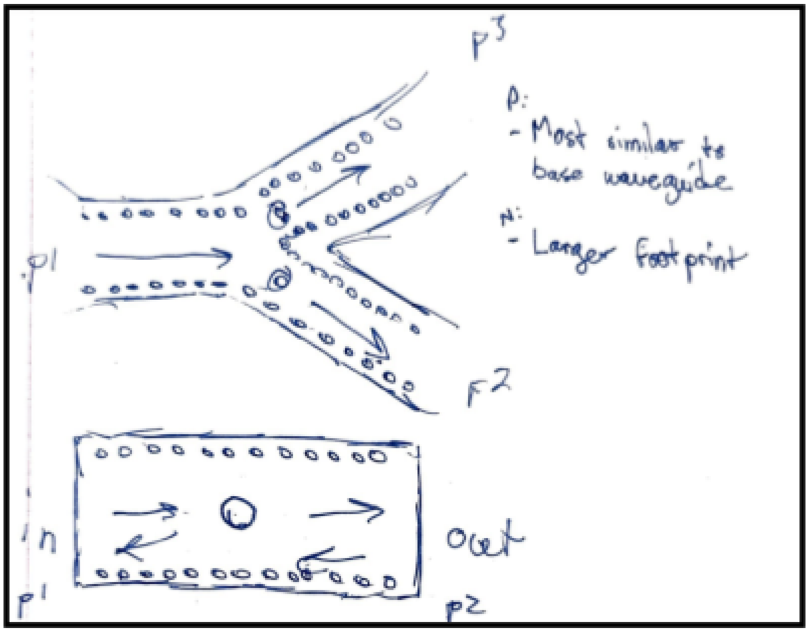


Figure 5.1 Initial Multiport Waveguide Design Sketch

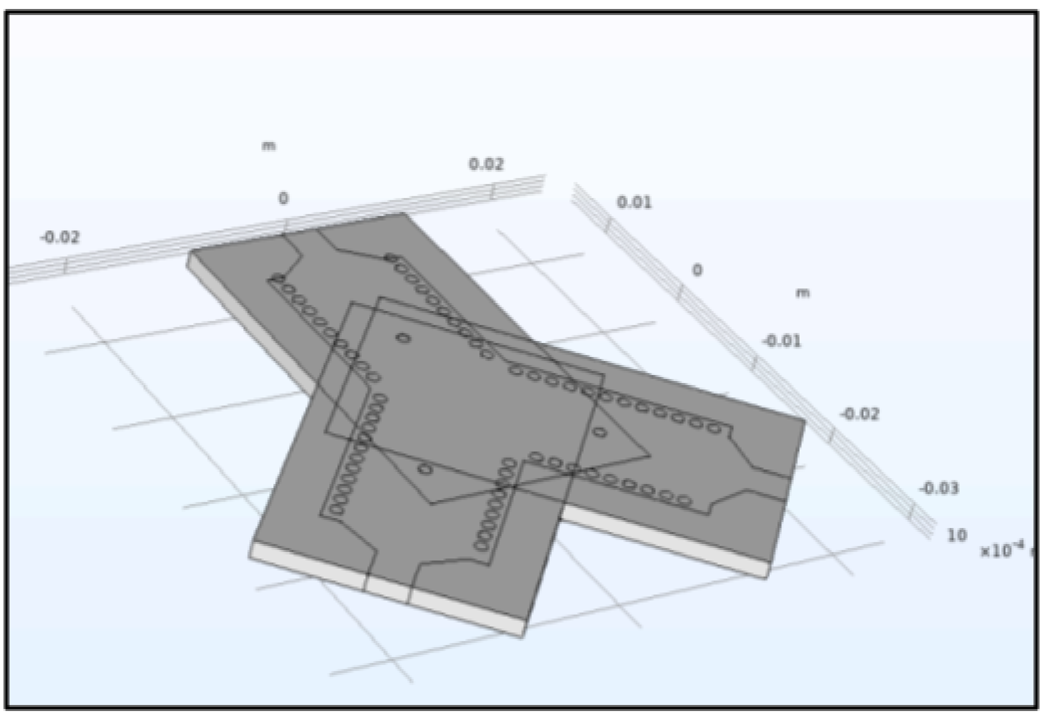


Figure 5.2 CAD Drawing of Multiport Design inside of COMSOL

Final Solution Design

Before we began our next design solution, we had slightly redefined what we were looking for from our research. While we were still optimizing for our figures of merit defined in our problem statement, we decided to alter our approach. Instead of increasing the number of ports, we sought to create a microcavity design that had high-Q resonances and interesting modes. The methodology for doing this was altering the edge topology and observing how the internal lattice and edge topology collectively interact.

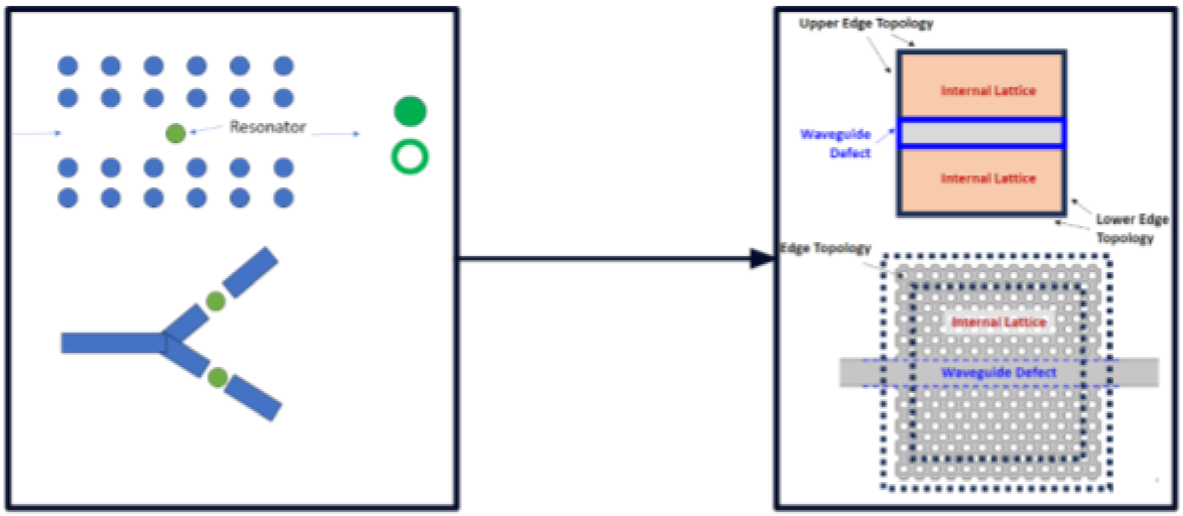


Figure 6.1 Transition from Multiport Resonator Waveguide to Edge Topology Waveguide

For the COMSOL simulations, we came up with six different edge topology designs. The first design is the *Offset Half-Circle* which is a microcavity waveguide with symmetrical semicircles on either side. The design parameter in this design is the offset of the two semicircles from the center of the waveguide. Another design is the *Dual Ring* waveguide which consists of a circle edge topology that is surrounded by a thick ring. The parameters for this design are the size of the inside circle and the gap size between the ring and the interior circle. Another design is the *Rectangular Defect* waveguide which has a rectangular edge topology that has a triangle defect in the corner of the topology. The parameters being changed in this design are the number of corners and the location of the defects in the topology. Another design is the *Star Design* which has an n-pointed star edge topology symmetrically placed across the x-axis of the waveguide. The parameter for this design is the number of points on the star. The last design is the *Four-Leaf Clover;* the leaves of a clover are used to surround the waveguide and the parameter being changed is the angle of the leaves.

Final Solution Design (cont.)

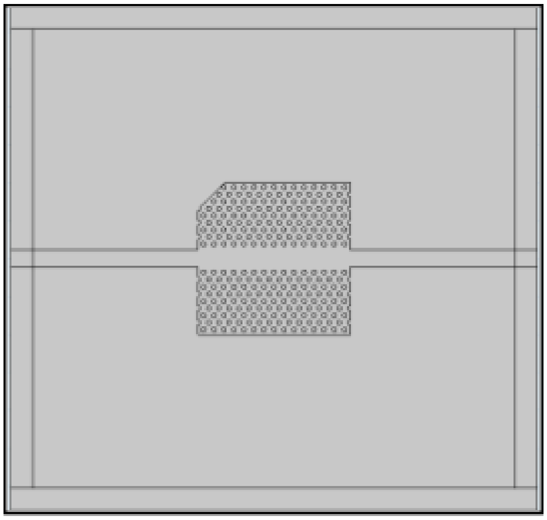


Figure 6.2 Rectangle With Corner Defects

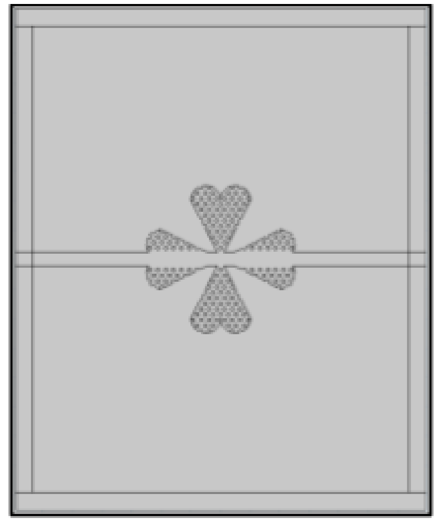


Figure 6.3 Four-Leaf Clover

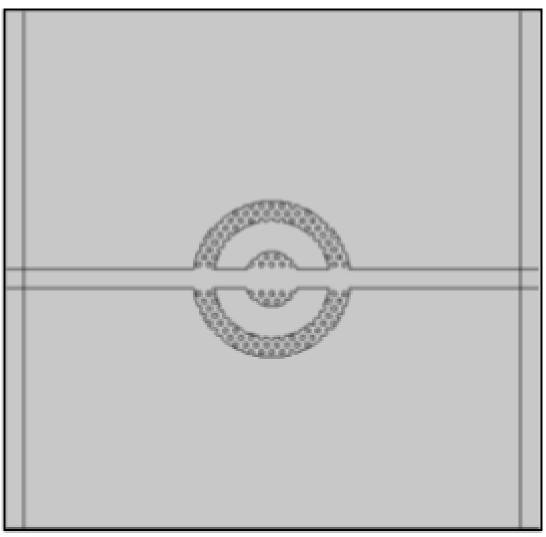


Figure 6.4 Dual Ring

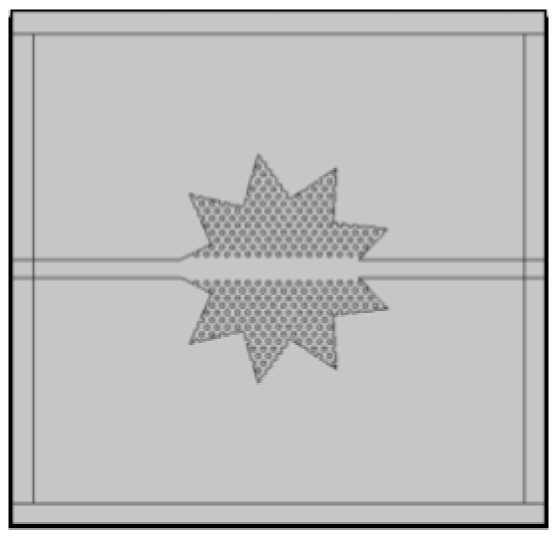


Figure 6.5 Star

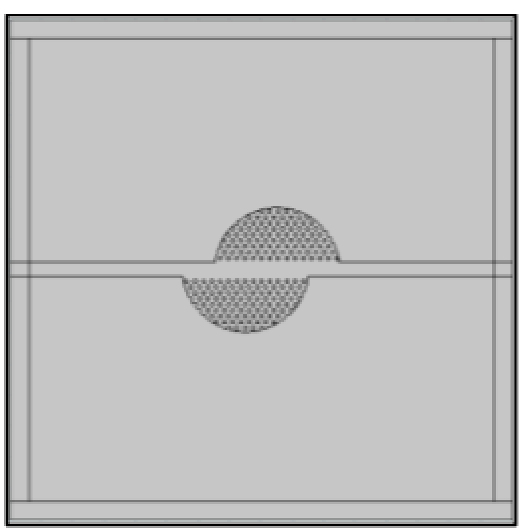
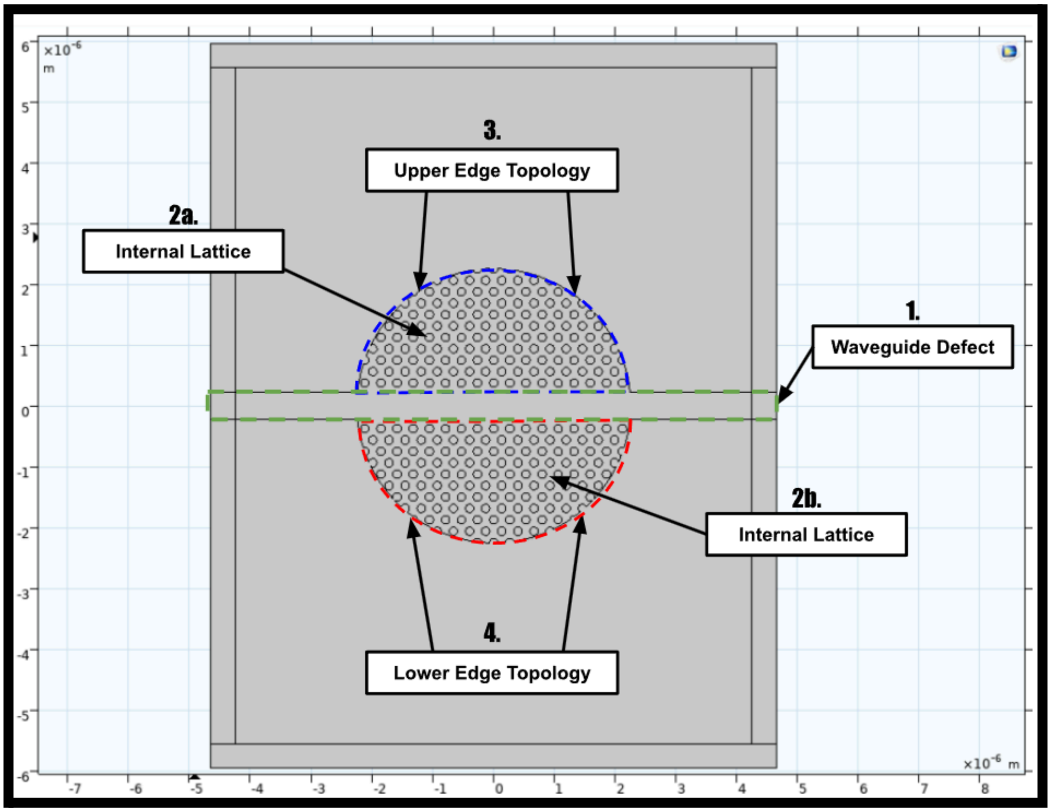


Figure 6.6 Offset Semi-Circles

__Component-Level Diagram__



We have designed a Non-Hermitian Microcavity consisting of a waveguide defect (1) to couple into an inline waveguide to excite a mode and propagate a signal. These microcavities consist of an internal lattice (2) and an edge topology which collectively interact to create resonant cavity modes. We created several designs to test asymmetry between the upper edge topology (3) and lower edge topology (4) to create interesting modes.

Agile Workflow and Weekly Plan

Sprint #1

Goal: Create 6-10 different edge/hole topologies and upload/create files in COMSOL.

Date	Weekly Development Task
1/30/2024	Quad Chart project overview w/ Dr. Seabron and graduate students
2/6/2024	COMSOL Training with Dr. Seabron and graduate students
2/13/2024	Reviewing designs with Dr. Seabron and recreating in COMSOL

Sprint #2

Goal: Simulate several NMC designs and make a record of designs with interesting modes, and further enhance designs for a single mode by optimizing for figures of merit.

Date	Weekly Development Task
2/20/2024	Take/export Em and Hm images of designs
2/27/2024	Take/export videos and gifs on Ex, Ey, Ez plane
3/5/2024	Optimize design for: - High Q-Value (freq/Δfreq) - Enhancement/Confinement (Norm-E) - Full Reflection/ Transmission (peak height)
3/12/2024	Continue optimization

Sprint #3

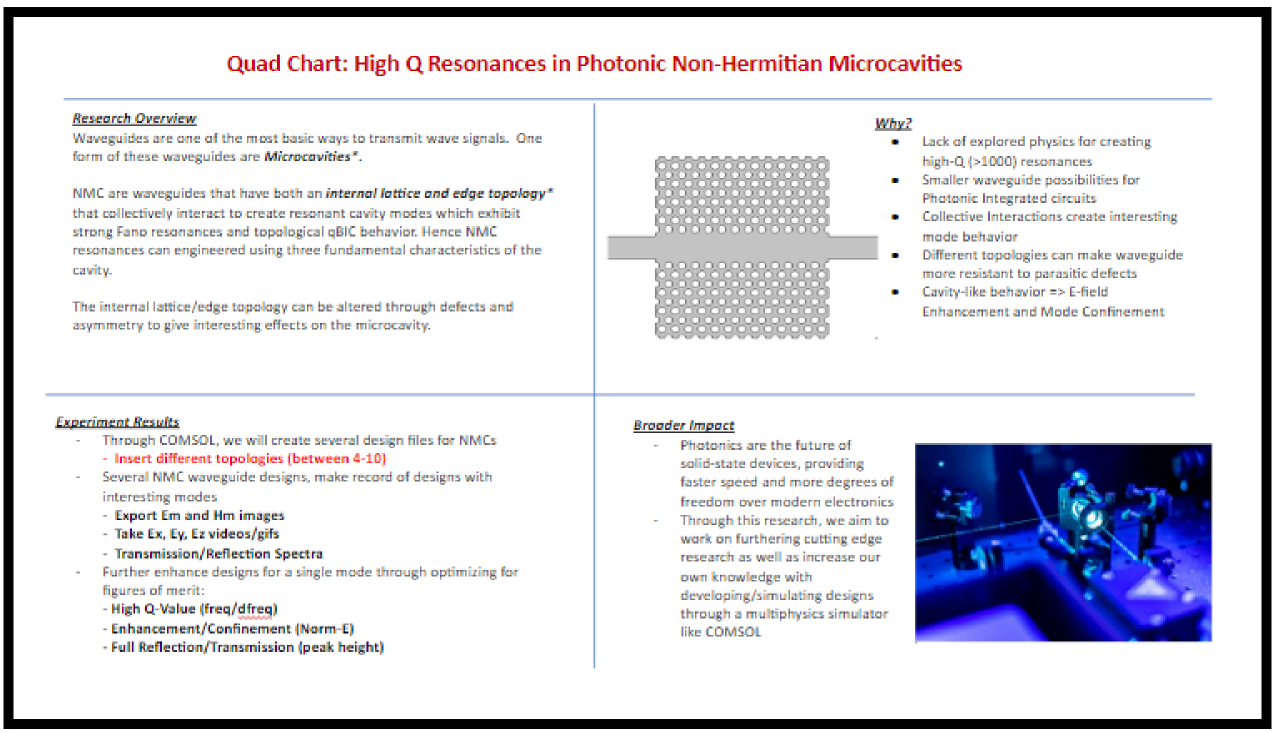
Goal: Prepare COMSOL Demo with Final Waveguide Model (with various inputs and outputs to test).

Date	Weekly Development Task
3/12/2024	Review data/testing from UMD testing/fabrication?
3/19/2024	Final testing & demo creation for EECS DAY
3/26/2024	Setting up presentation for EECS Day & final demo set-up

Project Implementation Process

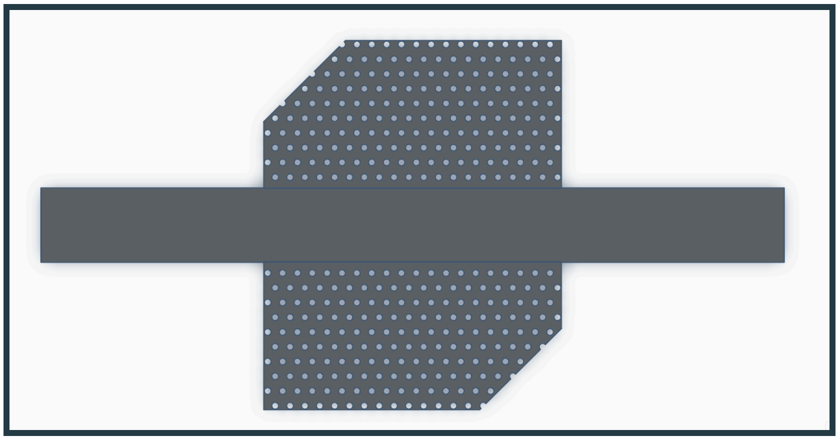
Weeks 1-3:

The first three weeks of our team's sprint were mainly spent getting accumulated with our new end goal/task and finding a way to mesh together Dr. Seabron's new research with what we had already begun to create by making a quad chart that would perfectly put into place our new main goal, the overview of our new research, the why and how of our project, etc. We had also tasked ourselves with taking his research - along with some of our own - to create between six and ten new edge/hole topologies to import those designs into COMSOL for further testing.

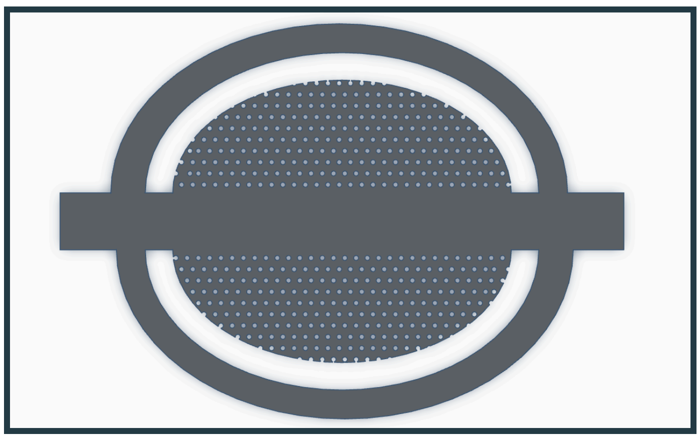


Newly Made Quad Chart

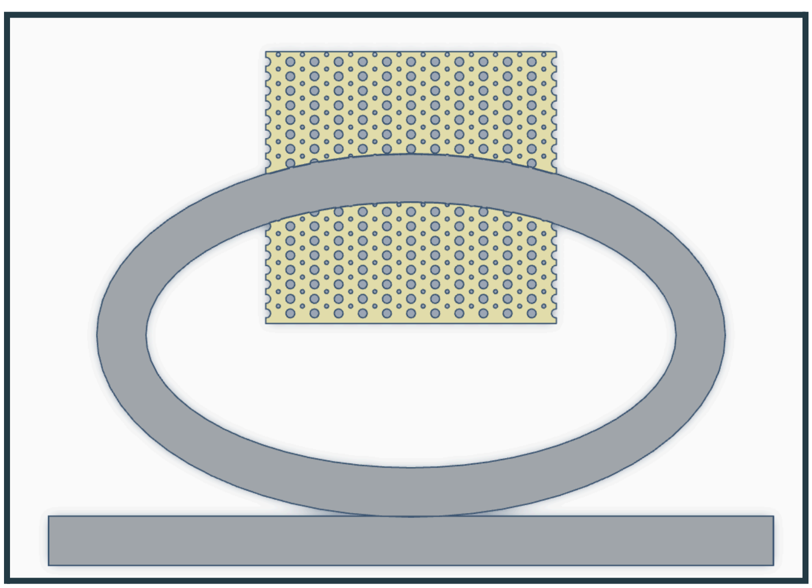
Those six to ten topologies were created within the 3D modeling program Tinkercad over the second week, including designs such as a broken symmetry edge topology, a dual ring edge topology, and a ring resonator with Swiss cheese-like holes on top of it. They were designed in the sense that they were supposed to be unconventional, shapes and figures with out-there/unique designs and potential that could be replicated within COMSOL easily.



Broken Symmetry Edge



Dual Ring Edge



Ring Resonator w/ Swiss Cheese

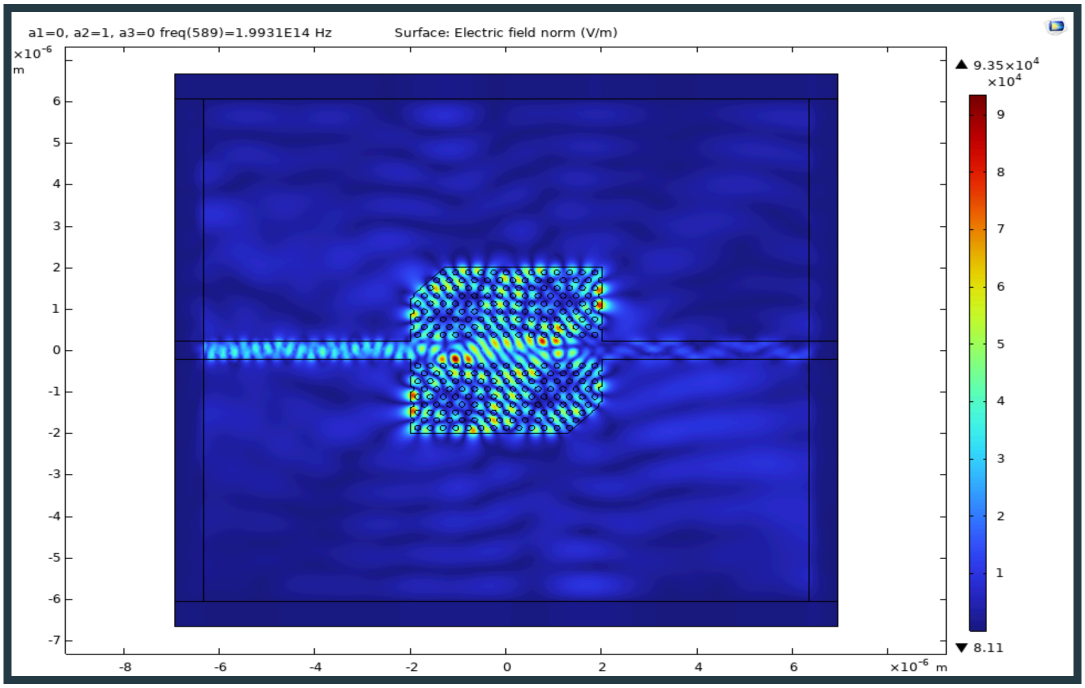
Along with the newly made quad chart and Dr. Seabron's feedback on the various Tinkercad designs, we were able to replicate our designs - along with a few other new ones - into CAD, a 2D design software. Overall, we had gotten a lot of positive feedback on our quad chart and had a lot of our general questions about our new end goal answered as we began to properly adjust to the new scope of our project. However, we did lose access to COMSOL during the duration of our first sprint and we were unable to meet with the graduate students and Seabron enough to continue the previously mentioned COMSOL training, which proved to be a huge setback when it came to initially transitioning our designs into COMSOL and simulating them within the application.

Weeks 4-7:

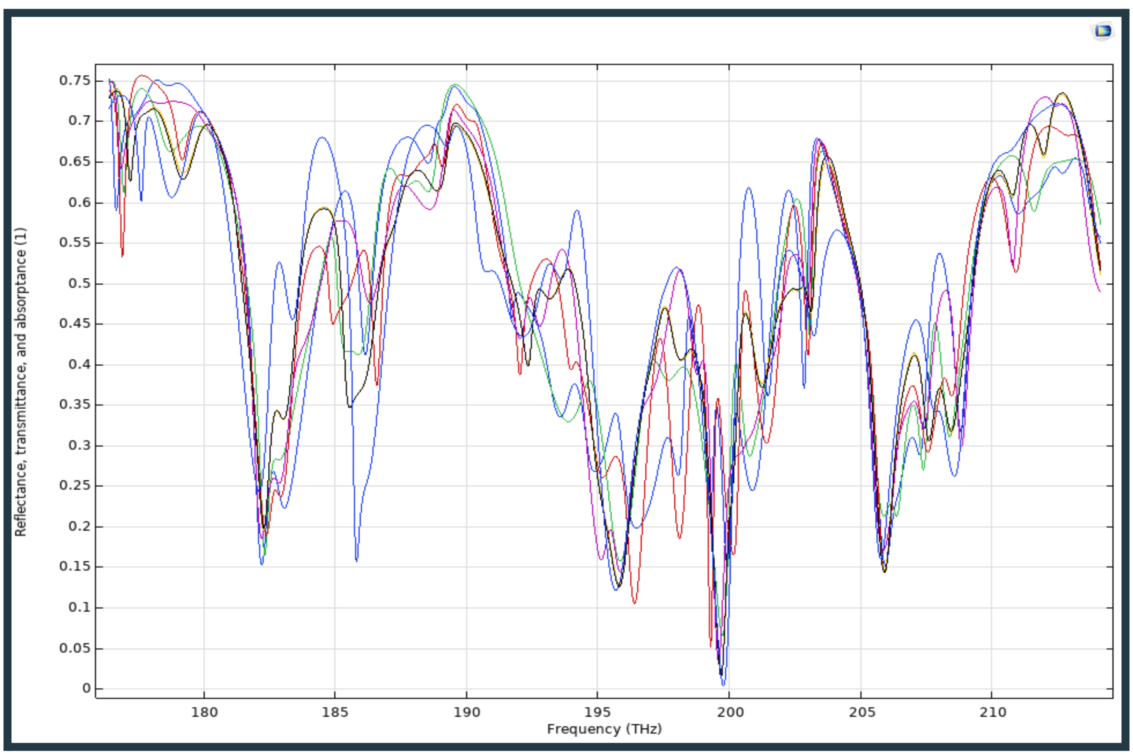
Weeks 4-7 were spent implementing the designs that were created within Tinkercad and CAD into COMSOL for testing and simulation, optimizing the designs that were eventually chosen for high Q-value, enhancement/confinement, reflection/transmission, etc. Over these four weeks, our team replicated our various designs into COMSOL with some tweaking to better fit COMSOL's testing and simulation parameters, and analyzed the results of these simulations as they were being completed. Our team had also planned on further enhancing any of the designs we had made for a single mode through optimization for better figures of merit.

With COMSOL simulations, however, they tend to take hours upon hours to be fully completed - sometimes over ten hours depending on how radical the design being simulated was. We were supposed to work with some of the graduate students on some Python code that would work in tandem with the COMSOL simulations to obtain results faster, but that eventually fell through due to time constraints and scheduling.

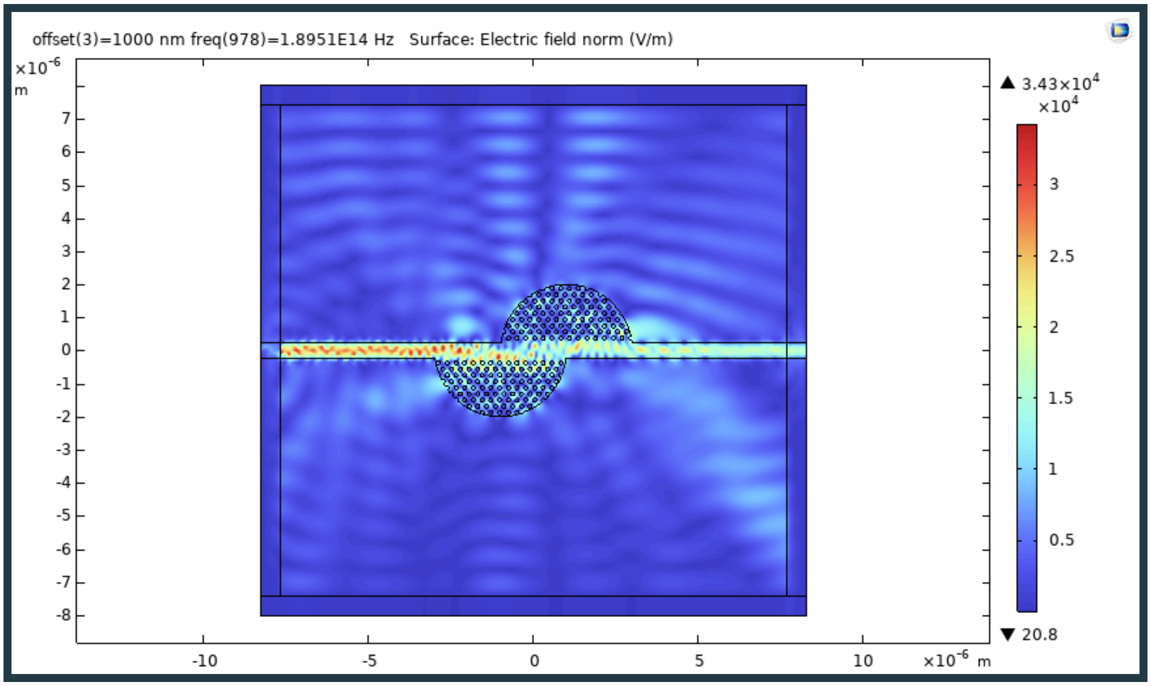
But despite some setbacks, we were eventually able to achieve simulation results from some of the designs we managed to create, including the rectangle with corner defects, the offset semi-circles, and a cloverleaf (each seen below), as well as exporting some videos and gifs of the simulations of the Ex, Ey, and Ez planes for further research and experimentation.



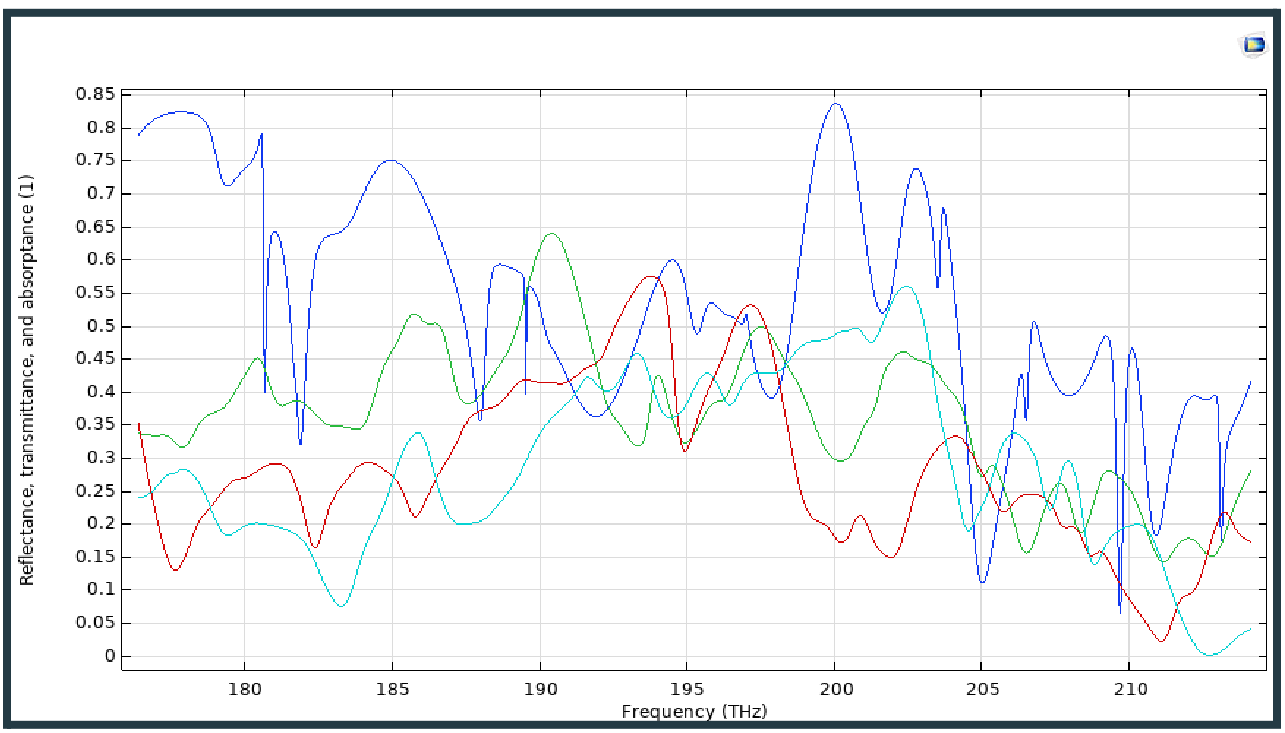
Rectangle w/ Corner Defects Design COMSOL Simulation - Surface Electric Field



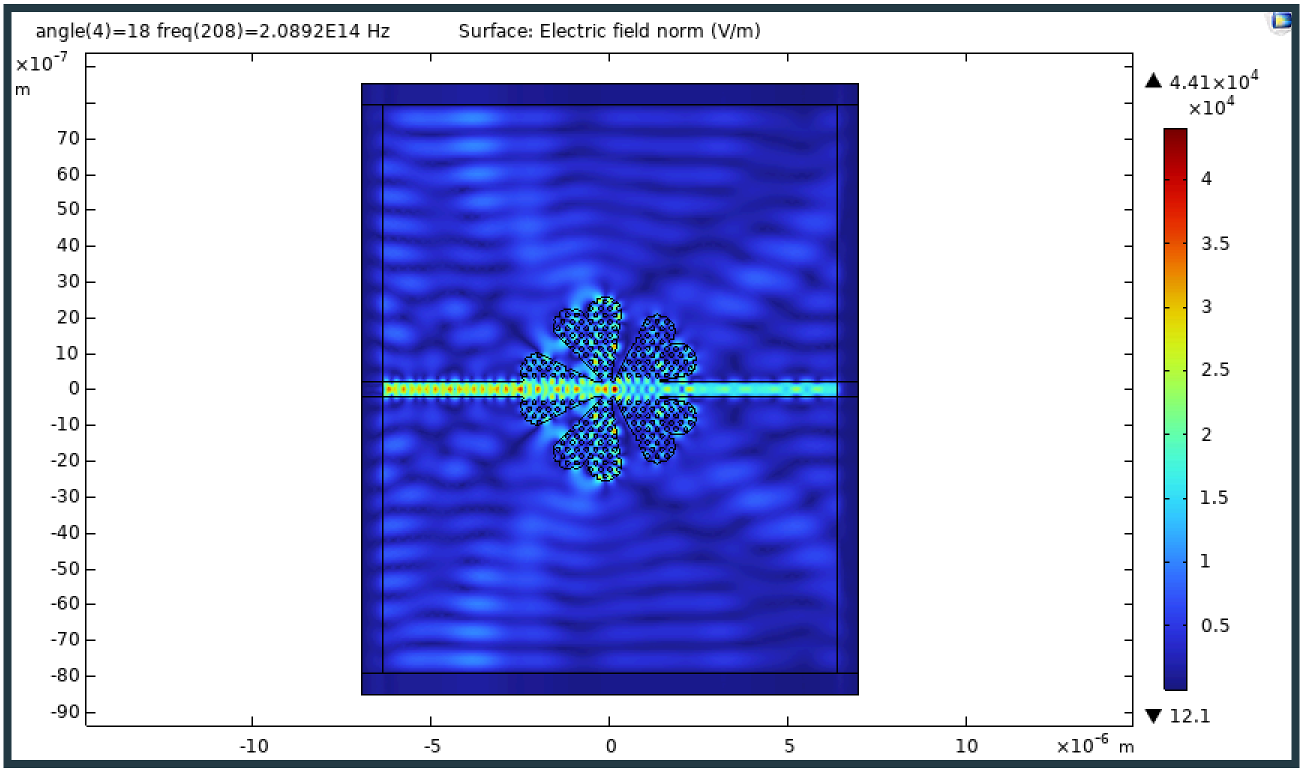
Rectangle w/ Corner Defects Design COMSOL Simulation - Freq vs FOM



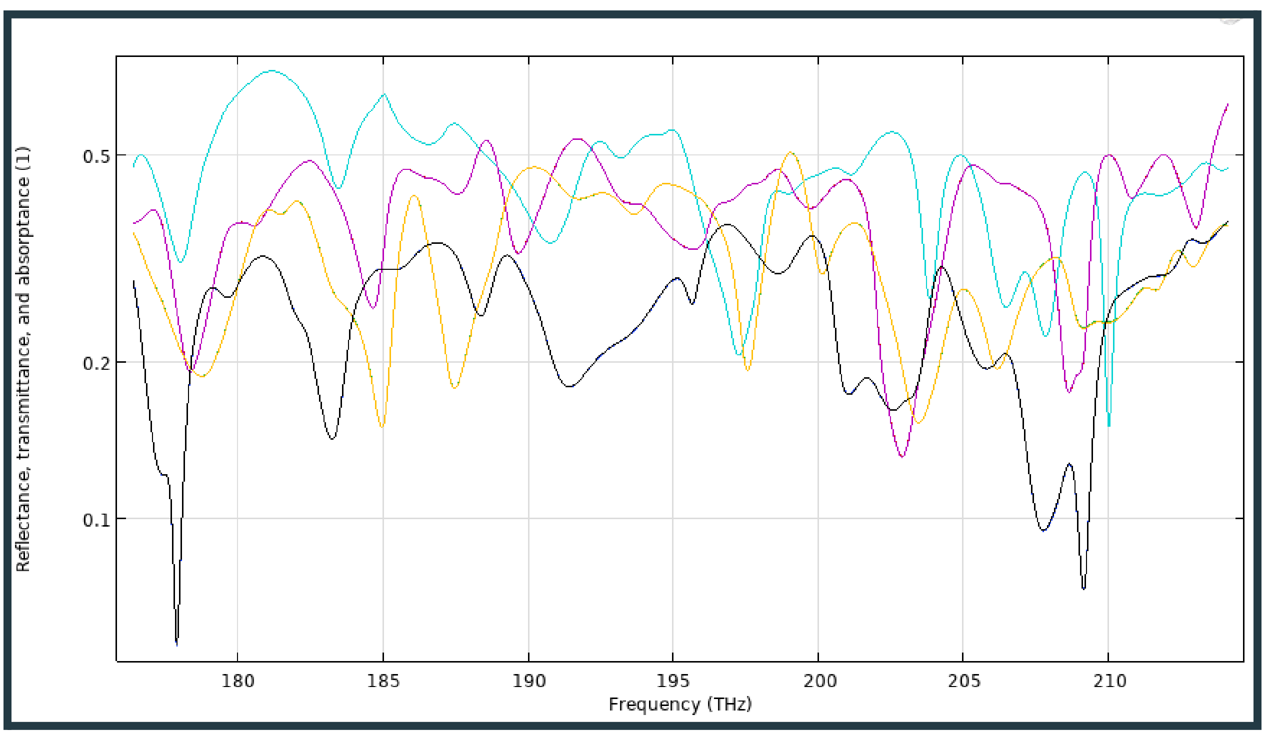
Offset Semi-Circles Design COMSOL Simulation - Surface Electric Field



Offset Semi-Circles Design COMSOL Simulation - Freq vs FOM



Clover Leaf Design COMSOL Simulation - Surface Electric Field



Clover Leaf Design COMSOL Simulation - Freq vs FOM

When simulating the designs over COMSOL, the two most helpful figures were a graphic of the Electric Field across the surface as well as the frequency of the signal applied versus the figures of merit. The figures of merit are all factors of the signal; reflectance, absorptance, and transmittance. When looking at the graph the most relevant or interesting data comes from sharp peaks across the x-axis of frequency. These sharp peaks are representative of a high Q factor, which is the change in frequency divided by the current frequency. The high Q factor would show the frequency that the device would be the most optimal for operation. The frequency shown here would be where the surface electric field would start.

When simulating the strength of the electric field, using the frequency from the high Q factor, the frequency is tuned to find the strongest impact on the device. That can be found with the colors shown across the device. A dark blue represents very weak coupling, a light green represents moderate coupling, and finally red represents strong coupling. Depending on where the coupling takes place, shows whether the effect is absorptance, reflectance, and transmittance. Transmittance is across the waveguide defect. Reflectance is in the borders of the upper edge and lower edge topology. Absorption is throughout the rest of the device. For each of these designs, the two figures of merit that are the most pressing are transmittance and reflectance.

Even though COMSOL simulations tend to take an increasingly long time, we were able to successfully implement most of our designs into COMSOL - along with a few new ones as well - as well as exporting lots of images of reflectance, transmittance, absorption, and overall electric field from the results of these simulations. From the designs that we were able to replicate within the application, we had decided collectively that the two most interesting results came from the offset semi-circles and the cloverleaf designs respectively.

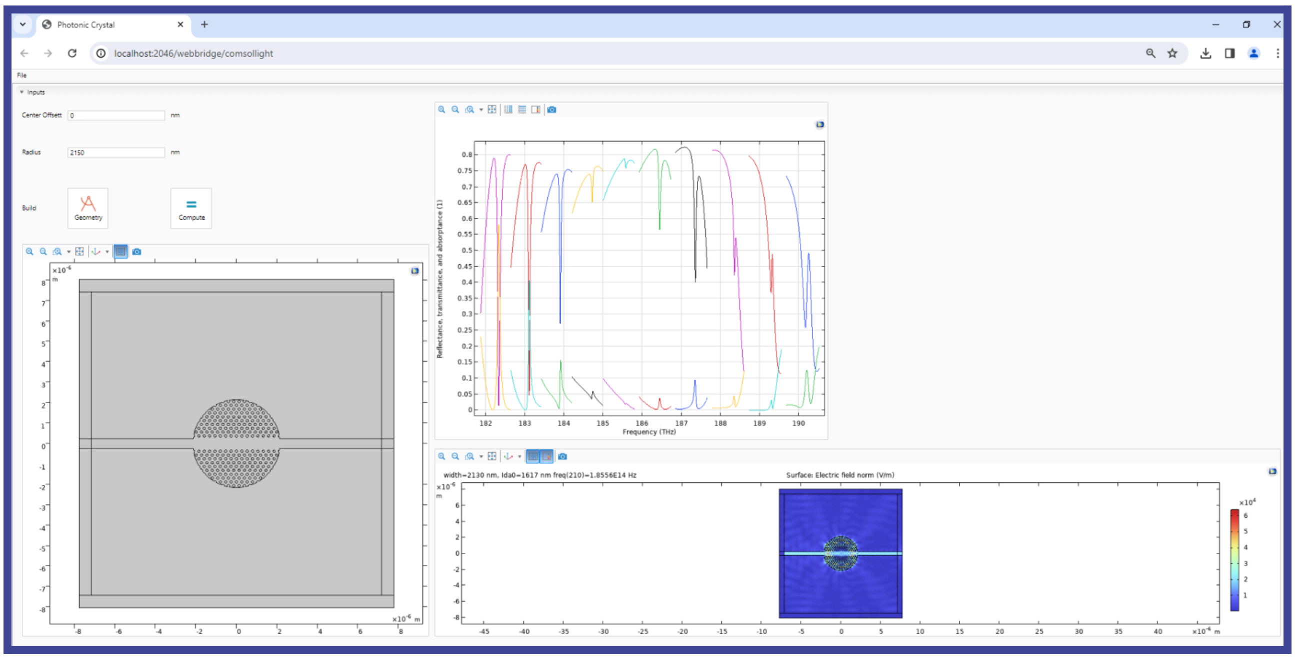
Weeks 8-10:

Finally, Weeks 8-10 were mainly focused on preparing the demo of our final waveguide model and our final presentation for EECS Day, as well as potentially reviewing the data that was collected from UMD's testing and fabrication.

The overall goal of working with UMD was to eventually cross-examine the data that we had simulated for our designs within COMSOL with real-world data alongside a physical version of said designs after initial COMSOL testing was completed with UMD's fabrication lab. Unfortunately, due to scheduling and timing conflicts, we could not travel to their fabrication lab to create a physical version of our edge/hole topology design and present that alongside our demo for EECS Day.

But, as a team, we were able to create a digital interactive demo within COMSOL that would go through the entire simulation process, as well as show in a more direct manner how the changes in topology would affect the overall transmission, reflection, and signal wave propagation when various parameters of the design being demoed would be changed.

We had decided to use COMSOL for a more in-depth simulation demonstration instead due to its simplicity, but we were unable to work with the graduate students once more in order to help automate the simulation demonstration in preparation for EECS Day. However, going back to reviewing our simulation results and our various implementation techniques proved to be a bit more successful than we originally had planned, and it proved to be successful for us in the end for EECS Day.



Screenshot of COMSOL Demonstration Software

<u>Conclusions</u>

In this research project, we delved into the intricate dynamics of Non-Hermitian Microcavities (NMCs), exploring how their internal lattice structure and edge topology interact to produce resonant cavity modes with exceptional properties, including strong resonances and topological quantum bound in continuum (qBIC) behavior. Through meticulous COMSOL simulations and design optimization, we investigated various NMC configurations, aiming to enhance key performance metrics such as Q-values and transmission/reflection coefficients.

Our journey began with the recognition of the pivotal role microcavities play in photonic integrated circuits (PICs) during the interim winter break, prompting us to develop unique PIC device designs focused on optimizing light propagation and signal clarity. As we progressed, our focus shifted towards creating microcavity designs with high-Q resonances and intriguing modes by manipulating edge topology and observing its collective interaction with the internal lattice.

Throughout the implementation process, we encountered challenges and setbacks, from software limitations, to design implementations and time constraints. However, our perseverance and collaborative efforts enabled us to overcome these obstacles and achieve significant milestones. Despite the limitations, we successfully replicated our designs in COMSOL, obtaining valuable simulation results that showcased the potential of our NMC configurations.

Our exploration led us to identify several promising designs, including the offset semi-circles and cloverleaf configurations, which exhibited remarkable resonant characteristics and mode behavior. While we were unable to validate our simulations with physical prototypes due to logistical, resource, and equipment constraints, our digital interactive demo within COMSOL provided a comprehensive visualization of the simulation process and its implications.

In conclusion, this research project has not only deepened our understanding of NMCs but has also paved the way for future advancements in photonic device design and optimization. By harnessing the synergistic effects of internal lattice structures and edge topology, NMCs hold immense potential for creating robust and efficient photonic devices with enhanced functionalities. As we conclude this project, we look forward to further exploration and innovation in this exciting field, driven by the insights and discoveries gained through our collective efforts.

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