

UNIVERSITY OF CALIFORNIA

Santa Barbara

Photonic Crystal Membranes

A Thesis submitted in partial satisfaction of the  
requirements for the degree Bachelor's of Science  
in Physics

by

Crystal Amber Roybal

Committee in charge:

Professor Claudio Campagnari, Chair

Professor Dirk Bouwmeester

June 2020

The thesis of Crystal Amber Roybal is approved.

DocuSigned by:

*Dirk Bouwmeester*

6D6C67693C4D467...

---

Dirk Bouwmeester

DocuSigned by:

*Claudio Campagnari*

66235628B4804A0...

---

Claudio Campagnari, Committee Chair

May 2020

## ACKNOWLEDGEMENTS

I would like to thank Dr. Dirk Bouwmeester for his guidance and for giving me the opportunity to work in his quantum optics lab at UCSB. This work has led me to discover an area of physics in which I would like to continue research going into graduate school and beyond. I would also like to thank Fernando Luna for his guidance and knowledge which helped me to complete this project and learn as much as possible. Lastly, I would like to thank my mother, Denuvia Alvarez, for supporting me through my undergraduate education and always providing encouragement.

## ABSTRACT

### Photonic Crystal Membranes

by

Crystal Amber Roybal

An analysis of how varying the geometry as well as the material of a photonic crystal membrane affects both the transmitted and reflected power. Analyzing the transmitted and reflected power allows for the quality of the device to be determined. For the purposes discussed in this thesis, if the device is of high quality, it will have a high reflectivity for the operational wavelength of 1064 nm. Hence, the study consists of a series simulations which model the behavior of the crystal when interacting with a plane wave at normal incidence. This is done for materials of gold, silicon nitride, and diamond. Changing the geometry of the crystals from hexagonal to square was also simulated.

The software used in the study is Lumerical 2020b, which is developed for simulating nano photonic devices like photonic crystals using the Finite-Difference Time-Domain (FDTD) solver. The FDTD is implemented to solve for an electromagnetic field within a complex physical object, and works by taking Maxwell's time dependent equations as differences instead of partial derivatives which then allows for the field to be solved for in one discrete cell of the structure as an approximation. The results from the hexagonal lattice

showed that the optimal material for use at 1064 nm was silicon nitride. The gold and diamond lattice did not work as well with the parameters of the silicon lattice, showing the changes that must be taken into account as material is changed. For the square lattice, the silicon nitride slab also had the best reflection and transmission spectra for use at 1064 nm. Parametric sweeps were ran, also on Lumerical using the FDTD solver, to determine optimal parameters for the slabs of gold and diamond for each geometry. The change between parameters as different materials were simulated was significant, as parameters could vary by as much as 200 nm. Hence, the study showed optimal materials and geometry for use in optomechanical experimentation at 1064 nm and by how much parameters must be changed based off of altering designs.

## TABLE OF CONTENTS

I. 2D Photonic Crystal Slabs.....	1
A. Materials of Photonic Crystal Slabs.....	6
B. Geometries of Photonic Crystal Slabs.....	9
II. Test for Optimal Material for Hexagonal Geometry.....	12
A. Discussion of Simulation.....	12
B. Reflection and Transmission Spectra.....	14
III. Test for Optimal Material for Square Geometry.....	15
A. Discussion of Simulation.....	15
B. Reflection and Transmission Spectra.....	17
Conclusions.....	19
1. Comparison of Reflection and Transmission Spectra of Gold Slabs.....	20
References.....	22

## ***1. 2D Photonic Crystal Slabs***

A photonic crystal is a structure with a varying dielectric constant and with discrete symmetry. Hence, the crystals are only invariant under translations which are multiples of a fixed step length. This fixed step length is known as the lattice constant and is typically referred to as  $a$ . The symmetry of photonic crystals is also described using the lattice vector defined as  $a\hat{x}$  or  $a\hat{y}$ . The value of the lattice constant depends on the type of geometry the crystal has as well as the desired wavelength of the incoming light. The two types of geometry discussed in this thesis are hexagonal and square. The crystal is the same as traditional crystals and has a periodic structure, hence, one unit cell of the crystal can describe phenomena which occurs at every point. The varying dielectric constant results in the restriction of certain modes of light, much like a potential well will restrict electrons with certain energies. Hence, the difference in the materials which make up the crystal must be high enough such that absorption is high.

Because the relative permeability is now a function of position vector  $\mathbf{r}$ , Maxwell's equations will be different for the case of light propagating within a photonic crystal. The solutions to Maxwell's equations for the fields of a photonic crystal are taken from a Hermitian eigenvalue problem and this is the reason why methods such as FDTD to solve for the fields. Maxwell's equations now become :

$$\begin{aligned} \nabla \cdot H(\vec{r}, t) &= 0 & \nabla \times E(\vec{r}, t) + \mu_0 \frac{\partial H(\vec{r}, t)}{\partial t} &= 0 \\ \nabla \cdot [E(\vec{r}, t)\epsilon(\vec{r})] &= 0 & \nabla \times H(\vec{r}, t) - \epsilon_0 \epsilon(\vec{r}) \frac{\partial E(\vec{r}, t)}{\partial t} &= 0 \end{aligned}$$

These are derived when only considering a mixed dielectric medium and ignoring dependence on the frequency of the relative permeability, as this will be chosen for the frequency range of interest. The field strengths are taken to be small enough in magnitude so that the problem is linear. The material is also assumed to be both macroscopic and isotropic, such that the electric field  $E$  and displacement field  $D$  are both related by

$D(\vec{r}) = \epsilon_0 \epsilon(\vec{r}) E(\vec{r})$ . A similar relation exist for the magnetic field  $B$  and auxiliary field  $H$ .

The relative permeability is related to the lattice vector by  $\epsilon(\vec{r}) = \epsilon(\vec{r} \pm \vec{a})$  as a result of the discrete symmetry of the crystal. After repeated translation it follows that for any integer multiple of the lattice vector, the relationship between the permeability and the lattice vector holds. There is also a reciprocal lattice vector which we may call  $\vec{a}'$  which comes from taking a component of the  $k$  vector for the modes of crystal which are plane waves and multiplying by  $2\pi n/a$  where  $n$  is any integer. The modes of the crystal can be expressed as a Bloch state, that is for example, a state with wave vector of  $k_y + (2\pi n/a)$  is the same, physically, as the state with  $k_y$ . It then follows that the mode frequencies are also periodic, and the  $k$  values that are of interest are those in the range  $-\pi/a < k \leq \pi/a$ . This is known as the Brillouin zone. A Brillouin zone is a region in the space spanned by the reciprocal lattice vectors, or reciprocal space where  $2\pi n$  cannot be added to the  $k$  vector to get from one region of the lattice to another. Hence all  $k$  values here are non redundant.

This thesis will focus on 2D photonic crystal slabs which are periodic in  $x$  and  $y$  and homogenous in  $z$ . More specifically, the crystals to be discussed are hole slabs, meaning that they have holes etched into their surface unlike the rod slab which is a lattice of dielectric rods in air. Upon analyzing which modes are prevalent for a rod or hole slab, it is the case

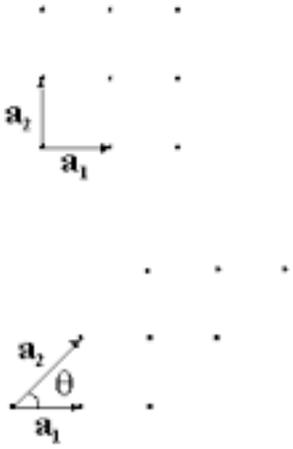
that a rod slab will have a TM-like gap and a hole slab will have a TE-like gap, knowing this information allows for choosing the correct parameters such as the slab thickness. The optimal thickness of the slab depends, firstly on whether it is a rod or a hole slab and how large or small the gaps are for the slab. For the case of a very thin slab, the gap may become too small as frequency differences between modes become too small. Whereas if the slab is very thick, the gap in the modes will become large. Hence the optimal thickness is close to half a wavelength, as this allows for a fundamental mode to be determined and also keeps higher order modes out.

As for determining the optimal values for the lattice constant  $a$  and the radius of the holes of the crystal, this is also determined based on what the operation wavelength is, the symmetry of the crystal, and the application. For the case of the crystals simulated in this thesis, the application of interest is in designing a mirror for use within an optomechanical cavity. Within an optomechanical cavity, the crystal is used to determine the modes, hence the crystals must be highly reflective of certain wavelengths of light. A way of determining what the optimal parameters are is by analyzing at which ratio of radius to lattice constant the largest band gaps are occurring. This will be where the highest quality will be, given a particular wavelength. To conduct this analysis, a simulation can be employed such as in this study, or the best radius and lattice constant can be determined by experimentation using a tunable plane wave source, such as a laser, power meter, and a spectrometer after fabricating a crystal of varying radius. The incoming wavelength from the laser is measured with a spectrometer so that the wavelengths for each power measurement is known. The three power measurements taken are the incoming, reflected, and transmitted. Measuring the

wavelength allows for the operational wavelength to be determined if it is not already known, and then the reflectivity versus ratio of radius to lattice constant can be visualized at the this wavelength.

Optimal geometry of the crystal is determined from the desired operational wavelength as well as fabrication limitations. Each type of geometry of a 2D photonic crystal slab will have a different band gap and hence a different value for lattice constant, thickness, and radius of holes or rods. The reason for this difference in band gap comes from the high symmetry points of the crystal in reciprocal space. The high symmetry points being points in reciprocal space where more symmetry operations can be done resulting in the point being copied onto itself. These points are denoted by  $\Gamma$ , M, and X for a square lattice and for a hexagonal lattice  $\Gamma$ , X, and K. When these points are determined, the value of the lattice constant  $a$  can be determined. To find the other parameters, the optimal ratio of thickness to lattice constant and hole/rod radius to lattice constant must be determined by analyzing where the highest reflectivity occurs for a given wavelength. In this thesis the parameters for the hexagonal photonic crystal were taken from a study in which these analyses were already done. For the square lattice crystals, this had to be done using a nested parameter sweep of the ratio of ratio to lattice constant and the same for the thickness. At first sweeps were done of only the ratios versus transmission and some interesting relationships were determined. The smaller the ratio of radius to lattice constant, the lower the transmission and the ratio of thickness to lattice constant showed a plot resembling a step function.

**Real lattice:**



**Reciprocal lattice:**

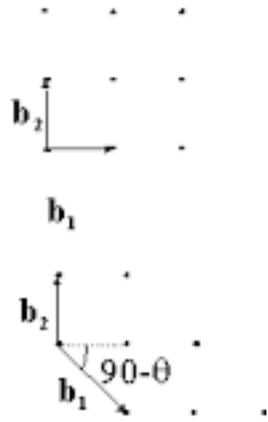


Fig .1. The lattice vectors of a square lattice, the real lattice vectors are shown on the left and reciprocal on the right. The reciprocal lattice vectors are related to the real lattice vectors by:  $b_1=(2\pi/a,0,0)$ ,  $b_2=(0,2\pi/a,0)$ .

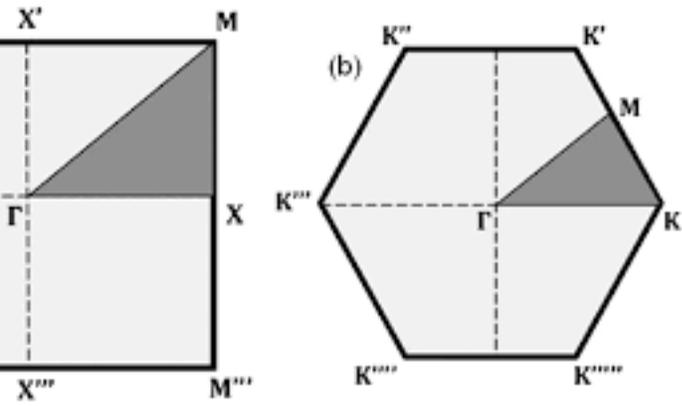


Fig.2. The high symmetry points of (a) square and (b) hexagonal lattices. The shaded region is the Brioullin zone of the lattice.

### *A. Materials of Photonic Crystal Slabs*

The materials of interest in this paper are gold, silicon nitride, and diamond. The motivation for choosing these materials is to compare the quality of a device made of a metal and one made of non metals. One benefit of using a metal for the material of the crystal is that the range of wavelengths absorbed by the crystal is large. Hence, the crystal will be highly reflective for a very specific wavelength. Metallic photonic crystals also have very interesting behavior when the operational wavelength is in the microwave domain. In one study from the Institut D'electronique Fondamentale, Université Paris, it was found that metallic crystals produced transmission spectra in the microwave domain which resembled that of a series of coupled optomechanical cavities, specifically Fabry-Perot cavities. The use of metallic photonic crystals is also prevalent for electrically controllable crystals because electronic components can be inserted into them.

Although metallic photonic crystals are in wide use and can be found to have useful properties, non metals are also frequently used for crystals. Non metals are also commonly used in combination with metals in certain designs of photonic crystals, however the non metal crystals in this thesis are pure silicon nitride slabs and pure diamond slabs. Unlike metals, non metallic photonic crystals do not take up the amount of volume and can produce very similar band structures, making them optimal for fabrication purposes. Silicon and doped silicon for example has been used in electronic components for many decades and now the optical properties of this material are being applied to the development of nano optics such as photonic crystals.

In photonic integrated circuits for example, silicon nitride is employed in order to construct low loss waveguides which can both withstand high optical power sources, as well as have both linear and non linear applications. Early use of silicon nitride began as early as 1970, when it was used for planar waveguides. These slabs were found to have small loss of around 1-2dB/cm. Much later around 2009, a project known as iPHOD was started at the University of California, Santa Barbara (UCSB) to create waveguide technologies. The goal of iPHOD was to design waveguides which demonstrated very low on chip loss. The efforts of UCSB along with LioniX produced waveguides which exhibited loss of 0.045dB/m loss at an operational wavelength of 1580 nm. There are also applications in biology, where silicon nitride photonic crystal arrays are used as biochips. A biochip can be designed to detect a certain type of biological phenomena which emits radiation, hence a silicon nitride array as a resonator can be applied for this. Overall, silicon nitride is a very dynamic material for optical experimentation and use in optical devices.

This thesis also examines the quality of devices made of diamond, another non metal. Diamond has been used in photonic devices such as crystals to make use of its sensitivity to certain wavelengths. In one study diamond photonic crystals were used to detect gases due to their ability to absorb polar molecules. Other applications which make use of the optically sensitive properties of diamond include biosensors. There have also been developments in the use of diamond nano structures and photonic crystals in developing quantum computing systems. This thesis will be analyzing the optimal geometry of a diamond photonic crystal.

The other material of interest in this thesis is gold, which has been found to possess interesting plasmonic effects. A plasmon is the quantization of plasma oscillation, just as a photon is quantization of an electromagnetic oscillation. Hence, a plasmonic effect occurs when free electrons in a metal or metal nano particles interact with incident light. Because there is what is called plasma oscillations, which are oscillations of the electron density within the metal, there is also a plasma frequency. If incident light is above the plasma frequency, then it will be transmitted as the electron density does not oscillate rapidly enough for any reflection to occur. Most metals are reflective in the visible range, as their plasma frequency lies in the ultraviolet range.

Most of current research for the use of gold in photonic crystals has been done by studying the optical phenomena when gold nano particles are added to the crystal's structure. The effects of adding gold nano particles to a natural occurring photonic crystal known as an opal was studied and it was found that the addition of the nano particles resulted in a magnification of light intensity for the visible spectrum. This in turn results in enhanced surface plasmon resonance. Surface plasmon resonance is the resonant oscillation of electrons at the interface of negative and positive permittivity. This phenomena is useful for the development of biochips as well lab-on-a-chip type devices. Photonic crystals with a metal film can also exhibit localized surface plasmon resonance, which allows for a tunable peak of reflectivity. This tuning can be achieved by varying the colloidal diameter or the film thickness.

In this thesis, the effects of constructing a 2D photonic crystal slab of pure gold will be investigated. The plasmonic effects of gold may be observed in a slab if they arise at all

based on examining the index of refraction of the gold photonic crystal slab, and possibly in the reflection and transmission spectra. So far there has been no use of 2D photonic crystal slabs of gold hence this simulation will show what the quality of these devices are and if they are useful for optomechanical experiments at the operational wavelength of 1064 nm.

### ***B. Geometries of Photonic Crystal Slabs***

The two types of geometry to be analyzed in this thesis are square and hexagonal. Because the physics of the photonic crystal itself does not have a direct relationship to the geometry for a 2D slab, numerical analysis such as the one done in this thesis are implemented. The numerical analysis typically involves a parametric sweep for the highest reflectivity or a sweep of the band structure versus ratio of one parameter to the lattice constant. Hence, to find the optimal design for a photonic crystal, fabrication limitations, and results of numerical optimization sweeps at the operational wavelength are taken into account.

It has also been found that certain geometries favor either TE (even) or TM (odd) modes. One study which analyzed the band structure of the same geometries discussed in this thesis found that a square slab was more likely to have a TM-like gap, while the hexagonal slab was more likely to favor a TE-like gap. It was found that this was a result of TE modes penetrating the regions on the crystal with a small permittivity. This was itself a result of the condition that the field lines had to be continuous for the square lattice. For the hexagonal

lattice, the issue of continuity did not occur, and the fields were able to enter the regions of high permittivity.

The correct ratio for other parameters such as thickness and hole or rod radius can also be determined from the band gap. This depends on what you would like the photonic crystal to operate as, whether it be as a mirror in an optomechanical cavity or a waveguide but ultimately the goal is to manipulate certain wavelengths of light. Hence to determine these parameters it is necessary to know what the operational wavelength is. There exist some equations which can relate the operational wavelength to the lattice constant. For example if the operational wavelength is to lie in the center of the band gap, the lattice constant is related to the frequency by  $\omega a/2\pi c = a/\lambda = f_0$ , where  $f_0$  is the mid gap frequency. Once the lattice constant is determined, the correct ratios for the thickness and radius can be found from a parametric sweep.

It has also been shown that a triangular lattice has a much wider band gap than a square lattice. This was found to be a result of the greater symmetry of the hexagonal lattice. Because of this greater symmetry and also a smooth curvature in the density of modes in the Brioullin zone, the triangular lattice makes a better candidate for the research of photonic crystals as waveguides. Hence it can be seen that the choice of geometry is dependent on the use of the crystal.

There have been other methods used to find a geometry that results in the maximum band gap. Voronoi centroidal tessellations which are constructed by distributing  $n$  points within the unit cell of the crystal and using what is known as Lloyd's algorithm to find the energy minimizing point, which is the point of least potential energy. The study which used this

method found that tessellations for  $n=1$  put to  $n=15$ , found that an array which resembled a honeycomb was optimal for a TE-like gap and a triangular arrangement for a TM-like gap. Further study found that the TM modes optimal geometry was evenly distributed pillars or disks, and for TE modes this was found to be closed wall structures, however this cannot be used for the case of a 2D hole slab, but could be used for the case of a rod slab.

There have been other methods used to find other ways of obtaining the desired band structure. In one study a change in the symmetry of the hole of a square lattice slab was found to produce wide band gaps. The study consisted of a numerical analysis of how the change in ratio between the lattice constant and the radius length in the vertical direction affected the band gap width. The same kind of analysis was done for the rotation of the horizontal axis which also found an increase in band width after performing a rotation.

Numerical analysis is most commonly used before fabrication of new photonic crystal designs, as it is costly to fabricate new devices which have no indication of yielding the desired results for an experiment. Discrepancies between the simulations and data taken from physical measurements will occur, hence a numerical analysis is not exact, however overall the results of a simulation will reflect that of the physical experiments. For a hole slab, discrepancies may occur due to a part of the manufacturing process known as etching. Etching is when the holes are created on the surface of the crystal by using a chemical to remove excess material. This is usually done by a specialized machine or by manually submerging the crystals in a bath of chemicals. The outcome of the etching can lead to more than the desired amount of material to be removed, for example an intended radius of 319 nm

can end up being closer to 311 nm. Error such as this can be the reason for differences in the numerical and physical experiments, however numerical experimentation is still reliable to predict how a crystal will behave with certain parameters.

## **II. Device Test for Optimal Material for Hexagonal Geometry**

### ***A. Discussion of Simulation***

Each of the simulations were done using the same parameters and showed very different reflection and transmission spectra. The plot for the gold photonic crystal slab seemed the most interesting as it showed both a peak reflectivity and peak transmission value within the same range around 1064 nm with 100% reflection. As expected, the silicon nitride slab showed only one peak although it was not exactly at 1064, but at about 1062 nm which is believed to be due to the difference in the index of refraction for the silicon nitride material that is available on Lumerical. The gold slab showed a peak reflectivity at about 1075 nm and had 89% reflection.

The simulation however showed that the gold slab may be a good candidate as a filter for certain experiments as it showed a peak transmission around the resonant frequency. However, after about 1500 nm the hexagonal gold lattice would function as a good reflector. Whether the results for the gold slab are physical is discussed later in this thesis.

The diamond lattice did not have good performance in transmission or reflection for a lattice constant of 1.185 microns and radius of 0.319 microns as expected, and a parametric sweep for the ratio and the lattice constant of the diamond hexagonal lattice was performed.

The maximum reflection was about 48% , at 1069 nm. The deviation from 1064 nm is

possibly due to similar reasons as the silicon nitride models, as the diamond material is simulated by defining a material with the same real and imaginary index values as diamond for the wavelength of interest. The negative reflected and transmitted power values are a result of the modes which exist within the diamond crystal being of the form of plane waves. These modes then interact both constructively and destructively with the incoming field which is itself a plane wave, both above and below the crystal. This results in the direction of power values at certain frequencies to be reversed in the simulation. This makes it difficult to conclude if peak reflectivity is occurring for the model of the crystal, as transmission is not zero in magnitude at the peak displayed in Fig.5 on the next page. The value of 48% reflection is however the largest value for reflected power on the range from 1034-1094 nm. The diamond slab exhibits much higher percentages for transmission on this range. The excited modes, which resemble plane waves, can be used to enhance reflection or transmission in the diamond crystal, however at 1064 nm 100% reflectivity was not seen, and instead transmission seemed to be the larger in magnitude from about 1075 nm and larger. The study hence showed that the design of a hexagonal silicon nitride lattice was the optimal design for peak reflectivity at 1064 nm, as this model gave the clearest results of peak reflection occurring.

### B. Transmission and Reflection Spectra

Fig.3. The transmission and reflection spectra versus wavelength ( $\lambda$ ) for the silicon nitride slab. The green curve is for reflection and the blue curve is for transmission. Peak wavelength is at 1.06298 microns.

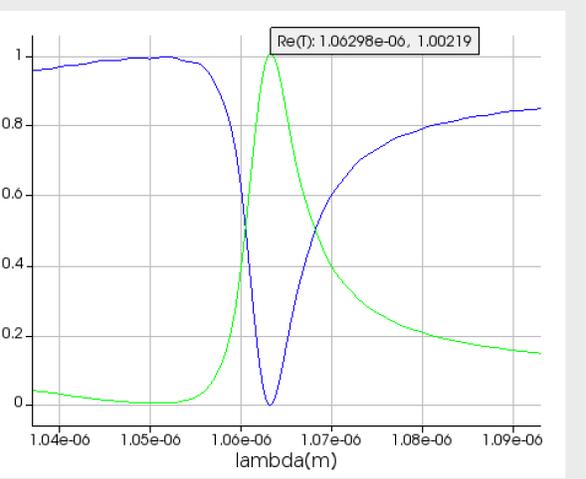


Fig.4. The transmission and reflection spectra versus  $\lambda$  for the gold slab. Green is reflection and blue is transmission. The wavelengths greater than 1500 nm are all mostly reflected, indicating that the slab could function as a band pass filter at resonance. Peak reflectivity is at a wavelength of 1.075 microns.

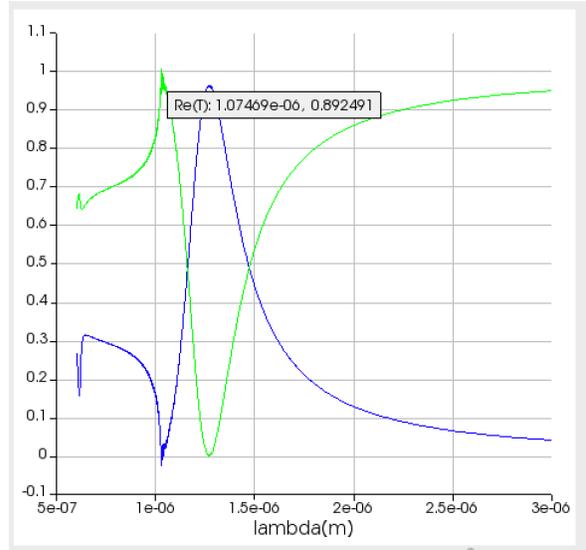
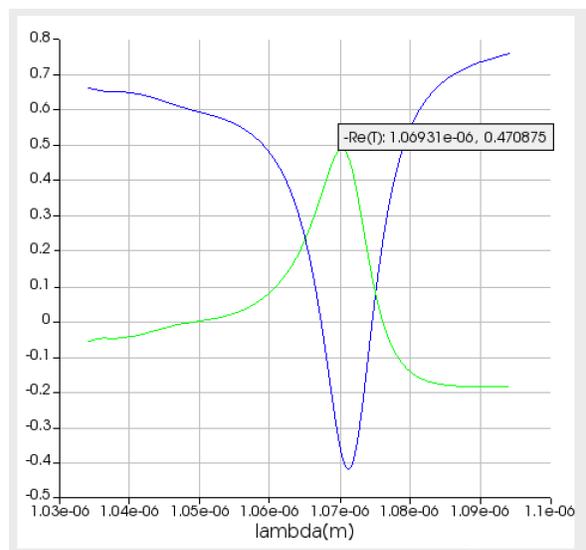


Fig.5. The transmission and reflection spectra versus wavelength for the diamond slab. Same color for reflection and transmission as gold and silicon nitride. Peak reflectivity occurred at about 1069 nm at about 48%. Negative power values are a result of constructive and destructive interference of the excited mode and incoming plane wave.



### **III. Device Test for Optimal Material for Square Geometry**

#### ***A. Discussion of Simulation***

For the simulation of the square lattice membrane, a nested parameter sweep of the ratio of hole radius to lattice constant was done first on Lumerical to determine the optimal sizing. A starting range for the parameter sweep of the lattice constant,  $a$ , was from 0.9-1.2 microns, using the operational wavelength as a metric, as  $a$  is typically around one half of a wavelength or more. A nested sweep was done for  $r/a$  versus  $a$  to minimize transmission. After performing multiple parameter sweeps over smaller and smaller ranges in order to increase the resolution, the optimal parameters for the silicon nitride square lattice crystal were found to be 0.9541 microns for  $a$  and 0.32 for  $r/a$ . The peak reflectivity was found at nearly the same wavelength as the hexagonal design at about 1062 nm, also for a range from 1034-1094 nm.

The square lattice did have a lower reflection than the hexagonal design, making a hexagonal design for a silicon nitride photonic crystal optimal for the operational conditions in this thesis. The reason for this discrepancy is a result of the modes favored by the crystal as mentioned earlier in the paper. Hence, a larger percentage of the mode which occurs at a wavelength of 1064 nm is allowed to propagate through the square lattice due to the geometry of the crystal. It is also interesting to note the difference between the lattice constant values for the hexagonal and square geometries, as there is a difference of about 231 nm between the values.

As this was a test of how changing materials effects the quality of device, the same parameters were tested on a gold slab just as was done with the hexagonal lattice. The results

of the square gold lattice were similar to the results from the simulation of the hexagonal design of gold, as the spectra for the square lattice slab also showed oscillatory behavior. The spectra of the gold lattice was observed over a range from 0.8-2 microns, as larger ranges produced some artifacts in the plot, such as unnormalized values.

The square geometry did perform about the same in terms of reflection, both showed maximum reflection of about 97%, however at different wavelengths. The gold slab did not show a clear peak of reflectivity, as there are many smaller oscillations which appear on the curves before what seems to be the peak. Both the hexagonal and square lattice gold slab designs have a high reflectivity as expected for a metal, however they both exhibit a peak for transmission rather than reflection at resonance. Hence, the results of these simulations showed that the optimal material for the square lattice geometry would also be silicon nitride rather than gold for the specified parameters.

A nested parametric sweep for  $r/a$  and  $a$  were run to determine the optimal parameters to obtain peak reflectivity at 1064 nm. The optimal lattice constant for the gold lattice was found to be 954.1 nm and the hole radius was found to be 114 nm. From these results, the difference in parameters between not only change in geometry, but also material must be noted, as the difference between the optimal parameters of the hexagonal and square gold lattice is large.

The diamond lattice did not show high reflectivity at 1064 nm, with a reflectivity of 35%, and much higher transmission values, similar to the hexagonal design. The same parameter sweep was done for the diamond lattice, however maximum reflection at 1064 nm was not observed. The diamond square lattice also showed higher transmission for

most of the wavelength range from 1034 nm to 1094 nm, where the peak reflectivity occurred at about 1072 nm. After performing multiple parameter sweeps there were very small changes in the transmission values with an apparent absolute minimum transmission of 45%. This was different than the outcome for the hexagonal design, which was able to be optimized for 1064 nm to some extent. The results of these simulations showed that both gold and silicon nitride were both able to achieve peak reflectivity at 1064 nm, as both of these designs were able to be optimized for this.

### ***B. Transmission and Reflection Spectra***

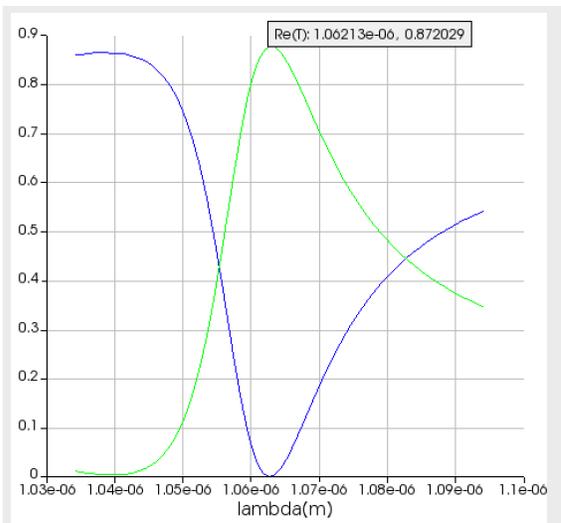


Fig.6. Reflection and transmission versus wavelength for a silicon nitride square lattice.

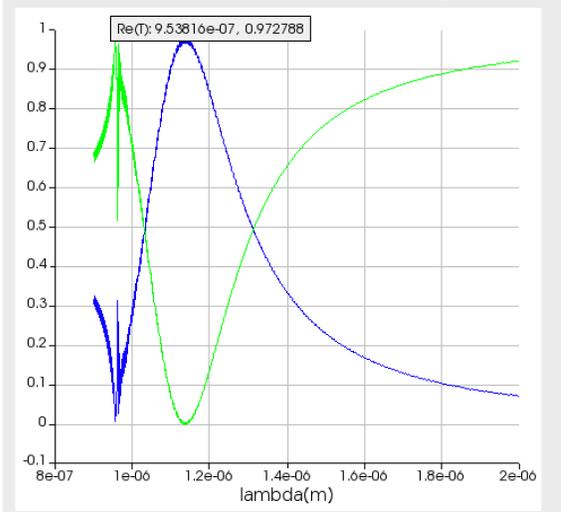


Fig.7. Reflection and transmission versus wavelength for a gold square lattice. The gold lattice shows potential to also be used as band pass filter, just as the hexagonal design for a lattice constant of 1.185 microns and a hole radius of 0.319 microns.

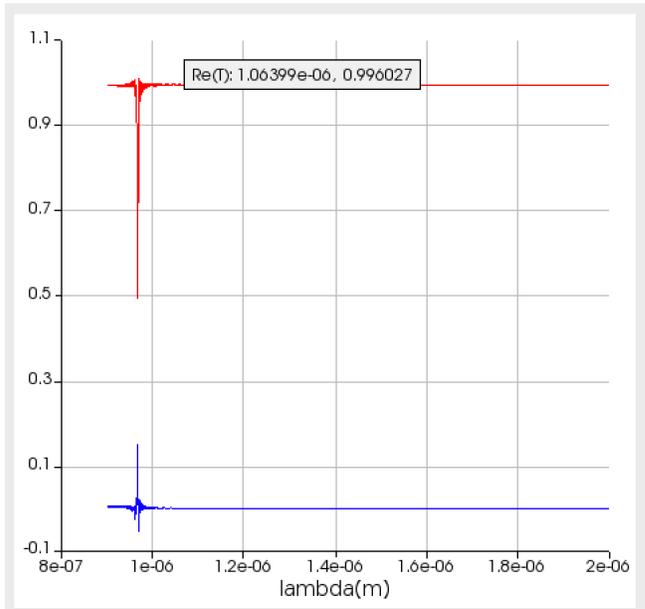


Fig.8. Reflection and transmission spectra of the optimized design for the gold hexagonal lattice. Hence, according to the simulations in this thesis, maximum reflection can be achieved in the range for 1064 nm.

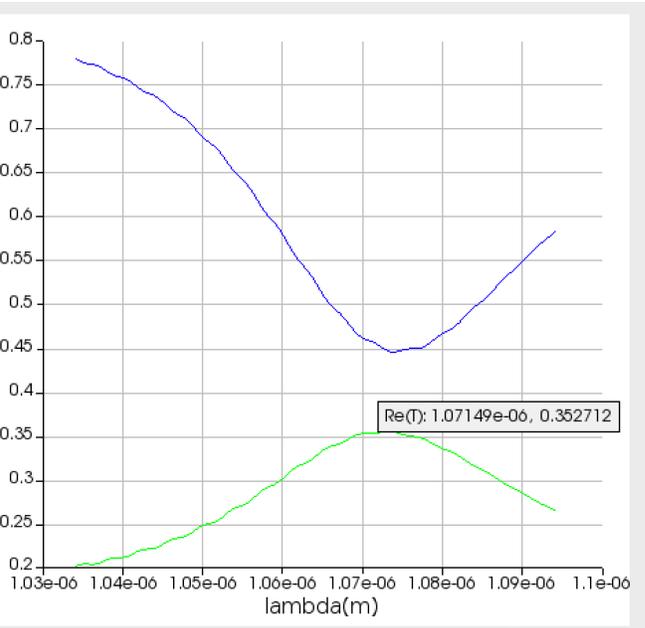


Fig.9. Reflection and transmission spectra for the diamond square lattice. Peak reflectivity occurs at about 1072 nm at 35%.

### *Conclusions*

For each series of simulations, the study seemed to consistently show either silicon nitride or gold as the optimal material. Perhaps if the square lattice diamond slab could have been optimized the best parameters for this design could have been found, however due to the cost in computational time, and the small decrease in transmission with each run, this was not able to be done using Lumerical. The minimum transmission found by the sweeps for diamond square was 45%, whereas the hexagonal lattice was able to be optimized to a peak reflectivity of 48%. It is difficult to say if the hexagonal design is achieving peak reflectivity, as the transmission values descend into the negatives due to the excitation of the plane wave modes of the crystal. Hence, diamond may still be a useful material, but would require further optimization for both of the designs.

The interesting spectra found for the gold photonic crystal slabs of square and hexagonal geometry must be physical, as a comparison of the reflection and transmission spectra of a solid gold slab with no defects was compared against the results of another study. From the simulations, it seems that an enhanced reflection and transmission can be obtained from adding the holes to the gold slab, however there is no way to verify if plasmonic effects are present as this would require an quantitative analysis of which effects, plasmonic or optical are predominant in the gold photonic crystal. Hence, according the simulations ran in this thesis, the gold crystal can exhibit maximum reflection at 1064 nm with optimal parameters. However due to the high loss when using metallic photonic crystals, it may still not be an optimal candidate for use in optomechanical cavities.

### 1. Comparison of Reflection and Transmission Spectra of Gold Slabs

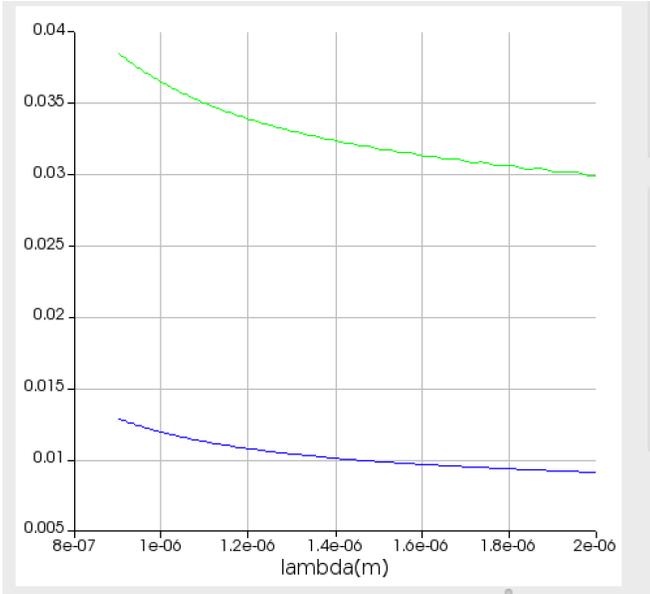


Fig.10. Reflection and Transmission spectra of a solid gold slab with no defects. As shown by the spectra below, all transmission and reflection is enhanced by the addition of the defect. The green is reflection and the blue is transmission

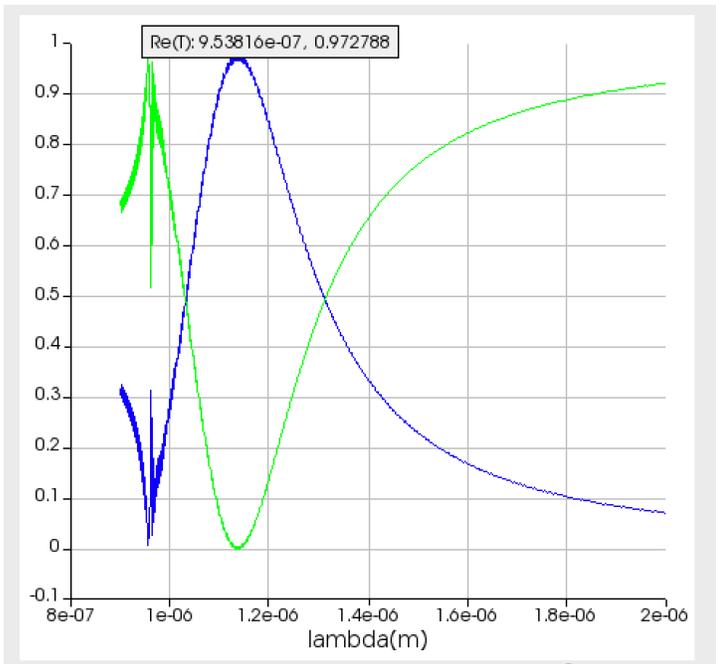


Fig.7. For comparison of the spectra of both a solid gold slab and a photonic crystal gold slab. The model of this design shows possible use as a band pass filter.

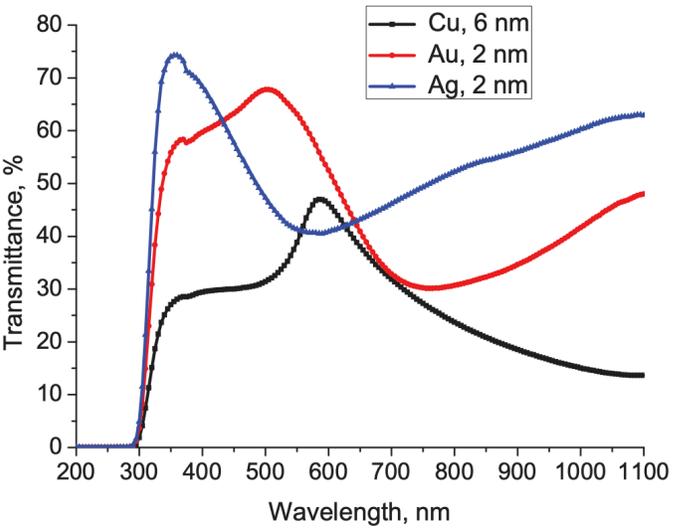


Fig.11. Taken from a study of the reflection and transmission spectra of thin gold slabs

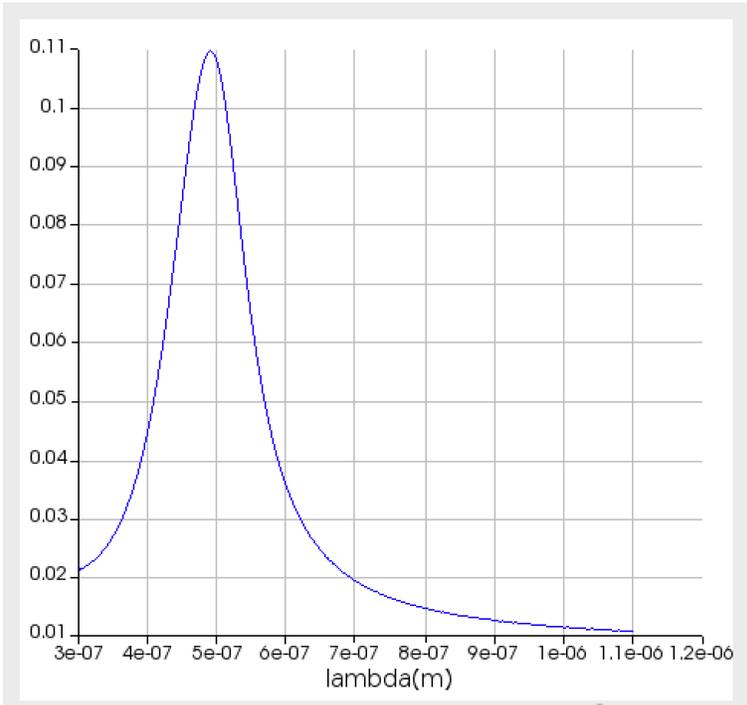


Fig.12. The results of the transmitted power of the model of a solid gold slab built on Lumerical, compared at the same wavelength range as the other study to show that the results of the gold photonic crystal are physical. Small power values are perhaps a result of scaling or material from the model.

## References

1. Saima Husaini, Huayu Teng, and Vinod M. Menon, “Enhanced nonlinear optical response of metal nano composite based photonic crystals”, *Applied Physics Letters*, 2012
2. Marko Lončar, Theodor Doll, Jelena Vučković, and Axel Scherer, “Design and Fabrication of Silicon Photonic Crystal Optical Waveguides” *Journal of Lightwave Technology*, Vol 18. No. 10 (2000).
3. Iole Venditti, “Gold Nanoparticles in Photonic Crystals Applications: A Review”, Department of Chemistry, Sapienza University of Rome (2017).
4. Jean-Michel Louritoz and Andre de Lustrac, “Metallic Photonic Crystals”, Institut d’électronique fondamentale, université Paris (2001).
5. R. Kazlauskas, P. T. Murphy, and R. J. Wells, “A new diterpene isocyanides from the sponge *Aplysilla rosea*,” *Tetrahedron Lett.*, p. 903 (1979).
6. Georgios Veronis, Robert W. Dutton, and Shanhui Fan, “Metallic Photonic Crystals with strong broadband absorption at optical frequencies over wide angular range”, *Journal of Applied Physics* 97, 093104 (2005).
7. Y Yu, B Yu, and X Gao, “Band Gap Design of Photonic Crystals Material”, School of Science, Beijing University of Posts and Telecommunications, Beijing 100876, People's Republic of China 2 School of Management Science and Engineering, Dongbei University of Finance and Economics, Dalian 116025, People's Republic of China, (2001)
8. Adrien Lalise, Gilles Tessier, Jerome Plain, and Guillaume Baffou, “Plasmonic efficiencies of nanoparticles made of metal nitrides (TiN, ZrN) compared with gold”, [www.nature.com/scientificreports](http://www.nature.com/scientificreports), (2016)
9. John D. Joannopoulos, Steven G. Johnson, Joshua N. Winn, and Robert D. Meade, “Photonic Crystals Molding the Flow of Light, Second Edition”, Princeton University Press (2008).
10. Ole Sigmund and Kristian G. Hougaard, “Geometric properties of optimal photonic crystals”, *Physical Review Letters* 10.1103/PhysRevLett.100.153904 (2008)

11. A. Axelevitch, B. Gorenstein, and G. Golan, “Investigation of Optical Transmission in Thin Metal Films”, Holon Institute of Technology, 18th International Vacuum Congress, Physics Procedia 32 (2012).

The following pages are intentionally blank.



























































