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TREBALL FI DE GRAU

Grau en Enginyeria Electrònica Industrial i Automàtica

3D PRINTED MICROWAVE SENSORS FOR FUSION PLASMA CHARACTERIZATION – PHOTONIC CRYSTAL TEMPERATURE SENSOR

Volum I

Memòria

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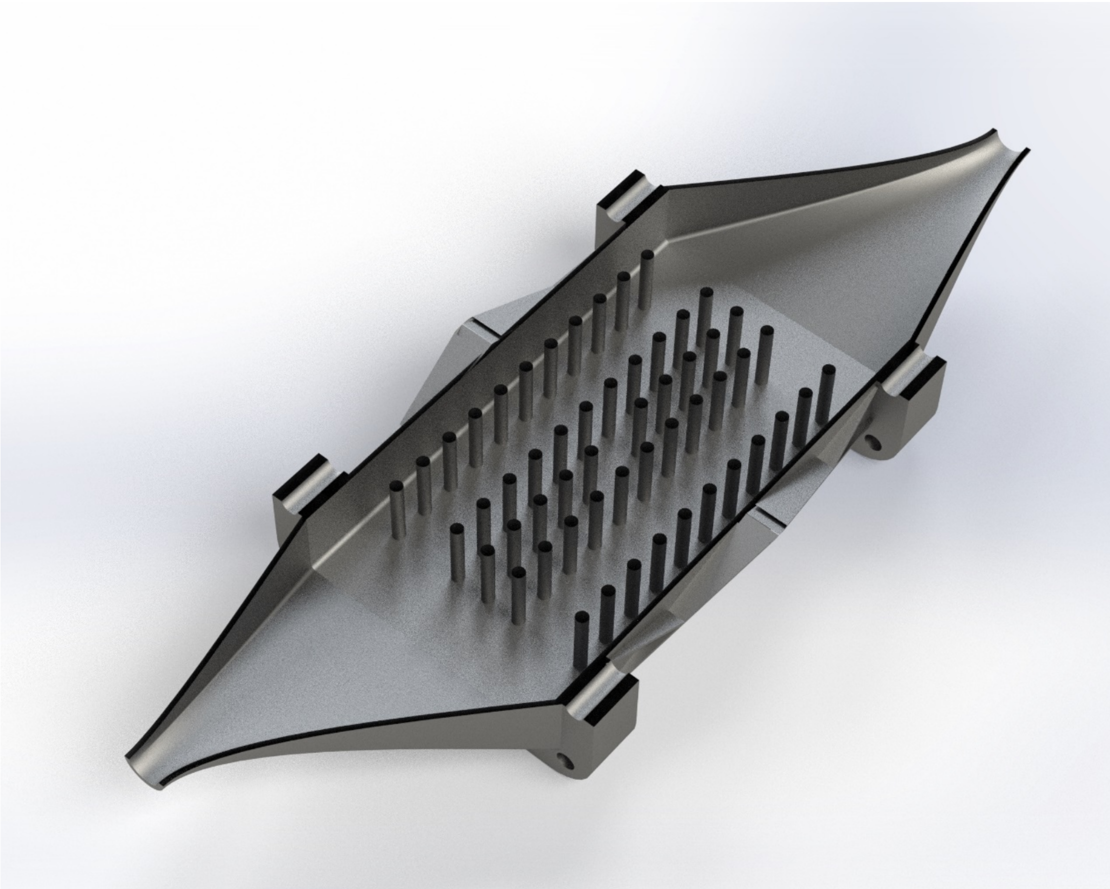
Departament Departament Electrònica
Convocatòria: Juliol 2022

PHOTONIC CRYSTAL TEMPERATURE SENSOR



1 JULI 2022

FONTYS HOGESCHOOL ENGINEERING

Minor Be creative

Semester 6

Students: Ahmed Baraako, Etienne de Kort, Thijs Luijten, Mohammad Abdulaal, Izaskun Comas

Tutor: Ralph Goes

Guiding Researcher: Chris Lee

I. FOREWORD

This is the report of the Be creative project group photonic crystal temperature sensor.

This report was written as part of the minor be creative. This is a research project to proof the concept of using a 2D photonic crystal to sense variations in temperature. This project is done by a group of 5 students with different technical backgrounds listed in 2.2 Cast.

The project group wants to thank Ralph Goes and Harold Benten for their guidance and organizational role within this minor. Furthermore, we want to give a special thanks to Chris lee for being our client this project and helping with the research and giving good technical feedback. Finally on behalf of the entire team we want to thank Differ for the guided tour and presentation about Differ and the PSI's.

Eindhoven, July 2022

Team: Photonic crystal temperature sensor

II. SUMMARY

This BeCreative minor project is focused on the development of an 3D-printed sensor. This sensor is being made to help the development of a fusion reactor. There are still issues with a fusion reactor, this BeCreative project group will try and overcome one of these issues. The issue lies within the diverter, a diverter is a part in the bottom of the reactor and because of the harsh conditions in the reactor will erode. The sensor that the group is developing will be used to get more information about this process and maybe come to a conclusion what other materials, structures or control strategies can be used to increase the lifetime this part of the reactor. The group is working together with the Dutch Institute for Fundamental Energy Research, they will help the group with additional information, resources, and equipment.

Because this is a research project the group has made a research question. This question will be answered at the end of the project. The main research question is: how is it possible to get data of the divertor's state of health during the exposure period of plasma? This question will be answered with a few sub questions, these can be found in chapter 4. Theoretical Research.

A photonic crystal is a repeating structure in which the refractive index changes periodically. The sensor will be made from a photonic crystal because it can be made to act an electromagnetic wave filter and designed to resonate at a chosen frequency. By making it out of a single heat resistant material (stainless steel, tungsten) the photonic crystal will be able to work at high temperatures and due to thermal expansion the resonating frequency will shift. This shift can be made visible using a network analyser temperature can be derived from it.

This photonic crystal will be made by a metal 3D-printer and the first prototypes will be made with the material stainless steel 316L. All the testing and measuring will be done on these prototypes, the follow-up project team to this project is going to make it out of tungsten so much higher temperature can be measured without the sensor breaking. During this project the photonic crystal will be designed to work between 4-8,5 GHz and measurements up to 200 °C this is purely because of the available equipment. In the future a sensor can be designed to work on much higher frequencies and temperatures. In this project the group will purely focus on proving the concept of using a photonic crystal as a temperature sensor. In the follow-up to this project the next steps will be detecting material degradation, Ion implantation and magnetic Flux density. But this is out of scope for this relatively brief research project of 20 weeks

The sensor will be tested by simulations in COMSOL and measurements in an oven and or on a hotplate with oil. The results that are listed in chapter 7. Results, are in comparison with the simulations in chapter 5.3 COMSOL Design this means that the conclusion is made that the temperature sensor works. There are few things that can be concluded after these tests, first the photonic crystal is temperature sensitive, and therefore can be uses as a temperature sensor. Second the results have demonstrate that 3D printing has sufficient precision and quality to make a microwave photonic crystal. And as last conclusion, the results show an agreement between theoretical models and experimental results, which indicates that the model can be used to optimize the designs without first experimentally testing each design.

III. ABBREVIATIONS

Table 1 Abbreviations

PSI	plasma surface interaction
NA	Network analyser
CAD	Computer aided design
Differ	Dutch Institute for Fundamental Energy Research
BIC	Brainport industries Campus
EMW	Electro Magnetic Wave
ITER	International Thermonuclear Experimental Reactor
2D	Two dimensional
T.B.A	To be announced
e.g	For example

TABLE OF CONTENTS

1. INTRODUCTION

The main problem that humanity is facing right now is global warming, the biggest problems is the generation of green and sustainable energy. One of the most promising solutions to this problem is energy produced by a fusion reactor, using the energy released when two different elements fuse together. The main benefit of a fusion reaction is that there aren't any greenhouse gasses released into the atmosphere and the lack of highly enriched nuclear material. The reaction of fusing atoms together in a controlled way releases nearly four million times more energy than chemical reactions such as burning oil, gas and coal. Figure 1 below here shows a tokamak fusion reactor and the part called the divertor.

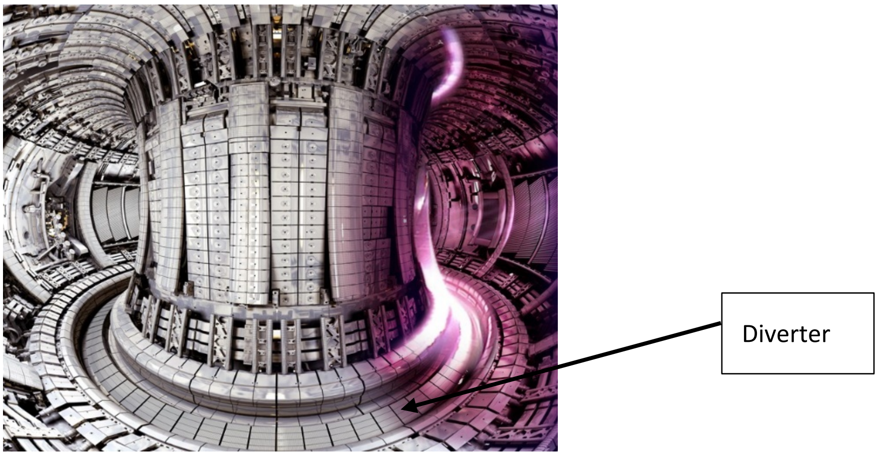


Figure 1 inside of a tokamak Fusion reactor

But there are still some problems with this technology which make it not viable yet. One of the problems of the fusion reaction is that at one point the plasma generated will come into contact with the surface of the reactor. This plasma has a lot of energy and will destroy all known materials, that's why the reactor has a sacrificial part at the bottom of the reactor called the diverter to prevent the plasma coming into contact with any other part of the reactor and thus protecting it.

This team's task during the project is to make a sensor that detect chance in different physical properties. This sensor needs survive in the environment of a fusion reactor and must be part of the structure of the wall and be made from the same materials. These physical properties could be, change in conductivity, temperature differences, changes in magnetic fields and material degradation and more. But for the first proof of concept this team will focus on making a sensor that will be highly sensitive to changes in temperature and temperature ranges other sensors are not able to survive.

A proof of concept will be 3D printed in metal and could be tested in the facility of DIFFER. In this facility there are two machine available for testing, the magnum PSI and the pilot PSI. With these machines the condition of a fusion reactor is recreated and therefore it can be used for testing prototypes.

1.1 PROBLEM DEFINITION

A lot of research is being done globally to find the best material and structure for the diverter. But because of the extreme temperatures of the plasma there aren't any sensors that can survive these conditions. Because of this the only data retrieved during an experimental test is the data comparing the test sample that was put into a reactor or PSI and with the one retrieved after the experiment is done. To better understand the process of heating and material degradation this team will make a proof of concept of a sensor that can collect data during the whole plasma exposure period of the test.

1.2 GOALS

The goal of this project is to aid in the fusion reactor research for a future sustainable energy source and to make a working sensor prototype that can detect changes in temperature by using a 2D structure photonic crystal.

The team has decided that the first and main goal is making a photonic crystal that can measure temperature. To start the first photonic crystal will be first designed to work around 4 GHz this means that the crystal will be quite big. This photonic crystal will be made purely to learn and test if it is possible to get any useful data when heating up the photonic crystal, further iterations of this sensor will be made smaller to comply with the dimensions allowed by the testing facility at differ.

The next goal is heating the photonic crystal and try to get measurements that can be translated into a temperature. When these measurements are successfully done a conclusion can be made and the concept is proven.

The last goal of the project is testing the photonic crystal at DIFFER in one of their PSI machines. This will be the last and hardest goal. When there are successful results from these tests there is a good possibility this type of sensor can help in the research of finding a suitable material/structure for the diverter.

1.3 ACTION PLAN

As listed above in 1.2 Goals there are few goals within this project. In this paragraph an action plan will be made on how these goals will be achieved. The approach for each iteration of the sensor will be the same four steps, the group will keep repeating these four steps (listed below) until the end of the project and making the sensor as good as possible within the given timeframe.

But before the team will start on making prototypes there will be some preliminary research done by each of the team members on a certain aspect of fusion reactors or photonic crystals. This way the team has an "expert" on all important topics for the project. Doing this makes it possible to get a lot of knowledge in the team in a short amount of time.

Four steps approach each iteration prototype sensor.

- Step one is designing a photonic crystal around a certain frequency.
- Step two is to simulate this prototype in COMSOL, the main goal of this is make sure the prototype is going to work before it is physically printed which costs a lot of money and time.
- Step three is to have the sensor printed in stainless steel 316L after which it will be machined on the mill to surface certain areas of the sensor to make it electrically conductive.
- Step four is to get the data out of the measurements to verify the simulation and making sure the iteration can be used as a temperature senor.

The following technologies will be used to create a sensor:

- Photonic crystals to filter/intensify certain frequencies.
- Metal 3D-printing, to create prototypes.
- The use of a network analyser to receive data from the sensor.
- Modelling the sensors in CAD.
- Physics simulation to verify concepts.
- Pilot PSI or Magnum PSI to test the prototype.

2. PROJECT MENAGEMENT

To guide this project in the right direction and to make sure to deliver results at the end of this project that the team can be proud of, several aspects have been carried out regarding project management. In this chapter all deliverables of the project will be described.

2.1 DELIVERABLES

There will be different deliverables presented throughout the project. Some documents must be submitted or updated every week. Other documents must be delivered during a midterm demo, at feedback sessions or at the end of the project. In this chapter all the different deliverables will be listed by category and chronological order.

Weekly deliverables

- Each member will update the weekly progress document where they describe in a few bullets points the progress they have made during the week and what they expect to do the next week.
- Each member will update a weekly blog where they describe the progress they made during the week and where they show on what soft/hard skills they have improved upon.

Midterm deliverables

- (11-mar / 1-apr / 25-may / 17-jun) Each member must make a Personal Development Plan, and these will be updated and discussed with the team and the tutor.
- (28-apr) There will be a midterm presentation and demonstration on the progress of the project
- (monthly's) To keep the costumer up to date on the progress and make it easier for future students to continue the project multiple midterm reports will be made.
- When a member has done some extensive research, they will make a report of this to share is with the other team members.

End of project deliverables

- A final report will be made about research findings, conclusions and problems encountered during the entire project.
- A final presentation about the entire project will be given to all the other students of the be creative minor.
- A video/demonstration of a proof of concept or functional concept will be presented.
- A poster that will be shown at the symposium at the end of the project.
- All members must have a written critical self-reflection based on feedback received and describe the progress on the soft/hard skills.

2.2 CAST

The Belbin test was used to divide the roles of the team members. The Belbin test gives a good indication of where everyone stands. The Belbin test can be found in appendix 11.2 Belbin Test.

The following roles were allocated through the test:

Team leader:
Etienne de Kort
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Mechanical engineer:
Thijs Luijten
thijs.luijten@student.fontys.nl

Electrical engineer:
Maite Comas Alvarez
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Electrical engineer:
Mohammad Abulaal
m.abdulaal@student.fontys.nl

Mechanical engineer:
Ahmed Baraako
a.baraako@student.fontys.nl

2.3 CONTRACT

The assignment must be carried out according to the schedule. The team leader will supervise this. The other team members are expected to communicate about the progress. If a deadline is not achieved, the schedule will be adjusted. If a meeting with the tutor cannot take place for whatever reason, Ralph Goes will be contacted. The KIVI code of conduct must also be adhered to.

The signed contract can be found in appendix 11.3 Code of Conduct

3. PROJECT DEFINITION

In the project definition, background information about the client is given, the package of requirements is set-up, and the boundaries of the project are described.

3.1 CLIENT

The client for this project is Chris Lee, Chris is doing research about photonic crystals with DIFFER. In the future they may want to use a photonic crystal for a sensor in a magnum PSI. for this research the team will help Chris to see if it is even possible to use a photonic crystal as a temperature sensor.

3.2 REQUIREMENTS

The requirements for the photonic crystal are drawn up by the team members. The wishes of the client have been considered. The following package of requirements is shown below:

Requirement	Temporary requirement	Final requirement
temperature	T>200°C	400.000°C
Dimensions	250*250*300 [mm]	T.B.A. by Differ
Frequency range	2-8,5 [GHz]	1-20 [GHz]
Measured physical properties	Temperature	Temperature, material degradation, Ion implantation, magnetic Flux density
Allowed materials	Stainless steel 316L	Chosen wall material for ITER reactor, which at this time is Tungsten.
Mounting	No requirement	T.B.A. by Differ

3.3 PROJECT FRAMEWORK

During the first period of the project, the focus is on coming up with and designing a concept for the photonic crystals but also to measure the temperature with a Network analyser and familiarize with the simulation software COMSOL. The concepts will be assessed, simulated and a concept will be developed into a working concept. Both 2D and 3D drawings will be made of the working concept.

4. THEORETICAL RESEARCH

In this chapter, the main question and sub questions will be answered. This will be done by the different research chapters listed below:

- Photonic crystals
- Microwave
- What it should look like (photonic crystal)
- How best to find out the measured value?

4.1 RESEARCH QUESTIONS

The first part of the project will be conducting research. To make sure the research is focused the correct way there is a main research question, to answer this question sub questions are made. The main research question for this project is: *how is it possible to get data of the divertor's state of health during the exposure to plasma?* This question will be answered with the following sub questions. *What is possible to sense using photonic crystals as a sensor?* To narrow the scope of the project it was decided to start with a temperature sensor and so the next sub question was made. *How does temperature influence photonic crystals?* Eventually a photonic crystal needs to be designed, the design will completely depend on the wavelength of the microwaves so therefore the second sub question is *How does the design of the photonic crystal influence the microwave response?* There are allot of different ways to design the photonic crystal, there are different dimensions, materials and measurements. So, the fourth sub question is *What structure does the photonic crystals need to be?* To make it work as efficiently/accurately as possible. Final sub question: *How to obtain useful data from the photonic crystal?* Without answering this question it is impossible to have a practical use for the PC.

Main question: *how is it possible to get data of the divertor's state of health during the exposure to plasma?*
Sub questions:

- *What is possible to sense using photonic crystals as a sensor?*
- *How does temperature influence photonic crystals?*
    - What kind of materials can be used as a photonic crystal in consideration with the available 3D printer materials?
- *How does the design of the photonic crystal influence the microwave response?*
    - *How can the response be predicted before 3D printing it?*
- *What structure does the photonic crystals need to be?*
    - What dimension does the photonic crystal need to be, 3d or 2d?
- How to obtain useful data from the photonic crystal?
    - *What is a Network analyser, and how does it work?*

4.2 PHOTONIC CRYSTAL

- *What structure does the photonic crystals need to be?*
    - What dimension does the photonic crystal need to be, 3d, 2d or 1d?

Photonic crystals can be defined as structures with a periodic structure filtering the propagation of certain emw frequencies and thus causing a change in the refractive index [2]. Photonic crystals can be one-dimensional, two-dimensional, or three-dimensional, depending on the structure being periodic in 1, 2, or 3 dimensions.

Although there are three different possibilities the 1D configuration does not achieve total control of the electromagnetic waves that propagate in more than one direction in space and is thus ruled out as a possibility for our purpose. Although the 3D structure will be able to give control of the wave propagation it will also add unnecessary complexity to the design, simulations and manufacturing. Therefore, the 2D PC is used as it sits right in the middle of complexity and give enough control of the wave propagation.

- *How does temperature influence photonic crystals?*

Another important point of this project is to determine how to find out the temperature sensed by our photonic crystal. That is why first needs to be found out how temperature influences the sensor.

For this it must understand that the refractive index of the photonic crystal material is altered as a result of the thermo-optical effect and the thickness of the layers or in our case of the pillars and spacing will expand due to thermal expansion. Therefore, the wave propagation of the crystal will change, and this can be measured over a frequency range.

- What kind of materials can be used as a photonic crystal in consideration with the available 3D printer materials?

For the material choice the thermal expansion and melting point must be considered. For the first question, it is essential for the material to be metal as it will be able to withstand higher temperatures and is a good conductor of heat. On the other hand, it must also be considered that the material should not be too expensive or difficult to machine (since a lot of different prototypes of the crystal are going to be made)

With all this in mind, the people responsible for 3D printing where contacted, and the only material option they offered that would suit our needs was 316L stainless steel.

4.3 MICROWAVE

How does the design of the photonic crystal relate to the wavelength of the microwave?

The microwaves are all the waves between the frequencies of 300 MHz and 300 GHz, with a wavelength between 1mm and 1m. As already explained the photonic crystal is a repeated structure with an exact dimension between two materials (e.g., air and steel), by changing this dimension the photonic crystal can reflect, block and filter different wavelengths. It has been found that if the spacing between the pillars of the 2d crystal is ¼ of the wavelength, this wave get blocked from passing through the photonic crystal.

4.4 NETWORK ANALYSER

What is a Network analyser, and how it was used during this project?

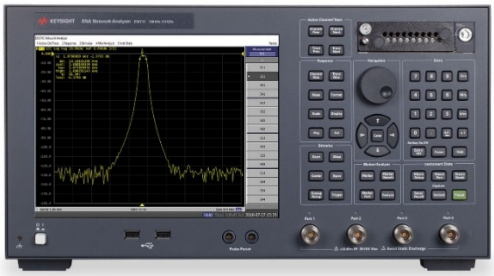


Figure 2 Network analyser

The network analyser (Figure 2) is an instrument that measures the network parameters of electrical networks. It was used during this project to measure the transmission and the reflection of the photonic crystal. This is done by using two of the ports of the network analyser, the first one emits a broadband of frequency, in this case it was between 3.5 and 5.3 GHz, through a small antenna to the other side of the photonic crystal, where it's received using another small antenna and sent back to the second port of the network analyzer. The difference between the two signals it is how the network analyzer calculate the transmitted and reflected frequency.

5. CONCEPT DEVELOPMENT

In this chapter the steps leading to the concepts will be described. Determinations such as: design, methods, choices etc will be justified.

5.1 CONCEPT OVERVIEW

For the design of the photonic crystal sensor, a frequency much be chosen. The whole photonic crystal will be designed around this frequency, the most important part is the spacing between the pillars, this is always ¼ of the wavelength. The other questions before printing are:

- How many pillars are needed?
- The thickness of the pillars?
- How wide can/should the protype be?

After answering and researching these questions, the first design was printed. this was done by the 3D printer that is available at the BIC.

The first printed concept is designed to resonate around 10 GHz see Figure 3. The spacing between the pillars is 8.83 mm with a diameter of 3.18 mm and a waveguide in the middle. The sides had to be as thin as possible 0.8mm to make the concept cheaper and less prone to warping, that is why ribs had to be made on the sides to improve stiffness.

The first concept was not able to be opened, this made it difficult to make antennas that would fit inside and receive the signal properly. For this reason the second concept (Figure 4) was made out of three sections that could be bolted together. Furthermore, the flanges needed to be thick to accommodate a place for clamping and reduction of material when they are surfaced. This is done to make the entire sensor electrically conductive. For the specific measurements of concept 2 see 11.4 Sensor Design.

The third concept that was printed is seen in Figure 6, this concept is allot smaller, the whole concept is $\frac{1}{3}$ the scale of concept 2. So the spacing between the pillars is 2.94 mm with a diameter of 1,06 mm. There are two waveguides and a distortion (defect of missing pillar) in the middle see Figure 6. This is done to be certain that all signals picked at the other end of the sensor are the result of the propagation in the distortion at the middle of the sensor. Before CAD modelling and 3D printing this sensor was simulated. The results were that it would work around 7,5 GHz.

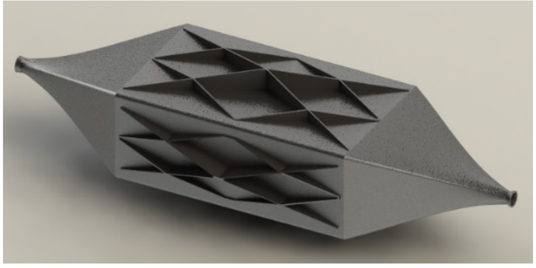


Figure 3 First printed concept

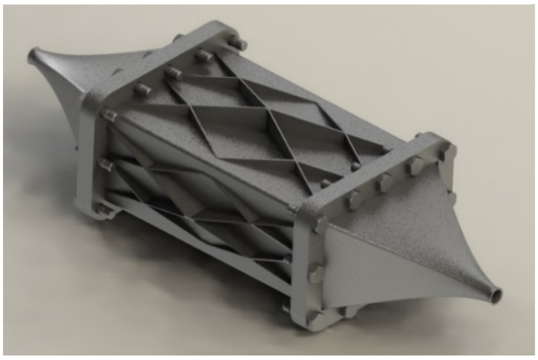


Figure 4 Second printed sensor

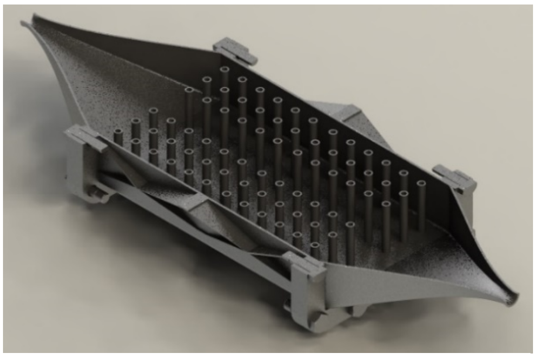


Figure 5 Section view second sensor

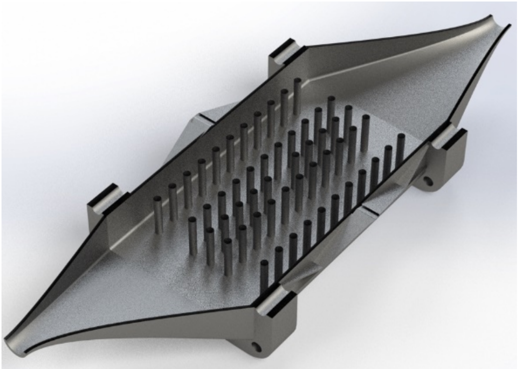


Figure 6 Sectionview third printed sensor

5.2 DESIGN DECISIONS

During the design process multiple decisions had to be made. To start a sensor was made with similar dimensions and spacing as out a research article [1]. This was done to be able to compare our values to the ones found in the article. But the available network analyser had a maximum frequency of 8,5 GHz and the range used in the article is 8-18 [GHz] so the comparison could not be made. However useful results were obtained at lower frequencies and where comparable with the simulations. for this reason the parameters where kept for all the concepts.

5.3 COMSOL DESIGN

Using COMSOL concepts can be created and tested before the physical PC is printed in metal. By doing this there can be made multiple minor changes to perfect the signal received by the network analyser.

To do this however the simulation needed to be verified so they could be trusted and perceived as reality. To do this there was made a concept which was printed in metal and recreated in COMSOL. The next step was to measure the response of the crystal when heated and compare this to the simulation results.

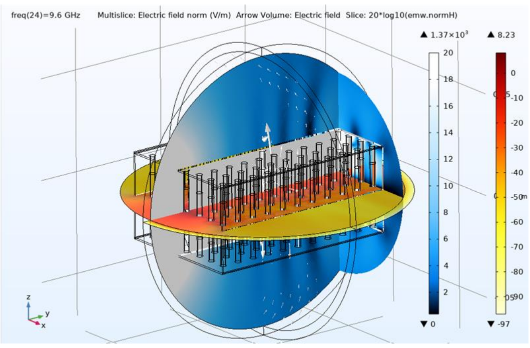


Figure 7 EMW propogration simulation

As shown in chapter

the measurements and simulation show the same type of response (down and left) at the valley when heated and at similar frequencies. The small deviation of frequency can be caused by a lot of different variables but is small enough to be considered as the same. Now the simulation is verified smaller concepts with different waveguides could be tested before they are printed, this saves a lot of time and material cost.

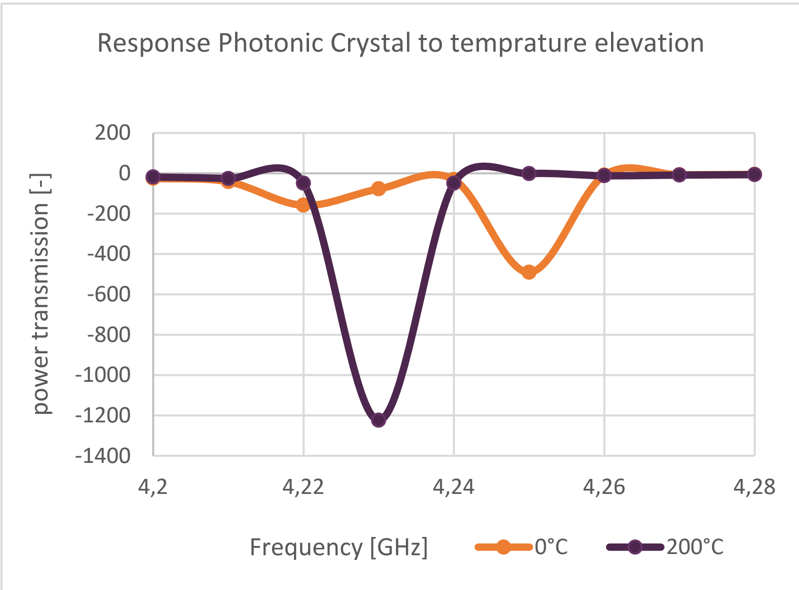


Figure 8 Response photonic crystal to temperature

The new concept as shown in 11.5 Comsol Simulation is smaller and with a different waveguide design. This will cause the valley to be at a higher frequency. But will also make the sensor itself smaller.

Fontys University of Applied Sciences

6. TESTS

Testing the different versions of the photonic crystal will be done using the network analyser and according to the following steps:

1. Testing the photonic crystal at room temperature to determine if the design works and is filtering the intended frequencies.
2. After establishing that the crystal works as intended at room temperature the heat test will begin and the temperature is slowly increased to 200°C with measurements taken at intervals of 20°C. this is all done in an annealing oven (Figure 9) to ensure good and even heating at all sides and after trying to do it in oil the first time. But This created a lot of smoke and only heated a single side of the sensor, for this reason this heating method was set aside for all future tests.

Figure 9 test-setup heating

7. RESULTS

To measure the results of our photonic crystal as a temperature sensor, the sensor was heated on a hotplate using oil to get good thermal contact with the sensor (1st experiment). The next step, to improve the results, was to heat the sensor in an oven (2n experiment) to get uniform heating on the entire sensor. The crystal was connected to the Network Analyzer and the following results were measured.

1st experiment

The result of the energy transmitted through the sensor in the first experiment is as follows.

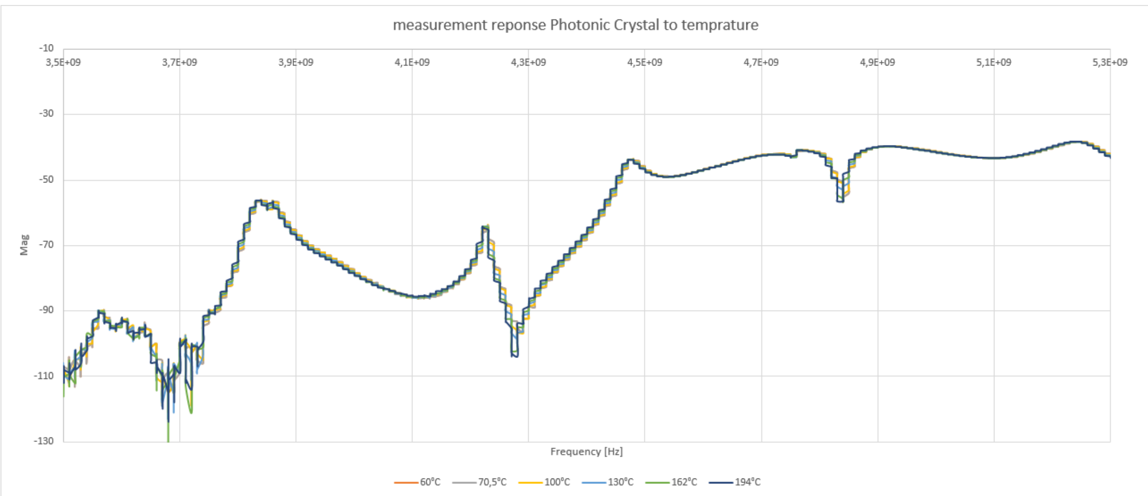


Figure 10 Frequency vs power transmission in the first experiment

The photonic crystal shows different changes in the energy passing through it according to the frequency sent to it with the Network Analyzer. Therefore, it can be deduced that the sensor is working. In addition, it can be seen that the shape of the graph obtained is very similar between the different temperatures to which the sensor is subjected; that is why it is also confirmed that the shape of the graph is not a random shape.

However, as the conditions of this first experiment were not the most suitable (as the movement of the wires was not considered and an inaccurate temperature sensor was used), it was decided to do a more in-depth analysis for the next experiment.

2nd experiment

The result of the energy transmitted through the sensor in the second experiment is as follows.

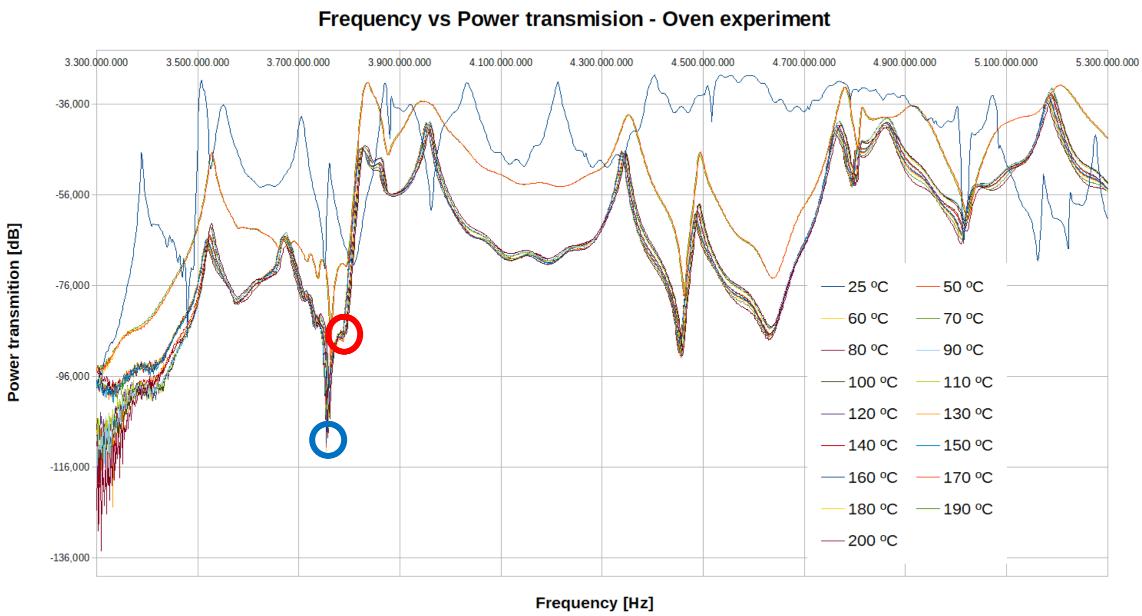


Figure 11 Frequency vs power transmission in the oven experiment

To see how temperature affects the sensor, the focus was set on two points on each temperature plot and measured their increase in frequency; in this way it can be deduced whether the plot widens or narrows depending on this property. For this purpose, the following two points on the graph where chosen: the minimum point of the graph around 3.75 GHz (blue circle in Figure 11) and the inflection point near 3.8 GHz (red circle in Figure 11).

The result of the increase of these two points at each temperature is as follows.

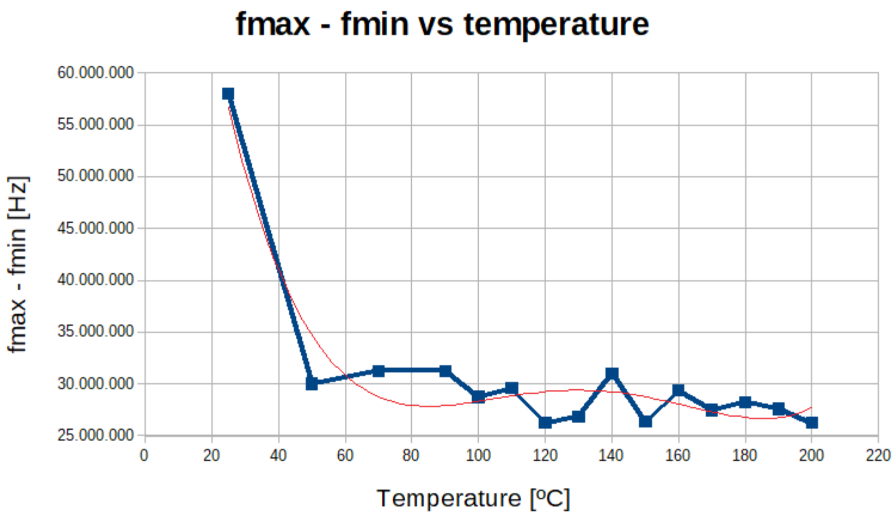


Figure 12 Temperature vs increase frequency between the two points.

As can be seen in Figure 12, the trend (red line in the graph) of the points as the temperature increases is that the distance between them is reduced. On the other hand, it can also be seen in Figure 12 that the transmission peak of the graph shifts to the right, on the X-axis, as the temperature increases.

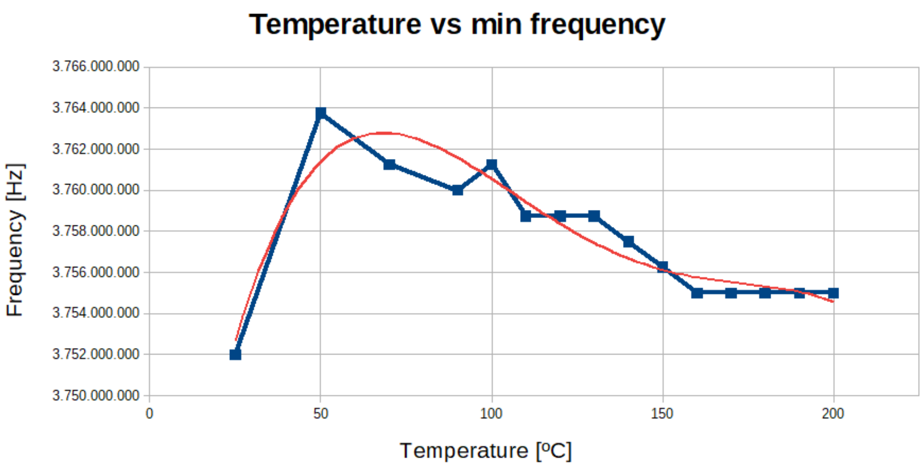


Figure 13 Temperature vs frequency in the deepest point of the graph.

As could be seen in the graphs, the tendency of the graphs is to narrow and shift to the right as the temperature increases. Even so, the first point (temperature of 25 °C) differs from this trend, but this effect is explained by the fact that the energy measurement under these conditions was performed outside the oven. This means that at the later time, when the photonic crystal was placed in the oven, there was a wire movement that caused this difference to appear.

7.1 RESULTS FINAL CONCEPT

the final concept as shown in Figure 6 and Figure 15was significantly decreased in size causing the resonating frequency to be higher compared to the other concepts. This concept was simulated in COMSOL with a temperature range from 0°C to 400°C and a step 0,02 GHz for the frequency. The resulting data was process into the graph shown below Figure 14. As can be seen the resonating frequency lays around 7.49 GHz and increases from 0°C until 250°C after which the signal becomes weaker again. The simulation was run until 400°C but the signal will continue to decrease in strength the higher the temperature will get. This range was good for the equipment we had to our disposal and to proof the concept. To make a temperature sensor that will work at the temperature expected from the plasma a different concept other parameters will still need to be designed. But this fell out of the scope of our project.

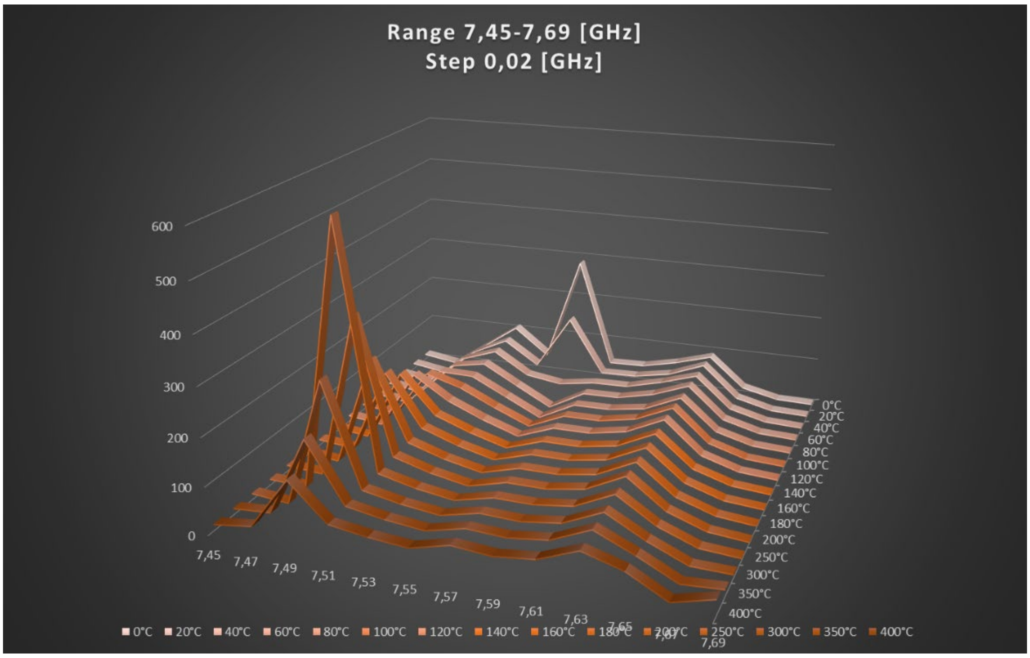


Figure 14 simulation results heating final concept

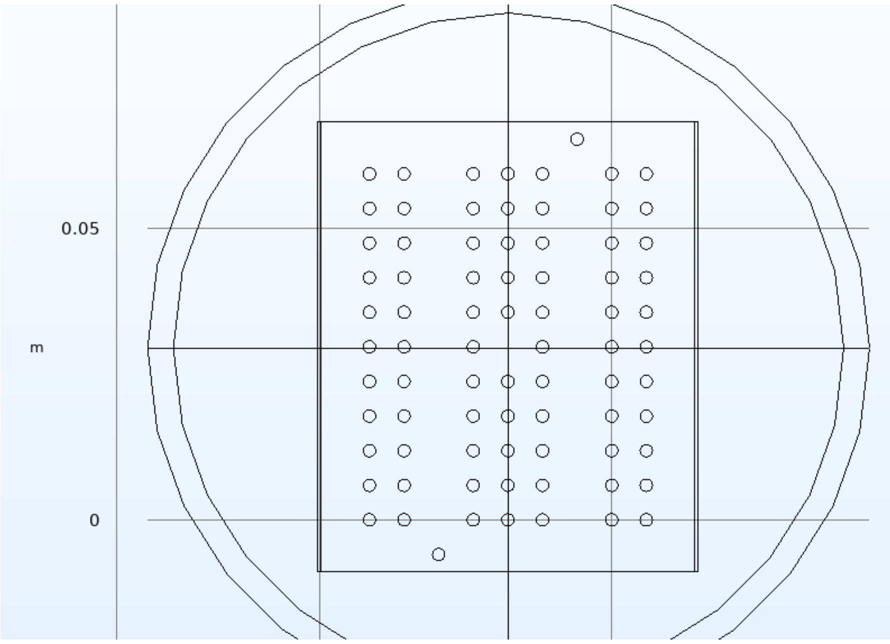


Figure 15 top view design final concept

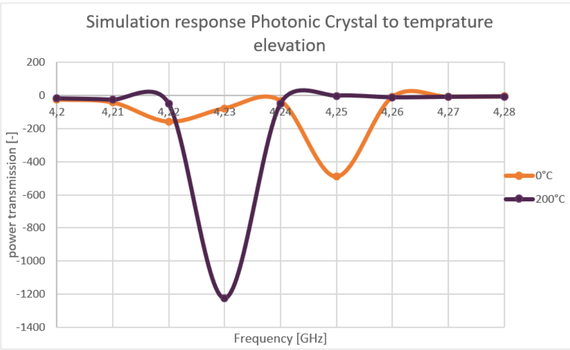
8. CONCLUSION

During the research of finding the best material/structure for the divertor a lot of data is missing. This is caused by the inability of having a temperature sensor in the fusion reactor during an experiment. The only data available now is the comparison of the test sample before and after the test.

To solve this problem the following research question has been formulated: *how is it possible to get data of the divertor during the exposure period of plasma?*

By using the property of a photonic crystal as a filter for certain frequencies and coupling this with the thermal expansion of the metal used to print the photonic crystal, should in theory give a filter with shifted filtered frequency as the temperature of the crystal is rising and this can be measured using the network analyser.

as shown in the results below (Figure 16) the team was able to make a simulation model that is comparable to the 3D printed version. Most importantly it is shown that an increase in temperature will lead to a shift in the graph, this means a successful temperature sensor was created using a photonic crystal.



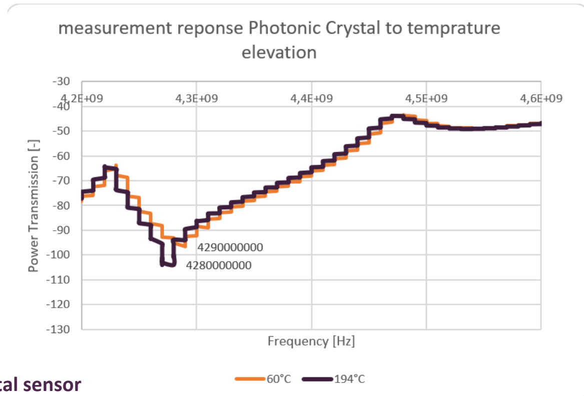


Figure 16 comparison measurement & simulation photonic crystal sensor response temperature increase

9. RECOMMENDATION

This group has been some good progress in this project, if another group will continue with this project there are a few recommendations for them.

- When a new group starts, try and first understand all the theory. Start again with research of all the big techniques that are used in this project.
- There is a new concept printed and simulated (7.1 Results Final Concept), look at the results in COMSOL and try to recreate these results in real life in the oven. Do the same steps as shown in the report. This concept has to waveguides and a pillar missing in the middle. Try and find if this works better or worse then one waveguide (the concepts in this report are made with one waveguide).
- Try and make the sensor so it can be measured at differ in one of the PSI's.
- Try to think about how to measure other deformities (material degradation, Ion implantation, magnetic Flux density besides).

10. BIBLIOGRAPHY

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11. APPENDICES

11.2 BELBIN TEST

The Belbin test was used to divide the roles of the team members. The Belbin test gives a good indication of where everyone stands. Through the test, the roles are divided fairly and respectfully.

Etienne de kort

	Roles	
==>	Implementor	10
	Coordinator	6
	Shaper	8
	Plant	5
	Resource Investigator	9
	Monitor Evaluator	4
	Team Worker	7
==>	Complete Finisher	12
==>	Specialist	10

Ahmed Baraako

	Roles	
	Implementor	7
	Coordinator	8
	Shaper	7
	Plant	7
	Resource Investigator	8
==>	Monitor Evaluator	10
	Team Worker	5
	Complete Finisher	6
==>	Specialist	12

Thijs Luijten

	Roles	
==>	Implementor	9
	Coordinator	3
	Shaper	8
	Plant	5
	Resource Investigator	3
	Monitor Evaluator	8
==>	Team Worker	11
	Complete Finisher	8
	Specialist	8

Mohammad Abdulaal

	Roles	
==>	Implementor	11
==>	Coordinator	10
	Shaper	9
	Plant	6
	Resource Investigator	4
	Monitor Evaluator	5
	Team Worker	8
	Complete Finisher	9
	Specialist	8

Izakun Comas Alvarez

	Roles	
	Implementor	7
	Coordinator	8
	Shaper	7
	Plant	7
	Resource Investigator	8
==>	Monitor Evaluator	10
	Team Worker	5
	Complete Finisher	6
==>	Specialist	12

11.3 CODE OF CONDUCT

3D PRINTED MICROWAVE SENSORS FOR FUSION PLASMA CHARACTERIZATION.

Attendance:

- If you come to the meeting later than 15 minutes, then it will count as if you are absent. Doing so twice, you will be expelled from the group. This will be also reported to the tutor.
- If somebody cannot come, he needs to inform it the day before the meeting. When somebody is quite often absent, the other students will decide in a meeting to expel him from the project.
- When you are late because of an unlikely circumstance we don't count it as being late if it doesn't happen occasionally

Assignments

- Individual assignments need to be delivered before 8 P.M. the day before the meeting or on another day/time if decided in the meeting.
- If somebody twice delivers the assignments late, or not deliver them, it will be discussed to expel him from the group.
- Wifi is no excuse
- Sport is no excuse
- Other course or assignment is no excuse
- Birthdays or parties are no excuse

C*ommunication:*

- If a question is asked in the WA group, everybody needs to answer it as soon as possible. If you don't know the answer you can say so in your response.
- The language used during the meeting and on WhatsApp is English. The final report and all assignments will be written also in English unless mentioned otherwise.
- If somebody needs help with finishing individual assignments, he needs to ask this on time, and not waiting until the next meeting or last moment. So, the group can find the solution in time.

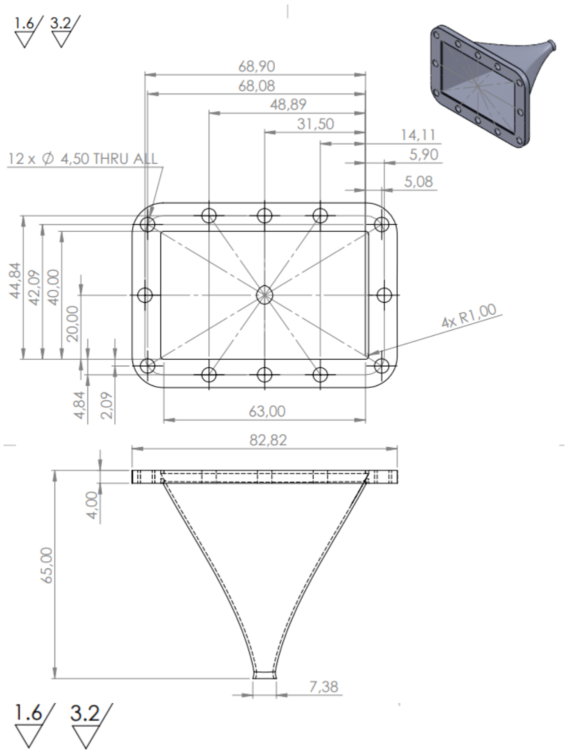
Deadlines:

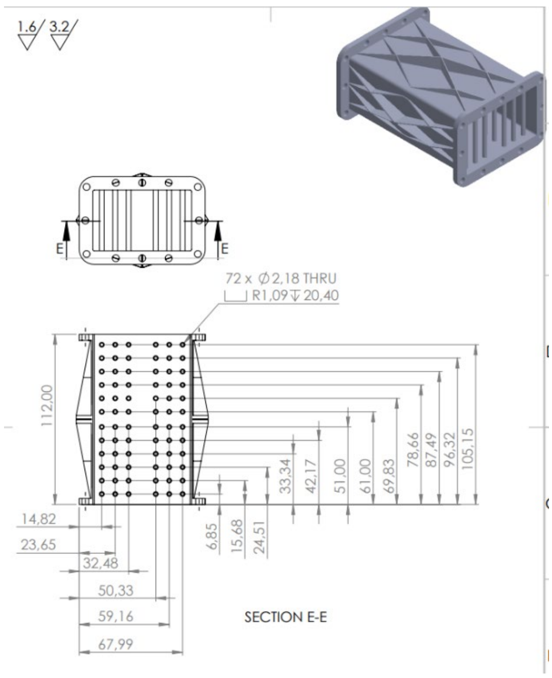
- The day before the meeting before 8 P.M, the assignments need to be delivered on OneDrive, unless agreed otherwise with the team leader.
- Before the meeting, everybody needs to read all the assignments.

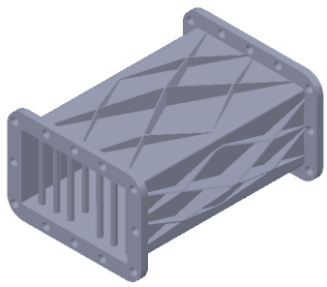
This contract is related to the persons mentioned below. By signing this contract everyone agrees with the terms and conditions:

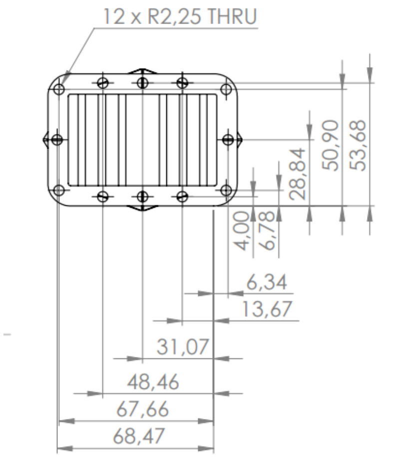
Etienne de Kort Izaskun Comas Ahmed Baraako Mohammad abdulaal Thijs Luijten

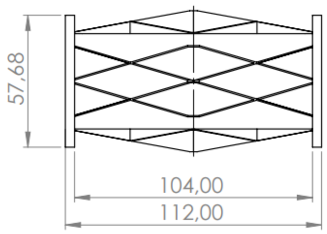
11.4 SENSOR DESIGN





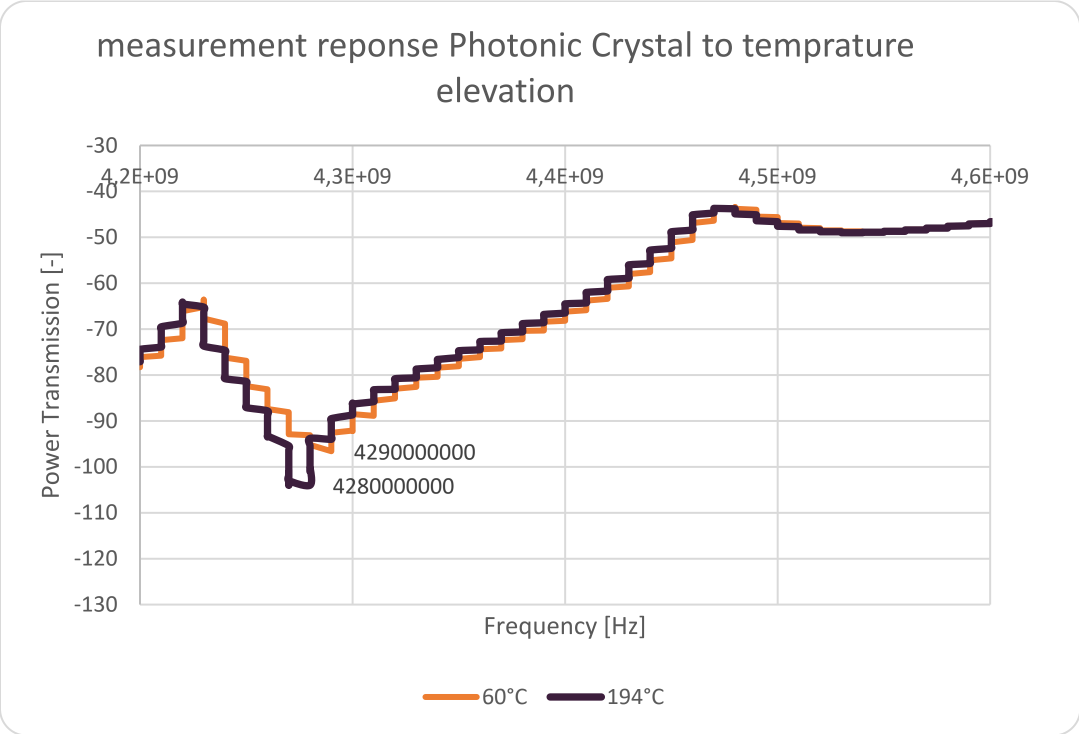




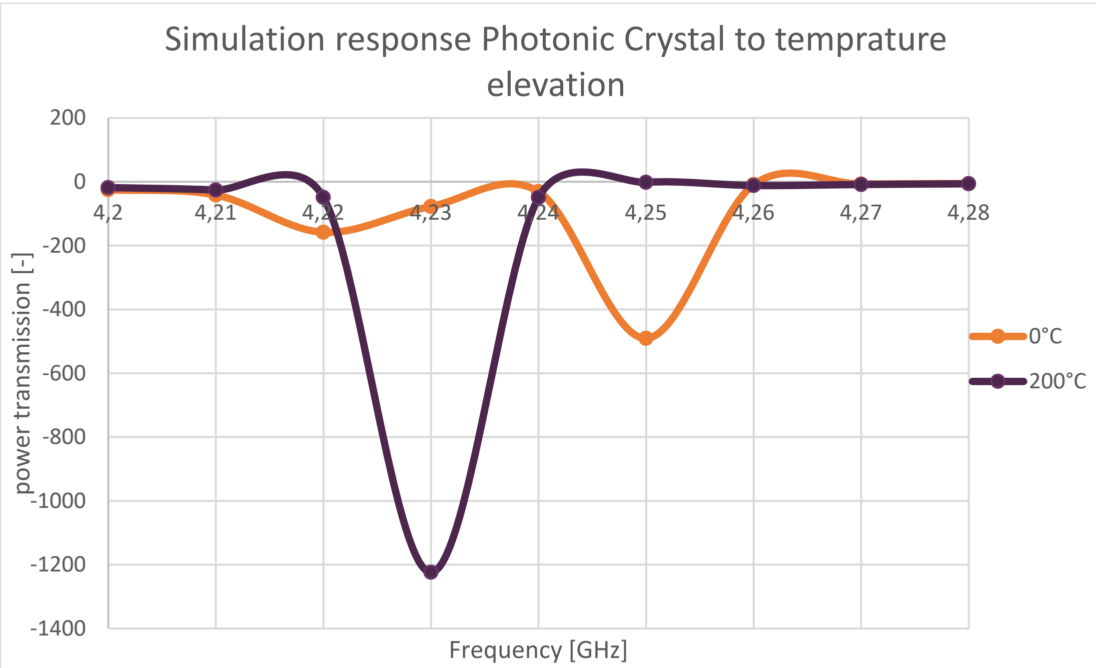


11.5 COMSOL SIMULATION

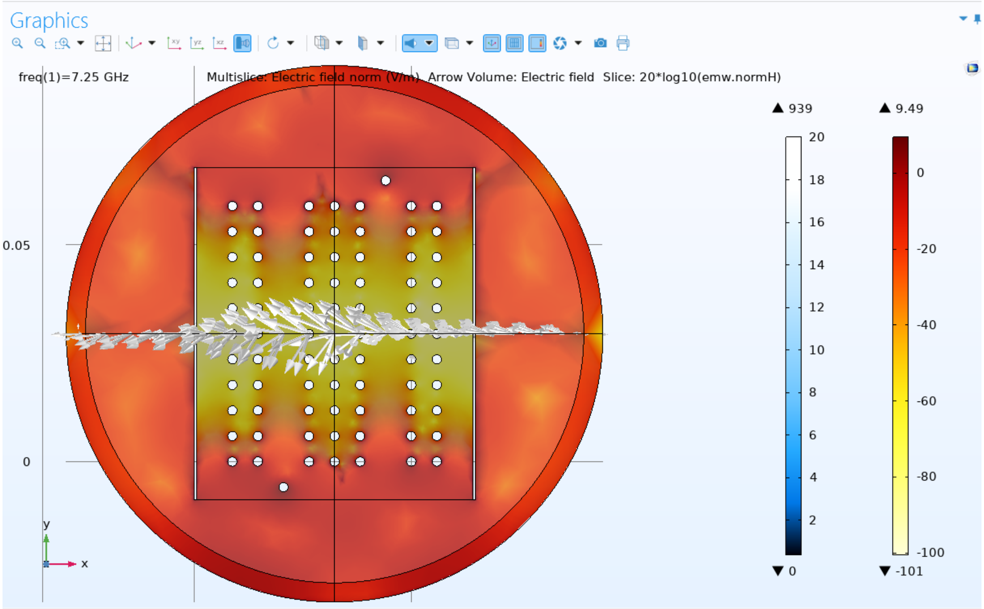
Measurement first concept PC



Simulation results first concept PC



EMW propagation third concept



Simulation respons EMW third concept.